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4th Baltic Earth Conference

Assessing the Baltic Sea Earth System

Jastarnia, Hel Peninsula, Poland, 30 May to 3 June 2022

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Front page photo: Beach access on Hel peninsula, Poland
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Acknowledgments

We thank our local partner institution, the Institute of Oceanology (IO-PAN) in Sopot, in particular Prof. Marcin Węsławski, for co-organizing this conference. We would like to specifically thank Karol Kuliński, Beata Szymczycha and Joanna Potrykus of IO-PAN for a dedicated and efficient collaboration in preparing the conference. Thank you also to Tomasz Jankowski of IO-PAN for technical support. Very special thanks go to Marcin Stokowski, Izabela Pałka and Michal Grabski, for organizing the Young Scientists Event.

Silke Köppen of the International Baltic Earth Secretariat at Helmholtz-Zentrum Geesthacht put together this abstract volume and the programme booklet, next to taking care of all the other small and large things necessary to make this conference a success. Sabine Billerbeck and Christin Menneking of Hereon, Berit Recklebe of IOW and Joanna Potrykus of IO-PAN were the team on site, taking care of registration and on-site organizing issues. Thank you very much to you all!

Last but not least, we would like to thank Marlena Lewicka of Hotel Dom Zdrojowy for helping with the local organization regarding the Hotel venue.

Preface

This is the second attempt for a Baltic Earth conference on the Polish peninsula of Hel. Two years ago, in early spring 2020, we had to cancel our preparation for an on-site conference in Jastarnia, due to the COVID-19 pandemic. Now, in 2022, the world can breathe a bit as the pandemic seems to fade out, or at least pause, and face-to-face meetings and conferences are possible again. So, we chose to have the 4th Baltic Earth Conference where the 3rd was planned, in Jastarnia on the Hel peninsula.

But then, just 2 years after COVID hit Europe in spring 2020, a man-made disaster has unfolded in the Baltic Earth region, in form of the Russian war against Ukraine. This war draws a terrible dividing line through the heart of the Baltic Earth region. We find ourselves confronted with a war, which is not a war of scientists, on either side. Still, we cannot ignore the situation and carry on as if nothing happened, also as sanctions entail rules which do not allow Russian and Belarusian scientists to benefit from jointly organized and paid Baltic Earth events. While we very much want communication and collaboration to resume as soon as possible, it is not clear how or when this will be possible. We deeply regret and condemn the circumstances that separate Russian and Belarusian scientists from the rest of the Baltic Earth science community. We hope for a future in which scientists from all nations can freely and peacefully share their research results at international events such as Baltic Earth conferences.

The scope of this 4th Baltic Earth Conference is "Assessing the Baltic Sea Earth System". This refers to the BEAR reports (Baltic Earth Assessment Reports), a series of assessment papers, which now have been published as Open Access papers in *Earth System Dynamics*. The BEAR papers encompass the range of Baltic Earth topics and represent overviews over the state of scientific knowledge of the respective topics. The BEAR assessments thus use the BACC reports as an example, but take this further to cover the whole range of Baltic Earth topics.

The sessions of this conference reflect the BEAR topics as well as the Baltic Earth Grand Challenges and topics:

Topic 1 Salinity dynamics (BEAR; GC 1)
Topic 2 Biogeochemical functioning and development: From catchment to the open sea (BEAR; GC 2)
Topic 3 Natural hazards and extreme events (BEAR; GC 3)
Topic 4 Sea level dynamics and coastal erosion (BEAR; GC 4)
Topic 5 Regional variability of water and energy exchanges (GC 5)
Topic 6 Human impacts and their interactions (BEAR; GC 6)
Topic 7 Sustainable management options (Baltic Earth topic)
Topic 8 Analysing and modeling past and future climate changes (Baltic Earth topic)
Topic 9 Comparing marginal seas (Baltic Earth topic)

The BEAR reports can be viewed as "wrap-ups" of the past 9 years of Baltic Earth. They represent the end of what could be called a first phase of Baltic Earth. Using these assessment reports, the closure or continuation of topics can be discussed, or new topics can be initiated.

This 4th Baltic Earth Conference is envisaged to be the forum to discuss these issues and generate ideas from which a second phase of Baltic Earth can be launched in a year´s time or so.

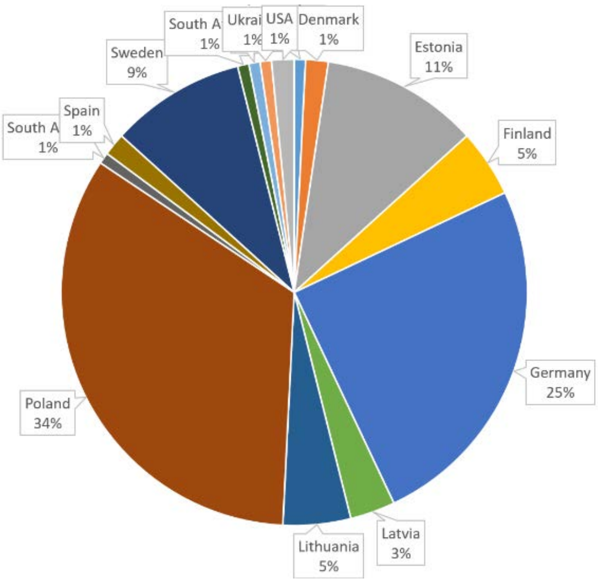
127 scientists have registered to participate in the conference. The conference is an on-site event, not a hybrid meeting. 116 presentations will be given at the conference, 68 as orals and 48 as posters. Speakers who did not have the opportunity to come to Jastarnia are given the opportunity to give a remote talk through zoom; 10 speakers took advantage of this possibility.

Participants from 14 countries have registered to the conference, among them also countries outside the Baltic Sea region. Strongest participation was from Poland and Germany, but when normalized to the number of inhabitants per country, the Baltic States, Poland, Finland and Sweden show the strongest participation. This mirrors that the Baltic Earth community is deeply rooted in the proper Baltic Sea countries.

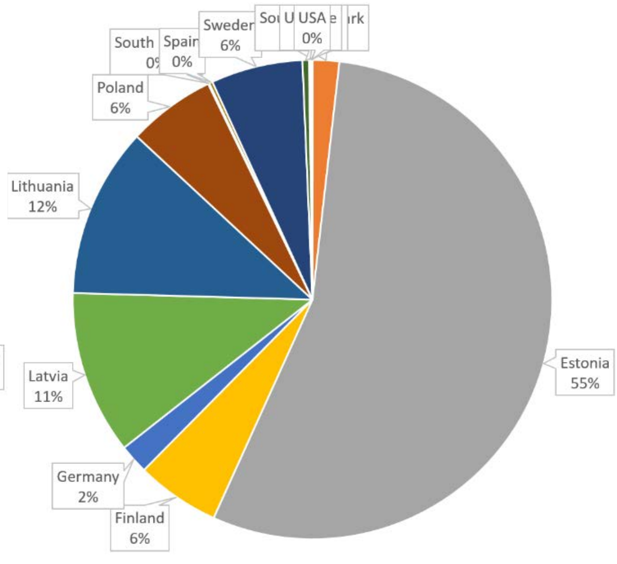
As usual, no discrimination is made in this volume regarding poster or oral presentation; they are all sorted alphabetically within topics.

We sincerely hope that this conference will be a fruitful and joyful experience for all participants, and that it may foster the international and interdisciplinary scientific exchange in the Baltic Sea region.

Marcus Reckermann, Markus Meier and Karol Kuliński



Participation by countries (affiliation)



Participation by countries (affiliation), normalized to population

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Contributions are sorted alphabetically within topics.

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Analysing and modeling past and future climate changes

Topic 9: Comparing marginal seas

Baltic Earth Poster

Abstracts are presented as submitted. No editorial changes were made.

Keynotes and special talks

Multiple drivers and natural and anthropogenic hazards creating risks for coastal and transitional systems - footprints of activities, pressures, effects and management responses

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1. Background and Hazard and Risk Typology

Coastal and transitional systems, such as those typical of the Baltic Sea area, are subject to endogenous and exogenous pressures which emanate respectively from hazards inside and outside the system (Table 1). In the case of endogenous managed pressures, both the causes and consequences of change are managed within the management area. In the case of exogenous unmanaged pressures, such as climate change, the causes of change are only managed at scales perhaps outside the management area, hence requiring action such as COP26, whereas the consequences (sea level rise, increased storminess, etc.) require to be managed inside the management area.

Those hazards may be both natural and anthropogenic although even the natural ones may be exacerbated by human actions (Table 2). For example, a natural hazard such as erosion of soft coasts may be exacerbated by the removal of vegetation (e.g. saltmarshes, mangroves) which could confer coastal protection.

When those hazards affect features valued by society for human safety and well-being they are termed risks which therefore need to be addressed by a risk assessment and management approach (for example, the ISO accredited and industry-compliant Bow-tie analysis). However, given the changes due to stressors such as climate change, and the potential for mitigation and adaptation, then opportunity assessment and management will also be important. For example, climate change may cause a stock of a fished species to move polewards but this could be replaced by another species moving from lower latitudes, thereby giving a fishery opportunity to balance the fishery loss due to climate-induced distribution changes.

Table 1 Examples of endogenic and exogenic pressures

Exogenic unmanaged pressures	Endogenic managed pressures
Alien species Sea level rise Increased temperature Increased storminess Flooding and erosion Changes to catchment run-off Repercussions of NAO Agricultural runoff in catchment Saline ingression	New infrastructure Energy generation Petrochemical industries Dredging and navigation Wetland loss and gain Urban discharges Mine-water discharges Subsidence Historical pollution residues

Table 2 Hazard and Risk Typology (Elliott et al., 2019)

Hazard	Natural or Anthropogenic (examples)
A) Surface hydrological hazards	Natural but exacerbated by human activities (e.g. High tide flooding, spring tide and equinoctial flooding; flash flooding, ENSO/NAO patterns; flow delivery repercussions of catchment modifications (land use increasing sediment loading, dams decreasing peak flows and sediment loadings, etc.))
B) Surface physiographic removal by natural processes - chronic/long-term	Natural but exacerbated by human activities (e.g. Gradual erosion of soft cliffs by slumping, estuary bank erosion by prevailing currents)
C) Surface physiographic removal by human actions - chronic/long-term	Anthropogenic (e.g. Land claim, removal of wetlands for urban and agricultural area)
D) Surface physiographic removal - acute/short-term	Natural (e.g. Cliff failure, undercutting of hard cliffs and intermittent erosion)
E) Climatological hazards - acute/short-term	Natural but exacerbated by human activities (e.g. Storm surges, cyclones, tropical storms, hurricanes, offshore surges, fluvial and pluvial flooding)
F) Climatological hazards - chronic/long term	Natural but exacerbated by human activities, or anthropogenic (e.g. Ocean acidification, sea level rise, storminess, ingress of seawater/saline intrusion)
G) Tectonic hazards - acute/short-term	Natural (e.g. Tsunamis, seismic slippages, earthquakes)
H) Tectonic hazards - chronic/ long-term	Natural (e.g. Isostatic rebound, subsidence)

I) Anthropogenic microbial biohazards	Anthropogenic (e.g. Sewage pathogens)
J) Anthropogenic macrobial biohazards	Anthropogenic (e.g. Alien, introduced and invasive species, GMOs, bloom-forming species)
K) Anthropogenic introduced technological hazards	Anthropogenic (e.g. Failures or mismanagement of infrastructure, coastal defences, catchment impedance structures (dams, weirs))
L) Anthropogenic extractive technological hazards	Anthropogenic (e.g. Removal of space, removal of biological populations (fish, shellfish, etc.); seabed extraction and oil/gas/coal extraction leading to subsidence)
M) Anthropogenic acute chemical hazards	Anthropogenic (e.g. Pollution from one-off spillages, oil spills)
N) Anthropogenic chronic chemical hazards	Anthropogenic (e.g. Diffuse pollution, ocean acidification, litter/garbage, nutrients from land run-off, constant land-based discharges, aerial inputs)
O) Anthropogenic acute geopolitical hazards	Anthropogenic (e.g. Terrorism attacks leading to damage on infrastructure)
P) Anthropogenic chronic geopolitical hazards	Anthropogenic (e.g. Wars created by shortage of resources (e.g. land, water, minerals))

2. Activity-, pressures- and effects footprints

By linking to several of the Baltic Earth Grand Challenges, this presentation interprets the natural and anthropogenic hazard and risk typology in the light of: (a) where and when human activities take place (the activity-footprints); (b) the area and time covered by the pressures generated by the activities on the prevailing habitats and species, in which pressures are defined as the mechanisms of change (the pressures-footprints), and (c) the area and time over which any adverse or beneficial effects occur on the natural system and on ecosystem services from which society extracts goods and benefits (the effects-footprints).

While the activity-footprint may be relatively small, the pressures emanating from the activity cover a larger area, especially in highly dynamic sea areas. The effects-footprints then cover an even larger area, especially where they affect highly mobile species such as cetaceans and seabirds which may be affected by the pressures and then move to breeding and feeding grounds well away from the site of the activity. The effects of activities and their pressures are relatively straightforward to determine on sessile habitats and species but especially more difficult on those highly mobile species. This results in the cause-consequence chains being difficult to discern.

3. Management response-footprints

These three types of footprints then need to be addressed by a spatial and temporal programme of management measures, i.e. the management response-footprints (Figure 1). The latter extend from small area management (such as carrying out Environmental Impact Assessments for individual activities, leading to permitting of the activity), through Baltic Sea wide initiatives (such as Regional Seas Agreements such as HELCOM), to global initiatives such as treatises and conventions (e.g. UN Convention on Law of the Sea, International Maritime Organisation).

This presentation explains the rationale behind this typology and their definition for future implementation of marine governance (policies, politics, administration and legislation). It emphasises the transboundary nature of these aspects and their inclusion in marine resource sustainable and successful management.

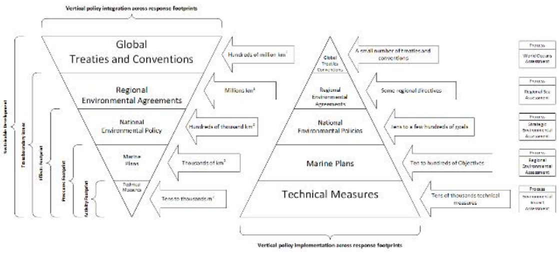

Figure 1. The management response-footprint pyramid (from Cormier et al., submitted).

4. Spatial Implementation of management measures

This internationally-based approach encompasses Maritime Spatial Planning, Cumulative Impacts Assessment and Strategic and Regional Environmental Assessments. This also reflects the global coastal assessment being promoted by Future Earth Coasts.

The analysis is included and developed in recently published and submitted papers (Borja & Elliott, 2021; Cormier et al., (submitted), Elliott et al., 2020a,b).

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Future climate change: Results from the Coupled Model Intercomparison Project Phase 6 (CMIP6)

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1. The Coupled Model Intercomparison Project Phase 6

The Coupled Model Intercomparison Project Phase 6 (CMIP6) coordinates global model simulations with the newest generation of global models (Eyring et al. 2016). CMIP6 consists of three major elements: (1) common experiments that every model has to do, the DECK (Diagnostic, Evaluation and Characterization of Klima) and CMIP historical simulations (1850–near present); (2) common standards, coordination, infrastructure, and documentation that will facilitate the distribution of model outputs and the characterization of the model ensemble; and (3) an ensemble of CMIP-Endorsed Model Intercomparison Projects (MIPs) that will build on the DECK and CMIP historical simulations to address the three broad questions:

- How does the Earth system respond to forcing?
- What are the origins and consequences of systematic model biases?
- How can we assess future climate changes given internal climate variability, predictability, and uncertainties in scenarios?

The Scenario Model Intercomparison Project (ScenarioMIP, O'Neill et al. 2016) is the primary activity within CMIP6 that will provide multi-model climate projections based on alternative scenarios of future emissions and land use changes produced with integrated assessment models.

This presentation will provide an overview on some major outcomes of ScenarioMIP.

2. Projected Future Changes

Global mean temperature and precipitation will continue to increase in the 21st century. Only under the lowest emission scenario ssp1-1.9, a small number of CMIP6 models show maximum warming rates below 1.5K compared to pre-industrial values while the majority of models simulates a warming between 1.5 and 2K. Already under the second-lowest emission scenario (ssp1-2.6) around 50% of all models exceed 2K compared to preindustrial values. The ssp2-4.5 scenario leads to an average global temperature increase of around 3K; in the strongest emission scenario (ssp5-8.5) around 5K warming are reached (Tebaldi et al. 2021).

Regionally, the strongest warming occurs in polar regions. Precipitation increases generally in polar and tropical regions while it decreases in some sub-tropical regions.

Arctic sea ice extent and volume decrease, and a majority of models simulate a total summer sea ice loss in all emission scenarios except for the two lowest emission scenarios (ssp1-1.9, ssp1-2.6). Uncertainty across models is largest; when selecting those models that represent present ice conditions best, summer sea ice might disappear as early as 2035 (Docquier and Koenigk 2021).

Ocean circulation will change with important changes on the regional climate. The Atlantic Meridional Overturning Circulation (AMOC) decreases in all CMIP6 models in the 21st century; depending on the model and the scenario between 4% and 53% (Weijer et al. 2020). This AMOC decrease reduces the greenhouse gas driven warming in the North Atlantic region and surroundings compared to other regions at the same latitude.

3. Comparison to CMIP5

CMIP6 model biases in historical simulations are smaller than in CMIP5 although the improvements since CMIP5 have been smaller than between CMIP5 and CMIP3 (Bock et al. 2020).

In general, the projected multi-model changes are larger in CMIP6 compared to CMIP5 for many variables. However, some cautious is necessary as the RCP-emission scenarios used for CMIP5 are not fully comparable to the new SSP-emission scenarios used in CMIP6 (Wyser et al. 2020).

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Climate Change in the Baltic Sea Region

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1. Summary

As part of the independent Baltic Earth Program for Earth System Research, the third assessment report of climate change in the Baltic Sea region was recently completed (Meier et al., 2021). The report focuses on the latest knowledge on climate change in the Baltic Sea region and its implications for marine and terrestrial ecosystems. Two such assessments were previously conducted in 2008 and 2015 (BACC Author Team, 2008; BACC Author Team, 2015). The third climate status report essentially confirms the findings of the previous reports. However, new observational data are now available, e.g., for Scandinavian glaciers, saltwater inflows, distributions of phytoplankton species, and new scenario simulations with improved models, e.g., for glaciers, inland sea ice, and the marine food web. In many cases, uncertainties can now be better estimated than before because more models have been included in the ensembles. The presentation summarizes the main results.

2. Selected Results

In the following, three selected results based upon recent data from the literature for past, present and future changes that are discussed in the assessment are presented (Figs. 1 to 3). These examples illustrate natural variability in air temperature of about 1°C over the Baltic Sea region during the past > 1000 years (Fig. 1), recent warming trends during the instrumental period with a maximum in spring of 0.14°C per decade in the northern Baltic Sea region (Fig. 2) and projected air temperature changes between 1970–1999 and 2070–2099 over land of 1.5, 2.6 and 4.3°C in the annual mean under RCP2.6, RCP4.5 and RCP8.5 scenarios.

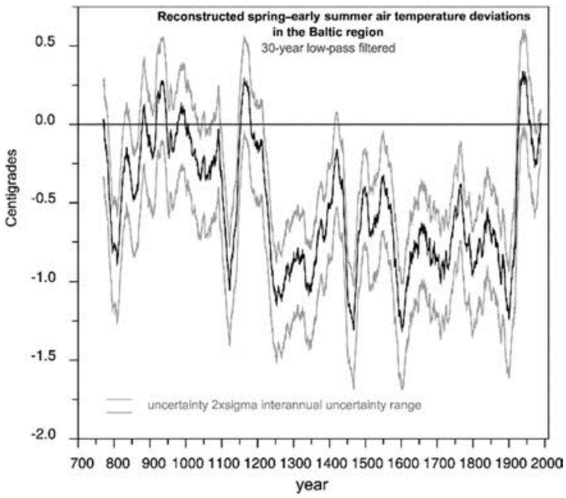

Figure 1. Reconstructed spring–early summer air temperature deviations in the Baltic Sea region (land areas in the box 0–40° E55–70° N; deviations from the 20th century mean). The record is smoothed by a 30-year low-pass filter. The approximate uncertainty range has been estimated here from the data provided by the original publication at interannual and grid cell scale. Source: Meier et al., 2021; their Fig. 4 distributed under the terms of the Creative Commons CC-BY 4.0 License

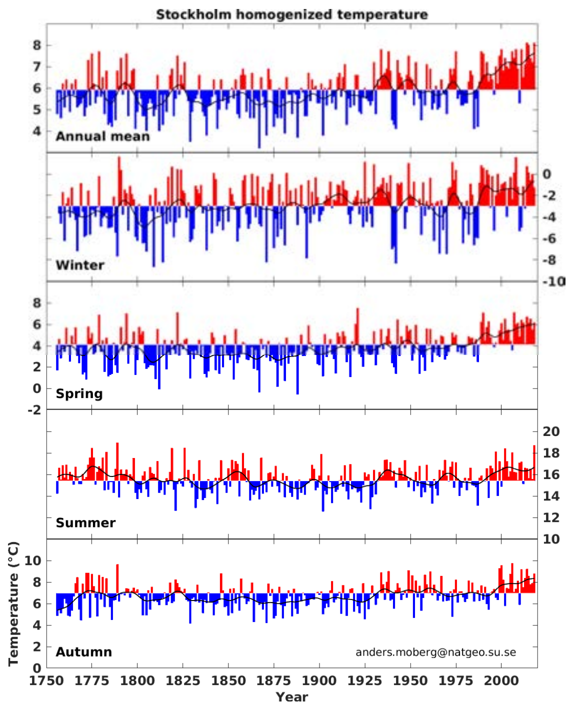

Figure 2. Annual and seasonal mean near-surface air temperature anomalies for the Baltic Sea basin for 1871–2020, taken from the CRUTEM4v dataset. The baseline period is 1961–1990. Blue and red show the Baltic Sea basin region north and south, respectively, of 60° N. Dots are the individual years, and smoothed curves show the variability on timescales longer than 10 years. Source: Meier et al., 2021; their Fig. 7 distributed under the terms of the Creative Commons CC-BY 4.0 License

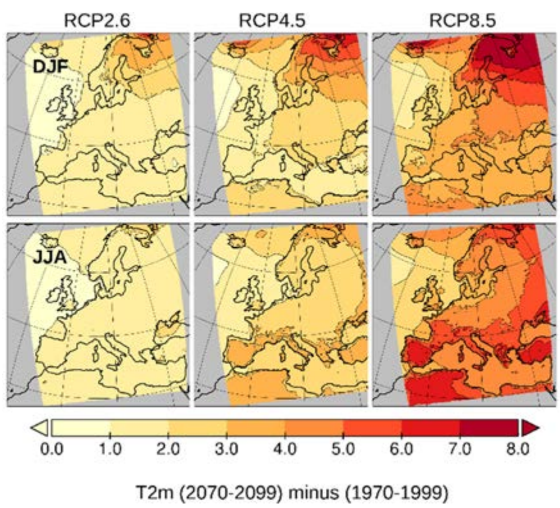

Figure 3. Ensemble mean 2m air temperature change (degrees Celsius) between 1970–1999 and 2070–2099 for winter (December through February; upper panels) and summer (June

through August; lower panels) under RCP2.6, RCP4.5, and RCP8.5. In total, eight different dynamically downscaled Earth system model (ESM) simulations are used. Source: Meier et al., 2021; their Fig. 26a distributed under the terms of the Creative Commons CC-BY 4.0 License

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The BALTEX/Baltic Earth programs: Excursions and returns

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1. Introduction

"The night passed, and the dawn came, and they sailed constantly."

The citation is a famous sentence in Homer Odysseus', where Odysseus sailed home ten years during many dangers and obstacles. This story has been interpreted and rewritten in many ways. It stands as a symbol and a starting point for a large part of our culture, created through literature, art, and philosophy. In philosophy, it is mainly the very structure of excursion and return that have come to develop. The first step is, belonging, the beginning, in the already familiar, in what we recognize ourselves in and start when we encounter something new, different, and exciting. The second step is the excursion itself, to leave home, the familiar, and open up to new experiences, "to put oneself at risk," to, as in a game, forget oneself and open up to other interpretations that lead to a new understanding. Returning home, the third step, is the essential element in a learning process. It is not "putting oneself at risk" but returning home that is the essence of education.

In this presentation, we examine the BALTEX/Baltic Earth programs through the lenses of excursions and returns. Of course, there are many achievements that scientists in a large number of papers and reports have published. But here, we speculated more about the overall achievements starting from the program goals.

2. The BALTEX phase I (1993-2002)

The goals for BALTEX I formulated 1995 were:

- To explore and model the various mechanisms determining the space and time variability of energy and water budgets of the BALTEX region and this region's interactions with surrounding regions.
- To relate these mechanisms to the large-scale circulation systems in the atmosphere and oceans over the globe.
- To develop transportable methodologies to contribute to the basic needs of meteorology, hydrology, oceanography, climate, climate impact, and environmental research.

IPCC started in 1988. Climate models matured for anthropogenic greenhouse gas experiments. In 1990, the First IPCC Assessment Report (FAR) underlined climate change as a challenge with global consequences requiring international cooperation. GEWEX, a core WCRP project, was initiated in 1990 with its phase I from 1990 to 2002 concentrating on water and energy cycles. At the beginning of 1990th, the Soviet Union broke down. Mann, Bradley, and Huges published in 1999 what would be named the Hockey stick graph and created an extensive discussion about global warming, data, and statistical methods. The BALTEX I took part in GEWEX, and the excursion included all countries around the Baltic Sea, joining scientists within meteorology, hydrology, and oceanography. In July 2000, the Öresund bridge opened for traffic. The return after ten years was a new science community addressing studies on heat- and water-balances for the Baltic Sea and its drainage basin, including data and models exchange. The research identified significant discrepancies between observed and climate-modeled water and heat balance components. Feedback mechanisms supported the development of coupled atmosphere-land-ocean models on the regional scale.

3. The BALTEX phase II (2003-2012)

The goals for BALTEX II were:

- Improved understanding of energy and water cycles under changing conditions.
- Analysis of climate variability and change, and provision of regional climate projections over the Baltic Sea basin for the 21st century.
- Provision of improved tools for water management, with an emphasis on extreme hydrological events and long-term changes.
- Biogeochemical cycles in the Baltic Sea basin and transport processes within the regional Earth system under anthropogenic influence.
- Strengthened interaction with decision-makers, with emphasis on global change impact assessments.
- Education and outreach at the international level

GEWEX Phase II 2003-2012 focused on how energy and water cycle processes function and quantify their contribution to climate feedback. In those days, eutrophication dominated Baltic Sea research efforts with a biology dominated community. In 2010 the BONUS program was launched as a Baltic Sea research program supported by the European Council, where science groups in BALTEX became active. The BALTEX II excursion started by increasing the BALTEX I goals by adding climate change and biogeochemistry. The return after ten years was the establishing of BACC as a science service with a first broad assessment of the knowledge about climate, climate change, and impact in the Baltic Sea Basin, and closer cooperation between scientists in many disciplines, mainly natural scientists. Significant improvements in open databases with observed and reconstructed data. Models were extended into biochemistry, starting to include the carbon dioxide cycles. Despite marked progress in Baltic Sea research, several gaps remained in knowledge and understanding. The issue of multiple stressors to the Baltic Sea began attracting attention.

4. The Baltic Earth program (2013 –)

The BALTEX network reorganized itself with a new name, Baltic Earth, a new program, and a broadening of the foci. Baltic Earth inherited the scientific legacy and networks of BALTEX. The new program identified several grand challenges, in particular:

- Salinity dynamics in the Baltic Sea.
- Land-Sea biogeochemical linkages in the Baltic Sea region.
- Natural hazards and extreme events in the Baltic Sea region.
- Sea level dynamics in the Baltic Sea.
- Regional variability of water and energy exchanges.
- Multiple drivers for regional Earth system changes.

GEWEX Phase III (2013-2022) was formed, building on results and experiences of GEWEX I and II. Future Earth with a background in the International Geosphere-Biosphere Programme, DIVERSITAS, and the International Human Dimensions Programme was officially announced in June 2012 at the UN Conference on Sustainable Development. The Baltic Earth excursion started from the BALTEX I and II programs and the success of BACC I now with inspiration from GEWEX and Future Earth. The research foci were anthropogenic changes and impacts and their natural drivers which served as a network for earth system sciences in the region.

Studies of the climate system got a significant boost by the bestowal of the Physics Nobel Prize 2021 to Klaus Hasselmann for suggesting and demonstrating approaches to deal with the high-dimensional and complex, inhomogeneous climate system, specifically with the Stochastic Climate Model from 1976 and the detection (of climate change) and attribution (of plausible causes of climate change). Even though the laureate was not part of BALTEX and Baltic Earth, his ideas infiltrated the foci of the work, with emphasis on the system, as opposed to many independent processes. While process studies, mandatory and urgently needed, are powerfully pursued by members of Baltic Earth, the system view has gained much attention, with readily available extended data sets of recent and past changes and scenarios of possible futures. A variety of coupled numerical models allow experimentation on the climate system and estimating impacts. Specifically, the role of elevated greenhouse gas concentrations on the regional climate has been assessed. New challenges are the separation of a. variety of signals, ranging from greenhouse gases, aerosols, discharge of various substances into the water body of the Baltic Sea, changing cities and flows of goods and people, and finally, the understanding of the interaction of scientifically constructed knowledge and societal, culturally constrained decision processes.
Through BACC II and forming of EN-CLIME, the cooperation between HELCOM and Baltic Earth developed. The different challenges were addressed in the BEARs article in a special issue in Earth System Dynamics (2021-2022). Increasing insights in multiple stressors through fishery, climate change, eutrophication, etc.

5. Summary and conclusions

After almost three decades of climate and environmental studies of the Baltic Basin within the BALTEX and Baltic Earth programs, we need to evaluate the essence of the vast body of scientifically constructed knowledge and the efforts for improving education. During three decades, we have seen significant progress in observations and available data sets, improved models for regional studies, and increased numbers of international summer/winter schools. The programs have illustrated the need to navigate actively in the European research arena and at the same time remain as an independent science network. The program planning based on decadal time scales strengthens the work in contrat to the often shorter national and European research programs. The well-organized international Baltic Earth secretariat, together with many dedicated scientists, made the excursions safe and successful.

The BALTEX/Baltic Earth learning process relates to improved knowledge about the region's anthropogenic climate and environmental changes and how global warming and regional human activities can be detected outside the natural variabilities. Attribution studies through IPCC on climate change linked to raising greenhouse gases are well established globally. The geographic position of the Baltic Basin, with significant variability in large-scale meteorological circulation, set unique challenges for detecting and attributing regional anthropogenic changes. At the same time, anthropogenic changes of different origins are acting, such as changes in, air pollution and aerosols, large scale atmospheric circulation, eutrophication, land-use change, coastal constructions, cities, fishery, and shipping. Without a clear understanding of the different drivers and how they interact on a regional scale, management may fail. However, many of these aspects can be studied using reliable, homogeneous long-term data sets describing co-variations in the regional atmosphere and the sea, and improved modelling tools developed during pasted decades. Building links to economic, social and human sciences helps transform academic knowledge about the changing environment into a useful basis for constraining regional policies to sustainable development paths.

Homers words echo:
"The night passed, and the dawn came, and they sailed constantly."

Hel Peninsula – geological structure and history

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1. Introduction

Hel Peninsula located in NW Gulf of Gdańsk is the most prominent landform on the southern Baltic coast. There are some similar forms worldwide. The nearest analogues are the Skagen Spit on the tip of Jutland in Denmark, Tendrovskaya Spit and Byriuczyj Ostrow Spit on the Ukrainian coast of Black and Azov Seas. However, the Hel Spit geological structure and history is unique and complex.

The research on the Hel Peninsula has a long history. The first borehole (106.5 m) was made in 1898 for ground water intake in Hel locality. During the next years several dozen of boreholes were made for various purposes. Sediments from dozen of them were investigated according to its lithology, age and sedimentary environment.

Figure 1. Location of Hel Peninsula

2. Morphology

The Hel Peninsula is 35 km long. The NW section, from Władysławowo to Kuźnica, is narrow and low. Its narrowest part it is only ca. 150 m wide. Most of the land surface is below 2 m a.s.l. and only the foredunes are up to 5 m high. The SE section, between Kuźnica and Hel, gradually widening towards SE and reach a maximum width ca. 3 km in the vicinity town of Hel (Fig. 1). Parabolic dunes high up to 24 m occur along both coasts, whereas the inner part of the peninsula is occupied by the ridges of the former foredunes up to 4 m high.

3. Geological setting

The Hel Peninsula is situated within the Precambrian platform, at the western boundary of the Peribaltic Syneclise. The ceiling of the crystalline Proterozoic bedrock occurs at a depth of 3,484 m b.s.l. Glacioisostatic adjustment vanished ca. 10,000 years ago. The recent vertical movements of the Earth crust are close to zero.

Pre-Quaternary bedrock of Hel Peninsula consist of upper Cretaceous glauconitic sand and claystone. The top of Cretaceous deposits is located at 100-110 m b.s.l., only locally narrow, erosional depressions deep up to 180 m b.s.l. occur. In the NW part of the peninsula there is sequence of Eocene silt and Miocene sand and silt with a thickness up to ca. 50 m laying on the Cretaceous deposits. The fossil slope of Eocene-Miocene deposits occur in the middle part of the Peninsula, between Kuźnica and Jastarnia. Two sections of the peninsula also differ in terms of thickness, lithology and origin of Pleistocene and Holocene deposits.

Within the NW section the till layer is thin and discontinuous. Above there are glaciofluvial and glaciolimnic sands with a thickness of 30-40 m. The direct substratum of the barrier sand consist, locally by early and middle Holocene peat and limnic gyttja and mainly by upper Holocene lagoonal mud.

Pleistocene in the SE section is built by till of 5-10 m thick and by Late Glacial brown clay of Baltic Ice Lake also 5-10 m thick. Locally, glaciofluvial sand and gravel with a thickness up to 30-60 m infill incisions in Cretaceous deposits forming productive aquifers. The direct substratum of the barrier sand in SE section consist of early Holocene clay of Ancylus Lake and middle and late Holocene mud of Littorina and Post Littorina Seas.

Summarizing, the palaeodepositional surface of the barrier sands lowers from the root of the Peninsula towards its head and occur at the depths: 3.5-4.0 m b.s.l. close to Władysławowo, 6.0-6.6 m b.s.l. in Chałupy, 8.5-11.0 m b.s.l. in Kuźnica, 33.5 m b.s.l. in Jastarnia, 55 m b.s.l. in Jurata and 69 m b.s.l. in Hel. The thickness of the barrier sands increases in the same direction (Fig.2).

4. Development of the Hel Peninsula

The diversity of geological setting of the NW and SE parts of the Peninsula indicates two different ways of its development. The NW part is an example of barrier shifting landward and encroaching onto the lagoon area. The traces of this process are the terrestrial sediments dated from early to late Holocene (Fig. 2) which occur under the barrier sand and outcropping locally at the foot of the seaward slope of the barrier (Uścinowicz, 2003).The geological setting and analysis of historical maps indicate that NW section of the Hel Peninsula had not been originally formed as a chain of islands connected in further times by longshore sediment transport. Visible on some old maps breaks in the continuity of the NW part of the Peninsula were effects of episodic storm water overflows and human activity, thus a myth of insular origin of the Hel Peninsula should fall into oblivion. (Tomczak, Domachowska, 1992).

In contrast, the SE part of the peninsula had been and is building as a spit by the longshore currents. The sand is deposited at ever greater depths and on ever younger depositional surface. The rate of spit growth depends in direct proportion on the amount of transported sediment, and inversely proportionate to the depth of the sea (depth of depositional surface).

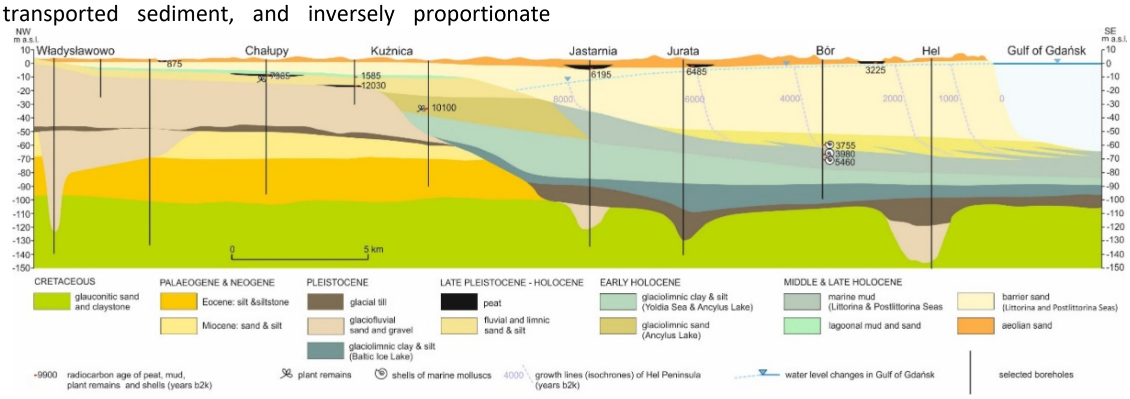

Figure 2. Simplified geological cross-section along the Hel Peninsula

5. The age of the Hel Peninsula

There is little information about the age of the Hel Peninsula, especially about its progradation in time. The youngest ^{14}C ages of peat outcropping on beach and lagoonal mud underlying the barrier deposits suggests that NW section of the peninsula occupies its present position for ca.1,500-1000 years. On the SE section, between Jastarnia and Hel, there are three sites where the lowermost part of inter-dunes peatbogs were dated (Fig. 2). The oldest known peat, dated for 6,485 years b2k, is situated in Jurata. Peat, dated for 3,225 years b2k is located ca. 5.2 km to SE direction (Fig.2). Distance from the last dated site to the Peninsula tip amounts another ca. 6.6 km. This sequence, although not many, allow for roughly estimation that the rate of Hel Spit progradation slowly decreased during last 6,500 years from ca. 1.6 to ca. 1.3 m/year. Nowadays, in the second half of the 20th century, according to cartometric analysis, the peninsula was growing at the rate of approx. 1.0-0.5 m/year.

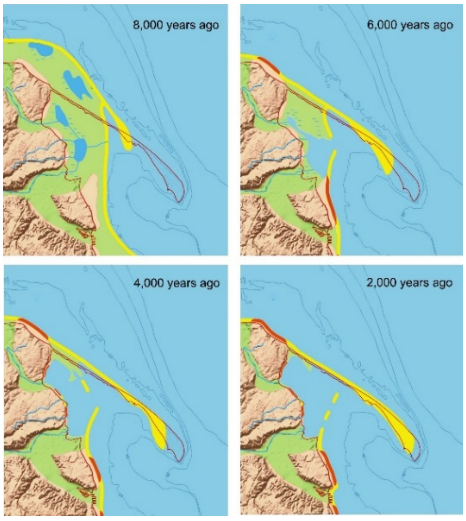

Figure 3. Evolution of the Hel Peninsula in the middle and late Holocene

The sequence of ^{14}C ages suggest that SE section of Hel Peninsula prograded along more or less the same line during at least the last 8,000-6,000 years (Fig. 3). Other issue is the position and migration route of the NW section of the Peninsula, especially before 6,000 yr b2k, because there are not recognized remains of former barrier position on the seabed. Approximate reconstructions can only be attempted by taking into account knowledge about history of water level changes in the southern Baltic, present day bathymetry and geology as well as general rules on development of transgressive type barriers (Fig. 3).

6. Volume of sand forming the Hel Peninsula

Based on 41 lithological profiles of the boreholes, the base of barrier sand was identified and numerical model of palaeodepositional surface was created. Farther, based on morphometric analysis of the seabed profiles, foot of the slope of the Peninsula was identified. Data integration has shown link the foot of the slope with the range of the sandy facies. The digital model of the palaeodepositonal surface in combination with the DTM of seabed and land surface allowed for construction of a 3D model of sandy lithesome of the Hel Peninsula. The calculations showed that the total volume of middle and late Holocene sandy sediments of the Hel Peninsula is 2,850,021,212 m^3, i.e. 2.85 km^3. The part of the Hel Peninsula located above sea level is only 95,998,058 m^3 (0.096 km^3), i.e. only about 3.4% of the total sandy lithosome. The main part (about 96.6%) of this form is under water (Fig. 4), (Damrat et al., 2017).

This is the crucial information for further analysis of coastal processes; what we observe on the shoreline, beaches and dunes, it results from the processes taking place on the underwater coastal slope. The underwater landslides occur near the tip of the peninsula, where there is a slope with a height of ca. 55 m and gradient up to ca. 20° (Rudowski et al., 2016).

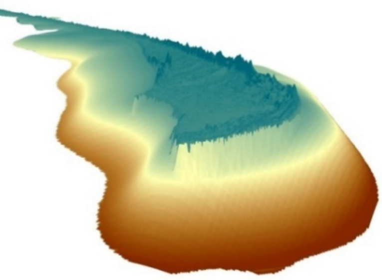
Figure 4. 3D model of the Hel Peninsula (bird's-eye view from the south, vertical exaggeration 25 times)

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Global climate change and the Baltic Sea ecosystem: direct and indirect effects on species, communities and ecosystem functioning

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1. Background

Global climate change affects the marine ecosystem through ocean warming, acidification, deoxygenation and through changes in nutrient loading and water circulation. In the Baltic Sea, the biological consequences range from shifts in species abundance and distributions, changes in dispersal and from modification of species interactions to altered food webs and decreasing productivity. These changes potentially also affect the human society dependent on marine ecosystem services.

2. Scope of the review

We review research on climate change effects on the Baltic Sea ecosystem, based on studies published in 2010—2021. Evidence is compiled from field, experimental and modelling studies that show responses of species, populations, and communities to climate-affected parameters. We highlight typical responses of phytoplankton, cyanobacteria, and microbes to changes in temperature, salinity, oxygen and pH; summarise the interactions between biogeochemical processes and primary and secondary productivity in both pelagic and benthic environments. Knowledge gaps and current issues of dissensus are identified and areas in need of more research are recommended.

3. Key results

Modelling studies project an increase in phytoplankton and cyanobacteria due to climate induced increase in external and internal nutrient loading (Meier et al., 2011a; Funkey et al., 2014). Eutrophication may however be counteracted by various factors. Increase of river-borne DOM may decrease primary production, at least in the Gulf of Bothnia (Andersson et al. 2013), and certain cyanobacteria may be negatively affected by increased temperature and acidification (Paul et al. 2018). Several modelling studies also conclude that nutrient reductions will be a stronger driver for ecosystem functions in the Baltic Sea than climate change (e.g., Pihlainen et al. 2020; Meier et al. 2021).

In the photic benthic systems, nutrient increase enhances eutrophication and if salinity also declines, habitat-forming bladderwrack, eelgrass and blue mussel will decline (Jonsson et al. 2018; Kotta et al. 2019). Their loss from rocky substrates cannot be replaced by the increase of vascular plants, because these only grow on soft sediments. Salinity decline will also harm deep benthic communities, but improvement of oxygen conditions may first increase their biomasses. Eventually, increasing stratification will weaken benthic-pelagic coupling and zoobenthos biomass will start to decline (Ehrnsten et al. 2020).

As for fish, salinity decline and hypoxia will have negative consequences on cod stocks (Gårdmark et al. 2013), whereas the increasing temperature favours sprat (Mackenzie et al. 2012) and certain coastal fish (Bergström et al. 2016).

4. Knowledge gaps and recommendations

The main challenge when analysing effects of climate change on the Baltic Sea is the possible synergistic effects of climate with other environmental drivers, especially eutrophication, and distinguishing effects from those caused by quasi-cyclic climate phenomena such as NAO.

Experimental studies are useful in pinpointing organismal responses, but their small spatial and temporal scales and simple food webs make upscaling of results to natural systems difficult. Experimental work should use full communities and investigate processes at spatial and temporal scales appropriate to the species studied.

Ecosystem modelling has advanced greatly in the past 15 years, but projections of salinity, stratification and hypoxia are still uncertain. Ecosystem models also rarely consider biological interactions or adaptation capabilities of species. It is therefore difficult to project the fate of plankton and benthos communities dependent on these parameters. Uncertainties are also caused by complex terrestrial and freshwater processes, as well as unknown societal development.

5. Recommendations

Experimental work should be better integrated into empirical and modelling studies, and more emphasis should be placed on studying effects of climate change on less studied environments, such as the microbial food web, sea ice communities, and the sublittoral ecosystem. More studies on heat waves would increase our understanding of the population level consequences of short term variability in environmental parameters. Continuation of spatial mapping programs and long term ecological studies will be crucial for validating experimental results and ecosystem models.

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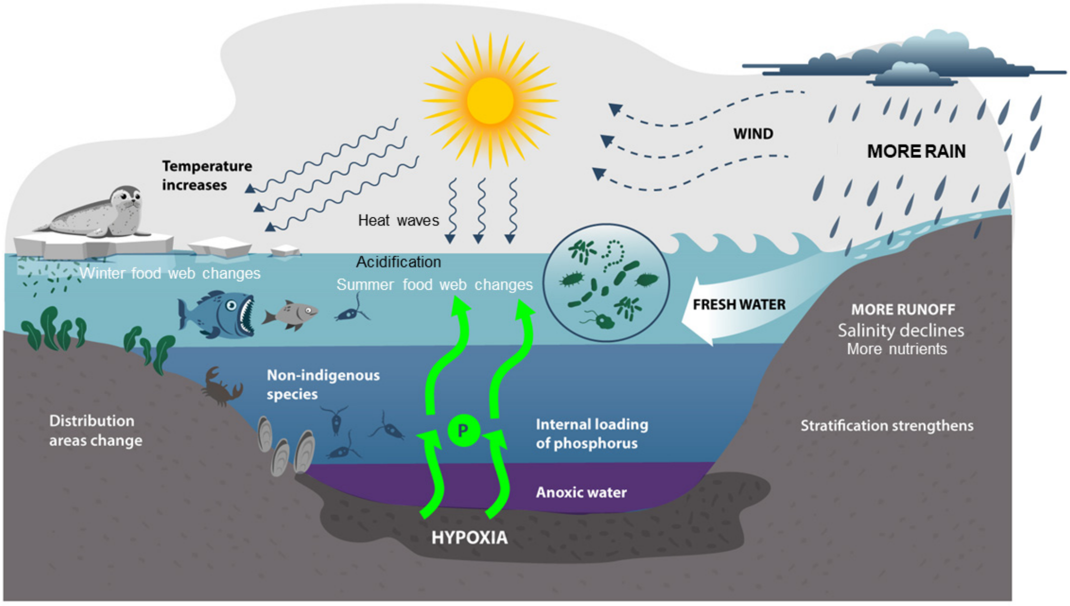

Figure 1. A schematic presentation of the potential effects of climatic variations on the Baltic Sea ecosystem. Art: Markku Viitasalo & Marianna Korpi, SYKE.

Systems and processes – my perception of the legacy of Klaus Hasselmann's approach to environmental science

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1. The Physics Nobel Price 2021 for Klaus Hasselmann – is there something to be learned for our community ?

Klaus Hasselmann was awarded the prestigious award in 2021, for work which he did some 40 years earlier. He shared the award with two others, among them Suki Manabe, another climate scientist. The Nobel committee referred to "for groundbreaking contributions to our understanding of complex physical systems" and specifically to their achievements in "physical modelling of Earth's climate, quantifying variability and reliably predicting global warming".

In case of Klaus Hasselmann, the recognized work was focusing on the "stochastic climate model" from 1976 and the "detection of change and its attribution to causes" (first published in 1979) as milestones. What is the legacy of his work for us? Did he enforce a paradigm-shift in our way of conceptualizing and analyzing environmental systems such as oceans and climate?

2. Paradigm shift – the PIPs-approach

My subjective answer is – yes, I believe he did. This paradigm shift was not only his work; in a sense it was already in the air; it developed over time, and as such it is hardly recognizable today. But nevertheless – there was a massive change.

Klaus Hasselmann has practiced "his" paradigm all the time, without uttering big claims, and in 1988 he published it in a hardly noticed paper – he named his concept PIPs, "Principal Interaction Patterns". The idea is that when we study a complex high-dimensional system, we need to identify a small "core" or "signal" space", and to project the overall dynamics of the full phase space (Figure 1, top), which spans very many if not infinite many degrees of freedom, on this subspace (Figure 1, bottom). This core space may depend on what we want to study – it will be different for the analysis of global warming or for the analysis of coastal morphodynamics. The myriads of processes outside the core space are disregarded and taken into account only by their expected conditional impact on the core space – in other words, parameterized.

The visible achievements, both the "stochastic climate model" and the "detection and attribution" may be seen in this concept. Also, all dynamical models are built in this way (von Storch, 2001).

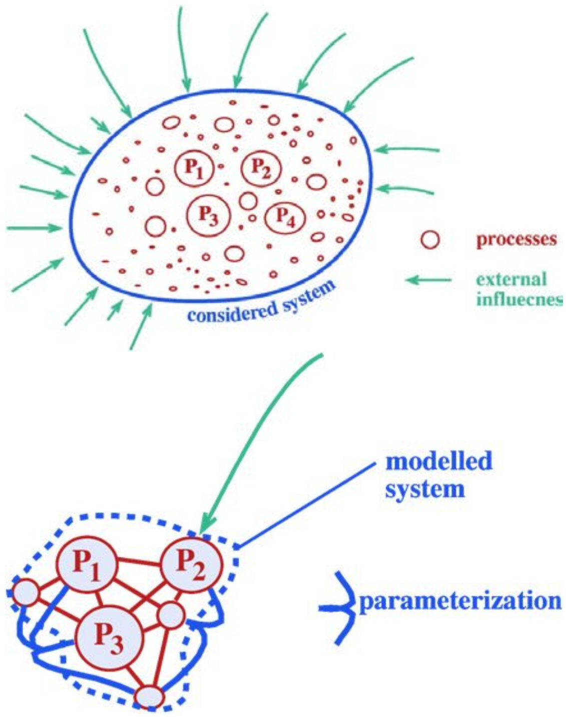

Figure 1
Top: Sketch of the full system **S,** all processes P_i and external factors F_k Bottom,: PIP-reduction of full space to core space, a forcing of interest F and significant processes P_i, while the rest ist parametrized.

3. The role of process studies

When studying a dynamical system **S** with an Infinite state vector S, we assume that its dynamics are given by $dS/dt = \Sigma_i P_i(S)$ with very many if not infinitely many processes $P_i(S)$. When we want to „understand" **S**, we look for answers of

1) How predictable is **S**?
2) How sensitive is **S** to different external factors F_k?
3) Which processes P_i are dominant for the dynamics of **S** given the forcing F_k?

For dealing with (1) and (2) we do not necessarily need specific knowledge about the processes, but empirical (or theoretical) evidence about the variations of **S**.

Klaus Hasselmann's "stochastic climate model" (1976) dealt with (1). It recognizes the presence of in the system, and a short-term forcing. This configuration leads to the dynamical equation $\underline{S}_{t+1} = (1-\lambda)\ \underline{S}_t + \delta_t$, with a one-dimensional projection $\underline{S}$ of S, a memory parameter λ and "white noise" δ. The predictability is that of a "red" spectrum.

The second Nobel-recognized contribution of Klaus Hasselmann was his strategy of "detection and attribution" (1979 and later), which attempts to detect a "signal" in the stochastic system **S**, and to attribute one or more forcings F_k as causal. Thus, it is an approach for (2). Also in this case, specific knowledge about the processes is not needed, but only the expected conditional impact of the P's on **S.** Such knowledge can be constructed from empirical evidence or numerical experimentation with quasi-realistic models, which feature as many processes as possible.

In (3), however, specific knowledge about the processes is required. To do so in numerical experimentation, proper signal-to-noise analyses are needed to separate the relevance of the different drivers, leading to similar approaches as in (2).

In our scientific practice, a significant scientific effort is the improvement of process understanding, which is claimed to improve our quasi-realistic models by adding new processes or improving the knowledge about the functioning and sensitivity of processes. This is for (3) important, also for the continuous development of quasi-realistic models, but such additions do not automatically lead to an added value in understanding of the considered system embedded in a variety of forcings $F_{k.}$

Instead, we often see an infinite cycle of model-improvements by adding continuously new details, without shedding new light on the above mentioned three challenges.

4. Conclusion

In our community we see many process studies, often associated with a vague claim that this approach would directly lead to the understanding of the system. Indeed, "Wüst's law" (von Storch et al., 1999), according to which you find something interesting if you take a closer look, is valid, and is a strong motivation for process studies. But without theoretical or empirical expectation of what to find, we will in general be lost in a sea of details and an ocean of numbers. Given this dilemma, it is not surprising that the claim, according to which the study of processes alone would lead to system understanding, is in most cases misleading.

5. Caveat

This is my understanding of Hasselmann's legacy for us – the system is not to be conceptualized as the sum of all processes, but understanding of the system implies knowledge about predictability, of sensitivity to external forcing, and of the stochastic character of the system.

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Topic 1

Salinity dynamics

Investigating the properties of small- and medium-size saltwater inflows into the Baltic Sea

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1. Introduction

The pronounced horizontal and vertical salinity gradients in the Baltic Sea are mainly determined by freshwater input from river runoff and saline inflows from the North Sea through the Danish straits. Two types of inflows can be distinguished. Barotropic inflows are driven by sea level differences between the Kattegat and the western Baltic Sea. The largest of them, so-called Major Baltic Inflows (MBIs), even reach the bottom waters of the central Baltic Sea basins. However, they only cause about 20 percent of the total salt transport to the Baltic Sea (Mohrholz, 2018). Another 30 percent stem from smaller barotropic inflows and half of the salinity import is caused by baroclinic inflows (Mohrholz, 2018). The latter are driven by baroclinic pressure gradients and mainly occur in late summer under calm conditions. According to Lehmann et al. (2021), the first observation of a baroclinic inflow was after 1996. Studies on such baroclinic inflows were inter alia published by Feistel et al. (2006) and Mohrholz et al. (2006). Since they are not caused by sea level gradients, baroclinic inflows are not easy to detect and many of their properties such as possible internal variability and/or long-term trends are still unknown (Lehmann et al., 2021). A better understanding of baroclinic as well as small barotropic inflows could help to reduce the knowledge gaps that still exist when it comes to the present and future salinity dynamics of the Baltic Sea. For instance, the reasons for the observed increased stratification (Liblik and Lips, 2019) are not yet clear since the barotropic inflows do not exhibit any long-term trend (Mohrholz, 2018).

2. Data and Methods

We study the salinity import of the Baltic Sea with data from an existing model run (Radtke et al., 2020) between 1850 and 2008 of GETM (General Estuarine Circulation Model; Burchard and Bolding, 2002). It has a horizontal resolution of 1 nmi and 50 vertically adaptive layers (Radtke et al., 2020). Atmospheric forcing was taken from the HIRESAFF v2 dataset (Schenk and Zorita, 2012) while open boundary conditions and reconstructed river discharge were defined in a previous model study (Meier et al., 2018). The salinity transport across multiple transects indicated in Figure 1 is analyzed. We classify the water masses according to their salinities in order to track possible inflows. Since (baroclinic) summer inflows are characterized by exceptionally warm temperatures in the halocline (Mohrholz et al., 2006), we analyze the temperature time series as well.

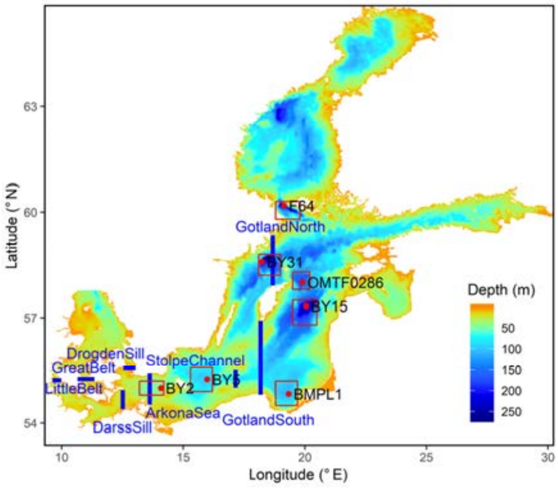

Figure 1. Model topography of the Baltic Sea (Radtke et al. 2020). Transects for salinity transport analysis are marked with blue lines.

As we want to detect and track especially small inflows, we further performed a GETM run between 2010 and 2018 with a very high resolution. The horizontal grid spacing is 250 meters and we applied 60 vertically adaptive layers in the overall model domain. Simulated area, visualized in Figure 2, is the whole southern Baltic Sea including the Kattegat, Danish straits and the Gulf of Finland and Gulf of Riga and excluding only the Bothnian region. The lateral open boundary conditions are taken from a coarse resolution simulation similar to Radtke et al. (2020). The model is run with the runoff and atmospheric forcing compiled within the BMIP project.

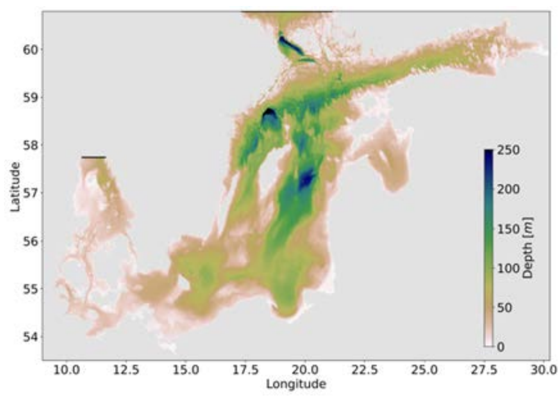

Figure 2. High resolution model bathymetry. Black thick lines are the locations of the open boundaries.

3. Results

Snapshots of bottom salinity in the Baltic Sea simulated with different resolutions are depicted in Figure 3. In principle both of the model runs show large scale similarities in the bottom salinity. The largest values are in the south-western part of the Baltic Sea, close to the Danish straits, and they reduce towards the remote areas of the sea, namely Gulf of Finland and Gulf of Riga. Also, the bottom salinity is larger in the offshore areas and much smaller close to the coast. In January 2014, i.e. approximately 1 year before the 2014/2015 MBI, water reaches the Gotland Deep. The largest values occur only in the Arkona and Bornholm Basin, while the bottom salinities in other regions are considerably smaller. In January 2015, one can observe the inflow from Bornholm basin towards Gotland Basin with salinities in Slupsk Furrow at their highest and higher salinity values extending towards Gotland Deep along the eastern flank of the basin. In addition, parts of the saline waters have also entered the Gdansk basin, where one observes higher bottom salinity compared to the situation in 2014-01. In January 2016, i.e. one year after the inflow, the salinities in the bottom layers of the Gotland Basin are at their highest, but also in the northern Baltic Proper and western Gotland Basin the salinities are increased. The salinities in the Slupsk Furrow are again reduced and gravitational flow towards EGB is no longer visible in the salinity map.

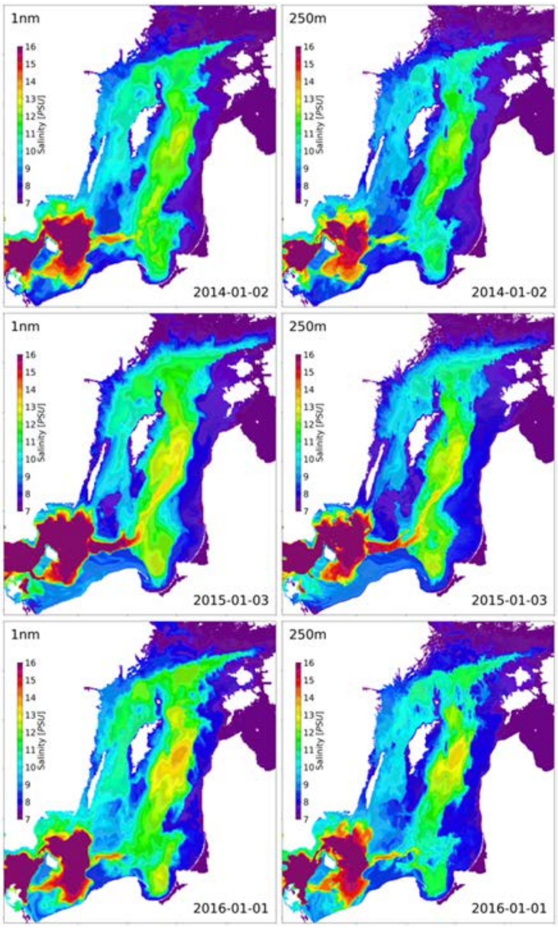

Figure 3. Bottom salinity in the Baltic Sea from low (left) and high (right) resolution simulations approximately 1 year before the 2014/2015 MBI (top panels), during the 2014/2015 inflow event (middle panels) and 1 year after the 2014/2015 inflow event.

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Turbulent mixing in the Slupsk Furrow: Microstructure observations in 2019-2021.

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Slupsk Furrow is located on the main pathway of the inflow waters from the North Sea, which provide salt and oxygen to the deep waters, and therefore is of key importance for the Baltic circulation and ecosystem. The dynamics of Slupsk Furrow make it one of the principal areas of intensive mixing and transformation of deep waters on their way father east (Piechura et al. , 1997) . Here, internal waves and mesoscale eddies are dominant features of the water transport through the channel.

We present a summary of the measurements collected in the Slupsk Furrow during in 2019-2021 focusing on the microstructure measurements collected every 5-10 nm during three cruises of *rv Oceania* (in February 2019, November 2020 and December 2021) through the central channel and at two stations (Figure 1). Microstructure observations were collected using a free falling Vertical Microstructure Profiler (VMP) 250 of Rockland Scientific equipped with two shear, one micro-conductivity, one micro-temperature and a standard CTD (64 Hz) sensors.
In total, 170 microstructure profiles were collected in November 2020, 109 profiles in May 2021 at the station close to the Slupsk Sill and 42 profiles were collected in December 2021 at the central southern slope of the channel. The spatial and temporal variability of mixing intensity is presented.

Acknowledgements

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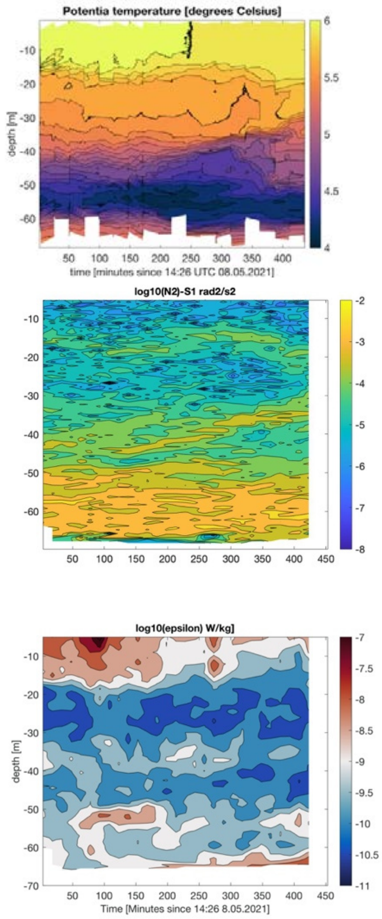

Figure 2. Time series of potential temperature (top) , buoyancy frequency (middle) and the rate of turbulent kinetic energy dissipation (bottom) collected in May 2021 at 55^0 11.12'N $16^0$40,4'E.

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Revisiting the challenge of Sea Surface Salinity satellite retrievals in the Baltic Sea

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1. Scientific Update on the Sea Surface Salinity retrievals in the Baltic Sea

The Baltic+ Salinity project (2018-2021) successfully retrieved Sea Surface Salinity from Soil Moisture and Ocean Salinity (SMOS) satellite (González-Gambau et al., 2022). The dataset produced under this project covers years 2011 – 2019 . It compares well with known in situ observations in key oceanic regions in the Baltic Sea like Bothnian Sea, Central Baltic Sea Proper, Arkona Basin, Bornholm Basin and Central Gulf of Finland (ref. Baltic+ Salinity Product Validation report). As part of the project outcome regional SSS data is now available also to the HELCOM platform.

The project demonstrated that it is possible to obtain SSS retrievals in small semi enclosed and cold seas, like the Baltic Sea. These results clearly suppose a breakthrough in Earth Observations science, which initially stated it was not possible. However, there is the need to further explore the use of SSS in combination with other data (i.e. satellite, in situ and model simulations) to enhance Climate studies and regular monitoring in the Baltic Sea. This presentation aims at encouraging the regional science community to try and use the newly retrieved SSS data in combination with other dataset to aid ongoing science challenges and to update the Science Requirements for future satellite missions.

2. Enhanced Sea Surface Salinity retrievals for scientific and operational applications

Monitoring of the Baltic Sea is very important for the environmental health of the sea and for its sustainable use. In-situ monitoring has long traditions, but it still suffers from relatively low spatial and temporal resolutions in comparison to the spatial and time scales of the relevant processes (Haavisto et al., 2018). Automatic methods and robots like FerryBoxes, Argo floats, gliders and profiling moorings have improved the situation, but they have their limitations, too. Baltic Sea numerical modelling has advanced with great steps in the last decade, but especially the salinity description in the models still needs development. Remote sensing is a way to put the traditional in-situ observations to the big picture and to give models information that is needed for initial fields and for data assimilation(Omstedt & Axell, 1998).

Baltic+ Salinity products keep a good agreement with salinity dynamics described using either model and in situ based datasets (González-Gambau et al., 2022). Hence it is possible to assume the newly retrieved SSS product may aid to improve oceanographic studies in regions where in situ observations are not available . Furthermore, it is possible to use SSS in combination with other satellite data (e.g. Sea Surface Height) to better characterize dynamic structures like eddies and fronts.

3. Potential science applications using SSS

This presentation will briefly describe the rationale of a selection of case studies where SSS in combination with other dataset may significantly further science knowledge in Baltic Sea (ref. Baltic+ Salinity Science Roadmap report). Some of these preliminary case studies included: [1] Study of the inflow and outflow dynamics from major river; [2] EO synergy studies like the ones seen between SSH and SSS; [3] Fusion of EO data with eco-hydrodynamic models to enhance monitoring of in fisheries with economical and societal interest; and [4] EO data to further characterize wintertime marine heat wave impact in the Baltic Sea.

4. Baltic+ Salinity project website and data access

Baltic+ Salinity website
https://balticsalinity.argans.co.uk/
Baltic+ Salinity L3 and L4 SSS v2.0 products can be found in the following sites.
Baltic+Salinity and BEC sFTP service
Baltic+ L3 and L4 SSS products will be freely distributed through the FTP server (sftp://becftp.icm.csices) in netCDF format. The Baltic+ SSS products are also published in https://digital.csic.es:
Baltic Sea Surface Salinity L3 maps (V.2.0):
DOI: 10.20350/digitalCSIC/13859
https://doi.org/10.20350/digitalCSIC/13859
Baltic Sea Surface Salinity L4 maps (V.2.0)
DOI: 10.20350/digitalCSIC/13860
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First SMOS Sea Surface Salinity dedicated products over the Baltic Sea

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1. Understanding surface salinity through satellite-based measurements

The Baltic Sea is a semi-enclosed, seasonally variable brackish water sea that is very vulnerable to environmental changes. Baltic Sea conditions have been studied and monitored for over 100 years with regular, though spatially and temporally rather sparse, ship observations since 1898. Remote sensing has been used for decades to follow the ice conditions, surface temperature and algal blooms. However, salinity conditions have remained outside of a quick overall synoptic view so far.

Earth observation Sea Surface Salinity (SSS) measurements have a great potential to help in the understanding of the dynamics in the basin thorough:

- The monitorization of long-term SSS changes in the different subbasins (determination of salinity inter annual trends).
- The detection of frontal areas where SSS gradients are stronger (river run-offs, ice formation and melting processes, etc.).
- The study of inflow and outflow dynamics (determination of anomalous salinity periods).
- Their use as initial fields and validation data to numerical models.
- They can complement temporally and spatially the sparse in situ measurements in the region.

Nonetheless, the available EO-based global SSS products over this basin are of a quite limited quality and spatio-temporal coverage, as it can be observed in Figure 1.

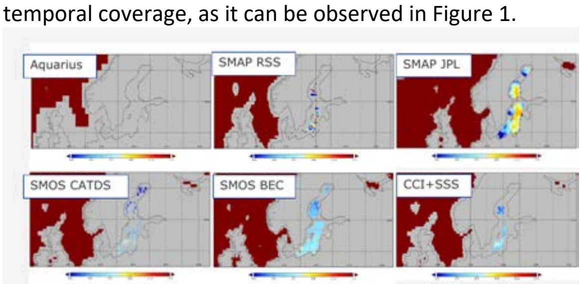

Figure 1: Coverage in the Baltic Sea of the available global EO SSS products. Top: Aquarius: version 4.0 CAP (left); SMAP RSS: version 3.0, 40 km (middle); SMAP JPL: version 4.2 (right). Bottom: SMOS LOCEAN: L3 debiased version 3 (left); SMOS BEC: L3 DNB, version 1 (middle); CCI+ Salinity product: version 1.7 (right).

2. Challenges in retrieving satellite SSS over Baltic

The Baltic Sea is one of the most challenging regions for the retrieval of satellite SSS due to several technical limitations that strongly affect the L-band brightness temperatures (TB), such as the high contamination by Radio-Frequency Interference (RFI) sources and the contamination close to land and ice edges, which is particularly crucial over the Baltic Sea. Besides, the sensitivity of TB to SSS changes is very low in cold waters and much larger errors are expected compared to temperate oceans. Salinity and temperature values are very low in this basin, which implies that dielectric constant models are not fully tested under such conditions.

In the context of the ESA regional initiative Baltic+ Salinity Dynamics, extensive research has led to the development and the refinement of the algorithms needed from raw data to Level 3 and Level 4 to develop the Baltic+ SSS products. The detailed methodologies used to develop Baltic+ SSS products can be found in (González-Gambau et al., 2022).

3. Baltic+ L3 and L4 SSS products

Two Baltic+ SSS products have been generated for the period 2011-2019 and are freely distributed through the BEC FTP service (http://bec.icm.csic.es/bec-ftp-service/).

The Level 3 (L3) product is daily generated and consists of 9-day maps in a 0.25 degree grid, (González-Gambau et al., 2021a) and the Level 4 (L4) product consists of daily maps in a 0.05 degree grid, (González-Gambau et al., 2021b). The L4 product has been generated by applying multifractal fusion to the Baltic+ L3 SSS with Sea Surface Temperature as a template (see details in González-Gambau et al., 2022)). An example of these L4 daily SSS maps is shown in Figure 2.

The accuracy of the L3 product is around 0.7-0.8 psu and around 0.4 for the L4 product. The comparison of Baltic+ L4 SSS with the collocated in situ measurements from SeaDataNet v2 (DOI 10.127701610aa44-0436-4b53-b220-98e10f17a2d4) are shown in Figure 3. Regions with higher errors have been identified in Arkona and Bornholm basins and in the Gulfs of Finland and Riga.

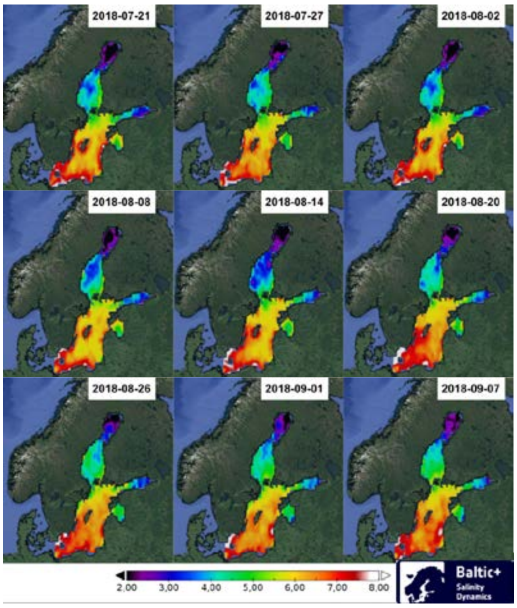

Figure 2 . Some examples of Baltic+ L4 SSS mapss in August 2018.

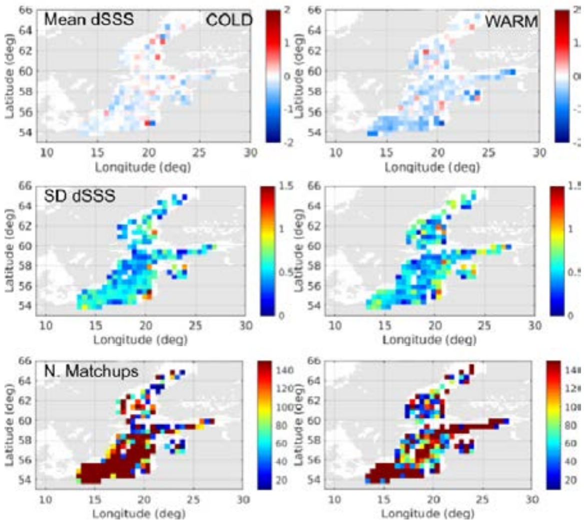

Figure 3: Spatial distribution of the differences between Baltic+ L4 SSS product and in situ salinity measurements provided by SeaDataNet (dSSS). 9 years of collocated measurements are accumulated in 0.5 degrees grid. The measurements are separated in cold (November-May) and warm (June-October) seasons (left and right columns, respectively). From top to bottom the plots correspond to the mean of the difference, the standard deviation of the difference and the number of match-ups.

4. Added-value of Baltic+ SSS products

We have also assessed the SSS dynamics captured by Baltic+ SSS products by comparing their performance with the ones of CMEMS Baltic reanalysis (Axell, 2019) and some in-situ observations from fixed stations (see Figure 12 in González-Gambau et al., 2022. Time-series of the different salinities are shown for the Western Gotland Basin in Figure 4. The salinity values of the model and the Baltic+ L4 SSS product have been averaged in the region and compared to the in-situ stations that fall inside.

An overall agreement in the described dynamics between satellite, reanalysis and in situ is observed. However, the variability shown by the satellite SSS reflects the variability captured by the in situ measurements better than the reanalysis. Therefore, these satellite SSS products present a clear added value with respect to in situ (since they cover in situ data gaps) and provide useful measurements for improving the models, particularly in regions where in situ data are sparse.

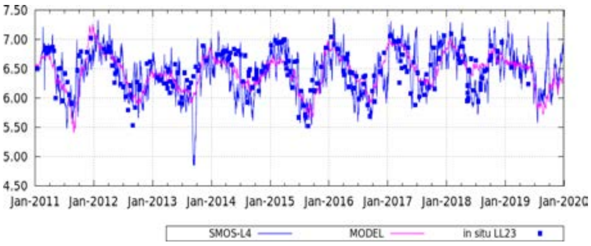

Figure 4. Averaged Baltic+ daily L4 SSS and daily CMEMS salinity fields in the defined box together with the in situ measurements that fall in the region defined in the Western Gotland Basin.

5. On-going scientific applications with Baltic+ SSS products

Baltic+ SSS data are being used in two on-going scientific studies:

(I) The analysis of the consistency between the structures detected in the Baltic+ SSS products and the circulation patterns derived from altimetric maps. Preliminary results show that at a monthly scale oceanic structures present in SSS and Dynamic Ocean Topography (DOT) are coherent and aligned. This suggests that Baltic + SSS products can contribute to better describe the circulation in the basin.

(II) A collaboration with HELCOM is on-going to analyze the correlation between the seasonal averaged of Baltic+ L4 SSS maps and the extreme events of different species. These seasonal averaged Baltic+ L4 SSS products are available at HELCOM catalogue: https://metadata.helcom.fi/geonetwork/srv/eng/catalog.search#/metadata/9d979033-1136-4dd1-a09b-7ee9e512ad14 and they can be visualized in the HELCOM Map and Data service https://maps.helcom.fi/website/mapservice/?datasetID=9d979033-1136-4dd1-a09b-7ee9e512ad14.

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Winter-time deep-water formation / convection in the Baltic Sea: a key to understand seabed dynamics and ventilation changes over the past 150 years

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1. Introduction

New geophysical, oceanographic data and studies on sediment core material obtained during the winter cruise MSM99 with R/V "Maria S. Merian" in 2021 strengthen the hypothesis that winter-time deep-water formation / convection played a critical role in seabed dynamics and bottom water ventilation during the last 7,000 years (Figure 1, cf. Moros et al. 2020). Moreover, we suggest that this process was also critical for marked environmental changes observed and reconstructed for the last 150 years, the transition from the cold Little Ice Age towards the Modern Warm Period.

2. Methods: Instrumental data and sediment proxy studies

Our inferences are based on a comparison of instrumental data comprising oceanographic measurements (temperature, salinity, oxygen - SMHI data), air temperature data from Stockholm (Moberg 2018) and sediment proxy records. A solid proxy for bottom water salinity changes are benthic foraminiferal counting data. Benthic foraminifera bloom in the Baltic Sea at sites where i) salinity is higher than c. 11 g/kg, and ii) bottom water conditions are oxic (e.g. Lutze 1965). X-ray fluorescence (XRF) scanning data of short sediment cores together with organic carbon content data are used to evaluate the input of terrigenous particles at the respective sites. XRF data are also used to identify manganese-carbonate layers that form at the sediment surface when anoxic bottom waters are ventilated. A sound chronostratigraphy for the last c. 150 years critical for a comparison between proxy and instrumental data is achieved by combining radionuclide, inorganic and organic pollutant downcore data (Moros et al. 2017).

3.Inferences

Our proxy records and the instrumental data indicate that during climate warming since AD 1850 the winter-time deep-water formation / convection decreased steadily as evident from deep basin study sites (e.g., in the Landsort Deep). A marked environmental change occurred in the late 1950s when the input of re-worked terrigenous material stopped suddenly and the bottom water conditions switched from oxic to hypoxic at different water depths at all sites (bathed at < 160 m water depths) in the Baltic Proper. This switch occurred shortly after the strong inflow of saline waters in the early AD 1950s when highest salinities were observed (instrumental data) and reconstructed (benthic foraminifera) in all sub-basins of the Baltic Proper. We argue that stratification strengthened markedly resulting from this pronounced increase in salinity, and the already rather weak winter-time deep-water formation / convection collapsed. The collapse led to a stop of fine-grained material input and bottom water ventilation decreased.

During the late 1980s, however, bottom water salinities decreased and therefore stratification weakened cause of a lack of significant inflows. This together with colder winter air temperatures lead to a bottom water ventilation of sub-basins located north of a marked topographic feature, the Baltic Sea Klint, due to the onset of the postulated winter-time deep-water formation / ventilation process.

After the early 1990s only the major saline water inflow of 2003 was able to effectively ventilate the bottom waters of the sub-basins north of the Baltic Sea Klint (Neumann et al. 2018), which is evident from instrumental and foraminiferal proxy data.

There is an urgent need to include the winter-time deep-water formation process in ecosystem modelling approaches as this may help to improve the relatively poor model performance for ventilation changes in sub-basins located North of the Baltic Sea Klint.

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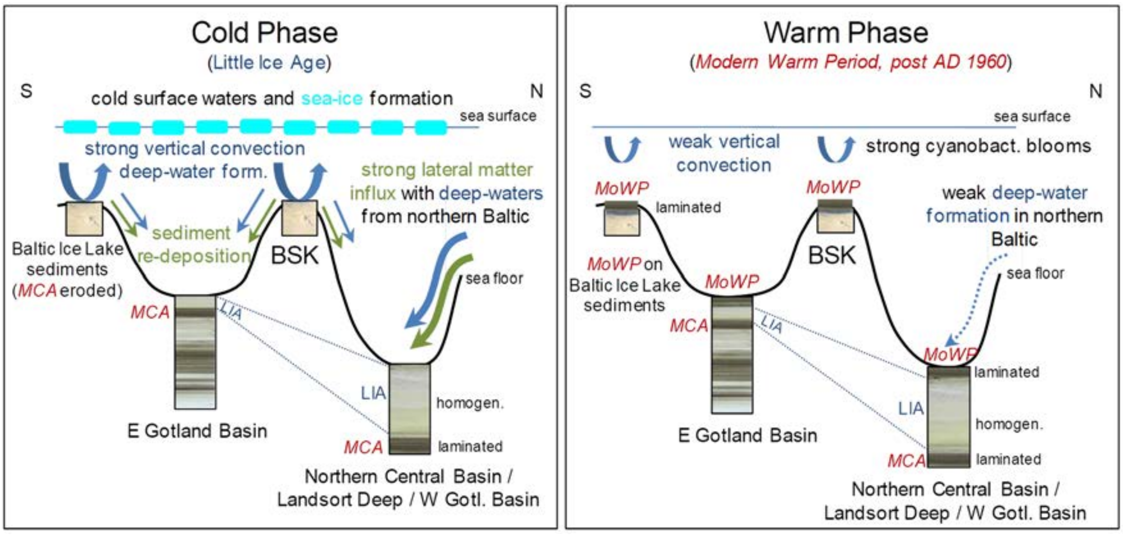

Figure 1. Schematic sketches of the effects of the suggested varying deep-water formation process on sediment accumulation during a cold (left) and a warm (right) phase with weak and strong formation, respectively, in sub-basins south and north of the Baltic Sea Klint (BSK)(modified from Moros et al. 2020).

Salinity Dynamics of the Baltic Sea

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1. Introduction

The Baltic Sea (Fig. 1) salinity is not only a physical variable, but it also describes in an integrated way the simultaneous effects of the energy and water cycles in the sea; some of these features are just typical for the Baltic Sea, as the low mean level of salinity and its pronounced variability. Several factors determine the observed structure of salinity. Due to the excess of river runoff to the sea, there is a continuous outflow of water masses in the surface layer. A compensating inflow to the Baltic Sea takes place from the Kattegat through the Danish Straits in the lower layer, strongly governed by the local atmospheric conditions. Also, the net precipitation over the sea plays a role in the water balance and consequently in the salinity dynamics. An essential role in salinity dynamics is played by the barotropic water exchange which comprises irregular Major Baltic Inflows (MBIs) and Large Volume Changes (LVCs), where MBIs are a subset of LVCs. These inflows have a significant impact on the modification of the observed patterns of stratification and oxygen conditions (for details see Lehmann et al. 2022).

The Baltic Sea ecosystem is adapted to the current salinity level: a change in the salinity balance would lead to ecological stress of flora and fauna and related negative effects on possibilities to carry on sustainable development of the ecosystem.

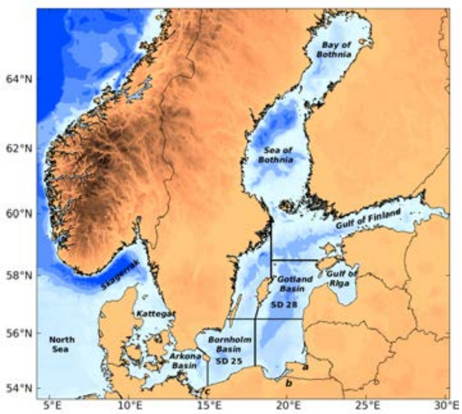

Figure 1. Map of the Baltic Sea and its sub-basins.

In December 2014, a Major Baltic Inflow took place and afterwards, several papers were devoted to study various aspects of such inflow events (for details see Lehmann et al. 2022). Those studies revealed new results on multiple factors not only concerning MBIs. Such are: the link between long-term (decadal-scale) variability in climatic conditions with the salinity development in the Baltic Sea, MBIs and related barotropic exchange of mass and meteorological forcing conditions, variations in salinity and fluxes on various scales (observation and attribution to changes in climate), salt budget changes and the related variations in the Baltic Sea circulation and induced changes in oxygen conditions.

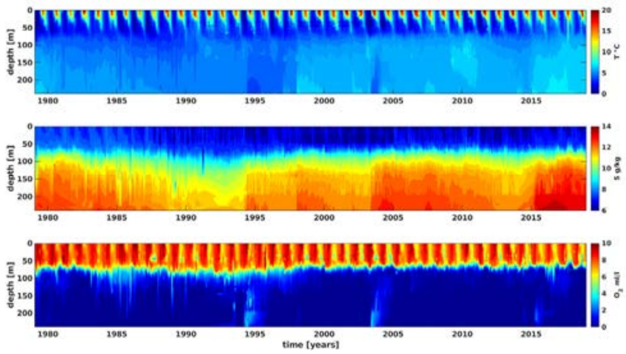

Figure 2. Observed temperature (top), salinity (middle) and oxygen (bottom) data as a function of depth and time. Subdivision 28 (SD 28, eastern Gotland Basin) for the period 1979-2018. Data from ICES Marine Data Centre (www.ices.dk).

2. Present knowledge gaps

There is still a need to better understand the role of freshwater balance on salinity distribution and its variability on seasonal to inter-annual time scales. The surface salinity of the eastern Gotland Basin varied over the recent four decades (Fig. 2). In the 1970s, it started at relatively high values of about 7.5 g kg-1, decreased until 2002 and slightly increased until 2018. There is a pronounced interannual variability of the surface salinity, which might be related to changes in the atmospheric forcing (wind and precipitation over the sea) and/or river runoff. There is still research needed to understand better the development of salinity stratification and its role in increasing hypoxia and to evaluate the changes in atmospheric circulation and its impact on inflows and salinity distribution in the Baltic Sea (Fig. 2). One key question is the complete mechanistic description of barotropic and major saltwater inflows, MBIs. Even if these have been studied for decades, we can question whether we really understand the process, can we predict MBIs? Extended outflow periods before the inflow reduce the mean sea level of the Baltic Sea, and in parallel lead to the formation of a haline stratification in the Danish Straits with the highly saline water propagating to the direction of Darss and Drodgen Sills. The frequency of low-pressure systems passing over the Baltic Sea and the strength of the wind will be enhanced for MBIs compared to LVCs. Thus, this leads to higher transport rates.

Forthcoming work needs to explore the chain of processes in detail, which additionally to large barotropic inflows leads to an influx of highly saline and oxygenated water. The freshwater input seems to play only a modulating role for the occurrence and strength of barotropic inflows. The total frequency of inflow events will not change, but the average amount of salt which an individual event transports into the Baltic Sea. Both river runoff and the strength of barotropic inflow show a variation on a 30-year timescale, and both show a stable and plausible phase relationship to be the driver of interdecadal salinity variations (for details see Lehmann et al. 2022).

Summer inflows of saline water masses can be traced in the Bornholm Basin by unusually high temperatures in the halocline zone (Fig. 2). Warm and salty summer inflows belong to baroclinic inflows. They might result in higher connectivity between nursery areas of pelagic fish species west of their principal spawning grounds and spawning stocks, e.g. for Baltic cod and flounder.

Detailed assessments of the exchange between coastal areas, including lagoons and open sea, and between sub-basins, the cold intermediate layer and turbulent mixing are still needed. Furthermore, the dynamics of small scale variability, eddies, frontal regions and vertical mixing are highly important for the salinity dynamics in total. Studies focusing on small-scale variability affecting low frequency variations in the Baltic Sea are not available. To improve our knowledge of these processes, we need detailed and joint modeling and observational studies.

One very topical issue, which is indirectly linked to salinity distributions, is the general circulation of the Baltic Sea. Do we understand all branches of the Baltic Sea haline conveyer belt? There are few regular observations of it, and the modeling exercises show significant discrepancies between their results and observations.

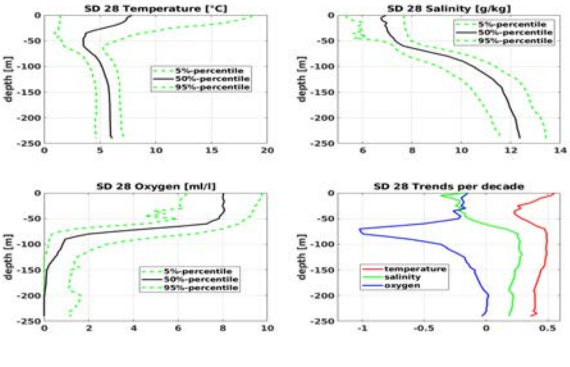

Figure 3. Percentiles (5, 50 and 95%) of temperature, salinity and oxygen profiles for Subdivision 28 (SD 28, eastern Gotland Basin) for the period 1979-2018. Trends per decade of temperature, salinity and oxygen based on SD 28 temperature, salinity and oxygen profiles for the period 1979-2018 (right lower panel).

3. Key messages

The long-term salinity dynamics is controlled by river runoff, net precipitation and the governing east-west wind conditions, i.e. the water mass exchange between the North Sea and the Baltic Sea. Changes in runoff are highly correlated with the development of the mean salinity of the Baltic Sea and explain about 50% of its variability. A 30-year variability has been found for surface and bottom salinity, river runoff and salt transport across the Darss Sill. There is no clear long-term trend of the mean salinity of the Baltic Sea, even if, during the last 40 years, surface salinity has decreased, and the lower layer salinity increased. This might be connected to changes in the vertical flux of salinity, but the explanation is still unclear.

Variations of salinity on shorter time scales (monthly to annual) are even more complex, especially in and below the halocline. Furthermore, there is a direct effect on temperature and salinity distributions. Stronger saltwater inflows can directly be traced by changes in the deep-water salinity and corresponding changes in temperature and oxygen (Fig. 2).

Over recent decades, negative salinity trends appear at the surface. At the same time, temperature increases, and oxygen decreases. The linear trend (~0.4 °C/decade) of the sea surface temperature of the Baltic Sea is about the same as the air temperature trend. The decreasing trend in oxygen can partly be explained by increasing temperatures which affect oxygen solubility and depletion rates. Maximum negative trends up to 1 ml l-1 per decade can be found in the halocline of Bornholm and Gotland Basin (Fig. 3).

The strength of the inflows and the amount of salt transported into the Baltic Sea depend on the intensity of the wind and the haline stratification in the Danish Straits.

It has been widely speculated that MBIs play the most crucial role in the development of deepwater salinity. Still, recent studies show that the frequency of major saltwater inflows did not change. So, the associated worsening of bottom oxygen conditions is caused by climate warming, excessive nutrient loading and related oxygen consumption and maybe due to increased stratification. This strongly suggests that reducing the external nutrient load to the Baltic Sea is still highly needed to improve its ecological state.

At regional scales, in addition to the interaction with the main Baltic Sea, the salinity regime of estuaries and lagoons is closely related to the local water balance components, including river runoff, precipitation, and evaporation. So, in the changing climatic conditions, the development of the salinity regime at regional scales may have various basic-specific features that might be diverse from corresponding trends in the main Baltic Sea. This fact will raise a high demand to carry out basin-specific studies to understand the changes in the local salinity regime.

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Changes of Mixed Layer Depth in the Baltic using in situ and model data.

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1. Introduction

The surface mixed layer in the ocean is a homogenous region of active turbulence generated by winds, surface heat fluxes and salinity/freshwater fluxes. Its depth provides valuable insight into short and long-term changes in stratification. Determination of mixed layer depth (MLD) involves computing vertical gradients of parameters such as temperature, salinity and density. MLD is therefore a good guide for validation of model results with in-situ observations.

Here we investigate methods of MLD calculation on different in situ data sets, then decide to apply one method to calculate mean MLD seasonal cycle from all in situ data in 1990-2021 and its changes in the last decades.

2. Methodology

Mixed layer depth was determined from CTD profiles using variety of in situ data :

- CTD collected during regular (4 cruises per year) IO PAN cruises of *RV Oceania* in 2000-2021 across the southern Baltic.
- ICES repository consisting of CTD data in 1993-2021. This data set covers large area over long period of time. However, those measurements are irregular and still leave some areas with very few data points.
- CTD collected by Argo floats in 2017-2021. These data are sparce and unequally distributed but help to fill the gaps.

Surface MLDs were estimated directly on individual CTD profiles. The reference depth was set to corresponding pressure of 10 dBar to avoid effects of diurnal cycle in the top few meters of the ocean. Then, in order to increase precision, a linear interpolation in vertical direction was performed between individual profile's data points to obtain profiles with values equally distributed by 1m. The results of MLD were averaged on a regular 0.2-degree grid.

Three methods for MLD calculations were tested:

i) Threshold temperature: The criterion is 0.2°C absolute difference from the reference surface:

Mixed temperature MLD = depth where ($\theta = \theta_{10dBar} + 0.2$ °C)

ii) Threshold density, where the fixed criterion in density is 0.03 kg/m3 difference from the surface

Mixed Density **MLD depth where $\sigma_0 = \sigma_{10dBar} + 0.15$ kg.m^{-3}**

iii) Temperature-pressure gradient threshold, which corresponds to the top of the seasonal thermocline depth: **MLD= $d\theta/dp > 0.15$ °C dBar^{-1}**

For the purpose of testing the above mentioned methods, a set of profiles from each data source were used. Sets were chosen to contain profiles in all seasons when possible (see Figure 1 as an example). It was necessary to perform additional tests for profiles from Argo floats as distance between measurements can significantly vary.

When comparing methods ii) and iii), results were usually very similar and performed well in all scenarios. When using data from ICES and IO PAN cruises, the results showed that the threshold density method provides very similar values of MLD to the temperature-gradient method. However, method ii) was not producing consistent results with data from Argo floats, that suffer from biases in salinity due to large uncertainty in the pressure measurements (3dBar). Therefore, temperature-pressure gradient (iii) method was chosen as it uses two directly measured parameters in contrary to threshold density method that requires the calculation of density from temperature, salinity and depth. In this way the uncertainty of MLD is reduced without compromising precision.

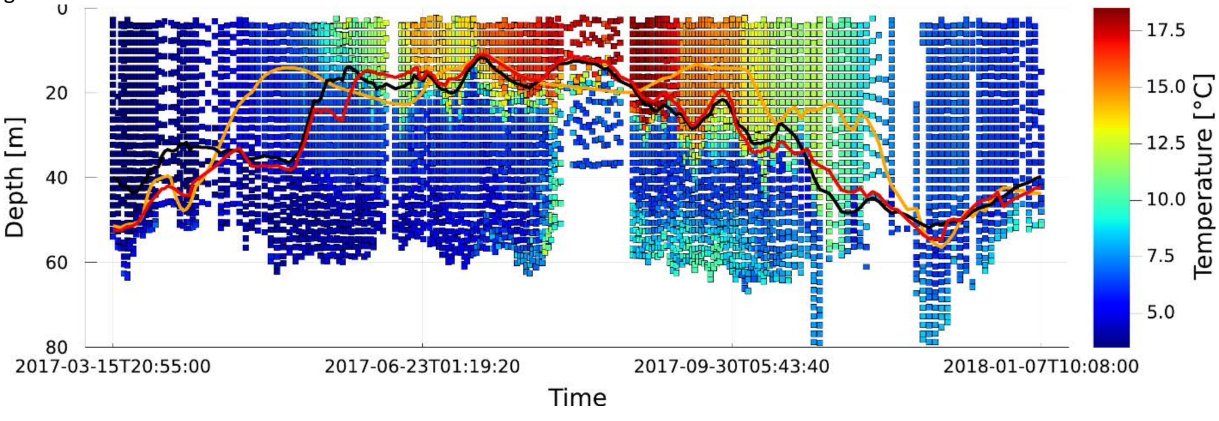

Figure 1. Comparison of three methods of MLD determination, applied to Argo profile. Black line represents result using threshold density method (threshold value of 0.15 kg m^{-3}), while red line represents temperature-pressure gradient threshold method (threshold value of 0.15°C/dBar), orange line represents threshold temperature method (threshold value of 0.2°C)

To calculate seasonal amplitude and phase a harmonic function was fitted to monthly MLD values, only when there were at least 6 values in each year. To determine long-term changes in seasonal amplitudes and phases, 5-years long means of these two parameters were calculated.

3. Results

As different MLD determination methods were compared, the temperature-pressure gradient (iii) was established to be the best compromise between computational efficiency and precision for considered data sources and considered geographic region. Using this method, MLD was computed for over 40 000 CTD profiles, measured over a period of more than 20 years. Such long timescale allowed for precise observation of the seasonal cycle, concluding that just in the last twenty years, minimal MLD has shifted by 3 weeks, from mid-July to the beginning of August. The seasonal amplitude of MLDs decreased during the analysed period.

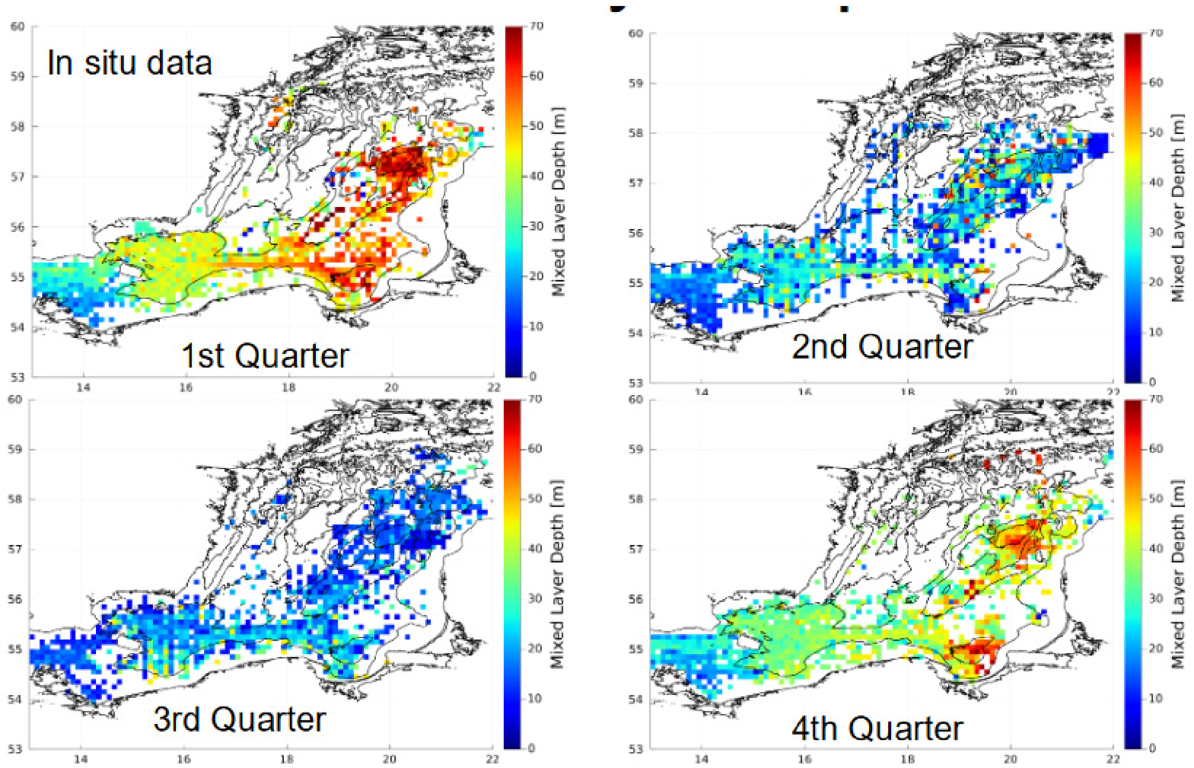

Figure 2. Mean MLD seasonal cycle using temperature-pressure gradient method combined from all data sources in 1990-2021. Results were split into quarters and then averaged on grid of 0.2°.

4. Conclusions

In this study different methods of MLD determination were compared to find the best suited one for character of Southern Baltic Sea. Based on data from Argo floats, ICES and cruises, MLD data was computed for a period of over 20 years. We noticed that climate change impacts MLD's seasonal cycle by reducing its amplitude and delaying its phase.

Acknowledgements

This study was funded by the NCN funded "Turbulent Mixing in the Slupsk Furrow" project grant nr. 2019/B/ST10/02189 and statutory activities of the Institute Oceanology, Polish Academy of Sciences, task II.1.

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Results from the first year-long continuous glider deployment in the Baltic: the importance of small scale processes on physical and biological dynamics

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As part of the long-term SAMBA (Smart Autonomous Monitoring of the Baltic) project, operated by VOTO Ocean Knowledge, multiple ocean gliders were deployed across two observatories (Bornholm and Skagerrak) from March 2021 to 2022. The observatories were occupied continuously for 1 year by the gliders with only ~5% downtime for vehicle turnarounds and refurbishments. The SAMBA project aims to 1) maintain a long-term time-series, 2) resolve the small-scale variability of critical physical and biological shelf sea processes which remain poorly constrained in dynamic shelf sea environments, and 3) offer insight into how these systems will function and evolve over time.

We present year-long time-series of physical (temperature, salinity, ADCP currents) and biochemical (chlorophyll a, dissolved oxygen) properties at both the Kattegat-Skagerrak transition zone and in the Bornhom Basin with vertical resolutions at 10-centimetre scale and vertical profiles with a mean temporal resolution of ~37 min. We first highlight marked differences in timing and intensity of the annual cycle of primary productivity at each site, driven by rapid changes in near-surface stratification and coupled to diurnal warm layers.

We then present two specific case studies which show how important both short term and small scale variability can be. At the Skagerrak site, we describe transient outflows of deoxygenated water (~60% saturation) in intermediate waters along the Swedish coast. At the Bornholm site, we observe repeated short-term salinity inflows into the basin and estimate a salinity flux using ADCP velocity data.

These preliminary results serve to show the importance of sustained, continuous high-resolution observations in regions such as the Baltic Sea to fully capture the magnitude and variability of relevant ecosystem processes. SAMBA is a collaboration between scientists at the University of Gothenburg and the Voice of the Ocean Foundation (VOTO).

On drivers and uncertainties in projected future salinity of Gulf of Bothnia

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1. Introduction

The total salinity on the Gulf of Bothnia is mainly determined by the net precipitation, river inflows and water exchange with the Baltic Proper. The variations within the Gulf of Bothnia are in addition affected by the stratification strength, bathymetry, current patterns and ice conditions. The Kvarken area dynamics also largely determine the salinity differences between the Bothnian Bay and Bothnian Sea. The salinity differences between the Bothnian Bay and Bothnian Sea are in addition also largely determined by the Kvarken area dynamics.

In this presentation we analyze the changes in salinity and overturning circulation development within the simulation runs.

The comparison between our simulation runs demonstrates that small changes in conditions can produce different salinity trends, as either weaken, or strengthen the general circulation of the Gulf of Bothnia. While the general salinity trend over the 2006-2100 period is slightly decreasing, the trend can be on the rise for decades within the simulation.

2. Model setup

The model setup used in this work is based on the NEMO-Nordic setup, described in Hordoir et. al (2019). In this setup NEMO 3.6 model is coupled with SCOBI biogeochemical model and LIM3 ice model. The model setup covers the Gulf of Bothnia area with 1 NM grid from 60° N northwards.

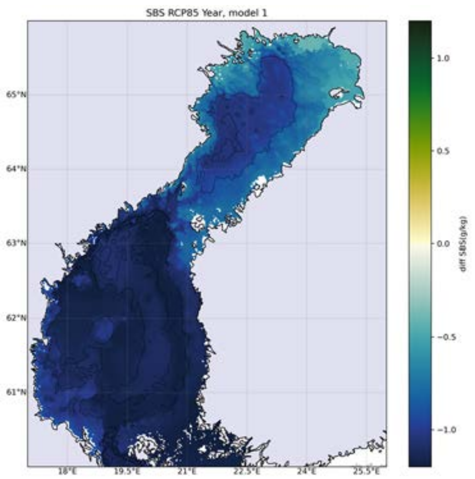

Figure 1. Yearly average Sea Bottom Salinity development between 30 year average at the start and end of the simulation period, 2006 - 2100 in one of the model runs studied.

Scenarios used in these studies are forced with 3 different downscaled global circulation model forcings (from MPI-ESM-LR, EC-EARTH and HadGEM 2-ES) and with two Representative Concentration Pathways, RCP 4.5 and RCP 8.5.

Historical comparison scenarios for each model span the years 1976 to 2005, and each future scenario continues from 2006 to 2100.

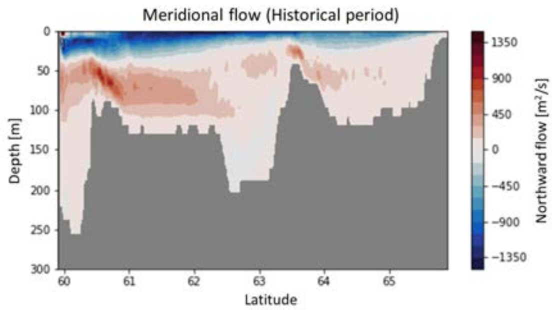

Figure 2. Meridional flow averaged over the historical period 1976 to 2005.

3. Salinity changes

Local changes in salinity within the Gulf of Bothnia are affected by the stratification, changes of current patterns and river inflows, although its general salinity development is largely determined by the changes in the Baltic Proper. The effect diminishes after the Kvarken area considerably. One example of the salinity development is shown in Figure 1.

4. Circulation

The overturning circulation is characterized by being divided into the two basins Bothnian Sea and Bothnian Bay divided by the Quarken, see Figure 2. The circulation in each of the basins is composed of a vertical estuarine circulation superimposed by a horizontal cyclonic one.

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Wind-controlled transport of saltwater in the southeastern Baltic Sea: a model study

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1. Introduction

In the semi-enclosed Baltic Sea (BS), the water exchange with the North Sea (NS) and northern Atlantic is hampered by the presence of narrow and shallow straits - the Great and Little Belts and Öresund. In addition, different basins of the BS are connected by the straits and the depth of the basins and straits increases eastward and northward with distance from the transit area with the NS. The saline water of the NS origin spreads along the chain of basins and straits in the form of a bottom gravity current. An important link in this chain of basins is the Słupsk Furrow (SF), an elongated, channel-like topographic constriction between the Bornholm Basin in the west and the Eastern Gotland / Gdańsk basins in the east (Figure 1).

The SF is the only pathway for saltwater of the NS origin to enter the deep basins of the eastern and northern Baltic Proper. In addition, the saltwater, leaving SF for the east, supposedly has two options to travel. First, it can turn to the southeast towards the Gdańsk Basin and then, having made a cyclonic loop, rush north to the Gotland Deep (GD) through the Hoburg Channel. Second, it can turn to the northeast to rush directly to the Hoburg Channel and further enter the GD. Which of the routs is actually realised is largely determined by dynamic processes in the bottom gravity currents.

In addition to the gravity current dynamics, the saltwater transport in the BS is greatly influenced by the wind forcing. Numerical modelling of circulation in the BS shows that the northerly and easterly winds promote transport of saltwater to the east in the lower layer of SF (Krauss and Brügge, 1991; Zhurbas et al., 2010, 2012). And vice versa, the southerly and westerly winds, promote a compensatory flow to the west in the lower layer of SF which weaken the eastward transport of saltwater, and, given a sufficiently strong southerly / westerly wind, can completely block it (Zhurbas et al., 2012).

Krauss and Brügge (1991) explained the wind-controlled saltwater transport through SF by a reasoning that the dominant wind-produced circulation is characterized by coastal jets in the wind direction and countercurrents in the central region, deflected by bottom topography. The water exchange between Bornholm and Eastern Gotland / Gdańsk basins occurs through SF, which is close to the center of the BS at this longitude. Accordingly, bottom currents opposite to the wind direction prevail, which can explain the saltwater transport in SF to the east at easterly winds but cannot at northerly winds. However, one can hypothesize that the saltwater transport in SF to the east at northerly winds is caused by the wind-driven Ekman transport to the west in the upper layer which develops compensatory countercurrents in the lower layer.

The objective of this study is to investigate the saltwater exchange between the basins of the southeastern Baltic Proper, including the Słupsk Furow, the Gdańsk Deep, the Hoburg Channel, and the Gotland Deep, depending on wind forcing based on multi-year numerical simulations and decide which effect, the wind-driven coastal jets or wind-driven Ekman transport in the open sea, prevails.

2. Materials and methods

The General Estuarine Transport Model (GETM; Burchard and Bolding, 2002) was applied to simulate thermohaline fields, salinity, currents, and overall dynamics in the southeastern BS.

The model domain includes the entire BS with an open boundary in the Kattegat and has the horizontal grid spacing of 0.5 nautical miles (926 m) and 60 adaptive layers in the vertical direction. The digital topography was obtained from the Baltic Sea Bathymetry Database (http://data.bshc.pro/). The model run is started from 1 April 2010 with initial thermohaline conditions taken from the Baltic Sea reanalysis for the 1989–2015 by the Copernicus Marine service. The atmospheric forcing was adopted from HIRLAM (High Resolution Limited Area Model) version maintained by the Estonian Weather Service with the spatial resolution of 11 km (Männik and Merilain 2007). For the lateral boundary conditions, time-series of observed sea surface height from Gothenburg Torshamnen coastal station and climatological profiles of temperature and salinity (Janssen et al., 1999) along the transect between Denmark and Sweden have been used.

More detailed information about the model setup is available in Zhurbas et al. (2018) and Liblik et al. (2020).

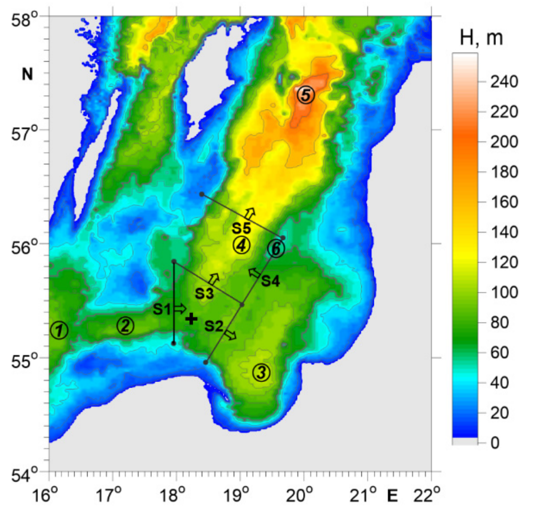

Figure 1. Bathymetric map of the southeastern BS. The encircled numbers 1–6 point at the Bornholm Basin (1), the Słupsk Furrow (2), the Gdańsk Basin (3), the Hoburg Channel (4), the Gotland Deep (5), and the Klaipeda Bank (6). The black lines labelled S1–S5 are the locations of 5 cross-sections through which the saltwater transport is calculated. The arrows at the cross-

sections show the direction corresponding to the positive value of the saltwater transport. The black cross points at the location of the IOW monitoring station TF0256.

3. Results

In accordance to arguments presented in the Introduction, the saltwater transport though SF is expected to be negatively correlated with the *y*-component of the wind stress τ_y. This expectation is clearly confirmed by Figure. 2 where a scatter plot of the daily saltwater transport T_{sal} through cross-section S1 versus the daily mean of the *y*-component of the normalized wind stress $\langle \tau_y/\rho_0 \rangle$ is presented. The correlation coefficient for the 10-year time series of T_{sal} and $\langle \tau_y/\rho_0 \rangle$ is $r = 0.704$.

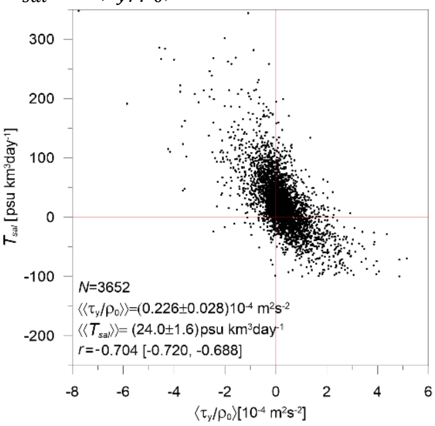

Figure. 2. A scatter plot of the daily saltwater transport T_{sal} through cross-section S1 versus the daily mean of the *y*-component of wind stress $\langle \tau_y/\rho_0 \rangle$; $\langle\langle \ldots \rangle\rangle$ is the 10-yr mean value. The numbers in the square brackets and next to the $\pm$ sign quantify the 95% confidence limits.

Correlation between daily saltwater transport T_{sal} for cross-section S1 and other four cross-sections S2–S5 is found to be positive varying between $r_{S1,S4}$= 0.187 (for cross-sections S1 and S4) and $r_{S1,S3}$= 0.488 (for cross-sections S1 and S3 (Table 1). The positiveness of the correlation in this case can be intuitively explained by the fact that the positive fluctuation of T_{sal} through the SF (cross-section S1) leads to an increase of T_{sal} through the other cross-sections S2–S5, and the correlation will be minimal for cross-sections S1 and S4, since the saltwater from the cross-section S1 reaches cross-section S4 along the longest route with a cyclonic bypass of the Gdańsk Basin.

Correlation between daily saltwater transport T_{sal} for cross-section S2 and cross-sections S3–S5 is negative varying within (-0.455, -0.401). Negative correlation in this case is quite expected because the saltwater transport to the north (south) corresponds to the positive (negative) fluctuation of T_{sal} through cross-sections S3–S5 but negative (positive) fluctuation of T_sal through cross-sections S2 (see Figure. 1 and the caption to it).

The fact that the saltwater transport to the north (south) corresponds to the positive (negative) fluctuation of T_{sal} through cross-sections S3–S5 causes the positive correlation between saltwater transports through pair of cross-sections S3–S4 ($r_{S3,S4}$= 0.415), S3–S5 ($r_{S3,S5}$= 0.862), and S4–S5 ($r_{S4,S5}$= 0.662). The highest correlation, $r_{S3,S5}$= 0.862, is found for daily saltwater transports through cross-sections S3 and S5, since these two cross-sections are equally oriented (from southeast to northwest), and the saltwater transport through them describes the same process of the northeast saltwater flow towards the GD.

Table 1. Correlation coefficient r between daily saltwater transports T_{sal} through cross-sections S1–S5 calculated from the 10-yr time series. Numbers in square brackets are the 95% confidence intervals.

S1	S2	S3	S4	S5	
$r_{S1,S1} = 1$	$r_{S1,S2} = 0.394$ [0.367, 0.420]	$r_{S1,S3} = 0.488$ [0.464, 0.512]	$r_{S1,S4} = 0.187$ [0.157, 0.218]	$r_{S1,S5} = 0.405$ [0.378, 0.431]	S1
	$r_{S2,S2} = 1$	$r_{S2,S3} = -0.401$ [-0.427,-0.374]	$r_{S2,S4} = -0.442$ [-0.467, -0.416]	$r_{S2,S5} = -0.455$ [-0.479, -0.429]	S2
		$r_{S3,S3} = 1$	$r_{S3,S4} = 0.415$ [0.389, 0.441]	$r_{S3,S5} = 0.862$ [0.853, 0.870]	S3
			$r_{S4,S4} = 1$	$r_{S4,S5} = 0.662$ [0.644, 0.679]	S4
				$r_{S5,S5} = 1$	S5

4. Conclusions

The daily saltwater transport to the east through SF is found to be highly correlated with the wind stress component towards south (the correlation coefficient is 0.704) which is in accordance with the Krauss and Brügge (1991) findings. Even a higher correlation, r= 0.812, is found for the daily saltwater transport to the northeast through the Hoburg Channel (cross-section S5) and the wind stress component towards southeast, which confirm the above mentioned hypothesis on the prevalence of the effect of open-sea Ekman transport rather than that of the coastal jets.

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Topic 2

Biogeochemical functioning and development: From catchment to the open sea

Benthic coastal buffers against climatic and eutrophication extremes

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1. State of the art

In the last decades wastewater discharge and human activities have produced a cascade of negative effects on aquatic ecosystems, from the river networks to the coastal zones (Viaroli et al. 2018). The most evident effect of these anthropogenic pressures is the process of eutrophication, which translates into excess concentrations of nutrients such as nitrogen and phosphorus in the water, favoring the growth of cyanobacteria (Conley 2012). Excessive algal blooms turn the water turbid and affect the quality, recreational and economic value of the coastal zones. The algal biomass in fact enriches the sediments with organic matter, and requires large oxygen amounts for its decomposition, often exceeding oxygen availability (Paerl & Huisman 2009). Ultimately, this sequence of events may lead to water anoxia and loss of species and may threaten the capacity of ecosystems to react and to recover from such pressures (Diaz & Rosenberg 2008).

Some coastal zones of the Baltic Sea are seriously affected by eutrophication, even though European Directives have improved agricultural practices, the efficiency of wastewater treatment plan and limited the use of fertilizers (Bouraoui & Grizzetti 2011). The expected, positive effects of these measures can be delayed by climate change, a new menace that act in synergy and worsen the impacts of eutrophication, by affecting the intensity and patterns of precipitation, the ice cover periods and the water temperatures (Magri et al. 2019). Climate change can increase nutrient transport to the coastal zone and can favor water stratification and heating. This synergic impacts of eutrophication and climate change (E-CC) may affect water chemistry and the biodiversity of large coastal areas, to an extent that is poorly known but potentially dramatic.

2. Objectives

The main aim of BUFFER project is to investigate the impact of the interaction between climatic anomalies and eutrophication on the capacity of the sediments to process and retain nutrients and contrast their regeneration to the water column (*the buffer capacity*). BUFFER will analyze if and how the capacity of sediments to control eutrophication consequences is menaced by climate change and will disentangle underlying mechanisms.

3. Working hypotheses

The main working hypothesis is that the synergic impact of eutrophication and climate change will affect also coastal zones at northern latitudes, which have been always characterized by low temperature regimes that represented a natural buffer counteracting nutrient regeneration, algal growth and oxygen shortage. Contrarily, southern sites should address better climatic extremes such as high temperatures and high freshwater discharge. This should be possible since those areas are normally exposed to a wide range of temperatures and precipitations. In the northern region, we expect therefore higher vulnerability to climate change, but also a higher capacity to restore and recover the buffer capacity of sediments, due to longer cold season.

4. Study areas

The main study site of BUFFER is the Gulf of Gdańsk (southern Baltic Sea), as it has been threatened by the combined effects of climate change and eutrophication (Figure 1). BUFFER project will investigate the buffer capacity of specific areas in the Gulf along multiple gradients of oxygen availability, sediment features, freshwater input, depth and light. The buffer capacity will be also analyzed with respect to the presence of different organisms, including primary producers as aquatic plants and algae and different functional groups of macrofauna, including filter-feeding bivalves and burrowing worms, to understand whether living macroorganisms also represent natural buffers. Sampling campaigns will be carried out in two additional sites: the Sacca di Goro Lagoon in Italy and the Kongsfjorden and Porsangerfjorden in Norway. Both sites are affected by high freshwater discharge, the former from the Po River and the latter from the ice melt from land, and both sites can encounter bottom water anoxia. The comparison among study areas will allow to understand whether the climate-eutrophication effects produce larger impacts in the northern as compared to southern latitudes.

Figure 1. Geographical location of the three study areas: Sacca di Goro lagoon (Italy), Gulf of Gdańsk (Poland), Kongsfjorden and Porsangerfjorden (Norway).

5. Methods

The BUFFER target compartment is the benthic system. All experimental activities are based on laboratory incubations of intact or reconstructed sediments under controlled conditions (Dalsgaard et al. 2000). Intact sediment cores will be employed in order to monitor processes in key seasonal moments or under specific environmental conditions (e.g., extreme events like heath waves or high river discharge affecting temperature, salinity or nutrient regimes). Reconstructed sediments will be used to isolate and test factors or to validate anomalies and processes emerging during monitoring activities.

The BUFFER project consists of 8 work packages that interact closely (Figure 2).

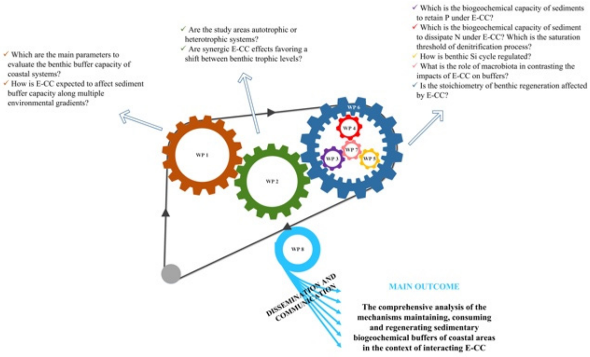

Figure 2. BUFFER project work packages and workflow. BUFFER integrates a complex array of field and laboratory activities: WP2 to 7 are research-oriented, WP1 is devoted to literature revision and WP8 deals with dissemination and communication of project results.

BUFFER will review the literature on benthic buffers of coastal zones and analyze how they are defined, quantified and restored in the context of eutrophication and climate change (WP1); evaluate if and how sedimentary buffers depend on the degree of sediment net autotrophy or net heterotrophy, defined according to the Trophic Oxygen Status Index (TOSI, Viaroli & Christian 2003), and how this status is affected by E-CC (WP2); evaluate how the biogeochemical capacity of sediments to retain P (WP3), to process and dissipate N (WP4) and to regulate Si fluxes (WP5) may be impacted by E-CC. WPs 2 to 5 will be analyzed along physico-chemical (e.g., depth and O_2 or organic matter availability) and biological gradients (e.g., bioturbation, primary producers growth forms). WPs 3 and 4 will be also investigated along the wide latitudinal gradient. Results from WPs 3, 4 and 5 will be elaborated in the perspective of the ecological stoichiometry theory to evaluate how a balanced regeneration of nutrients (*sensu* Redfield) is buffered and if the synergic E-CC effects alter such stoichiometry (WP6). BUFFER will analyze via manipulative experiments how physical factors (e.g., wind, resuspension, high discharge) and specific macrobiota (e.g., primary producers, macrofauna, including invasive species) enhance or reduce the biogeochemical buffer capacity of the benthic system (WP7). Outcomes from the 7 work packages will produce novel, comprehensive analysis and understanding of the mechanisms maintaining, consuming and regenerating sedimentary biogeochemical buffers of coastal areas in the context of interacting E-CC. Results will be disseminated and will produce scientific publications (WP8).

6. Expected results

BUFFER will allow reconstructing a) how interacting eutrophication and climate change differentially affect the biogeochemical cycles of key macronutrients (N, Si and P), b) the mechanisms underlying such changes, and c) the role of the biota in contrasting or delaying such changes.

Results from BUFFER will allow to outline the impacts of climatic anomalies and eutrophication along a wide latitudinal gradient and the quantification of how local biogeochemical buffers are affected by such anomalies. Furthermore, BUFFER will identify the critical zones in the Gulf of Gdańsk in terms of limited or null buffer capacity of the benthic system. Additional and important outcomes will be the identification of effective measures aimed to contrast the enhancement of nutrient enrichment. Such actions will be useful for the management of coastal areas, not only in Poland, but also in other threatened aquatic environments.

7. Acknowledgements

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Micron-scale biogeography of seawater biofilm colonies at solid substrata affected by organic matter transformation in the Baltic Sea

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1. Abstract

The aim of the research was to determine temporal and spatial evolution of biofilm architecture formed at model solid substrata submersed in Baltic sea coastal waters in relation of organic matter transformation along a one-year period. Several materials (metals, glass, plastics) were deployed for a certain time, and the collected biofilm-covered samples were studied with a confocal microscopy technique using advanced programs of image analysis. The geometric and structural biofilm characteristics: biovolume, coverage fraction, mean thickness, spatial heterogeneity, roughness etc., turned out to evolve in relation to organic matter transformation trends, trophic water status and biofilm microcolony transition from a heterotrophic community (mostly bacteria) to autotrophic (diatoms). In addition to the previous work (Grzegorczyk et al., 2018), the structural biofilm parameters could become further novel trophic state indicators.

2. Introduction

In most aquatic ecosystems, a complex mixture of algae, cyanobacteria, heterotrophic microbes and detritus called periphyton can be found attached to submerged surfaces. Particular biofilm features like: short generation time, sessile nature and fast responsiveness to environmental condition stressors make them an effective seawater chemistry monitoring tool as demonstrated in recent Baltic Sea eutrophication studies (Grzegorczyk et al., 2018). In this research, geometric and structural, commonly evaluated biofilm characteristics like: biovolume, coverage fraction, area to volume ratio, spatial heterogeneity, number of species, mean thickness, roughness, fractal dimension in 2D etc. were on-line determined from confocal reflection microscopy (COCRM) images data (Inaba et al., 2013), processed with graphical programs on samples collected at Baltic sea submerged artificial solid substrata. The aim of the study was twofold: establishment a time- dependent biofilm structure parameters evolution to create the modified biofilm kinetics model, and to exhibit their correlations to water body chemical trophic state indexes, seasonal evolution of autotrophic system, and man-made pollution stresses.

3. Materials and Methods

Several artificial solid materials (glass, metallic, polymeric) of varying surface energy were submerged at a depth of 0.5 m in near-shore waters of the southern Baltic Sea as biofilm collectors, for a certain time, as described in details elsewhere (Grzegorczyk et al., 2018). Biofilm accumulation time was ranging from 1 to 24 days; probes were studied every month from May to November, 2016. The trophic status was evaluated with the parameters: pH, dissolved O_2, phosphate, nitrite, nitrate, ammonium concentrations using a spectrometric method. Primary production, *Chl. a*, nitrogen, phosphorus concentrations were taken from SatBałtyk system data base (available at http://satbaltyk.iopan.gda.pl). Spearman's rank correlation routine was adopted to establish cross-correlations between the geometric-structural biofilm parameters and trophic state indexes.

A confocal scanning microscopy system working under the reflection mode configuration was used to biofilm surface morphology analyses, as described in (Grzegorczyk et al., 2018). From a vertically-separated stack of sample images, detailed surface geometric and structural signatures were evaluated with advanced graphical analysis programs (CMEIAS, PHLIP, ImageJ). The mean thickness, biovolume, area to volume ratio, coverage area fraction f, roughness parameter, fractal dimension, Hopkins aggregation index were selected (Dazzo, 2010; Mueller et al., 2006).

4. Results and Discussion

Apart from the quantification of biological components (bacteria, micro-algae and EPS), reflection images of biofilms visualized solid inorganic material (Fig. 1), being similarly analyzed using PHLIP program (Mueller et al., 2006). Different reflective materials were distinguished as the bare glass substratum (I), silica frustules of diatoms present in the biofilm (II), and considerable amounts of amorphous material (III). Biovolume estimates showed that for the image stack in Fig. 1, about 85 % of the biofilm consisted of inorganic reflective material, while an organic material represented the remaining 15 % of the total biovolume.

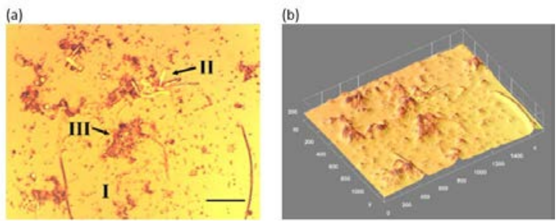

Figure 1 (a) A microscopic projection image of a biofilm grown on glass slides (14-day old) in Baltic seawater (covered area 460 x 570 µm). Black arrows indicate the different reflective structures containing bare glass substratum (I), silica frustules of diatoms (II), and amorphous material (III). Bar= 10 µm. Figure 1 (b) 3D reconstructed image from Fig. 1 (a); geometric film structure parameters: total f= 10.3 %, mean thickness= 43 µm, biovolume = 35,800 μm^3, fractal dimension= 1.24, Hopkins aggregation index = 2.79. Diatom abundance = 1.3 x 10^4 ind. cm^{-2}.

The fractal dimension (varying between 1 and 2) reflects a contact border line complexity between the object and the surrounding area, higher values point to a more developed line geometry (Yang et al., 2000). Hopkins' aggregation index is a measure of biofilm colony dispersion state, for randomly distributed structures is < 2 (Dazzo, 2010).

EPS components are difficult to visualize microscopically because of their low density and molecular complexity. To determine a fraction of EPS-glued biofilm species, we stained the 3-day old sample with $KMnO_4$ oxidant, which is known to react with EPS components yielding brown MnO_2 precipitate deposition on the EPS. The microscopic image of such a sample is shown in Fig. 2 (a) with the geometric parameters of 3-D structure summarized in Fig.2 (b) caption.

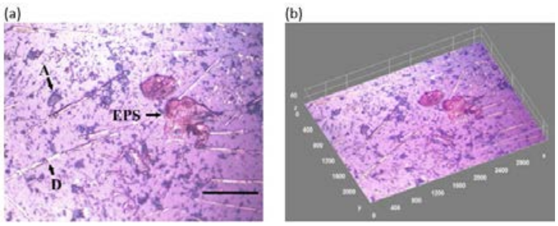

Figure 2 (a) Microscopic reflected signal from the EPS stained with $KMnO_4$ (brown areas) of biofilm sample grown on glass slides (3-day old) in seawater. Bar= 10 µm. Figure 2 (b) 3D reconstructed image. Geometric film structure parameters: total f= 11.4 %, mean thickness= 23 µm, biovolume= 27,500 µm^3, fractal dimension= 1.67, Hopkins aggregation index = 2.93. Diatom abundance= 2.6 x 10^4 ind. cm^{-2}.

The temporal development of biofilm structure parameters, shown in Fig. 3 (a-d). The algal community evaluated from small to larger species, which correlated to an increase in biovolume (R= 0.96), and demonstrated the biofilm thickness grow (R = 0.87) with time. Bacteria were appeared at measurable quantities close to the solid surface, whereas microalgae occupied intermediate parts of the layered structure. EPS covered the outermost surface of the microcolony.

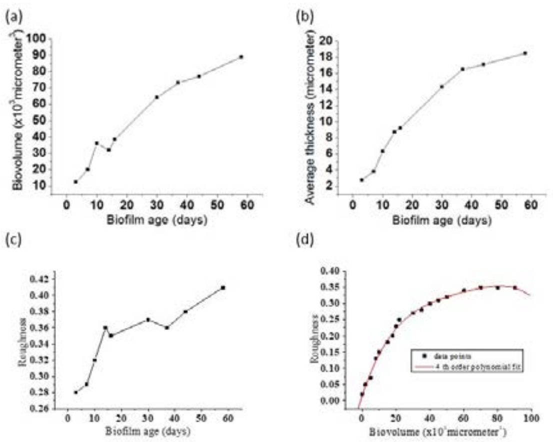

Figure 3. Structural parameters temporal development of a natural biofilm grown on glass slides in seawater. (a) biovolume, (b) average thickness, and (c) roughness. (d) correlation between biofilm roughness and biovolume; the line represents the 4th order polynomial fit to the data (R= 0.89).

The results suggest that the contribution of bacteria in phototrophic biofilms may be low (1-4.9 %) in comparison to the algal and EPS components, which represented 20–76 % and 19–77 % of the biofilms, respectively. Growth of the micro-algae dominated the development of biofilm. This led to a significant increase in biovolume, thickness and roughness of the biofilm. Phototrophic microorganisms (diatoms) became the dominant component of this biofilm.

5. Conclusions

The spatial organization of complex natural biofilm colonies is critical to understanding the interaction of the individual taxa that comprise a community. Bacteria are micron-sized, and many of the forces and factors that underlie their distribution patterns operate at micron scales and area qualitatively different from the large scale factors, such as a trophic state status, primary production or man-made pollution stresses.

A clear transition was observed from a heterotrophic community (enriched in bacteria) to an autotrophic community consisting largely from diatoms. It is in agreement with the Baltic phytoplankton taxa seasonal changes (Pogorzelski et al., 2013). The biofilm development leads to an increase in its heterogeneity since a strong correlation between roughness and biovolume was noticed. These comprehensive studies confirmed that a strong correlation appeared between: biovolume vs biofilm wet weight (BWW) (R = 0.78), coverage fraction f vs BWW (R = 0.82), biofilm thickness vs surface wettability parameters: surface film pressure Π (R = 0.86), and surface energy γ_{SV} (R = - 0.83) if referred to our previous work (Grzegorczyk et al., 2018).

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Investigation of the potential use of the N_2/Ar ratio for the estimation of the seasonal and spatial variability of denitrification and anammox in the water column of the Baltic Proper

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1. Introduction

Denitrification and anammox are the main nitrogen (N) removal pathways in seawaters. Both processes are very important in regions, such as the Baltic Sea, which receive high nutrient loads from land that enhance primary production and eutrophication. The Baltic Sea is also characterized by a strong vertical salinity gradient and the presence of a permanent halocline hampering mixing in the water column and ventilation of the deep water layers. Rare events of deep water renewal (so-called Major Baltic Inflows), together with high oxygen consumption, lead to suboxic and anoxic conditions in the Baltic Sea (Rak et al., 2020), which are favorable for denitrification and anammox – processes for which the end product is a non-reactive N_2 (Codispoti et al. 2001).

In seawater, the concentration of dissolved gases is controlled by biogeochemical and physical processes. The latter can be traced by measuring inert gases such as, for instance, argon (Ar). Hence, the N_2/Ar ratio can be further used to separate physical and biological effects influencing N_2 fields. This approach may suit especially to the stratified water bodies, where deep suboxic and anoxic waters are separated from the surface water layer influenced by the gas exchange with the atmosphere (Löffler et al. 2011; Schmale et al. 2019; Shigemitsu at al. 2016).

2. Aim of the study

The study aimed at investigating the potential use of the supersaturation ratio – ΔN_2/Ar as a tracer of denitrification and anammox processes in the water column of the Baltic Proper.

3. Methodology

The supersaturation ratio (ΔN_2/Ar) was derived as an anomaly from the N_2/Ar ratio in seawater being at equilibrium with the atmosphere and was calculated as shown in following Equation:

$$\Delta N_2 / Ar = \left(\left(\frac{N_2}{Ar}\right)_{mes} - \left(\frac{N_2}{Ar}\right)_{sat}\right) \cdot Ar_{mes}$$

where: $(N_2/Ar)_{mes}$ and $(N_2/Ar)_{sat}$ are the ratios measured and in equilibrium with the atmosphere for the potential temperature and salinity of the seawater sample, respectively.

Seawater samples were collected from the water column of Baltic Proper between 2017 and 2021 from nineteen stations (including Gdańsk Deep, Gotland Deep, and Bornholm Deep). Sampling locations are presented at Figure 1.

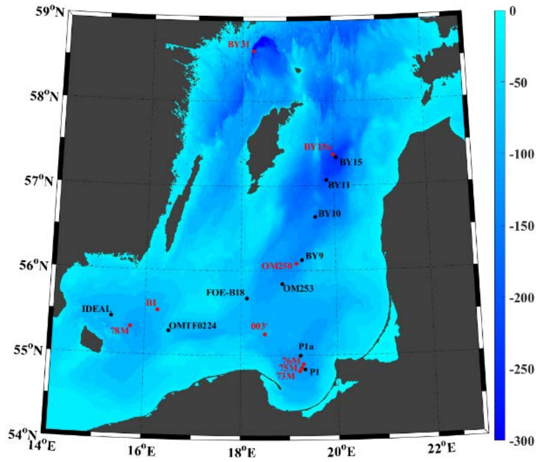

Figure 1. Location of the study sites. In black stations used for the estimation of spatial variability were marked

The technique used for nitrogen and argon measurements was Membrane Inlet Mass Spectrometry (MIMS). This technique allows performing high-precision measurements of dissolved N_2 and Ar in water (molar masses 28 and 40 were detected, respectively). The MIMS instrument consist of a PfeifferVacuum model 422 quadrupole mass spectrometer (QMA 400 analyzer with cross-beam ion source) with a flow-through silicone capillary membrane inlet (Bay Instruments, Easton, Maryland). Data were collected with the use of QuikDATA software. Precision (coefficient of variation) was determined as <0.5% for N_2 and Ar concentrations.

Sample were collected from water layers, which were named as: A – above the halocline; B – halocline; C – under the halocline; D – bottom water. The layers were determined for each station separately, basing on the obtained salinity profiles.

4. Results and discussion

Figure 2 shows the obtained N_2/Ar ratios. The results indicated N_2 accumulation in the oxygen minimum zones below the halocline with the highest values found in the bottom layers. This can be explained by both denitrification and possibly anammox in the water column and with N_2 release from sediments.

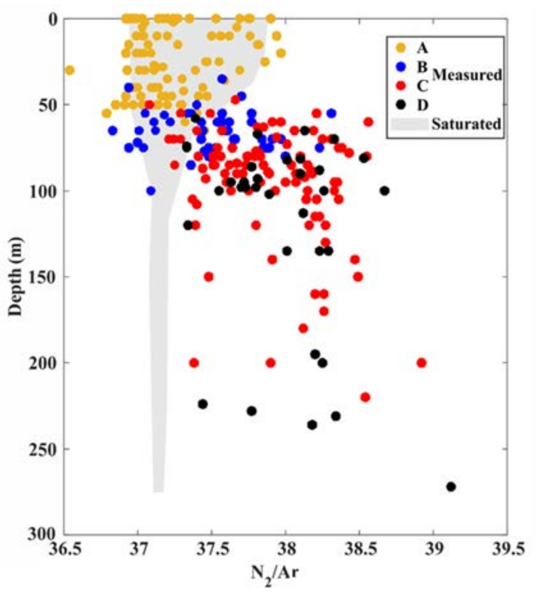

Figure 2. Measured N_2/Ar ratios in different layers (dots) and saturation concentrations (the shaded area)

The presented study focuses mainly on water layers below the halocline (layers C and D). There, the supersaturation ratio ΔN_2/Ar values for ranged from 1.0 to 32.6 µmol L^{-1}. In autumn 2021 a significant difference in ΔN_2/Ar ($p = 0.0008$) between all the studied sites was observed. For example on one station located in Gotland Deep ΔN_2/Ar values were in the range from 17.6 to 32.6 µmol L^{-1}, while on station located in the Central Baltic Proper the maximum was 6.1 µmol L^{-1}.

The seasonal ΔN_2/Ar changes (autumn, spring, and winter) were investigated for two stations located in the Gdańsk Deep and indicated statistically significant variability ($p=0.0077$) with the highest ΔN_2/Ar observed in winter.

Additionally, ΔN_2/Ar was negatively correlated with nitrate ($R^2=0.5469$) and oxygen ($R^2=0.6382$), positively with phosphate ($R^2=0.4382$) and ammonium ($R^2=0.2898$), while no clear dependency was observed for nitrite ($R^2=0.0388$).

5. Conclusion

The presented study was the first attempt performed on such a large scale in the Baltic Proper to trace the effects of denitrification and annamox with the MIMS technique. It demonstrates a high potential in the use of supersaturation ratio for identification of the active sites for both these processes and for quantification of their cumulative effects in the deep Baltic Sea waters.

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Short-term vs. long-term rewetting affects nutrient and nitrous oxide release: Comparison of two coastal peatlands on the Baltic Sea

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1. Introduction

Coastal areas are highly dynamic interfaces between terrestrial and marine ecosystems. They are impacted by rising sea levels, higher precipitation in winter and higher temperatures in summer due to climate change (IPCC, 2013). While nutrient inputs via rivers are monitored regularly, less is known about nitrogen (N) inputs or retention capacities of unconnected catchments along the German coastline (Hannerz & Destouni, 2006; HELCOM, 2018).
Land that had been used for agricultural purposes and been drained for decades is not well studied although rising storm surges and coastal protection measures now call for rewetting of coastal peatlands. Whether and to which extent this measure could contribute to eutrophication by leaching N or by releasing greenhouse gases like nitrous oxide (N_2O) is mostly unknown (Seitzinger & Kroeze, 1998).

Here we studied two peatlands in different rewetting phases, one only recently (November 2019) connected to the Baltic Sea, the other already 30 years ago. One hypothesis is that leaching of N decreases over time because N is washed out, so that a longer rewetted peatland may contain and discharge less N than a freshly rewetted one. By examining the N exchange between the coast and adjacent rewetted peatlands, it is possible to gain information about potential impacts of future sea level rise and its further consequences on fueling eutrophication and climate change.

2. Study sites

The two study sites are both located in Mecklenburg-Western Pomerania, Germany (Figure 1).

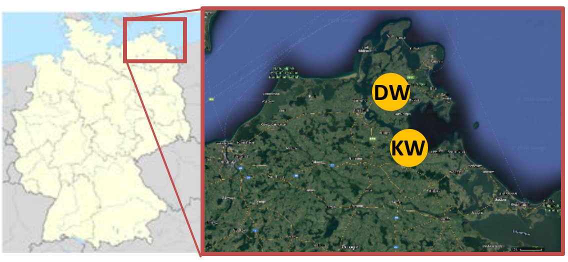

Figure 1: Locations of the two study sites within Germany. One site is located within a nature conservation area near Greifswald (KW = Karrendorfer Wiesen), the other one further north on the island of Rügen (DW = Drammendorfer Wiesen).

The site "Karrendorfer Wiesen" (KW) was drained and used for agricultural purposes over decades. The rewetting took place roughly 30 years ago. Since then several small channels connect to the Baltic Sea.

The site "Drammendorfer Wiesen" (DW) was also drained for agricultural use over decades but was only recently rewetted by removing parts of the dyke in November 2019 and by creating a channel for water exchange with the Baltic Sea.

3. Material & Methods

Sampling in KW was conducted monthly from April 2019 to September 2020. During each sampling campaign, 3 stations in the adjacent bay and 2 stations in the peatland were sampled. Surface water samples for nitrate, nitrite, ammonium and N_2O were taken. Additionally, the porewater of the peat soil was sampled and analyzed for nutrients.

DW was sampled weekly to monthly from December 2019 to December 2020. Surface water samples from the bay and the peatland were taken for the same variables as in KW at 3 and 6 stations, respectively. Porewater was sampled in the peatland from July 2020 on.To finally calculate the exchange of dissolved inorganic nitrogen (DIN) between the peatlands and the adjacent bays, water level and topography data will be combined with the respective nutrient concentrations.

To compare KW and DW, samplings from 2019 and 2020 were merged for KW. Data are presented on a seasonal basis starting with winter as the first season after the rewetting of DW.

4. Results & Discussion

The study sites were significantly different with higher DIN concentrations in DW than in KW especially in the first two seasons after rewetting (Figure 2).

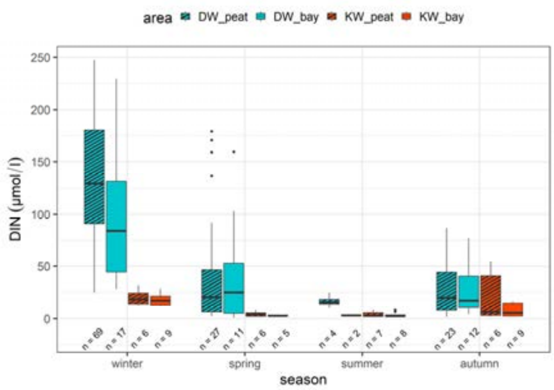

Figure 2. Timeseries of dissolved inorganic nitrogen (DIN) in both study sites. "peat" (dashed) and "bay" (not dashed) represent the respective areas within the study sites. DW = Drammendorfer Wiesen (blue), KW = Karrendorfer Wiesen (orange).

This is in line with other studies which reported that degraded topsoils are still nutrient-enriched due to former fertilization and remineralization (e.g. Zak & Gelbrecht, 2007). This leads to high porewater nutrient concentrations that diffuse into the surface waters (Van de

Riet et al., 2013). Since porewater nutrient concentrations in DW were much higher than in KW (data not shown), higher nutrient concentrations in the surface water were detected.

N_2O saturation was highest in DW during the first weeks after rewetting (winter) with up to 4000 % (Figure 3).

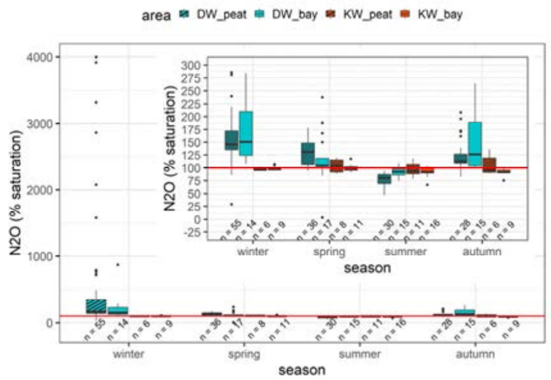

Figure 3. Timeseries of N_2O saturations in both study sites. "peat" (dashed) and "bay" (not dashed) represent the respective areas within the study sites. DW = Drammendorfer Wiesen (blue), KW = Karrendorfer Wiesen (orange). The red line indicates the atmospheric equilibrium (100 % saturation).

N_2O saturations were generally higher in DW than in KW, except in summer. While DW was a source of N_2O, KW was rather a sink over the year with no clear trend towards higher saturations in the peatland compared to the coastal Baltic Sea. The immediate production of N_2O in DW after rewetting is probably fueled by the increase of microbial rates like nitrification and denitrification due to enhanced nutrient availability. This mostly short-term, but strong N_2O production after rewetting was already found elsewhere (Goldberg et al 2010).

Overall, DW was identified to be a source of DIN and N_2O in its first year after rewetting. On the other hand, KW appeared to be more balanced by showing less variability and very similar conditions in the peatland and the adjacent bay. Preliminary results for the DIN exchange between the peatland and the bay in DW yield a net annual DIN-N export of roughly 11.8 t for an area of approximately 45 ha (at 0 m above sea level).

These results indicate that regular monitoring of small, unconnected catchments along the coastline should be established to take these seemingly important areas into account.

5. Acknowledgements

This study is funded by the German Federal Environmental Foundation (in German "Deutsche Bundesstiftung Umwelt") and A. Breznikar is associated to the graduate school "Baltic TRANSCOAST" which is funded by the DFG (grant number GRK 2000/1).

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Enrichment of the sea surface microlayer in organic matter and the occurrence of phytoplankton blooms

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1. Abstract

Studies on enrichment of the sea-surface microlayer (SML) into organic matter (OM) of different origin were carried out during several Baltic cruises. The results allow recognizing the relations between the amount of absorbing and fluorescing molecules of OM and the concentration of phytoplankton.

The results confirmed that there is a linear relationship between values of the enrichment factor, EF, of the SML in organic matter of marine origin (fluorophore C) and the EF of the SML in Chlorophyll a.

2. Motivation

The main aims of our research is to recognize the influence of the natural marine and terrestrial organic matter (OM) on the enrichment of the SML in OM and to assess the role the SML as a barrier for air-sea interaction processes (light and gas exchange).

3. Methodology

Optical surveys of the Baltic Sea surface waters were conducted during four spring and autumn research cruises of RV Oceania, 2018, 2019 and 2021. Sampling of the surface microlayer (SML) and subsurface water (ULW, 1m) allowed us to count the enrichment factor (EF) of the SML in organic matter (OM) and in phytoplankton pigments - based on absorption and fluorescence measurements and HPLC analyses of the collected samples. The results of measurements (CTD, E_2:E_3, S_R, $a_{CDOM}(\lambda)$, fluorescence intensities at the peaks of the main fractions of chromophoric DOM in the sea: A, C, M and T, the ratio (M+T)/(A+C), HIX index, composition and concentration of phytoplankton pigments) allow calculations of the values of the EF of the SML in the specific OM (Drozdowska et al. 2018, Ston-Egiert and Kosakowska, 2005).

4. Results and conclusions

The enrichment of the SML in the total fluorescing OM ranged from 0.24 to 2.44, with the lowest EF values registered in the Slupsk Channel and the highest ones in estuarine areas.

The conducted studies on phytoplankton pigment concentrations yielded specific spatial and temporal distributions of various phytoplankton pigments, while the highest variability was recorded for Chlorophyll a.

Studies on enrichment of the SML in OM and in phytoplankton confirmed that there is a linear relationship between values of the EF of the SML in organic matter of marine origin (fluorophore M) and the EF of the SML in Chlorophyll *a* (Fig.1).

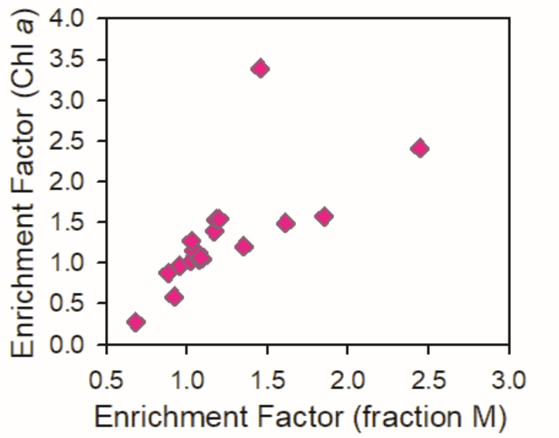

Figure 1. The relation between the EF of the SML in Chlorophyll a and in fluorescing OM of marine origin, containing the fluorophore M.

5. Acknowledgment

We thank the crew of the RV „Oceania“. This work was co-funded by a grant SURETY, from the Polish National Science Centre, contract No. 2021/41/B/ST10/00946.

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Modeling the impact of agriculture on coastal waters on the example of the Bay of Puck

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1. Introduction

Anthropogenic pressure is usually evaluated by characterizing the flux of contaminants using separate models such as SWAT for surface run-off, Modflow for groundwater flow, and 3D models for presenting complex processes in the marine environment being under contaminants discharge. However, our approach is based on the assumption that different elements of the environment should be modeled at the same time and connected to each other. This was the main motivation for developing the WaterPUCK project, which is an interdisciplinary and innovative approach integrating knowledge of different disciplines into the implementation of the environmental protection policy, sustainable growth and improvement of the competitiveness of the Polish economy.

WaterPUCK online toolkit enables researchers to identify the sources of nutrient and pesticide pollution, understand the main mechanisms responsible for the transport of these pollutants in surface and groundwater, calculate their flux via rivers and SGD, and directly assess the influence of pesticides and nutrient flux on the Bay of Puck ecosystem. Additionally, within the service, we present the way the different environmental data such as in situ measures and model outcomes can be operated. The study focuses on the description of the full modelling framework. Detailed presentation of some components can be found in earlier publications from our group (Dzierzbicka-Głowacka et al. 2019; Dybowski et al. 2019; Dybowski, Dzierzbicka-Glowacka, et al. 2020; Dybowski, Janecki, et al. 2020; Szymkiewicz et al. 2020; Kalinowska et al. 2020; Wielgat et al. 2021).

2. Research area

The Puck District and the Puck Bay are examples of a region where sustainable growth and management is a challenging task due to the region's complex structure. The Puck Bay is an inner basin of the Bay of Gdansk, which covers an area of approximately 40,000 ha. Its inner part is a shallow (average depth of 3 m), sandy seagrass bed, while the outer part's average depth is 20.5 m. The Puck Bay's salinity ranges from 3 to 7 and is known as a nursery ground and breeding area for a number of fish and bird species. The bay contains several types of habitats (from muddy to stony bottom) located at a variety of shore types (i.e., sandy beaches, gravel beds, stony outcrops, clay cliffs, vegetated river mouths, etc.). The Puck Bay is protected as a Natura 2000 site under both the birds and habitats directives. It is also a designated Baltic Sea Protected Area, and its inner waters are part of the Coastal Landscape Park. The area has also been subjected to strong anthropogenic pressure. The main sources of pollution for the Bay of Puck are rivers, SGD, atmospheric deposition, and point sources, while the coastal ecosystem controls the biogeochemical transformations of P and N compounds (e.g., phosphate, nitrate, dissolved organic nitrogen, etc.) through close coupling between water and sediments.

3. Methods

The method of modelling the impact of farms and land-use structure on the quality of land (surface water and groundwater) and coastal waters was developed and verified as part of the WaterPUCK project. The service is a set of computer models interconnected with each other, operating continuously, forced with meteorological data and combines four main modules (Fig. 1):

Agricultural holdings — survey system and two calculators for farms as interactive applications;

LAND WATER — a comprehensive model of surface water run-off based on SWAT model and a numerical model of groundwater flow based on Modflow which we named GroundPuck;

COASTAL WATER — a three-dimensional numerical model of coastal ecosystem consisting of a hydrodynamic and biochemical part with a nutrient spread module based on Community Earth System Model (CESM);

MARINE WATER — a three-dimensional numerical model of the marine ecosystem providing boundary condition to COASTAL WATER module.

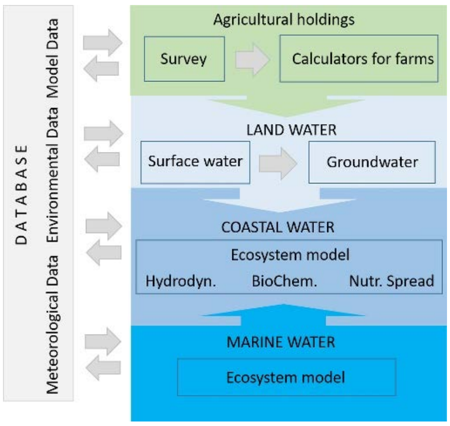

Figure 1. Structural scheme of the WaterPUCK toolkit.

A schematic flowchart of the modelling system is presented in Figure 2. We coupled the EcoPuckBay model from the land side with two models: SWAT (surface water) and GroundPuck (groundwater). Information about the water volume discharged by rivers is being provided by the hydrological model SWAT that has been implemented as one of the WaterPUCK project's stages (Kalinowska et al. 2020). The SWAT model includes the preparation of the innovative and complex hydrological model coupled with the nutrient concentration module including meteorological data (precipitation, wind, temperature, and atmospheric pressure). The transformation of precipitation data into surface run-off have been achieved with the SCS (Soil Conservation Service) curve number procedure through the accumulated run-off volume and the time of concentration (the time from the beginning of a rainfall event until the entire subbasin area contributes to flow at the outlet) (Kalinowska et al. 2020).

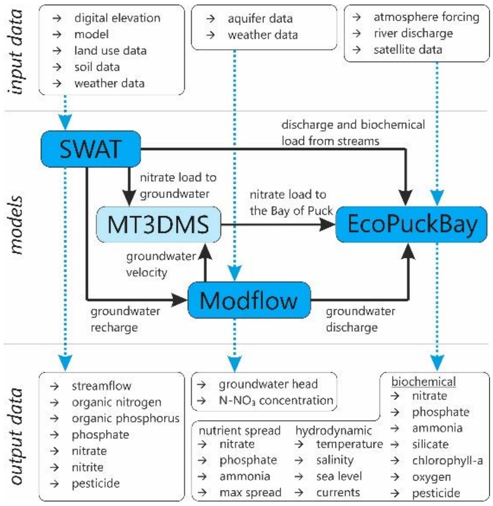

Figure 2. Schematic flowchart of the modelling system.

A numerical transport model based on the Modflow code (GroundPuck) allows determining the nitrate load in the groundwater flowing into the Bay of Puck. The MT3DMS numerical code was applied to solve the advection–reaction–dispersion equation. Transient calculations were performed with the third-order total-variational diminishing (TVD) numerical method for the advective term, while for the steady-state solution, the standard finite difference discretization was applied. This model was calibrated based on actual NO_3^- concentration values and was joined with the EcoPuckBay model through a coupling module.

The results of the 3D EcoPuckBay model are limited to the area of the Bay of Puck. However, the entire model grid covers a wider area (Dybowski et al. 2020). This is to ensure that boundary conditions are properly simulated. Along the line of the northern border of the 3D EcoPuckBay model, data from the 2.3 km three-dimensional Coupled Ecosystem Model of the Baltic Sea (3D CEMBS) prediction model are transferred to the EcoPuckBay model. Results from 3D CEMBS are used to provide forcing fields in the EcoPuckBay model through sequential information transfer. The mechanism of this module is to interpolate values from 3D CEMBS to EcoPuckBay model's grids.

4. Conclusion

Solutions that comprehensively connect the marine and land environment are essential for resource monitoring and management, especially in the coastal zone, which plays a beneficial role for humans. Moreover, considering the individual elements of the solution as separate and unconnected may lead to an underestimation/ overestimation of the potential effects of planned regulation. Improved understanding of sea-land interactions, in the context of hazardous substances, will contribute to achieving the goals set by European legislation, which aims to improve the state of marine waters that is also the ultimate result of WaterPUCK project implementation. The systematic use of the WaterPUCK toolkit by farmers (particularly the farm balance calculator, nitrogen leaching calculator and SWAT's Calculator mode) allows for more efficient management of production means while respecting the environment. The WaterPUCK toolkit is designed so that it can be applied to other regions around the world. A necessary condition for the success of its application is to carry out the calibration process described in this study. The key was to set up the database in such a way that each of the system's component tools could easily use the necessary information for its correct operation, which was ensured in our solution.

Acknowledgements

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Multi isotope investigation of distinct coastal sediments affected by submarine groundwater discharge, southern Baltic Sea.

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1. Introduction

Submarine Groundwater Discharge (SGD) acts as a source of fresh water and dissolved substances for coastal ecosystems, however its fluxes may strongly depend on the benthic biogeochemical dynamics at the sediment-water interface.

The present study investigates the impact of near-shore SGD on the biogeochemical process at the sediment water-interface and at the coastal waters in Puck Bay (PB), southern Baltic Sea. Our strategy is to quantify the rates of early diagenetic process and the element fluxes in SGD impacted sites, as well as reference sites, encompassing different lithology.

2. Methods

Seawater samples were collected on board of research vessels between 2009 and 2021. At mud sites, sediment cores were retrieved and pore water samples were extracted (including one site at Gdansk Bay). At the sand sites, the porewater was extracted by using push-point sampler (MHE products). Samples were taken for the analysis of stable isotopes (H, O, C, S), radium and radon isotopes, dissolved inorganic carbon (DIC), total alkalinity, nutrients, and major cations. Groundwater from wells and piezometers, and rivers were investigated as freshwater endmembers.

3. Result and discussion

Porewater gradients of salinity and conservative elements at SGD sites show an advective upward flow of freshwater in sandy sediments and diffusion-dominated behavior in muddier sediments. The porewaters at the sand SGD-impacted site were essentially depleted in dissolved sulfate at depth due the upward freshwater flow. SGD sites showed impact at the most of their hydrochemical gradients, e.g. increase DIC and nutrients.

The isotopic composition of porewaters in the SGD impacted sites showed a range of values from -10 to -5 ‰ and -76 ‰ to -42 ‰ for $\delta^{18}O_{H2O}$ and $\delta^{2}H_{H2O}$ respectively. The signatures from the mud SGD impacted sites plotted still very close to the Baltic Sea line and to the surface water of PB (Figure 1). However, the sandy SGD impacted sites shifted towards the GMWL and the isotopic composition of Krakow precipitation (about 500 km south), indicating the discharge of young groundwater. However, the very light isotopic signatures found in some sand SGD sites are lighter than literature values for Holocene meteoric waters for this area showing that the SGD discharge represents two different groundwater systems.

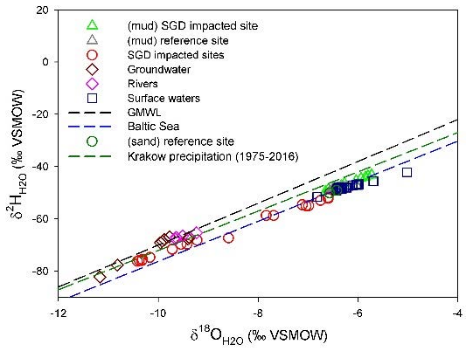

Figure 1 - Scatter plot of $\delta^{18}O_{H2O}$ and $\delta^{2}H_{H2O}$ for porewaters impacted and not-impacted by SGD (mud and sand), rivers, surface water, groundwaters, Baltic Sea, Global Meteoric Water line, Krakow precipitation (GNIP)

Values of $\delta^{13}C_{DIC}$ in the porewaters ranged between -26 and +14 ‰, and it indicates active carbon cycling in the surface sediments. Possible sources of DIC are the mineralization of organic matter and groundwater input. At the mud sites, the influence of methanogenesis is also clear shown by the higher positive signatures (Figure 2). DIC concentrations in the sand SGD sites are higher compared the sand reference sites, indicating that SGD can act as a potential source of excess CO2 to the investigated coastal waters.

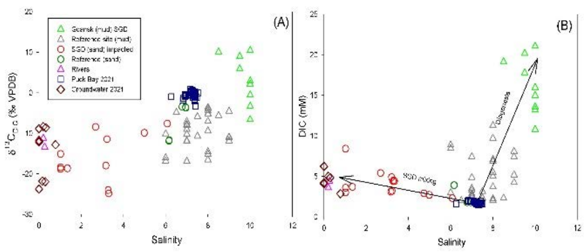

Figure 2 - Scatter plot of $\delta^{13}C_{DIC}$ versus Salinity (A) and DIC versus salinity (B) for porewaters impacted and not-impacted by SGD, rivers, surface water, and groundwaters.

4. Conclusion

To conclude, freshwater discharge is observed at the sand sites coming from at least two different aquifers. The impact of SGD on DIC values is clearly seen in the sand sites, as the mud sites methanogenesis is also taking place. Further work is on the way to estimate the contribution of SGD to the PB based on isotope traces, and the overall contribution of elements based on transport process.

5. Financial support

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Riverine Phosphorus Transport Assessment

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1. Introduction

It has been acknowledged in the past that the excess of surplus phosphorus from fertilizers in agricultural practices resulted in a negative impact in marine ecosystems. Nevertheless, due to the lack of both, long observational time series and high temporal and spatial resolution of model datasets, the total amount of phosphorus discharged into the ocean remains uncertain. This work presents a new scheme for phosphorus transport based on the IMAGE nutrients dataset. It uses the traces transport capability of the hydrological model HDmodel to account for the lateral transport of total phosphorus losses with a particular focus on losses from cropland areas. The total phosphorus discharged in semi-enclosed European seas, in particular the North Sea, is presented and time series trends of phosphorus in different socio-economical scenarios are analyzed.

2. Model

To simulate the phosphorus transport the hydrological model (HD5) was used (Hagemann et al., 2020). The HD5 model is designed to run on regular grid of 5 minutes (8-9 km) resolution over the European region.

The HD5 model calculates river discharge based on the lateral transport of overland flow and baseflow (this represents within grid box flow and it considers lake and wetland fraction areas of a particular grid box for water residence time), and riverflow (flow between adjacent grid boxes). The riverflow is then routed to the discharge grid box for each catchment following the topography morphology. This calculation is set to a sub-daily time step. The model output comprises daily accumulated discharge.

Similar to the riverflow calculation, a new capability to transport tracers in rivers has been recently implement within the HD5 model. In this work, this new capability is used to transport phosphorus nutrient.

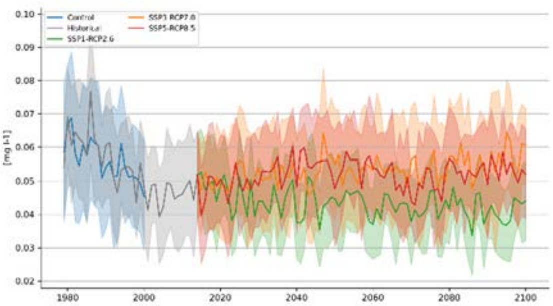
3. Method

For historical simulations, the total phosphorus concentrations were calculated based on the phosphorus load provided in Beusen et al. (2016) (IMAGE model). This dataset provides phosphorus load for wastewater, agricultural land, natural land, aquaculture, allochthonous organic matter and background values for weathering and atmospheric deposition.

As for the scenario simulations, only concentrations from aquaculture and allochthonous organic matter were used from IMAGE. Concentrations for wastewater, natural land, and pasture areas were transformed into urban, forest and pasture areas using corresponding land use types from the Land-Use Harmonization[2] (LUH2) dataset. This transformation ascribe new concentration values to the LUH2 land types assuring a conservative calculation at catchment level. The phosphorus load from the weathering process is implemented using Hartmann et al. (2014) scheme. The atmospheric P deposition is considered constant with a value over water areas of 16.7 [kg km-2 y-1] equivalent to phosphorus to 0.0074 [g m-2 yr-1] (Berthold et al. 2019). A new parametrization has developed for P losses from cropland.

4. Phosphorus discharge at the Baltic and North Sea basins

The total phosphorus load discharged into the Baltic Sea and North Sea accounts for approximately 26 and 72 kt y-1, from which approximately 45% and 25% of the total contribution comes from small catchments (considering small catchment as a river that individually contribute with less than 1.5% to the basin total).



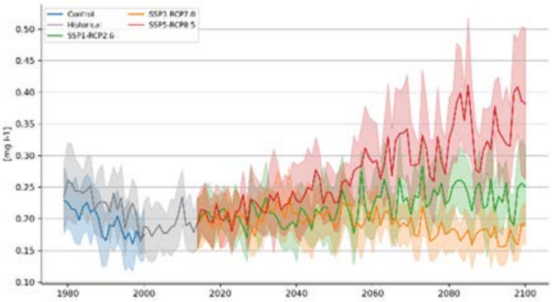


Figure 1 shows the total phosphorus concentration scenario time series from rivers with discharge into the Baltic and North Sea basins (top and bottom respectively). Solid lines represent yearly averages and shades the yearly standard deviation of each time series. The negative trend at the beginning of the historical period is due to the agricultural water pollution reduction policies established during the 1980s. The trends in the scenarios are driven by the narratives of the SSPs. SSP1 and SSP5 consist on a rapid economic growth that increases the demand of agricultural products. They differ in that SSP5 is based on fossil-fuel economy whereas SSP1 in sustainable practices. SSP3 assumes a regional competition scenario, where industrialized countries (mostly around the North Sea and Baltic Sea) results in a decrease of population which in turn reduces crop, pasture and urban activities (Riahi et al. (2017)) decreasing the amount of phosphorus losses into the rivers.

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Nitrogen cycle in the Baltic Proper: metagenomic approach

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1. Introduction

Nitrogen is a key element for all living organisms. As an indispensable element of cellular components biosynthesis, availability, and concentration of this nutrient is the main factor limiting life on our planet. Biologically available nitrogen is rare in a multitude of environments. Its bioavailability is controlled by reactions conducted by microorganisms. Thus, microbial transformations of nitrogen compounds play a crucial role in maintaining balance in the ecosystems (Zumft 2009). Alterations in the maintenance of this balance come in the forms of anthropogenic activity. Large fluxes of human-induced nitrogen are posing a great threat to marine ecosystems. Nearly 4.8 x 10^7 tons of nitrogen per year enter the marine environment via rivers (Galloway et al. 2009). The Baltic Sea is characterized by little water exchange and water column stratification promoting stagnation periods. The significant nitrogen fluxes promote primary production, eutrophication, increased oxygen consumption causing hypoxic and anoxic areas enlargement and as a result may impact the marine trophic web. Therefore, understanding the microbial N-transformations in the marine N cycle could give answers on how to preserve and change the fate of this reservoir. The main goal of this study is to resolve the taxonomic structure of the nitrogen transforming network using a metagenomic approach.

2. Methods

Our studies were located in the Baltic Proper and were represented by three stations, namely: the Bornholm Deep (IDEAL 55˚26.623' N, 15˚18.009' E), Gotland Deep (BY15 57˚20.062' N, 20˚03.022' E) and Gdańsk Deep (P1 54˚50.079' N, 19˚19.082' E). Seawater samples were collected from the Oxygen Minimum Zone (OMZ), using a CTD-rosette equipped with Niskin bottles, deployed aboard the R/V OCEANIA in September 2020. Water samples were pumped through a 2 µm glass fiber filter and target hydrophilic polycarbonate membrane filter 0.2 µm and frozen. The extraction of nucleic acids was carried out after the cruise.

3. Results and Discussion

Denitrifiers can switch to anaerobic respiration at low oxygen concentrations (Seitzinger, 1988). Such conditions were met at 81.5m, 80m, 92m below sea surface at the IDEAL, BY15, P1, respectively. We assessed microbial community potential capability of nitrogen transformations based on gene coverage encoding enzymes engaged in the N cycle. Coding sequences found within metagenomes were assigned to their appropriate taxonomic levels, and binned based on their nucleotide composition, revealing key organisms capable of nitrogen transformations. For all three depths denitrification genes encoding reductases were found to be most abundant in comparison to anammox, DNRA, and nitrification-related genes. Consistent throughout three depths the most diverse phylum-bearing denitrification gene was archaea within which the most abundant family is nitrosopumilaceae. This genus has the potential to reduce nitrogen compounds from nitrate to nitrite, however, is not able to conduct complete denitrification as it does not contain nitrous oxide reductase (*nosZ*) genes. Gene *nosZ* is found also in Bacteroidetes, and unclassified sequences within three depths. Geochemical analysis revealed considerable differences in nitrate (NO_3^-) within Bornhol deepth in relation to two other depths (NO_3^-= 8.94 µmol/L) which is linked to higher oxygen levels elevated by presence of nitrosopumilaceae family. Information regarding microbial composition coped with geochemical analysis poses a great tool to assess the potential for nitrogen loss from the marine environment. Furthermore, monitoring microbial composition not only is crucial since denitrification is a process resolved by multiple organisms, but it is essential to extract valuable information on how to preserve or promote the state which is the most beneficial for the Baltic Sea.

4. Acknowledgments

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Controls of air-sea CO_2 exchange in the Baltic Sea under high and low wind-speed conditions

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1. Introduction

Coastal and marginal seas are dynamic regions that play a relevant role in the global carbon system. In terms of air-sea CO_2 fluxes, the contribution per surface area of these regions is disproportionately large when compared to the open ocean (Laruelle et al., 2014). The spatial and temporal variability of the fluxes in the coastal seas is often attributed to the heterogeneity of the physical and biogeochemical processes (Roobaert et al., 2019). In the Baltic Sea, the variability of the carbon system elements has been address in several studies (e.g; Omstedt et al., 2009; Rutgersson et al., 2009; Schneider and Müller, 2018). The spatial and seasonal variability of the seawater pCO_2 in the region is, to some extent, well understood (Thomas and Schneider, 1999; Rutgersson et al., 2008). However, large uncertainties on the air-sea CO_2 flux remain and the effect of the control mechanisms on the gas exchange is still poorly understood.

In this study, we evaluate the effect of forcing mechanism on the air-sea CO_2 exchange under different wind-speed regimes in the central Baltic Sea. The fluxes and associated gas transfer velocities ($\boldsymbol{k_{660}}$) are calculated from eight years (2013-2021) of eddy covariance data and sea surface pCO_2 measurements from the Östergarnsholm station.

2. Data and measurements

We use data collected between 2013 and 2021 from the Swedish marine Integrated Carbon Observation System (ICOS) station Östergarnsholm. The station (57°27'N, 18°59'E) is located in the central Baltic Sea on a small and flat island 4 km east of the island of Gotland. Measurements are performed in a 30 m land-based tower located in the southern tip of the island. Several studies have been published describing the oceanic and atmospheric characteristics of the Östergarnsholm site (Högström et al., 2008; Sahlée et al., 2008) and assessing the air-sea interaction processes in the region (Smedman et al., 1999; Rutgersson et al., 2008; Rutgersson et al., 2011).

The tower is instrumented with high-frequency sensors for continuous turbulence measurements at 10 m height from the mean sea level. Air-sea CO_2 fluxes are calculated from the 20 Hz observations over 30 min averages following the eddy covariance methodology (e.g. Baldocchi et al., 1988). Additionally, measurements of the CO_2 partial pressure (pCO_2) in the seawater are carried out within the footprint of the tower at 4 m depth. Gas transfer velocity values are calculated using these data and normalized using a Schmidt number of 660 ($\boldsymbol{k_{660}}$).

3. Results and Discussion

The resulting $\boldsymbol{k_{660}}$ values show a good agreement with commonly used wind-based parameterizations (i.e. Wanninkhof, 2014; McGillis et al., 2001). This is true only when particular conditions occurred on both sides of the interface. Large scatter of the half-hourly values is observed along the entire range of wind speeds, suggesting that mechanisms—other than wind speed—play a relevant role in the exchange, and might be essential to explain the variability of $\boldsymbol{k_{660}}$.

The mechanisms that seem to explain the remaining observed variability in $\boldsymbol{k_{660}}$ vary significantly depending on the wind-speed regime. At high wind speeds (U_{10} > 8 m/s), both atmospheric and water-side controls are necessary to explain the rapid increase of $\boldsymbol{k_{660}}$. Water-side processes are well known to be of relevance in the transfer of slightly soluble gases, like CO_2. However, at high wind speeds, atmospheric stability conditions, relative humidity and the enthalpy fluxes seem to play a relevant role in modulating the effect of the water-side processes on the exchange. Based on these findings, we suggest that sea spray—under particular conditions, which promote high evaporation rates—might be the key mechanisms to create higher-than-expected values of k_{660}. Such values cannot be explain solely by turbulent processes at the interface associated to wind and waves. On the contrary, at wind speeds lower than 6 m/s, atmospheric controls are not relevant for the exchange and processes such as water-side convection seem to explain most of the variability.

4. Conclusions

We present a large dataset of air–sea CO_2 fluxes directly measured using the eddy covariance technique at a land-based station in the central Baltic Sea. The analysis of the gas transfer velocity shows that the controlling mechanisms of the gas exchange across the interface vary depending on the wind-speed regime. While water-side controls are well known to play a relevant role on the gas transfer process, here we suggest that underlying atmospheric conditions are also relevant, particularly under high wind speed conditions.

The Baltic Sea can be seen as a test field with wide variety of physical and biogeochemical conditions to further understand the role of coastal and marginal seas in the global carbon cycle. The results presented in this work are most probably relevant for other regions.

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An estimate of the net carbon production in the Bothnian Sea during the spring bloom using carbon system data

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1. Introduction

Eutrophication is still considered as one of the major challenges for the Baltic Sea ecosystem. The increased inventories of nutrients lead to enhanced biomass production and mineralization, and thus enhanced algal blooms, decreased light penetration and stronger deep water oxygen demand. Following Nixon (1995), eutrophication can be defined as enhanced supply of carbon to an ecosystem.

Over the last decade, increasing evidence was assembled that both the spring and summer blooms in the major basins of the Baltic Sea do not follow a classical Redfield stoichiometry, and attempts have been made to implement variable carbon-nitrogen-phosphorus stoichiometry of organic matter formation in biogeochemical models of the Baltic Sea (Kreus et al., 2015; Schneider et al., 2015; Fransner et al., 2019). Quantification of the net carbon production has been achieved to a large part by the use of continuous observations of the partial pressure of CO_2 (pCO_2) from cargo vessels for more than a decade, and a methodology to derive net carbon production from these data (e.g. Schneider and Müller, 2018).

Such data are, however, not available for the Bothnian Sea, although an attempt has been made to estimate the seasonal cycle of pCO_2 in that area based on a compilation of pCO_2 data from individual research vessel expeditions (Löffler et al., 2012). Very recently, Fransner et al. (2019) used these data to validate a model with a flexible C-N-P stoichiometry. Yet, direct observational data to constrain the carbon cycling during the productive phase in the northern basins of the Baltic Sea during the productive season are sparse.

In this study, we use data from two research expeditions in winter and late spring 2019 to derive the net carbon production in the Bothnian Sea.

2. Materials, methods and aproach

The data for this study were gathered during the cruise *BONUS INTEGRAL Winter* of RV Aranda (28.2.–11.3.2019), and the cruise EMB 214 *BONUS INTEGRAL Summer* of RV Elisabeth Mann Borgese (20.5.–5.6.2019).

During both cruises, a surface measurement system was employed for continuous monitoring of pCO_2, CH_4, N_2O, and O_2 using a bubble/showerhead type water air equilibration system coupled to two cavity enhanced absorption spectrometers. Only the pCO_2 data are used in this study. The principle of the instrumentation is described in Gülzow et al. (2011), though the system has been considerably modified and extended. During the winter cruise, the pCO_2 was also measured using a standalone sensor (HydroC, Contros), the data of which are used here. Essential hydrographic data were recorded from the same surface seawater supply. In addition, several hydrographic stations were run and sampled for inorganic nutrients, dissolved and particulate organic matter, as well pH (measured spectrophotometrically) and total dissolved inorganic carbon (C_T) using an absorption based measurement system (AIRICA, Marianda).

We used the pCO_2 data and a normalized total alkalinity (A_T) based on an A_T–salinity relation (similar to Müller et al., 2016) to derive the C_T loss from the surface layer between the winter and early summer cruise, the latter timed right after the spring bloom in the Bothnian Sea, and use the approach to calculate net primary production as outlined in Schneider and Müller (2018). We also consider potential loss of carbon to the atmosphere between the winter campaign and the time immediately before the onset of the spring bloom, which is however small compared to the calculated biological uptake of carbon.

The results are compared to an estimate of the C_T loss based on comparison of the salinity-normalized C_T data from both campaigns.

3. Preliminary results

The summer cruise took place right after the spring bloom of 2019 in the Bothnian Sea. Nitrate was completely depleted in the surface layer, and the pCO_2 in the surface waters was mostly between 100–200 µatm, and locally reached values of less than 100 µatm (Fig. 1), which has not been reported before (e.g. Löffler et al., 2012).

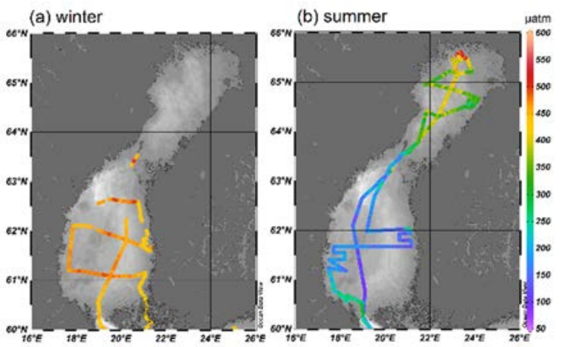

Figure 1. Surface pCO_2 analyzed from the flow-through system for (a) the winter and (b) the summer of 2019.

This is far below the minimum values for pCO_2 of 200–250 µatm in the model by Fransner et al. (2019), suggesting an underestimation of the carbon uptake during the spring bloom in our current understanding of the biogeochemistry of the Bothnian Sea.

The change in dissolved inorganic carbon in the surface waters derived from pCO_2 showed a large spatial heterogeneity (Fig. 2).

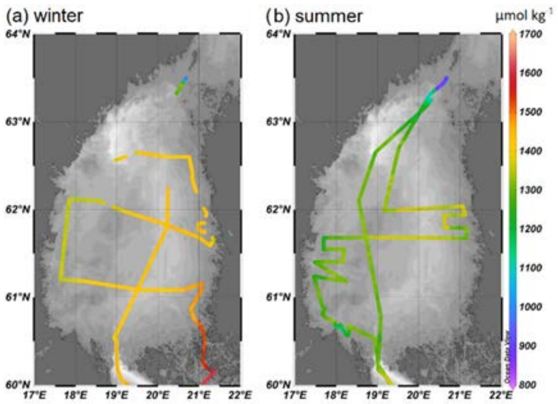

Figure 2. Surface C_T calculated from the pCO_2 and parameterized A_T.

The change varied between ca. 40–130 µmol kg^{-1}. Smallest values were found to be clustered in the northwestern part of the basin, which could be partially due to the horizontal movement of water masses.

Based on the vertical profiles of C_T, other biogeochemical and hydrographical data from the station work, we will also attempt to assess the depth structure of the carbon removal from the near surface waters.

4. Acknowledgments

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Biogeochemical functioning of the Baltic Sea

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Location, specific topography and hydrographic setting together with climate change and strong anthropogenic pressure are the main factors shaping the biogeochemical functioning and thus also the ecological status of the Baltic Sea (Fig. 1). The recent decades have brought significant changes in the Baltic Sea. First, the rising nutrient loads from land in the second half of the 20th century led to eutrophication and spreading of hypoxic and anoxic areas, for which permanent stratification of the water column and limited ventilation of deep water layers made favourable conditions. Since the 1980s the nutrient loads to the Baltic Sea have been continuously decreasing. This, however, has so far not resulted in significant improvements in oxygen availability in the deep regions, which has revealed a slow response time of the system to the reduction of the land-derived nutrient loads. Responsible for that is the low burial efficiency of phosphorus at anoxic conditions and its remobilization from sediments when conditions change from oxic to anoxic. This results in a stoichiometric excess of phosphorus available for organic matter production, which promotes the growth of N2-fixing cyanobacteria and in turn supports eutrophication.

Since the work on the last assessment (BACC II, 2015) was carried out, intensive research on the biogeochemical cycling in the Baltic Sea has been conducted, including studies on past, present and future changes. This paper (Kuliński et al., 2021) not only summarizes the results of these recent studies but comprehensively assesses currently available, published knowledge on the biogeochemical functioning of the Baltic Sea, while pointing out knowledge gaps and future research needs. In its content, the paper covers the aspects related to changes in carbon, nitrogen and phosphorus (C, N and P) external loads, their transformations in the coastal zone, changes in organic matter production (eutrophication) and remineralization (oxygen availability), and the role of sediments in burial and turnover of C, N and P. In addition to that, this paper focuses also on changes in the marine CO_2 system, structure and functioning of the microbial community and the role of contaminants for biogeochemical processes. This comprehensive assessment allowed also for identifying knowledge gaps and future research needs in the field of marine biogeochemistry in the Baltic Sea.

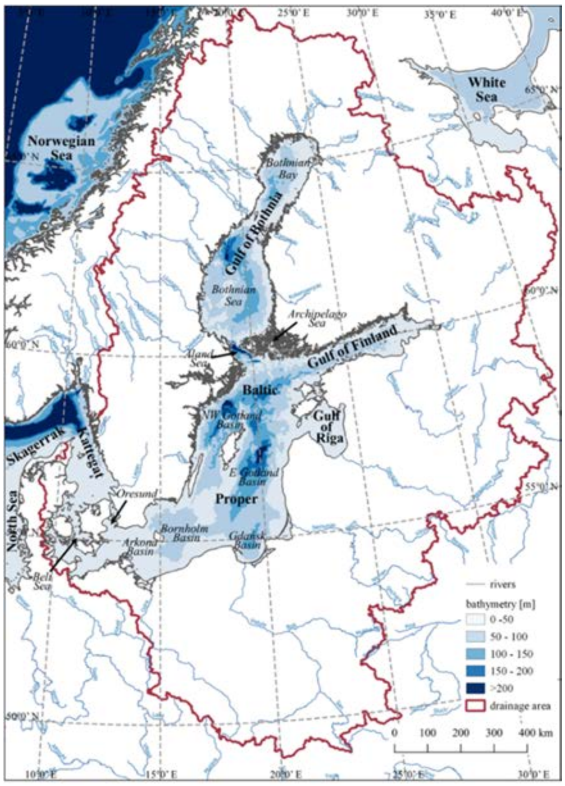

Figure 1. The Baltic Sea and its catchment (Kuliński et al., 2022).

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Robustness of trophic network and carbon flows in coastal freshwater-impacted pelagic system: focus on lower food-webs and seasonal aspects

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1. Background

Changes in food webs are hard to interpret as good or bad. Network metrics help translate them into effects on the system and its functioning. Fath (2015) introduced *robustness* as a useful network information that reflects both redundancy and efficiency of the system.

Here we analyze pelagic system of coastal Gulf of Riga using Ecological Network Analysis (ENA) approach (Figure 1). The main objective is to identify key functional guilds significant for maintaining stability (expressed via *robustness*) in highly dynamic freshwater-impacted ecosystem and also evaluate seasonal variability on the roles of functional guilds. The focus of the study is on lower webs, i.e., microbial loop and plankton.

The Gulf of Riga (GoR) is strongly influenced by freshwater runoff with 86% of it being discharged in the south-eastern part (Berzinsh 1995) – area analyzed in the present study. GoR is shallow and the most eutrophied sub-basin of the Baltic Sea (Snoeijs-Leijonmalm, Andrén 2017) with strong impact of both allochthonous and autochthonous organic matter, therefore evaluating carbon fluxes within and from the microbial loop is essential for comprehension of all ecological aspects and potential threats.

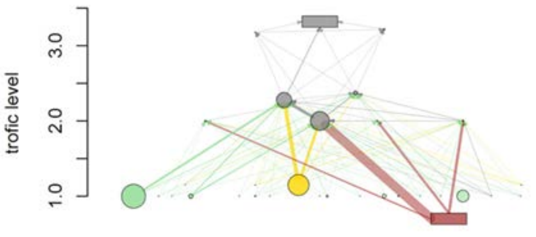

Figure 1. Conceptual scheme of the Gulf of Riga coastal pelagic food web. Autotrophs (phytoplankton) in green; mixotrophs in yellow; heterotrophs in grey; microbial loop in red. Width of fluxes are respective to its quantitative flow; size of circle - respective to carbon mass of the element. Carbon flows are calculated based on an equilibrium hypothesis using 'fluxing' function from package *fluxweb* (Gauzens 2018) within R software (R Core Team 2018).

2. Synopsis

Trophic network was evaluated using functional groups (guilds) as nodes. Division of phytoplankton guilds were based on trophy and size group; zooplankton guilds were identified using trait-based clustering; herring and herring larvae were distinguished and considered as the highest trophic level. In total, 31 functional guilds were included in the trophic network of coastal southern GoR.

Three differently functioning periods were identified: (i) spring phytoplankton bloom, (ii) early summer, when pressure from planktivorous fish is low, and (iii) late summer/early autumn, when pressure from planktivorous fish is high. Still, the prevailing carbon pathway throughout the seasons (but especially during early summer) were from microbial loop via herbivorous filtertrants to omnivores emphasizing significant role of the bacterio- and microplankton activity. Mixotrophic ciliate *Mesodinium rubrum* was also identified as a key functional element pathing ca 10% of total carbon requirements for 1st level consumers.

Evaluated trophic network metrics, including r*obustness*, did not show pronounced seasonal variability. Overall connectance within trophic network was typical for marine food webs (aprox. 11%; Landi et al. 2018) and it was dominated by generalists (each node with 3 or more links). However, *robustness* was low compared to the range observed for ecological trophic networks (0.3-0.5; Fath 2015) implying decreased efficiency. Potential relation between the results and environmental parameters are inspected.

Funding

The study is ongoing and jointly supported by the Ministry of Environmental Protection and Regional Development, project no. IL/106/2017, and the Administration of Latvian Environmental Protection Fund project no. 1-08/191/2020.

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Assessment of temperature influence on remineralization of sediment-derived DOC from the Baltic Sea depositional area

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1. Introduction

Sediment pore waters in the Baltic Sea are enriched with the dissolved organic carbon (DOC), which results in a diffusive flux of DOC to the water column (Reader et al., 2019; Lengier et al., 2021). Returning DOC may alter processes occurring in the water column e.g. increase of oxygen demand in the bottom waters (Reader et al., 2019). It is still little known about the bioavailability and remineralization rates of sediment-derived DOC. The temperature dependence of organic matter decomposition has been recognized as a critically important determinant of any long term changes in response to global warming. Elevated temperatures may lead to positive feedback of increasing future warming by organic matter decomposition and release of greenhouse gases e.g. CO_2 (Burdige and Komada, 2015). Temperature has been recognized as in important factor influencing the processes taking place in the sediments and as such it is expected to be one of the main factors influencing also sediment-derived DOC decay rates (Lønborg et al., 2009). Since, still little is known in this regard, we decided to assess the temperature impact on the decay of sediment-derived DOC.

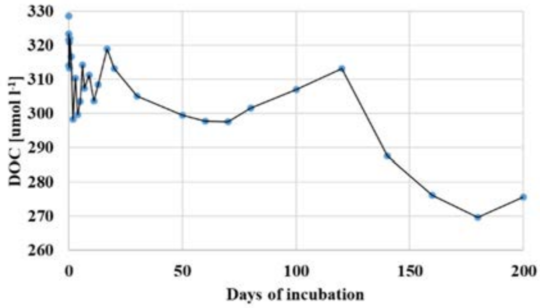
2. Methods

Seawater and sediment samples were collected from the Gdańsk Deep during r/v Oceania cruise in October 2019. The bottom water samples were collected using Niskin bottles (~2m above the sediments), while surface sediments (0-5 cm) were collected using Gemax gravity corer. The bottom water was collected in pre-cleaned 10l bottle directly after sampling. Seawater samples were passed through pre-cleaned and pre-combusted 0.4 µm MN G5 glass-fiber filters (pre-combusted at 450°C for 8h). The pore water was collected from the upper-most 5 cm by means of Rhizons. Then, bottom water was spiked with pore water in a volume ratio of 4:1. To ensure oxic conditions in the experiment, the mixture was bubbled with the ambient air to reach 100% O_2 saturation. Both control (only bottom water) and spiked samples were placed in the dark in three batches representing three different temperatures: 5±0.1°C, 10±0.1°C, and 20±0.1°C. Incubation of the prepared samples was conducted in for 200 days. The individual samples were analyzed for total dissolved organic carbon (DOC). The concentrations of DOC were analyzed on an automated total organic carbon analyzer TOC-L (Shimadzu).

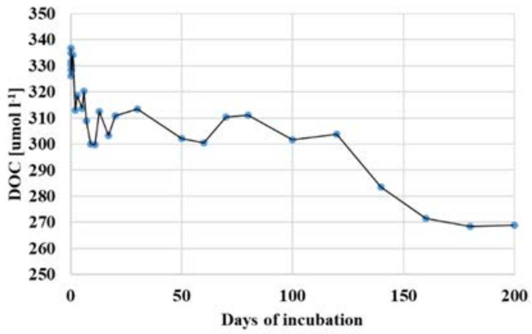
3. Results and conclusions

The observed development of the DOC decay had an exponential character. The highest dynamics of DOC remineralization was at the beginning of the experiment and it gradually decreased over time.

a)



b)



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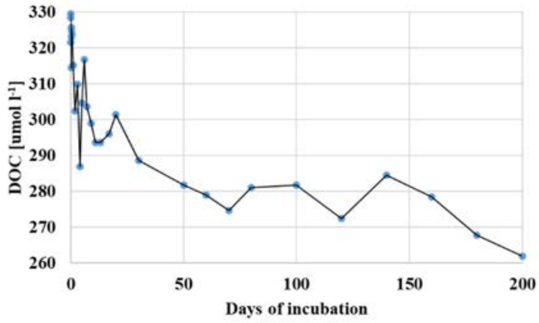

Figure 1. DOC concentration changes during 200 days of incubation experiment in a) 5°C, b) 10°C, and c) 20°C.

During the incubation period DOC concentration decreased in different amounts in each temperature: in 5°C it dropped from 328 to 276 µmol l^{-1}; in 10°C from 328 to 267 µmol l^{-1}; and in 20°C from 328 to 262 µmol l^{-1} (Figure 1). The concentration changes indicate that increased temperature lead to greater decrease of DOC concentration in time. Thus, the higher the temperature, the DOC remineralization is more effective.

The results indicate evident influence of temperature on the DOC decay. Following data combined allowed obtaining information about remineralization rates, bioavailability, and half-life times of different DOC fractions in three different temperatures for sediment-derived DOC in the Baltic Sea depositional area.

Acknowledgements

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Influence of the shoots density of *Zostera marina* on the bioturbation activity of macrofauna

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1. Introduction

In the Baltic Sea, the meadows of *Zostera marina* Linnaeus 1758 are one of the most productive and diverse ecosystems (Boström and Bonsdorff 1997). They have unique living conditions, based on the increased amount of organic matter stored in sediments, which results in a greater density of macrofauna than the neighboring non-covered areas (Dąbrowska et al. 2016). Despite the fact that underwater meadows are extremely valuable areas in the Baltic Sea, the issues concerning their functioning, and in particular the bioturbative activity of benthic infauna communities, have not been discussed so far. Macrofauna influence the conditions in the sediment by active mixing sediment particles (bioturbations) and irrigating it by creating tunnels in which they cause the water flow (bioirrigation) (Kristensen et al. 2012). The substances dissolved in water flowing through the tunnels improve the oxygen conditions in the sediment and increase the pH. The move of sediment surface, as a result of bioturbation, enables the exchange of biogenic compounds stored in the sediments through water-sediment interface (Michaud et al. 2006; Janas et al. 2019; Casado-Coy et al. 2020). Although bioturbation determines the balance of entire biotopes and makes an extremely valuable contribution to our understanding of how marine ecosystems work, research in underwater meadows is rare. Despite the fact that the participation of macrofauna in the processes taking place in the coastal zone is crucial, the knowledge on this subject is still insufficient (Thoms et al., 2018, Janas et al. 2019). The coastal zone acts as a filter - it retains nutrients and organic matter that is processed, among others, by bioturbating organisms (Carstensen et al. 2019, Janas et al. 2019).

Ecosystem functions, such as bioturbation, can be measured during experiments or determined through indirect methods such as the calculation of the BPc bioturbation potential index (Solan et al. 2004a, Wrede et al. 2017). BPc allow to estimate the bioturbation potential only of the macrozoobenthic community living there, not the total rate of bioturbation of all components in the environment. This method is much simpler and enables its use during routine environmental surveys to define the value of a given area in terms of its functionality.

2. Aim of the research

The main goal of this project is to determine the influence of the *Z. marina* seedlings density on the bioturbation activity of macrofauna in the underwater meadows in the Puck Bay. Additionally, we will compare the bioturbation potential (BPc Index) and the activity of organisms determined by using luminophore tracers.

3. Materials and methods

The research was carried out in August 2021 on the area of the southern Baltic best-preserved *Z. marina* meadows, located in the Długa Mielizna (Puck Bay). Four research stations were located in an increasing number of macrophytes gradient - from areas not overgrown with vegetation to those with high shoot density. The number of macrophytes was determined on the basis of the estimated number of *Z. marina* seedlings determined using a frame with a side of 50 cm (Boström and Bonsdorff 2000).

Sediment cores collected at the sampling sites were incubated in laboratory for 8 days with the prior application of luminophore markers to the sediment surface. After incubation, cores were sliced in 1 cm layers and frozen. Each layer was analyzed separately in order to obtain luminophore distribution profile and macrofauna vertical distribution in each core (Solan et al. 2004b, Bernard et al. 2019).

BPc was calculated (for each core) following the approach by Solan et al. (2004a) with modifications described in Gogina et al. (2018).

4. Preliminary results

Initial results indicate that only 17 taxa were observed in the seagrass meadows area. The abundance of organisms is strongly dominated by Hydrobiidae snails at all investigated stations. Fraction of individual taxa in the biomass is more evenly distributed. At all stations the same taxa have a relatively large share – *Hediste diversicolor, Cerastoderma glaucum, Mya arenaria* and Hydrobiidae. Mean BPc Index value together with abundance and biomass of macrofauna are the highest one the station with the highest density of *Z. marina*. BPc Index values will be compared with the values of the bioturbation rate determined on the basis of the luminescent markers

5. Acknowledgements

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Oxygen dynamics in the Baltic Sea: a budget.

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1. Introduction

The Baltic Sea is a semi-enclosed sea located in Northern Europe. This sea is widely known as one of the aquatic areas suffering from lack of oxygen (*Kuliński et al., 2021*) called hypoxia (oxygen concentrations less that 2 ml/l (*Carstensen et al., 2014*) or 2 mg/l (*Savchuck, 2018, Meier et al., 2019a*) or anoxia (absence of oxygen) due to both natural environmental conditions (long residence time of the bottom water) and anthropogenic pollution (increased nutrient loads caused by an agriculture) (*Reckermann et al., 2022*). One of the ventilation mechanism for Baltic Sea are Major Baltic Inflow (MBI) events (*Lehmann et al., 2021*). They occur under certain meteorological conditions and transport salt, oxygen rich water from the North Sea into the Baltic Sea (*Lehmann and Post, 2015, Mohrholz, 2018*). Despite the MBI events the Baltic Sea cannot be supplied with enough amount of oxygen. Due to the higher density, North Sea water flows near the bottom and fills the deep Baltic Sea basins where transported oxygen is quickly consumed both in the water column and in the sediments (*Meier et al., 2018*).

To mitigate Baltic Sea eutrophication the Baltic Sea Action Plan has been developed and implemented by HELCOM and countries surrounding the Baltic Sea (*HELCOM, 2021*). But even with nutrient reductions sometimes it still unknown yet how marine system will respond. (*Meier et al., 2019b, Neumann et al., 2002*). The main goal of this study is to estimate Baltic Sea oxygen dynamics on decadal time scale and to decompose oxygen sources and sinks to perform an additional analysis of their dynamics and reveal main oxygen sources and sinks for the whole sea as well as for separate basins (e.g. *Savchuk, 2005*).

2. Materials and methods

In this research the coupled 3-dimensional MOM-ERGOM model has been used (*Neumann et al., 2021*). The model was forced by COSMO-CLM atmosphere model (*Rockel et al., 2008*). The integration period was from 1948 to 2018 years. In this setup the rectangle orthogonal 3 nm grid has been used.

The model output analysis was based on oxygen budget calculation. If the oxygen sources prevail over the sinks, oxygen concentration within considered volume decreases, and vice versa (*Fennel and Testa, 2018*). To perform budget calculation, it is necessarily to divide the study area into the limited number of boxes and then calculate the overall oxygen sources and sinks as well as the oxygen change for each box (*Li et al., 2015*).

For the current research the Baltic Sea was separated into seven boxes. Each box represents a dynamically special region where different processes can dominate in terms of oxygen consumption and production. All boxes have their upper boundaries at 70 meters depth ending at the bottom. The map that depicts chosen boxes can be found on figure 1.

The mathematically equation for the budget of each box can be written as:

$$\frac{d}{dt}\iiint_V O_2\,dx\,dy\,dz - \iint_S \vec{v}\vec{n}O_2\,dx\,dy - \iiint_V \frac{\partial O_2}{\partial t}\,dx\,dy\,dz = 0 \qquad (1)$$

Where the left part represents oxygen change within the box per time and the right part represents both oxygen uptake through the borders, namely advection and diffusion (first term), and oxygen change in time due to the internal processes, namely biological consumption and production (second term).

Based on equation (1) the accuracy of the model in terms of mass conservation has been verified. Obtained results suggest that errors in budget calculation are relatively small (around 1% in average and 3% for the Bothnian Bay, which is the worst score). Based on obtained errors it can be concluded that the ERGOM model represents the mass conservation law with high precision and oxygen sources and sinks can be analyzed for each box.

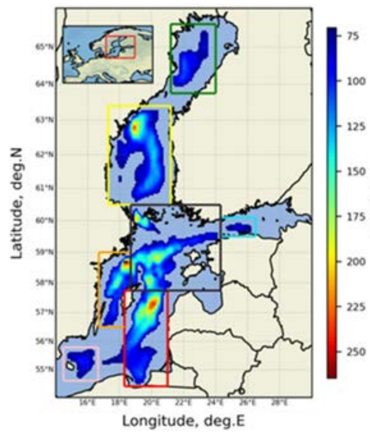

Figure 1. Research domain and chosen boxes. The green box represents Bothnian Sea, yellow – Bothnian Bay, black – Northern Gotland Basin, red – Eastern Gotland Basin, orange – Western Gotland Basin, pink – Bornholm Basin and turquoise – Gulf of Finland.

3. Results

Based on the described budget analysis as outlined as in the previous section, oxygen sources and sinks for all boxed were analyzed. At the first step the basic separation for oxygen sink terms into sediment and water column processes has been made. Oxygen source terms at the first step have been separated into diffusion and advection terms. Linear trend analysis has been done as well using Mann-Kendall test. Figure 2 illustrate our results.

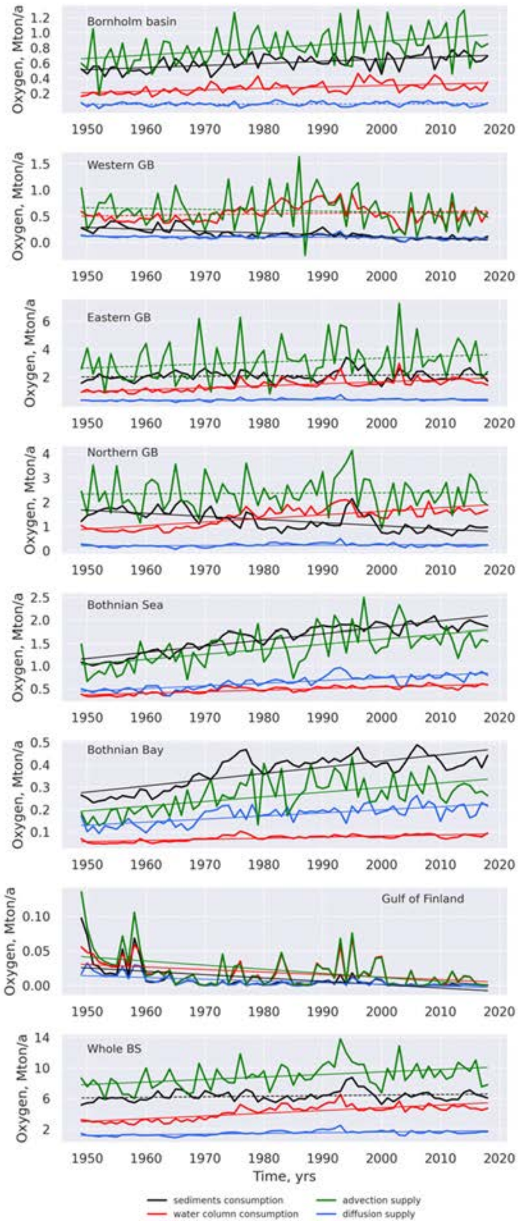

Figure 2. Linear trend analysis for oxygen sources and sinks (solid trend lines represent statistically significant trends based on Mann-Kendall test with 95% confidence interval).

Based on Figure 2 it can be concluded that oxygen dynamics is different from basin to basin, thus for Bornholm Basin, Bothnian Sea and Bothnian Bay as well as for the whole study area oxygen consumption in the sediments are larger than the water column consumption. For Bothnian Sea and Bothnian Bay it can be explained by their relatively oligotrophic conditions and therefore not intensive water column consumption. The Bornholm Basin is relatively shallow, that is also might be an explanation for sediments dominated oxygen consumption. For the rest of the basins oxygen consumption in the water column exceeds sediments consumption or it is comparable with it.

Both increasing and decreasing pronounced linear trends also can be seen (Figure 2). For the Bornholm Basin all trends are statistically significant except the oxygen diffusion trend. The western Gotland Basin is characterized by decreasing trends in sediment consumption and oxygen diffusion. The eastern Gotland Basin, on the other hand, shows positive trends in the same terms. The northern Gotland Basin has two significant trends with different sights (increasing water column consumption and decreasing sediments consumption). For both Bothnian Sea and Bothnian Bay all term have pronounces positive trend, especially oxygen advection supply and sediments consumption. In the Gulf of Finland region all terms have a significant negative trend. For the whole study area significant positive trend in the oxygen supply can be noted as well as increasing water column oxygen consumption.

4. Conclusions

The coupled 3-dimensional model output has been analyzed based on budget calculation. Our results suggest that the oxygen consumption in the water column is usually comparable with the consumption in the sediments and in some basin even exceeds it. Statistically significant linear trends have been found in each basin.

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Flux dynamics of CO_2, CH_4 and N_2O in a highly degraded coastal peatland during transition from drained to inundated conditions by rewetting with brackish water

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1. Introduction

More than 5 % of the global greenhouse gas (GHG) emissions derive from drained peatlands (Kaat and Joosten, 2009). The rewetting of drained peatlands is known to reduce emissions of carbon dioxide (CO_2) and nitrous oxide (N_2O), but is often accompanied by high short-term emissions of methane (CH_4). The effects of rewetting with brackish water on GHG fluxes remain unclear, but sulfate-containing brackish water might be beneficial regarding CH_4 emission reduction due to a likely inhibition of methanogenesis.

Here, we report on the effects of brackish rewetting of a coastal fen on the GHG fluxes (CO_2, CH_4 and N_2O) during transition from pre- to post-rewetting conditions, derived from surface water concentrations and chamber measurements in the first year after the flooding.

2. Study site and methods

The study site "*Drammendorf*" is located at the northeastern German Baltic Sea coast on the island of *Rügen* in Mecklenburg-Western Pomerania. The coastal peatland was transformed from a drained and agriculturally used to a rewetted state by flooding with brackish water in November 2019. The rewetting was achieved by opening a small section of the dyke, resulting in an immediate inundation of the low-lying land by brackish water from the adjacent *Kubitzer Bodden*. The inundated area covers 54 ha with a permanent mean water depth of about 50 cm. Before rewetting the top-soil was highly degraded down to 50 – 70 cm, with a well-preserved peat layer of up to 100 cm underneath. The top-soil was not removed prior to flooding.

We used manually operated closed chambers to measure the pre-rewetting gas exchange at locations along a soil moisture transect and at locations within the main drainage ditch. After rewetting, we continued the measurements of GHG fluxes under inundated conditions at the same locations. Moreover, we took surface water samples in the adjacent *Bodden* and the flooded peatland and analyzed them for temperature and salinity as well as for concentrations of oxygen, chlorophyll a, and some nutrients (NO_3^-, NO_2^-, NH_4^+, PO_4^{3-}). In addition, we measured the concentrations of dissolved GHGs and used these in combination with a wind-dependent air-sea exchange parameterization (Wanninkhof, 2014) as an alternative way to calculate air-sea exchange.

3. Results and discussion

Temperature and salinity showed no significant differences between the adjacent *Bodden* and the flooded peatland due to rapid horizontal exchange and lateral mixing. Moreover, no water column stratification in the peatland was observed over the entire year suggesting the absence of stagnant water conditions.

Before rewetting CO_2 fluxes were highly dynamic ranging from -79.1 to 72.0 g m^{-2} d^{-1} with a mean value of 7.1 ± 19.8 g m^{-2} d^{-1} (see figure 1A). CO_2 fluxes from the ditch showed a similar mean flux, but less variability. High CO_2 fluxes from drained peatlands are common due to aerobic mineralization of organic matter (OM). After rewetting, CO_2 fluxes from formerly dry stations got less variable but both the fluxes from these and the ditch fluxes remained at a relatively high level. The water table increase likely was the main driver of CO_2-flux reduction on formerly terrestrial locations (Bubier et al., 2003, Strack et al., 2008). However, the die-back of vegetation provided OM for mineralization possibly leading to continuously high CO_2 emissions.

Before rewetting, CH_4 fluxes were expectedly low at the dry stations with an average flux of 0.003 ± 0.024 g m^{-2} d^{-1} (see figure 1B) whereas the ditch showed higher CH_4 fluxes of, on average, 0.27 ± 0.9 g m^{-2} d^{-1}. After rewetting, CH_4 fluxes from formerly dry stations increased slightly, whereas fluxes from the ditch decreased to 0.20 ± 0.6 g m^{-2} d^{-1}. Hahn et al., (2015) showed a 190-fold increase of CH_4 emissions after rewetting of a coastal peatland compared to pre-flooding conditions but there, the flooding occurred with fresh water. We assume that the availability of terminal electron acceptors (e.g. NO_3^-, SO_4^{2-}) enabled other microorganisms to outcompete methanogens for organic substrates. Moreover, anaerobic oxidation of the produced CH_4 in particular by sulphate reduction is likely to have contributed to the relatively low CH_4 emissions after rewetting in the study area.

The rewetted peatland was a minor source of N_2O with an annual mean flux of 0.72 ± 2.13 mg m^{-2} d^{-1}, whereas the highest fluxes occurred one week after rewetting (winter; see figure 1C). The annual N_2O fluxes after rewetting were comparable with the literature (Strack et al., 2008). Due to a significantly positive correlation of N_2O-exchange with the N-nutrients, it is likely that N_2O emissions originated from nitrification within the water column or in the soil.

4. Implications

Restoration of formerly drained peatlands is discussed as a potential measure to mitigate greenhouse gas emissions and in some cases, to re-establish carbon soil accumulation in the pan-Baltic area. Near the coasts, rewetting is feasible with both freshwater and brackish water. Our initial results suggest that rewetting with brackish water appears to be favorable with respect to the GHG balance. Future work in *Drammendorf* and generally should address the long-term development and the carbon balance of GHG fluxes of brackish-rewetted coastal peatlands and investigate their short-term dynamics.

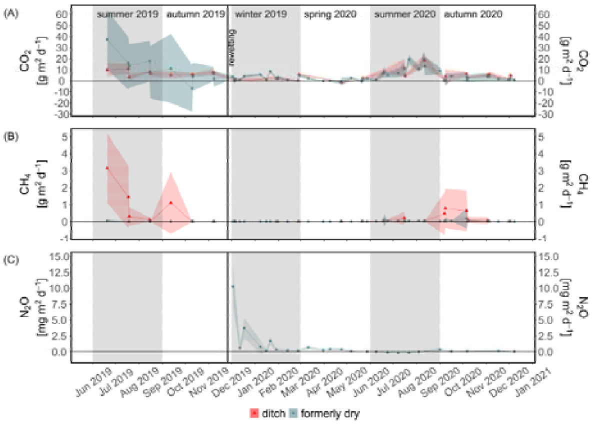

Figure 1. Time series of the fluxes for A) CO_2 B) CH_4 and C) N_2O in [m]g $m^{-2}d^{-1}$ before and after the rewetting. The rewetting date is indicated by the solid black line. Fluxes for the ditch (red) and the formerly dry stations (blue) are shown as mean values ± standard deviation as shapes.

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Baltic Sea coastal peatland water stimulates growth of benthic diatoms along the sea-land ecocline.

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1. Introduction

The coastal shallow water zone of the Baltic Sea and the adjacent terrestrial areas such as peatlands are often separated from each other by dunes and dikes, thereby preventing naturally occurring exchange processes. In the light of climate change the importance of intact peatlands has increased as they can store large amounts of carbon. To obtain the original state of previously drained coastal peatlands, dunes and dikes often get removed to facilitate hydrodynamic and biogeochemical exchange processes. These processes will also lead to an exchange of marine and peatland organisms, with consequences for their ecology and physiology due to suddenly facing new environmental settings. Especially phototrophic organisms, such as benthic diatoms, may strongly be affected by such changes due to alterations in salinity, light, temperature and nutrient conditions, with consequences for growth and photosynthesis.

2. Organisms and sampling area

To investigate the ecophysiological response of benthic diatoms to the intermixing processes between the shallow coastal Baltic Sea and coastal peatlands, three Baltic Sea (PTM9a, PTM12 and PTM17) and three peatland benthic diatom strains (PTM7, PTM10, PTM25) along the German Baltic Sea coast were isolated. Sampling areas include three peatlands that vary in the stage of renaturation as investigated by the graduate college Baltic TRANSCOAST along terrestrial marine gradients (Jurasinski et al., 2018, Janssen et al., 2019).

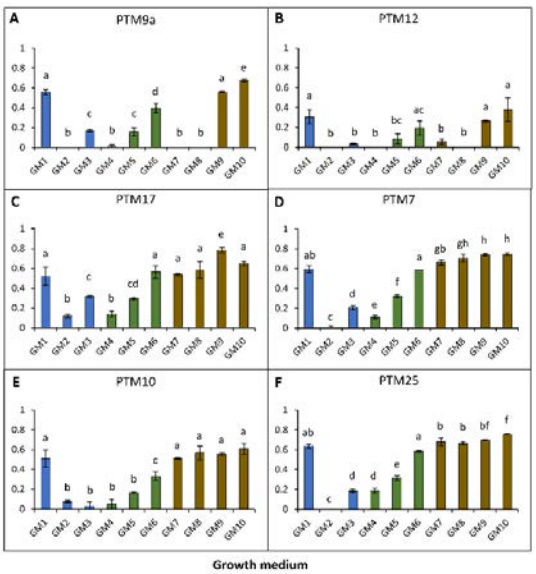

Figure 1. Growth rates (µ d^{-1}, mean value ± SD (n=3)) of three Baltic Sea diatom strains (A-C) and three peatland diatom strains (D-F) cultivated in ten different growth media (GM). Lower case letters represent significant levels among all means (one-way ANOVA, Tukey's test, p = <0.05). A) PTM9a, B) PTM12, C) PTM17, D) PTM7, E) PTM10 and F) PTM25 (Prelle & Karsten, in prep.).

3. Growth rates of diatoms

With respect to the intermixing processes, established unialgal cultures were grown in ten different growth media for eight days, that were based on Baltic Sea water and/or peatland water with varying additives such as nutrients and artificial sea salt to adjust nutrient availability and salinity. Growth rates were calculated after measurement of chlorophyll *a* via *in vivo* fluorometry (Karsten et al., 1996). Results clearly showed a stimulation of growth in the peatland water-based media compared to the Baltic Sea medium. Furthermore, growth is inhibited in some species in the freshwater peatland media making salinity an important co-parameter for species-specific growth.

4. Photosynthetic performance of diatoms

The photosynthetic performance of the six diatom strains was measured in two of the growth media - one in peatland water with added artificial sea salt (15 S_A) and selected nutrients and one in ½ peatland with added selected nutrients and ½ Baltic Sea water - using oxygen optodes (Prelle et al., 2019). Species-specific photosynthetic rates were measured with increasing photon fluence rates (0 - 1400 µmol photons m^{-2} s^{-1}, recorded at 20°C). Light saturated photosynthesis was measured at 19.6 - 93.8 µmol photons m^{-2} s^{-1} and maximum primary production rates at 14.1 - 190.8 µmol O_2 mg^{-1} Chl *a* h^{-1} with no severe photoinhibition, indicating high photo-physiological plasticity. However, the photosynthetic performance was not impacted by the growth medium, except for one species.

5. Temperature dependent photosynthesis

Under saturated light conditions (>300 µmol photons m^{-2} s^{-1}) and increasing temperatures (5-40 °C) all six diatom strains exhibited eurythermal traits with species-specific optimum for photosynthesis (5-35°C) and respiration (25-40°C) for both growth media. A strong photosynthetic effectivity > 80% of the maximum photosynthesis was generally found at higher temperatures for the peatland strains compared to the Baltic Sea strains.

6. Conclusion

The presented data clearly document a stimulation of growth in the benthic diatom strains by peatland water components with salinity as an important co-parameter. We speculate that organic compounds in the carbon-rich peatland water are responsible for our observations. While all strains exhibited a high photo-physiological plasticity and a broad temperature tolerance, the investigated growth media did not influence photosynthesis and respiration.

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Nitrogen fixation in the Baltic Sea evaluated using long-term, high-resolution pCO_2 records and N_2, Ar measurements from a cargo ship

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1. The pCO_2 approach

Automated measurements of the surface CO_2 partial pressure (pCO_2) have been performed since 2003 on a cargo ship traveling along a transect between the Gulf of Finland and the southwestern Baltic Sea (Schneider and Müller, 2018). According to the cargo ship's schedule, data will be obtained with a temporal resolution of 2–4 days. The spatial resolution amounts to ~2 nautical miles. The data can be used to characterise the seasonality of total CO_2 (C_T) in surface water and to identify biomass production events on the basis of C_T depletion. The focus of this study was mid-summer production which is based on the growth of nitrogen-fixing cyanobacteria. During most of the analysed years, there was one or more sudden pulses of distinct C_T depletion, each lasting 1–2 weeks and indicative of the occurrence of cyanobacterial bloom events (Schneider et al., 2014). Taking into account the air-sea CO_2 gas exchange, the decrease in C_T was used to calculate the rates of net organic carbon production for individual bloom events. These rates were then converted to N_2 fixation rates by applying the mean observed C/N ratio of the particulate organic matter produced during the blooms.

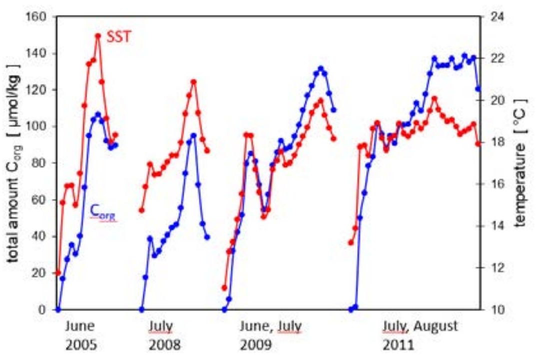

Figure 1. Pulses of C_{org} production and sea surface temperature, SST. C_{org} represents the concentration of organic matter that would accumulate during a production event in case that no sedimentation had occurred. Hence, the slope of the corresponding line (blue) represents the production rate. The decrease in C_{org} indicates mixing with water that was not subjected to C_{org} production (dilution). Likewise, the decrease in SST is due to mixing with below-thermocline water.

In all observed cases the accumulated production of C_{org} paralleled the increase in temperature (examples for the years 2005 – 2011 are given in Fig.1). This coincidence was attributed to a common cause: efficiency of solar radiation as modified by vertical mixing. As a consequence the production rates and thus the N_2 fixation rates were distinctly correlated with the rate of the temperature increase. A relationship with temperature as such did not exist (Fig. 2) because it is the exposition to solar radiation that controls the growth of cyanobacteria and of N_2 fixation! Rate limitation by phosphate or any other factor was not detected.

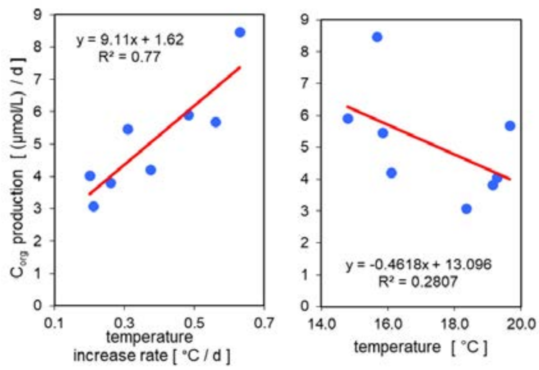

Figure 2. C_{org} production rates as a function of the temperature increase rate (left) and of the temperature (right).

2. Direct measurements of N_2 depletion

Measurements of the pCO_2 offer an indirect assessment of N_2 fixation. It requires knowledge about the C/N ratio of the produced organic matter and about the contribution of dissolved organic matter to C_{org}, and is accordingly prone to uncertainties. Within a pilot study we therefore tested an alternative method for the determination of N_2 fixation that was based on direct measurements of the N_2 loss during mid-summer cyanobacterial blooms (Schmale et al., 2019). In that approach, ambient air was equilibrated with surface water in a bubble-type equilibrator and analysed for N_2 and Ar by mass spectroscopy. The surface water concentrations of N_2 and Ar were then calculated from their solubility constants. Distinct N_2 depletion was detected in regions where the pCO_2 data indicated growth of cyanobacteria and thus N_2 fixation. This motivated the development of a measurement system for the continuous recording of the surface water N_2 concentrations in parallel with the above mentioned automated pCO_2 measurements on a cargo ship. In contrast to the previous version of the measurement device, the gas phase equilibration is generated by a membrane equilibrator. The e-fold equilibration time amounts to about 5 min and corresponds to a spatial resolution of the N_2 measurements of less than 2 nautical miles. The concurrent Ar measurements will be used to estimate the effect of gas exchange on the depletion of N_2 by fixation. Initial tests showed that the performance of equilibration procedure and the precision/accuracy of the mass spectroscopic analysis technique together allow the reliable detection and quantification of N_2 fixation in the Baltic Sea. The measurement system will be deployed on the cargo ship for the first time in summer 2022.

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Short term variability of benthic nutrient, carbon, and oxygen fluxes in the coastal zone – the importance of environment and macrofaunal community

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1. Introduction

The coastal zone plays an important role in the transformation of nutrients and carbon (e. g. Carstensen et al., 2020). Accordingly, multiple studies addressed how environmental conditions and local benthic communities shape benthic fluxes in the coastal zone of the Baltic Sea (e.g., Janas et al. 2019, Thoms et al. 2018). While these studies acknowledged the temporal variation in benthic fluxes among seasons, knowledge about short term variability in benthic fluxes is still missing.

To close this gap, the aim of this study is to measure carbon, oxygen, and nutrient benthic fluxes in the coastal zone during early summer and relate them to the abiotic and biotic environment.

2. Material and methods

Samples for this study were collected bi-weekly in June and July 2020 from a single coastal location in Puck Bay (southern Baltic Sea, 54.728°N, 18.596°E, 0.5 m depth) with bare sandy sediments, approximately 30 m from the shoreline and in close proximity (~5 m) to a *Zostera marina* meadow. During each sampling event (Table 1), 5 replicate sediment cores (inner diameter: 11.43 cm; height: 30 cm) and additional sea water were collected to measure benthic fluxes via incubation experiments. Surface sediments and water were collected to determine a variety of environmental parameters.

Table 1. Sampling date and selected environmental parameters for each sampling event. Temp - Temperature [°C]; Chl/Pha – sediment Chlorophyll *a*/Phaeophytin ratio; SiO_2 – water SiO_2 concentration (in situ; µmol L^{-1}). *Note*: The study was conducted in the period of high biological activity when the nutrient contents (NO_3^-, NO_2^-, PO_4^{3-}) decrease to around the detection limit.

	I	II	III	IV	V
Date	02.06.	18.06.	30.06.	16.07.	28.07.
Temp	14.1	20.3	19.6	19.6	21.2
Chl/Pha	4.10	2.95	2.75	6.00	5.30
SiO_2	8.35	6.75	10.47	11.35	15.13

Two separate multiple factor analyses (MFA; Escofier and Pagès 1994) – one for abundance and one for biomass benthic community data – were used to identify common patterns in benthic communities, environmental parameters, and benthic fluxes across all experiments. In principle, MFA is a global principal component analysis (PCA) of the combined data of multiple data sets with equal weight given to each data set (Borcard et al. 2018). Objects, variables, and axes of PCAs of each individual data set are then projected on the MFA space to identify common patterns within them.

3. Results

A distinct temporal pattern was observed for many fluxes. O_2 and DIC fluxes were high in cores collected during the first three sampling events and dropped extremely in the second half of July (Fig. 1). A slight average release of DOC occurred in the first experiment. After this, the DOC uptake of the sediment increased over time. This coincided with a higher variation of DOC fluxes among replicate cores starting from experiment III (Fig. 1). NH_4^+ release was low during the first experiment. After this, it peaked during the second experiment and declined gradually afterwards, reaching levels during the fifth experiment almost as low as at the beginning of the study. SiO_2 fluxes were highest during the first 2 experiments, when its concentration in the water was lowest (Table 1) and declined after that. Fluxes of oxidized nitrogen (NO_2^-, NO_3^-) were low and often 0.

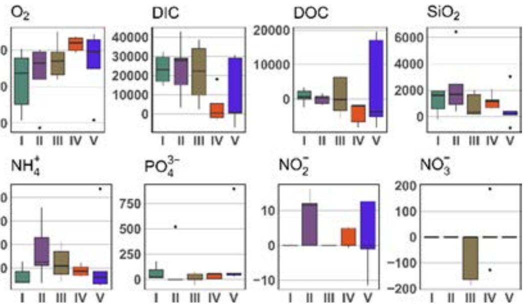

Figure 1. Boxplots showing measured benthic fluxes for all experiments. Black horizontal lines give median values. Boxes present 25th and 75th percentile. Whiskers are drawn to the maximum and minimum value. Outliers given as points. Fluxes are given in µmol m^{-2} d^{-1}.

Cluster analysis of the multivariate fluxes did not identify distinct clusters associated with a specific sampling event. Instead, a main cluster that contained 16 replicate cores from all experiments with intermediate values for most fluxes emerged as the most homogeneous group (Fig. 2). Within this group, the cores V-c and V-e were distinct by a strong DOC release and core IV-e by a strong release of NO_3^-. The remaining cores diverged from this group because of elevated fluxes in some of the measured substances. They all shared a higher oxygen consumption and higher DIC release than the cores in the main cluster. Within this group of 7 cores, the cores II-e and V-e were most distinct, since they had a high NH_4^+, PO_4^{3-}, and SiO_2 release in addition to high O_2 uptake and DIC release (Fig. 2). Cores III-a and IV-a had a strong NO_3^- uptake.

The first MFA (based on community abundance data) showed that benthic community and environmental parameters shared a similar first dimension in the MFA plane. In principle, the first MFA axis sorted the replicate cores in the order of the sampling events reflecting the seasonal succession of environment and benthic community composition. In terms of the environmental variables, MFA axis 1 separated the sampling events primarily according to parameters measured in the water. MFA axis 2 was more strongly affected by environmental parameters measured in the sediment. The first two dimensions of the benthic fluxes, however, were both almost orthogonal to the first MFA axis and therefore independent of the seasonal succession of the community and the water parameters that were best described by the first axis (Fig. 3a). Accordingly, the benthic fluxes were more strongly connected to the sediment and the community component that is shaped by the differences in sediment properties. In addition, the second dimension of the abundance data falls along the second MFA axis. Despite the contribution of benthic fluxes to MFA axis 2, the combined effect of environment and community determined the MFA plane and fluxes had little influence on the analysis.

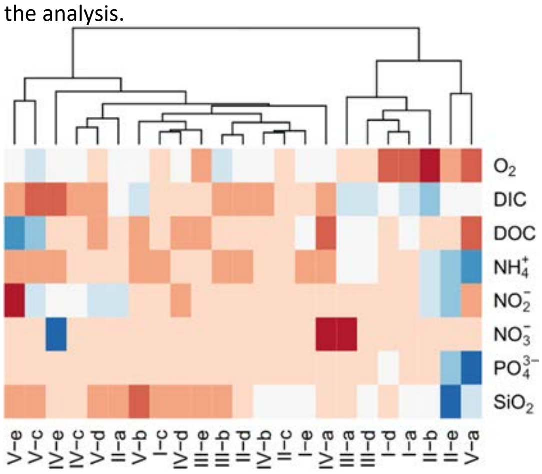

Figure 2. Heatmap of the standardized fluxes in all replicate cores. Color scale indicates the standardized flux from most negative (dark red) to most positive (dark blue). A dendrogram showing the results of Ward's Minimum Variance Clustering of the multivariate fluxes is shown on top. Roman numerals indicate experiments (compare Table 1). Letters a to e represent the replicates within each experiment.

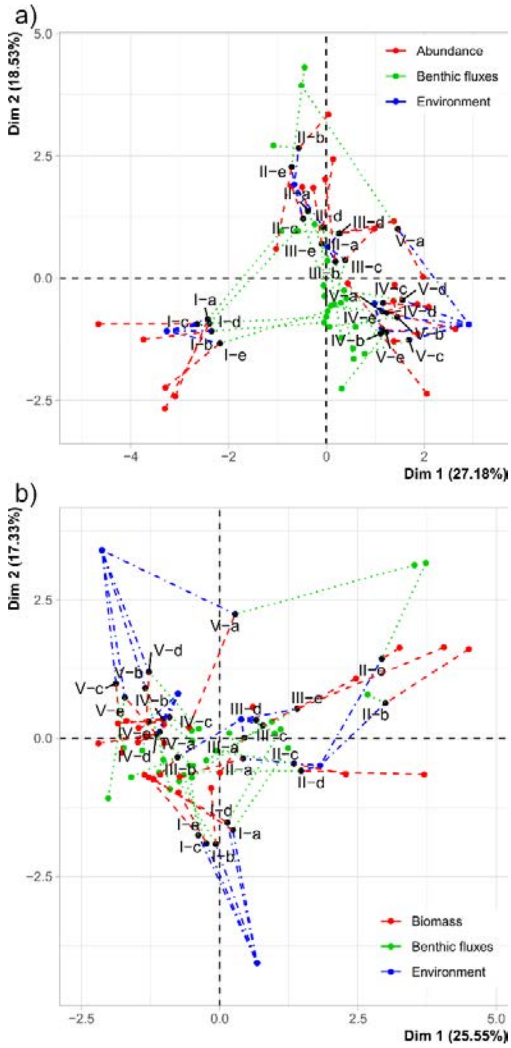

Figure 3. Individual factor maps of the multiple factor analyses (MFA) with macrofauna represented as (a) abundance and (b) biomass. MFA site scores for each core (centroids; labeled black dots) and the corresponding PCA site scores with links (colored dots and lines). Roman numerals indicate experiments. Letters a to e represent the replicates within each experiment.

In contrast, the community and benthic fluxes shared more similar dimensions in the second MFA (using community biomass data), while the seasonal succession in the form of the environmental parameters was mostly reflected in the second MFA axis (Fig. 3b). Along the first axis, high standardized DIC, SiO_2, and NH_4^+ and low standardized O_2 fluxes were associated with positive axis scores. MFA axis 2 is mostly reflecting the fluxes of NH_4^+, NO_2^-, and PO_4^{3-}.

4. Conclusions

Our study demonstrates high variation in benthic fluxes on short temporal scales. This has implications for the current practice of calculating nutrient and carbon load, which typically extrapolate measured fluxes from individual experiments to account for an entire season. The common patterns in benthic fluxes of NH_4^+, PO_4^{3-}, and SiO_2 suggest that the same drivers are responsible for shaping the fluxes of these three nutrients, while oxidized nitrogen fluxes are seemingly unrelated to the other nutrient fluxes. Our results suggest that benthic communities (particularly benthic fauna biomass) and the sediment play an important role in shaping benthic fluxes.

5. Acknowledgements

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Hypoxia in seasonally stratified coastal basins – the 2018 Gulf of Riga case and future projections

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1. Introduction

The Baltic Sea is strongly influenced by eutrophication, caused by excessive input of nutrients, and changing climate conditions (Gustafsson et al., 2012; Kabel et al., 2012). One of the signs of eutrophication is near-bottom oxygen depletion that could be influenced by the openness of the basin and the strength and onset of stratification. Anoxic and hypoxic conditions in the Baltic Sea are found as quasi-permanent, seasonal, or exceptional infrequent phenomena (Conley et al., 2009).

The Gulf of Riga (GoR) is a shallow basin in the eastern Baltic Sea where seasonal hypoxia can occur (Eglīte et al., 2014; Aigars et al., 2015). The decrease in the near-bottom oxygen levels from spring to autumn is a common feature in the gulf, but data from regular monitoring cruises and targeted surveys revealed extensive near-bottom hypoxia in the GOR in summer-autumn 2018.

The meteorological and hydrological data from the study year were analyzed and compared with their long-term means and variability. The aim was to reveal the reasons behind the observed hypoxia and whether it is a feature that could occur in the GoR and similar basins regularly and/or even more often in the future.

2. Data and Methods

We analyzed historical data from the environmental databases, vertical profiles of temperature, salinity, and dissolved oxygen available since 2012 and data of six monitoring campaigns in 2018. The water column structure was characterized by temperature, salinity, and density in the upper mixed layer (UML) and near-bottom layer (NBL) and potential energy anomaly, calculated as introduced by Simpson et al. (1990). Wind data were used to find the periods with inflow-favorable conditions through the Irbe Strait.

We introduced a rough method estimating oxygen consumption rates in the gulf NBL based on the measured changes in salinity and oxygen in the central gulf and Irbe Strait. Vertical diffusion and lateral advection/mixing were the physical processes considered to transport oxygen to NBL. The same approach was used to estimate phosphate fluxes due to physical processes and phosphorus release from the sediments.

3. Results

Late summer-autumn hypoxia has occurred in the Gulf of Riga in seven years in 2005–2018. A statistically significant decreasing trend of oxygen concentrations in the NBL was found based on monitoring data from October-November. The duration and vertical extent of hypoxia differed between the years. The deepest oxygen minima were observed in 2014 (0.8 mg l^{-1}) and 2018 (1.5 mg l^{-1}). The estimated spatial extent of hypoxia was the largest in 2018, when the hypoxic waters covered 5.2% (830 km^2) of the gulf's bottom area. Also, a statistically significant increase in phosphate concentrations in the NBL was detected for 2005-2018.

The years with strong stratification related to high UML temperature, low UML salinity, and high NBL salinity were among those with near-bottom hypoxia. In 2017, the stratification was the weakest, and hypoxia did not develop. However, the overall stratification of the water column alone did not explain the occurrence, duration, and spatial extent of hypoxia. A remarkable feature observed in spring 2018 was the existence of the deep haline stratification.

Strong stratification in 2018 was related to high sea surface heat flux and weak winds. Wind forcing from February to the end of July supported the near-bottom inflows through the Irbe Strait, forming the saltier NBL separated from the water layers above. From the beginning of August, the winds from the opposite direction prevailed, blocking the further advective flux of oxygen.

Based on the introduced method, we found that consumption could cause oxygen depletion in the NBL by 2.94–4.24 mg l^{-1} $month^{-1}$. It corresponds to the 2018 average consumption rate per unit bottom area of 1.67 mmol O_2 m^{-2} h^{-1}. Such consumption rate is high enough to cause near-bottom hypoxia in the years with strong stratification and thin NBL. In the years with weaker stratification and thicker NBL, hypoxia could develop if vertical mixing did not reach the seabed before late October (as it was in 2015).

We estimated the phosphate flux from the sediments as high as 13.6 µmol m^{-2} h^{-1} from the end of May to mid-July 2018, although the oxygen concentrations fell below the hypoxia threshold later.

4. Discussion and Conclusions

Possible future changes in climate influence the extent of hypoxia in the Baltic Sea (Meier et al., 2011). Strengthening of vertical stratification can be predicted based on the projected increase in sea surface temperatures (Gröger et al., 2019; Meier and Saraiva, 2020) and an increase in the total runoff to the Baltic Sea (Saraiva et al., 2019), although the latter is uncertain.

Weaker winds in spring also create more favorable conditions for a steady outflow in the surface layer and inflow in the sub-surface layer through the Irbe Strait. Although climate projections for wind are uncertain in the Baltic Sea area (Christensen et al., 2015), a slight decrease in wind speed in spring is expected (Ruosteenoja et al., 2019). A predicted winter river runoff increase due to intermittent melting (Stonevičius et al., 2017), which would potentially bring additional nutrients to the sea, could lead to more frequent and severe hypoxic events in the future.

In conclusion, we suggest that the sequence of certain processes triggered the observed extensive hypoxia in the Gulf of Riga in 2018. Enhanced seasonal stratification was created by the rapid warming of the surface layer and calm wind conditions in spring, leading to restricted vertical mixing. In spring-early summer, inflows of saltier waters through the Irbe Strait maintained haline stratification, keeping the near-bottom layer relatively thin. The projections of meteorological and hydrological conditions anticipate that the frequency and extent of hypoxia will likely increase in the future. Since the internal load of phosphorus is linked to the near-bottom oxygen conditions, this scenario also predicts no fast reduction of nutrient concentrations in the Gulf of Riga and similar coastal basins.

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The marine CO_2 system in the estuaries of the Vistula and Oder rivers – structure, variability and potential implications for the Baltic Sea

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1. Introduction

The ocean CO_2 system is relatively well understood. It is controlled to a large degree by the CO_2 air-sea gas exchange and the production and remineralization of organic matter. In the shelf and marginal seas, more factors add to the dynamics of the CO_2 system like riverine input and also processes occurring in the hypoxic and anoxic regions. The Baltic Sea is exceptionally influenced by rivers and despite signs of important consequences (Beldowski et al., 2010), the impact of river inflow on the entire marine acid-base system is still poorly studied.

In this study, we examined the structure and variability of the carbonate system in two estuaries of the southern Baltic Sea.

2. Study Area

The study has been performed in the estuaries of two big, high-carbonate, continental rivers, Vistula and Oder.

The Vistula River is the second biggest river entering directly the Baltic Sea which forms the coastal plain estuary. The mean discharge of 1065 m^3 s^{-1} and high TA concentrations (>3000 µmol kg^{-1}) make the Vistula River likely the largest source of TA to the Baltic Sea.

The Oder River is the seventh-largest river entering the Baltic Sea. The Oder River forms a lagoon-type of the estuary, which can be divided into four main sections the lower Oder River; the Szczecin Lagoon; the Świna, Piast Channel, Dziwna and Peene rivers and the Pomeranian Bay.

3. Methods

Measurable parameters describing the CO_2 system were investigated: the partial pressure of carbon dioxide (pCO_2), total alkalinity (TA), together with salinity, temperature, oxygen concentration, particulate inorganic carbon (PIC), and inorganic carbon (IC) in sediments.

4. Results and Discussion

In both estuaries, the pronounced gradients of measurable parameters of the CO_2 system were observed. The pCO_2 was highest in the rivers (reaching >1000 µatm) and decreased along the mixing zone (lowest reaching <70 µatm). The negatively correlated pCO_2 and oxygen concentration in all seasons suggest that both were inversely controlled by the net ecosystem production (NEP).

The TA varied from ~1700 µmol kg^{-1} in the marine part to ~3000 µmol kg^{-1} in the river end-member. TA usually showed conservative dependency, however, in the Oder River estuary in May 2016 TA showed anomaly (Fig. 1). It was caused by calcite precipitation during a high production period, possibly leading to loss of TA loads to the Baltic Sea.

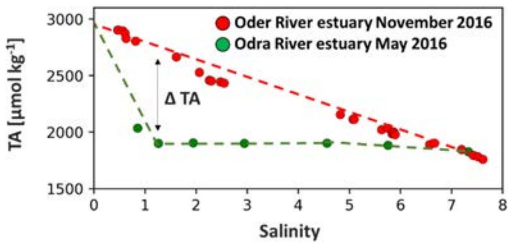

Figure 1. The TA loss in the Oder River estuary in May 2016 (Stokowski et al., 2020).

For the first time, we present experimental data on PIC and IC in the sediments in the Vistula River estuary, which suggest possible deposition of inorganic forms of carbon to the sediments near the river mouth (Fig. 2). The observed undersaturation of carbonates (Ω<1) in the cold season may indicate the dissolution of deposited carbonates. This may increase loads of TA to the Baltic Sea system in winter.

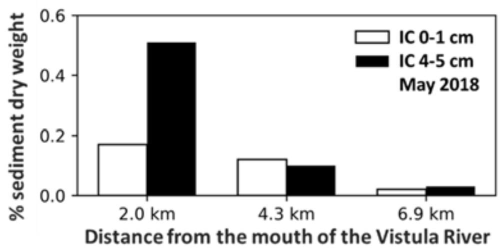

Figure 2. Inorganic carbon in the sediments in the vicinity of the Vistula River mouth (Stokowski et al., 2021).

5. Conclusions

- The first detailed studies on the structure of the CO_2 system in the coastal zone of the southern Baltic Sea were performed.
- The variability of the acid-base properties in the mixing zone was high, shaped mainly by mixing and NEP.
- The results suggest that the coastal processes have a potential to influence the whole marine acid-base system of the Baltic Sea.

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Microphytobenthos composition along the Baltic Sea shore-peatland ecocline (the Heiligensee and Hüttelmoor nature reserve, Germany)

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1. Introduction

A rapid increase in sea level worldwide and in the Baltic Sea, where it is aggravated by the subsidence of the coastline and increased precipitation (Jurasinski et al., 2018), may increase exchange processes between the sea and the surrounding land affecting all inhabiting biota, e.g., benthic microalgae (Karsten et al., 2012).

Benthic microalgae fulfil essential ecological functions in the marine littoral. They make up to 30% of the global total coastal primary production and influence various exchange processes between the sediment-water interfaces they inhabit (Cahoon, 1999; Wilhelm, et al., 2006, Kuriyama, et al., 2021). Commonly, these communities predominantly consist of diatoms (e.g., Cahoon, 1999). However, the structure and functioning of the microphytobenthos along the terrestrial-marine ecocline of the Baltic Sea coast remain poorly known.

2. Objective and Hypotheses

We aimed to study taxonomic diversity of microbenthic algae along the ecocline between the Baltic Sea shore and wetland Hütelmoor, southern Baltic Sea coast.

Our hypotheses were: (I) The microphytobenthos communities of the intertidal and coastal zones of the Baltic Sea and the coastal peatland (Hütelmoor) differ in their taxonomic composition, with a predominance in each of the habitats of taxa typical of brackish water or freshwater reflecting a high ecological valence to such an environmental factor as salinity. (II) Seasonal change in the taxonomic composition of the microphytobenthos in the peatland area is more pronounced than in the ecocline of the intertidal zone-coastal zone due to a higher physical disturbance in the coastal area, e.g., by the wind-wave activity.

3. Study sites, Material and Methods

The coastal study area is the nature reserve “Heiligensee und Hütelmoor” (Hütelmoor) located as coastal peatland next to the Baltic Sea near Rostock, Mecklenburg-Western Pomerania, north-eastern Germany. This site was chosen on a transition zone between Atlantic maritime and continental climate in the frame of the DFG Research Training Program "Baltic Transcoast" as model for studying transport and transformation processes in the marine and the terrestrial part of the Baltic Sea coast (Jurasinski et al., 2018).

Three undisturbed replicate sediment samples of 1 cm depth layer each were collected using Petri dishes (d=5 cm) from the ecocline of the intertidal zone-coastal zone (sites S17 A, B, C, D, E) and the peatland area (sites MP6 and MP7) at the following dates representing four different seasons (winter, spring, summer, autumn): 16.01.2019; 09.04.2019; 13.06.2019; 08.10.2019; 13.01.2020. In total, 99 quantitative samples of microphytobenthos were analysed. Diatoms were counted and determined using a Zeiss Axio Scope light microscope and the standard identification literature (as in Schultz et al., 2015).

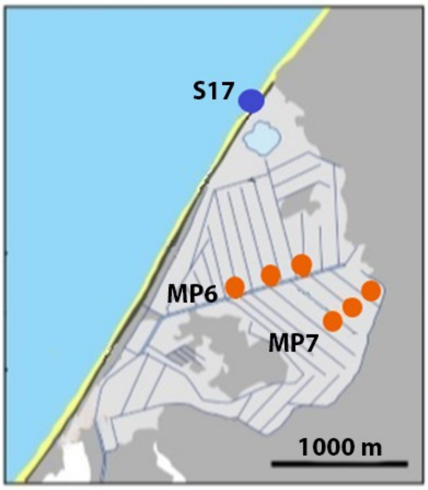

Figure 1. The sampling sites of microphytobenthos on the Baltic Sea (S17), and in the coastal peatland (MP6 and MP7) Hütelmoor, southern Baltic Sea coast.

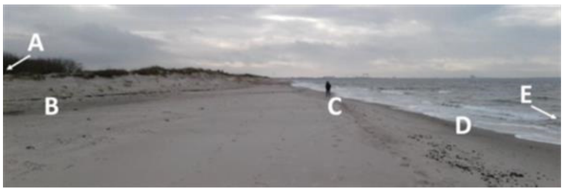

Figure 2. The vertical transect for microphytobenthos sampling along the ecocline of the intertidal zone-coastal zone of the Baltic Sea shore at site S17 (see Figure 1).

4. Preliminary results

259 taxa belonging to phylum Bacillariophyta, 3 subphyla, 19 orders, and 24 families were identified in this study. 114 taxa were found only in the ecocline of the intertidal zone-coastal zone, and 122 taxa were found only in the peatland area. Diatom composition in the peatland sites was typical for brackish or eutrophic freshwater bodies and significantly differed from community composition in the ecocline of the intertidal zone-coastal zone. This striking difference indicate a lack of direct intrusion of Baltic Sea diatoms into the peatland area, for example, after storm surges. The data rather suggest a steady subsurface influx of brackish water via ditches.

In contrast to the peatland sites, the composition of diatoms along the ecocline of the intertidal zone-coastal zone was strongly disturbed in terms of time and space, and hence it was represented mainly by small-sized taxa. This is consistent with the hypothesis about the strong disturbance of the microphytobenthos due to considerable, permanent movement of the substrate by water, wind, and anthropogenic use, such as trampling damage. In conclusion, benthic diatoms have a high bioindicator potential for environmental gradients along the terrestrial-marine coastal ecocline.

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Microphytobenthos in sandy permeable sediment of the Southern Baltic Sea: laboratory study of potential primary production and respiration quantified with oxygen microelectrodes

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1. Introduction

In shallow coastal water microphytobenthos contributes significantly to primary production, thus to the trophic web and biogeochemical cycles of carbon, nitrogen, phosphorus and silicon. In the southern Baltic Sea, where most areas are covered by permeable sandy sediment, this community is dominated by benthic diatoms. Yet, the potential importance of this benthic-microphytic production in sandy sediment has received little attention compare to pelagic production and production in muddy sediment. This study investigated the primary production of diatom-dominated sandy sediment from the southern Baltic Sea in a laboratory experiment.

2. Sampling and laboratory measurement

Sandy sediment and sea water (15 psu) were sampled from a shallow coastal area of Warnemünde beach, southwestern Baltic Sea. The sediment was mixed and placed into cylindrical benthic chambers, which then were filled with sea water and cultures of three benthic diatom species; *Navicula perminuta, Nitzchia pusilla, Hyalodiscus scoticus*. The incubation was conducted at 15°C, controlled light condition (40 µmol photons m^{-2} s^{-1}), and nutrients input (f ½ and metasilicate). After a biofilm had developed, photosynthesis and respiration measurement with Clark-type oxygen (O_2) microsensors (Revsbech 1989) were performed at low photon flux (0- 100 µmol photons m^{-2} s^{-1}).

Gross photosynthesis was measured with the conventional light-dark shift method (Revsbech and Jorgensen 1983), while net photosynthesis was determined through modelling of O_2 concentration gradients in the light. Respiration was calculated as the difference between gross and net photosynthesis as well as O_2 flux into the sediment in the dark.

3. Preliminary Results

Areal net photosynthesis (9 – 20 mmol O_2 m^{-2} d^{-1}) increased with irradiance and reached saturation at 70 -100 µmol photons m^{-2} s^{-1}. Calculated gross production (57 – 190 mmol O_2 m^{-2} d^{-1}) exceed net production (7 to 60-fold). Respiration in the photic zone in the light was higher compare to the dark respiration, indicating an overall underestimated areal respiration in the light. This suggest that O_{2}- consuming processes, such as photorespiration, may play an important role.

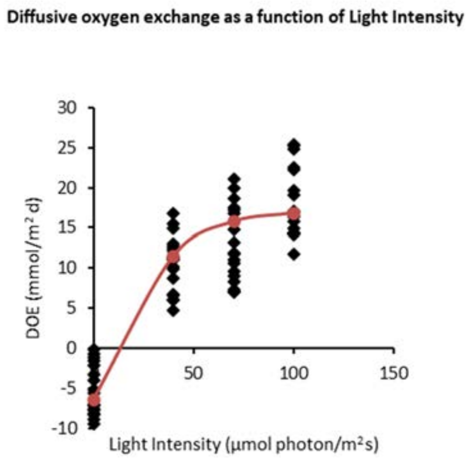

Figure 1. Diffusive oxygen exchange (DOE) as a function of light intensity. Data is fitted to a hyperbolic tangent function (Gattuso et.al, 2006)

4. Outlook

Several variables such as chlorophyll a biomass, sediment characteristics, and permeability were determined, and nutrients measured in the pore water and surface water.

The magnitude of primary production as a function of chlorophyll a will be quantified, while pore water profiles and nutrient measurements will be used to interpret the benthic mineralization processes. Our measurements fill an important gap in the understanding of primary production for sandy permeable sediments of the southern Baltic Sea. However, to which extend those contribute to the total primary production of the Southern Baltic coastline needs to be evaluated.

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Manganese biogeochemistry in boreal estuaries affected by acidic and metal-rich drainage: the roles of bacterial communities and water chemistry

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1. Background

Many parts of low-lying coastal areas around the world are covered by sulfide-bearing sediments. When these sediments are exposed to air, sulfides in the sediments are oxidized, resulting in the formation of acid sulfate (AS) soils and the liberation of acidic and metal-rich drainage. This imposes deleterious impacts on water quality and ecosystem health. As one of the most prominent biogeochemical processes when the acidic drainage enters its recipient water bodies, the oxidation of dissolved Mn(II) followed by the formation of Mn (hydr-)oxides (MnOx) with high sorptive and oxidative capacities has a strong impact on the bioavailability and environmental fate of metals and other pollutants carried by the acidic drainage. In most previous studies, microbial-mediated Mn oxidation and formation of MnOx were investigated using a specific Mn(II)-oxidizing bacterial species under controlled experimental conditions (Saratovsky et al., 2009; Webb, 2005). Considering the diversity of Mn(II)-oxidizing bacteria and physicochemical conditions in natural aquatic environments, the results obtained by these studies might not be directly applicable to the natural systems. Therefore, it remains largely unknown how bacterial communities interact with environmental factors (e.g., pH, salinity) and control the biogeochemical processes of MnOx and associated metals.

This project focuses on the brackish estuaries of three Finnish creeks (Figure 1), periodically loaded with abundant acidic and metal-rich drainage from AS soils. Our previous study on the estuary of the Vörå creek revealed a strong variation in Mn concentrations in a sediment core, with peaks episodically reaching up to about 1-2 %, which was hypothesized to reflect episodic massive formation of MnOx in the water column (Yu et al., 2015). This study aims to explore (i) how the structure of bacterial communities interacts with the environmental pH-salinity-temperature regimen along the estuarine mixing zones; and (ii) how the interactions regulate Mn oxidation and subsequent formation of MnOx in the water column and oxygenated sea-floor as well as diagenetic processes of MnOx within sediments, under natural conditions.

2. Samples and methods

Three types of samples were obtained from different sites along the mixing zones of the three creek-estuary systems on two occasions (May 2017, 2018): unfiltered and filtered (0.1 μm) surface waters, suspended particulate matters (SPM, via centrifugation of a large volume of surface water), and sediments (Figure 1). For the surface water at each site, physicochemical parameters (pH, electric conductivity, temperature) and the concentrations of several anions (Cl^-, NO_3^-, NH_4^+) were measured in the field, using a water quality multi-probe (MANTA-2). Both filtered and unfiltered water samples were analyzed for concentrations of metals, while unfiltered water samples were analyzed additionally for total and dissolved organic carbon Surface chemical composition of selected SPM samples (as fast-frozen wet pastes) was characterized by cryogenic X-ray photoelectron spectroscopy (cryo-XPS) following a precooling procedure (Shchukarev et al., 2007), while the speciation of Mn in selected samples of SPM and sediment was evaluated by Mn X-ray absorption spectroscopy (XAS). The XAS data of the samples and references were recorded on the HXMA beamline at the Canadian Light Source, the Balder beamline at the MAX-IV lab, and the HelXAS beamline at the University of Helsinki.

For bacterial community analysis, microbial cells in water sample at each site were collected by filtering water through 0.1 μm sterilized filters. Genomic DNA was extracted from filters and sediment samples and partial 16S rRNA genes were amplified using the primer set 341F and 805R (Herlemann et al., 2011). The Illumina libraries were constructed and sequenced at the Science for Life Laboratory, Sweden. The DADA2 pipeline was used for sequencing analysis (Callahan et al., 2016).

Figure 1. The location of the three studied creaks (Munsala, Vörå, and Toby).

3. Key findings and further analyses

The surface waters sampled close to the outlets of three creeks were weakly acidic (pH=4.8-5.8) during the sampling campaigns. The concentrations of dissolved Mn (filtered) were highest at the creek outlets (300-567 µg/L), and decrease successively along the transects from the creek outlets to outer parts of the estuaries. The decrease of dissolved Mn concentrations, in particular for the central and outer parts of the estuaries, was faster than predicted by mixing between creek water and sea-water end-members. This suggested that dissolved Mn was being removed as colloidal/particulate phases, which was further supported by high concentrations of Mn in the SPM samples from the same sites (up to 0.52%) (Figure 2).

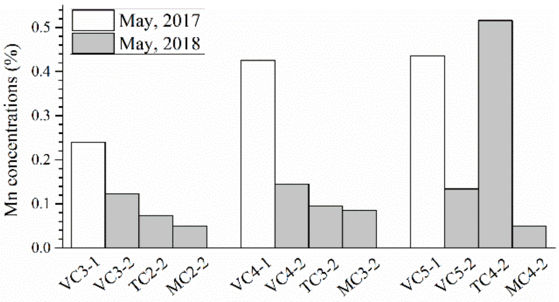

Figure 2 Spatio-temporal variations of Mn concentrations in the SPM samples

Cryo-XPS data revealed lower loadings of Mn (<0.1% to 0.16-0.22 %) on the outmost layers of fast-frozen wet samples of SPM. However, these samples could contain nearly 90% water (assuming they have similar water contents as the surface sediments as reported by Yu et al. (2015)), meaning that the concentrations of Mn on the surface of dried SPM should be multiplied by a factor of approximately ten and thus, much higher than Mn concentrations in bulk samples of dried SPM (Figure 2). This suggested that Mn was strongly enriched on the surfaces of sinking particles. The Mn XANES data for four SPM samples with lowest Mn concentrations (<0.12 %) displayed spectral features characteristic of biotite and chlorite, such as a weak shoulder at 6548 eV, two strong peaks at 6552 and 6557 eV, and a weak peak at 6570 eV (Figure 3). Also, the intensity of the shoulder and peaks gradually decreased with increasing Mn concentration, suggesting lesser contributions of silicate-bound Mn due to increasing occurrence of secondary Mn-rich phases. The XANES spectra of the two Mn-rich SPM samples had a weak shoulder at approximately 6561-6562 eV, coinciding with the main absorption peaks for the birnessite and vernadite references (Figure 3). All these spectra features suggested that MnOx phases occurred in these Mn-rich SPM samples.

The position of the main absorption peak for the surface sediment (0-2 cm, containing 1.2% Mn) at site S2 matched well with those of the birnessite and vernadite references (Figure 3). Also, the EXAFS spectrum of this sediment overall followed these references. In contrast, the absorption peak for the spectrum of the underlying subsurface sediment (2-4 cm, containing 1.5% Mn) shifted to the lower energy side and matched with those of Mn(II) references. These features suggested that (i) Mn was deposited as MnOx (structurally similar to birnessite/vernadite that are the most common biogenic MnOx in natural environments); and (ii) deposited MnOx was rapidly reduced and transformed to Mn(II) phases within near-surface sediments. In line with these findings, the microbial data indicated the presence of Mn-oxidizing genera in the SPM samples (e.g., *Flavobacterium*) and sediment samples (e.g., *Hyphomicrobium* and *Manganitrophus*). Additionally, genera including known Mn reducing bacteria (e.g., *Shewanella*) were also found in the sediment samples.

It is also worth to mention that Mn XAS data will be obtained for (near-)surface sediments at the other two sites. The data will further strengthen our Mn XAS dataset and, together with other chemical and microbial data, will provide a more complete picture of Mn biogeochemical processes in the water columns and sediments of the three creek-estuary systems.

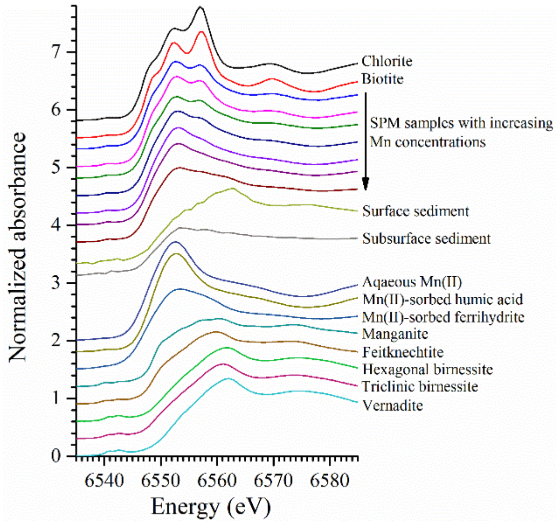

Figure 3. Normalized Mn K-edge XANES spectra for selected SPM and sediment samples, in comparison with those of references.

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Topic 3

Natural hazards and extreme events

Sea Level Rise Impact on Compound Flood Risk in Coastal Klaipėda City

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1. Abstract

Due to the fact of climate change, extreme floods are projected to increase in the 21st century in Europe. As a result, flood risk and flood-related losses might increase. It is therefore essential to simulate potential floods not only relying on historical but also future projecting data. Such simulations can provide necessary information for the development of flood protection measures and spatial planning. This paper analyzes the risk of compound flooding in the Danė River under different river discharge and Klaipėda Strait water level probabilities. Additionally, we examine how a water level rise of 1 meter in the Klaipėda Strait could impact Danė River floods in Klaipėda city. Flood extent was estimated with the Hydrologic Engineering Center's River Analysis System (HEC-RAS) and visualized with ArcGIS Pro. Research results show that a rise in the water level in the Klaipėda Strait has a greater impact on the central part of Klaipėda city, while that of the maximum discharge rates of the river on the northern upstream part of the analyzed river section. A sea level rise of 1 m could lead to an increase in areas affected by Danė floods by up to three times. Floods can cause significant damage to the infrastructure of Klaipėda port city, urbanized territories in the city center, and residential areas in the northern part of the city. Our results confirm that, in the long run, sea level rise will significantly impact the urban areas of the Klaipėda city situated near the Baltic Sea coast.

2. Introduction

Flood hazards and accurate economic risk assessments for the 21st century should not be limited to past floods or monitoring. To develop an accurate future flood risk assessment, it is necessary to assess all factors related to flood hazards in the context of climate change. The vulnerability of coastal river reaches is growing due to the increasing number of extreme hydrometeorological events caused by climate change (Ghanbari et al. 2021, Bermúdez et al. 2021, Khanam et al. 2021, Hsiao et al. 2021, Couasnon et al. 2020). Thus, the assessment of compound flooding with respect to climate change scenarios in coastal river reaches has become more relevant.

Scientists are increasing their focus on different types of floods and their causes in specific areas. The collision of physical oceanographic, hydrological, and meteorological factors can cause compound floods (Couasnon et al. 2020). Compound floods are one example of a combination of compound weather and climate events caused by many climatic fac-tors or hazards (Zscheischler et al. 2020). It is important to determine the influence of different components on the hydrometeorological event. Lack of consideration for all factors that can con-tribute to the occurrence of compound flooding may result in hazards being underestimated (Kumbier et al. 2018). A compound flood can occur when two hydrometeorological events take place at the same time or with offset times but maintaining joint probability. In coastal river reaches, compound flooding occurs when high river discharge coincides with the sea level of a storm surge. During this combination, either the river flow becomes blocked or a back wave is formed; in both cases, in the lower reaches, water level rises and increases the risk of a flood (Khanam et al. 2021, Hsiao et al. 2021). Individual components can be non-extreme, but their general interdependency can cause extreme situations (Emanuele Bevacqua et al. 2017). In order to determine the anthropogenic effects on different characteristics on compound floods these flood types require a systematic approach (Zscheischler et al. 2020). Compound floods are common in coastal are-as, but it is difficult to analyze them on a large scale; therefore, it is recommended to analyze such type of floods on a local scale (Paprotny et al. 2018), because topography elements and flood protection factors must be included in the analysis (E. Bevacqua et al. 2019). At the regional scale, smaller rivers are insignificant, but such rivers can cause a considerable risk at the local scale. All studies at the regional European scale cover data only from major river stations and are included in a database (Paprotny, Morales-Nápoles, and Jonkman 2018) that contains data on historical floods in Europe since 1870. Akmena–Danė River floods are significant for Klaipėda city and local people, and they are expected to increase both in size and frequency by the end of the 21st century.

3. Methods

We created eighteen compound flood scenarios in the study area combining Danė River discharge with the water level in the Klaipėda Strait and climate change effect on Baltic Sea water level rise: nine scenarios with historical water levels in the Klaipėda Strait and nine scenarios if the water level rose 1 m due to the fact of climate change.

For the scenarios, we used hazard data calculated during the EU Floods Directive's implementation (2012). The mean historical water level in the Klaipėda Strait is 0 m in the Baltic Sea height system (BS), the 10% probability (10 year water level) water level was 1.4 m (above BS); the 1% probability (100 year water level) water level was 2 m (above BS) (Dailidiene et al. 2012). A 10% water level probability in Curonian Lagoon is caused by severe storms in the Baltic Sea and the inflow of seawater into the lagoon, and this is the high probability that water levels can occur, on average, 1 time in 10 years. A 1% water level in the Curonian Lagoon probability is equal to 2 m according to the Baltic Sea level elevation system, which occurs in extreme situations when a strong storm forms in the Baltic Sea, westerly winds prevail at the mouth of the Danė River, and heavy rainfall fall occurs. Then, the water of the Danė River cannot flow into the la-goon and can rise even higher. This is a low probability water level that can occur, on average, 1 time in 100 years.

We made the hypothesis that due to the fact of climate change, the mean sea water level in this southeastern part of the Baltic Sea, including in Curonian Lagoon, would rise by 1 meter. After the addition of 1 m, the mean, 10%, and 1% probability water levels were respectively 1.0, 2.4, and 3.0 meters.

The mean annual maximum discharge of the Danė River is 59 m^3/s, a 10% probability (10 year flood) flood peak discharge of is110 m^3/s, and a 1% probability (100 year flood) flood peak discharge of is 156 m^3/s. We made an assumption that river discharge in the future will remain the same as in the past. This assumption might not reflect the baseline real hazard changes, but we used it to highlight the effect of sea level rise on compound flood risk.

Compound flood maps for each scenario were created using HEC-RAS 5.0.4 (Hydrological Centers River Analysis System) model. Using GIS (Geographic Information System), a terrain elevation template was created and visualized flood scenarios.

4. Results

The research shows that the central part of Klaipėda city is especially sensitive to changes in water levels of the Curonian Lagoon, and the northern part is sensitive to the Danė River's discharge rates. If the water of Klaipėda Strait were to rise by 1 meter due to the effect of climate, a large part of the Old Town, the Port Quay, and industrial areas would be flooded in the central part of the city. The rising water level of the Klaipėda Strait during storms due to the wind and more rainfall would raise the water level of the Danė River faster; then, large areas of the city with all the infrastructure would be inundated. If the water level in the Klaipėda Strait rises more than 2 meters (10 year water level), water would flow into the river valley. If the water level in the Klaipėda Strait rises 1 m, the likelihood of an extreme situation (corresponding to a 100 year water level) due to the fact of wind gusts into the Danė River, wind-driven floods of stronger storms, or hurricanes may increase.

5. Conclusions

Compound floods risks and hazards in coastal Klaipėda city are influenced by external Danė River floods, wind caused sea storm surge, and because of the climate change effect on the sea level rise in the SE part of the Baltic Sea;

An integrated approach is needed to assess flood risks and hazards for the evaluation of compound flooding, as when considering together the average rise of the SE Baltic Sea and Curonian Lagoon caused by climate change, its maximum forecast is possible according to the climate change process as well as the extreme Akmena–Danė River floods in the mouth of the river, located in the city of Klaipėda;

The rising long-term water level in the Klaipėda Strait increases the possibility of a rise in the maximum water level to 3 meters. Such an increase corresponds to a 100 year flood and could become more frequent;

The construction of residential houses in the inundated areas near the Danė River should be suspended in Klaipėda (according to 10 year and 100 year probabilities).

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Compound Extreme Events in the Coastal zone: a study case at the city of Halmstad

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1. Introduction

Floods cause damage and disruption to the activities in harbors and coastal communities. These events can result from different meteorological, hydrological and oceanographic phenomena such as coastal floods from storm surges, flash floods from rivers runoff or precipitation during rain showers. Storm surges corresponds to the sea water level being pushed by the wind stress and the barometric pressure effect under deep low-pressure weather systems. Heavy precipitation forms under different weather types as intense cyclonic activity or convective weather. River runoff can also be of different origins such as snow melting upstream or intense precipitation. River runoff and precipitation takes some time to drain into the sea and can therefore be slowed down or even momentarily blocked when storm surge happen (Wahl et al., 2015).

The combination of multiple factors happening at the same place and time potentially results in compound flooding event. It can lead to the most severe damages for the environment and society. Moreover, Reanalysis and climate models indicate an increasing trend of mean and extremes during the last forty to sixty years in Northern Europe but with high uncertainties (Rutgersson et al., 2021).

Couasnon et al. (2020) highlight the importance to consider the interactions between river discharge and storm surge extremes. The dependency between those variables is not random and seem to result from the relation between the weather systems at the synoptic scale with the local conditions such as the topography. In Northwestern Europe, it has been shown that fluvial flood hazard increases with high sea-level and stronger storms. It becomes critical in the populated and low elevated coastal area (Ganguli et al., 2019).

Eilander et al. (2020) presents the Baltic Sea and the Kattegat basin as a compound dominated area for flood hazards based on the dependency between skew surge level and river discharge. It also shows an underestimation of the flood depth if the storm surge factor is not taken in account. It would result in an underestimation of the population exposed to river floods in this area. Moftakhari at al. (2017) demonstrates that sea level rise increases compound flooding impact by 2030 and 2050 under the representative concentration pathways 4.5 and 8.5.

Compound flooding can also be caused by heavy precipitation and high sea level. The probability of this type of compound flooding will significantly increase in the future between 2070 to 2099 compared to today´s situation in the Baltic and North Seas. Between 1980 and 2014, a return period value of compound flood event was around 60 years but it is projected to be around 10 years during the period 2070-2099 in the Baltic sea. Increase in extreme sea level and heavy precipitation due to a warmer atmosphere carrying more moisture seems to cause this effect (Bevacqua et al., 2019).

Not taking in account those compound flooding effect could result in an underestimation of the flood hazards in the coastal zone. Thus, both analyzing and understanding these events is relevant to the coastal communities. In this study, we evaluate the potential impact of extreme compound events for the city of Halmstad (Sweden).

2. Data and methods

We selected the city of Halmstad located on the West coast of Sweden as a study case (figure 1).

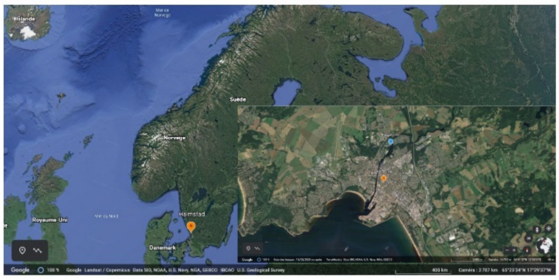

Figure 1. Map of Sweden including the city of Halmstad (orange marker) and the river Nissan (blue marker).

The goal is to find if any type of potential flooding events were happening within the same time window and, if so, if co-occurring events would lead to higher impact at the local scale. The correlation on those co-occurring events have been studied as it gives some input on the relationship between each set of two variables. The probability to get an extreme river discharge associated with a high sea water level and the opposite permits to assess the potential compoundness effect between those 2 variables. We analyzed time-series records of precipitation, sea level and Nissan River discharge data from SMHI at Halmstad (figure 2).

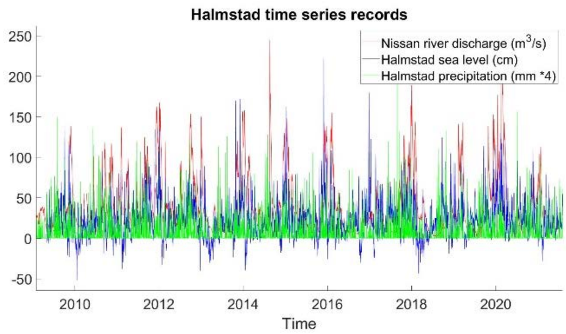

Figure 2. Time series record from SMHI on which we based our analysis, period of the records differs between each variable according to the availability of the dataset.

We analyzed correlation of each couple of events happening at the same time and then focused on sea level and river discharge and studied the co-dependency between those two variables in finding a probability distribution function fitting as good as possible for compound events. We compared it with a similar distribution but assuming the two variables were independent.

3. Preliminary-results and Discussion

We have performed compound flooding events analysis for Halmstad (Sweden).

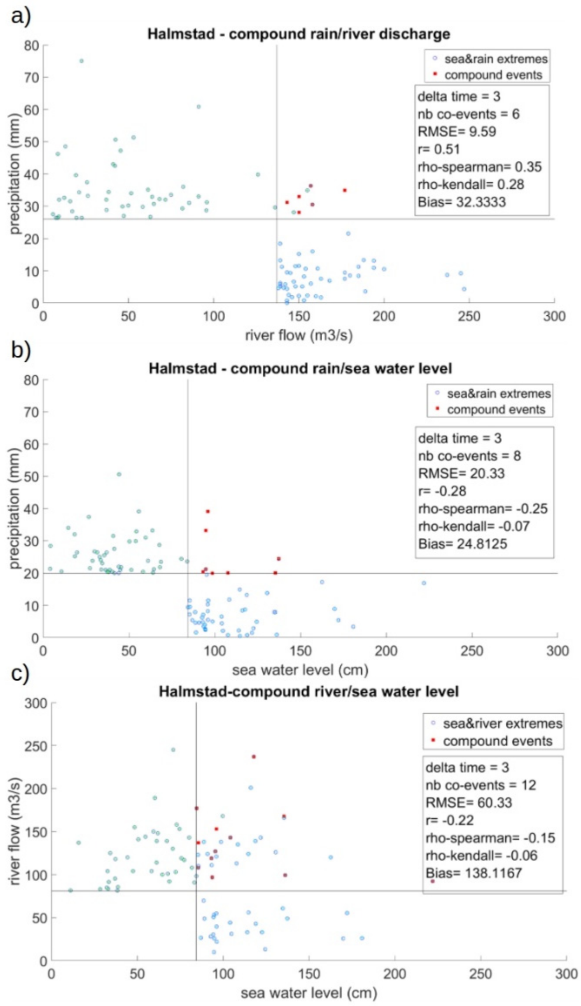

Figure 3. 50 highest recorded observations values from precipitation and river discharge (a), from precipitation and sea level (b), from river discharge and sea level (c) and respectively co-occurring events happening within a 3-days time window in red. The correlation coefficients between co-occurring events are also displayed.

The results are showing few events where we have co-occurring events happening within a 3 days' time-window: 8 compound events from rain and sea level; 6 from rain and river discharge; 12 from river discharge and sea level (figure 3). We then performed a statistical analysis on the compound events between river discharge and sea level. It seems there is a dependency between both variables as the dependent and independent curves are not superposed (figure 4). The return period value for flooding extremes can then be higher than expected if we would not take in account the compoundness of each event.

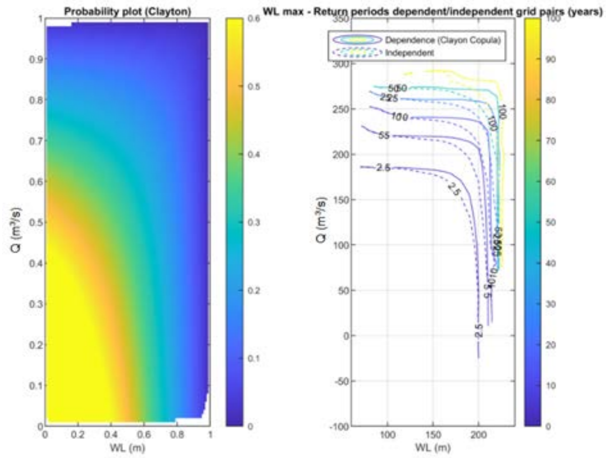

Figure 4. Clayton probability distribution of associated maximum sea level with corresponded river discharge (left panel) and return periods values based on the found Clayton probability distribution (dependents variables) and corresponding values from assuming the independency of each variable (right panel).

4. Conclusions

We present an analysis of compound meteorological, hydrological and oceanographic extreme events. The Halmstad case can be seen as a pilot study to further understand the role and risks of compound events. The results presented in this work are most probably relevant for other cities and regions.

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Evaluation of droughts‘ distribution and intensity using satellite data

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1. Introduction

Drought is a complex phenomenon affecting many different sectors of the economy (Blauhut et al., 2016). Therefore, the identification of droughts, the assessment of their extension as well as their impact has recently become an increasingly important topic. Droughts are becoming more frequent not only in arid or semiarid regions but also in higher latitudes and cause significant damage to both agriculture and industry (Coumou et al., 2020). In recent decades, many indices have been developed to evaluate droughts. However, the way they are calculated and the initial information used are different and cannot be applied equally successfully in different regions of the world (Zhang et al., 2017).

With the advance of satellite based remote sensing in the second half of the 20th century, a number of new drought indices have been developed to identify and assess droughts. Among these indices are the TVDI (*Temperature Vegetation Dryness Index*) and the CWSI (*Crop Water Stress Index*). Both of them are valued for their quite simple calculation routine and clear interpretation. However, these indices have hardly been used to analyse droughts in the Baltic Sea region.

The main objective of this paper is to assess the applicability of TVDI and CWSI for drought identification and impact assessment in different land use types in Lithuania during 2002-2019.

2. Data and methods

Droughts in Lithuania during the period from 2002 till 2019 were identified using TPI (Temperature – Precipitation Index) which is officially used for drought identification in Lithuania. Calculations were based on daily air temperature and precipitation data from 18 Lithuanian meteorological stations. According to TPI, there were four droughts in the territory of Lithuania during the analyzed period: in the spring of 2008 and 2019 and in the summer of 2002 and 2006. However, this index provides little information on the effect of drought. Therefore, the intensity and impact of these droughts on vegetation were assessed using the TVDI and CWSI. The eight-day composition land surface temperature (LST) and the sixteen-day composition normalized vegetation difference index (NDVI) data were used to calculate the TVDI. The eight-day composition evapotranspiration (ET) and potential evapotranspiration (PET) data were used for the estimation of CWSI. All data required to calculate these indices were obtained from MODIS instrument aboard the Aqua satellite (NASA).

TVDI is calculated according to the formula:

$$TVDI = (LST - LST_{min}) / LST_{max} - LST_{min}),$$

where LST is the land surface temperature at the grid cell, LST_{min} and LST_{max} are the minimum and maximum surface temperatures, respectively. NDVI is used for calculation of LST_{min} and LST_{max}

In this study TVDI is calculated using the methodology of I. Sandholt et al. proposed in 2002. The values of TVDI varies from 0 to 1. The higher the value, the drier the surface.

CWSI values are obtained applying the formula:

$$CWSI = 1 - (ET/PET).$$

As in case of TVDI, the values of CWSI vary from 0 to 1 (Jackson et al., 1981).

The values of both indices in the territory of Lithuania were also calculated for six different types of land use: arable land, pastures, deciduous forests, coniferous forests, mixed forests and wetlands. Land use types were identified using Copernicus CORINE landcover data. In order to assess the suitability of TVDI and CWSI for drought assessment in Lithuania their relationship was also separately evaluated in the entire study area and in different land use types.

3. Results

According to the TVDI values the first drought (2002) was the most intense in fertile central and south-western parts of Lithuania as well as in the coastal region. The drought reached its peak in the second half of August. At that time, according to TVDI values dry (TVDI> 0.6) conditions were identified in 46.5%, while very dry (TVDI> 0.8) conditions in 4.6% of the study area (Fig. 1a). The spatial distribution of CWSI values was very similar, with the driest conditions in the central and south-western parts of the country. The estimated CWSI values were slightly lower compared to TVDI. CWSI values higher than 0.6 were determined in 37.5% of Lithuania ‘s territory while values higher than 0.8 in 1.9% of the study area (Fig. 1b). During the drought of 2002 the strongest relationship between TVDI and CWSI values was found (r = 0.57) (Fig. 1c).

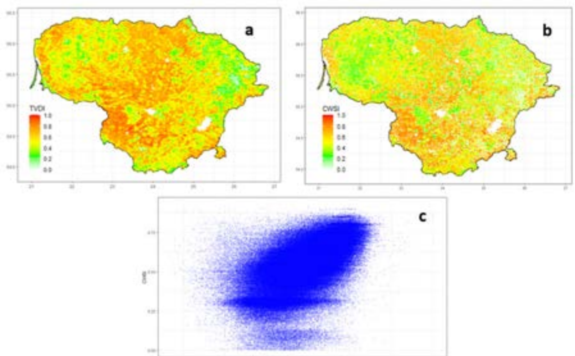

Figure 1. The distribution of TVDI (a) and CWSI (b) values in Lithuania and relationship between the indices values on August 21, 2002 (c).

Another summer drought of 2006 reached its maximum intensity in early July. Highest TVDI and CWSI values were estimated in the central and western parts of the country. At that time, according to the TVDI, dry conditions were identified in 45.4% of Lithuania's territory (Fig. 2a). Meanwhile, according to the CWSI, this drought mostly affected southern Lithuania, with only 18.3% of the country's territory being dry or very dry (Fig. 2b). The correlation between TVDI and CWSI values during this drought was weak (r = 0.22) although statistically significant ($p<0.05$).

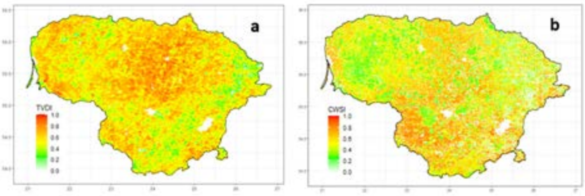

Figure 2. The distribution of TVDI (a) and CWSI (b) values in Lithuania on July 4, 2006.

The application of the TVDI and CWSI indices to evaluate spring droughts is quite complicated. The analysis of the droughts of 2008 and 2019 showed that the values of these indices calculated during the spring are not primarily due to the lack of moisture, but due to the sharp increase in the greenery of the vegetation and duration of sunshine in the spring.

The assessment of droughts according to TVDI and CWSI in different types of land use was also made in this study. The drought of 2002 was particularly strong in arable land. Dry or very dry conditions during this drought were identified in more than a half of arable land cells (70.1% and 59.1% according to TVDI and CWSI, respectively). Coniferous forests (according to TVDI values) and broad-leaved forests (according to CWSI values) remained the least affected by drought. During the drought of 2006, dry or very conditions were identified not only on arable land territories but also in wetlands. Again, coniferous forests and broad-leaved forests were least affected by the drought (similar to 2002). Forests have better capability to retain moisture during the droughts compared to arable land. Beside that most of these forests are in the eastern part of Lithuania. This part of the country was least affected by the drought in both 2002 and 2006.

During the spring droughts (2008 and 2019), it is difficult to determine the general trends in the distribution of droughts using satellite measured data, as there are significant differences in the onset of vegetation time both territorially and between land use types.

The strongest relationship between TVDI and CWSI values was found in arable land in August 2002 (r = 0.57) (Fig. 3), while correlation coefficient in pastures was slightly lower (r=0.50). In the other types of land use this value was much lower but still statistically significant.

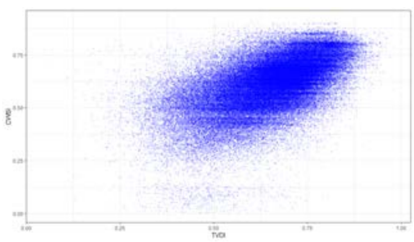

Figure 3. The relationship between TVDI and CWSI values in arable land on August 21, 2002.

4. Conclusions

TVDI and CWSI can be used for more accurate droughts intensity and distribution assessment. However, these indices are more suitable for estimating summer droughts (such as in 2002 and 2006) than for droughts that occurred at the beginning of vegetation season. Although in general the indices estimate the intensity of the drought in a similar way, the relationship between the values of TVDI and CWSI is not very strong due to the differences in the calculation methods.

Summer droughts were the most intensive in arable land and pastures. As these land uses are agricultural, a proper assessment of the spread of droughts and their impact is essential.

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Major controls on storm surge flooding: sea-level rise, climate or coastal landforms? Insights from the coastal sedimentary record of southern Baltic Sea

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1. Background and research site

Lowland coasts, accounting for ca. 30% of the global coastline, are significantly threatened by the climate change, related sea-level rise, enhanced storminess and storm surge flooding (Luijendijk et al., 2018). Extreme water level defined as storm surge flooding is associated with a rapid increase of the water level due to influence of wind, waves and atmospheric pressure on the sea-surface combined with tides. Although the storm surges are classified into 4 categories: swash, collision, overwash and inundation (Goslin and Clemmensen, 2017); the catastrophic events are associated with inundation regime. The role of key factors controlling the frequency and extent of extreme storm surges of inundation regime are not yet fully understood. In the present research we seek for the answer what are factors governing the susceptibility of the coast to storm surge flooding: is it coastal landforms development, storminess or rising sea-level?

The southern Baltic Sea coast presents an ideal target for the research on the frequency and intensity of catastrophic storm surge flooding as it is nontidal/microtidal sea, where major water level fluctuations are related to well-documented past sea-level changes and storm surge floodings. Moreover, it is located in the area highly sensitive to latitudinal shifts in North Atlantic Oscillation and changes of the westerly storm tracks. Furthermore, the southern Baltic coast has recently been identified as the region where the storm surge flooding overtopping coastal barriers is one of the highest in the world and is expected to increase in the near future together with the climate change.

2. Results

In the current research we document the longest to date, high-resolution sedimentary succession from the Polish coastal wetland located at Mechelinki, Puck Bay within the Gulf of Gdańsk at the southern Baltic sea coast. There, high-resolution records of extreme storm surge flooding of inundation regime within two periods: 3.6-2.9 ka BP and from ca. 0.7 ka BP until present, are preserved. The studied wetland succession, including sedimentary archive of storm surges, has been analyzed by sedimentological (grain size, loss-on-ignition, micromorphology), geochronological (14-C, 210-Pb, 137-Cs), geochemical (XRF), mineralogical (heavy minerals) and micropaleontological (diatoms) methods. The results indicate that both periods were characterized by high-frequency storm surge flooding in order of 1.3 – 4.2 events per century. They are correlated to widely recognized enhanced storminess periods in NW Europe and took place during both rising and fluctuating sea levels. Our results show that the storm surge driven coastal inundation frequency and extent largely depend on the development of coastal barriers (e.g., beach ridges) (Fig. 1). Sandy barriers may protect the coasts against flooding although being subjected to constant pressure from the rising sea-level and storm surges. Thus, in the context of the future coastal storm surge hazard, the protection of existing coastal barriers should be the prime concern.

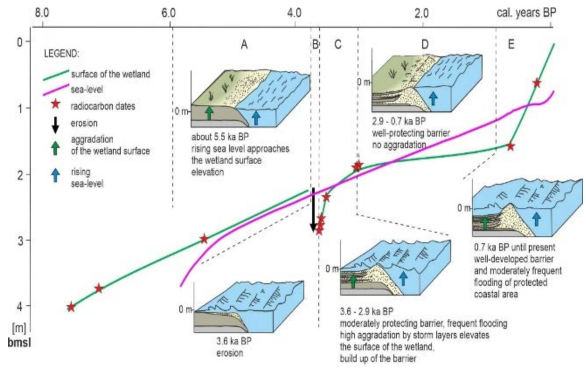

Figure 1: Sea level and coastal landform development reconstruction. Sections A to E depict discrete time spans represented schematically within the block-diagrams.

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Model-based soil moisture during droughts in Lithuania

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1. Introduction

Soil moisture is one of the Essential Climate Variables approved by the World Meteorological Organization, whose measurements are important for understanding and predicting climate change and assessing the risks associated with extreme events.

Soil moisture is an important factor not only for plants, but also plays a significant role in the hydrological cycle, controlling the transformation of precipitation into runoff, evaporation as well as infiltration (Jian et al., 2009; Owe et al., 2001; Wang, Qu, 2009). Soil moisture depends on the granulometric properties of the soil as well. Therefore, the effects of intensity and frequency of hazardous phenomena such as drought may be unequal on light and heavy soils (Trnka et al., 2014).

From 1999 soil moisture is not measured in Lithuania. It was measured by the gravimetric (weighing) method before the network of agrometeorological stations was closed. In 2009 the network was re-established, but the data obtained from the installed automatic sensors could not be used due to low quality. However, soil moisture data are needed to assess impact of such extreme events.

The aim of this study is to evaluate modelled soil moisture values during the droughts in Lithuania.

2. Data ant methods

Data from six meteorological stations (MS) were used in this study (Figure 1). Analysed period is the warm seasons (April–October) of 1951–2020. Raseiniai, Dotnuva and Kaunas MS are in Central Lithuania where heavier soils (loam, silty loam or sandy clay loam) are predominant, while Utena, Lazdijai and Varėna are in the eastern and southern parts, which are dominated by lighter soils (loamy sand or sand). These six stations also have the most homogeneous data set of *in situ* soil moisture measurements.

***In situ* data**. The average, minimum and maximum air temperature (°C), precipitation amount (mm) and soil moisture (mm in 20 cm layer) data provided by the Lithuanian Hydrometeorological Service were used in this study.

Soil moisture measurements were performed every 10 days during period from 1982 to 1998. Soil moisture was measured under the grass cover in quite constant observation fields. The quality of the initial soil moisture data was verified using multivariate regression method.

Temperature-precipitation index (TPI). The droughts during investigation period were identified using TPI**:**

$$TPI=(P/T)*100,$$

where P is the 30-day precipitation sum (mm) and T – 30-day air temperature sum (°C). This index is used to identify droughts in Lithuania. An extreme drought is identified when the TPI 30 days average values falls below 3.5 (Rimkus et al., 2020). The first day of an extreme drought describes the air temperature and precipitation conditions of the last 59 days. Extreme drought cannot be recorded earlier than at the beginning of May.

Figure 1. Meteorological stations which data were used in this study.

Soil moisture model. The SWAP (Soil, Water, Atmosphere and Plants) model is designed to simulate the transfer of water, soluble substances and heat to soil (https://www.swap.alterra.nl/). Initial model input data include daily minimum and maximum temperature, precipitation and reference evapotranspiration calculated by Hargreaves (1994). Soil properties (percentage of sand, clay and dust, organic matter, etc.) were obtained from ESDB (European Soil Database).

Model calibration period is 1982 to 1998. The most appropriate soil input coefficients for the model were obtained from Kroes et al. (2017) considering the existing soil type in each station.

After calibration the soil moisture (transformed from cm^3/cm^3 to mm) was modelled for each station for the period from 1951 till 2020.

3. Comparison of modeled and *in situ* soil moisture

The average soil moisture values (top 20 cm layer) in May–September varies from 31 mm in Varėna to 59 mm in Kaunas. In heavier soils the average is between 50 and 60 mm and in lighter soils between 30 and 40 mm.

Model calibration results shows quite good model performance and the RMSE values are small. The correlation coefficient at all stations reach 0.77–0.83, so the relationship between the model and the *in situ* soil moisture data can be considered strong enough. The model slightly smooths out changes in moisture over the season.

Modelled soil moisture does not fit to *in situ* data so well in some years. This may be related not only to the uncertainty of the soil input data or model algorithms but also to the different aspects of measuring *in situ* soil moisture.

4. Soil moisture during droughts

During the investigation period (1951–2020) the extreme droughts were recorded at least in one station for 22 years. The recurrence of droughts is not the same in different stations. The highest number of years with extreme drought was recorded in Dotnuva (13 years) and Kaunas (12), while the lowest in Utena (7).

The duration of an extreme drought differs a lot (up to 55 days in Varėna in 2019). Even a drought lasting one day cannot be considered as insignificant because extreme drought according to TPI reflects the temperature and precipitation conditions of the last 59 days.

Seasonal distribution of droughts has been evaluated after calculation of the mid-date of each drought during the entire investigation period. The highest recurrence of droughts was observed in spring (second half of May to first half of June) and early autumn (late August to late September).

Two indicators were used to assess soil moisture during droughts: the minimum value during the entire drought period (MIN) and the value at the first day of drought (FD). It was found that on average MIN value in heavier soils is 36 mm, while FD is 38 mm. Meanwhile the average MIN value on lighter soils is 12 mm and FD – 13 mm. The values of MD and FD are close to the 10th percentile of the total soil moisture distribution in both soil types (Figure 2).

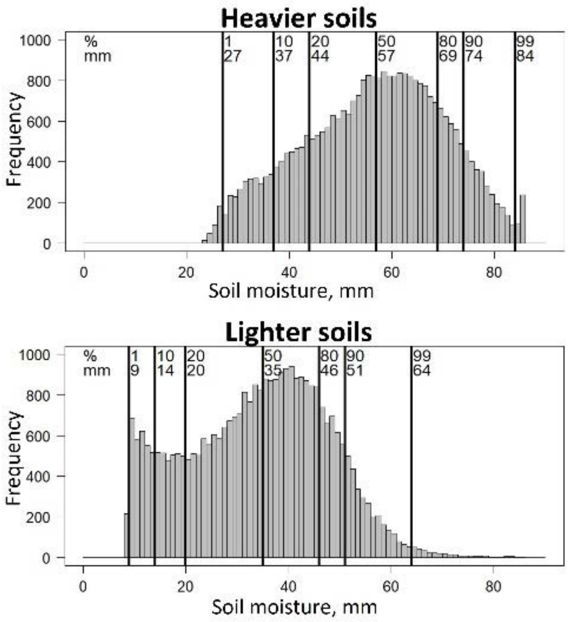

Figure 2. Distribution of soil moisture values (1st, 10th, 20th, 50th, 80th, 90th, 99th percentiles) in heavier and lighter soils in May–September 1951–2020.

At the beginning of the droughts the soil moisture is close to the minimum value. This means that by the day it was identified (according to the TPI), the soil moisture has been falling for several weeks and the moisture content is significantly reduced. During propagation of drought the soil moisture values change little. Due to significant precipitation the soil moisture rises dramatically several days before the drought officially ends.

Also, in the study droughts were distinguished according to the 10th percentile of the soil moisture distribution. In such case it was determined more droughts than according to the TPI. Moreover, the start and end of most droughts were determined earlier. This is due to the fact that soil moisture has a lower inertia to changes in precipitation conditions than to changes in temperature.

Also, significantly less droughts were found in the spring under the soil moisture threshold than under the TPI. This is a major weakness of the droughts assessment using soil moisture values. As soil moisture is normally higher in spring than in the rest of the season due to the amount of water accumulated after winter, the soil moisture threshold needs to be seasonally adjusted to identify droughts.

5. Conclusions

The study found that previously measured *in situ* soil moisture data can be used to calibrate the SWAP model for each station. The modelled moisture content values are close to *in situ* data, so the output data of SWAP model are suitable for drought assessment.

Average soil moisture values during droughts which were determined according to TPI are close to the 10th percentile of the soil moisture distribution. According to this moisture threshold, which is different for light and heavy soils, the number of droughts is higher than according to the TPI. Beside that the beginning and the end of the drought are recorded earlier. Soil moisture is usually higher in the spring, than in summer and autumn, so the threshold should be different.

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Directional variation of return periods of water level extremes in the Gulf of Riga, Baltic Sea

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1. Introduction

The core input for coastal management and design are water level extremes and wave parameters. Usually, their joint impact causes the most damage. It is customary to address the extremes of water levels but much less attention is paid on the synchronization of water level and high waves, the direction of approaching waves and the wind direction. This position is sometimes justified when a coastal section is oriented so that extreme water levels and high waves never occur together; for example, on beaches of the northern Estonia that are open to the east (Pindsoo and Soomere 2015).

In this work we focus on the Gulf of Riga, a relatively large semi-enclosed water body. It is connected to the Baltic Sea via comparatively narrow and shallow straits (Figure 1). The size of this gulf is about 130 × 140 km (Otsmann et al. 2001). It has a surface area of 17 913 km², a volume of 406 km³ and an average depth of about 23 m.

The main connection of the Gulf of Riga with the Baltic Sea proper is Irbe Strait that has a width of 27 km, a sill depth of about 21 m and a cross-sectional area of 0.37 km². Another outlet functions via Väinameri (Moonsund). These two sub-basins are connected by Suur Strait. The narrowest part of this strait is 4–5 km wide and the sill depth is about 5 m (Otsmann et al., 2001).

2. Data

We use observed hourly water level data of Estonian Weather Service and Latvian Environment, Geology and Meteorology Centre from 01.01.1966 till 31.12.2020 (Table 1). The observed water level time series are not fully homogeneous as the sampling procedure, frequency, and devices have undergone changes. The Haapsalu data set has extensive gaps. We covered those gaps with data from an adjacent station at Rohuküla (~10 km away), considering a bias (~21 cm) between the stations.

The uncertainties of recordings are estimated using the fact that the spectral density of water level time series in the Baltic Sea is flat (indicating random white noise properties) on timescales of <3 hr (Medvedev et al. 2013). Using a running average with the window length of 3 hr, we extracted the non-random signal and estimated measurement errors from the residuals. The Daugavgriva station showed uncertainty of individual measurements of ~0.7 cm, Liepaja ~1.2 cm, and Pärnu ~1.6 cm (Männikus et al. 2020).

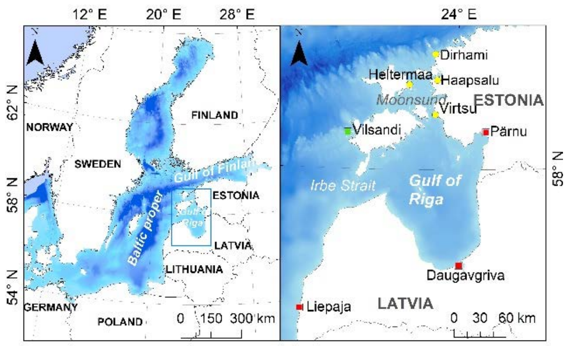

Figure 1. Water level measurement sites in the Gulf of Riga and on the open coast of Latvia. Red rectangles show locations with the highest quality and coverage of observations. Yellow circles depict stations where measurements were less frequent.

Wind data are also from Estonian Weather Service. The data recorded at Vilsandi represents generally well, wind properties in the northern Baltic proper, but may distort the properties of easterly winds (Soomere and Keevallik, 2001). However, east and, in particular, south-east winds are less frequent and much weaker in the study area than south-west or north-north-west winds.

3. Methods

The data from stations listed in Table 1 were employed to calculate return periods of very high water levels. The longer and more complete data sets in terms of hourly completeness (Liepaja, Daugavgriva and Pärnu) were analyzed further to evaluate the dependence of these estimates on wind directions. It was assumed that the wind direction is a suitable proxy for the wave direction in the Gulf of Riga since both the fetch and memory of wave fields in the Gulf of Riga and Moonsund are relatively short

Tabel 1. Co-ordinates of measurement stations, water level parameters (European Vertical Height System) and data completeness

Location	Measurements since	Co-ordinates	Mean measured level (cm)	Max measured level (cm)	Min measured level (cm)	Hourly data completeness for 01.01.1966–31.12.2020
Dirhami	12.05.1954	59°12′41′′N, 23°30′02′′E	20.9	174	–67	25.03%
Haapsalu	1941	58°57′29′′N, 23°31′39′′E	21.9	196	–68	22.36%
Heltermaa	01.01.1946	58°51′59′′N, 23°02′49′′E	15.6	125	–94	23.95%
Virtsu	1899	58°34′29′′N, 23°30′37′′E	20.9	174	–67	28.72%
Pärnu	(1893) 01.11.1949	58°23'12''N, 24°29'33''E	22.7	294	–106	99.69%
Liepaja	28.07.1931	56°29'7"N, 21°1'32''E	2.4	174	–86	99.70%
Daugavgriva	01.01.1875	57°3'22"N, 24°1'40"E	9.5	224	–107	99.98%

(Eelsalu et al. 2014) and therefore wave directions tend to follow wind direction. Hence, water levels were sorted according to 12 different wind directions (step: 30°).

To have serially uncorrelated data sets of high water levels for extreme value analysis, we select out the maxima of water levels over so-called stormy seasons (from July till June of the next year). This approach is more plausible than the use of annual maxima since the subsequent annual maxima could be correlated (Männikus et al., 2020). These maxima are directionally sorted and compared with the total water level maxima. To evaluate the parameters of the General Extreme Value (GEV) distribution and its realisations (Gumbel, Fréchet or Weibull distributions) we used *Hydrognomon*, a freeware for the processing and analysis of hydrological data (http://hydrognomon.org/).

Selecting a suitable theoretical extreme value distribution is a complicated task since the data has also outliers that may represent different water level populations (Männikus et al. 2020). A feasible solution is the concurrent use of several extreme value distributions. Ensembles of projections of extreme water levels and their return periods were constructed based on the above mentioned commonly used distributions of extreme values. The average of such an ensemble of projections eventually provides a reasonable estimate of the true value (Eelsalu et al. 2014). Following this conjecture, we include results obtained using the Gumbel distribution into the ensemble of projections.

4. Results and discussion

The highest estimated water levels for different return periods are at the bayheads of the Gulf of Riga (Pärnu and Daugavgriva) (Figure 2). The longer is the return period, the larger is the difference between estimates. Notably, recorded outliers from the storm in January 2005 in the northern part of the study area (Virtsu and Pärnu) are at the upper estimates of the ensemble that are projected to occur once in 100 years.

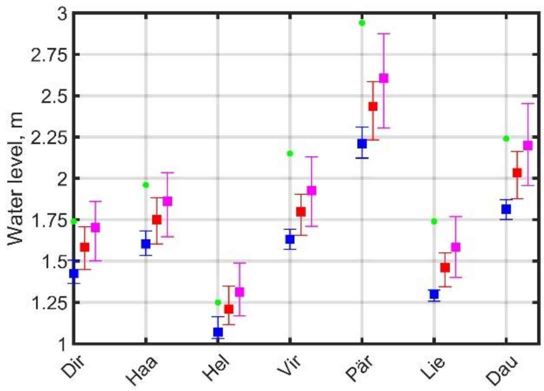

Figure 2. Ensemble averages of water levels with different return periods are marked with dots (20, 50 and 100 years; marked with blue, red and magenta, respectively) and the extent of estimated values (shown as error bars) for different locations. Dir – Dirhami, Haa – Haapsalu, Hel – Heltermaa, Vir – Virtsu, Pär – Pärnu, Lie – Liepaja, Dau - Daugavgriva. Green dots show water level maxima in 1966–2020.

The estimated extreme water levels at Liepaja are lower than the respective values in almost all other stations. Although the station of Liepaja is in the city and it might have some local effects, it acts as a proxy of water levels at the open Baltic Sea (Männikus et al. 2020).

The projected extreme water levels are the lowest at Heltermaa. This feature might be attributed to (i) a short data set that failed to record the highest values (e.g., the neighbouring Haapsalu have higher values) and (ii) this station is the only one in this study that is open to the east. However, Haapsalu is located in a small and shallow bay that opens to Moonsund. Therefore, local effects may play a relatively large role in this location.

Water levels at Daugavgriva and Pärnu reach the maximum values for a specific wind direction (285° for Pärnu, 315° for Daugavgriva, Figure 3). It is known that the highest water levels in the Gulf of Riga are jointly influenced by three major drivers: the water volume of the entire Baltic Sea that changes on multi-weekly scale, water occasionally pushed by a sequence of cyclones into the gulf for 1–2 days and local storm surges with a duration of a few hours. Interestingly, the last component turns out to be important for Daugavgriva which is open to the north, but for Pärnu (open to south-west) the worst case scenario probably has not occurred yet.

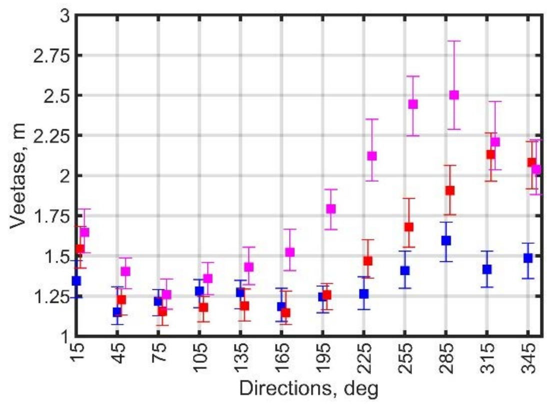

Figure 3. Averages of water levels of 50-year return periods for different locations (blue – Liepaja, red – Daugavgriva, magenta – Pärnu) and different wind directions. Error bars show the extent of estimated values.

5. Acknowledgements

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Extreme event in the Coastal zone - a multidisciplinary approach for better preparedness

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1. Introduction

Costs of natural disasters and weather-related accidents can be enormous, both in terms of death toll and economic costs. According to the European Environment Agency, increases in the frequency and/or magnitude of extreme events such as floods, droughts, windstorms or heatwaves will be among the most important consequences of climate change. The coastal zone is a focus area for human activities, high population densities, large urban areas, transport and critical infrastructure. It is a complex area in the climate system, a dynamic interaction between land, sea and atmosphere takes place, e.g., large gradients in time and space of geophysical parameters result in mesoscale circulation systems in the atmosphere and ocean that interact with the dynamics of the larger scales.

Flooding is a natural consequence of the coastal zone dynamics and a main driver of high impact events. The severity of flood events depends on several factors: the total water level, the topography of the terrain (the flood plains), and the exposure of socio-economic values. In addition, when storm surges and heavy precipitation (and in turn river run-off) occur concurrently impacts on coastal areas can be much greater than the effects in isolation. The likelihood of the joint occurrence of multiple phenomena is largely unknown, and therefore the associated risk is uncharted. To mitigate these potential high impact events, improved knowledge on the probability of these compound events under current and climate change conditions, understanding the processes driving them and including the information into risk analyses (and ultimately design processes) is essential. Model ensembles represent the most common tool for sampling the uncertainty in the case of numerical weather prediction and climate models and are increasingly explored in terms of producing probabilistic forecasts/climate projections. Thus, such forecasts generally have a lower forecast error than a deterministic forecast as the averaging of the ensemble members filters out less predictable parts of the forecast. Conversely, the use of ensembles and more generally systematic approaches to assess uncertainties in connection with, e.g. hydrological and economic models, needs further evaluations.

2. Data and methods

We selected one Swedish coastal urban area (the city of Halmstad, figure 1) as a case study and for method development. An integrated modelling linking a global and a regional climate model, a detailed physical impact model and a socio-economic impact model. Key aspects of each component are a more detailed and accurate (better representation) of features relevant for coastal extremes and decision making on climate change adaptation. By using a system of single-model ensembles the uncertainties of the resulting extreme estimates are estimated (Figure 2).

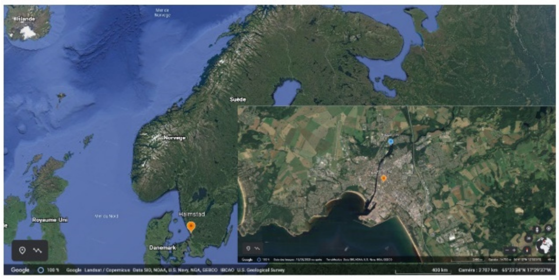

Figure 1. Map of Sweden including the city of Halmstad (orange marker) and the river Nissan (blue marker).

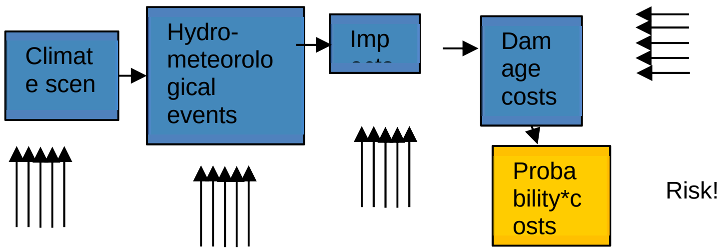

Figure 2. Illustration of range of models, with ensembles for risk estimate.

3. Preliminary-results and Discussion

A decision making tool for flood detection is used taking into account a range od sectors, storm surge information and damage functions (Figure 3).

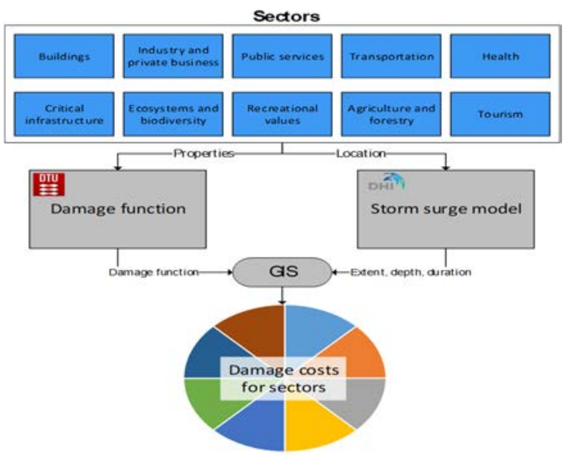

Figure 3. Illustration of decision-making tool developed within the COHERENT project.

Sea level observations are from 22 sites with more than 25 years of data after 1979, used together with ERA5 data for machine learning, in figure 4 are shown 5 years for testing for 6 cities on the west coast of Sweden.

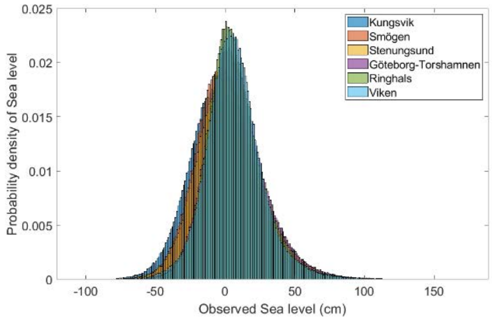

Figure 4. Illustration of decision-making tool developed within the COHERENT project.

4. Conclusions

We present sensitivity analysis for coastal urban flooding based on a multidisciplinary approach.

Natural Hazards and Extreme Events in the Baltic Sea region

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1. Introduction

Natural hazards and extreme events may have severe implications on society including threat to human life, economic losses and damage to ecosystems. A better understanding of their major causes and implications enables society to be better prepared, to save human lives and to mitigate economic losses. Many natural hazards are of hydro-meteorological origins (storms, storm surges, flooding, droughts) and impacts can sometimes be due to a mixture of several factors (e.g. a storm surge in combination with heavy precipitation and river discharge).

What is defined by "extreme" depends on the parameter and the application in relation to thresholds of the extreme to generate extreme consequences in society or ecosystems. Besides the actual magnitude of extremes (quantified in terms of probability/return frequency or absolute threshold), other relevant aspects from an impact perspective include the duration, the spatial area affected, timing, frequency, onset date and continuity (i.e., whether there are 'breaks' within a spell).

Natural hazards and extreme events have been identified as one of the grand scientific challenges for the Baltic Sea research community (Meier et al., 2014). Changes in extreme events can be caused by a combination of changes in local/regional conditions with changes of the larger scale; atmospheric circulation patterns are thus of crucial importance. Extreme events occur over a wide range of scales in time and space; short term events range from sub daily to a few days (basically meso-scale and synoptic scale events) while long-lasting events range from a few days to several months. There is no clear separation between short term and long term events and sometimes the presence of a long-term event may intensify the impact of a short-term one. We here summarise existing knowledge of extreme events in the Baltic Sea region. We focus on past and present state, as well as future climate scenarios and expected changes when possible. The events considered here include wind storms, high and low sea level, heat waves, drought, ice seasons, heavy precipitation, sea-effect snowfall, river floods, ice ridging, and extreme waves. We also address some ecological extremes and some implications of extreme events for society (phytoplankton blooms, forest fires, coastal flooding, offshore infrastructures, and shipping). We focus on the current base of knowledge, but also identifies knowledge gaps and research needs.

2. Summary

Regional atmospheric events, cyclones and blocking, are directly causing storm damages or triggering heat waves and forest fires, respectively. Cyclones are also generating storm surges and hazardous coastal flooding and ocean waves. Summertime blocking situations are frequently causing heat waves while in winter they are connected to cold spells. For long lasting situations, impacts of blocking are not restricted to land but also marine heat waves are generated and consequently massive algal blooms are formed, as in 2018. An important aspect is that the most hazardous events are often combinations of several factors (i.e. compound events). For example, every cyclone can generate a storm surge, but the level of coastal flooding depends on the total water volume in the Baltic Sea. Positive water volume, which is caused by persistent westerlies, can provide an additional 50 cm to the maximum sea level. Moreover, a single storm is always causing a seiche oscillation and a sequence of storms can produce combined sea level changes due to the storm surge and seiche oscillation. In cities located at the river mouth, a sea flood can be further amplified by the river flood. Trends in circulation patterns are difficult to detect, the long-term temporal behavior of NAO is essentially irregular. There is, however, weak evidence that stationary wave amplitude has increased over the North Atlantic region, possibly as a result of weakening and/or northeastward shift of the North Atlantic storm track. There is an upward trend in the number of shallow and moderate cyclones, whereas there is no clear change, possibly a small decrease in the number of deep cyclones during the past decades. Sea level extremes are expected to increase in a changing climate and are directly related to changes in mean sea level, wind climate, storm tracks and circulation patterns.

European summers have become warmer over the last three decades, partly explained by changes in blocking patterns. There is a clear link between warmer summers and an increased risk of drying (in particular in spring) and heat waves in most of the area. Floods decrease in a large

part of the Baltic Sea in spring but streamflow has increased in winter and autumn during the last decades while the mean flow shows insignificant changes. Stronger precipitation extremes associated with warmer climate can have strong impacts on society, in particular in urban regions, and are strongly associated with flooding and more intense cloud bursts. Results from new, high-resolution convective-permitting climate models indicate that increases in heavy rainfall associated with cloud bursts may increase even more than what has previously been found in coarser-scale regional climate models.

Sea-effect snowfall events can be a serious threat to the coastal infrastructure and should be considered also in the future, although likely with an overall lower risk on an annual basis. More research is still needed for deepening the understanding of the sea-effect snowfall and for developing a reliable way to assess the occurrence of such events also in the changing conditions. Another wintertime phenomena of potentially hazardous consequences is ice ridging, being one of the sea ice extremes with the greatest impact potential on coastal infrastructures and shipping.

Phytoplankton blooms are extreme, but natural biological events. However, eutrophication/de-eutrophication, pollution and changes in irradiation, temperature, salinity, carbon dioxide etc. may change their magnitude, timing and composition. Examples of extreme and mostly potentially toxic blooms are given, but reasons can hardly be identified. Their sudden and sporadic appearance complicates trend analyses and modelling. One trend that seems to be prominent is the prolongation of the phytoplankton growing season. Climate change is the most probable reason for this.

Table 1 summarizes the changes of some extreme events for the past decades and using scenarios for the upcoming decades, here a positive trend means increasing probability of occurrence and a negative trend decreasing probability of occurrence.

Table 1: Selected event and the estimated frequency of occurrence. Scale for changes (major decrease, minor decrease, no change, minor increase, major increase). Color, confidence scale (Low, medium, high).

Event	Past decades	Future scenario
Moderate, shallow extratrop. cycl.	Minor increase	no significant change
Deep extratrop. cyclones NA	Minor increase	Minor increase
Extreme ocean waves North of 59°N South of 59°N	no significant change no significant change	minor increase in frequency in wintertime no significant change
Extreme sea levels North of 59°N South of 59°N	minor decrease minor increase	minor increase major increase
Ice ridging	unknown	major decrease
Intense precip	minor increase	minor increase
Sea-effect snowfall	Unknown	Unknown
Heat waves	minor increase	major increase
Cold spells	major decrease	major decrease
Marine heat waves	minor increase	increase
Phytoplankton blooms	minor increase	minor increase
Extreme mild ice winters	major increase	major increase
Severe ice winters	major decrease	major decrease
Drying North of 59°N South of 59°N	decrease increase	decrease increase
River Flooding	increasing in winter/autumn, decreasing in spring	decrease in spring increase in winter

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On future development of Marine Heat Waves in Gulf of Bothnia

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1. Introduction

The marine heatwaves (MHW) can have a severe impact on the underwater species and habitats. These effects have been observed with kepls, reefs and other underwater ecosystems, as described recently for example by Holdbrook et al. (2022). Being able to estimate their possible future severity is vital for aquaculture and for other maritime activity. In this work we analyze the projected change on the marine heatwaves in the Gulf of Bothnia area up to 2100 based on the climate simulations produced in the SmartSea project.

2. Model setup and dataset used

Model setup covers the Gulf of Bothnia from 60° Northwards with a 1 NM grid. Scenarios used in these studies are forced with 3 different downscaled global circulation model forcings and with two Representative Concentration Pathways, RCP 4.5 and RCP 8.5. Historical comparison scenarios for each model span the years 1976 to 2005, and each future scenario continues from there to 2100.

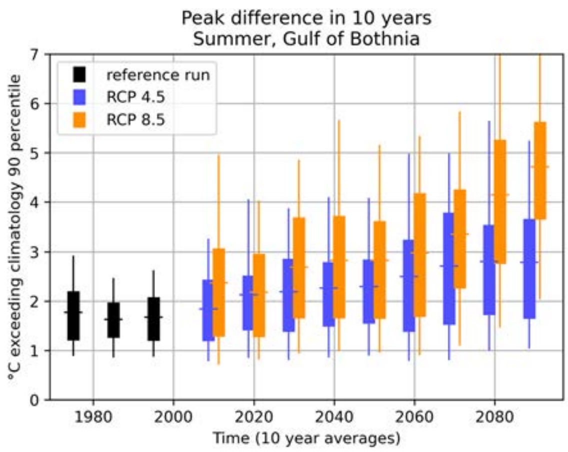

Figure 1. Projected development of an average peak difference of MHW peak temperature to the climatology 90 percentile during summer months (June, July, August).

Daily values of selected measuring points are used from the simulations for the analysis of heatwaves as well as the development of ice conditions to evaluate their impact on the MHW.

3. Marine Heatwaves

The marine heatwaves here are defined according to Alistair et. al (2018) based on the exceeding the 90 percentile of the climatology on the area.

First results indicate definite increase of the MHWs throughout the area, both in frequency, severity, and length. Local and seasonal differences in the development can be seen. For example, the development of local ice conditions impacts the MHW. The RCP 8.5 produces a clearly stronger increase on MHW intensity at the end of the inspected period than RCP 4.5 both in summer (Figure 1.) and in winter (Figure 2.).

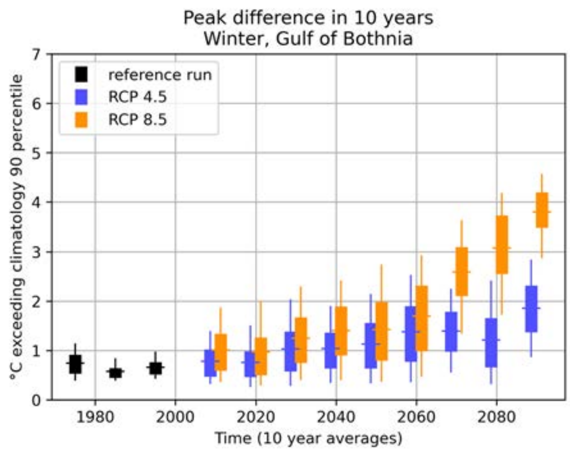

Figure 2. Projected development of an average peak difference of MHW peak temperature to the climatology 90 percentile during winter months(December, January,February).

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Topic 4

Sea level dynamics and coastal erosion

Analysis on cohesive cliff erosion using high-resolution AUV field measurements at Stohler Cliff, Schleswig-Holstein (Germany)

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1. Introduction

The cohesive cliffs along the German Baltic Sea have been subject of ongoing erosion since the beginning of the Littorina Transgression (~8400 BP) (Fleming et al. 1998, Niedermeyer et al. 2011). Commonly it is understood that this cliff retreat is controlled by hydrodynamic and environmental forces (Sunamura 1992, Schrottke 2001, Hupfer et al. 2003), the resisting nature of the cliff (Richter 1989, Sunamura 1992) and the coastal morphology (Davidson-Arnott and Ollerhead 1995, Schrottke 2001). The mobilized material serves as a sediment source for the adjacent marine areas.

Especially in a sediment-starved environment, such as the Baltic Sea coastline of Schleswig-Holstein (S-H), this material supply is of vital importance for the coastal transport, build-up and stabilization of nearshore bar and beach systems and natural coastal protection (LKN.SH 2015, Averes et al. 2021). For the planning and installation of effective coastal protection measures an understanding of the complex recession dynamics and a quantitative assessment of the supplied sediments are crucial.

2. Objectives

This study presents a time series of high-resolution morphology field data on cliff erosion. The analysis aims at a better understanding of the short-term dynamics along the cohesive cliffs of the Baltic Sea coastline of S-H and the formulation of a model, which allows quantitative predictions of the cliff retreat and the resulting material supply under prevailing and upcoming hydrodynamic scenarios.

To achieve this overall goal, we

1. measure the morphology along an active cliff section and analyze the morphological development over time on selected cliff profiles,
2. identify and determine the relevant geotechnical parameters,
3. relate hydrodynamic forcing and subaerial processes that drive the morphology changes.

3. Regional Setting

The field data is derived on a ~1km long coastal section along the Stohler Cliff, which is located on the Dänischer Wohld Peninsula between Kiel Fjord and Eckernförde Bight (Fig. 1). The cliff is exposed towards the NE and has a maximum height of 25 m (Ziegler and Heyen 2005). The geological sequence is composed of two glacial till complexes, deposited during successive Weichselian ice advances (Piotrowski 1992, Prange 1987). The grey and massive lower till complex makes up the majority of the cliff material and shows signs of glacio-tectonical overprinting (Prange 1987, 1991). Interstadial sediments, i.e. glaciofluvial or glaciolimnic sands and silts, are partly intercalated between or within the till layers (Kabel 1982, Prange 1987). The lower part of the outcrop is covered by an up to 15 m high colluvial wedge of debris, here referred to as talus. Due to the glacial formation of the cliff deposits, the material appears rather irregular distributed along the cliff section, which suggest variable physical parameters and, thus, locally variable responses to hydrodynamic and environmental impacts (Richter 1989, Sunamura 1992).

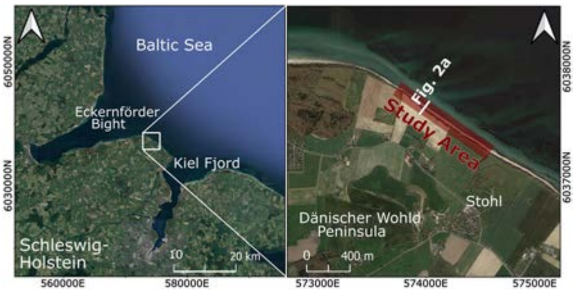

Figure 1. Overview map of the study area Stohler Cliff on the Dänischer Wohld Peninsula in Schleswig-Holstein, Germany.

4. Data & Methods

Ongoing observations comprise measurements of the local morphology of the cliff face and the beach by AUV photogrammetry (DJI Phantom 4 RTK). The field surveys have been performed since April 2020 in monthly intervals with some additional measurements after storm surges. The drone footage allows to build georeferenced, high-resolution Digital Elevation Models (DEM) for the observed coastal section.

Additionally, geological, geomechanical and sedimentological parameters of the cliff section were derived by *in-situ* measurements and laboratory analyses of material samples.

For the relation of the hydrodynamic impact and environmental drivers to the erosion intensity at the cliff face, we use wind, water level, and precipitation data as well as wave data measured by a Waverider buoy deployed offshore the study area in December 2020.

5. Preliminary Results

For the observed ~1-year period, June 2020 to May 2021, the morphological analysis indicates varying intensities of erosion at the cliff toe and, partly, the mid and upper cliff face (Fig. 2a). No erosion of the upper cliff edge has been observed yet.

In the drone imagery, the temporal changes of different slope angles are identified as relevant descriptors for the erosion dynamics. They indicate the alternating removal of talus material by marine impact and delayed gravitational movements, i.e. toppling or slumping, from the higher cliff face. As expected, the highest material displacement took place during winter season.

The correlation with water level and wave data (if available) shows the hydrodynamic impact that may have led to the morphological changes (Fig. 2b).

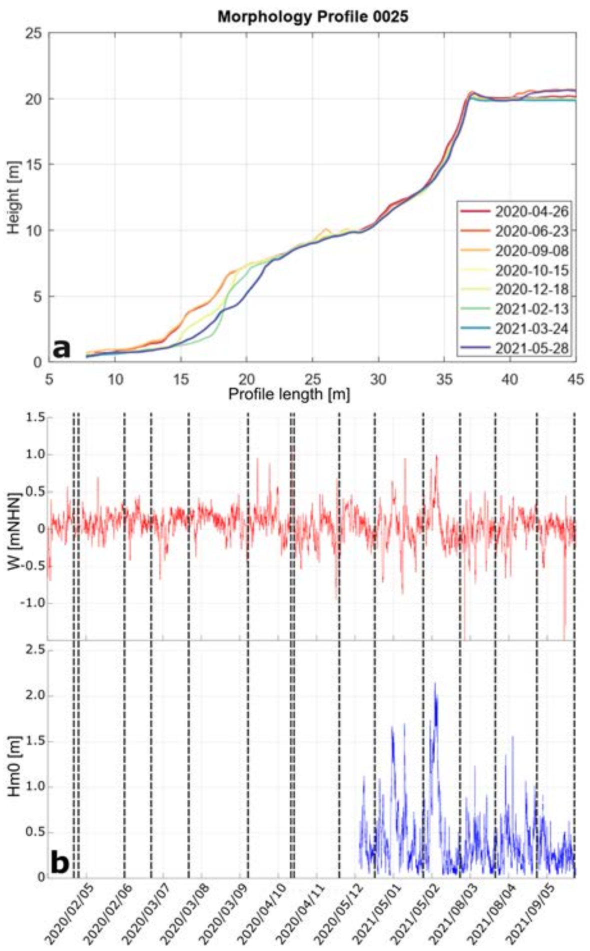

Figure 2. (a) Cross profiles through cliff and beach morphology at different survey dates (Profile location in Fig. 1). (b) Water level relative to NHN (data provided by WSA Ostsee) and wave height (Hm0) measured with a Waverider buoy (data provided by LKN-SH). Black dashed lines represent the dates of AUV surveying at the Stohler cliff.

6. Outlook

Further AUV surveys will be performed to extend the morphological time series. A second winter season with assumed high hydrodynamic impact will extend information on cliff development mechanics. In further field campaigns additional parameters describing the resisting force of the cliff and the talus will be obtained. In a next step, we are going to focus on the conception of a customized model capturing the complex cliff dynamics at the Stohler Cliff.

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Coastal sea level along the Polish coast: Comparison of altimetry and tide gauge observations in 1995-2020.

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1. Introduction

The aim of this study is to validate and compare two products of sea level measured by satellite altimeters with *in situ* tide gauge (TG) observations along the Polish coastline at 9 stations (Szczecin, Swinoujscie, Kolobrzeg, Darlowo, Ustka, Leba, Hel, Gdansk, Wladyslawowo) in 1995- 2020.

This study was motivated by the recent publication of a new altimetry-based sea level product (Passaro et al., 2021) dedicated to the Baltic Sea. Although, this product was validated in the majority of the Baltic Sea, it was not validated in the Southern Baltic especially along the Polish coastline. Furthermore, it is interesting to see how this new product compares with the previous satellite altimetry product (Copernicus Marine Service, http://marine.copernicus.eu).

2. Data

Three data sources of sea level measurements are used:

i) Daily and monthly gridded (0.25^0 square grid) sea level anomaly (SLA) measured by various satellite altimeters in 05.1995-05.2020 obtained from CMEMS (http://marine.copernicus.eu). There is no missing data, all data gaps were interpolated in time and space.

ii) Monthly gridded SLA measured by various satellite altimeters using data from BalticSEAL project (http://balticseal.eu). These data are described in Passaro et al. (2021).

iii) Tide gauges data using records from 9 stations along the Polish coastline in 05.1995-05.2020. Four stations (Gdansk, Ustka, Wladyslawowo, Kolobrzeg) had compete daily records in the analysed period. In Hel and Swinoujcie 1 year-long gaps occurred in 2016 and 2017, and 65 days of observations were missing at Leba station. In Darlowo, in situ sea level measurements started in 07.12.2006.

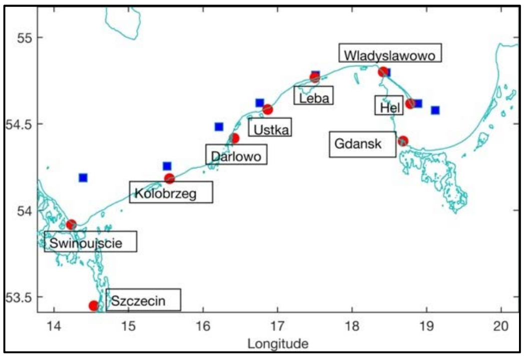

Figure 1. Location of tide gauges stations and BalticSEAL grid points with at least 250 months of good data in 1995-2019.

3. Methods

Tide gauge (TG) data was measured with different sampling frequencies (every 10 min, 1h, or 6h) at 9 stations. As altimeter data have daily (CMEMS product) and monthly (CMEMS and BalticSEAL products) temporal resolution, in situ data were daily- and monthly- averaged. Erroneous data were filtered out before the comparison by using the quality flag of the grid product. For the comparison i) data from the nearest grid point to the TG location or ii) averaged grid points within 20 km from TGs were used. Only grid points with at least 250 months of data were used. For each type of data, the following statistics were calculated for daily and monthly data at each location: standard deviation, range, linear trend, phase and amplitude of seasonal cycle. The pairs of sea level values from TGs and SLA were detrended and then root mean square error (RMSE) and the Pearson correlation coefficient (R) were calculated for each pair of data at each location along the Polish coastline.

Acknowledgements

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BRACER Coast: Establishing Joint Research on Coastal Protection and Erosion Control in the Baltic Sea Region

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1. Background

Coastal protection strategies and methods differ due to e.g. different natural and administrative conditions as well as the uses of the coastal zone along the Baltic Sea coast. Moreover the phenomena of coastal erosion is one of the major challenges for coastal and the consequences and can be seen at many places, especially along the southern shores of the Baltic Sea were sustainable coastal protection strategies and methods are needed (Harff et al., 2017).

Moreover, climate change will have effects on both the hydrodynamic conditions and wave induced-processes, like e.g. the long-shore sediment transport (Dreier and Fröhle, 2015; Fröhle et al. 2011).

For bringing together the knowledge about past and possible future developments of the coast and the linkages to the concepts of coastal protection, the joint cooperation project "BRACER Coast" was launched in the end of 2020. The partners of the project are: i) Tallinn University of Technology (TUT), Department of Cybernetics, Wave Engineering Laboratory; ii) University of Szczecin (US), Faculty of Geosciences, Institute of Marine and Environmental Sciences; iii) Institute of Hydro-Engineering of the Polish Academy of Sciences (IBW PAN), Department of Coastal Engineering and Dynamics; and iv) Hamburg University of Technology (TUHH), Institute of River and Coastal Engineering.

2. Research Program

Different workshops support the research aims of the cooperation project. The first workshop in 2021 focused on natural and administrative conditions for coastal protection. Other workshops are planned on i) measurements of hydrodynamics, sedimentology and morphological developments in nature - measurement methods, analysis procedures and statistical evaluation of results and ii) numerical methods - water levels, currents, sea state, sediment transport and morphology.

Moreover, joint field measurements (Figure 1) are conducted in cooperation between TUT and TUHH since 2020 to record the sea state (wave measuring buoy) as well as wave-induced loads on coastal protection structures (wave run-up step gage) at a breakwater of Kakumae Harbor near Tallinn using innovative measurement techniques.

3. Results

The first workshop resulted in an overview on the different i) concepts for coastal protection, ii) uses of the coast and iii) present and future challenges for coastal protection that depend on the different policies as well as the natural and administrative conditions of the countries. Along the erosive shores of the South-Western Baltic Sea (e.g. Poland and Germany), the concepts for erosion control focus e.g. on sediment management strategies and methods, with a large demand for the effective use and the coastal monitoring of sand nourishments etc. Moreover, climate change will enhance the problem of coastal erosion and hence making the effective use of coastal sediments more challenging due to the limited amount of sediment resources for coastal protection. In the presentation we will give more information on the natural and administrative conditions and future challenges for coastal protection in Poland, Germany and Estonia.

Figure 1. Field measurements in Kakumae Harbor, near Tallinn (source: TUT).

4. Acknowledgements

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Coastal erosion, protection structures and subsequent shoreline effects. Case study from the western polish coast (southern Baltic Sea)

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1. Introduction

The southern Baltic Sea coasts, includes dune coast composed of Holocene marine and Aeolian accumulation sediments, mainly sands and also some sections of cliff coast, composed of unconsolidated Pleistocene sediments, mainly glacial till and sands, are very prone to erosion.

Morphogenetic processes of this coasts are determined by a complex interplay of the geological setting, eustatic sea-level change, glacio-isostatic adjustment, wind, waves, sediment dynamics, storm surges and eaolian processes, acting on different time scales (Musielak et al. 2017, Harff et al. 2017, Dudzińska-Nowak 2017). Sediment budget is determined by the dominant long-shore sediment transport, along most of the coast areas at the southern Baltic coast (Zhang et al. 2013, Soomere and Viska 2013). The most important erosional coastline changes occur during extreme conditions (Furmanczyk and Dudzińska-Nowak 2009) connected with strong wind, high waves and relative sea-level fluctuations associated with storm surge reinforced by water filling.

In terms of presently occurring climate changes, which pose a threat to the coast - an increase of number and intensity of observed storm events and a general deficiency of sediments in the coastal zone - the determination of the accurate spatio-temporal distributions of change occurring on the coast, as well as influence of hydro-engineering protection methods, is of particular importance for broadly defined coastal safety (Dudzińska-Nowak 2017).

The aim of this study was to determine the impact of hydro-engineering structures and protection measures on changes of the coast.

2. Materials and methods

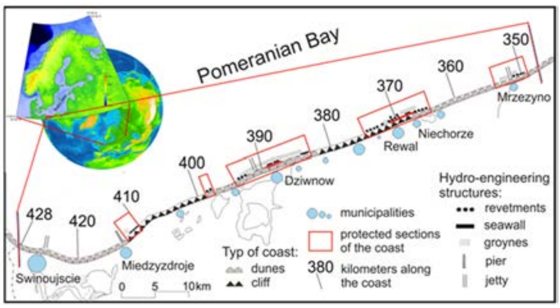

Figure 1. Area of investigation indicating coast type and protected by different type of hydro-technical constructions and protection measures sections (Dudzinska-Nowak 2019).

The analyzes of the dune base/cliff foot line position movement, based mainly on remote sensing datasets photogrammetrically processed, historical and modern aerial photographs and numerical terrain models, allowed to determine the magnitude and rate of long-term coastal changes of the following periods: 1938-1951, 1951-1973, 1973-1996, 1996-2011 and 2011-2021) of almost 80 km-long (Figure 1) coastal section of the Pomeranian Bay (southern Baltic Sea).

The analysis of the technical documentation provided information on types of hydro-engineering structures and protection measures applied in the past and present day enabled to determine their influence on the temporal and spatial variability of the shore in the aforementioned periods.

3. Results and conclusions

Conducted analyses show unequivocally that any intervention in the coastal zone, in the form of both hydrotechnical construction deployment and shore protection-aimed measures, induces changes in natural hydro-, morpho-, and lithodynamic processes, and ultimately results in enhancing changes in the dune base/cliff foot in the vicinity of the intervention site.

The results obtained allow to conclude that hydrotechnical interventions permanently and significantly affect the processes operating in the coastal zone and enhance the shore destruction rate. Particularly noteworthy are the negative effects of heavyweight hydrotechnical constructions and groyne systems, visible as the link side effect observed during the 83 years of records; on the other hand, the positive effects of other, less invasive, protection measures such as artificial beach nourishment, should be borne in mind. The nature, extent and magnitude of changes produced by both the direct and indirect effects of hydrotechnical constructions deserve further in-depth studies, as knowledge on these processes may aid in effectively counteracting their negative effects in the future.

The considerable temporal and spatial variability of the coastal changes taking place in neighbouring, geomorphologically and geologically uniform coastal segments which are similar also in terms of evolutionary trends, is very important in case of future scenarios developing. This result points to the high importance of appropriate selection of representative sites at which to forecast the magnitude of coastal changes. Not less important than the observation site location is also the selection of periods of time for the analyses, as confirmed by the high variability of morphodynamic effects in the periods analysed. An accidental location and a too short period of observations, not accounting for the hydrometeorological variability, may substantially bias the forecast and pose a potential threat for the infrastructure planned to be deployed at such sites.

Further interdisciplinary studies based of measured and modelled data of the long-term variations of waves regime, water level changes, storm surges structure and long-shore sediment transport analyses in relation to coastal zone changes as a consequences of such phenomena's are necessary and strongly recommended in order to reveal a mechanism of the coast development as well as a long-term influence of protection structures.

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Attribution of coastline changes in the southern and eastern Baltic Sea to climate change driven modifications of main coastal drivers

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1. Introduction

Climate change induced sea level rise (SLR) has been identified as the principal forcing function of large-scale shoreline retreat. However, attribution of observed changes on the coast to climate change driven impacts and associated SLR remains challenging. Climate change usually has an overarching, integrating impact on all of the other factors. It can be interpreted as a background effect, which has different implications for the other factors (Reckermann et al. 2022). Multiple factors and processes such as sediment availability, local features of the wave climate, extensive spatio-temporal variation in the properties of storm surges, and human interventions also affect the evolution of beaches. Consequently, the signal of climate change may often be masked by remarkably complicated behavior of beaches.

This study focuses on the attribution of observed changes on sedimentary coasts of the Baltic Sea to the impacts of climate change in the region. Even though many of coastal changes are just a natural course, some of these may have been accelerated due to climate change. We discuss the possible link between climate change and changes to the main coastal drivers, highlight the specific role of different drivers in different coastal segments, and make an attempt to identify which projected changes create the largest loads on the coast. This knowledge is essential for determining mitigation measures of existing and future marine-driven impacts and for the sustainable management of the coastal zone.

2. The southern and eastern Baltic Sea coast

The response of a particular coastal stretch to a given set of environmental forcing components depends largely on site-specific geomorphological features (Harff et al. 2017). The Baltic Sea coast is comprised of two main types, based on their structural properties such as bedrock and sedimentary segments. We focus on the sedimentary coast that is characteristic on the southern and eastern Baltic Sea shore.

Most pronounced short-term drivers in the Baltic Sea are intermittent wave fields, the aperiodic course of the water level, and the presence of sea ice. Much slower processes, such as isostatic land uplift or subsidence, SLR, and fluvial sediment supply are responsible for the long-term coastal evolution. The relative contribution of these processes to the evolution of shoreline is case-specific and varies strongly along the Baltic Sea coast depending on the shoreline orientation, exposedness etc. To reflect this variation, the south-eastern sedimentary shores of the Baltic Sea are divided into six segments (Figure. 1).

3. Observed changes

Coastal areas along the shores of the Baltic Sea have experienced a multitude of changes and evolution scenarios

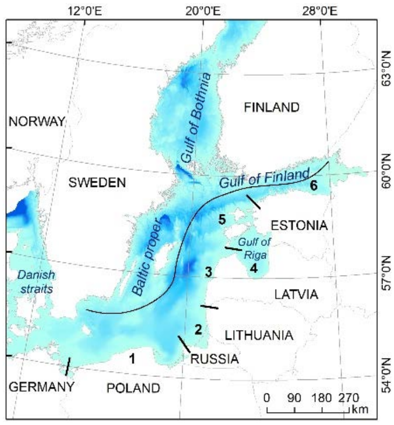

Figure 1. Segments 1–6 of the south-eastern Baltic Sea coast addressed in this study. Black curve indicates the division of bedrock/limestone coast and sedimentary coast.

over recent decades. A common signal on the southern and eastern sedimentary coasts is the intensification of coastal processes and accelerated coastal erosion in many locations.

Significant changes have occurred along the Polish coastline (Pruszak and Zawadzka, 2008). The retreat rate over 100 years is about 0.1 m/yr. Since the mid-80s this process has greatly accelerated, up to 0.9 m/year (segment 1). The shoreline changes in the Russian sectors of the south-eastern Baltic Sea have a complex pattern. Changes over the last ten years show an acceleration of coastal retreat of up to 1.4–1.6 m/yr (Ryabchuk et al. 2020). A large part of Curonian Spit and most of the Lithuanian coast are considered stable under the current two-peak structure of predominant wind (segment 2).

The changes along the Latvian Baltic proper coast (segment 3) show that the erosion sections become straighter and longer over time. Many coastal sections that experienced accumulation in previous decades are now eroding. The average long-term retreat varies between 0.5–1.5 m/year and reaches up to 2.5–3.5 m/year to the north of the major ports of Liepaja and Ventspils, and at Cape Kolka (segment 3). The coasts of the Gulf of Riga (segment 4) have been generally stable during the years 1935–1990. Some sections of the western and eastern coasts of this gulf have experienced erosion with an average and maximum recession rate of 1.5–2.6 m/year and 5 m/year, respectively (Eberhards and Lapinskis 2008).

Shoreline changes along the West Estonian Archipelago (segment 5) have gradually intensified since the last century. The northern side of Harilaid Peninsula has a rapid change in the shoreline, towards the east, of about 40 m in the period 1955–1981 (Suursaar et al., 2015). In the late 1980s rapid changes at the northern tip of Harilaid Peninsula continued. Intense shoreline changes occurred also on the southern side of Harilaid Peninsula, on Kelba Cape. Suursaar et al. (2015) note that coastal processes have gradually intensified since the 1950s at this site and are up to 5 times faster now.

Sedimentary coasts of the eastern Gulf of Finland show long-term average annual coastal escarpment retreat of about 0.56 m/yr in the period 1989–2009. This rate reached 1.45 m/yr in the period 2009–2017 (Sergeev et al. 2018).

4. Changes in the drivers of coastal evolution

Most of the tide gauges in the Baltic Sea demonstrate acceleration of relative SLR, which is about 3.4±0.7 mm/yr over the last decades (Madsen et al. 2019). The impact of SLR in the Baltic Sea varies considerably due to the different rates of land vertical movement. The rate of relative SLR is the highest on the southern shore, about 1 mm/yr, and decreases towards the north-east direction.

The presence of sea ice greatly affects coastal dynamics at higher latitudes. Climate change, and particularly global warming, has significantly affected sea ice properties and ice period length in the Baltic Sea. The ice period has significantly decreased in the West Estonian Archipelago and the Gulf of Finland, by more than a month (HELCOM, 2013). This decrease implicitly means that sedimentary beaches have become more vulnerable to storm events that combine high water level and strong waves.

The role of large-scale atmospheric circulation patterns is unclear. In particular, the North Atlantic Oscillation (NAO) that governs the intensity of the main coastal drivers, such as wind and wave fields, has high interannual variability but shows no significant trend during the last century.

The overall wind speed and significant wave height have not systematically increased in the Baltic Sea region during the last century. However, changes to the directional structure of moderate and strong winds in winter have changed considerably since the 1950s. Airflow direction that is controlled by large atmospheric processes has experienced a certain shift (Bierstedt et al. 2015). This rotation of wind direction results in an increase in the frequency of westerly winds in winter.

The shift in the directional structure of winds apparently has caused changes to the frequency and properties of storm surges in several locations. The number of storm surges in 1960–2010 has increased considerably at some locations along the eastern and southern part of the Baltic Sea (Wolski et al. 2014). The areas with the largest number of storm surges in the Baltic Sea have also had the biggest increase in extreme sea levels. In the eastern Gulf of Finland, extreme sea levels have increased at a rate of 8–10 mm/yr and, about 6–9 mm/yr in Gulf of Riga based on the RCO model output. (Pindsoo and Soomere 2020).

5. Discussion and concluding remarks

Over the last decades, several segments of the shores of the Baltic Sea have experienced a number of changes. A common signal at its southern and eastern sedimentary coasts is the intensification of coastal processes and accelerated coastal erosion in many locations.

The properties and intensity of factors that drive a large part of the coastal evolution are highly variable along the coast of the Baltic Sea. Remarkably, changes in most of these drivers demonstrate distinct spatial patterns.

The outcome of our analysis reflects, at least to some extent, the impact of climate change on the Baltic Sea region. It is likely that climate change induced global SRL (that is enhanced by subsiding land on the southern shores of the Baltic Sea) has contributed to the coastal retreat. To date the north-eastern shores of the Baltic Sea have been stabilised by uplifting land.

Some parameters of weather patterns that are affected by climate change play a fundamental role in the coastal evolution. Higher temperatures in the Baltic Sea region have a direct impact on the presence of sea ice. In the southern part of the Baltic Sea frozen sea is uncommon. The frequent presence of ice cover during the windy season stabilises the beaches of the north-eastern shores. The significant decrease in the ice season length at northern latitudes in the Baltic Sea have reduced the natural protection of beaches and possibly promoted higher rates of coastal erosion.

The shift in weather patterns has resulted in more frequent western or north-western winds. As a result, storm surges occur more frequently and reach more intensively the eastern bayheads of the Baltic Sea. The presence of possibly longer waves from other directions than in the past may greatly affect coastal processes in the eastern Baltic Sea and may eventually disturb the fragile balance of alongshore sediment transport.

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A new approach to sea level bias correction using neural networks

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1. Introduction

Sea levels rose faster during the last century than during any other century in the last 3000 years (Fox-Kemper et al., 2021). Moreover, the sea level rise is currently accelerating, and the current century will almost certainly see a greater sea level rise than the last. Mean sea level rise increases the baseline from which sea level extremes occur and thus increases the risk of flooding. This is particularly problematic for already flooding prone areas, but also areas that hitherto has been at low risk of flooding, like large parts of the Baltic Sea coast, will be affected in the future.

Infrastructure planning in coastal areas thus requires both projections of mean sea level rise and estimates of sea level extremes (Hieronymus & Kalén 2020, Hieronymus 2021). Our focus here is on estimates of sea level extremes. When such estimates are used in coastal spatial planning they are most often based on high frequency tide gauge data, and the Baltic Sea harbors several of the tide gauges with the longest time series in the world. A few even exceeding 100 years in length. Nevertheless, even time series exceeding a century in length are often much to short to contain information about the most severe conditions coastal spatial planners are interested in. An obvious remedy for the shortness of the observational record would be to use longer sea level time series from ocean models. The problem with such an approach is that ocean models often have large biases particularly in sea level extremes, which increases the risk of misjudging the frequency and/or strength of sea level extremes. A novel method aiming to correct such biases is the topic of this work.

2. Method

Machine learning methods are currently used in a large number of scientific disciplines (Al-Jarrah, 2015). One noteworthy example from the Baltic Sea is the study by Hieronymus et al. (2019), which showed that even with relatively simple means, machine learning algorithms can often outperform numerical ocean models in sea level prediction. Here we train neural networks in various different configurations to correct errors in already predicted sea levels from a regional climate model. Generally speaking bias corrections in climate models are almost always statistical in nature. Meaning, in this case, that corrections are applied to the distribution of the corrected variable independently of the model state. In essence, and taking sea level as an example; with standard bias corrections methods all modeled sea levels at a given locations that are equal to x m would be corrected by the same amount regardless of what the meteorological conditions were at the time. It is of course evident, however, that biases, in reality, are not independent of the prevailing meteorological conditions and thus that the standard methodologies have some severe limitations.

The approach spearheaded here is not statistical in the sense mentioned above. Here we instead use the fact that regional climate models can be run in hindcast mode, and regress observed sea levels on concurrent modeled atmospheric and ocean states using neural networks. This gives rise to a state dependent bias correction algorithm that can be applied not only to hindcasts, but also to for example future or past climate scenarios.

3. Results

An example of the bias correction method applied to data from the station Klagshamn is shown in Fig. 1. The nondimensional Taylor diagram in a) shows the correlation coefficient and nondimensionalized standard deviation and RMSD. Panel b) shows the difference between the modeled and observed yearly maximum sea level before and after the correction has been applied. It is abundantly clear that even though these results are preliminary, a considerable improvement has already been achieved. Moreover, these improvements are clearly visible both for normal conditions as in panel a), and for extremes as shown in panel b).

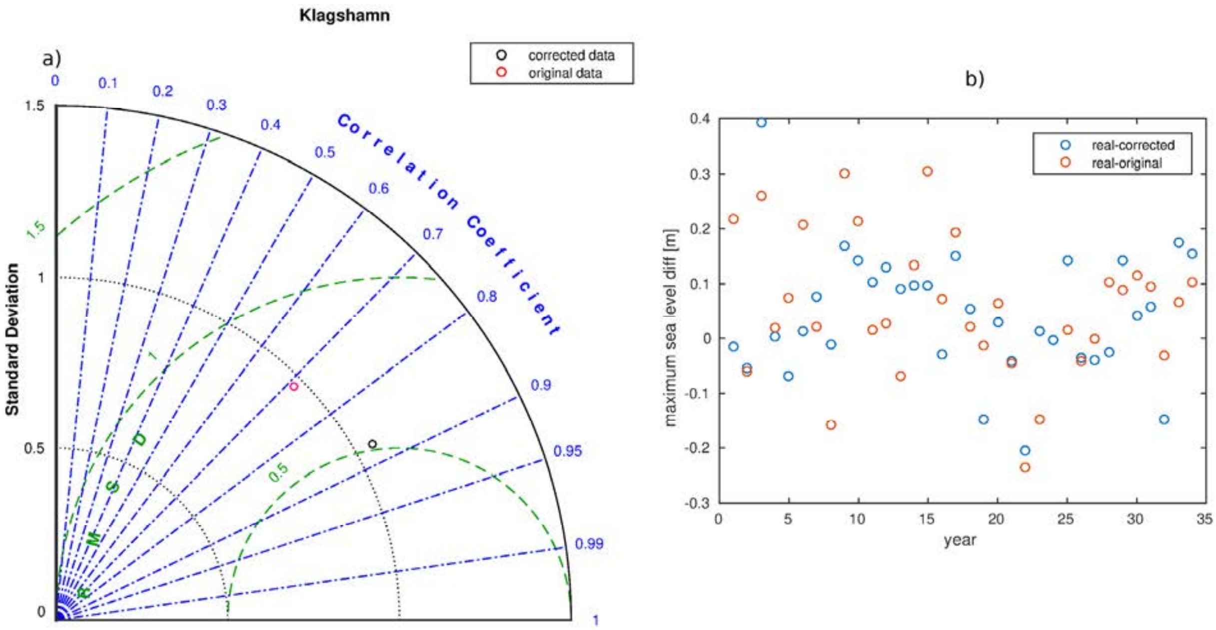

Figure 1. Nondimensional Taylor diagram comparing corrected and uncorrected data to hourly sea level observations (a), and bias relative to observed yearly maximum sea level for corrected and uncorrected data (b). In both panels the data is from the station Klagshamn and show data from a 35 year long hindcast.

4. Conclusions & Outlook

It is evident that state dependent bias corrections can greatly improve sea level projections from numerical ocean models. Apart from yielding useful data the methodology can also be used to study how the model bias depends on the modelled meteorological conditions, which can be helpful information for further model developments. The same methodologies can also be applied to other problematic variables and in a longer perspective they be used online in the model like data assimilation techniques, but without the requirements of needing data to assimilate. That is, assuming that biases are known time independent functions of meteorological conditions then these corrections functions can be applied not only to hindcasts but also to future and distant past climates.

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Natural and anthropogenic factors shaping the shoreline of Klaipėda, Lithuania

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1. Introduction

Erosion is a significant problem affecting sandy beaches that will worsen with climate change and anthropogenic pressure. Sandy shorelines are highly dynamic due to altering wave conditions, sea levels and winds, geological factors, and human activity.

Shoreline dynamics depend on different causes, mainly on the sediments in the sea-land system (Phillips et al., 2017, Viška, 2014, Soomere et al., 2011). Also, the different coastal stretches have particular favorable hydrometeorological conditions for the accumulation or erosion processes. The rapid urbanization of the coastal zone has a significant impact on shoreline development (Bulleri and Chapman, 2010, Schlacher et al., 2007). Sustainable coastal development requires knowledge of the coastal processes combined with incorruptible urbanization and properly chosen shoreline erosion mitigation methods (Hegde, 2010, Mohamed Rashidi et al., 2021). Often the insufficient understanding of the coastal processes causes costly incidents.

In this study, shoreline dynamics were analyzed in the context of climate change and increased anthropogenic pressure, focusing on identifying long- and short-term shoreline movement tendencies and identifying the direct impact zone of the Port of Klaipėda as well as to answer the question of whether and how shoreline evolution is affected by the artificial sand nourishment carried out in accordance with the Port of Klaipėda management plan.

2. Materials and methods

The study area extends 10 km from Klaipėda seaport jetties to the north and 10 km to the south. This particular area was chosen based on the following aspects: (i) the broad demand spectrum of recreational uses (Baltranaitė et al., 2021); (ii) the high risk of coastal erosion (Bagdanavičiūtė et al., 2018, Žilinskas, 2005); (iii) the possibility of direct and indirect anthropogenic impacts (Jarmalavičius et al., 2012).

A period of 35 years of shoreline position variation tendencies for 1984–2019 was analyzed. All shoreline position changes were determined using the available high accuracy (1:10 000) cartographic data for the years: 1984, 1990, 1995, 2005 obtained from Lithuania's National Land Service under the Ministry of Agriculture. And GPS survey data for 2015 2019. Shoreline position was established at the middle of the swash zone by dual-band GPS receiver "Leica 900". Shoreline position changes were analyzed with ArcGIS extension DSAS v. 5.0 (Digital Shoreline Analysis System) package, developed by the United States Geological Survey (USGS) (Thieler et al., 2009).

Three statistical parameters – net shoreline movement (NSM), end-point rate (EPR), and the shoreline change envelope (SCE) – were estimated and analyzed along with each transect every 25 m along the shoreline (796 transects in total) (Kondrat et al., 2021).

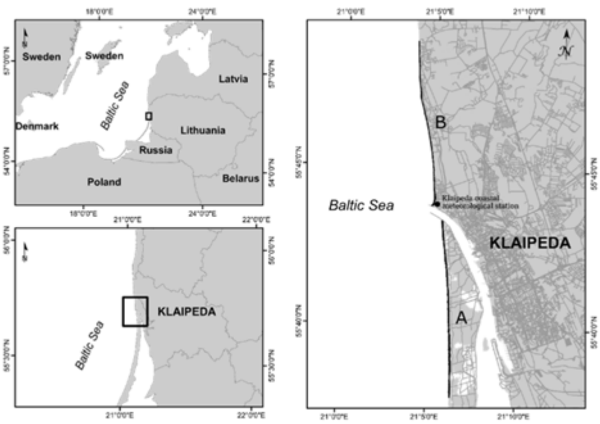

Figure 1. Study site, where A: the Curonian Spit coast, B: the mainland coast

K-Mean cluster analysis was applied to identify shoreline zones with similar evolution tendencies (Laccetti et al., 2020). It is a point-based clustering approach that starts with cluster centers located initially in arbitrary locations and goes through each stage of the cluster center to reduce cluster error (Laccetti et al., 2020, Kelpsaite-Rimkiene et al., 2021).

The meteorological data (annual mean wind speed and direction) of the 1960-2019 time period were analyzed to detect the wind direction's regime shift (Kondrat et al., 2021). The meteorological data were acquired from the Marine Environment Assessment Division of the Environmental Protection Agency (EPA) and derived from the Klaipėda coastal meteorological station (Figure 1) under the Lithuanian Ministry of Environment's environmental monitoring program. The program has been prepared in line with the legislation of the European Union.

3. Results and conclusions

In order to analyze the shoreline change dynamics of the South-Eastern Baltic Sea coast between 1984 and 2019, it is essential to assess the tool for evaluating the quality and quantity of coastal development management methods and techniques that affect the nature and economics of the coastal environment. The analysis of long and short-term shoreline changes should provide the required knowledge for reducing the extent of the anthropogenic intervention factor into the natural coastal system and long-lasting consequences.

Coastal development has changed in the long-term perspective, and the eroded coast length increased 3 times from 1.5 to 4.2 km in the last decades. After comparative cartometric shoreline analysis of the 1984-2019 period, the following findings were made at the 19.90 km long coast of the study site: 1) 12.03 km long coast affected by erosion processes 2) 3.70 km long stable coast 3) 4.13 km long accumulating coast (Figure2) .

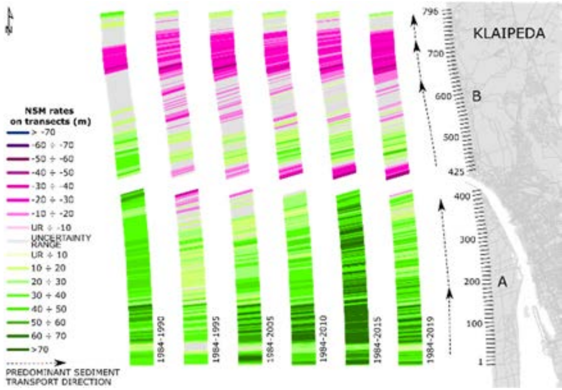

Figure 2. Net Shoreline Movement (NSM) rates 1984-2019 short-term vs. long-term tendencies. Annual shoreline change rates are shown on the transects graph.

The reconstruction of Klaipėda jetties disrupted the settled equilibrium stage and activated erosion processes. As a result, in the long-term (1984–2019) perspective, the northern part of the coast became erosive, length increased from 4,4 (1990) to 16,1 (2019) km. Also, in this study, short-term shoreline changes correspond with shifts in wind direction and reflect the impact of the Klaipėda seaport reconstruction and the effect of the dredging works in the Klaipėda strait.

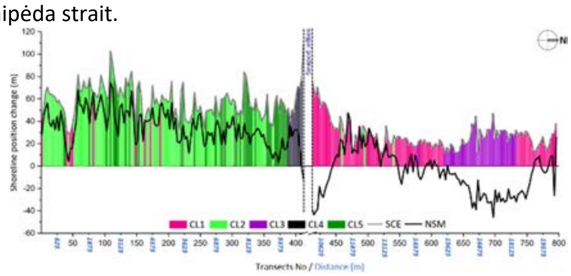

Figure 3. Graph showing the distribution of shoreline change envelope (SCE) (gray line) and net shoreline movement (NSM) (black line) along the study area for 1984-2019, and five clusters: cluster No. 1 (CL1), cluster No. 2 (CL2), cluster No. 3 (CL3), cluster No. 4 (CL4), cluster No. 5 (CL5).

Short-term shoreline changes reveal the importance of hydrometeorological conditions on shoreline development. Therefore, detailed and continuous monitoring and forecasting system of meteorological and hydrological conditions along the Lithuanian coast is necessary. Such a system will help assess the impact of short-term changes in wave climate, wind regime, and conditions on long-term shoreline development. In combination with the anthropogenic factors, wind direction is the key driver for the coastal development tendencies (accumulation/erosion).

Five groups of transects were identified based on the K-means cluster analysis (Figure 3) of NSM indicators. Cluster No. 1 stands out with the highest dynamics, where shoreline changes (NSM) in transects ranging from -45.53 to 65.62 meters. Part of the shoreline of cluster No. 1 (transects from 445 to 550) acquires other dynamic properties of the shore – accumulation. Although according to the hydrometeorological and litho-geomorphological characteristics and the impact of the port, erosion processes should prevail. This occurs due to coastal zone nourishment works. There is a need to continue research on this site, which is sensitive to anthropogenic and meteorological conditions. Also, carry out regular monitoring of the coast nourishment, as the development of coastal infrastructure, coastal use for recreational purposes, and planning of coastal protection measures depend on it.

Acknowledgment

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Occurrence of the pressure forced SWL changes in the Klaipeda Strait, SE Baltic Sea

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1. Introduction

The port of Klaipeda is in Klaipėda Strait that connects the Curonian Lagoon with the south-eastern Baltic Sea. Its quays are well sheltered from open sea waves, but the port area still hosts dangerous water level oscillations that are apparently generated in the system consisting of the Curonian Lagoon and a strait that connects the lagoon with the Baltic Sea proper.

The depicted features of Port of Klaipeda give rise to hazardous situations of a different kind. Some of them have led to major accidents. The most significant incident happened on 22 November 1981 when the UK tanker Globe Asimi sank in Klaipėda Strait. This event led to the dumping of 16493 tons of fuel oil into the sea. The outflowing current transported the oil slick to into the Baltic Sea proper and stormy winds carried it by more than 80 kilometers along the seafront so that oil reached even the Latvian shores (Kelpsaite-Rimkiene, Soomere, Bagdanaviciute, Nesteckite, & Zalys, 2018).

High-frequency sea-level oscillations, such as infragravity waves, seiches, tsunamis, and meteotsunamis, have periods of several minutes to several hours (Rabinovich, Vilibić, & Tinti, 2009). Among them, meteotsunamis are high-frequency and tsunami-like sea-level oscillations (Monserrat, Vilibić, & Rabinovich, 2006) that are dominant in the tsunami frequency band (2 min to 2 h). However, unlike tsunami waves of seismic origin, meteotsunamis are atmospherically generated and amplified by multi-resonant mechanisms (Pattiaratchi & Wijeratne, 2015). Meteotsunamis occur by a well-known, three-stage mechanism (Monserrat, et al., 2006). Initially, long waves are generated by air pressure disturbances in the open sea. Subsequently, these propagating long ocean waves are locked to the air pressure disturbance with a similar speed, causing resonance amplification, specifically the Proudman resonance. Finally, internal resonance occurs between the dominant period of the pre-amplified waves and the fundamental periods of shelves, bays, or harbors (Rabinovich, 2009). As a result, sea-level oscillations of several centimeters in the open sea can be increased to destructive amplitudes of several meters along the shoreline. Pressure forced meteotsunamis occur more frequently, both temporallyand spatially, than seismic tsunamis (Pattiaratchi & Wijeratne, 2015) and have been consistently reported (Kim, Woo, Eom, & You, 2021).

This study aims to identify the occurrence of large amplitude oscillations with typical periods from a few minutes to almost half an hour and determine the causality of the hazardous events in the Klaipėda Strait.

2. Methods and data

Data of Klaipėda strait water level fluctuations for the 2021 were obtained by the Lithuanian Hydrometeorological Service. SWL changes with the period of 5 min were taken in the Data frequency was one measurement in 5 minutes. Sea level pressure and wind data were also obtained from the Lithuanian Hydrometeorological Service (Figure 1).

The necessary data for the analysis of atmosphere pressure changes and wind regime was taken from the year 2021 on Klaipeda meteorological stations. The data have also been gathered from the Lithuanian Hydrometeorological Service.

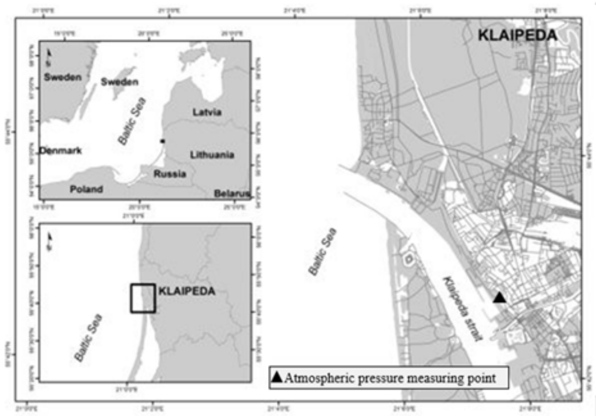

Figure 1. Sudy site

As there no universal definition or criteria for what can be named as a meteotsunami, as almost all sea level changes in the tsunami frequency range are of atmospheric origin. We in this study for detecting meteotsunamis used the period and height of the sea level oscillations and the occurrence of a rapid change in air pressure simultaneously with the sea level event.

Hazardous SWL oscillations in the port of Klaipeda is defined when in 5 min records difference between min and max SWL values are more significant than 0,2m. Atmosphere pressure changes over 1,5 hPa/10 min (Kim, et al., 2021) were used as a threshold to determine the occurrence of the meteotsunami.

3. Results and conclusions

In 2021, 41 cases with hazardous SWL oscillations were observed in the Klaipeda Strait (Table 1). 36 of it can be classified as pressure-forced meteotsunami, as were induced by the atmospheric pressure jump higher than 1,5hPa/10min.

The probability of such events is the same at all times of the year, 25%. When the stormy season considered as autumn and winter (Dailidienė, Davulienė, Kelpšaitė, & Razinkovas, 2012 ; Kelpšaite, Herrmann, & .Soomere, 2008), that does not apply to pressure forced SWL fluctuation.

If the number of the events over the year is distributed evenly, except Jun, from July 2021, recorded pressure forced SWL changes were more intense and lasted more than one day (Figure 2).

Table 1. Occurrence of the hazardous SWL changes in the Klaipeda straight in 2021

Date		Amplitude, m	Atmosphere pressure jump, hPa/10min
01	02	0,2	+3,8
	17	0,2	+8
02	08	0,23	-10,3
	17-19	0,23	-9,6
	21	0,2	-3,7
03	06-07	26	-16,3
	11-12	0,3	-12,8
	23	0,24	+4
	25-28	0,25	-1,8
04	11	0,2	-4,7
	15-16	0,24	-3,4
	22	0,26	+1,1
05	05	0,2	-14,1
	07	0,2	+8,3
	13	0,2	-3,8
	21	0,23	-24,
06	13	0,2	+4,1
07	11	0,2	+3,2
	19-20	0,3	-1,5
	22-24	0,3	-3,3
	30-31	0,3	-3,7
08	01-02	0,26	-1,8
	04	0,25	+1
	14	0,32	-6,2
	18-19	0,32	-3,8
	24	0,22	+4,3
09	03-04	0,27	-5,9
	06	0,3	+0,5
	24-25	0,26	-10,5
	30	0,2	-2,8
10	05	0,24	+3
	22	0,22	+11,8
	25-26	0,28	-5,9
11	06	0,2	+3,9
	10	0,25	-6,5
	17-20	0,28	-11,3
12	03-05	0,24	+18,2
	08	0,2	-1
	14-15	0,23	-2,6
	19	0,22	-11,6
	28	0,34	-2,3

Amplitudes of waves with periods from several minutes to half an hour correspond with periods of tsunami-like waves (Monserrat, et al., 2006; Rabinovich, et al., 2009) in Klaipeda straight can exceed 0,5 m (Kelpsaite-Rimkiene, et al., 2018). Such phenomena can break mooring systems and damage sizable vessels and need to be further explored.

This is the first study dedicated to guiding on when, where and how often pressure forced occurred in the SE Baltic Sea. The study showed that the occurrence of the hazardouse SWL changes are highly probable not only during the traditional stormy season.

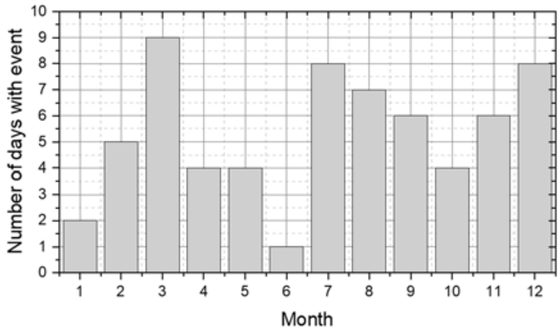

Figure 2. Number of days with hazardous SWL changes in 2021

Acknowledgment

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Development of sea level quantiles in an ensemble of future projections for the Baltic Sea

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1. Overview

An ensemble of CMIP5 climate downscalings (Dieterich et al. 2019) was analysed for the projected changes in sea level around the Baltic Sea. A focus was on the question whether high sea levels will change differently from the mean.

2. Background

For some practical applications, the knowledge of the mean sea level changes alone is insufficient. Global warming can systematically change different drivers of sea level variability, such as regional wind patterns or ice cover, and thereby influence the distribution of sea levels that we expect in the future, including their extreme values. Making projections for these dynamic regional changes is challenging and cannot be done with global models, which do not resolve the relevant regional scales.

3. Methods

Therefore, a regional coupled atmosphere-ice-ocean model was applied to generate future projections of sea level changes around the Baltic Sea. These were analyzed for trends using the quantile regression method (Koenker and Hallock 2001).

4. Results

The results depend on the emission pathway: In an optimistic RCP2.6 scenario, no difference is found on average between the change of the 99th percentile of sea level and the median. In an RCP8.5 scenario, which represents a stronger warming, this difference rises by 0.2 mm/year, meaning that the 99th percentile of absolute sea level will rise by 20 cm more than the median during the 21st century. This additional rise substantially differs between individual ensemble members, though, stressing the importance of an ensemble approach. Reasons for the variation between individual models will be discussed, as well as regional variations between stations.

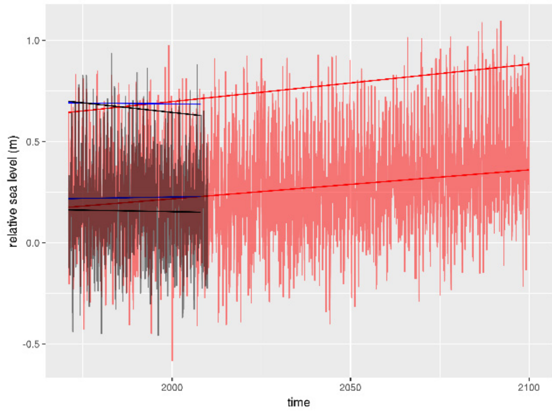

Figure 1. Sea level at station Visby. Observations from GESLA3 dataset (Haigh et al. 2021, black) vs model results from a downscaling of an RCP8.5 scenario of the NorESM-M model (Dieterich et al. 2019). Straight lines indicate the slope of the 50th and 99th percentile. Blue lines show this slope in the model data for the reference period only. This model suggests a future rise of relative sea level, with high sea levels rising faster than median sea levels.

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Baltic Sea level extremes from synthetic low-pressure systems

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1. Introduction

We present numerical simulations of extreme sea levels in the Baltic Sea using synthetic low-pressure systems. These simulations can be considered as estimates of the highest sea level that can be reached at a certain location when a low-pressure system with strong intensity and optimal track passes the Baltic Sea region.

In the Baltic Sea, the short-term sea level variations can be several meters, even if the tides in the Baltic Sea are negligible. The short-term sea level fluctuations are caused by passing windstorms, that induce sea level variation through wind-induced currents, inverse barometric effect and seiches. Due to the shape of the Baltic Sea with several bays, the highest sea levels are found in the ends of baysFig like the Gulf of Finland and the Bothnian Bay. The sea level extremes caused by the large-scale windstorms depend strongly on the storm tracks. We have studied extreme sea levels that are not found in the observation time series, having mainly less than 150 years of data. We have reconstructed storms that are physically realistic but have not occurred during the era of sea level observations in the Baltic Sea.

2. Methods and results

To model the atmospheric conditions related to such low-pressure systems, we have generated synthetic cyclones. The cyclone is modelled by describing the pressure field by a spatially varying time-dependent function that reproduces the typical cyclone characteristics. This method has been used to study sea levels in the Gulf of Finland (Averkiev and Klevannyy, 2010, Apukhtin et al., 2017), and in the Bothnian Bay (Gordeeva and Klevannyy, 2020).

In our method for generating synthetic cyclones, the mean sea level pressure and surface winds of the cyclone are calculated from the pressure field of the cyclone propagating with a constant velocity. The pressure field of the cyclone has the form of a Gaussian function. Wind field is calculated from the pressure field from geostrophic balance and making some corrections to obtain surface winds. An example of the pressure and wind field of a synthetic cyclone is shown in Fig. 1.

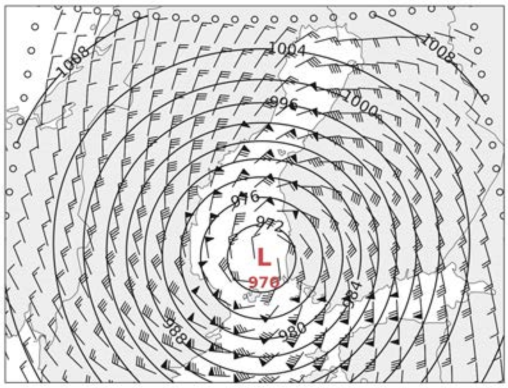

Figure 1. Example of synthetic cyclone and induced winds. Contours represent sea level pressure and wind barbs represent 10 m winds .

To study the variability of sea levels, induced by varying tracks of the passing windstorms, we construct an ensemble of synthetic low-pressure systems. In this ensemble, the parameters of the low-pressure systems (e.g., point of origin, velocity of the center of the system and depth of the pressure anomaly) are varied.

The ensemble of low-pressure systems is used as an input to a numerical sea level model based on shallow-water hydrodynamic equations. The sea level model is fast to calculate, enabling a study of a large set of varying storm tracks. As a result, we have an ensemble of simulated sea levels. From the simulation results we can determine the low-pressure system that induces the highest sea level on a given location at the coast.

Our simulation method does not include the filling of the Baltic Sea due to the water flow from the North Sea through the Danish Straits. Instead, we may add the maximum sea level rise due the the filling to the estimates by adding 1 meter to the local sea level maximum (Särkkä et al., 2017). This describes the extreme situation when preceding weather conditions have affected mean sea level and raised it high, and then the propagating low-pressure system causes fluctuations on top of the already high mean sea level.

Until recently, our studies have concentrated on the Finnish coast. There the highest simulated sea levels were found in the northern end of the Bothnian Bay and the eastern end of the Gulf of Finland, where 2.5 meters extremes are possible, and sea level peaks exceed 1 meter during 1.5 days in both areas. We will present results also for other areas on the Baltic Sea coast.

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Effects of climate change on coastal hydrodynamics focusing the South-Western Baltic Sea – a modelling approach

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1. Introduction

The Ministry of Energy, Agriculture, the Environment, Nature and Digitalization (MELUR) of the federal state of Schleswig-Holstein is working on a new strategy for coastal protection along the Schleswig-Holstein Baltic Sea coast for the year 2100. As a basis for the development of the strategy, detailed information on the actual status and possible future changes of the coastal hydrodynamics and sediment dynamics including morphological developments along the coast are needed. Therefore, a joint cooperation project between the Institute of River and Coastal Engineering of Hamburg University of Technology (TUHH) and the Institute of Geosciences (IfG) of Kiel University (CAU) in close cooperation with the local authority responsible for coastal protection (LKN) and the state agency for agriculture, the environment and rural areas (LLUR) was launched in 2019. One of the main goals of TUHH is to investigate the effects of climate change on the coastal hydrodynamics as a basis for the assessment of both sediment- and morpho-dynamic (IfG).

2. Methods

For the assessment of the long-term past conditions and future changes of the coastal hydrodynamics, a hydrodynamic numerical model for the calculation of water levels, currents and waves has been set-up for the whole Baltic Sea and for a regionally refined area (SHC-model) on the basis of an unstructured grid (Figure 1). The model for the whole Baltic Sea has about 310,000 elements and there are around 480,000 elements in the regional SHC-model.

In this study, Telemac2d (Ata 2017) is used for solving the hydrodynamic equations. The Telemac modules "Tomawac" and "Sisyphe" are used for the wave and sediment transport modelling respectively. The hydrodynamic boundary conditions to drive the model are extracted from a model hindcast for the North Sea (Hagen et al. 2021) that was extended until the end of the year 2017. The initial salinity conditions are predefined according to the data from the "Baltic Atlas of Long-Term Inventory and Climatology" (BALTIC, Feistel et al. 2010). For the bathymetry, a combination of measured laser scan data from the LKN, measurement data of the BSH (http://data.bshc.pro/) and from "EMODnet" (http://www.emodnet-bathymetry.eu) is used. The main rivers around the Baltic Sea are also considered in this study.

The model has been calibrated and validated against measurements from numerous tide gauges and wave observations. Hydrodynamics as well as waves are approximated very precisely in terms of both magnitude and dynamics. The root mean square error (RMSE) of the calculated water levels along the Baltic Sea coast of Schleswig-Holstein ranges between 10cm to 14cm and for the reference year 2016. Moreover, a good agreement for the significant wave heights (RMSE $H_{m0} \leq 16$cm), mean and peak wave period (RMSE $T_{m02} \leq 1.2$s; $T_p \leq 1.6$s) as well mean

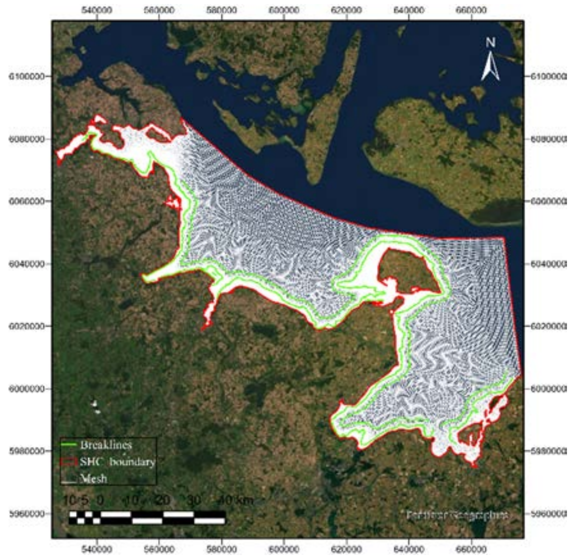

Figure 1. Unstructured computational mesh for the regional SH-model.

wave direction (RMSE $\Theta_m \leq 17°$ for significant wave heights $H_{m0} \leq 30$cm) is found.

A major advancement of this model is the ability of online coupled simulations of hydrodynamics, waves and sediment transport resolving particularly coastal processes in a high temporal and spatial resolution. The model is forced by a high-resolution regional reanalysis, "COSMO-REA6" (Bollmeyer et al. 2015), for the past and will be forced by selected future climate scenarios for water levels and meteorology.

A delta approach, based on a detailed analysis of ensemble data from regional climate models, will be applied to modify the long-term past conditions.

Future changes of the wind conditions in the area of the South-Western Baltic Sea are analyzed on the basis of future climate projections from the "EURO-CORDEX" ensemble (Jacob et al. 2014; Jacob et al. 2020) as well a high-resolution ensemble on the basis of the regional climate model "REMO" (Jacob 2001) and for three forcing scenarios (RCP8.5, RCP4.5, RCP2.6) from the 5th assessment report of IPCC (2013). Possible scenarios for the future changes of water levels will be applied from the 6th assessment report of IPCC (2021).

3. Results

Changes of the future wind conditions have been identified e.g. on the basis of the high-resolution ensemble of REMO for different locations along the German Baltic Sea coast (Dreier et al. 2021). The future changes of wind speed 10m above the surface and mean wind direction have been analyzed with the help of moving averages over

30 years for the time period 2006-2100 and compared to values of the reference period 1971-2100. The largest changes of the 30-year annual averages of the wind speed at the end of the 21st century (2071-2100) where found for the forcing scenario RCP8.5 and at westerly wind exposed locations (+3.8%). The changes have been analyzed taking model agreement and statistical significance into account. The changes show a strong seasonal variability with a larger bandwidth and larger increases occurring in summer (+5.5%) and autumn (+6.7%). An opposite climate change signal exists at easterly wind exposed locations, where mainly decreasing values are predominant.

For a scenario based analysis of the effects of climate change on the coastal hydrodynamics, different climate sensitivity simulations have been carried out. Here, exemplarily results for the effects of changes of the long-term wind conditions on the resulting long-term wave conditions are discussed for two locations at the German Baltic Sea coast (Figure 2).

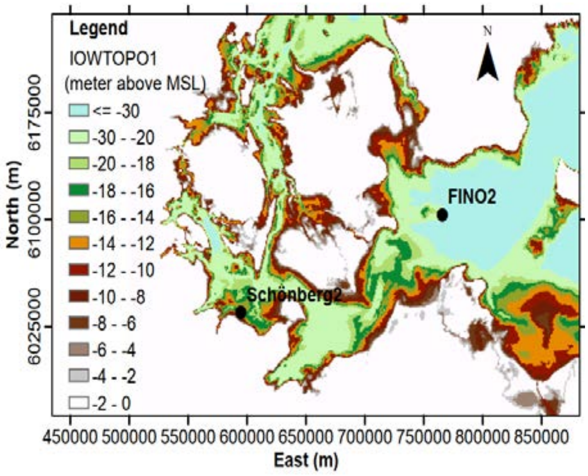

Figure 2. Selected wave locations

Two scenarios have been analyzed exemplarily for a modification of the COSMO-REA6 wind conditions of the year 2017 by a relative wind speed increase of +5% and +10% respectively. The relative increases have been applied constant over space and time for the sensitivity runs and without any water level and wind direction changes.

From the comparison of the frequencies of the modified run with the run of the reference year 2017 it can be concluded that near the location of "Schönberg2": i) westerly wave directions becoming more frequent and ii) higher wave events from W, NNE and ENE occur, resulting in a relative increase of the annual mean significant wave height by +13.5% (+5cm) and minor changes of the annual mean wave direction of +2° towards more NNW.

Near "FINO2" more wave events and higher significant wave heights from SW to NW and from ENE are noted resulting in a relative increase of the annual mean significant wave height by +13.6% (+12cm) compared to the values for 2017.

In the presentation we will give more information on the effects on the local water levels, currents and waves at selected locations along the German Baltic Sea coast.

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Natural conditions, human impact and future challenges for coastal protection at the Southern Baltic Sea Coast

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Natural development of the Southern Baltic coasts takes place on top of the post-glacial rebound, in a defined coastal morphology with its geological structure and along with changing climatic conditions (Furmańczyk, 2013). The recently discussed climate changes causing accelerated sea level rise and increased intensity of storms (IPCC, 2021) require special attention in the discussion and planning of coastal protection. Serious difficulties are caused by the ambiguity of determining the increase in the global ocean level due to the existence of many factors that are ambiguously included in the models, which means that several scenarios of the increase in the level of the Baltic Sea can be distinguished at present. The most moderate scenario (SSP2-4.5) foresees an increase in the level to 0.7 m in 2100. Other scenarios are more pessimistic and will not be considered here, as they would require a radically different approach to the protection and coastal zone management of the polish Baltic coast.

The Hel Peninsula is relatively narrow and low (with a small volume of a cross section), exposed to high waves (up to about 10 m height of a significant wave) coming from the NE direction. Such waves, combined with a storm surge, put continuity of the peninsula at risk (pose a risk of breaking the peninsula), especially in its lowest and narrowest part – the base, which has already been interrupted several times in the past (Furmańczyk and Musielak, 2015).

Observed for tens of years, coastal erosive phenomena constitute a serious threat to the supply lines and other objects located in the vicinity of the shoreline. Therefore, protection of the seashore of Hel Peninsula is important and necessary. The protection used to be based on a groyne system, stretching along a 10 km longshore segment from the Hel Peninsula root. The groynes were constructed in 1946-1969 as timber palisades, each about 60 m long, spaced from each other by about 90 m. They were intended to mitigate erosion on the lee side of the harbour of Władysławowo, the breakwaters of which had disturbed the natural longshore sediment flux. Because of unsatisfactory efficiency of the groynes, artificial beach nourishment was implemented in the eighties of the 20th century. The nourishment has been carried out till now and slightly mitigated the erosive processes at the site. A large project of artificial coast supply since around 1990 has radically improved the condition of the peninsula shores (Furmańczyk, 1994). The accumulative nature of calming storms and weak waves (Bugajny and Furmańczyk, 2020) did not sufficiently compensate for storm losses, nevertheless it decreased the overall erosion rate of the peninsula. The current method of protecting the peninsula has resulted in a relative, dynamic stabilization of the coasts, which may turn out to be insufficient with further sea level rise.

The groynes, coexisting with artificial beach fills, are subject to gradual damage manifested by loss of piles at various sections of the structures. The above mentioned coastal protection system is supplemented by a seawall at the lee side of the Władysławowo harbour and light revetments (the gabion structures built into artificial dunes).

Looking into the future poses a number of challenges in the field of the coast protection due to the small volume of the peninsula, the steep nearshore area on the eastern side allowing higher waves to approach the coast, and the specificity of undiscovered shore processes (gates, energy windows). In order to predict changes of the coastline position more accurately, a relatively accurate, possibly comprehensive classification of the coast, the inshore and hydrodynamic conditions (Musielak et al. 2017) should be created, which would be the basis for determining the degree of shore safety on both sides of the peninsula, and thus the forecast of the risk of shore erosion.

The study comprises the analyses of impacts of various coastal structures built at the Hel Peninsula that lead to local morphological changes on the coastal topography, medium-term coastal development trends depending on medium-term changes (fluctuations) in sea level ranges, beach accumulations occurring during weak waves and winds conditions. Based on Hel Peninsula study site a classification of different coastal zones is presented. In the analysis, a calculations of beach and dune erosion induced by extreme waves and water level is carried out. As a results of calculations, a different scenario of morphological changes for different segments of Hel Peninsula is presented. Finally a three potential scenarios of management of coastal zones of Hel Peninsula are discussed. First, large beach nourishments projects carried out in crucial segments of study site and technical formation of dunes is considered. Secondly, coastal protection measures (e.g seawalls, submerged breakwaters) and their potential impacts on study site is analysed. Third discussed strategy assume no coastal protection methods carried out in Hel Peninsula and as a result of this strategy formation of natural channels between Baltic Sea and Gdansk Buy is considered.

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Evaluation of UAV LiDAR for monitoring of coastal cliffs.

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1. Introduction

A significant change in winter cyclonic activity has been observed over the Baltic Sea during the second half of the 20th century. Increased storms and higher storm surge levels significantly alter the coast of this non-tidal sea, where extreme water levels depend largely on the volume of water flowing in from the North Sea (Tonnison et al., 2013, Terefenko et al., 2019).

It has been proved that nearshore morphology is influenced by single or cumulative effects of storm events as well as different factors such as variability in wave regime, geological settings and sediment grain size (Deng et al., 2014; Paprotny at al., 2014). Nevertheless the impact of variable storm frequency on coastal morphology have still not been fully addressed, especially for coastal cliffs which are often the most dynamic and on the other hand difficult to access therefore hard to measure. Scientific progress in this area is limited by the availability of representative datasets for investigating processes as well as calibrating, validating, and verifying morphological models (Furmańczyk et al., 2014).

2. Cliff monitoring

To track cliff changes and identify the processes of its modifications, data must be collected frequently over consistent time intervals (Andrews et al., 2002). Data collection using classic field methods is a long and laborious process, which in the case of numerous and extensive research areas may not provide the required results. Laser-based surveys are pointed as the most effective technique allowing for rapid and accurate collection of large amounts of topographic data. During the last decade, terrestrial laser scanner (TLS) has been successfully applied to topographic surveys and to the monitoring of coastal processes (Almeida et al., 2015, Vousdoukas et al., 2020).

Numerous studies prove that high temporal resolution in TLS surveys realized in cliff coastal sections enables the analysis of correlations between the influence of several factors (wave height, length and period, water level, storm energy, precipitation, etc.) and the geomorphological response of coast during isolated storm events, as well as with cumulative effects for season-long analysis (Almeida et al., 2015, Terefenko et al. 2019).

On the other hand unmanned aerial vehicles (UAVs) are now used in many areas to monitor and protect sea coasts (Śledziowski et al., 2022). Research areas include especially progressive changes in the coastal zone (Turner et al. 2016), analysis of subaerial morphology (Talavera et al. 2018), estimation of volumetric changes (Gómez-Gutiérrez et al. 2020) or quick mapping of beach areas after the occurrence of storms and large waves (Cheng-Hao et al. 2016). The UAV-based photogrammetry is becoming a fundamental monitoring and analytical tool thanks to its low-cost and user-friendly techniques which are well comparable with traditional topographic surveys (Fabbri et al., 2021).

Here we combine both most effective methods and present the development, evaluation, and application of a UAV equipped with high-resolution topographic LiDAR and Red-Green-Blue (RGB) imaging system for purposes of monitoring coastal cliffs. The aim of the study is to evaluate the relative performance of UAV LiDAR in mapping coastal cliffs when compared to the widely used UAV photogrammetry.

3. Methodology

A custom-built UAV-based mobile mapping system was used in this study for simultaneously collecting both LiDAR and imagery data. The system consists of a DJI Matrice 300 multirotor which carries a laser scanner (Zenmuse L1), an integrated 20MP RGB mapping camera, and an integrated GNSS for direct georeferencing, as shown in Figure 1.

Figure 1. DJI Matrice 300 with Zenmuse L1 LiDAR module.

The test site is located along the Polish coast on Wolin Island. Situated next to Międzyzdroje town Biała Góra cliffs has a NW exposition. The field site had a the role of a "real-scale" laboratory, where high quality and high-resolution datasets were collected. Different types of topographies has been monitored along the 1 km coast section, and thus was used for assessing the quality of UAV

LiDAR point clouds and evaluating the difference between UAV LiDAR and UAV photogrammetry. The investigated area is an actively eroding cliff where we investigate the ability of UAV LiDAR for quantifying rapid coastal changes between surveys.

The quality of the UAV-based LiDAR point cloud is evaluated based on a comparison against UAV photogrammetry. For the comparison several criteria was used: (1) spatial coverage, (2) point density, (3) horizontal and vertical alignment at selected profiles, and (4) overall elevation differences between point clouds.

4. Results and Conclusions

Point cloud analysis showed that the LiDAR point cloud compared to the image-based point cloud covers a larger area and has a higher point density. In addition to higher point density, LiDAR distributes points more uniformly over the terrain. Further the LiDAR point cloud has similar coverage both on the ground surface and vegetation. At the same time image-based point cloud mostly covers the ground surface, and is relatively scare over the different vegetation types. This clear advantage of UAV LiDAR was very important during the process of quantifying the coastal volumetric changes along the test area between realized surveys.

The spatial patterns were analyzed by calculation of the elevation differences between the LiDAR and image-based point clouds. This enabled also to evaluate the overall discrepancy between the two point clouds. The mean elevation difference between LiDAR and image-based point clouds is 0.05 m. Overall, the point clouds generated by both techniques are compatible within a 5 to 10 cm range. The biggest advantage of LiDAR data was visible for the most vertical parts of the cliff face. The image-based point cloud on this area was quite sparse and thus the accuracy of this segment was low. However the result suggests that both UAV LiDAR and image-based techniques generate point clouds that exhibit a good degree of agreement with an overall precision of several centimeters when used for the beach part of the coast. This finding proves that image-based reconstruction is more sensitive to environmental factors. Furthermore based on performed test they are also very vulnerable to different flight configuration and settings.

With the help of the GNSS module, point cloud reconstruction brings all measurements into one reference frame and enabled comparison along X and Y directions. The overall discrepancies between LiDAR and image-based point clouds are 1 cm and 2 cm, respectively. The discrepancy along Z direction ranges from -8.5 cm to 7.6 cm, with an average of 0.3 cm, suggesting that the image-based surface is slightly higher than the LiDAR-based surface.

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Sea level dynamics and coastal erosion in the Baltic Sea region

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1. Introduction

Regional climate change in the Baltic Sea basin has been assessed systematically in two comprehensive assessment reports (BACC I and BACC II) initiated by the Baltic Sea Experiment (BALTEX) and its successor Baltic Earth. (BACC Author Team, 2008; BACC II Author Team, 2015). As a follow-up, a series of review papers (the Baltic Earth Assessment Reports, or BEAR reports) summarizing and updating the knowledge around the major Baltic Earth science topics were organized. Here we present results and findings of one of these review papers (Weisse et al., 2021) concentrating on sea level dynamics and coastal erosion in the Baltic Sea region.

2. Major results

Long-term changes in relative mean sea levels in the Baltic Sea are dominated by glacial isostatic adjustment (GIA), global sea level change, and other regional- to local-scale components and their interaction. This includes for example thermo- and halosteric contributions, effects from long-term changes in wind and surface air pressure, processes in the North Atlantic that affect large-scale sea level, or variations in freshwater input in the Baltic Sea.

While relative mean sea level changes and their trends are strongly affected by vertical land movements and thus vary considerably across the Baltic Sea, absolute mean sea level increased in the whole basin with rates depending on region and period considered. For example, Passaro et al. (2021) reported rates between about 2 and 3 mm yr^{-1} in the southwestern parts and about 5 and 6 mm yr^{-1} in the northern parts for the period from 1995 to 2019. Generally, current (1993 to 2015/2017) altimetry-derived Baltic Sea mean sea level trends are still comparable with the global average (Madsen et al., 2019).

It is anticipated that most of the future Baltic absolute mean sea level rise will be strongly linked with corresponding large-scale changes in the North Atlantic and the factors modulating these changes. These factors are mainly the thermal expansion of the water column, contributions from melting of the Antarctic ice sheet (e.g., Grinsted, 2015), or imprints from the variability and change in the Atlantic Meridional Overturning Circulation (e.g, Börgel et al., 2018).

Future Baltic mean sea level is substantially more sensitive to melting from Antarctica than from Greenland. For the Swedish coast, Hieronymus and Kalén (2020) provided sea level projections accounting for such variations. When compared to earlier estimates, this resulted in lower projections in 2100. The IPCC AR6 (Fox-Kemper et al., 2021; Garner et al., 2021), for the southern Baltic Sea, provided ranges of relative mean sea level rise between 20 cm and 120 cm towards the end of the 21st century relative to 1994-2015 across their medium confidence scenarios. In the northern Baltic Sea, sea level is still expected to fall because of the ongoing GIA.

Variability and long-term changes in Baltic extreme sea levels occur for various reasons but are mainly linked to changes in the relative mean sea level and atmospheric conditions. Depending on period and data, several studies reported trends in Baltic sea level extremes. These trends were found to originate mainly from a corresponding change in mean sea level (e.g., Marcos and Woodworth, 2017) or from an increase in the magnitude of the preconditioning (e.g., Pindsoo and Soomere, 2020). Here preconditioning refers to periods of prevailing westerly winds that increase the sea level gradient across the Danish straits which, in turn, leads to higher inflow and higher Baltic Sea water volumes.

While rising mean sea levels are expected to contribute to increasing future extremes, projections of future wind waves and storm surges in the Baltic Sea are still highly dependent on the atmospheric scenario, the climate model, and the realization used for the projection. Potential future changes in long-term mean and extreme wind speeds are also highly uncertain (Räisänen, 2017).

As tides are small in the Baltic Sea, elevated water levels providing conditions conducive to erosion can be maintained for extended periods (e.g., Johansson and Kahma, 2016). Therefore, Baltic Sea volume, storm surges, wave setup, the presence or absence of sea ice, long-period wave energy from infragravity or edge waves and their long-term variability and change are the main factors influencing duration and locations where erosion may occur. Additionally, a strong relationship was found between rates of coastline change and the relative level of human development (e.g. Deng et al. 2014).

3. Research challenges

Several knowledge gaps and future research challenges are discussed in the contribution of Weisse et al. (2021) to the BEAR reports. Among others, they include the quantification of future melting from ice-sheets, in particular from Antarctica; the development of approaches on how evidence for high-end and plausible upper limits may be accounted for reliably and acceptably for stakeholders with different levels of risk aversion; improved modeling of extreme sea levels at spatial resolutions applicable to small coastal segments, which are sensitive to minor shifts in wind directions and intensities, also to adequately account for contributions of coastal processes such as wave setup on total nearshore water levels. Other challenges comprise improvements of coastal satellite altimetry; development of a systematic database for coastline changes in the entire Baltic Sea; or steps towards a universally accepted model of coastal change under sea level rise.

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Theoretical maximum and minimum sea levels and the probability of their occurrence at selected Baltic tide gauge stations.

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1. Introduction

The Baltic Sea currently has many rationally located water gauges (around 220 mareographs along the entire Baltic coast) which allow the characterization of phenomena and processes responsible for raising and lowering sea levels. Extreme sea levels, i.e. the highest and lowest levels recorded over a many years, a single year, or at a specific storm event, are especially likely to stimulate coastal abrasion, the accumulation of sedimentary material, and the destruction of shore infrastructure during storm floods. The primary method for analyzing hydrological threats to coastal zones is the probabilistic forecasting of extreme sea levels. Probabilistic analyses help determine so-called theoretical sea levels, i.e., the highest and the lowest water levels that may occur every certain number of years, e.g., once every 50, 100, or 200 years. This number of years is called the return period. Probabilistic forecasts are needed for engineering in the coastal zone, the foundations of hydraulic engineering structures, and to determine the ordinates of port quays and flood embankments. The probability of extreme water levels is also applicable in urban housing and industrial coastal areas.

The aim of this study is to analyze the probability of the occurrence of extreme water levels along the entire Baltic Sea coast from 1960-2010. To this end, this study determined the height of theoretical water. The paper analyzes changes in the 100-year theoretical water levels, from the open waters of the Baltic Sea to the innermost parts of bays and gulfs . The next part of the analysis presents the distribution of maximum theoretical water level on a map of the Baltic Sea for return periods of: 100, 200, 500, and 1000 years. The last part of the analysis concerns the variability of theoretical water levels over the last century, and water levels during two 50-year periods, 1910-1960 and 1960-2010, were compared.

2. Material and methods.

Research materials included observations of maximum and minimum annual sea levels from 47 water gauge stations located along the entire Baltic Sea coast. A 51-year period from 1960-2010 was chosen as the longest possible period that could provide sea level data from national meteorological and hydrological institutes of Baltic countries

The calculation of the probability of water levels consisted of appropriately selecting theoretical probability distributions. Next, statistical data was used to estimate the assumed parameters of a selected distribution. To determine the maximum theoretical levels (the probability of occurrence) over different return periods, the Gumbel distribution was used (Gumbel 1958). A Pearson type III distribution, typically used in hydrology (Kaczmarek 1970), was used to determine the theoretical minimum water levels.

The ArcGIS program was the primary tool for visualizing theoretical extreme water levels in the Baltic Sea. The advantage of the GIS software is that it links analyzed research features with their precise geographical locations. Spatial analysis was primarily based on an ArcGIS module called kriging, a geostatistical method for interpolating parameter values which is widely used and recommended for environmental research, including the creation of maps based on data interpolation (McGrath et al. 2004).

3. Results and discussion

Theoretical water levels were determined based on annual maximum and minimum sea levels for 6 water gauges deployed in different regions of the Baltic Sea, with distinct rhythms of water-level fluctuations. The resulting maximum and minimum water levels are shown in Table 1 and Table 2, respectively

Table 1. Theoretical maximum sea levels [cm], the probability of their occurrence (P) and return periods (T) at selected Baltic Sea gauge stations from 1960–2010

T (years)	P (%)	Gauge station					
		Korsør	Gdańsk	Visby	Ristna	Helsinki	Vassa
1000	0.1	209.4	227.6	112.6	257.8	223.0	233.7
500	0.2	197.1	213.3	106.2	241.2	209.3	217.9
200	0.5	180.9	194.5	97.7	219.1	191.3	197.0
100	1	168.6	180.2	91.3	202.5	177.6	181.2
50	2	156.3	165.8	84.9	185.7	163.8	165.3
20	5	139.9	146.7	76.3	163.4	145.5	144.1
10	10	127.2	131.9	69.6	146.1	131.3	127.7
5	20	113.9	116.5	62.7	128.1	116.6	110.6
2	50	93.9	93.2	52.3	100.9	94.3	84.8
1.01	99	60.5	54.3	34.8	68.5	57.0	41.6

Table 2. Theoretical minimum sea levels [cm], the probability of their occurrence (P) and return periods (T) at selected Baltic gauge stations from 1960–2010

T (years)	P (%)	Gauge station					
		Korsør	Gdańsk	Visby	Ristna	Helsinki	Vassa
1.01	99	-42.2	-21.4	-20.2	-15.1	-34.4	-31.0
2	50	-65.9	-52.2	-41.6	-55.2	-56.9	-60.7
5	20	-77.3	-64.1	-50.7	-65.2	-69.0	-73.2
10	10	-83.9	-70.5	-55.9	-69.7	-76.2	-80.2
20	5	-89.5	-75.7	–64.0	-72.5	-82.5	-86.0
50	2	-95.2	-80.8	-67.5	-75.4	-88.9	-91.7
100	1	-100.8	-86.0	-68.7	-78.3	-95.3	-97.5
200	0.5	-105.4	-89.8	-72.1	-75.5	-100.5	-101.9
500	0.2	-109.9	-93.7	-75.5	-72.8	-105.8	-106.4
1000	0.1	-114.5	-97.6	-78.9	-70.0	-111.1	-110.9

Further in the paper, theoretical water levels are calculated for a 500-year return period and visualized on a map of the Baltic Sea (Figure 1).

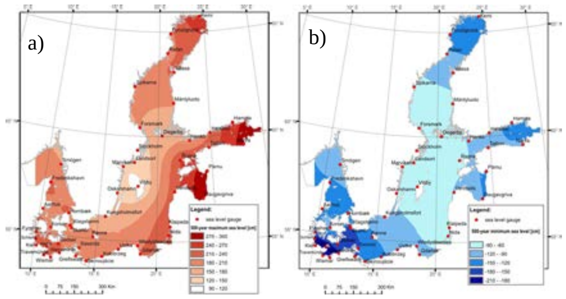

Figure 1. The distribution of theoretical water with a 500-year return period: a) theoretical maximum sea level, b) theoretical minimum sea level.

The results in Tables 1 and 2 and Figure 1 indicate that theoretical water levels at individual gauge stations depend on their geographical location. For example, in Visby, the 500-year maximum water level was 106.2 cm, and its annual minimum was –75.5 cm, the smallest range in the whole Baltic Sea for the 500-year period. The range is so small because the station is located in the Baltic Sea's open waters (Central Baltic, Gotland), where the water level fluctuations are the smallest (the so-called nodal points of fluctuations). For the other stations, the theoretical water level ranges were significantly higher.

Based on Figure 1, the theoretical water levels increased for water gauges located in the open waters of the Baltic Sea (Gotland, Visby) to the innermost parts of gulfs (the Gulf of Bothnia – Kemi, the Gulf of Finland – Hamina, the Gulf of Riga – Pärnu, Western Baltic – Wismar). This study was confirmed by analyzing the theoretical water level distribution for return periods of 100, 200, 500, and 1000 years (Figure 2). The lowest theoretical water levels invariably occurred along the Swedish coasts of the Central Baltic and Gotland. On the other hand, the most extreme theoretical water levels were found in the innermost parts of the Gulfs of Bothnia, Riga, Finland, and the Western Baltic.

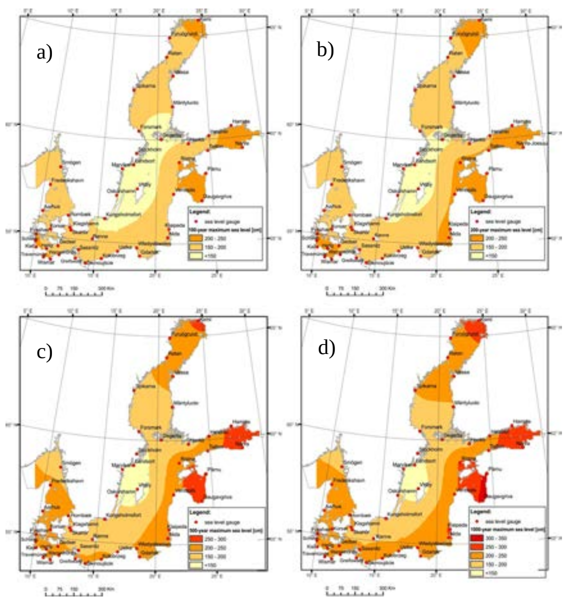

Figure 2.The distribution of theoretical maximum water levels over different return periods: a) 100-year, b) 200-year, c) 500-year, d) 1000-year.

The final-stage analyses compare the theoretical water levels between two 50–year periods, 1910-1960 and 1960-2010, for selected gauging stations. Differences were calculated for water gauges with archival data available since 1910 along Swedish, Finnish, and Polish coasts . As indicated by the positive values , the theoretical water levels were higher from 1960–2010 for all analyzed water gauges in the full range of quantiles (from 0.1 to 99%). At the same time, the return period was shortened for these water level gauges. For example, for Kungsholmsfort, after 50 years, the 100-year water level shifted to the 50-year water level , and in Helsinki, it shifted to about the 15-year water level. These results show on the steady increase in the theoretical (and thus observed) maximum annual water levels of the Baltic Sea in the last half-century .This mechanism is associated with an increase in the average sea level and an intensification of the western atmospheric circulation. The processes describing the increase in the average and maximum water levels in the Baltic Sea are covered in a number of research papers (Stigge 1993, Johanson et al. 2004, Richter et al. 2012)

Conclusions

Theoretical sea levels with a specific probability of occurrence are used to identify the characteristics of extreme sea levels and storm surges. They also have a wide range of practical applications in hydraulic engineering, floodplain management, and flood protection of various sea shores. In the coming years, there is a need to expand research on extreme sea levels, both based on contemporary and archival mareographic data, as well as GPS and satellite measurements of the Baltic Sea water level. Additional research materials include the calculated probabilities of occurrence of extreme sea levels based on the longest series of available observation data. The use of an extended measurement range and calculated data, as well as an understanding of the specificity of extreme water levels in various Baltic water regions, will allow for an improvement in the methods of operational forecasting of storm surges and negative storm surges. Additionally, it will enable a precise assessment of the climate change threats to the coastal zone of the Baltic Sea..

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Erosion assessment using remote sensing data: A case study of Latvian coastline

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1. Introduction

Latvian territory is located on the eastern shore of the Baltic Sea with a dynamic coastline extending for about 500 km. The shore mostly consists of low-lying sand beaches and is highly susceptible to storm-induced erosion which poses threats to natural and man-made landscape. IPCC SSP's predictions for the 21st century indicate increasing sea surface height and storm frequency in the Baltic Sea region (IPCC, 2021). Along with other complex interactions these changes will amplify the erosion rate and emphasize the need for a deeper understanding of the intensity of coastal erosion. We propose to create an atlas type structured dataset based on satellite flights, describing erosion on the Latvian coastline in the period covered by over 11000 Sentinel-2 measurements. Development of database and data processing mechanisms is therefore required to provide means for further analysis.

2. State of the art

Majority of the monitoring conducted until this day in Latvia is based on beach profile in-situ measurements. These measurements have proven to be sufficient for a broad overview of the dynamics on the coastline and also contribute additional analysis in some of the more widely known districts on a case-to-case basis (Soomere et al., 2011). However, lack of regular homogeneous measurements creates data gaps that can obscure details and have an impact on comprehensive description of coastal evolution.

Remote sensing data has proven to be a valuable resource of geospatial information and provides an opportunity to understand the rate of change in time and space. Recent research along with developments in sensor metrics and data availability provide means for building useful applications on top of the raw data.

The primary stage of activity is the build-up of the geospatial data catalogue within LEGMC (Latvian Environment, Geology and Meteorology Centre). Sentinel-2 was chosen as the initial data source due to a slightly better resolution and spatiotemporal coverage than provided by Landsat. The main focus is to create a database of geospatial data and develop a common work-flow to monitor coastal dynamics. Full description of the task includes the hardware and database setup issues, but within the scope of this paper an emphasis is put on shoreline extraction methods to compare and discuss the results of coastline detection and analysis.

3. Methodology

Atmospheric corrections and georeferencing were performed on Sentinel-2 L2C datasets to control the homogeneity of data using Acolite (Vanhellemont et al. 2018) and Arcosics (Scheffler et al., 2017) geospatial data processors (Fig.1). Available Sentinel-2 scenes were filtered to identify the best observations, taking into account environmental conditions like sea-surface height, cloudiness, wave and ice conditions. A reference baseline (waterline) was created from most fitting scenes to allow tracing the coastal dynamics and provide means of data verification - this is later used for quality control.

Radiometric indices and single-band grayscale images were used for analysis to derive information about the location of the coastline. For initial image analysis unsupervised K-means clustering was performed using SharkKMeans processor within Orfeo ToolBox (Grizonnet et al., 2017) to classify the land and water areas. Further a simplified coastline is extracted from the classified image by tracing the edges of the polygons. Waterline is quality controlled by the reference baseline previously determined from the best fitting Sentinel-2 scenes (Fig. 1) This instant water-land border will then be used for definition and placement of the coastline.

This simple and resource-effective process provides good all-round results in straight sections of the beach, with gentle beach slope (Fig.2). Most obvious errors are removed during quality-control process with land-sea masks and statistical analysis of the results.

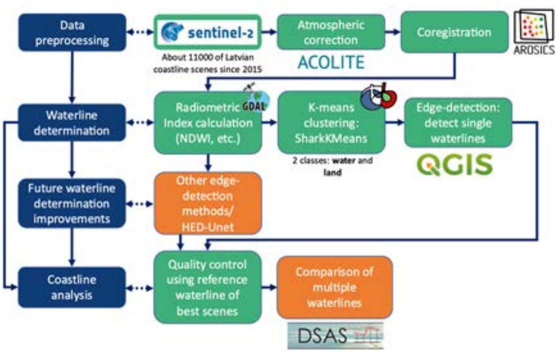

Figure 1. Data processing workflow for waterline and coastline determination. Orange boxes mark work-in-progress

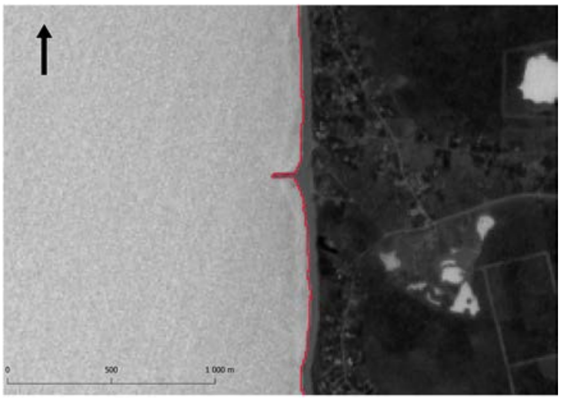

Figure 2. Result of single K-means cluster derived waterline (red) in Tuja, Latvia. Underlying Normalized Difference Water

Index (NDWI) image is used to create a set of two clusters (land and water) using random sampler with a training set size of 100 performed over 1000 iterations.

4. Discussion and future work

Overall we achieved good accuracy and robustness even with the most basic processing mechanisms and the majority of the waterlines can be distinguished within a reasonable margin of error, which coincides with the Sentinel-2 pixel resolution of about ±10 m. Apparent problems are observed on steep beaches and in areas of shallow and turbulent waters, where the radiometric signature is partly obscured or does not provide a sharp contrast.

Majority of previous work regarding coastline detection from remote sensing data has been performed using processors for clustering, edge detection or a mix of both techniques. Even though edge-detection processors intuitively seem to be the apparent means of data analysis for the task of water-land boundary location, these processors introduce blurriness into the base image due to pixel value smoothing. The loss of crisp edges (waterlines) is a major drawback for the use of classic edge detection processing mechanisms. Simplified clustering offers robust results, but lacks sophistication and capacity for development. To further increase the quality of waterline detection additional work is planned with the use of machine learning and advanced waterline detection that combines statistical classification and edge detection. In this regard it can be noted that there are successful implementations of processing software that resolves these issues, notably the HED-UNet processor developed by the German Aerospace Center (Heidler et al., 2022). Additionally successful results and experience gained using this open-code processor could allow radar data analysis to be implemented into the results of this activity.

During the project we shall extract the instant waterline location from over 11000 Sentinel-2 measurements of Latvian coastline. Afterwards we intend to analyze these waterlines by their spatial displacement using Digital Shoreline Analysis System (DSAS) software (Himmelstoss et al., 2018). This would allow us to create a reproducible methodology for ongoing erosion monitoring using remote sensing data and statistically evaluate coastline change during years 2015-2023.

Acknowledgements

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Topic 5

Regional variability of water and energy exchanges

Towards a water-isotope framework of the Baltic Sea

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1. Introduction

The water cycle on local, regional and global scales is reflected by specific water isotope signatures ($^2H/^1H$; $^{18}O/^{16}O$, $^{17}O/^{16}O$) found in different water reservoirs (precipitation, glaciers, surface, soil, ground, sea water) (e.g., Dansgaard, 1964; Craig & Gordon, 1965; Gat, 1996; Luz & Barkan, 2010). Strong salinity and water stable isotope gradients are found to develop in the mixing zone between fresh and saline surface water, as found in estuaries and coastal areas, or on a larger scale coastal seas like the Baltic and North Sea (Böttcher et al., 2014). Furthermore, the hydrological impact of submarine ground water discharge (SGD) belongs to the still unsolved questions in hydrology (Blöschl et al., 2019) and may further add substantial compositional gradients and to the complexity of coastal hydrology (Jurasinski et al., 2018). Since fresh waters of different development and ages may enter the coastal area it can be expected that they carry characteristic seasonal dynamic water isotope signatures (Böttcher et al., 2014). Information about the areal distribution of water isotopes allows for the identification of water sources, mixing processes. Vertical profiles in coastal areas, in addition, may help to identify the impact of SGD via benthic-pelagic coupling. An extension towards sediment pore-water systems allows for a transport modeling and the identification of temporal changes in the hydrological cycle with time (Ni et al., 2020). The modern fresh water cycle along the NE German coast line as a regional Baltic example was evaluated by analyzing the areal distribution of the composition of ground waters, the seasonal dynamics within a riverine estuary on a seasonal base, and establishing the LMWL for precipitation at a coastal site.

Results are furthermore linked to the hydrochemical composition for a deduction of the link between hydrography/hydrology and biogeochemical element cycles.

Methods

Water samples were collected via different devices during several cruises through the Baltic Sea and during land-based field campaigns in the coastal area. In addition, precipitation samples were collected on a continuous base (2013-2021) at a site near the southern Baltic Sea coastline using a Hellman-type sampler.

Isotope measurements were carried out by means of Laser-cavity ring-down spectroscopy using a L2140-i system (Picarro). International (VSMOW, SLAP, GISP, USGS) as well as in-house standards were used to scale the isotope measurements. Results are related to salinity measurements for surface waters, and amounts and characteristics for precipitation samples.

2. Results and discussion

Fresh surface waters entering the Baltic Sea display isotope signatures that may allow for a separation of water sources. It is found that that the ground waters of Mecklenburg Western Pomerania are positioned on the LMWL at Warnemünde, but H-O isotope pairs from the southern Baltic Sea water are shifted towards heavier stable isotope effects due to the enhanced impact of evaporation. Changes in salinity and, therefore, mixing ratios with freshwaters originating from catchments with different temperature regimes lead to the development of a gradient in the stable water isotope composition and deuterium excess values through the Baltic Sea (Fig.1). The results are used to establish different characteristic regional water lines.
Vertical profiling allowed for the identification of submarine ground water discharge, at the coast close to the Bay of Gdansk. Pore water analysis, on the other hand, added a time component and allow the identification of bottom water compositions originating from melt water after the last glaciation.

The established water-isotope framework for the Baltic Sea will ask for a combination with models to predict the past, modern and future water cycle in the Baltic Sea and its catchment areas.

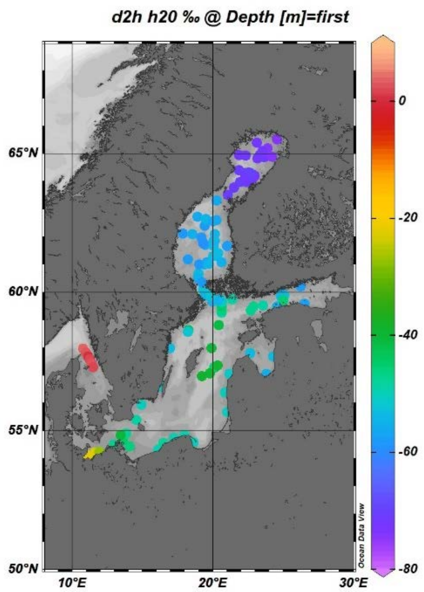

Figure 1: An example for the areal distribution of the hydrogen isotope composition of bottom water in the Baltic Sea.

3. Financial support

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Variability of water column properties in a downwelling prevailing area

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1. Introduction

Downwelling and upwelling are important processes that shape the physical and biogeochemical properties of the water column.

High-resolution profiling and cross-gulf transects have revealed a high contribution of the wind-driven pycnocline variability to the water column structure in the Gulf of Finland (Liblik & Lips, 2017; Liblik & Lips, 2012). In the current study, we focus on the variability of pycnoclines off the Saaremaa island in one of the most frequent downwelling zones in the Baltic Sea (Myrberg; Andrejev, 2003) and the consequences of their variability on physics and biogeochemistry.

This is a follow-up work for the larger-scale circulation study in the Baltic Proper (Liblik et al., 2022). We found the quasi-steady circulation patterns occur under prevailing forcing conditions. The patterns were in geostrophic balance and high-persistent.

The main aim of the present work is to concentrate on coastal processes during the steady patterns and have a high-resolution view of the pycnoclines variability and its implications at the eastern coast of Baltic Proper.

2. Data

Three monthly glider missions were conducted at the zonal section in the Northern Baltic Proper in 2019-2020. CTD+ profiles onboard R/V Salme were collected when depolying and recovering the glider.

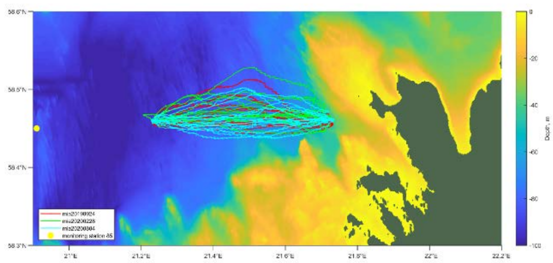

Figure 1. Bathymetry and glider tracks in the Baltic Proper, NW of Saaremaa Island.

2. Results and conclusions

The first survey was arranged during seasonal thermocline decay in September-October 2019. The second survey was done in the absence of seasonal thermocline in February-March 2020, and the last one in August 2020.

On top of the seasonal developments of water properties, the wind-driven pycnocline variations at the coastal slope considerably impacted the water column structure. The share of the three water masses (upper layer, cold intermediate layer, and deep layer) varied remarkably at the section. The variability was related to the divergence and convergence and to the vertical mixing and advection. For instance, from September to October 2019, the decrease of volume of the CIL was observed while the upper mixed layer thickened (Figs. 2-3).

As a result of pycnocline variations, the depth of the upper mixed layer varied considerably, likewise, the halocline and the hypoxic water mass changed their position remarkably. This in turn might cause an impact on the ecological variables. In summer, the upper mixed layer was occasionally thicker than the euphotic zone depth, which could impede phytoplankton growth. The sinking of the hypoxic water mass and its uplift at the coastal slope cause rapid switches from hypoxic to oxic state and vice-versa, impacting the benthos in the large sea areas (hundreds of km^2). Knowing the sensibility of the fluxes between the near-bottom water and sediments, this process could be important in the marine carbon cycle (van de Velde et al., 2020).

The next step of this ongoing work is to quantify the effects of boundary processes on the vertical mixing in the Baltic Sea and water column structure in general. Observations and simulations using numerical model GETM (Burchard & Bolding, 2002) will be combined to achieve this aim.

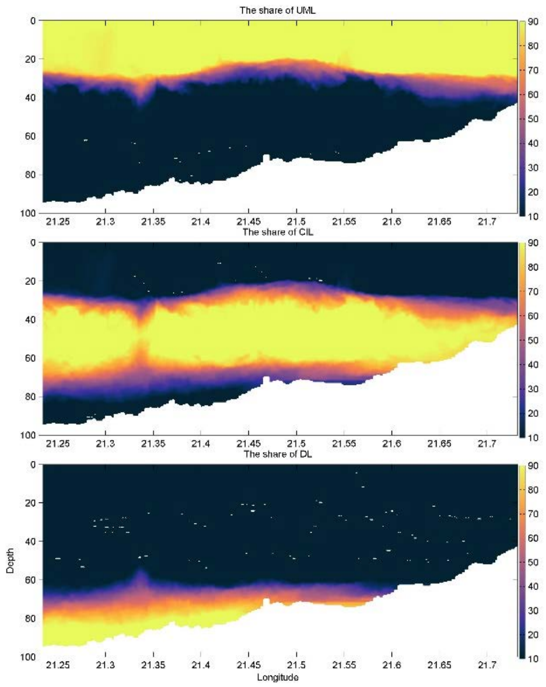

Figure 2. The share of the upper mixed layer, cold intermediate layer and deep layer water masses on 25-26 September.

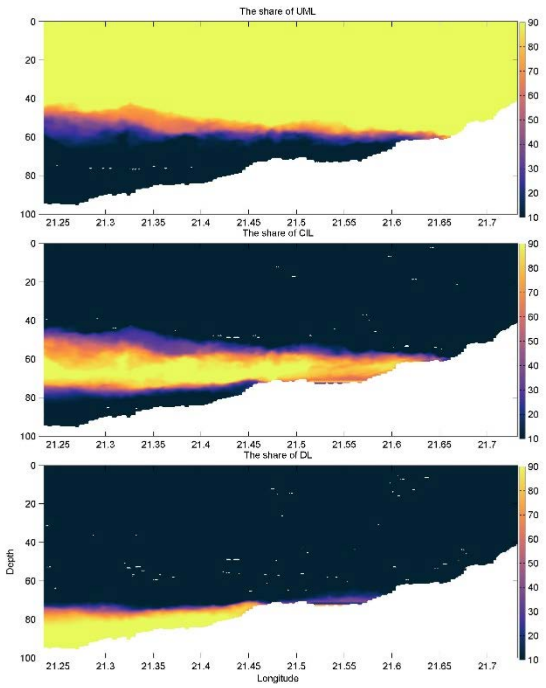

Figure 3. The share of the upper mixed layer, cold intermediate layer, and deep layer water masses on 15-17 October.

Acknowledgments

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Upwelling characteristics in the Gulf of Riga (Baltic Sea) – multiple data source approach

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1. Introduction

In summer upwellings are usually associated with lower temperatures as well as with higher nutrient concentrations (necessary for biological productivity) at surface layers which is a direct result of vertical transport of bottom layer waters to the surface. Besides promoting the biological productivity in the area, upwelling events also hold the potential to affect the transportation of different fish larvae and/or juveniles through initiated currents as well as influence the climate locally - usually the cold water cools the coastal air above and mist is being formed.

Previous investigations regarding upwelling in the Gulf of Riga (GoR) have been considered mainly in the context of the whole Baltic Sea (BS) region where applications of satellite data (e.g. Uiboupin and Laanemets, 2015; Dabuleviciene et al. 2018), model data (e.g. Wu et al. 2019) or combination of both (e.g. Kowalewska-Kalkowska and Kowalewski 2019) have been used. Besides that, more detailed investigations have been made concentrating on specific gulfs (e.g. Kikas and Lips 2016 – Gulf of Finland), parts or regions (Bednorz et al. 2019 – southern Baltic Sea) of the BS and exploring various aspects of upwelling-related topics – e.g. atmospheric forcing (Bednorz et al. 2021), submesoscale structures, surface transport, excess of phosphorus in surface layer, chlorophyll-a variability etc. Nevertheless, aforementioned studies have concentrated mainly on areas outside the GoR and we feel that there is a gap in knowledge regarding the upwelling characteristics specifically in the GoR.

The main goal of the present study is to detect upwelling events and describe their characteristics (e.g. frequency, location, extent) in the GoR. As the study is still ongoing (started in 2021) many sections are still in progress and in this extended abstract only first results will be described.

2. Methods

The study area is the GoR, a semi-enclosed water basin in the eastern part of the BS. Current study aims to aggregate historical monitoring data, data sampling surveys/cruises in 2021 and 2022, smartbuoy data, satellite data and model data.

During the targeted data sampling surveys in 2021, CTD profiles together with water samples from surface and bottom layers were collected in the upwelling affected area and outside it (see Fig. 1). Water samples were used to determine nutrient abundance and at some locations phytoplankton and zooplankton (WP-2 net; mesh size 100 µm) samples were taken as well.

Smartbuoy data was obtained from smartbuoy system deployed in the eastern coast of the GoR near the Skulte port (see Fig. 2). Available data consists of CTD measurements as well as currents (speed, direction) and wave characteristics. All data have temporal resolution of 1 h.

Satellite data were collected from 2010 till 2021 using Landsat 7, Landsat 8 (resolution 60 m and 100 m per pixel, respectively) and Sentinel-3 (Level-2 data; resolution 1 km per pixel) data sources. To reduce the amount of data only period from 1st of May – 30th of September was selected with cloud cover less than 40% in the GoR area. All the data were further analyzed in Quantum GIS to select the datasets where upwelling signal was evident.

The General Estuarine Transport Model (GETM, Burchard and Bolding, 2002) was applied to simulate the conditions in the GoR since 2010. The horizontal resolution of the model grid is 0.5 nautical miles (approximately 926 m); there are 60 adaptive layers in the vertical direction. The main output parameters include sea surface temperature and current components in the Gulf of Riga along with the 3D thermohaline field. The analysis of the model data is still ongoing.

3. Data analysis

During the summer 2021 targeted surveys were performed with the aim to detect the upwelling. One of such events occurred in mid-August at the southwestern (SW) coast of the GoR where strong (9.0-10.0 ˚C lower temperatures in upwelling area) but very local - length approx. 15 km along coastline, offshore distance approx. 1.5 km at maximum - upwelling was detected (Fig. 1) accompanied with a strong mist along the coast.

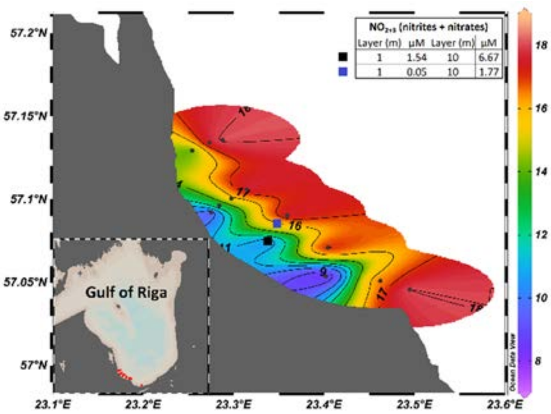

Figure 1. Data sampling survey on 17.08.2021 at southwestern coast of the GoR, black dots show the data sampling locations. Color scale represents the surface temperature (˚C). The table on upper right corner represents the results of nutrient abundance in respective locations marked with black and blue rectangles in the map.

Strong upwelling influence was also confirmed by nutrient measurements (nitrites + nitrates) where surface and bottom layer concentrations in the upwelling area considerably exceeded those outside of the affected area (see Fig. 1, blue and black rectangles) despite the fact that the distance between these two locations is approx. only 1.3 km. We suggest that such local, small scale upwellings could be detectable mainly with *in situ* measurements, otherwise, the resolution of satellite/model data needs to be considerably better than 1 km to come up with meaningful analysis.

As opposed to previously described small scale upwelling event, deployed smartbuoy near Skulte port could only detect upwelling signals from bigger, stronger events as its distance from the coast is approx. 2.5 km. Nevertheless, during the period of 01.05 – 30.09.2021 it was possible to detect some weaker and shorter upwelling events (e.g. 18-20th of May with temperature drop of approx. 6.0 ˚C; 13-14th of June with temperature drop of approx. 5.5 ˚C) as well as stronger and longer events from smartbuoy temperature data (Fig. 2).

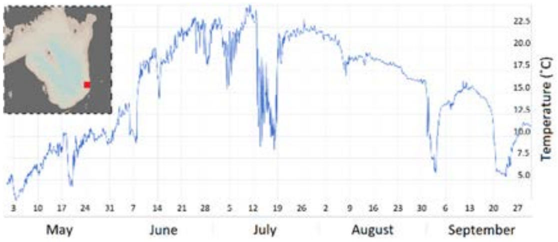

Figure 2. Temperature data during the period 01.05 – 30.09.2021 from smartbuoy deployed near Skulte port.

The most prominent and longest upwelling event occurred during 13-19th of July when temperatures from 23.0-24.0 ˚C decreased to values less than 10.0 ˚C at some occasions. Afterwards, a slightly shorter and weaker upwelling event was discovered during 31st of August - 4th of September (temperature drop of approx. 10.0 ˚C) and, finally, upwelling signal was evident starting from 18th of September (temperature drop of approx. 8.0 ˚C) with subsequent but comparatively slow relaxation phase when temperature increased back to 11.0 ˚C only at 28th of September.

To sum up, smartbuoy data provided a valuable information about the upwelling signals in the eastern coast of the GoR with good temporal resolution. Nevertheless, it does not allow to draw any conclusions or analysis about the spatial distribution of these events. To fill this gap the satellite data proved to be useful source.

Strong and rather lengthy upwelling event in the middle of July at eastern coast of the GoR was also visible from the satellite image (Fig. 3). Satellite data revealed that the upwelling event was evident along the whole eastern coast of the GoR. Values below 13.0 ˚C were found as far as 3 km offshore at some areas and values ≤15.0 ˚C were detectable as far as 50 km along the eastern coast. Moreover, from satellite data it was possible also to detect another rather small, local upwelling signal (temperature values below 13.0 ˚C) at the northern coast of the GoR (southern tip of Sõmeri preservation area in Estonia). Thus, the satellite data in this example complemented smartbuoy data and provided the missing information regarding the spatial distribution.

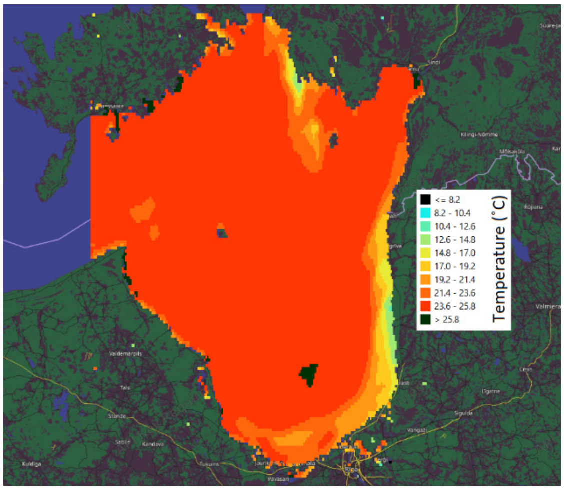

Figure 3. Sea surface temperature (SST) from Sentinel-3 satellite data at 17.07.2021 over the GoR. Black spots/areas in map represent biased values over the GoR.

Further work includes the addition of data analysis from model output to see if model was capable to capture upwellings and to which degree. Targeted data sampling surveys will also continue in 2022 emphasizing the necessity of biological (phytoplankton and zooplankton) and chemical (nutrients) parameter sampling next to CTD profiling. The combined approach can ensure further upwelling-related studies with particular emphasis on the influenced biological processes.

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Argo floats as virtual moorings in Southern Baltic

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1. Introduction

Argo floats are designed to study the deep ocean. However, experiments conducted by Finnish and Polish oceanographers have shown that they can also be used in the conditions of the Baltic Sea. Recently, Germany has joined the group of countries using floats in the Baltic Sea. Several Argo floats were launched in the Baltic Sea as part of European programs. In total, by January 2021, 48 floats were launched in the Baltic Sea, 14 are active. More than 7700 CTD profiles were obtained, giving a large database for Baltic Sea research. In addition, BioGeoChemical (BGC) data was obtained, mainly dissolved oxygen in seawater, but also other BGC data.

2. Argo at Southern Baltic

The South Baltic Sea is a body of water that is difficult to study by Argo Floats. Strong stratification makes it hard for Argo floats to reach the bottom, a pycnocline is sometimes read as the bottom. In addition, intense currents, especially flows through the Slupsk Channel between the Bornholm Basin and the Gdansk Deep, cause a fast migration of floats from the south-western part to the Gotland Deep (Fig. 1)

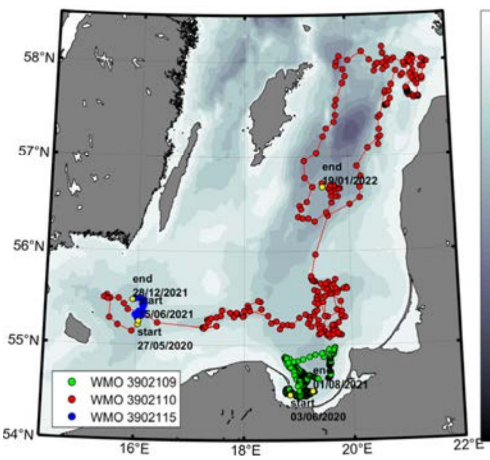

Figure 1. Three routes of Argo float in the Baltic Sea: standard route of float deployed in the Bornholm Basin (WMO 3902110, red color), bottom moored float in the Gdansk Bay (WMO 3902109, green color), bottom moored float in Bornholm Basin (WMO 3902105, blue color) .

3. Argo as a virtual mooring.

In the Euro-Argo Research Infrastructure Sustainability and Enhancement (E-A RISE) program, experiments are carried out with different float settings allowing for their optimal use. One idea is to use Argo as 'virtual moorings'. Instead of setting a fixed 'parking depth' at which the float drifts between the profiling, a parking depth greater than the actual depth of the water body is set. This causes the float to remain on the bottom between profiling and limits its drift. This method gave good results both in the Bornholm Basin and in the Gdansk Bay (Fig 1). The drift was limited, the float remained in one area for a long time.

4. Data and methods

Float 3902109 worked from 03.06.2020 to 01.08.2021 and performed 500 profiles. The region of measurements covered Gdansk Bay, all measurements were within a circle with a radius of 30 km. Systematic measurements lasted over a year, which made it possible to reconstruct the annual cycle of temperature and salinity at various levels, vertical displacement of thermocline and halocline. Determination of water column heat content changes enables calculation heat fluxes between water and atmosphere. The obtained results were compared with data from other sources.

Similar operations were used for data from the Bornholm Basin. In this case, the time series does not cover the whole year yet, float 3902115 was launched on May 15, 2021 and is still in operation. This floats, except typical CTD sensors set (Seabird) is also equipped with the dissolved oxygen sensor (Aanderaa), so evolution of dissolved oxygen content in water column is possible.

5. Results

High seasonal variability of water temperature in both regions exist. However there are big differences between the dynamics of water column temperature in the Gdansk Bay (Fig. 2) and Bornholm Basin (Fig. 3). Changes of water column temperature and heat content in Gdansk Bay are mainly due to the heat exchange between the sea and the atmosphere. In the Bornholm Basin, in a layer below 60 m deep, advection processes play much bigger role. Properties of water at greater depths are here mainly influenced by the inflow of highly saline water from the North Sea. Therefore temperature changes at these levels are often out of phase with the climate forcing.

6. Conclusions

Everything indicates that Argo floats are becoming a standard tool for the Baltic Sea exploring. Floats are useful both for monitoring and for processes studying in this water area.

Already at the early stage of Argo use, many modifications have been made to the rules of their use. These are mainly:

1. changing the frequency of profiling,
2. allowing contact with the bottom,
3. recovering and redeployment of floats.

Shelf and shallow sea versions of floats are already under development. The most important change that is needed is increasing of the sampling rate during profiling. This will allow a much better study of the processes taking place in the water column.

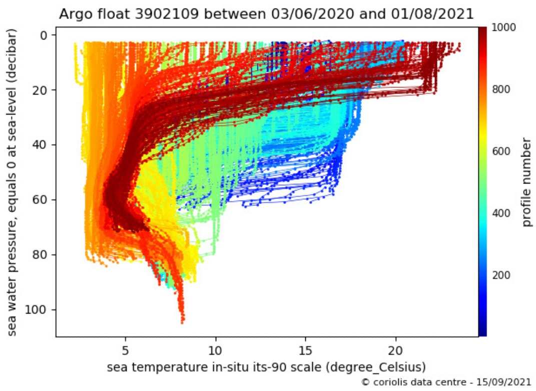

Figure 2. Temperature profiles of Argo float WMO 3902109 in Gdansk Bay. Raw data.

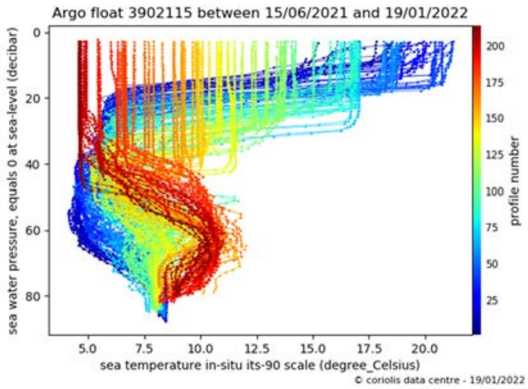

Figure 3. Temperature profiles of Argo float WMO 3902115 in Bornholm Basin. Raw data.

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Radiation budget at the Baltic Sea surface in 2010-2021

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1. Introduction

The relations between the amount of radiant energy reaching and leaving the Earth's surface determine our climate. On a global scale, the invariability of the climate should guarantee the balance between the amount of energy reaching the upper atmosphere in the form of solar radiation and energy leaving the Earth's atmosphere in the form of solar radiation and long-wave (thermal) radiation. While the first parameter is determined mainly by geographical factors, the amount of energy leaving the upper limit of the atmosphere depends on the composition of the atmosphere, temperature and surface temperature and its type. These, in turn, are now closely related to human activity and directly affect the observed climate changes. These changes should be reflected in disturbances, inter alia, in the radiation budget on the Earth's surface, also observed on a local scale.

The aim of this work is to show the changes in the Net radiation budget on the surface of the Baltic Sea in 2010-2021 and the possible trend of these changes.

The analyzes cover the area of the entire Baltic Sea and its selected regions. The presented values were determined according to the same methodology for each year.

2. Methodology

The analysis used maps of the distribution of the radiation budget Net on the surface of the Baltic Sea determined within the SatBaltyk system (satbaltyk.iopan.gda.pl). Net is the difference between sum of downward shortwave SWd and longwave LWd radiation and sum of upward shortwave SWu and longwave LWu radiation. Net algorithms component used satellite information from SEVIRI, AVHRR, SBUV / 2, TOVS, MODIS radiometers as input data and as auxiliary data from numerical models M3D, 3D CEMBS, UMPL. The algorithms are described in the works Zapadka et al. (2020), Paszkuta et al. (2019), Krężel et al. (2008). The algorithms were verified with MD (mean bias difference) and RMSD, respectively, for monthly averages SWd 2.9 Wm^{-2} and 2.7 Wm^{-2}, SWu 0.1 Wm^{-2} and 1.1 Wm^{-2}, LWd -0.8 Wm^{-2} and 4.5 Wm^{-2}, LWu 2.6 Wm^{-2} and 3.7 Wm^{-2} and Net -0.5 Wm^{-2} and 3.7 Wm^{-2}.

The spatial resolution of the maps used is 1 km. Monthly and annual maps were created on the basis of daily maps.

The input data for the entire analyzed period came from the same sources.

3. Results

Figure 1 shows the changes in the radiation budget at the surface of the Baltic Sea, averaged for the entire area and selected points in the years 2010 - 2021. The graph was prepared on the basis of the maps in Figure 2. The Net varies from 20 Wm^{-2} to 100 Wm^{-2} on these maps. Average annual values for entire Baltic Sea and individual years range from 59 Wm^{-2} to 75 Wm^{-2}. Figure 1 shows an increase in the value of the Net in the analyzed period. By analyzing the time sequence of Net maps (Figure 2), we observe regions of increase and decrease in the value of NET. The maximum differences from the average for this period are -9 Wm^{-2} for 2010 and 6 Wm^{-2} for 2020. Much greater differences appear in the areas of ice occurrence (blue points on the Fig. 1).

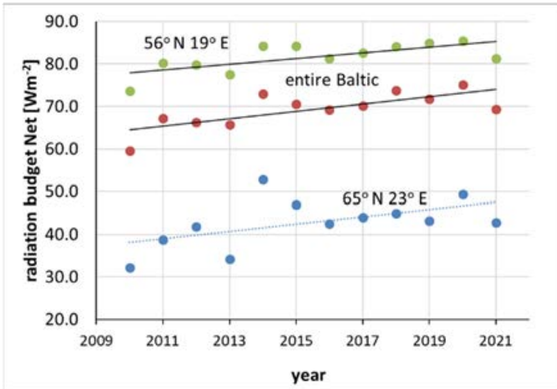


Figure 1. Change of radiation budget Net in 2010 – 2021 for the entire Baltic Sea and two chosen points.

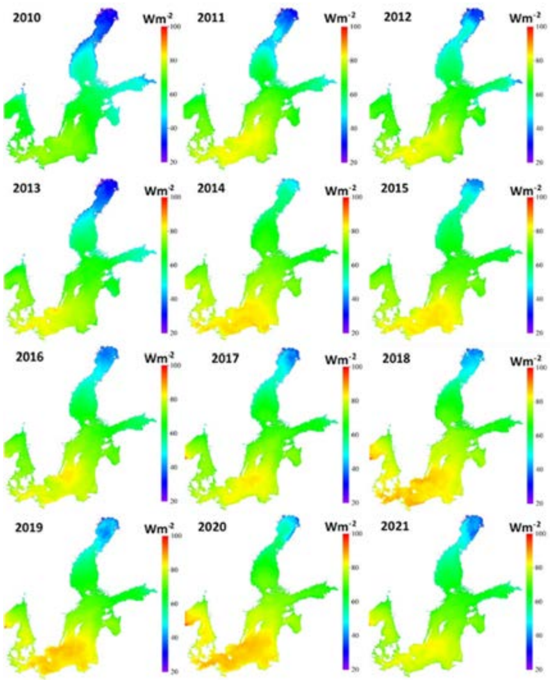


Figure 2. Maps of the radiation budget Net for 2010 – 2021 at the Baltic Sea surface.

Figure 3 shows the Net changes for all months. A growing trend occurs in March, June, July and December. In each month of the analyzed period, there will also be values that significantly increase or decrease the monthly average for all years. As can be seen from this figure, the Net averages for the entire Baltic Sea remain positive from March to October. Which means more energy reaches the surface of the sea than comes out of it. In the remaining months, the

Baltic Sea gets cold. A minor anomaly occurs in February 2014. The monthly average value is 6 Wm^{-2}, while in the remaining years it is even – 24 Wm^{-2}.

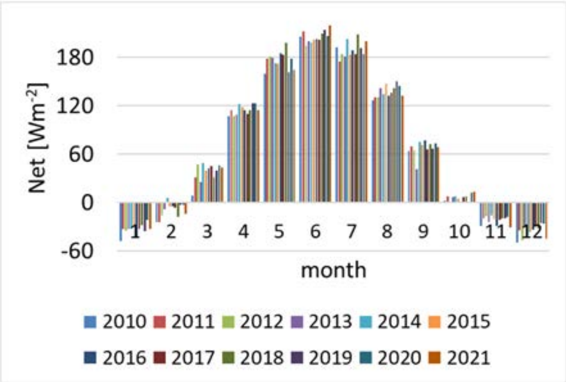
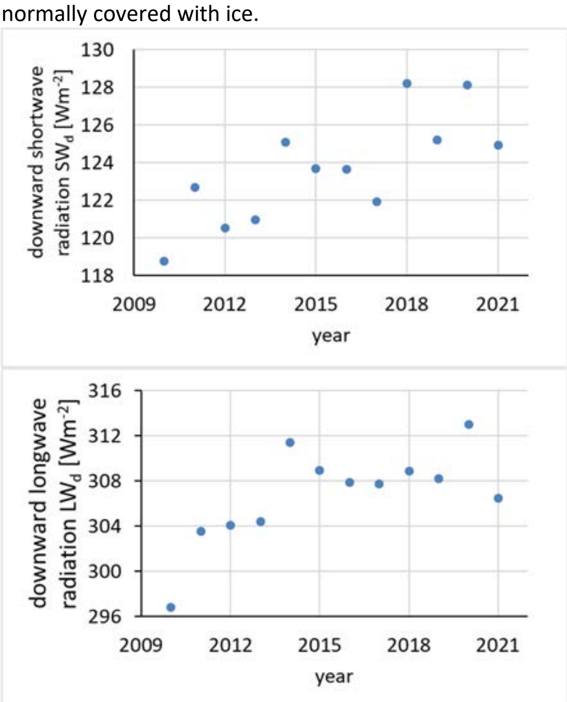


Figure 3. Changes of the radiation budget Net for 2010 – 2021 at the Baltic Sea surface for each moth.

4. Summary

The presented results show the Net growth trend in 2010-2021 on the Baltic Sea surface. This means an increase in the value of downward radiation fluxes (SWd and LWd) in relation to the upward radiation fluxes (SWu and LWu). However, if we look at the changes in all fluxes, we can see a growing trend (Figure 4). An increase in SWd must be associated with a decrease in cloud cover or a decrease in the share of low layered clouds in the cloud cover. An increase in LWd is associated with an increase in air temperature and, assuming a decrease in cloud cover, an increase in greenhouse gases. In the analyzed years, the temperature of the water surface also increased (look LWu Figure 4). This could be translated into a decrease in the areas covered with ice and the length of its occurrence. This effect reduces the value of reflected radiation for areas normally covered with ice.



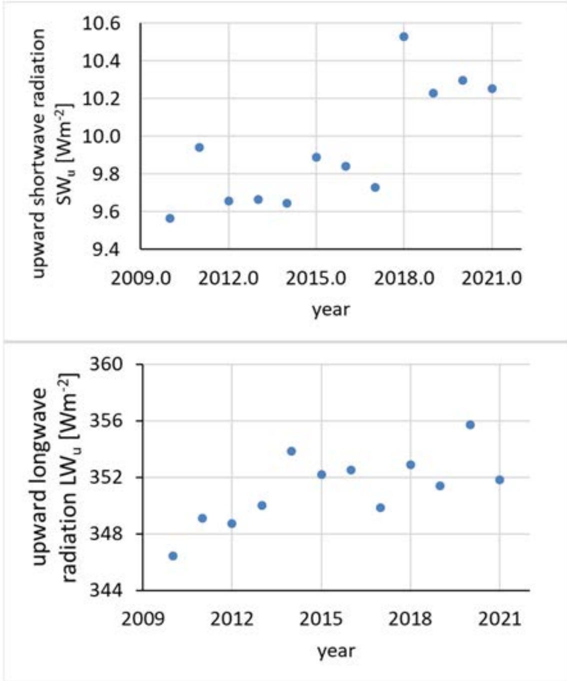


Figure 4. Changes of the radiation budget components SWd, LWd, SWu, LWu in 2010 – 2021 for entire Baltic Sea surface.

The presented results of changes in Net in the analyzed period undoubtedly fit into the observed trends of changes related to the warming of the region. The uniform methodology used for these studies, as the material is collected, will allow in the future to answer whether it is a periodic trend or a permanent increase related to climate warming.

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Topic 6

Human impacts and their interactions

120 years of research on benthic habitats, human-induced threats and climate change affecting the Puck Lagoon – a literature review

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1. Location

The Puck Lagoon is the innermost part of the Puck Bay and the western part of the Gulf of Gdańsk, the southern Baltic Sea. The Baltic Sea displays a specific gradient in species richness and functional diversity that falls away with diminishing salinity from W to NE. The Polish Exclusive Economic Zone (Polish EEZ) is situated in the center of the above gradient, and the Puck Bay is regarded as the most diverse and biologically valuable part of the Polish Marine Areas. The Puck Lagoon is under strong anthropogenic pressure, hence eutrophication, chemical pollution, and mechanical disturbance of the seabed are the main determinants of negative changes in benthic communities (Zima 2019; Pazikowska-Sapota et al. 2020).

2. Uniqueness of the Puck Lagoon environment

The Puck Lagoon is a unique reservoir in the southern part of the Baltic Sea. Its average depth is about 3 m and it's characterized by relatively low salinity (Demel 1935). Despite shallow depths throughout the area, the influence of wind and surface currents on the bottom of the Puck Lagoon is negligible. (Szymczak and Rucińska 2021). In the north it is separated from the Baltic Sea by the Hel Peninsula, while in the south its border is marked by sand bank. This unusual topography of the sea floor causes limited water exchange with the rest of the Gulf of Gdańsk and high susceptibility to wind. Specific hydrological and geomorphological conditions affect the development of diverse and relatively rich plant and animal communities, multi-species underwater meadows shape the richness of benthic and pelagic fauna communities. Many types of habitats in its area - from the dominant sandy substrate, through coastal reed beds and regenerating underwater meadows of *Zostera marina*, to stone reefs at the foot of the 'Orłowo' cliff, known as biodiversity oases. Apart from naturally formed elements of boulder reefs, in the Puck Lagoon one can also encounter hard substratum of anthropogenic origin such as old military buildings or harbour constructions. Like the natural hard bottom, it is characterized by an increased biodiversity of organisms compared to the nearby sandy areas, but it is also more likely to be inhabited by alien species.(Gic-Grusza et al. 2009; Włodarska-Kowalczuk et al. 2010; Sokołowski et al. 2015, 2021; Brzana and Janas 2016).

The Puck Bay creates specific Baltic micro-habitats, e.g., low salinity, high influx of freshwater from rivers and groundwater sources, covering a range of benthic habitats. Benthic animals are typical "ecologically tied" to a particular section of the seabed that is considered their habitat. Each species has different habitat type preferences based on its biology. The main factors determining the presence of a given species are its sensitivity to chemical pollutants, physical disturbances of the bottom, or anthropogenic pressure (stress factors), which indirectly contributes to increasing the negative impact of the other two factors. The sensitivity of benthic animals, incl. on environmental disturbances, it can be used to assess its quality. The structure of the benthic community inhabiting a given ecological niche directly indicates the prevailing living conditions for organisms.

3. Anthropogenic pressures

Puck Lagoon is under strong anthropogenic pressure. Cultivated areas and river runoff significantly contribute to the increased amount of nutrients flowing into the waters of the Inner Bay of Puck. On its shores there are many small towns that are popular tourist accommodation, especially in the summer. Increased numbers of tourists cause more litter being left on beaches, and the "trampling" process affects beach and dune organism assemblages such as sand hoppers (Koziel 2004; Duarte et al. 2010, 2020).

4. Long story short

The Bay of Puck, is one of the most studied regions in the Baltic Sea and has been selected as a site with a long-term biodiversity record, thus representing a class of European Marine Biodiversity Monitoring Sites, since 1920-ties regular marine biological research are going on. In addition, there are even older reports about the condition of the Puck Bay from pre-war times (Lakowitz 1907). From the 1950s, the ecological condition of the Bay of Puck was deteriorating from year to year, among others, through runoff of untreated municipal wastewater, and extremely valuable habitat types have gradually disappeared. The worst condition of the environment was recorded in the early 1980s when the residual underwater meadows were present only in the vicinity of Rzucewo. Since the beginning of the 1990s, there has been a continuous improvement in water purity and the revival of underwater meadows, which indicates an improvement in the quality of the environment in the Bay of Puck. In the post-war times, intensive urbanization resulted in an increase in the amount of sewage discharged into the waters of the Bay of Gdańsk. Pollution has led to significant degradation of many habitats or even their loss, eg *Fucus vesiculosus*, so far this species has not been returned. Currently, a significant improvement in the water quality of the Puck Lagoon is observed, but it is not known what condition individual habitats are in and how much pressure is exerted on them.

5. Conclusion

The purpose of this literature review is to examine changes occurring in the Puck Lagoon and its habitats. Identification of the threats that have the greatest impact on the inhabiting benthic communities is critical to both assessing the past and making important decisions for the future of the Puck Lagoon.

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Beach litter composition along the southern coast of the Baltic Sea (2015-2021)

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1. Introduction

Human activity and widespread use of plastic materials led to an increasing number of discarded, disposed, or abandoned litter in the marine environment. With almost 95% of litter accumulated on shorelines, the sea surface, and the seafloor, made of plastic (Galgani et al., 2015), marine debris is one of the most ubiquitous and fastest spread types of pollutants in the marine ecosystem (Beaumont et al., 2019; Pierodomenico et al., 2019).

The study aimed to describe the abundance and variability of beach litter on the southern Baltic coastline based on a 7-year dataset. Our research was also aimed at checking whether and to what extent the pandemic situation influenced the number and type of beach litter

2. Materials and methods

Litter was collected from 15 sections located along the entire Polish coast of the Baltic Sea. To improve the reliability of the results, sections length was set up to 1 km. Sampling locations were chosen to represent both urban and rural beaches. Some sections were also located close to the most significant Polish rivers, Vistula and Odra. The study period covered the years 2015-2021. Surveys took place four times a year – during spring, summer, autumn, and winter.

The area of each section covered the entire section's width, from the seashore to the beach border. Every litter item found, was assigned to one of seven categories: artificial polymer materials, processed/worked wood, metal, glass/ceramics, paper/cardboard, cloth/textiles, and rubber, or was classified as undefined. Sources of litter origin were classified into four basic categories: tourism and recreational activities, fisheries, sanitary and medical and other (including intentionally discarded litter). All data were stored in a dedicated database enabling statistical calculations.

3. Results

The total number of items collected in 2015-2020 was 97 384, with the highest number in 2016 (20 322) and 2018 (20 829). The lowest value was recorded in 2017 (10 523). In other years number of identified litters ranged from 12 298 (2020) to 17 448 (2015). Results from 2021 (5 895) did not include data from the winter season.

Artificial polymer material was indisputably the most abundant category on the Polish coastline (Figure 2). Almost 70% of collected items were classified as plastics. Processed/worked wood was the second most frequent category during the entire study period, followed by paper and metal (>10% and <10%, respectively). Glass/ceramics and paper/cardboard shared 3-6% depending on the year of sampling. In most cases, the percentage share of cloth/textiles, rubber, and undefined litter was at a constant level of about 1-2%.

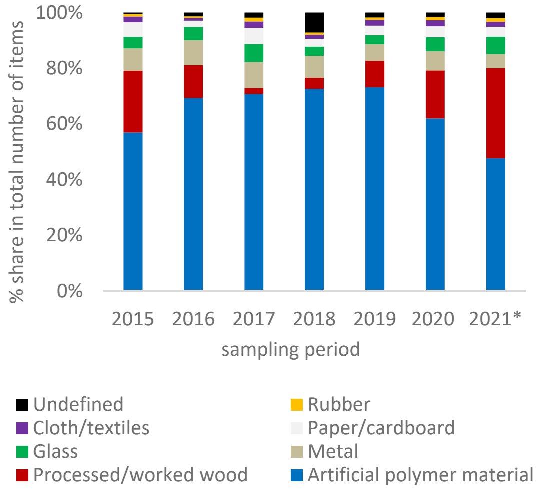

Figure 1. Categories of beach litter collected along the southern Baltic coast from 2015-2021 (*data not available for winter).

The type of the beach seemed to have an impact on litter abundance (Figure 2). Rural beaches, located in the areas outside the city and beyond their direct influence, were characterized by almost half the lower number of collected litter items (33 250 vs. 64 371 items).

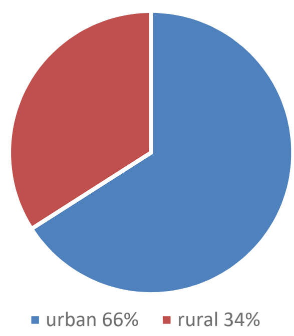

Figure 2. Percentage share of litters found on different type of beaches (urban, rural) along the southern Baltic coast in 2015-2021.

Considering the seasonal variability of beach litter (Figure 3), it was noticed that litter collected during summer and autumn represented more than 50% of the total number of items collected each year. Such data distribution reflects intensified human activity (tourism and recreation) in this part of the year. It is supposed that the amount of litter could have been even greater.

However, cleaning activities were usually more frequent during this time.

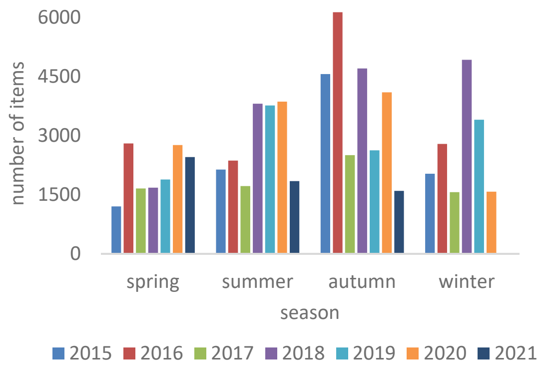

Figure 3. Total number of items collected along the southern Baltic coast from 2015-2021 divided into four seasons.

Sources of marine litter can be divided into land and ocean-based. On a global scale, land-based sources are of more significance. The vast majority of litter (63%) described in this research was abandoned on the beach due to tourism and recreational activity. Only 4% originated from fisheries. Litters assigned to sanitary and medical items should also be considered an effect of tourist activity. It is difficult to identify their other origins, given that rivers could be the only other source. Although it is forbidden to throw such waste into toilets, such litter is retained in sewage treatment plants if it gets there. Then, their presence in rivers can only come from tourist activity.

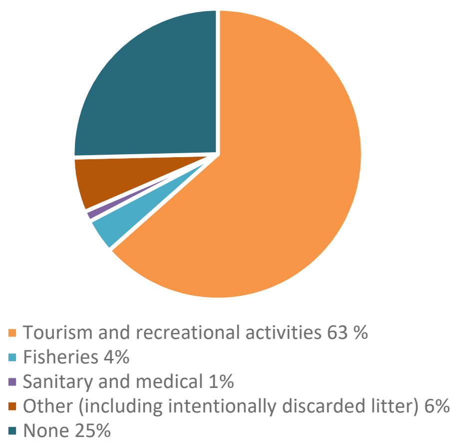

Figure 4. Sources of beach litter collected along the southern Baltic coast in 2015-2021.

Covid-19 pandemic had influenced human activity and forced authorities to introduce restrictions which may have helped limit the spread of the virus (e.g., closing hotels and restaurants, limiting the number of people in those kinds of facilities, temporary ban for visiting the beaches and forests). A decrease in the number of litter originating from tourism (Figure 5) and recreational activities in 2020 and 2021 may be related to the reduced beach accessibility caused by the pandemic.

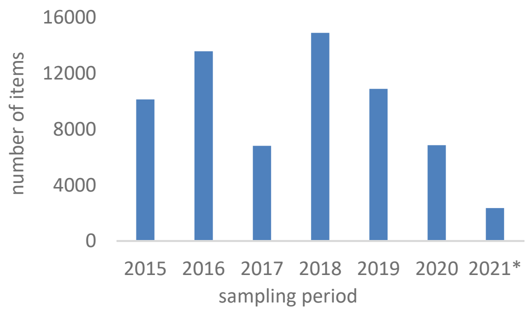

Figure 5. Number of litters related to tourism and recreational activities collected from beaches of southern Baltic Sea in 2015-2021 (*data not available for winter).

4. Summary

Over 100 000 litter items were collected, identified, and described during this study. The dominant category of beach litter along the Polish coastline was artificial polymer materials with a share of almost 70%. A comparison of urban and rural beaches showed differences in litter abundance with almost two-fold dominance for urban areas. More than 50% of the debris collected each year was recorded during spring and autumn. Tourism and recreational activities were identified as the primary source of beach litter. The pandemic situation may have caused a decrease in the total number of items collected along the Polish coastline recently.

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Sediment stratigraphy studies reveal variable POP concentration trends in the Baltic Sea environment

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1. Proof of effectiveness of conventions is needed

There is an urgent need in practically all international conventions (Stockholm Convention on POPs, Minamata Convention on Mercury, LRTAP, OSPAR, HELCOM) and EU legislation to show the effectiveness of the already implemented regulation of the most dangerous substances.

Sediment core studies are a cost-effective method to reveal the recent history of substances with high affinity to particle phase. This method has been used in different fora for decades but has been somewhat forgotten at least in Europe in regulatory monitoring in the 2000's, due to focusing on quality standards based on water and biota. However, sediment core sampling and analyses may actually be much easier to harmonize between countries, compared e.g. to differences in food web structures affecting the species selection for monitoring.

2. Sediment cores – cost effective tool for trend assessment

The concept is based on sampling of short sediment core (height of ca. 10 to 30 cm) which is cut to1–2 cm thick subsamples. Based on chemical analysis and Pb210 and/or Cs137 -dating of these samples the concentration trends of contaminants and their sedimentation rates can be assessed.
We have analysed and dated sediment cores from the Gulf of Finland (figure 1) for PAHs, PCBs, PCDD/Fs, PBDEs and PFASs.

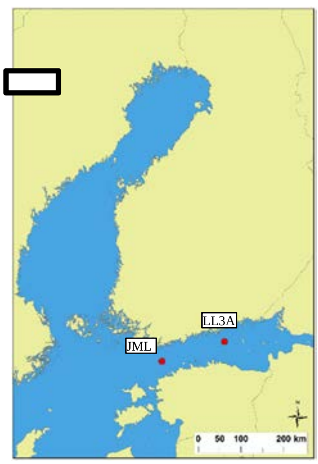

Figure 1. Locations of the sediment core sampling sites.

3. Concentrations of "new" compounds are rising

The results show declining concentrations for most of the contaminants, especially for PAHs, PCDD/Fs and PCBs over the last couple of decades (figure 2). This indicates that restrictions previously set have been effective and have had impact on contaminant levels in the environment.

However, results also reveal recent increase in concentrations of several long-chained PFASs, e.g PFOS, PFUnDA and PFTrDA (figure 3). Also, the results indicate the substitution of restricted PFOS by other PFASs and support the need of regulation of PFASs as a group, rather than as individual compounds.

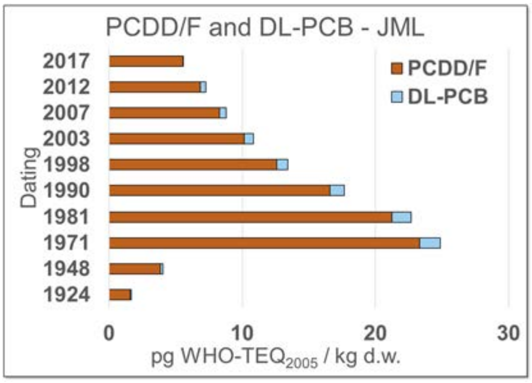

Figure 2. Concentrations and PCDD/Fs and DL-PCBs in dated sediment samples from the site JML.

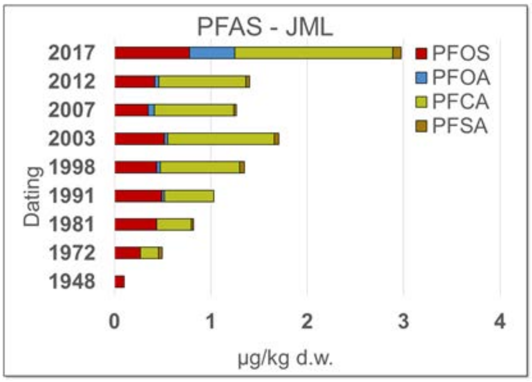

Figure 3. Concentrations and PFASs in dated sediment samples from the site JML.

Environmental impact of the water exchange blocking in a shallow strait

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1. Introduction

Straits play an important role in water and matter exchange between basins. Väike Strait is a narrow (2–4 km wide) and shallow passage in the sensitive Natura 2000 habitat area in the West Estonian Archipelago (Fig. 1). Water exchange in the Strait has been blocked by a 3 km long road dam (Fig. 2) since 1896. The only opening connecting the two parts of the strait is a 4 m wide canal near Muhu Island (Figs. 1 and 2).

The main aim of the present work is to assess the environmental impact of the dam and estimate the potential effect of the construction of openings (bridges).

2. Data

Measurement campaign and numerical simulations were arranged in 2020–2021 to understand the conditions and dynamics of the marine area. Six spatial mappings of the physical and biogeochemical parameters in the water column were conducted. Likewise, time-series of currents and several water column parameters were registered at the buoy stations. Samples were collected and ROV observations were conducted to map the phytobenthos and zoobenthos community. Fish sampling on both sides of the dam was conducted. Likewise, sediment samples were collected to determine the hazardous substances and total nitrogen and total phosphorus content. The numerical model GETM with a high resolution grid spacing (Burchard & Bolding, 2002) was applied to study the water exchange and physical parameters of the water column in the area.

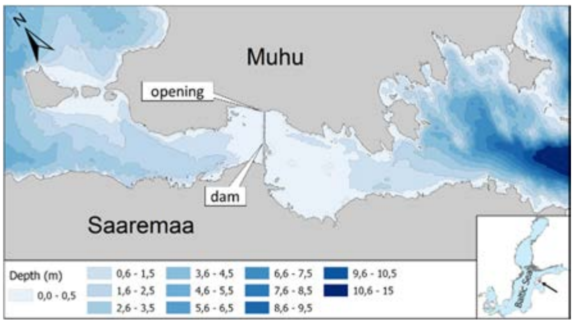

Figure 1. Bathymetry of the Väike Strait.

2. Results and conclusions

Prior to the construction of the dam, the movement of water in the strait was free. Nowadays, there are virtually two bays with separate circulation systems. The simulated circulation showed that the water exchange between the areas close to the dam and the neighboring areas have decreased 10–12 times.

Earlier investigations have claimed that the dam separates the two water masses: fresher and nutrient-rich Gulf of Riga water, and saltier and lower nutrient content water in the Väinameri Archipelago. Our observations showed that high salinity in summer (up to 8 g kg^{-1}) occurs near the dam. Such high surface salinity is common in the western Baltic Sea (Karlson et al., 2016), but not in the eastern Baltic. Salinity maximum near the dam was likely the result of the restricted water exchange. Since the advection is weakened, the role of vertical processes, including the exchange with the atmosphere, has a relatively higher contribution in the change of water characteristics. Thus, in the conditions of low- horizontal water exchange and mixing, the role of evaporation could lead to a salinity maximum near the dam in summer. Another implication of the weak water exchange was the strong diurnal cycle in water temperature and dissolved oxygen. The diurnal amplitude occasionally reached over 4 °C and 4 mg l^{-1} in summer, respectively.

Probably, also due to weak water exchange and high productivity, the total nitrogen content maxima in the water column were observed near the dam. Oxygen saturation and concentration occasionally dropped below 30% and 4 mg l^{-1}, respectively, during the presence of ice cover.

Nitrogen content in sediments near the dam was also 3-4 times higher than in neighboring areas. Likewise, elevated content of hazardous substances in the sediments was detected near the dam.

Figure 2. Photo of the dam from Muhu Island side. The canal is the only opening through the dam. The photo was taken by Heiki Hanso.

Phytobenthos community near the dam was dominated by the filamentous annual algae. Zoobenthos community was more diverse in the northeastern area from the dam. Although the fish community in the two sides of the dam were generally similar, some discrepancies in species composition were found.

Despite the small size of the existing opening, its impact on the water column parameters, such as salinity, chlorophyll *a* and total suspended matter concentration was detected by measurements. The numerical simulations showed that two openings with a total width of 56 m would enhance the water exchange near the dam 32–45% and likely will alleviate the described effects resulting from restricted water exchange, including high nutrient concentrations near the dam. The openings will improve the fish migration.

Acknowledgments

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Selenium in marine plankton in the Gulf of Gdansk, southern Baltic Sea

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1. Introduction

The major toxicological hazard associated with selenium (Se) is its efficient incorporation into aquatic food webs by primary producers and subsequent trophic transfer to the higher trophic levels via dietary pathways. However, our understanding of the factors controlling Se accumulation in marine food webs is surprisingly limited. Very few studies have investigated Se interactions with primary producers at the base of marine food webs (Stewart et al., 2010; Janz, 2011), especially in the Baltic Sea region.

The natural Se concentrations in most freshwater and saltwater environments are low (0.01–0.1 g·dm^{-3}), but certain anthropogenic activities can increase Se loading into aquatic ecosystems (Maher et al., 2010). In addition, the composition of phytoplankton assemblages often shifts seasonally, so Se uptake by the prevailing algal assemblage might also vary, consequently affecting overall Se accumulation in organisms at higher trophic levels.

The aim of the present study was to identify the levels of total selenium concentration in water, phytoplankton and zooplankton community of the Baltic Sea, and to determine the factors affecting the spatial and temporal variability of selenium concentration in plankton. By combining chemical and biological analyzes, we want to determine which organisms are particularly responsible for Se absorption from the environment and its transfer to higher trophic levels.

2. Study area

Samples were taken from the southern Baltic during seven cruises from the r/v Oceanograf research catamaran, which took place in 2019-2020. Samples were collected in the Gulf of Gdansk, where three regions were distinguished (figure 1): Vistula mouth (stations Sw2 and Sw4), central part of the Gulf of Gdansk (So4 station) and open sea (LIVIA station). The cruises took place once a season. The exception was summer, when there were three cruises (twice in July and once in August), due to the high variability of species composition of plankton in this period. At that time, one of the cruises took place in the southern Baltic region at stations P1, P2, P3, P5, P16, P140 and Ł7 (figure 1).

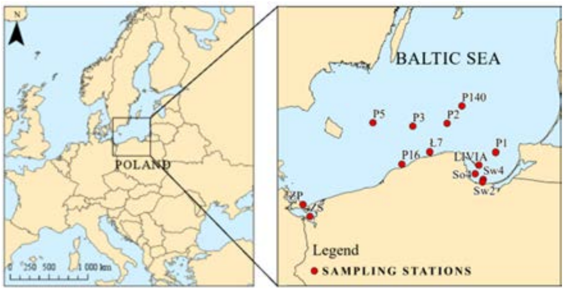

Figure 1. Sampling stations

3. Materials and methods

During the cruises, samples of water, zooplankton and phytoplankton were conducted. Bathometer was used for water sampling, but also surface water were collected. Whereas phytoplankton and zooplankton were collected by phytoplankton net (25 µm) and closed-type WP-2 zooplankton net (100 µm), respectively. Phytoplankton were collected on the surface, zooplankton from the surface to the halocline and below the halocline or from the entire water column. For chemical analysis water samples were preserved by adding 4 ml of HCl (0.4% v/v), while plankton samples were stored at -20 °C.

Plankton samples for total selenium analyzes were concentrated on pre-cleaned Whatman GF/F filters, then frozen, freeze-dried and mineralized (Polak-Juszczak, 2015). Total selenium concentration in plankton and water samples was determined by inductively induced plasma mass spectrometry (ICP-MS). Qualitative and quantitative analysis of phytoplankton cells was performed using an inverted microscope (Nikon TMS, Tokyo, Japan) equipped with phase contrast and magnification 100 ×, 200 × and 400 ×. The samples were analyzed using the Utermöhl method as recommended by the Helsinki Commission (HELCOM, 2020). The qualitative and quantitative analysis of zooplankton was performed using the NIKON SMZ-18 stereoscopic microscope. Depending on the compaction of the planktonic material, the samples were divided into subsample using a Motod box-splitter (Motoda 1959). Zooplankton analysis was in accordance with HELCOM procedures (HELCOM 1988, Hernroth 1985).

4. Results and discussion

The concentration of selenium in water in the studied regions of the Baltic Sea had a wider range than that presented in the literature (table 1). Median concentration of this element in water in the Gulf of Gdansk was 0.34 µg·dm^{-3}, in phytoplankton - 1.11 µg·g^{-1} d.w., in zooplankton - 1.22 µg·g^{-1} d.w. Se concentrations in open area of southern Baltic were within the Se concentration range in the Gulf of Gdansk, which may indicate a certain specificity of the research area.

Table 1. Comparison with literature data

research region	TSe in water [μg·dm^-3]	TSe in phytoplankton [μg·g^-1]	TSe in zooplankton [μg·g^-1]	author
Gulf of Gdansk	<LOD - 1,09	<LOD - 3,40	<LOD - 5,85	current research
Region of southern Baltic	<LOD - 0,69	0,05 - 0,76	0,05 - 2,00	current research
Baltic Proper	n.d.	0,00 - 0,60	0,00 - 2,00	Kumblad, 2008
Coasts of Norway	n.d.	n.d.	2,20 - 4,90	Bryszewska and Måge, 2015
Ligurian Sea	n.d.	n.d.	0,22 - 0,52	Batuello et al., 2016
	n.d.	0,10 – 5,30	n.d.	Boisson and Romero, 1996
Laptev Sea	n.d.	n.d.	3,62 - 6,19	Lobus et al., 2019
Bay of Bengal (Indian Ocean)	0,11 - 0,18	n.d.	1,19 - 1,90	Srichandan et al., 2016
Gulf of Aqaba (Red Sea)	0,18 - 0,74	n.d.	n.d.	Al.-Taani et al., 2014
Suruga Bay (Pacific Ocean)	n.d.	n.d.	0,10 - 0,32	Sakata et al., 2014

In the case of selenium concentration in water, statistically significant differences were observed at the LIVIA station between the selenium concentration in the surface layer of the water and the deeper layers. On the basis of the available literature, it was found that the reason for these differences could be downwelling and the accumulation of dead organic matter being the source of selenium. Statistically significant differences were also observed in the case of the seasonal variability of phytoplankton and zooplankton. It was found that the concentration of selenium in water did not determine the concentration of selenium in phytoplankton and zooplankton. Most likely, it was the form of selenium in the water that influenced the concentration of selenium incorporated into the plankton. It was found that an important source of selenium in plankton in the Gulf of Gdansk, apart from the Vistula river, could also be atmospheric deposition and dumping ground.

An important role in shaping the selenium concentration in phytoplankton and zooplankton in the Gulf of Gdansk had the biomass of organisms. In summer, when high biomass of cyanobacteria (Cyanobacteria), clam larvae (Bivalvia veliger), flagellates (Flagellates) and the total biomass of zooplankton was found in plankton, the process of selenium biodilution was observed. In consequence, the lowest Se concentration in plankton was measured. However, during this time, the highest biomagnification factor occurred. This suggests that in summer, during the intense blooms of phytoplankton (cyanobacteria), the incorporation of selenium into the sea trophic chain was most effective. On the other hand, in autumn and winter, when copepods (Copepoda), *Mesodinium rubrum* and snail larvae (Gastropoda velger) dominated in plankton biomass, the process of selenium enrichment in plankton was observed. During this period, bioaccumulation and biomagnification were also effective. Nevertheless, to fully understand the dynamics of changes in selenium concentration in water, phytoplankton and zooplankton more research is needed.

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Heavy metals transfer routes to the Baltic Sea and ecohydrological approach to their reduction

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1. Introduction

Due to the constantly progressing anthropogenization of the environment and the increasingly denser population of the Baltic Sea catchment area, significant amounts of pollutants constantly enter this basin (Kuliński et al., 2021). The fact that the area of the Baltic basin is four times the surface of the sea itself (Figure 1) and is inhabited by 84 million people means that it is constantly exposed to the influx of anthropogenic pollutants, including toxic heavy metals (Kiedrzyńska et al., 2014; HELCOM, 2018; HELCOM, 2021). Moreover, its inland location means that the time of complete water exchange with the North Sea ranges from 25-35 years. In addition, the Baltic Sea is supplied with freshwater flowing from the area of nine highly industrialized and well-developed agricultural Baltic countries. All this makes the Baltic Sea one of the most polluted sea basins in the world (Kiedrzyńska et al., 2014; Lodenius, 2016). Therefore, the aim of the research is a holistic analysis of the main sources of pollution of the Baltic Sea with heavy metals and to propose model ecohydrological remediation activities in the field of nature-based solutions (EH Nature Based Solutions) (Zalewski 2020, Kiedrzyńska et al. 2017) to reduce their transfer from the catchment area to the sea.

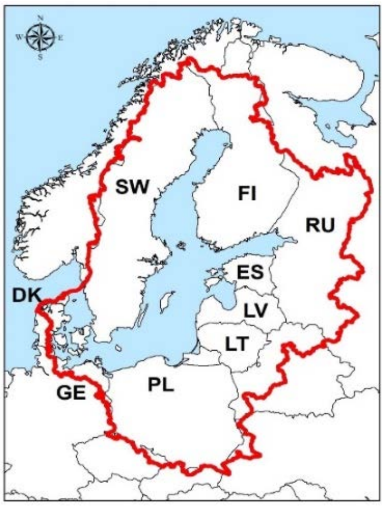

Figure 1. The catchment area of the Baltic Sea (PL-Poland, LT-Lithuania, LV-Latvia, ES-Estonia, RU-Russia, FI-Finland, SW-Sweden, DK-Denmark, GE-Germany).

2. Sources of heavy metals emission

Heavy metals are one of the key pollutants of the Baltic Sea ecosystem. The sources emitting their greatest amounts to the environment include: agriculture, industry, transport, extraction of amber in the coastal zone, urbanization and wastewater discharges from sewage treatment plants (Jitar et al., 2015). For example, in 2014, in the Baltic Sea catchment area (nine surrounding Countries), there were 487 treatment plants discharging treated sewage directly into the sea (direct pollution sources), 4230 treatment plants discharging sewage into surface waters (indirect pollution sources), and 1814 industrial plants constituting direct and indirect sources of pollution with heavy metals (HELCOM, 2019). Moreover, in the Baltic states belonging to the European Union, included in the Baltic catchment area (Germany, Denmark, Lithuania, Latvia, Estonia, Finland, Poland, Sweden), in 2007 there were approx. 3 308 300 farms, which constituted almost 24% the total number of such farms across the EU. It is estimated that in the same year the area of agricultural land in these countries amounted to approx. 458 018 km^2, and compared to 2005, their increase was recorded by 1.16% (EUROSTAT, 2011; EUROSTAT, 2008). Additionally, in 2007, 1 011 975 vehicles were withdrawn from use in the above-mentioned countries. Eight years later, in 2015, it was 1 288 382 cars (excluding Denmark) (EUROSTAT, 2017). All this proves the extremely rapid progress of anthropogenization processes, and thus increased anthropogenic pressure on the environment in the Baltic states.

3. The influence of heavy metals on living organisms

Even a small increase in the concentration of heavy metals in aquatic ecosystems can lead to the generation of negative effects both for individual living organisms (through bioaccumulation and biomagnification as well as toxic effects and impact on the decline in species biodiversity) (Wang et al., 2018; Krek et al., 2019); as well as for the trophic chain (through accumulation), ultimately ending up in the human body (Zhang et al., 2015; Jitar et al., 2015). A study by Perttilä et al. (1982) showed that heavy metals were present in the organisms of the cod. Moreover, these studies showed that metals, i.e. lead, cadmium, mercury, were detected in the organisms of Baltic herring, and their concentrations per kilogram of body weight were, respectively: for Pb 0.05 mg / kg; for Cd 0.006 mg / kg and for Hg 0.021 mg / kg. The impact of heavy metals on the human body is very negative, as they can cause many negative effects, incl. carcinogenic effect, visual and hearing impairment, headaches, balance disorders, loss of coordination, fatigue, motor apparatus damage, impaired immune system, but also irreversible fetal defects and delays in prenatal development of children whose mothers were exposed to increased concentrations of heavy metals (Bosch et al., 2016).

4. Data analysis

Among the main routes of heavy metal emissions from highly industrialized areas to the Baltic Sea are atmospheric deposition and river runoff (HELCOM, 2021). In 2012, 162.92 tons of heavy metals were released from atmospheric deposition into the water environment of the Baltic Sea (HELCOM, 2014). In the period 2016-2018 the sea received, among others, 12.3 tons of cadmium and 8.5 tons of mercury (HELCOM, 2021). In 2012, waste incineration processes generated 2.2162 tons of lead, 0.1984 tons of cadmium and 0.3928 tons of mercury, and the combustion processes generated by the industry released a total of 343.716 tons of these compounds, which was a 25,5% increase compared to 2010 (HELCOM, 2014; HELCOM, 2012).

The Baltic Sea is supplied by water with loads of heavy metals through river systems (Lodenius, 2016). A large freshwater inflow from around 200 rivers provides about 400-500 km^3 of freshwater annually (Köhn, 1998). These rivers transport waters contaminated with heavy metals, nutrients and micropollutants from the catchment area of 1 749 209 km^2 (Kanwischer et al., 2021), including from point sources (municipal and industrial wastewater treatment plants, landfills) and from dispersed sources (runoff from urban areas, agriculture, industrial and mining sites). The largest seven rivers flowing into the Baltic Sea are: Neva, Wisła, Niemen, Dźwina, Odra, Göta älv, Kemijoki, with a total catchment area of 751 760 km^2 (HELCOM, 1998). The annual average inflow of river waters to the Baltic Sea is 14 000 m^3 (Kanwischer et al., 2021). According to HELCOM (2021), in the years 2012-2014 the Baltic received a total of 1 537.5 tons (t) of heavy metals (1 449 tons of lead, 75 tons of cadmium and 13.5 tons of mercury), of which 81% of the cadmium load and 62% the lead load and 30% of the mercury load came from the river runoff. In 2015, the amount of heavy metals (lead, cadmium, mercury) that entered the Baltic Sea along with river run-offs amounted to 257.7 tons. It accounted for almost 60% of the total amount that got into the basin that year. In 2016-2018 to the Baltic Sea with river run-offs were transported, among others, 478 tons of lead, 55 tons of cadmium and 5.7 tons of mercury. What is more, a 9.309 tons of these metals were released from point sources (HELCOM, 2021).

5. Summary

Although the uncontrolled release of heavy metals is prohibited in many countries, there are still many cases of contamination of the marine environment with these compounds (Manzetti, 2020). Only a thorough understanding of the sources of emissions and the scale of pollution with heavy metals allows for the development of an effective prevention policy and methods of remediation of water ecosystems. Nature Based Solutions are now an inseparable element of environmental remediation, therefore only through the use of integrated methods is it possible to have a real impact on the purification of aquatic ecosystems.

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Human impacts and their interactions in the Baltic Sea region

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1. Introduction

As part of the Baltic Earth Assessment Reports (BEAR), we present an inventory and discussion of different human-induced factors and processes affecting the environment of the Baltic Sea region, and their interrelations. Some are naturally occurring and modified by human activities (i.e. climate change, coastal processes, hypoxia, acidification, submarine groundwater discharges, marine ecosystems, non-indigenous species, land use and land cover), some are completely human-induced (i.e. agriculture, aquaculture, fisheries, river regulations, offshore wind farms, shipping, chemical contamination, dumped warfare agents, marine litter and microplastics, tourism, and coastal management), and they are all interrelated to different degrees.

We present a general description and analysis of the state of knowledge on these interrelations. Our main insight is that climate change has an overarching, integrating impact on all of the other factors and can be interpreted as a background effect, which has different implications for the other factors. Impacts on the environment and the human sphere can be roughly allocated to anthropogenic drivers such as food production, energy production, transport, industry and economy. The findings from this inventory of available information and analysis of the different factors and their interactions in the Baltic Sea region can largely be transferred to other comparable marginal and coastal seas in the world.

2. Factors of regional change

The industrial revolution and the subsequent developments like the industrial production of nitrogen fertilizers have dramatically changed the world, with massive benefits for humans and concomitant detrimental effects like anthropogenic climate change, eutrophication, overfishing, pollution and others. There is a growing understanding that the connections between these intertwined factors must be addressed. Many investigations have focused on the harvestable upper part of the food chain, e.g. fish and their food resources, and the Baltic Sea region or parts of it have been treated by various investigations.

Food production on land and in the sea has severe consequences on the ecosystems, through nutrient loads and resulting eutrophication and hypoxia, but also on the climate, due to the conversion of forests to agricultural fields. Offshore wind power production will presumably increase in the future, as the demand for renewable energy is growing in the effort to mitigate climate change, and extensive sea areas will be dedicated to wind power generation. Maritime transport of goods not only affects the climate through the combustion of fossil fuel but also has many direct consequences for marine life and water quality. It was shown in the past that regulations work slowly but efficiently (e.g. double-hull tankers, ballast tank regulations, antifouling regulations), so a transfer to more sustainable shipping can be expected in the future.

Climate change directly affects atmospheric and marine properties such as air and water temperature, precipitation, runoff, salinity, sea ice, sea level, and acidification. It affects the food production sector, as the growth of crops on land is temperature and water dependent, and in the sea, temperature is a significant growth factor for cultured fish and shellfish. Fish stocks are dependent on climate-sensitive availabilities of food organisms and stratification. In some cases, climate change affects different factors, which work antagonistically, and the net effect is not apparent. Sea level rise, for example, is expected to have a strong impact on the southern coasts and ecosystems of the Baltic Sea. Salinity is an essential factor for marine life in the Baltic Sea, and many species live in narrow tolerance bands. Hence, it is vital to know how salinity will change in the future. It may increase through intensified inflows (as sea level rise would widen the passages in the Danish belts and sounds), but conversely, it may be reduced by increased runoff. Currently it is unclear which effect is prevailing.

Looking at our analysis of the different drivers, it becomes evident that the pressures caused by climate change, food production, transport, energy production, industries and tourism have the largest impacts on the Baltic Sea region. We see that climate change, shipping and land use/agriculture have the strongest impact, while fishing, marine ecosystems and agriculture are most strongly affected. This semi-qualitative assessment holds for the Baltic Sea region but may be different for similar regions of the world, with different foci of human activities.

Human needs and values are the ultimate drivers determining the aggregate demand of different goods and services, strongly affecting the level of production, land use and environmental footprint of economic activities in the area. The large sectors that provide goods and services to humans (food, energy, transport, recreation) have the most direct impact on the Baltic Sea environment. From a scientific point of view, it is not possible to render a verdict on the most harmful impact on the environment, as this is largely not a scientific but a social construction. Different stakeholders, e.g. scientists, coastal dwellers, people who make a living from the sea, local policy makers or environmental activists, may all have different conceptions. This is also the case between the different riparian countries. Science can provide the facts as far as possible to help establish and support management options.

Full article with references:

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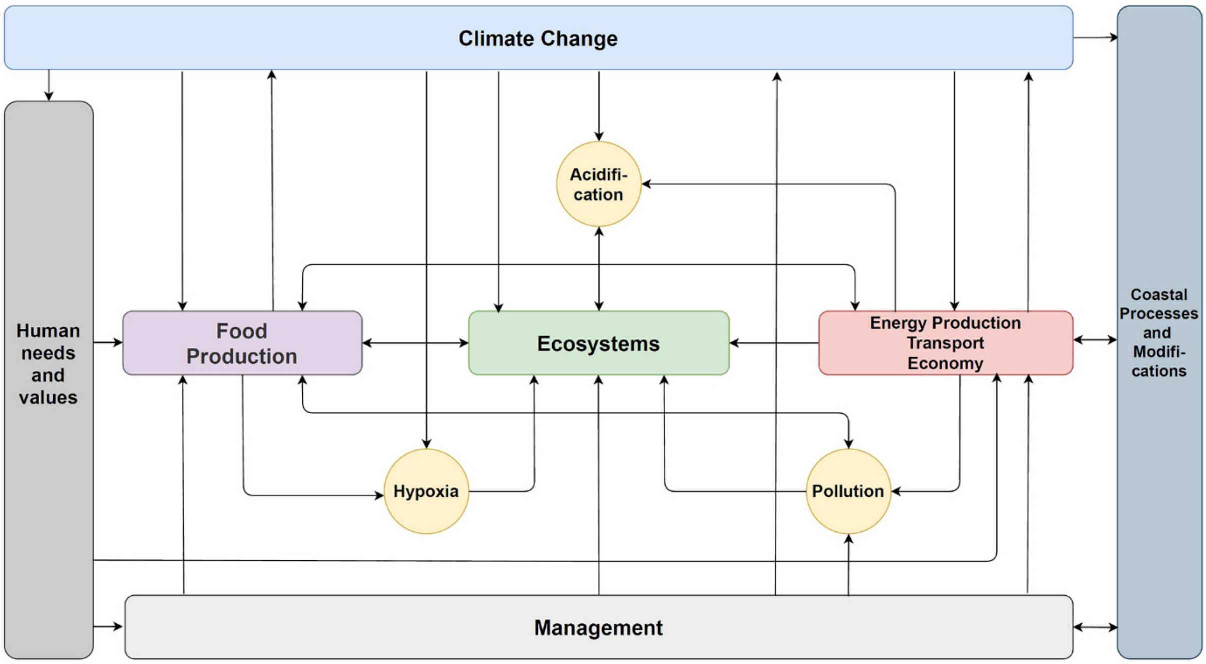

Figure 1. Interrelations between the different factors.

Application of photoacoustics-based methodology to complex plastics, biotic and chemical sea water pollution sensing

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1. Abstract

The aim of the research was to demonstrate the potential and operational novelty of photoacoustics (PA)-based techniques for sensing and quantitative characterization of complex chemical, plastics and photosynthetically-active contamination species occurring in natural water bodies. An alternative PA approach, so-called the diffusive reflectance (DR) PA modality, was used to study a variety of model seawater pollution samples (chemical drug (paracetamol)), plastics (PET) suspension and Baltic sea green algae cultures. Unique photoacoustic spectra features i.e., spectral maxima and bands intensities, were found unequivocally pointing to the particular pollution-forming component. Particularly, DR technique allowed to distinguish between the overlapping each other spectral maxima and stands for a complementary spectroscopic methodology being an effective tool to measure troublesome highly scattering light and opaque samples.

2. Introduction

Depending on the target contaminant quantification or classification of the water quality variables, several laboratory analysis techniques have been standardized for the water pollution control. These includes water pH, turbidity and conductivity measurements, spectroscopic (absorption, fluorescence, Raman), chromatographic or electrochemical water analyses etc. (Ting and Yee, 2020). Several sea water pollution monitoring techniques were created and utilizing light field interactions with a water sample mostly as reflection, scattering, adsorption-transmission, fluorescence and photoacoustics; their schematic presentation can be found in Fig. 1. of (Fisher et al., 2016).

Classical spectroscopic techniques such as transmission or reflectance are not amenable to biological materials due to opacity, scattering, poorly defined or heterogeneous biofilm surface properties. In particular, photoacoustic (PA) techniques are becoming increasingly useful for the measurement of spectroscopic properties of biological systems in vivo and in vitro (Guskos et al., 2008). This technique is based upon, so called, the photoacoustic effect, that is production of acoustic waves following the absorption of (modulated) light. The PA probing consists of two-steps. The first one includes a periodic photoexcitation of a sample enclosed in an air-tight chamber (see Fig.1); the excitation beam is usually modulated at frequencies up to approximately 1 kHz. The periodic light absorption by a sample is assumed to follow the Bear-Lambert law. The second step involves the PA response detection. The periodically generated heat diffuse throughout the sample up to the surface, where it induces periodic heating of the surrounding gas which acts as a piston and generates sound waves detected by a microphone. The optical absorption depth is only related to the optical properties of the sample. In the photoacoustic spectroscopy the thermal diffusion length μ_s (a certain sample thickness, which affects the signal amplitude at a fixed modulation frequency f), according to the theory (Charland and Leblanc, 1993), and is interpreted assuming a classical Rosencwaig-Gersho model (Rosencwaig, 1980).

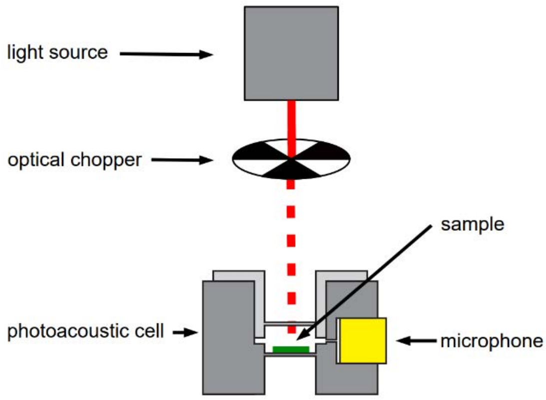

Fig.1. Principles of PA detection.

The aim of this research is to demonstrate the potential of photoacoustic-based techniques for the monitoring of water pollution. In particular, the following model samples were tested: 1. water drag solution, 2. plastics (PET-Polyethylene Terephthalate) water suspension, 3. green alga colonies in natural water body, as differentiated complex pollutants to be sensed with PAS technique.

3. Materials and Methods

The model studies were performed on commercially available material samples, including a model drug (Paracetamol, Polpha Lodz, Poland) solid state tablet composed of the active substance, sorbitol, starch and magnesium stearate), and PET-G (Polyethylene Terephthalate) plastic substratum suspension (diameter ~ µm), as well as natural water samples containing filamentous green algae species, collected in coastal shallow Baltic sea waters (Gulf of Gdansk, Poland; site coordinates: 18^o 37' E, 54^o 26' N). The natural water samples were filtered using the Sartorius system with cellulose acetate membrane filters of 0.45 µm pore diameter (Carpentier et al., 1989). A basic PAS experimental set-up was constructed and modified for these studies, as described in detail elsewhere (Rochowski et al, 2020).

4. Results and Discussion

Exemplary PA spectra of pilot measurements were performed for model polluted water systems, selecting microplastics (PET-G) and chemical (paracetamol) as contaminants, and on a natural seawater sample containing photosynthetically-active species.

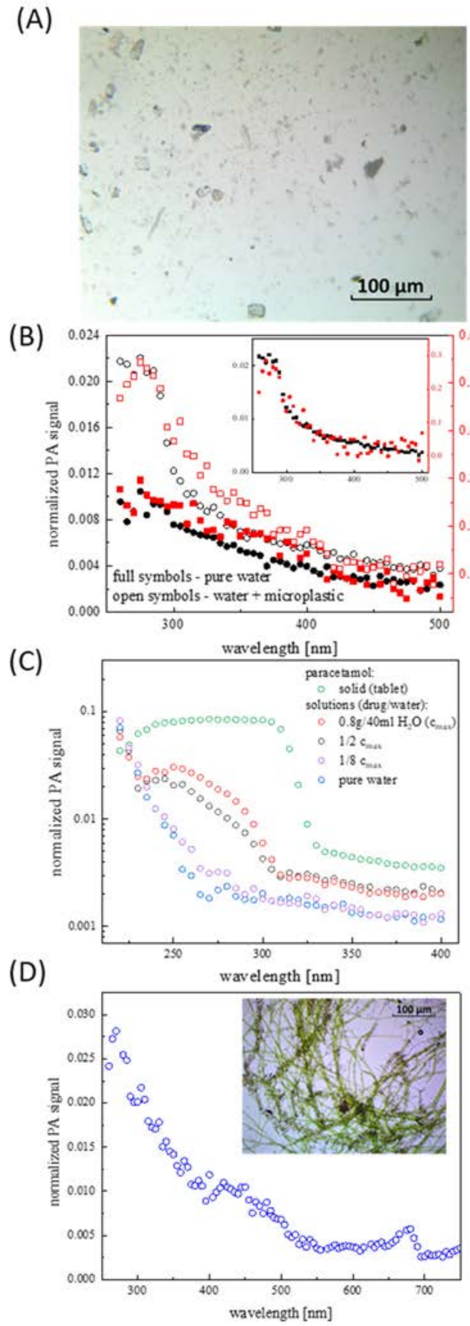

Fig. 2. Micrograph of a model microplastics/water suspension system (A) , and the corresponding PA and DR spectra recorded at f=120Hz (B). The inset demonstrates subtracted microplastics-suspension system spectra with the characteristic maximum at ~280 nm (Arangdad et al., 2019), obtained by means of the two photoacoustics modalities. Fig (C) demonstrates photoacoustic spectra, for commercially available solid paracetamol tablet along with the tablet/water solutions, and reference pure water. A characteristic band around at ~ 250 nm becomes less distinguishable as the solution concentration decreases. Fig (D) presents PA spectrum (120 Hz) recorded for the Baltic sea water (with naturally occurring microorganisms – filamentous green algae species – inset) reflecting signatures of photosynthetic pigments (in particular, *Chl.a* spectral peak ~ 680 nm).

Previously, close cross-correlations were evidenced between photosynthetic energy storage efficiency and PAS amplitude spectra of hard submerged solid substrata covered with biofilm colonies and the seawater chemical parameters-trophic state indexes (Boniewicz et al., 2021). These studies demonstrated that PA techniques were useful for the monitoring of natural sea water macroscopic (> 0.5 µm) constituents, including dissolved contaminants, photosynthetically-active organisms, and microplastics particles.

5. Concluding Remarks

Both PA and DR techniques provided qualitatively similar results (in terms of general spectral features) for the model microplastics-contaminated water system. PA data appeared, however, to offer higher spectral resolution compared to DR results (higher signal-to-noise ratio). It is supposed that the spectral resolution of DR method can be enhanced by increasing the photoacoustically-active (carbon black-covered) area of the detector.

Finally, both techniques were utilized for the monitoring of natural sea water macroscopic (> 0.5 µm) constituents, including photosynthetically-active organisms and microplastics contamination. It was shown, that due to various efficiency of specific light-matter interactions, the two modalities provide considerably different spectral signatures; in particular, DR data revealed higher sensitivity to microplastics particle presence compared to PA data. By keeping in mind that PA technique can be considered as a method-of-choice for the monitoring of photosynthesis efficiency via the energy storage parameter (sensitive to water composition and contamination), the research presented, especially in the light of synergy between the results provided by means of PA and DR modalities, can be considered as a promising step towards designing of a new class of photoacoustics-based sensors for the monitoring of water quality.

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Anthropogenic impact of mobile ground-contact fishing on the biogeochemistry of Baltic Sea surface sediments Part I: Short term effects from a monitored trawling experiment

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1. Introduction

The research project MGF-Ostsee deals with the consequences of the exclusion of mobile bottom-contact fishing in the southern Baltic Sea, specifically to assess its effects on the biogeochemistry of surface sediments and across the benthic-pelagic food chain. In Summer 2021, an in-situ monitored experiment was conducted at a coastal site in the region of Warnemünde/Rostock to investigate the impacts of bottom trawling. Learning from the short-term responses shall additionally help understanding patterns observed from other, monitored, areas. Herein, we present first results on how the bottom-trawling affected biogeochemical processes and associated elemental cycling.

2. Methods

We analyzed porewater and sediment, as well as the water column for major, minor and trace elements, and the stable isotope composition (C, S, O) of dissolved and solid carbon and sulfur species. Porewater gradients are combined with lander-based oxygen-consumption- and radiotracer-based microbial sulfate reduction rates to elucidate how the disturbances by the fishing gear affect element (C, P, Mn, Fe, S) and mineral (re)distribution.

In the central trawled area, short cores were taken with a MUC prior and one to two hours after the experiment, and on the following day. In addition, sediment cores were recovered by divers from furrows and mounds of recent trawl marks. Background information on sediments and morphology as well as water column imaging of the suspension cloud were done by multibeam echo sounder surveys.

3. First results

The controlled trawling experiment generated a re-suspension plume that reached up to 2 m above the sea floor, with 4 NTU in the lowermost portion. The suspension plume was confirmed in acoustic data. First elemental results suggest that in the trawled area, the coupled Fe-Mn-P cycle reacts very sensitively, as expressed by altered porewater gradients and diffusion rates. In the trawl marks, porewaters are affected differently whether sediments are removed, as in trawl furrows (erosion), or added/topped, as in trawl mounds (burial). In general, the tentative results point towards a Mn loss in the trawling area and in the furrows, whereas in the mounds Mn becomes enriched (Figure 1), a result similarly portrayed for instance in particle bound chlorophyll pigments. The observed short-term changes in geochemical patterns from the experiment in the Warnemünde region are compared to data from a monitored region in the Fehmarn Belt. There, the observed patterns are tentatively associated to meso-scale areas with a history of low or high trawling impact.

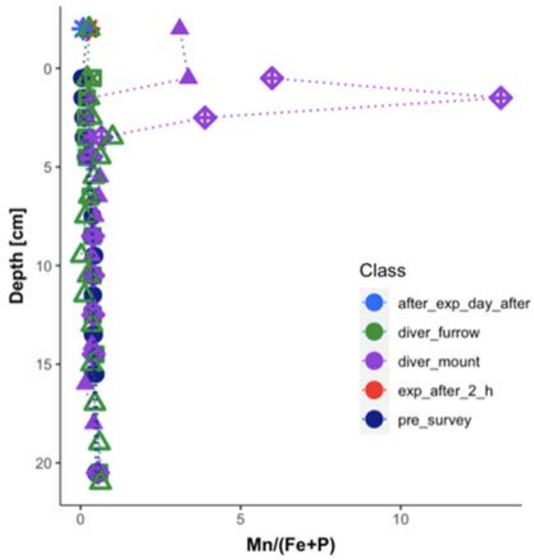

Figure 1: Porewater Mn/(Fe+P) ratio with depth from sediment cores of furrows (green) and mounts (violet), aside values from pre-survey cores (dark blue); showing the relative Manganese enrichment in the upper centimeters of mount-type cores. Red and blue represent water column samples.

Benthic macroinvertebrates as reference indicators for monitoring of anthropogenic isotope ^{137}Cs contamination in the marine environment

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Radiocesium (^{137}Cs) is an anthropogenic radioactive isotope produced by nuclear fission with a physical half-life of 30 years. Due to the chemical properties similar to potassium and accumulation by living organisms, it is considered as one of the most harmful of long-lived anthropogenic radionuclide contaminants. The Baltic Sea is one of the world's largest brackish water basins with limited water exchange, making it an area particularly vulnerable to pollution. As a result of contamination by radioactive ^{137}Cs after Chernobyl accident in 1986 and slow exchange of water between the Baltic Sea and the North Sea, it is the most polluted with ^{137}Cs water body in the world (WOMARS, 2005). Due to the need of the marine environmental contamination status assessment in terms of risk from the presence of hazardous substances, including radioactive isotopes, it is critical to understand which organisms are the best bioindicators of specific radionuclides and would provide the most rapid warning of any potential leakage or movement into the environment.

Due to the limited studies dealing with isotopes levels in benthic macroinvertebrates other than *Mytilus* sp., in period 2011-2018 macroinvertebrates and seawater samples from the southern Baltic Sea were collected and compared with the activities of zoobenthic organisms from the polar regions.

To determine the bioindication potential of organisms, there were calculated concentration ratio (CR) based on the activities of ^{137}Cs in organisms (Bq kg^{-1}) every year divided by weighted average ^{137}Cs activity (Bq dm^{-3}) in bottom seawater corresponding to the years of sampling macroinvertebrates. The lowest values of CR and variability in the years were found for bivalves: *Astarte sp., C. glaucum, L. balthica, M. arenaria, M. trossulus*. The mean BCF values in 2011-2018 were 22 dm^3 kg^{-1} in the case of *M. trossulus* with the range from 14 dm^3 kg^{-1} to 30 dm^3 kg^{-1}, 67 dm^3 kg^{-1} in the case of *C. glaucum* (11 dm^3 kg^{-1} - 128 dm^3 kg^{-1}) and 76 dm^3 kg^{-1} found for *L. balthica* (64 dm^3 kg^{-1} - 100 dm^3 kg^{-1}) The biggest differentiation of CR values in the period 2011 – 2018 was specific to *M. neglecta* with the range *from* 200 dm^3 kg$^{-1}{}_{fw}$ to 1700 dm^3 kg$^{-1}{}_{fw}$. CR calculated for benthic organisms from the Baltic Sea were several times lower than in the polar regions, although the isotope concentrations in seawater in these areas are at much lower levels. In species from Arctic the average CR was *Cribrinopsis similis* (6300 dm^3 kg^{-1}), *Henricia sanguinolenta* (12300 dm^3 kg^{-1}), *Hormathia nodosa* (7000 dm^3 kg^{-1}), *Ophiopolis oculeata* (15100 dm^3 kg^{-1}), *Strongylocentrotus droebachiensis* (1800 dm^3 kg^{-1}). For species from Antarctic the mean CR were around 1000 dm^3 kg^{-1} (Fig 1)

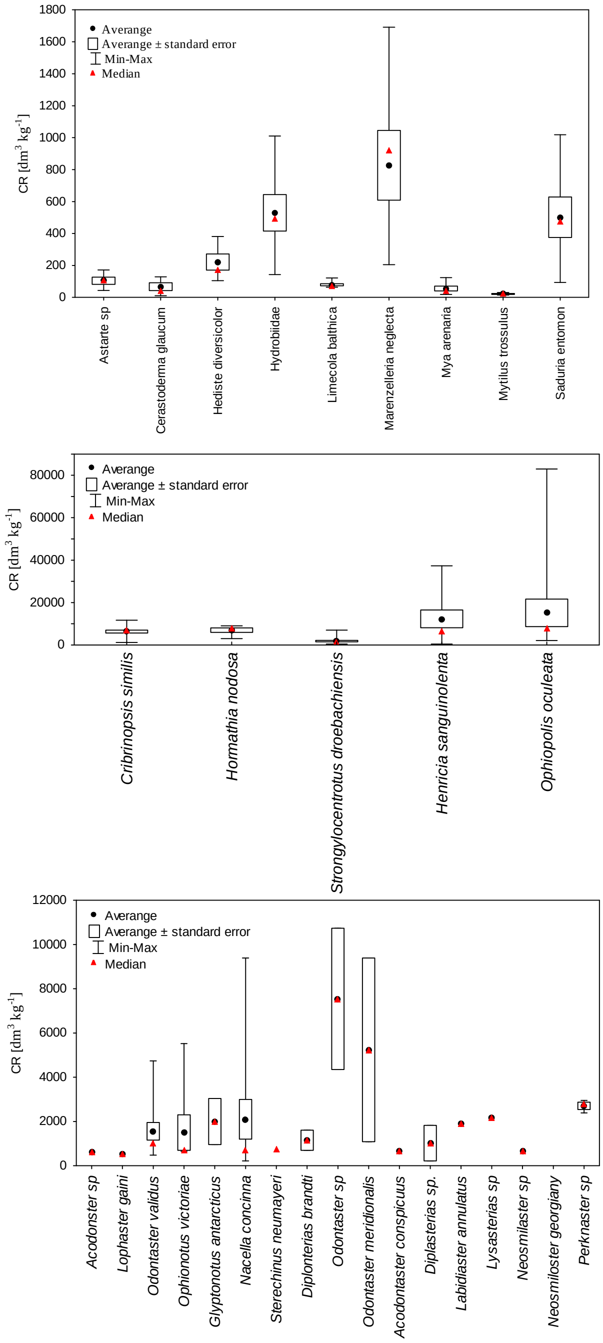

Fig 1. Bioconcentrations factors (CR) for zoobenthic organisms from a) Baltic Sea b) Arctic c) Antarctic

Taking into account the narrow range of CR values, statistically significant correlation between ^{137}Cs activities in seawater and species, a high frequency of occurrence and thus high biomass and the common occurrence, only *L. balthica* could potentially serve as indicators for shallow and deep-sea areas accordingly. Widely spread *M. trossulus* was characterised by large size variability in samples which may impact on bioaccumulation and shows no significant correlation between activities in species and seawater and appears not so common as *L. balthica*. These results are difficult to compare with species from polar region where, due to long-lived organisms, they have a much higher bioaccumulation capacity than zoobenthic organisms from the Baltic Sea. Highest values of ^{137}Cs in polar species were observed in the organisms at station near seabird colonies and close to river mount which could indicate the fecal material and melting glacier as a significant source of studied radionuclide. An important factor affecting bioaccumulation of ^{137}Cs was the body mass. In smaller specimen, the bioaccumulation occurred most intensively. When the biomass increased, so-called dilution effect was observed. This process was confirmed by biomass to activity correlations for analyzed isotope.

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Anthropogenic impact of mobile ground-contact fishing on the biogeochemistry of the Baltic Sea surface sediments Part II: Long-term effects on iron sulfide authigenesis

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1. Introduction

Mobile ground-contact fishing (MGF) from commercial fishing activity can have profound impacts on the sea floor, as trawling gear can both resuspend the surface sediments, release porewaters, and shift sediment horizontally to form furrows and mounds. This disturbance can thus affect the benthic biogeochemistry, in a number of ways, as these surface sediments generally contain the most labile organic matter, and the porewaters are elevated in dissolved redox sensitive species (such as Fe, Mn, and sulfide).

Here, we report on a research endeavor from the interdisciplinary project MGF-Ostsee, where we extensively sampled in the Fehmarn Belt (southern Baltic Sea, June 2020). The broader aims of the project MGF-Ostsee are to consider the geophysical, biogeochemical, and ecological consequences of the exclusion of MGF from marine protected areas (MPAs) in the German EEZ of the southern Baltic Sea, beginning prior to the exclusion of MGF from these areas.

2. Methods

The Fehmarn Belt region of the southern Baltic Sea experiences extensive bottom contact trawling by commercial fishing. Our sites were distributed both inside and outside of a marine protected area (MPA), however at the time of sampling MGF was still allowed and widely occurring inside of the MPA. We collected surface sediment cores from a variety of sites ranging from undisturbed (due to a nearby shipwreck and boulders) to heavily trawled.

From these cores we analyzed a suite of porewater parameters (including: dissolved sulfide, Fe, Mn, SO_4, nutrients, and ^{13}C-DIC), solid phase parameters (including: T_{Hg}, TIC, TOC, CNS, reactive Fe and Mn, AVS, and CRS), as well as depth resolved rates of sulfate reduction (SRR).

3. Results

Our research focuses on the impact of MGF on the iron and sulfur cycles, and has revealed potential long-term impacts of MGF in the form of decreased Degree of Sulfurization (DOS) and Degree of Pyritization (DOP, Figure 1) in areas of heavy trawling history. These findings suggest that the introduction of oxygen into deeper sediments through MGF disturbance can oxidize FeSx species, which can have long-term implications for pyrite and other FeS_x species distribution.

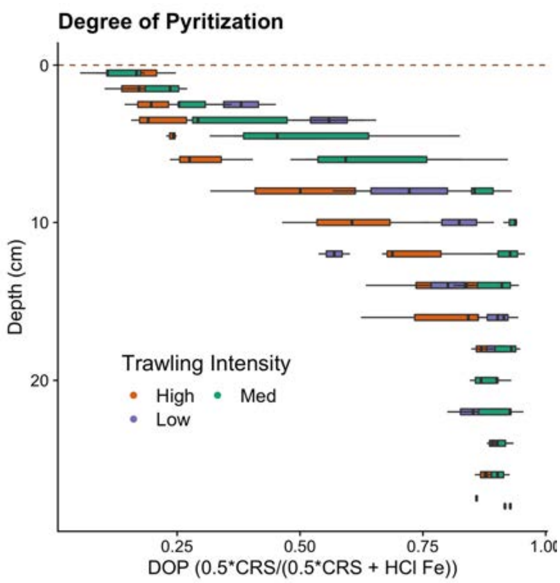

Figure 1: Degree of Pyritization (DOP) with depth, calculated from the chromium reducible sulfate (CRS) and HCl extractable iron (HCl Fe) and provided in terms of Fe stoichiometry. Trawling Intensity (High n = 3, Med n = 3, Low n = 2) is a rough estimate based on areal manually counted trawl marks nearby each site, and may be subject to change as geophysical analysis is ongoing.

We present these results in the context of a more recently undertaken and monitored MGF experimental trawl (June 2021), where we studied the short-term impacts of MGF on the biogeochemistry of coastal sediments, including iron and sulfur cycling.

Topic 7

Sustainable management options

An approach for monitoring strategy assessment and optimization based on the analysis of variability from an ecosystem model

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1. Introduction

Despite best efforts, observations never are able to cover the full spatiotemporal domain. I.e., data from any monitoring system by necessity deliver a potentially biased view due to the selection of observation locations and times.

In order to assess the utility of a sample or different sampling approaches, its respective footprint needs to be established in order to identify gaps in and complementarity between observations, and to yield an optimal return from the observational effort.

Here, we present an approach to put such assessments on a more quantitative basis and illustrate its potential on the example of surface pCO_2 observations.

Such information can then be used to devise a monitoring network that is fit for purpose, e.g., to resolve the seasonal carbon cycle for eutrophication assessment, or to track progress or failure of CO_2 removal mitigation efforts in the Baltic Sea.

2. Method

First we employ an approach to map surface pCO_2 and to quantify the associated mapping error with the help of patterns of surface pCO_2 variability from a biogeochemical model. The reduction of mapping error is then used as quantifiable metric for the impact of an observation or a network of observations.

As input data, daily resolved surface pCO_2 for the period 2014-2018 from an ecosystem model are used. Model-based patterns of surface pCO_2 variability are obtained by empirical orthogonal function (EOF) analysis of the model data, i.e., by decomposition of the data covariance matrix into a series of orthogonal functions, the eigenvectors or EOF patterns, ordered by the amount of variance they explain.

By applying the DINEOF variant, the number of significant EOFs is determined by a cross-validation procedure from the data (Beckers & Rixen, 2003) and temporal coherence in the covariance matrix is accounted for (Alvera-Azcárate et al., 2009).

Observational data can then be used to reconstruct or map the original pCO_2 field by solving the corresponding eigenvalue equation, where following Kaplan et al. (2000) the uncertainty of the observational data is taken into account in the EOF mapping. This way, one obtains both a mapped pCO_2 as well as an estimate of the mapping error.

Here, we use specifically the mapping error P, which is reduced near observations as they (locally) provide a data constraint to the reconstruction. Using the mapping error P in absence of any observations as reference, the reduction in P is used to assess and quantify the impact and footprint of a given sample location or sampling scheme.

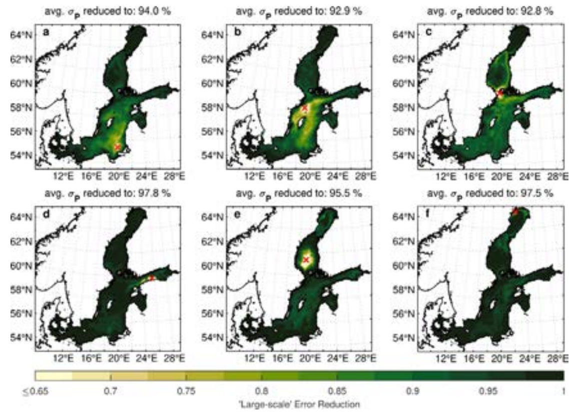

Figure 1. Reduction in large-scale error by a single surface pCO_2 sample at different locations.

3. Results

Single points of observations have the highest impact within their respective subbasins (Fig. 1), e.g., an observation in the Bothnian Sea reduces the error in the respective basin but has only a small impact on the central Baltic (Fig. 1e). Conversely, an observation in the Eastern Gotland basin (Fig. 1a) or the Northern Baltic proper (Fig. 1b) affects the central Baltic, while it has little impact on the adjacent basins. Similarly, observations in low-variance areas have a larger spatial footprint than those in high-variance areas such as upwelling regions (Fig. 1d) or shallow, near coastal areas (Fig. 1c,f).

4. Example: SOOP surface monitoring of pCO_2

Ships of opportunity (SOOP) with surface pCO_2 instrumentations provide a dense and continuous series of observations along the ship transect.

A number of SOOP lines are operating or are on their way to operational status in the Baltic. They all provide regular repeats of high quality pCO_2 measurements along their typical shipping routes, and their impact to constrain surface carbon distribution is assessed below (Fig. 2).

In terms of spatial coverage, SOOP Tavastland is most influential due to its coverage of many subbasins, notably the Northern basins for which it is the only SOOP platform. However, smaller SOOP lines are also an important contribution to constrain the surface pCO_2 distribution and its variability, e.g., like SOOP Agat in a high variability region as the Oder bight. From an observation network perspective, they are an essential component besides the basin-spanning SOOPs Finnmaid or Tavastland. If all combined, they provide an impressive (albeit not gap-free) spatial footprint on pCO_2 (Fig. 2f). Room for improvement pertains particularly to the Gulf of Riga, the Eastern Gulf of Finland towards the mouth of the Neva river, as well as the Southern shores of the Gulf of Finland.

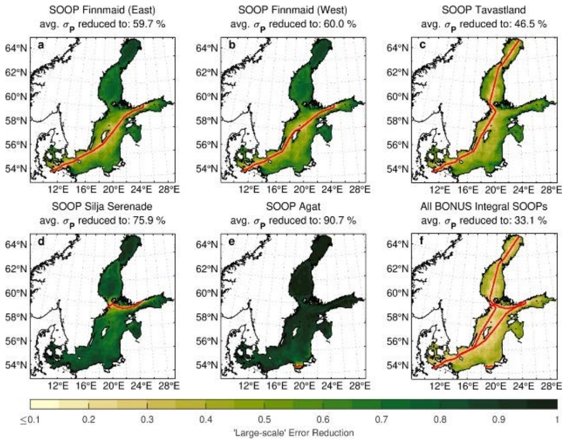

Figure 2. Reduction in large-scale error by SOOP line surface pCO_2 sampling for (a) Finnmaid on Eastern route, (b) Finnmaid on Western route, (c) Tavastland, (d) Silja Serenade, (e) Agat, and (f) all SOOP lines of BONUS INTEGRAL combined.

To have some overlap and redundancy between lines, e.g., in the Western Baltic by SOOP Finnmaid and SOOP Tavastland, also makes the system more resilient to potential outages, failures, or maintenance periods.

5. Example: Frequency of monitoring

In practice, one faces the challenge to optimize the effort and return also in terms of temporal frequency of observations. The goal is to find a balance between 'too regular' repeats, where one observation is essentially not different from the previous one, and 'too seldom' repeats, where one misses variability in between observations because of too sparse coverage, as the extremes.

To get an estimate on the minimal frequency of observations required, we used the time series provided by the daily-resolved model. For a given time step, correlation to an adjacent time step is typically high and decreases with additional time steps. By evaluating the correlation between the time series at a given point and its own, lagged time series at the same point, one obtains the lagged autocorrelation $R(t,t+lag)$. By subsequently increasing the lag, a decorrelation time scale can be derived as the lag (in days) at which the lagged autocorrelation falls below a threshold of 0.63.

The model-based decorrelation time scale (Fig. 3) shows a small temporal decorrelation scale of within 1–2 weeks in near-coastal waters, which is expected because of high dynamics nearshore. In the open Central Baltic, this scale is more on the order of 6–7 weeks, indicating that a monthly monitoring would cover most of the variability. Decorrelation time scales are somewhat smaller in the Bothnian Bay (4–5 weeks) and even smaller in the Bothnian Sea (2–3 weeks) based on this analysis, which is likely linked to intense surface pCO_2 variations over a rather short productive spring and summer season, which reduces temporal coherence.

6. Conclusions

Sustainable management requires that adequate data are available to inform decision making as well as evaluation. Fit for purpose data are only obtained by a fit for purpose monitoring strategy.

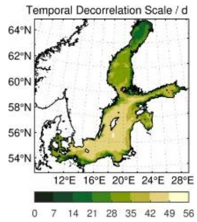

Figure 3. Decorrelation time scale of model-based surface pCO_2 data. The decorrelation time scale is given by the lag (in days) at which the autocorrelation $R(t,t+lag)$ of the time series at a given location first drops below 0.63.

Here, an approach to assess the impact of observations was developed, which can be used to quantitatively assess and compare observation network designs.

While the present example centers around carbon observations, which deliver, e.g., information on eutrophication status or CO_2 sequestration/storage, it is transferable to other parameters or applications where there is a need to evaluate the return for a given effort.

In a larger perspective, systematic evaluation of our current Baltic Sea monitoring network and with a range of ecosystem models as input to the variability estimation, our approach can be used as a tool to identify (1) gaps that need to be filled, (2) key players or regions that are crucial for a certain management option and would benefit from redundant observation for resilience of the monitoring system, and (3) areas where redundancy may not be as needed and efforts could be distributed more evenly, thus helping to build a better, integrated observation network.

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High-resolution wave model for coastal management and engineering in the eastern Baltic Sea

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1. Introduction

A successful coastal management and engineering requires comprehensive understanding of the properties of waves and their extremes in various spatio-temporal scales. Since there are usually not enough measurements at hand for a specific site, numerical modelling is used to provide information about the core wave parameters. However, the modelling has its own risks.

Complex topography and bathymetry of the Baltic Sea is one of the reasons why the local wave climate is very inhomogeneous (Räämet 2010). Wave models, typically at 3 nautical miles (nm) or coarser and at best at 1 nm resolution for the entire sea (Björkqvist et al. 2018), are too coarse to account for the irregular shorelines in local studies of the eastern Baltic. The validity of simulation results largely depends on the wind fields used. In the Baltic Sea, an extensive mismatch between wave properties and wind has been observed (e.g., Nikolkina et al. 2014).

We try to overcome these issues by developing a triple-nested wave model with multiple high-resolution grids along the nearshore of Estonia, Latvia, Lithuania and Gdańsk Bay. The results will be used, among the others, in studies of variability of wave-induced loads offshore and nearshore, sediment transport and coastal vulnerability.

2. Input data

We implement two different modelled wind data sets which have overlapping time periods to further investigate the influence of wind forcing. The first wind dataset, ERA-5 Reanalysis, is the fifth-generation global atmospheric reanalysis produced by ECMWF from 1979 to present, with trimestral updates. Compared to its predecessors, ERA-5 uses a more recent version of the ECMWF Integrated Forecast System model (IFS 41r2), with increased temporal output, horizontal and vertical resolutions (1 h, 0.25° and 137 vertical levels, respectively), and several improvements to different parameterisations (e.g., convection and microphysics) and to the data assimilation scheme (Hersbach et al. 2018).

The second wind dataset originates from the ERA-40 and ERA Interim datasets (1979–2005), and their regionalisation BaltAn65+ for the Baltic Sea (Luhamaa et al. 2011) made through the atmospheric model HIRLAM-B with a 6 h resolution. The hourly near-surface u- and v-components of wind velocity at 10 m from ERA-5 model, for the 1995–2020 period, are used to compute the wind speed and direction. The second dataset was used to perform additional runs for the period 1995–2006 to better assess the quality of wave reconstruction using the first dataset.

The bathymetry data has been acquired from Baltic Sea Hydrographic Commission (2013). Additionally, the data for the Estonian waters (with resolution up to 50 m) was provided by the Transport Administration of Estonia.

For validation purposes, the model results have been compared against recorded historical visual observations, as well as instrumental wave measurements. These were downloaded from Swedish Meteorological and Hydrological Institute (https://www.smhi.se), Finnish Meteorological Institute (https://www.ilmatieteenlaitos.fi/) and field measurements in Estonian waters (Figure 1) carried out by Ülo Suursaar (Suursaar 2015).

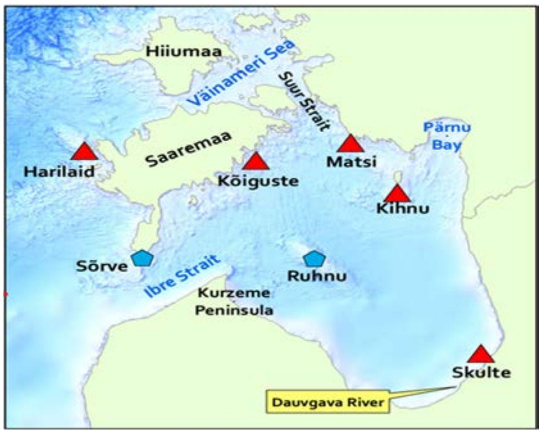

Figure 1. The locations of instrumental measurements (red triangles) and visual observations (blue pentagrams) in the Gulf of Riga.

3. Model setup

The wave parameters are calculated for the time frame 1995–2020 using the SWAN wave model, cycle III, version 41.31A. We employ the OpenMP 2.0-compliant version to take advantage of a 24-core processing unit. The wave model SWAN (Booij et al. 1999) is a third-generation phase-averaged spectral wave model that has been used for the Baltic Sea before (e.g., Björkqvist et al. 2018). The model outputs hourly values of wave parameters (e.g., significant wave height, mean absolute wave period, direction etc.).

The wave spectrum is computed with a resolution of 10° (thus, over 36 directions) and over 32 logarithmically distributed frequencies, in the range 0.05–1 Hz (periods from 1 to 20 s). Wind forcing is provided by previously described, partially overlapping datasets. We used wind drag parameterisation suggested by Wu (2012), since it showed better results than default set-up of SWAN. Model is run without ice information and does not include currents and varying water levels.

The main (first level) grid of the triple-nested wave model covers the Baltic Sea at the resolution of 3 nautical miles (approximately 5500 m) (Figure 3). The results are used as boundary conditions for finer second level grids. These cover Gulf of Finland and Gulf of Riga with a resolution of about 1700 m and part of Latvia, Lithuania and Gdansk Bay (Figure 2) with a resolution down to about 500 m. This resolution is apparently sufficient to analyse changes in the wave properties and wave-driven sediment transport in the nearshore.

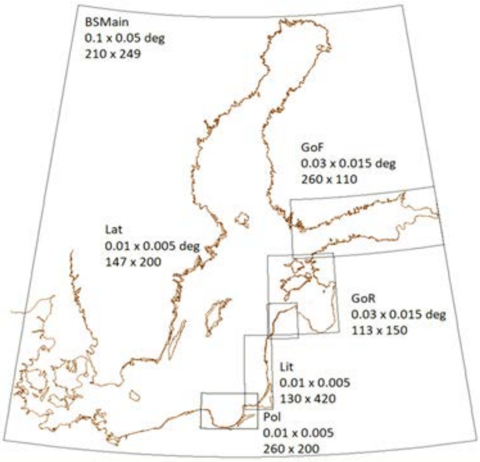

Figure 2. Overview of the first and second level grids used in the model. BSMain covers all the Baltic Sea, GoF – Gulf of Finland, GoR – Gulf of Riga, Lat – western Latvia, Lit – Lithuania, Pol – Gdansk Bay. The second line below the title of the grid shows resolution in degrees and the third line – the number of grid cells in both directions.

In the Gulf of Finland (Figure 3), we used 5 subgrids with different resolutions (from 260 to 560 m) to account for varying coastline and multiple peninsulas. In the Gulf of Riga (Figure 4), 11 subgrids (with a resolution 260–560 m) were used due to islands mainly. The proposed grid system should catch abrupt changes in the bathymetry and resolve the complicated geometry of the relevant sea areas, and should result in better estimation of tempo-spatial variation of waves and coastal processes.

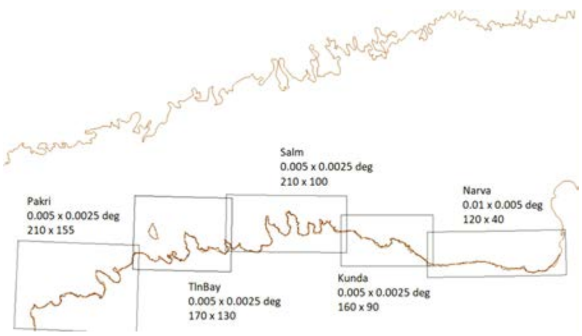

Figure 3. Nested grids near the southern shore of the Gulf of Finland. The second line below the title of the grid shows resolution in degrees and the third line – the number of grid cells in both directions.

4. Validation and model tuning

While SWAN produces acceptable results when using BaltAn65+, we found that in order to produce the same level of accuracy (i.e., significant wave height offset <0.3 m across short-term stormy events), using the ERA5 dataset, a finer tuning of the inner parameters of the model is required. This fact is not surprising as BaltAn65+ is a regionalisation of a global dataset and is expected to produce better results at the smaller scales. As such, further optimisation and validation is currently underway, as to improve the model accuracy and proceed with the studies over trends in the eastern Baltic Sea wave climate.

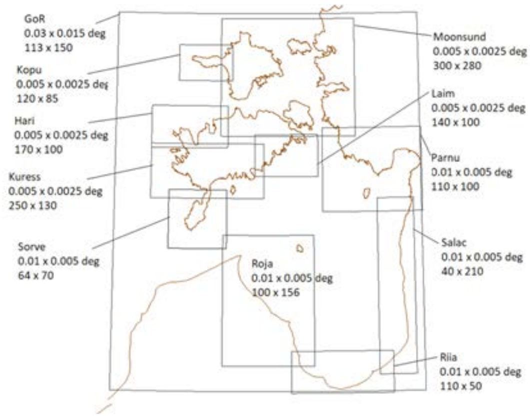

Figure 4. Nested grids in the Gulf of Riga and West Estonian Archipelago. The second line below the title of the grid shows resolution in degrees and the third line – the number of grid cells in both directions.

5. Acknowledgements

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Beyond sustainability and ICZM: The future for management of Baltic Sea coasts

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1. Introduction

For the past few decades, sustainability and Integrated Coastal Zone Management (ICZM) has been the goal of much coastal management. Since climate change, has been recognized as a management issue, adaptation has also been a common theme. Success stories within the frameworks of ICZM, sustainability and adaptation are rare, and few jurisdictions would claim that sustainable coastal management has been achieved. Even locations that are sustainably managed now, with climate change, might not be sustainable in the (even relatively near) future.

In the context of the Baltic Sea environment, we explore the coastal management paradigms of the past 40 years. We discuss whether the current mechanisms are achieving goals, and whether they are sufficiently robust for the future. By exploring concepts of 'rights', we discuss a management framework that might assist to achieve goals.

2. Forty years of coastal management – the world

Environmental management paradigms that influence, guide or drive coastal management practices change over time.

With respect to physical coastal management, the late 1970s to early 1990s were dominated by the identification, understanding and mitigation of coastal hazards. The 'Coastal hazard zone' is often determined using formulas such as $CHZ = [(N \times R) + C + S] \times (1 + F)$, where CHZ is the hazard prone width of land adjacent to the coast (m), N is the planning period (years), R is the rate of long-term shoreline change (m/year), C is short-term erosion from the design storm (m), S is erosion due to sea level rise (m), and F is a safety (or uncertainty) factor, typically between 0 and 1. The method was popular because it provided apparent quantitative certainty that could be defended in legal settings. However, results were often wildly inaccurate, and not supported by qualitative assessments by experts.

An outcome of the 1992 Earth Summit of Rio de Janeiro, Agenda 21, was the ICZM approach to coastal management that dominated coastal management thinking from the 1990s, arguably through to the present. Linked closely with the concept of sustainability, it is a resource management system defined by the EU as "A dynamic, multidisciplinary and iterative process to promote sustainable management of coastal zones /--/ uses the informed participation and cooperation of all stakeholders /--/ to take actions towards meeting objectives /--/ to balance environmental, economic, social, cultural and recreational objectives within the limits set by natural dynamics /--/" (COM (2000) 547 final). The goals of ICZM are worthy but there are few examples of successful implementation (Shipman and Stojanovic 2007; Soriani et al. 2015).

'Adaptation' (to climate change) has been an important paradigm since the early 2000s with governments developing responses such as hard and soft engineering, and spatial planning (including 'managed retreat').

Underlying the implementation of effective physical coastal management in most countries are issues relating to property rights, particularly the right to protect private property and the right to use private property as the owner wishes. Such rights can conflict with public property rights, including questions relating to who pays for adaptation or remedial action. A classic example is the right to protect coastal assets from erosion using hard engineering (such as seawalls), where entrenched rights to protect private property conflict with public rights to be able to enjoy coastal amenity. When coasts are eroding, these two 'world views' are incompatible.

3. Forty years of coastal management – the Baltic Sea

The coasts of Sweden and Finland are dominated by bedrock coasts, and combined with continued isostatic uplift, climate-change related physical coastal problems are likely to be relatively few and isolated.

The southern and eastern Baltic Sea coasts are clastic sediment dominated, or have soft and erodible sedimentary cliffs. On these coasts there is relative sea-level rise and erosion problems can be significant. Most Baltic states have implemented coastal setbacks for new buildings (e.g. Poland 200 m, Germany 100–200 m, Denmark 300 m), and have managed-retreat policies for already developed coasts. Coastal management in some ex-soviet bloc countries is still significantly influenced by policies that restricted coastal use and access due primarily to security and military concerns. Building of private assets immediately adjacent to the coast was not permitted. This heritage has, upon the removal or abandonment of military assets, resulted in a wide undeveloped coastal buffer, the like of which is unachievable elsewhere and has provided a base for coastal spatial planning without significant costs. Most of the eastern and southern Baltic Sea coast is included in the 'European Green Belt' (www.europeangreenbelt.org), an initiative to save natural assets that existed alongside the 'iron curtain'.

In Estonia, the Nature Conservation Act (2004) does not permit (most) new buildings closer than 200 m from the shores of islands and 100 m from the shores of the mainland coast (50 m in densely populated areas). This is generally achievable due to the historical advantage. The law is currently in the early stages of reconsideration in the parliament, with a proposal that would leave only a mandatory 20 m setback zone, which local governments could expand if desired. The proposed change has been the subject of considerable opposition.

4. The adequacy of sustainability and ICZM

Despite ICZM and sustainability being a dominant paradigm for at least three decades, few would argue that coasts are becoming less degraded and less vulnerable over time. Successful ICZM stories tend to be small scale, and mostly local 'feel-good' projects. This is not surprising given that the processes require stakeholder compromise, in a political environment where societal and economic imperatives are of at least equal importance as the natural environment. The lessons of the 'Tragedy of the Commons' apply, and when the desire or need to exploit is combined with entrenched private property rights, it is not surprising that ICZM is an almost unachievable goal.

5. The future beyond sustainability and ICZM

It is refreshing that highly respected Baltic Sea scientists are considering environmental issues from viewpoints that extend traditional science (e.g. Omstedt 2020; von Storch 2021). In recent times, 'rights of nature' or 'environmental jurisprudence' ideas have been gaining momentum. This approach describes inherent rights associated with environments, ecosystems and species, akin to the concept of human rights (Figure 1). It recognises nature as a legal stakeholder with inalienable rights in law. In the coastal context, this raises questions such as, *does a beach have a legal right to a functional existence, even if it intrudes on private land*? Put another way, *should a private land owner have the right to protect private assets if doing so will degrade the beach*?

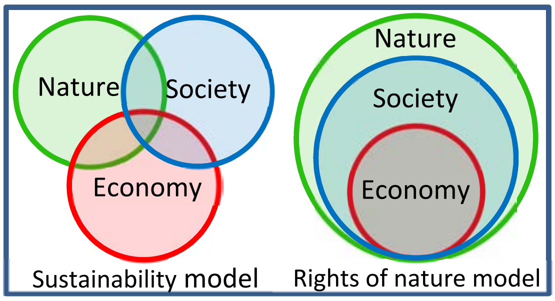

Figure 1. Approaches to environmental management using a sustainability model and a rights of nature model.

'Rights of nature' is frequently regarded as an extreme viewpoint, however, there are now examples where the principle has achieved legal status, in Ecuador, Colombia, New Zealand, India, Bangladesh, Uganda, Mexico, Bolivia, and in some parts of the USA. In New Zealand, for example, in 2017, the Whanganui River was granted the status of legal personhood. Two guardians, one representing Maori indigenous people and one representing the government, reconciling two world views, are appointed to speak and act legally on its behalf. Its application is being explored in the scientific literature (e.g. Brierley et al. 2019). The European Union is sponsoring reports on the 'rights of nature' approach (Darpö 2021; Carducci et al. 2019).

6. The sediment budget as a defining variable

The coast is a complex geomorphic system, reflecting landforms and drivers, through the process of sediment transport (Figure 2), determining the sediment budget. In the context of a 'rights of nature' approach, a requirement to maintain the coastal sediment budget is a possible way forward. Applied at appropriate scales, this addresses both alongshore and shore-normal exchanges. For hard coasts, where little sediment moves, it would reflect the minimal coastal problems. For soft, cliffed coasts, it would require the maintenance of sediment inputs that feed downdrift locations. Sandy beaches would have the right to change shape and position. For hard structures, it would give priority to the natural functioning of the coast. Important infrastructure required for the functioning of society would require mitigation measures to be considered, such as bypassing or beach nourishment. Such an approach requires quality science to understand sediment transport, including the definition of sediment compartments at a range of scales.

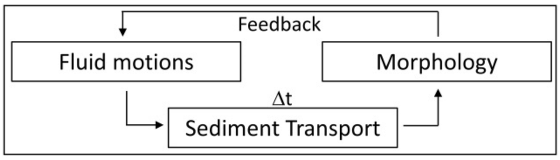

Figure 2. The morphodynamic model of coastal processes.

7. Rights, requirements and the coast (private, societal, nature)

That we have a sustainable a Baltic Sea coast is a proposition that can be debated. But even where we do, that is unlikely to remain the case into the future. Few countries will be able to afford the adaptations required for climate change, to maintain the coast's amenity and health. Compromises will be required to ensure that infrastructure essential to the functioning of society, and features of our coast that society demands (such as usable beaches) are maintained. 'Inalienable' rights, such as private property rights may have to be sacrificed.

8. Conclusions

The fact that we are presented with ICZM ongoing case studies more often than ICZM success stories shows that the optimism that followed the 1992 Earth Summit was not warranted. There have been successes, such as coastal setbacks for new buildings being legislated. It is important to ensure these are maintained into the future. Climate change presents new challenges for coastal managers and the legal system, particularly with regard to property rights. A changed way of thinking, beyond sustainability, is required, and a 'rights of nature' approach may be one way forward.

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The global challenge of the sustainable management of seas and shores

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1. Introduction

It is becoming an overexploited cliché to say that sustainable management must rely on the best scientific evidence. Statements of this kind are common in our information space, from citizens through to political leaders, ever since this paradigm was embraced at the 1992 United Nations Conference on Environment and Development. While the relevant aspects are relatively well understood for mainland applications and, at least, the necessity of this position is gradually being accepted in coastal management, the content of sustainable management is still almost tangential in the sea.

Similar to the variability of landscape, different sea and coastal areas, albeit seemingly identical, may have radically different properties, threats, and reactions to external forcing. This becomes massively evident in various features of marine and coastal behaviour, such as the variability of offshore currents and ice patterns, the structure of coastal sedimentary compartments, and the various reasons for stability of different beach segments.

2. The core issue and framing the message

The core problem of sustainable management of seas and oceans is that their water masses and clastic sediments are permanently in motion. The water parcel or sand grain we observe today has been usually replaced by another parcel or grain the next day.

An associated hindrance is the intricacy of developing quantitative indicators of the status, exposure or vulnerability of marine and coastal areas based on partially qualitative, often non-ordered, and sometimes even highly controversial estimates (Barzehkar et al., 2021). A fundamental limitation is limited knowledge of the truly natural status of many seas and their shores that sometimes cannot be specified at all.

Another difficulty in implementation of general principles of sustainable management of seas and shores is the global nature of many of these environments. Similar to the atmosphere, motions of water, mobile sediments and associated substances, from neutral suspended matter to nutrients, pollution and toxic substances cross political borders and do not follow our division of seas and oceans into sub-basins. It is thus an imperative to address and frame the relevant issues also globally.

There is no frameless communication, as Erving Goffman demonstrated half century ago (Goffman, 1974). All text, messages, agreements etc., contain and require a frame or structure of definitions and assumptions. This is the only way to organise coherence, connections, and, ultimately, meaning – or in other words, an adequate perspective on reality.

Sustainable development goals (SDGs) form an underlying framework for moving towards a future that is worth living. The five drivers that determine whether or not ocean governance evolves aligned to the SDGs are well known: formal rules and institutions, evidence and knowledge-based decision-making, legitimacy of decision-making institutions, stakeholder engagement and participation, and empowering communities (Haas et al., 2021). The main question is how we fill these categories with content.

3. Changing paradigms

A means to implement the sustainable management of coasts was the application of integrated coastal zone management (ICZM) that was developed in the U.S. in the 1980s. Its corner stone was framing "the coast" as a definable, manageable and value-laden entity rather than a frontier transition zone between land and sea (Nichols, 1999). It is thus not surprising that ICZM was *inter alia* used as regulatory instrument to try to reorganise coastal spaces and political systems towards easier investment penetration into the coastal zone.

Shipman and Stojanovic (2007) underline a policy vacuum that is constraining implementation of sustainable options for coastal management from national to local scales. They also highlight significant informational obstacles that prevent co-ordination between science and policymakers, and between different sectors. These factors implicitly moderate efforts directed towards holistic management of seas and their shores.

The necessity for paradigmatic changes in fishery and fisheries management was formulated around the turn of century (Caddy, 1999), after the decade of the 1990s that had seen growing concern at the uncertain effectiveness of most fisheries assessment and management approaches.

4. Does science help?

The situation with communication of management needs and issues of seas and shores to some extent reminds us of the informational cacophony during many months of the COVID-19 pandemic (Arif and Ali, 2020). Both the cases of this pandemic and climate change highlight the central role of scientific research that is supposed to guide political decision-making – which is the core of any management. In both cases, however, there is a tension between elements of uncertainty of most facts and the justification of political actions (Grundmann, 2021).

The flux of partially contradicting recommendations, regulations and restrictions has often led to misunderstandings and, according to some opinions, sometimes even to protests. Things are actually more complicated. Social science tells us that rejection of official information, whether changing in time or not, is first of all related to a lack of trust in public institutions (Reicher and Stott, 2020), and not to the misunderstanding of science (Grundmann, 2021).

Trust is considered the core asset in science advice at all levels, and this is definitely true in marine and coastal science. The reaction of different parts of the seas and shores to changes in external drivers and human interventions is as complicated and variable as the reaction of human bodies to infections. This feature makes suggestions for best management highly site-specific, especially in water bodies of complicated shape and with variable hydrophysical and geological properties.

Consequently, in the fragmented political governance system under which we address the Baltic Sea present and future, it may often occur that recommendations for one fragment (or country) of the system must be different from those given to a neighbouring fragment. This implies that the building of trust between scientists and managers is particularly complicated and has to include a global (at least Baltic Earth) dimension.

5. From science to policy and politics

The above discussion has clearly demonstrated that, similar to other environmental professions, marine and coastal management is not immune to politics. The progression towards a disruptive and highly polarised society in the 21st century presents unprecedented challenges to both scientists and managers. We have to cope with distrust of institutions, divided societies, scepticism, fake news, extremism and terrorism, and even with brutally aggressive war in the heart of Europe.

The situation where crises and disjuncture are commonplace and where politics is an inescapable feature of management has impacts also on marine and coastal professionals (Edwards, 2021). Moreover, ocean and coastal researchers, practitioners, and decision makers ought to engage with the political processes and injustices occurring in the ocean. Probably the right thing to do is to move from critical insights to constructive engagements (Bennett, 2019).

6. Towards an ecosystem of science advice

The tasks for the marine and coastal science community are similar to those that are currently being implemented on the EU level to develop a fully functional pan-European ecosystem of science advice.

The core problem here is that science cannot tell policy-makers what to do (Grundmann, 2021). It does provide a wide pool of facts, metrics, indicators etc. But it also inherently contains uncertainties, especially in future projections that simply reflect climate sensitivity to its multiple driving factors. This is the intrinsic reason for the systematic failure of attempts to reach a global scientific consensus on which, ideally, all actions should be based. These aspects should be communicated much more effectively to build trust. Moreover, decisions are to a large extent based on considerations pertaining to fundamental values that cannot be verified or falsified by science.

To move forward it is thus insufficient to build a strong evidence basis for effective, holistic and sustainable management of seas and shores. It is not enough to know how a particular segment functions or how we could make it sustainable. It is necessary to consider this segment in connection with others; ideally in the global context, to understand what role this piece has in the ecosystem. It is essential to understand that manipulation in one area, as a rule, affects processes in other areas. As a partial task, it is an imperative to develop an interconnected system of marine and coastal protected areas instead of just increasing their total area.

7. Conclusions

All the above, however, is worthless if we are not able to communicate important aspects to policy-makers, to fill the policy vacuum on the way to implement sustainable options and to remove the many informational obstacles between science and policymakers. These are the classic tasks of science advice for policy.

Our task is much simpler than handling the COVID-19 pandemic. We either already have, or can derive in a straightforward manner, large pools of standardised data and their adequate interpretations. Different from the case of pandemic that had very limited internationally shared metrics and that was constantly affected by rapidly shifting policy goals, development of sustainable management of seas and shores seems to be a fairly simple task, far simpler than adaptation to climate change.

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ROPEWALK - a digitization project for three centuries of weather observations on board of Danish ships

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The project ROPEWALK (Rescuing Old data with People's Efforts: Weather and climate Archives from LogbooK records) is a joint initiative of the Danish National Archives and the Danish Meteorological Institute. The aim of the project is to digitize and transcribe all weather observations in ship journals and logbooks stored in the National Archives. The collection in the archive is remarkable for several reasons.

A huge amount of data is stored (more than 750 shelf metres), beginning already in the 1680s. As the political system in Denmark was absolutistic between 1660 and 1848, logbooks from different periods resemble each other much more than is the case for the nautical heritage in other seafaring nations. In addition, the data is complete, with the exception of the Napoleonic times and the Danish state bankruptcy in 1814. In particular, there were no losses during the Second World War. Many of the logbooks are therefore well suited for transcription with machine learning techniques.

In the archive, logbooks from Danish ships over large parts of Northern Hemisphere are found. Of particular interest are observations from two regions, the Øresund and Greenland.

In connection with the Sound duties which every ship passing the sound or belts had to pay between 1426 and 1857, weather observations were made on board of war ships placed at strategic locations near Copenhagen, Helsingør and Nyborg. These ships had to ensure that no one passed without paying the duties. Presumably for practical reasons, weather observations were tabulated as early as the first half of the 18th century. In several cases, observations were conducted every time the ship bell was struck, resulting in the matchless temporal resolution of 48 observations in the course of one day.

The other group of logbooks which are of particular interest are from voyages to the colonies, in particular to (western) Greenland. The Greenlandic Merchant Company had a monopoly for trade with Greenland for nearly 200 years, and foreign ships would not be allowed to call a Greenlandic port. These "Greenland Voyages" were conducted several times per year. In many cases, detailed sea ice observations have been made.

The original logbooks will be scanned by the National Archives in highest possible resolution. The scans will then be transcribed by means of machine learning techniques and, where this is not possible, with the help of volunteers. For the oldest logbooks, which are in free text, we could locate older transcriptions which are much easier to read, either by machine or manually.

The transcribed data will be made publicly available. They will e.g. contribute as input for further reanalyses in the framework of the 20CR and similar projects.

Topic 8

Analysing and modeling past and future climate changes

Chironomid-based reconstruction of July average temperatures of Postglacial in Northern Europe: new training sets from Eastern Europe and their application

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Life cycle of non-biting midges from family Chironomidae (order Diptera) depends on ecological conditions of the water body, where larvae live (trophic state, oxygenation level etc.) along with climatic factors, mainly average July temperature. Therefore, sub-fossil Chironomidae remains (fig.1) deposited in lakes and bogs provide a record of past terrestrial and aquatic environment and could quantitatively reconstruct the environmental conditions (Eggermont&Heiri, 2012).

Figure 1. Chironomidae larvae.

Collecting modern analogues training sets and producing transfer functions based on them are the main approaches in paleo-chironomidae research. I am creating new "Baltic States" training set which covers understudied territories of Estonia, Latvia, Lithuania and Belorussia. July average temperature range Baltic States transect is 1,5 degrees (17,5-19,0 0C) and prolongs temperature range of already done Finnish training set by Luoto (2009). Moreover, it provides more adequate modern analogues for the Chironomidae-based reconstructions in Baltic region.

Based on this new and already existed datasets was developed new inference model using weighted averaging-partial least squares (WA-PLS) regression outperformed based on maximum likelihood regression. July average temperature transfer function was applied on several lake cores from Estonia and resulted in preliminary temperature reconstruction in the time interval 300 - 13500 years BP. The reconstruction showed main climatic events during Holocene, Younger Dryas and Bølling–Allerød periods.

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The impact of Atlantic Multidecadal Variability on North European climate

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Original reference: Florian Börgel et al 2020 Environ. Res. Lett. 15 104025

1. The Atlantic Multidecadal Variability and its imprint on the Baltic Sea variability Hemisphere

Several studies showed that the Atlantic Multidecadal Variability (AMV) impacts regional climate all around the world. However, for the first time it was shown that the Baltic Sea variability is exposed to the remote forcing of the AMV (Börgel et al., 2018). By using a regional climate model it was shown that the AMV changes the atmospheric circulation, influencing the precipitation over the Baltic Sea region. Ultimately, this impacts the river runoff into the Baltic Sea, affecting the mean salinity of the Baltic Sea. The AMO constantly influenced the Baltic Sea during the whole model simulation of the pre-industrial period from 950 - 1800, which provides strong evidence for long-term changes in the Baltic Sea because of alternating AMO phases.

2. The impact of the AMV on the spatial structure of the NAO

The aim of this study was to show the influence of the AMO on the spatial structure of the NAO (Börgel et al., 2020). The NAO is often used to explain changes in regional climate variables, assuming a constant spatial pattern. However, the results of this study showed that the AMO changes the zonal position of the NAO. This is of great importance for studies dis- cussing regional climate and demonstrates that the assumption of a constant spatial structure of the NAO does not hold. Using the Baltic Sea as an example for the impact of the NAO on North European climate, it was found that the correlation between regional climate variables and the NAO varies on multidecadal time scales. For example, the correlation between the NAO and SST varies immensely with correlations ranging from 0.0 - 0.8. In this study a combination of a GCM (ECHO-G) and a regional climate model (RCA3) was used (see Data and Methods). The SLP fields and the SST fields were taken from ECHO-G. Wind fields and SLP fields for the calculation of the storm tracks were taken from RCA3. In this work it was shown that the AMO influences the spatial pattern of the NAO on multi-decadal time scales. The state of the AMO influences the zonal position of the IL causing it to shift westward during AMO+ states (see Figure 1). A westward shift of the IL reduces the regional importance of the NAO for the North European climate. The impact of the AMO on the spatial position of both NAO centers of action (IL and AH) was analyzed for the MCA and the LIA. Independent of the respective climate state it was found that during AMO+ states, the Icelandic Low moves further towards North America while the Azores High moves further towards Europe and vice versa for AMO- states.

The shift of the IL and the AH is of great importance for the climate in Northern Eu- rope and is often neglected in studies discussing global and regional climate. The Baltic Sea is exposed to a variety of anthropogenic pressures. However, this study focused only on the im- pact of natural variability because it may be even more important than anthropogenic climate change soon, as approximately 60 % of the decadal variability of the mean SST can be attributed to the AMO (Kniebusch et al., 2019a). While Beranová and Huth (2008) found a higher correlation between the NAO and the European climate when the NAO centers of action are located farther east. However, this study showed that only the location of the IL is relevant for the regional correlation between the NAO and North European climate. Summarizing, the AMO influences the east-west position of the IL and the AH, with a NW and SE shift respectively during AMO+ phases. Therefore, it is important to consider the respective state of the AMO since it indicates whether the correlation between the NAO and regional climate will increase or decrease.

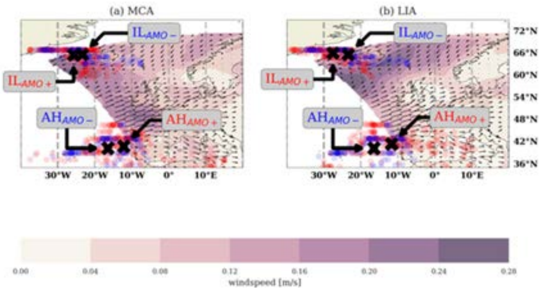

Figure 1 Spatial shift of the Icelandic Low and the Azores High sorted by AMO+ and AMO- phases during MCA (a) and LIA (b). Each marker corresponds to the center position obtained by the EOF analysis with overlapping time windows. Red (blue) markers indicate AMO+ (AMO-) phases. The black markers show the mean position of both NAO centers of action (AH and IL) during AMO+ and AMO- phases. The arrows show the mean wind field and are scaled to [m/s]. The contour shows the wind speed difference between AMO+ and AMO- phases. MCA = Medieval Climate Anomaly; LIA = Little Ice Age.; IL = Icelandic Low; AH = Azores High

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Atmospheric regional climate projections for the Baltic Sea Region until 2100

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1. Background

Main results will be presented from a BEAR paper (Christensen et al., 2022) describing the expected future change in atmospheric climate, based on the data available from the extremely large collection of regional climate simulations in the EURO-CORDEX project (Jacob et al., 2014).

The recent regional climate model projections strengthen the conclusions from previous assessments. This includes a strong warming, in particular in the north in winter. Precipitation is projected to increase in the whole region apart from the southern half during summer. Consequently, the new results lend more credibility to estimates of uncertainties and robust features of future climate change. Furthermore, the larger number of scenarios gives opportunities to better address impacts of mitigation measures. In simulations with a coupled atmosphere-ocean model, the climate change signal is locally modified relative to the corresponding stand-alone atmosphere regional climate model. Differences are largest in areas where the coupled system arrives at different sea-surface temperatures and sea-ice conditions.

2. Results

In the following, we will describe temperature and precipitation results. In Christensen et al. (2022) also wind speed, wind and precipitation extremes, snow and sea ice cover are analyzed and discussed, as they are simulated in the EURO-CORDEX ensemble.

In Fig. 1 we show scatter plots, where the change between 1981-2010 and 2071-2100 of precipitation is plotted against the corresponding change of temperature for each model and scenario. Ensemble means for the three scenarios are indicated. This has been done for subsets of the Baltic Sea catchment. The entire region; only land points; only sea points; only land points north and south of 60 degrees north, respectively.

There is a strong correlation between temperature and precipitation in winter with significant regression slopes of around 5 percentage points per degree and squared correlation coefficients of 0.5 to 0.6 depending on the sub-area. This is an indication of an approximate common sensitivity of precipitation change to local temperature change. This correspondence breaks down for summer, where the plots contain much more noise, indicating large model-dependent influences on the precipitation signal. The north-south gradient in summer precipitation change is apparent in the model averages (compare the northern and southern land point plots), but the inter-model spread is large.

Due to the roughly 20% higher average global warming in the current RCP8.5 ensemble than in the GCMs underlying BACC II ((BACC II Author Team, 2015), we would have expected general climate change to be around 20% larger for EURO-CORDEX RCP8.5 than those presented in BACC II. This difference is not generally seen in the figure, where we also show results from BACC II simulations (BACC II Author Team, 2015). The BACC II results correspond to the RCP8.5 results both with respect to temperature and precipitation change apart from land areas in summer where the BACC II change is only about 80% of the RCP8.5 result (+6.5% vs. +8.2%).

In Christensen et al. (2019) a thorough comparison of change patterns of mean temperature and precipitation has been performed for the PRUDENCE simulations behind the first BACC report (BACC Author Team, 2008), the ENSEMBLES simulations behind the second report (BACC II Author Team, 2015), and the EURO-CORDEX data behind the present study. This analysis used patterns of change scaled with global temperature change and is therefore useful for pinpointing differences between the BACC reports extraneous to the variations of general scenario strength, i.e., differences in local sensitivity and/or change patterns apart from those due to differences in emission scenarios. The most important differences between BACC II and the current simulations are a slightly reduced winter warming per unit of global warming in EURO-CORDEX compared to BACC II; a smaller wintertime precipitation increase, but a slightly larger increase of summer precipitation over the Baltic Sea. These conclusions do not contradict the results from Fig. 3, since a scaling with global warming would increase both local precipitation and local temperature changes for the BACC II ENSEMBLES results relative to RCP8.5.

3. Acknowledgments

It is with great sadness that we received the news that our co-author Christian Dieterich passed away during the review of the BEAR manuscript.

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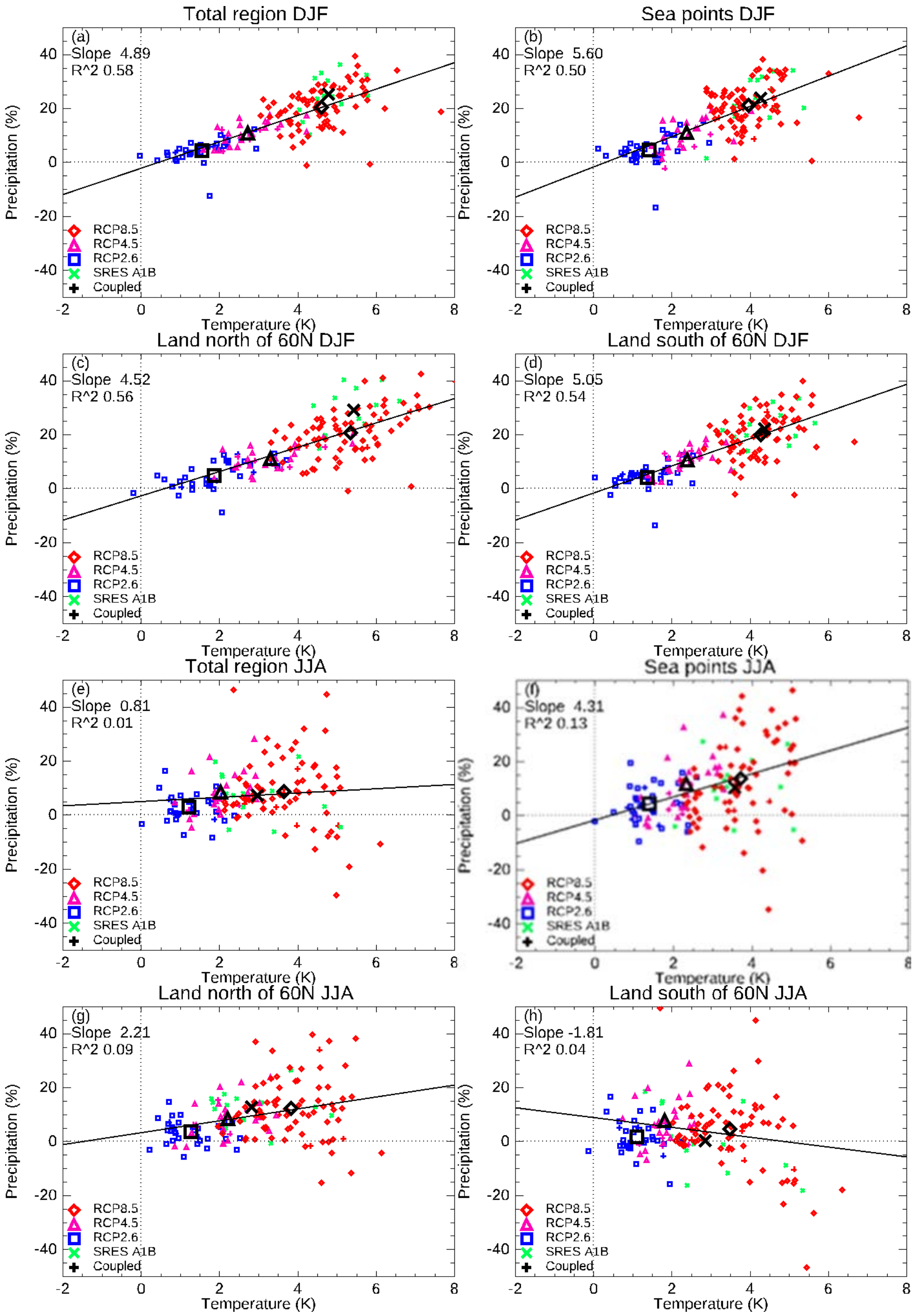

Figure 1 Relative change 1981-2010 to 2071-2100 of precipitation against temperature change for individual models and all scenarios. Scenario means are indicated by larger black symbols. Blue squares: RCP2.6; Pink triangles: RCP4.5; Red diamonds: RCP8.5; Green crosses: The ENSEMBLES simulations analyzed in BACC II (2015). Plus signs: RCA4-NEMO atmosphere-ocean coupled simulations. Calculation performed for subsets of the Baltic Catchment: The entire catchment; sea points; land points north and south of 60 degrees north, respectively. Panels a-d show winter; panels e-h show summer. The lines, with quoted slope and squared correlation coefficient, are best fits to all EURO-CORDEX and ENSEMBLES data, but do not include coupled-model results. There are 72 ensemble members following RCP8.5, 22 following RCP4.5, and 30 following RCP2.6.

Probabilities of wind velocity and wind wave parameters over the Baltic Sea based on 44-year long hindcast data

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1. Introduction

The principal goal of this study is to determine probability distributions of wind speed and direction, and for the significant wave height, mean wave period and mean wave direction for the eight selected locations representing various Baltic Sea basins (see Fig. 1). The probability distributions for the wind velocity are derived from 44-year REMO reanalysis database generated in the framework of the project HIPOCAS (Cieślikiewicz and Paplińska-Swerpel, 2008). The wind wave data modelled within the HIPOCAS project have been already compared with measured data. However, in previous comparative analyses, it was done based on basic statistics of errors (differences between modelled and observed data). In this study, not only the modelled and observed time series are compared. To deepen the assessment of the quality of the modelled data, the probability distributions estimated from modelled and measured wind wave data are compared against each other. To this end, the wind wave data measured at the station located south of Öland (see Fig. 1) were utilised. These data were taken from the database made available by the Swedish Meteorological and Hydrological Institute (SMHI).

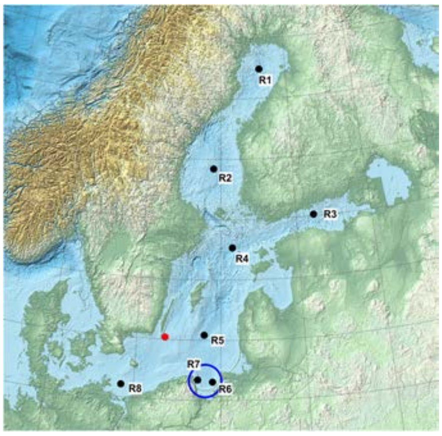

Figure 1. Locations R1, R2,…,R8 selected for estimating probability distributions (black circles). Location of SMHI Ölands Södra Grund measurement station is marked with red circle. Gulf of Gdańsk is indicated by a larger blue circle.

The wave fields over the Baltic Sea vary significantly both in time and space. That characteristics of the Baltic Sea wave climate is especially pronounced in smaller Baltic's basins and bays. It is caused by a diverse coastline and a variable bottom topography. A good example of such a Baltic basin is the Gulf of Gdańsk. The Gulf of Gdańsk is an important sea region for Poland, as its coastal zone is highly populated and it plays a significant role in maritime transport and tourism. In this study we are taking a closer look at the Gulf of Gdańsk by comparing probability distributions of basic wind and wind wave parameters for five selected locations in the Gulf. They are presented in Fig. 2.

Various probability density functions (PDF) are examined against the data and those best fitted are selected and presented in this work. In our approach, not only the marginal PDFs are determined, but also an attempt is made to establish joint probability distributions for wind speed and direction, and for significant wave height and mean wave period at each of the eight selected locations in the Baltic Sea, and the five selected in the Gulf of Gdańsk.

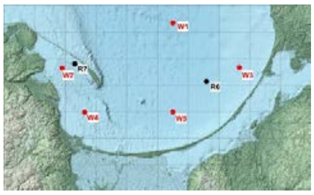

Figure 2. Gulf of Gdańsk with locations W1, W2,…, W5 indicated by red circles. Black circles show R6 and R7 locations.

The main purpose of this work was to go a little further than calculating series of basic statistics describing the wave climate of the Baltic Sea. Using the hindcast data, spanning almost half century over years 1958–2001, we are using a more comprehensive long–term description of statistical properties of wind and wind wave fields, by determining probability distributions of their basic parameters.

2. Methods

Within the framework of the HIPOCAS project, the input meteorological data, e.g., wind velocity fields came from dataset produced by hindcast with the REMO model (Jacob and Podzun, 1997; Feser et al., 2001) Wave data have been produced with wave model WAM in a rectangular grid in spherical rotated coordinates with the resolution 5'×5' and 1-hour time step.

In the present study we analyse the wind velocity vector at elevation 10 m $\boldsymbol{U}_{10}$ in polar coordinates represented by the wind speed $U = |\boldsymbol{U}_{10}|$ and the wind direction angle φ. The wind direction angle φ is defined clockwise from the north. When it comes to the variables characterising wave fields, we examine the significant wave height H_S, mean wave period T_z and the mean wave direction angle θ. This last one is defined in the same manner as wind direction angle, i.e., clockwise from the north. In this extended abstract both φ and θ angles are expressed in degrees.

To determine probabilistic characteristics of the analysed physical variables, first, the empirical frequency histograms are determined. It is done for each variable separately, and for chosen variable pairs to describe binomial empirical probability distributions in form of 2D histograms. All the frequency histograms presented here are normalised in the PDF-like manner allowing for direct comparison with theoretical PDFs. In the next step some selected theoretical PDFs are fitted to the observed data. It should be emphasised that all the data in their raw form are used in fitting procedures, not just their binned values taken from the prepared histograms.

To compare probability distributions estimated based on modelled wind wave data with those obtained from observations we used data collected at the SMHI Ölands Södra Grund station (56.0694°N, 16.6802°E) over period 19.10.1978–26.03.2004.

For fitting, the Method of Moments (MoM) and the Maximum Likelihood (ML) techniques were usually applied in this work. To fit the bivariate probability distribution of (H_S, T_z), the Conditional Modelling Approach (CMA) was used. An attempt to apply some other methods of determining binominal PDFs for various variable pairs has been made, and the results will be presented during the Conference.

3. Exemplary results

In Fig. 3 the comparison of frequency histograms obtained for modelled and observed data are shown. The station is located at depth of about 40m. At such water depths the influence of the bottom topography may be seen in the height, period, and the direction of storm waves. Thus, the modelled data taken from the four closed computational nodes were interpolated for the exact position of the recording station using bilinear interpolation method. In Fig. 3 the three parameter Weibull distribution fitted to the modelled (dark blue) and measured (red) data are also shown. It can be noticed that both the frequency histograms and the fitted Weibull PDFs compare very well between modelled and measured data.

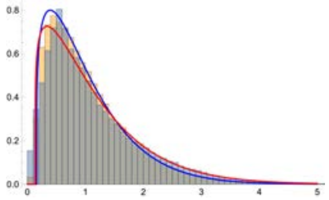

Figure 3. Frequency histograms of modelled (blue) and observed at the Ölands Södra Grund station (orange) significant wave heights H_S. Continuous curves represent estimated PDFs of three parameter Weibull distribution for modelled (dark blue) and measured (red) data.

In Fig. 4 the estimated 2D frequency histograms for modelled and observed joint empirical probability distributions are compared. Based on visual examination, one can see that the modelled data agree with measured data very well also in terms of joint empirical frequency distributions.

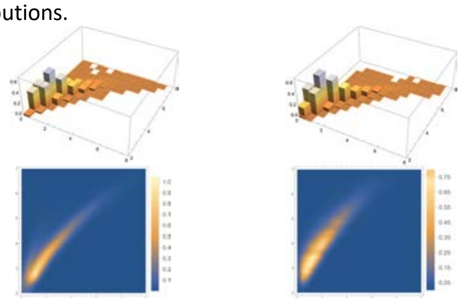

Figure 4. 2D frequency histograms of modelled (left) and observed at Ölands Södra Grund station (right) joint variables (H_S, T_z). Lower figures present smoothed contour plot of histograms shown above.

In Figs. 5 and 6 the modelled 2D distributions of various joint variables are compared between locations W1 and W4 in the Gulf of Gdańsk. In Fig. 5 the 2D frequency histogram for wind speed and wind direction (U_{10}, φ) is shown. The empirical PDFs are similar for both points with westerly winds being the most probable. However, for W1, located more towards the open sea than W4, stronger winds are a little more likely.

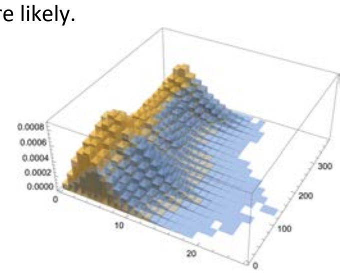

Figure 5. 2D frequency histograms of modelled joint variables (U_{10}, φ) for W1 (blue) and W4 (orange) locations at the Gulf of Gdańsk.

The differences in joint probability distributions of (H_S, φ) and (H_S, θ), between points W1 and W4, are more pronounced (see Fig. 6) due to the different characteristics of their locations in the Gulf. The detailed discussion of those differences and their interpretation will be given during the Conference.

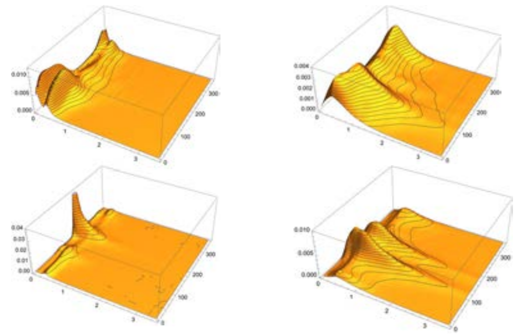

Figure 6. 2D frequency histograms of modelled joint variables (H_S, φ) (top figures) and (H_S, θ) (bottom figures) for W1 (left) and W4 (right) locations at the Gulf of Gdańsk.

4. Conclusions

In this study a number of various univariate and bivariate probability distributions of wind velocity and wind wave parameters are determined for different selected locations in the Baltic Sea. They show the diversity of the Baltic Sea meteorological and wind wave conditions. Probability distributions estimated for modelled and observed data provide a comprehensive tool for validating accuracy of the applied models. They give additional insight into the efficiency of modelling, compared to the traditional validation based on basic statistical analysis of differences between modelled and observed data.

Acknowledgements

This study has been conducted with partial funding from eCUDO.pl project No. POPC.02.03.01-00-0062/18-00. The E.U. Copernicus Marine Service Information has been used to compare HIPOCAS data against observations in nature. Calculations were carried out at the Academic Computer Centre (TASK) in Gdańsk.

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Climate change indicators (SE Baltic Sea, the Curonian Lagoon, Lithuania)

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1. Introduction

The climate describes the perennial totality of the area's weather, its typical changes, daily and annual weather fluctuations. Various climate indicators are used to assess climate change, which summarizes the meteorological information and makes it possible to compare the climate in the past, present and help predict the future. Understanding and managing climate change processes is an important task not only at the global level but also at the level of various regions and countries.

Knowledge of climate change is needed in the development of environmental conservation and climate strategy plans. When evaluating and reporting on the results of climate change research or adaptation plans, we find that there is a lack of information available to the public. As a result, even policymakers often have a misleading understanding of climate change. People are worried and anxious because they do not feel safe due to more frequent floods, air pollution, heat waves, intensifying storms, and so on. Of greater concern is the ignorance of the real facts about climate change and the short-sighted understanding of society only through the consumer prism.

It has been shown that climate change impacts the Baltic Sea region. Coupled atmosphere-ocean regional climate models project an increase in annual mean air temperature by between 1.5 and 4.3℃ (Meier et al., in review, 2021) over the Baltic Sea catchment area at the end of the century. It confirms that needed continuous comprehensive research and understanding how to move towards sustainable governance and the economy while protecting our earth's nature and public health by specialists in various fields are required. The observed environmental changes are often caused by a mixture of interwoven factors, among them climate change and its associated impacts.

In this work, we briefly present climate change indicators in the coastal areas of the South-eastern (SE) part of the Baltic Sea part, including the Curonian Lagoon (Lithuanian part).

2. Research area

Changes in the components of the climate system have a stronger impact on the coastal areas of the Baltic Sea, including the coastal areas of the South-eastern (SE) part of the Baltic Sea and the Curonian Lagoon (Fig. 1). Natural physical parameters are key indicators of climate change. Long-term observations and trend analysis help to explain why we are currently observing changes in the ecosystem.

Lithuanian Baltic Sea coastal zone is defined as unique, therefore most of its territory is protected areas. Curonian Spit separates the Baltic Sea and Curonian Lagoon and is a worldwide landscape park, which was included in the World Heritage list in 2000 at the UNESCO World heritage. There are unique resort and recreational settlements in this area. The Curonian Lagoon and the sea are separated by the Klaipeda Strait, where one of the biggest Lithuanian seaports and Klaipeda City is located (with a population of about 150,000).

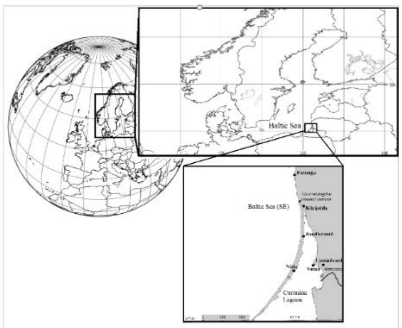

Figure 1. Research area.

3. Climate change indicators

The climate change indicators consist of a set of parameters: air temperature, sea surface temperature, sea-level change, atmospheric pressure field, and circulation, which describe the changing climate and trends.

The geographical location of the Baltic Sea and zonal positioning lead to different expansion of local climatic zones. The increasing rise in air and water temperatures since the late 20th century in the Baltic Sea region may have contributed to these larger differences. Observed slight changes in the prevailing winds in SE Baltic Sea coast. The land areas affected by local breeze circulation may increase due to larger temperature differences (gradients) during the day between land and sea. The extent to which the Baltic Sea influences air temperature in its coastal areas is an important factor for determining local coastal climates in the Baltic region (Dailide et al., 2019).

The atmospheric circulation in the Baltic Sea region is associated with variation in the North Atlantic Oscillation (NAO). It leads also of variations in the local air pressure, wind speed and direction, and sea level.

One of the main indicators of climate change is sea level change. The water level in the Curonian Lagoon has changed and increased during the observation period (1902–2018), increasing by 21 centimeters (Cepiene et al., 2022). The perennial rise in water levels on the SE Baltic Sea coast is related to the oscillation of atmospheric circulation in the North Atlantic region.

The results of the analysis clearly showed an increase of the water level taking place on all research time scales, from 1898 till 2018, in the SE part of the Baltic Sea and in the Curonian Lagoon. Sea level has risen by about 2-4 mm per year in all SE Baltic Sea tide gauge time series since 1898 and risen by about 3 mm year^{-1} since 1960, and by about 5-6 mm year^{-1} since 1980.

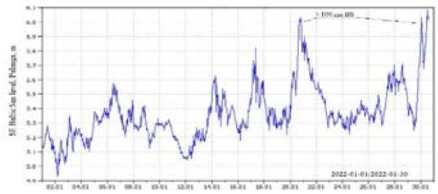

Figure 2. Sea level variation in the SE Baltic Sea near Palanga City, 2022 January (data of the Lithuanian Hydrometeorological Service).

Recently observed leaching of beaches in the shore of the Baltic Sea and abrasion of the shores is related to the change in the sea level. More intense storms are being observed. An example is the stormy winter of 2021/2022. In January, cyclonic circulation prevailed, during which a higher-than-usual rise in water levels was often observed near the coast of the SE Baltic (Fig. 2). The storm system (known as Nadia in Germany and Malik in other countries, 2022-01-30), brought hurricane-level winds to the North Sea and Baltic Sea coasts during the formation of a deep cyclone over the Baltic Sea (Fig. 3). According to the data of Klaipeda Seaport meteorological station, the maximum wind reached 34.81 m. in Klaipeda City and Seaport area. On the shores, the protective dune was washed up to 3 m high (with a continuous strip; Fig.5). Across the Lithuanian Western Country, about 200 000 people were without power.

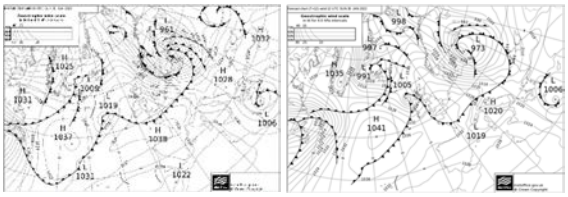

Figure 4. Surface pressure charts, 2022-01-30. (Data of MetOffice, https://www.metoffice.gov.uk/weather/maps-and-charts/surface-pressure).

Figure 5. The protective dune was washed up to 3 m high (the storm Malik, 2022-01-30).

In recent years, society has faced a significant increase in economic and insured losses from weather, storms, floods, and climate-related hazards. Regional climate change is one of the multiple drivers, which have a continuing impact not only on the environment but also on the socio-economic environment.

4. Conclusions and discussions

The Baltic Sea constitutes a sensitive ecosystem, which is constantly changing in response to climate variations and the rise of human activities. Specific warming „jump“ observed in all physical parameters in the SE Baltic Sea started in the 8-9th decade of the 20th century (Dailidiene et al. 2012, BACC II Author Team, 2015), and these changes not only continue but in many cases intensify.

The component of water level change can be analyzed as one of the indicators of change in atmospheric circulation. The trends results showed an increase in sea levels at the coastal areas of the SE Baltic Sea and the Curonian Lagoon. The water rise could modify the invasion of salty water into the Curonian lagoon and its process could slowly change the ecosystems in its northern part. This allows us to prompt further studies of sea level variability in the area, also because of the important practical and economic consequences of the potential further rise. As the climate change brings negative effects, the need to evaluate geophysical factors with social impact in establishing a united Baltic coast ecosystem assessment perspective is increasing. Ordinarily, the human population and economical concentrations are in coastal areas, and therefore it is in our biggest risk areas.

The Curonian Lagoon is the largest lagoon in the Baltic Sea. But in fact, this lagoon may be characterized as a hypertrophic water body, because more intensive summer warming in combination with other factors creates conditions for "hyperblooms" of Cyanobacteria and affected seriously on the ecosystem, ecosystem services, and recreation conditions of the Curonian Lagoon.

Climate has been and is the most important factor in the geophysical sphere that determines the processes of landscape formation. However, it must be acknowledged that humanity is also creating a new landscape by adapting and changing the environment to its own needs. The new and constantly growing component in the Climate-sphere is the Homo-sphere. And this only increases humanity's responsibility not only to adapt to a changing environment and Earth climate but also to protect it sustainably. Understanding and managing climate change processes is an important task not only at the global level but also at the level of various regions and countries. A synergistic approach to the impact of natural and human activities on the Baltic Sea environment can help to adapt eco-services and management to climate change.

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Marine heat waves in past and future climate

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1. Heat waves during the historical past

The most recent IPCC AR6 on climate change highlights marine heat waves (MHW) as particular challenge for physical, biological, social and other geoscientific and environmental disciplines. Studies suggest that many regions of the world ocean could end in a permanent heat wave state at the end of the century based on present-day metrics. The Baltic Sea is among the most rapidly warming regions worldwide and therefore particularly vulnerable to MHWs. Therefore, it is excellently suited to study the impact of MHW on various climate and environmental services.

Here we assess the capability of state-of-the-art Baltic Sea models from the Baltic Sea Model Intercomparison Project (BMIP) to simulate marine heat waves. We further explore the frequency, duration, the spatial extend, and intensity of MHW during the last 6 decades (1961-2018). Finally, we employ a high resolution future climate ensemble to investigate future MHW dynamics up to 2100 and provide a first estimation on uncertainties.

Figure 1 demonstrates that Baltic Sea models mostly differ in the high temperature regime. Accordingly, the representation of MHWs may substantially differ between models. Hence to robustly assess uncertainties, more models are needed.

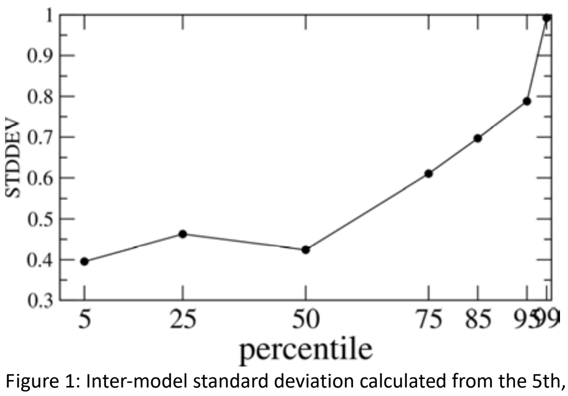

Figure 1: Inter-model standard deviation calculated from the 5th, 25th, 50th, 75th, 85th, 95th, and 99th percentiles surface temperatures. The percentiles represent area averages over the whole Baltic Sea. Standard deviations are calculated from spatial percentile averages over the whole Baltic Sea from each of the six models. Analysis period is 1990-2007.

Our results indicate pronounced decadal variations during the hindcast period which is robustly represented in all BMIP models. However, significant differences are found in the most extreme MHW classes on the year-to-year scale and in particular during the most recent decade. In parallel, we find stronger rising trends of yearly maximum temperatures than in annual and seasonal average water temperatures. Systematic model differences are likewise found in the duration and frequencies of MHW along with differences in the spatial pattern: Largest discrepancies occur in the Bothnian Sea and Bothnian Bay. Overall, we conclude that inter-model discrepancies are more pronounced in the extreme temperature regime compared to the average regime which translates in higher uncertainties regarding MHW.

2. Heat waves in future climate

Global climate change projections up to the year 2100 were downscaled using a hierarchical suite of existing high resolution regional atmosphere and ocean models for the Baltic Sea. We find significant increases in frequency, intensity, and spatial extension already in the mid-century around 2050 that clearly exceed the decadal variability of the historical period. At the end of the century most Baltic Sea basins end up in a permanent moderate MHW state when present day metrics are applied. However, our preliminary results further indicate that at least the most extreme effects of climate change on MHWs could be avoided by already moderate climate mitigation efforts and by limiting global warming to the 1.5° or 2°K targets of the United Nations Framework Convention on Climate Change (UNFCCC).

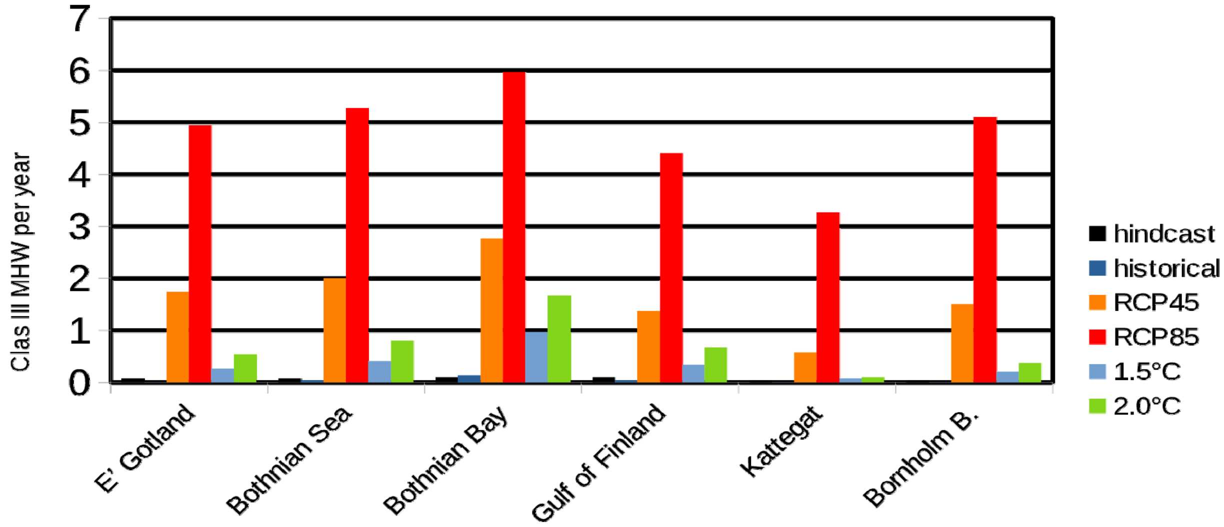

Figure 2: Frequency of severe and extreme (class III or higher) heat waves for the hindcast simulation, the historical simulation (1970-1999), the moderate and high greenhouse gas emission scenarios RCP45 and RCP8.5 (2070-2099), as well as under assumption of reaching the UNFCCC targets goals for limiting global climate warming to 1.5 or 2.0 degree. The bars represent ensemble means over six models.

Three new wave hindcasts for the Baltic Sea using different atmospheric forcing

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Abstract

Wave hindcast become a common tool to analyse the wave climate and is used as a surrogate for the real climate for on and offshore applications such as the design and construction of coastal defences or wind farms. However, wave hindcast strongly depend on the atmospheric forcing which made it hard to access the uncertainty of the results. Comparing several different wave hindcasts can have some difficulties as normally not only does the atmospheric forcing differ between simulation, but also the resolution, bathymetry, wave model and model setup.

Here, a set of three wave hindcasts that only differ by the atmospheric forcing are used to access the uncertainty due to this different forcing. The hindcast simulations are validated against observations in the whole Baltic Sea. It is shown that each of the hindcasts shows reasonable good agreement with the observations and whereas some can be better used for climate change analysis due to their longer simulation period the other one is capable of better reproducing the observed climate over a shorter period.

Simulated climate in the Baltic Sea region in a standalone atmospheric RCM and in an atmosphere-ocean model: evaluation and future climate change

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1. Introduction

Coupled regional climate models (RCMs) involving not just the atmosphere and the land surface, but also ocean and sea ice are successful in representing the climate of the Baltic Sea region (e.g. Döscher et al. 2002, Wang et al. 2015). For some climate features such coupled models have been shown to outperform standalone atmospheric models using prescribed sea sea-surface temperatures (SST). An example relates to the simulations of convective snow bands over the Baltic Sea (Van Pham et al. 2017).

Despite the successful performance of such coupled models most RCM climate change projections for the Baltic Sea region are from standalone atmospheric RCMs. This involves the recent EURO-CORDEX largest ensemble of RCM simulations covering all of Europe at 12.5 km horizontal resolution (e.g. Jacob et al. 2014).

From a regional and local perspective in the Baltic Sea area the lack of a realistic representation of oceanic processes at relevant resolution may have strong influence on the results (e.g. Kjellström and Ruosteenoja, 2007). This representation tends to differ between different global climate models (GCM); thereby making the potential for a coupled regional model more or less pronounced (Meier et al, 2011). In this work we examine results from one RCM used in both coupled and standalone mode to downscale two different GCMs for present day and a future climate change scenario. We aim at quantifying to what degree the results are altered by using a coupled model.

2. Model and experimental setup

The RCA4 regional climate model (Kjellström et al. 2016) has been setup and run for a domain covering Europe (Figure 1) at 25 km horizontal resolution. The model has been run with different boundary conditions in two configurations:

i) The standalone RCA4 atmosphere-land model using prescribed SST and sea-ice conditions from the driving GCM.

ii) The coupled RCA4-NEMO model (Wang et al., 2015) including a physical model interactively calculating sea-ice and ocean conditions in the Baltic Sea and in the North Sea (see Fig. 1). The ocean model has been operated at two nautical miles (c. 3.7 km) resolution.

The models have been run with boundary conditions from the reanalysis ERA-Interim (Dee et al., 2011) and from two different GCMs; EC-Earth (Hazeleger et al. 2010) and the MPI-M-ESM (Popke et al. 2013). The GCM results are taken from CMIP5 (the fifth phase of the Coupled Model Intercomparison Project, Taylor et al. 2012). For the period before 2006 the GCMs have been using historical forcing conditions as prescribed in CMIP5. For the future period 2006-2100 we are focusing on the representative concentration pathway scenario RCP8.5 (Moss et al. 2010). For model evaluation purposes we compare with observations from E-OBS v20.0e (Cornes et al. 2018).

3. Results

The results show that the coupled model performs similarly as the uncoupled model. This implies that differences are small and mostly concentrated to the areas of coupling. An example is given in Figure 1 showing summertime (June-August) seasonal mean temperature in E-OBS and as simulated by the two versions of the model when forced with boundary conditions from the MPI-M-ESM. The large picture reveals that the simulated climate is too cold in northern Europe, a feature shared with the driving GCM. In more detail it can be seen that differences between the two versions are very small and confined to coastal areas around the Baltic Sea where the coupled model tends to be slightly warmer than the uncoupled model.

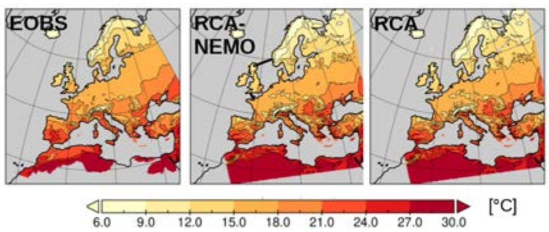

Figure 1. Summer (June-August) seasonal mean temperature according to E-OBS (left), the coupled RCA4-NEMO model (middle) and the atmosphere stand-alone RCA4 model (right). The middle panel also illustrates where the coupling between the NEMO model and the driving global ocean model takes place (black lines).

Also the climate change signal is similar in the two model versions and the impact of the coupling is most pronounced over the coupled region, i.e. the Baltic Sea and the North Sea. Figure 2 illustrates changes in summer (June-August) seasonal mean temperature in the coupled version of the model driven by the MPI-M-ESM. The typical land-sea warming pattern with more warming over land due to less effective heat capacity compared to the ocean is seen. Also, the impact of the well-known weak warming over the North Atlantic due to changes in large-scale ocean circulation in the Atlantic and reduced oceanic northward heat transport can be seen. Over the northernmost oceanic regions there is instead stronger warming related to reductions in sea-ice cover in the Arctic region. All this applies likewise to the uncoupled RCA version (not shown). The difference in anomaly climatologies (2070-2099 minus 1970-1999) between the coupled minus the uncoupled version indicates the "coupling effect" in summer is most intense directly over the coupled area in the North Sea and the Baltic Sea. The amplitude of the difference reaches locally about half of the climate induced temperature change in both model versions. The shape and length scale of the local anomalies indicate changes in ocean circulation as driver between the coupled and uncoupled RCA versions.

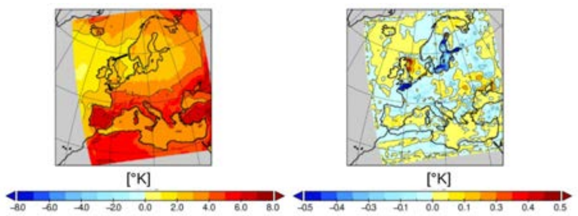

Figure 2. Change in summer (June-August) seasonal mean temperature in the coupled RCA4-NEMO run downscaling the MPI-M-ESM under RCP8.5. The comparison is between 1970-1999 and 2070-2099. The left panel also illustrates where the coupling between the NEMO model and the driving global ocean model takes place (black lines).

4. Conclusions

The presented analysis show that the regional coupled model reproduces features of the observed climate in a good way over the Baltic Sea and North Sea region. Differences between the coupled version and the uncoupled version are relatively small and confined to the coupling region or its proximity. The results also indicate that the coupling may impact climate change in the region. Again, differences are most pronounced over the immediate coupling region. Differences are shown to be significant. The preliminary results showed here points to the fact that such a coupled model is a useful, and possibly necessary, tool for projecting climate change in the Baltic Sea region. In the forthcoming analysis we will make a more in-depth analysis of differences between the coupled and uncoupled model versions with the aim of being able to make a more robust conclusion.

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Changing impact of the large-scale atmospheric circulation on the climate variability of the Baltic Sea in winters 1950/51–2020/21

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1. Introduction

A detailed assessment of climate variability of the Baltic Sea area for the period 1958-2009 (Lehmann et al. 2011) revealed that recent changes in the warming trend since the mid-1980s were associated with changes in the large-scale atmospheric circulation over the North Atlantic. The analysis of winter sea level pressure (SLP) data highlighted considerable changes in intensification and location of storm tracks, in parallel with the eastward shift of the North Atlantic Oscillation (NAO) centres of action. Additionally, a seasonal shift of strong wind events from autumn to winter and early spring existed for the Baltic area.

Lehmann et al. (2002) showed that different atmospheric circulation regimes force different circulation patterns in the Baltic Sea. Furthermore, as atmospheric circulation, to a large extent, controls patterns of water circulation and biophysical aspects relevant for biological production, such as the vertical distribution of temperature and salinity, alterations in weather regimes may severely impact the trophic structure and functioning of marine food webs (Hinrichsen et al. 2007).

To understand the processes linking changes in the marine environment and climate variability, it is essential to investigate all components of the climate system, including large-scale atmospheric circulation. Here we focus on the changes/shifts in the large scale atmospheric conditions and their impact on the regional scale variability over the Baltic Sea area for the period 1950-2021. This work extends previous studies which focused on the response of the Baltic Sea circulation to climate variability for the period 1958-2008 (Lehmann et al. 2011). Now extended time series of ECMWF ERA5 global reanalysis for 7 decades are available, highlighting recent changes in atmospheric conditions over the Baltic Sea. The main focus of this work is to identify predominant large scale atmospheric circulation patterns (climate regimes) on a monthly/seasonal time scale influencing the regional atmospheric circulation over the Baltic Sea area. Furthermore, long-term changes on the annual to decadal time scale will also be investigated.

2. NAO and mean sea level changes

The Landsort sea level can be used as proxy for the changes of the mean sea level elevation of the Baltic Sea. Thus, describing the barotropic water exchange between Skagerrak/Kattegat and the Baltic Sea (e.g. Lehmann et al. 2017). It is well-known that the sea level at Landsort is well correlated with the NAO winter index at about 0.5 to 0.6. Fig. 1 shows the monthly mean sea surface elevation at Landsort(https://www.smhi.se/en/services/open-data/search-smhi-s-open-data-1.81004) and the NAO-index for the period 1887–2021 (updated from Jones et al. 1997). The patterns are similar, but the NAO index shows higher seasonal variability. The NAO-winter index explains about 35% of the mean sea level variability of the Baltic Sea.

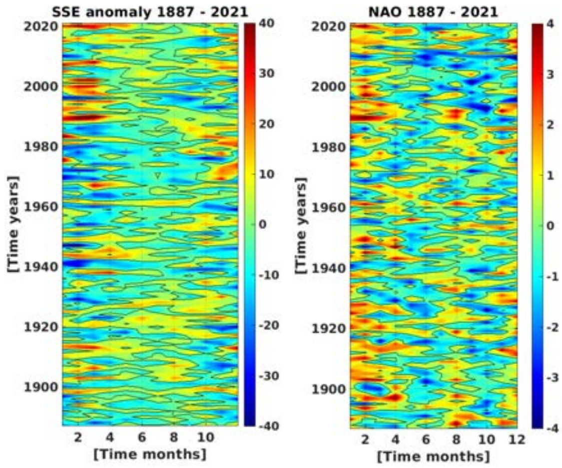

Figure 1. Hovmöller diagrams of sea surface elevation anomaly [cm] at Landsort and the NAO-index for the period 1887--2021.

The total correlation of the NAO-winter index DJF comprising the entire time series 1887-2021 is r= 0.6. However, the correlation between the NAO-winter index and sea surface elevation at Landsort is changing over time (Fig. 2, Andersson 2002). Thus, the strength of the influence of the NAO on the mean sea level elevation of the Baltic Sea is changing correspondingly.

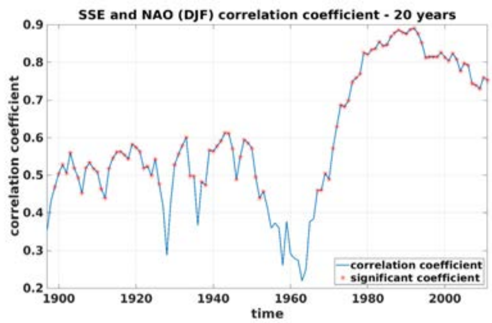

Figure 2. Running correlation with 20-year window between sea surface elevation at Landsort and the NAO-winter index DJF for the period 1897–2011.Red stars denote statistical significance of correlation coefficients ($p < 0.05$).

The running correlation coefficient (20-year window) between NAO-index and sea level at Landsort is below 0.5 between 1951 and 1970, and it reaches maximum correlation of > 0.8 from 1979 to 2003 (Fig. 2). This change in correlation is most probably associated with a shift of the NAO pattern to the east (Andersson 2002, Lehmann et al. 2011).

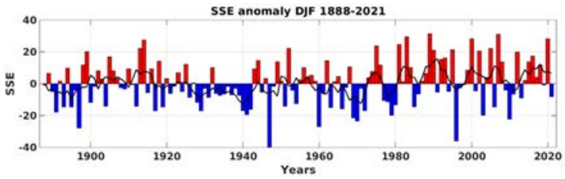

Figure 3. DJF-average of sea surface elevation anomalies at Landsort, and five-year running mean (black line) for the period 1888 to 2021.

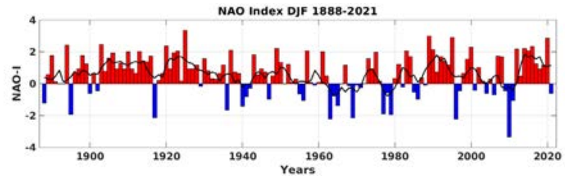

Figure 4. DJF NAO-winter index for the period 1888 to 2021. Black line denotes 5 year running mean.

The change in correlation coefficients (Fig. 2) could be explained by comparing the time series of the seal level anomalies averaged over DJF (Fig. 3) and the corresponding NAO winter index (Fig.4). After 1960 positive and negative sea level elevation anomalies correspond to positive and negative alternating NAO indices. Before 1940, the NAO winter index showed mostly positive values for periods over several years.

3. Detailed analysis 1950-2021

A detailed analysis of the large-scale atmospheric circulation regimes and their influence on the climate variability of the Baltic Sea will be carried out based on ECMWF ERA5 atmospheric reanalysis data for the period 1950 to 2021. A special focus of our analysis will be the comparison of the period with low correlation between the sea level at Landsort and the NAO index (1950-1970), and high correlation (1979-2003) and the following years until 2021.

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Application of the coupled Regional Ocean Modeling System (ROMS) and the Los Alamos sea ice model (CICE) for the Baltic Sea

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1. New model set for the Baltic Sea.

Regional Ocean Modeling System (ROMS) and the Los Alamos Sea Ice Model (CICE) coupled via Model Coupling Toolkit (MCT) are being prepared for the Baltic Sea. The use of these two models together with the high horizontal resolution of the grid will be a unique approach for this sea.

"Coupled" in this case means mutual exchange of parameters during the simulation: ocean model sends a bottom boundary conditions to sea ice model and other way round – ice cover affects surface boundary layer of the sea. Variables sent from the sea towards the sea ice include: currents, temperature, salinity, surface elevation and freezing/melting potential. From sea ice model to sea model MCT redirects: ice concentration, freshwater and salt fluxes, nonradiative and radiative heat fluxes and stress components.

2. Reasons to choose these particular models.

CICE model is the leading tool of its kind for simulating sea ice. Work with its standalone version (not coupled with any other model) for the Baltic Sea started in 2018. Simulation results were compared with satellite data. These results showed fairly good agreement at the start of the winter, but faced divergence at the end of ice season. It was decided to carry out further work on the CICE model, but after first coupling it with the sea model. This overlapped with the need to replace the old ocean model used in the department. An important criteria for the selection of the new model were: its suitability to the regional scale, inclusion of nonlinear free surface model and fact of being continuously improved. ROMS is a model that met these requirements and additionally have some interesting features like sigma vertical layers and Arakawa-C grid.

3. Initial configuration of the coupled model.

For the first launch of the coupled CICE and ROMS model, the infrastructure of the previously used ocean model was utilized. Thus an atmospheric forcing and computational grid had a horizontal resolution of 2.3 km.

The input data included runoff from the largest rivers of the Baltic Sea, as well as lateral boundary conditions (LBC). Some changes have been made to the original code to allow LBC to operate inside the domain. As a result, the connection between the Baltic and the North Sea is cut off at the Kattegat and northern boundary conditions are implemented in this area.

4. High resolution grid.

After the relatively good results of the initial configuration, construction of a higher resolution model was started. Bathymetry with 500 m resolution, shared by BSH, was used as a basis. However, the use of vertical sigma levels requires more preparation than z-coordinates used in previous sea model. The bathymetry must be smoothed to avoid errors in calculating the horizontal pressure gradient and to keep hydrostatic consistency. Both of these features are expressed by the so-called Beckman & Haidvogel number and Haney number.

In this way, a new grid with a horizontal resolution of 0.25 NM and 40 sigma layers was created. This corresponds to the horizontal number of nodes: 2700x3200.

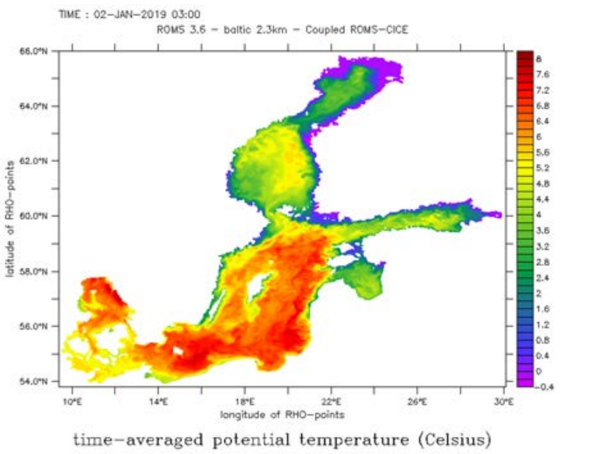

Figure 1. Sea surface temperature at the beginning of January 2019 in simulation on 2.3 km grid.

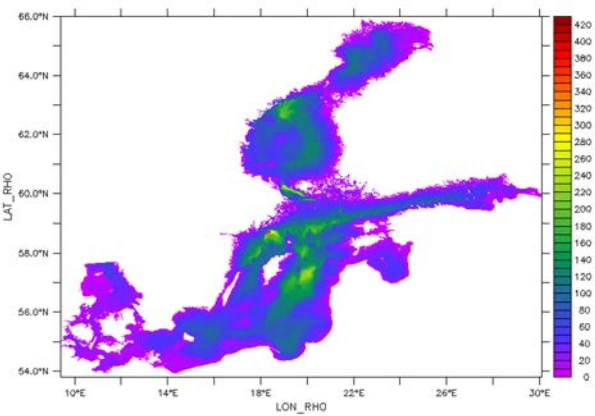

Figure 2. Bathymetry (in meters) prepared for new model with 0.25 NM horizontal resolution.

Such a large number of points imposed a new changes in code, which let atmospheric forcing being interpolated during model run from lower resolution data (which occupy much less disk space).

5. Future plans.

The presentation will show an up-to-date work progress and a results from high-resolution coupled models. Validation simulations are planned first, followed by long-term (several decades) hindcast simulation.

In next stages, the prepared set of models will be used for further work with CICE model. In particular, this includes the tuning of the parameters and the possible introduction of new mechanisms responsible for fast ice simulation. This will be a first step in a sea ice deformation analysis project.

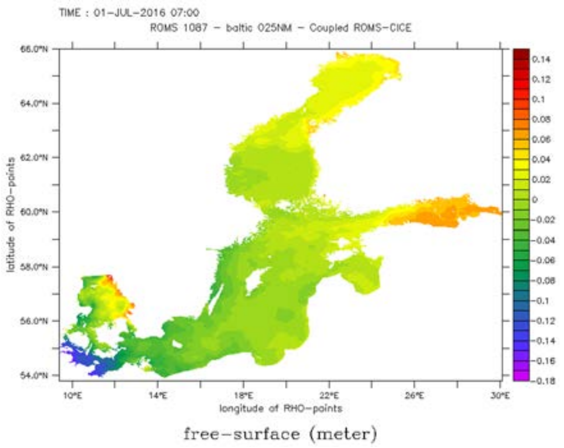

Figure 3. Free surface simulated on 0.25 NM grid. 7 hours after simulation start with flat (equal 0 m across the domain) initial condition.

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Future sea ice conditions for maritime traffic in the northern Baltic Sea

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1. Introduction

The Baltic Sea is seasonally ice covered and in the northern part the sea-ice season can last for up to 7 months. The maximum total sea-ice extent is usually reached in late February and between mid-February and mid-March the ice covers on average 45 % of the total Baltic Sea area. However, interannual fluctuations around this mean are very large and during severe winters the entire Baltic Sea can be completely ice covered.

With roughly 15 % of the world's cargo transportation, the Baltic Sea is one of the heaviest trafficked seas in the world (HELCOM, 2009). Despite the sometimes very harsh wintertime sea-ice conditions, intense maritime traffic proceeds throughout the year, with ships continuously operating to the northernmost ports of the Baltic Sea. This usually requires some assistance by ice-breakers and traffic restrictions (TraFi, 2010) based on the ship's Finnish-Swedish ice class are therefore imposed by the ice-breaking authorities (HELCOM, 2004).

We have previously studied how changes in future sea-ice conditions might impact on the maritime traffic in the Baltic Sea (Höglund et al, 2017). Here we revisit the topic with a larger ensemble of simulations, and a focus on slightly shorter time scale.

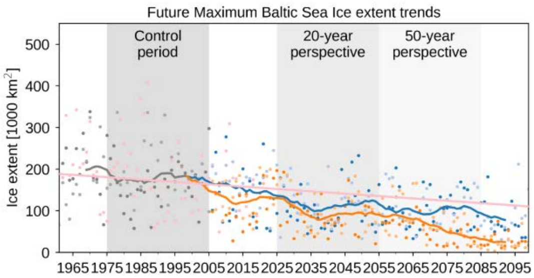

Figure 1. Maximum sea ice extent in the Baltic Sea. The dots show the yearly maximum for the observations (pink), historical simulation period (grey), RCP4.5 (blue), and RCP8.5 (orange). The solid blue and orange lines show the 15-year rolling mean for RCP4.5 and RCP8.5, respectively. The pink line shows an extrapolation of the observed trend for the 100-year period (1920–2019). Gray shaded box indicated the control period and two future periods.

2. Method and data

Here we present a summarized version of a more extend analysis (Pemberton et al, 2021) where we analyzed how sea ice conditions in the Baltic Sea and mainly its northern parts (Bothnian Bay, Bothnian Sea, Åland Sea and northern Baltic Proper) may change in a 20- and 50-year perspective relative to 2020. The change is estimated for two future 30-year periods 2025–2054 (20-year perspective) and 2055–2084 (50-year perspective) relative to a historical 30-year control period (1975–2004). The study is focused on seven indicators describing different aspects of sea ice change, see Table 1. The indicators were identified jointly with the Swedish Maritime Administration (SMA), and chosen based on available data and relevance to ice breaking operations and maritime traffic. The study is based on historical observations from SMHI, the Finnish Meteorological Institute (FMI) and SMA, and climate scenario data from previous projects.

Regional downscalings of global climate scenarios representing two different representative concentration pathways (RCP4.5 and RCP8.5) have been analysed based on a total of ten different climate model simulations from two different regional models. Scenarios based on the lower representative concentration pathway (RCP2.6) are absent because existing datasets for this pathway did not have sufficient quality for sea ice parameters.

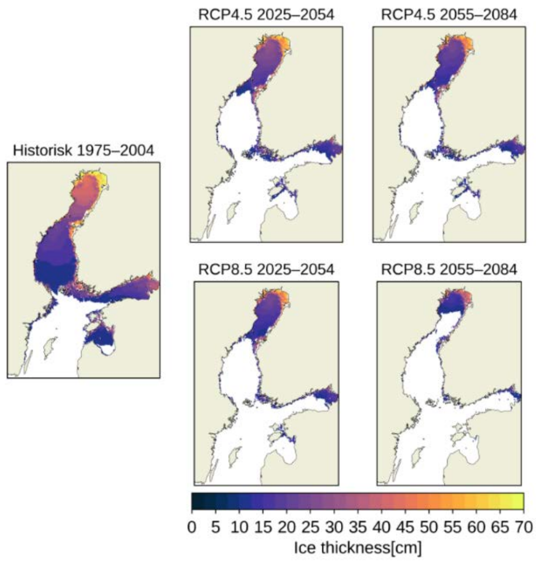

Figure 2. Mean level ice thickness [m] for the historical control period (left) and the two future periods (subfigures in the middle and right columns), for the two scenarios RCP4.5 (upper row) and RCP8.5 (lower row). Ice with a mean thickness lower than 10 cm has been masked out.

3. Results

The results show, in agreement with previous assessments (BACC II Author Team, 2015; Meier et al., 2021) that future winters will gradually, on average, have a smaller maximum ice extent compared to the control period, see Figure 1. Ice seasons will also get shorter, with the largest differences in the southern areas. None of the scenarios yield ice free winters during the 21st century, and at least Bothnian Bay is expected to become fully ice covered on average, also during future winters. However, in the RCP8.5 scenario, ice with an average thickness of 10 cm or more disappears from the southern Bothnian Bay.

In a 20-year perspective, changes in maximum ice extent are less distinct due to large inter-annual variations. In a 50-year perspective the change becomes more distinct and shows decreasing ice extents and smaller inter-annual variations (Figure 1).

Level ice (the thermodynamically grown ice) is expected to get thinner on average in all analysed areas (Figure 2), and the presence of heavily deformed ice is expected to decrease. However, models lack the ability to simulate brash ice barriers, which are formed when thin ice is pressed against a thicker ice edge or land by wind and waves. These types of barriers can be problematic for ships even in mild winters, and are expected to occur also in the future. Thinner and less dense ice fields also lead to increased ice drift in the Bothnian Bay and Bothnian Sea.

The number of days with ice class based traffic restrictions for Swedish harbours are expected to decrease as sea ice thickness become thinner and ice seasons become shorter. The distribution of restrictions will also change, mainly in the Bothnian Bay where days with heavier ice classes (1A/B) decrease and days with lighter ice classes (1C/II) increase, see Figure 3.

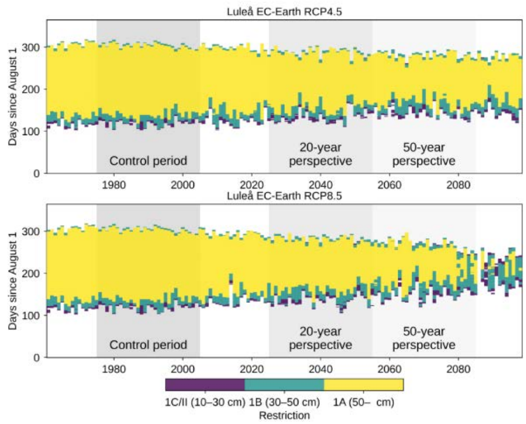

Figure 3. Time periods when the different traffic restrictions 1C/II (10–30 cm), 1B (30–50 cm), and 1A (50– cm) are imposed on ships operating in the Luleå harbour area according to the climate scenarios RCP4.5 (upper) and RCP8.5 (lower), here shown for a regional downscaling of the EC-Earth model.

4. Conclusions

Changes in maximum ice extent, length of ice season and average level ice thickness are judged to have a low uncertainty as the results are supported by both historical observations, and by the fact that model simulations are relatively close to the observations during the historical period. Changes in ice deformation, ice thickness distribution, and ice drift are judged to have a higher degree of uncertainty as there are no or very few observations to support model results (Table 1).

The study is partly limited by the lack of data for the lower RCP2.6 and by lacking a more thorough analyses of possible changes in meteorological conditions. Another limiting factor is the relatively low number of regional climate model simulations with reliable ice parameters used in the study.

Indicator	Uncertainty	Description [unit]
Maximum sea ice extent	Low	Totala area [1000 km^2] maximum ice extent during a season
Length of ice season	Low	Number of [days] a region is ice covered
Level ice thickness and extent	Medium	Thickness [cm] of thermodynamically grown ice.
Ice concentration of deformed ice	High	Fraction of ice [%] grown due to dynamical processes (ridging and rafting).
Ice thickness distribution	High	Areal distribution [%] of ice in a given thickness interval.
Ice drift	High	[cm/s]
Ice class based traffic restrictions	Low/Medium	Time period [days] when different Finnish-Swedish traffic restrictions are imposed.

Table 1. The seven different sea-ice Indicators defined in the study. The uncertainty of the estimate change of each indicator is roughly estimated (with low, medium and high uncertainty) by considering how much observations are available during the historical period, and how close to the observed state each simulated indicator is.

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Changes in cloudiness cause a changing seasonality in the Baltic Sea region

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1. Motivation

In the Baltic Sea region, a significant decrease and subsequent increase in solar radiation have been detected during the past half-century (Pfeifroth et al., 2018). But the rise in shortwave irradiance is not seen for all seasons; significant changes appear in the seasonality of the cumulative sum of daily shortwave irradiance and the sea surface temperature of the Baltic Sea. Kahru et al. (2016) show that the accumulated incoming shortwave energy has decreased in winter and increased during the spring and summer. The cumulative thresholds of surface incoming shortwave irradiance up to 1000 W/m^2 are reached later in the season, but higher thresholds are reached earlier. The shift from later towards earlier cumulative thresholds occurs in spring, around March 15.

Changes in shortwave irradiance are associated with atmospheric transparency and cloudiness parameters like cloud fraction and albedo. The more substantial factor here is cloudiness, and therefore, we concentrate on reasons for changes in clouds properties.

The dimming and brightening periods of Northern Europe in the last half-century are often associated with large scale atmospheric circulation, with North Atlantic Oscillation (Russak, 2009; Pfeifroth et al., 2018). This connection is through clouds. The phase and position of the North Atlantic Oscillation describe the westerlies' strength and location in the broad North Atlantic sector. The storm track of midlatitude cyclones, the main reason for frontal cloudiness, is associated with the position of westerlies. It is a monthly scale relation. While looking for seasonal shifts, it is reasonable to look for mechanisms on a daily scale. As the temporal and spatial scales should be coherent, we use the synoptic-scale atmospheric circulation patterns. Sfîcă et al. (2021) have shown an essential link between atmospheric circulation and cloud cover.

During the last tens of years, the most significant changes in cloud cover in the Baltic Sea area have happened in March (Russak, 2009; Post and Aun, 2020). A decrease of anticyclonic conditions in this part of the continent may explain at least partially the regional trends observed in surface solar radiation. We show that changes in early spring shift in seasonality in the Baltic Sea are directly linked through cloudiness changes to synoptic-scale atmospheric circulation.

2. Data and methods

We analyse cloud cover changes over the Baltic Sea region using EUMETSAT's CLARA-A ed. 2.1 dataset (Karlsson et al., 2020) from Satellite Application Facility on Climate Monitoring (CM SAF). It covers the time range 01.01.1982 – 30.06.2019 and is derived from the AVHRR sensor onboard polar-orbiting NOAA and METOP satellites. Daily mean cloud fraction cover (CFC) with 0.25° x 0.25° grid was used. CFC is defined as the fraction of cloudy pixels per grid square (point) compared to the total number of analysed pixels in the grid square (Karlsson et al., 2020).

The study area includes the Baltic Sea and surrounding countries from 52 to 70° N and 5 to 32° E. The climate of the region is characterised by distinct seasons. Only one month - March - as a sensitive month to a seasonal shift in climate variables is analysed. These variables are at first influenced by atmospheric circulation.

CM SAF Toolbox, Climate Data Operator (CDO), and Python were used to analyse the data. Monthly mean values were calculated from daily mean values received from CM SAF. Missing values were ignored during the calculations.

For describing synoptic-scale atmospheric circulation, sea level pressure fields were classified using synoptic-scale Gross Wetter Typen (GWT) weather types (Philipp et al., 2016). The selected method offers the simplicity of interpretation and flexibility to make sensitivity studies. Eight are directional of 10 circulation types: W, NW, N, NE, E, SE, S, SW, plus cyclonic (C) and anticyclonic (AC). The classification is centred in 58.75°N, 25°E.

GWT's were calculated for all days between 1979 and 2019 using gridded MSLP data of ERA5 reanalysis at 12:00 UTC with the cost733class software package. The frequency distributions of GWT circulation types for all Marches 1979–2019 were used to show that the changes in synoptic-scale circulation are at least partly responsible for the cloud fraction interannual variability.

3. Changes in monthly CFC

In March, the cloudiness is distributed evenly over the area, mostly due to overwhelming frontal cloud generation processes. The mean values are higher over the Norwegian Sea and lower over the Baltic Sea (Fig. 1). The mean CFC for the entire region was 71.8 % (std. 4.9 %, median 70.8%) in 1982—2019. Means for the period for a single pixel range from 62.2% up to 90.0%.

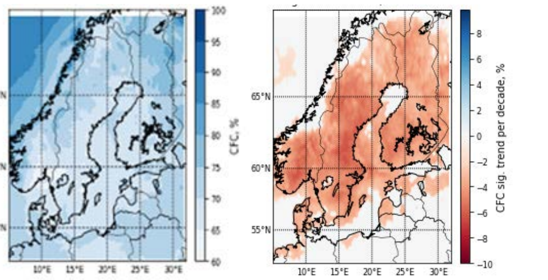

Figure 1. Mean CFC and a significant trend per decade in CFC from satellites for March from 1982 to 2019.

The monthly CFC-s for the study area from the satellite and ERA5 reanalysis show a similar decreasing trend (Fig. 2). The lowest mean CFC from satellite data, 61.0 %, was recorded in 2013. Since then, the mean cloud cover has been rising. For 2015-2019 the linear regression was positive. Including 2013 and 2014 would increase the slope up to 1.2 %. It means that the falling trend that could be followed since the start of the satellite measurements has turned to rise in the last ten years. This is a general tendency over the Baltic Sea area. Looking further to the reason for these changes, we look at territorial distributions of daily cloud fractions.

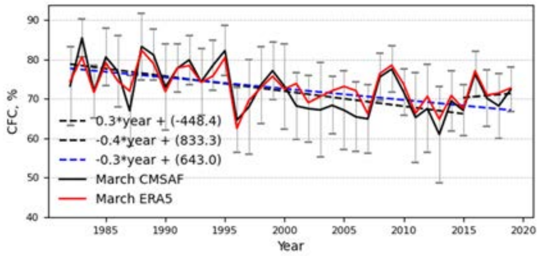

Figure 2. March monthly mean CFC over the region from ERA5 (red line) and satellite (solid black line) with std (grey) 1982--2019. Linear regressions are shown for the satellite data. The blue dashed line is for the entire period, and the black dashed lines are for 1982--2015 and 2015--2019.

4. Daily statistics

The daily grid points were divided into five different CFC ranges to understand better whether the decrease in cloud cover is due to more clear days or because all days have become less cloudy. These five groups are: clear (CFC=0), almost clear (CFC<=5%), low cloud cover (5%<CFC<=30%), almost overcast (CFC>=95%) and full overcast (CFC=100%). For each year number of grid points in all groups were summarised.

The change in total CFC in the Baltic Sea area comes mainly from the decrease of almost overcast and full overcast cloud cover days, while the number of grid points in these groups has significantly decreased (Fig. 3). However, as for total CFC, since 2013, the number of almost overcast and full overcast cloud cover days has increased. No such rapid change is visible for the other groups: the number of clear and almost clear days are practically stable. At the same time, there is a slight increase in the number of days with low cloud cover for the entire period, with no visible change after 2013.

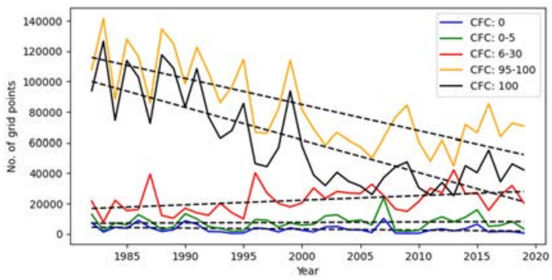

Figure 3. The number of grid points with certain CFC ranges over the region in March 1982--2019.

For each grid point, trends in each group were calculated to see a territorial distribution of changes in cloudiness. The highest territorial trends are for almost overcast and full overcast days and, of course, the negative ones by the changes in areal means. Strong significant trends in the number of days with full or almost complete cloud cover are over the whole study area, slightly lower over the sea than land (Fig. 4).

5. Changes in atmospheric circulation

Cyclonic and western circulation types are responsible for almost overcast and fully overcast days, while anticyclonic and eastern types are related to clear or almost clear days. Daily time-series of GWT-s calculated from ERA5 pressure data centred in Estonia were used to show the variability in synoptic-scale atmospheric circulation. Both the clear days and overcast days show a sizeable interannual variability (Fig. 5), but the tendencies coincide with the trends in CFC groups.

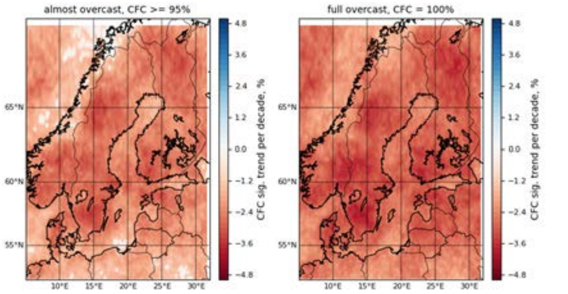

Figure 4. A significant change (% per decade) in CFC for almost overcast and full overcast days 1982--2019.

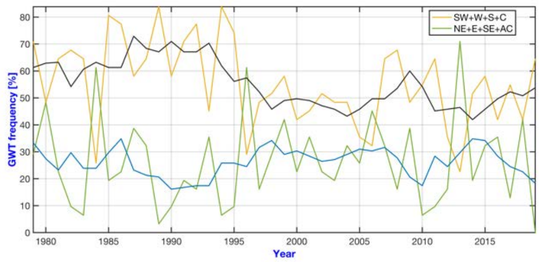

Figure 5. Relative frequencies of circulation types that could be associated with overcast situations (SW+W+S+C) and clear days (NE+E+SE+AC) for March 1979--2019. Black and blue lines show the five-year running means.

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Coupled hydrological and hydrodynamic modelling application for climate change impact assessment in the Nemunas River watershed – Curonian Lagoon – Baltic Sea continuum

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1. Introduction

Adaptation to climate change is a central issue for the planning and implementation of measures to reduce nutrient inputs to the rivers and, subsequently, to the coastal and marine environment. The ECO-NEWS project's objective is to predict the environmental changes in the Nemunas River watershed – Curonian Lagoon – Baltic Sea - Lithuanian coastal zone continuum, and possible impacts of these changes on the biosphere, using a set of state-of the-art coupled hydrological, hydrodynamic, and water quality numerical models to quantify these changes. We have set-up the modeling framework using, where possible, the local available high-resolution data. We use SWAT model to predict the future changes of the Nemunas River basin in hydrology, sediment, and nutrient load under changing climate. We couple the basin model with SHYFEM to predict the changes in the Curonian Lagoon and the Baltic Sea (Lithuanian EEZ) under the same possible future conditions.

Currently we have the predicted results of the changes in the watershed and possible nutrient and sediment loads. The long-term hydrodynamic simulations are running, and we expect the results to be available soon.

2. Study site

The study area is located in the southeastern part of the Baltic Sea, comprising of the Nemunas River watershed, Curonian Lagoon, and an exclusive economic zone of the Republic of Lithuania (Figure 1).

Curonian Lagoon is the largest coastal lagoon in Europe, with an area of 1 578 km^2 and a drainage area of 100 458 km^2 (Čerkasova et al., 2016). Although, the drainage area of the lagoon consists of several river basins, the most important of them is the one of Nemunas River, which is supplying about 98% of the total inflowing water (Jakimavičius, 2012).

3. Climate projections

We used CORDEX (Coordinated Regional Downscaling Experiment) scenarios for Europe from the Rossby Centre regional climate model (RCA4), which consisted of five sets of simulations (downscaling) driven by the following five global climate models: EC-Earth (ICHEC), CNRM-CM5 (CNRM), IPSL-CM5A-MR (IPSL), HadGEM2-ES (MOHC), and MPI-ESM-LR (MPI). The dataset covers a period of 1970-2100 according to three Representative Concentration Pathway (RCP) scenarios: RCP2.6, RCP4.5, and RCP8.5.

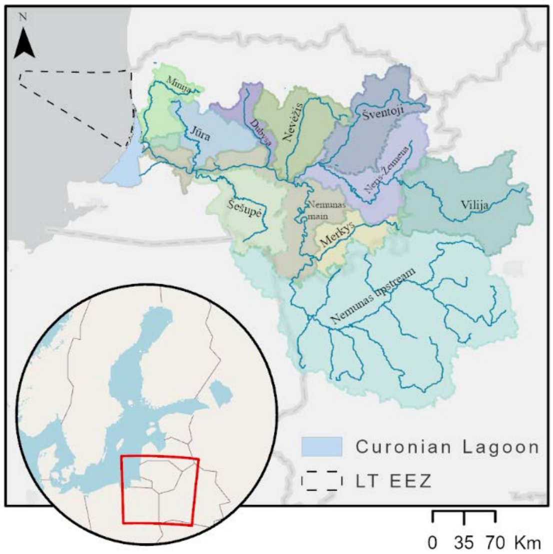

Figure 1. Study area with respect to the Baltic Sea. Colored polygons in the mainland are the basins of discharging rivers in the Nemunas River watershed.

4. Coupled modelling framework

For the Nemunas River watershed, a hydrological model SWAT was applied. For the Curonian Lagoon a hydrodynamic finite element model SHYFEM has been set up. Models were coupled using the water temperature and discharge data from SWAT model as boundary data in Nemunas and Minija entry points in the SHYFEM numerical grid. The modelling framework will allow us to quantify the possible changes in flow, nutrient, and sediment delivery to the Curonian Lagoon from all sources, including transboundary, in the light of climate change.

5. Results

The projected changes imply a shift towards higher river discharges during winter season with a net increase in nutrient load, which are related to the ongoing land use management and increased soil freeze-thaw cycles with more liquid precipitation during winter in the future.

The increased river discharge could indicate a transformation in the exchange mechanisms in the different parts of the Curonian Lagoon, leading to a higher exchange between the lagoon and the sea in winter and lower in summer. This will affect the water residence time

(WRT), shortening already short WRTs in winter and increasing already long WRTs in summer.

Saltwater intrusions events from the Baltic Sea into the lagoon could be expected to decrease, while the water temperature in the lagoon increases steadily.

6. Conclusions

Considering the current climate change trends for the region, the undertaken efforts to reduce the negative impact on the biosphere might not be sufficient. Policymakers must undertake actions to mitigate or minimize the possible negative effects of extensive use of resources (crop and land use management, livestock production, water resource management), although the implemented measures might not lead to immediate results. The end goal of the ECO-NEWS project is to provide policymakers and public authorities scenarios of the quantifiable effects of climate change on the water cycle, water quality and biosphere of the Nemunas River - Curonian Lagoon - Baltic Sea continuum with possible evidence-based solutions to deal with these emerging issues.

7. Acknowledgements

This project has received funding from the Research Council of Lithuania (LMTLT), agreement No S-MIP-21-24.

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Physicochemical changes in the southern Baltic Sea in 1959 – 2019 forced by the climate change

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1. Introduction

The study of changes in the physicochemical conditions described by the parameters: temperature, salinity, and pH in the southern Baltic area was carried out based on the analysis of long-term measurement data from 1959 - 2019. The data comes from measurements made at 18 stations during regular cruises in the southern Baltic area and from measurements carried out at eight coast stations. Seawater surface temperature data was supplemented with satellite and ERA5 data (European Center for Medium-Range Weather Forecasts - ECMWF). ERA5 data was also used to analyze changes in air temperature over the same period, which were linked to changes in physicochemical conditions through statistical analyzes.

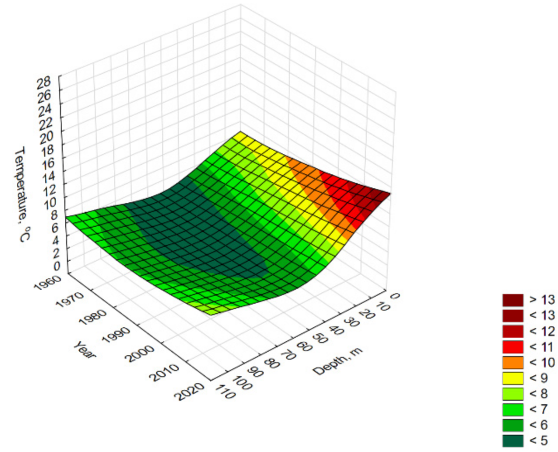

Figure 1. Temperature changes in the water column of the southern Baltic in 1959-2019

2. Seawater temperature

The analysis of long-term changes in seawater temperature in the offshore zone showed a statistically significant increase, taking into account the data from the entire water column and the entire area of the southern Baltic Sea (Fig. 1). In 1956 - 2019, the average increase in temperature for ten years was 0.63°C. In the Bornholm, Gdańsk and eastern Gotland Basins, the change level was very similar. At the same time, higher increases were characteristic of the shallower areas of the Pomeranian Bay (0.7°C) and the Puck Bay (0.9°C). Our study has shown that a statistically significant increase in temperature is also observed at various depths, but the dynamics of these changes is of a different nature. The highest temperature increase at the level of 0.6 - 0.7°C per decade is valid in the layers from 0 to 20 m. The smallest increase (below 0.1°C) was recorded at a depth of 70 m, below which the average temperature increase for ten years rises to 0.2°C at a depth of 110 m. The increase in the mean surface water temperature per decade was 0.64°C, while in the case of the maximum values, it was slightly higher - 0.69°C. The use of satellite data made it possible to obtain the spatial characteristics of surface temperature changes, including the spatial temperature increase per decade. The results obtained in this way were largely consistent with the data calculated from the measurements (Fig. 2). Statistical analyzes showed a very good agreement of the measurement data with satellite and ERA5 data, for which Spearman's rank coefficients were 0.992 and 0.988, respectively.

Analyzes of the time trend of surface water temperature at coastal stations from 1949 to 2019 also show a statistically significant upward trend, but the mean temperature changes per decade are, in this case, visibly lower from 0.15°C to 0.21°C.

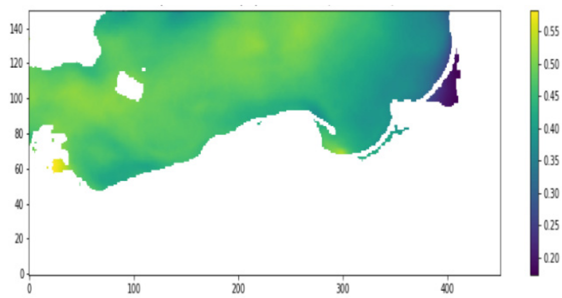

Figure 2. Surface water temperature changes per decade in 1982-2018 (based on satellite data)

3. Salinity

Analyzing the long-term salinity variation in the southern Baltic Sea (Figure 2), a statistically significant downward trend was found for the well-mixed water layer. However, the rate of the observed changes was slight, e.g., for the surface layer (0-10 m), salinity decrease per decade was 0.06 for Bornholm Basin, 0.07 for eastern Gotland Basin, and 0.10 for Gdańsk Basin.

For bottom water, the trend direction overtime is not unequivocal. Salinity in this part of the water column is related to the occurrence or absence of water inflows from the North Sea. Major Baltic inflows observed in 1993, 2003, and 2014 caused a periodic increase in salinity under the halocline.

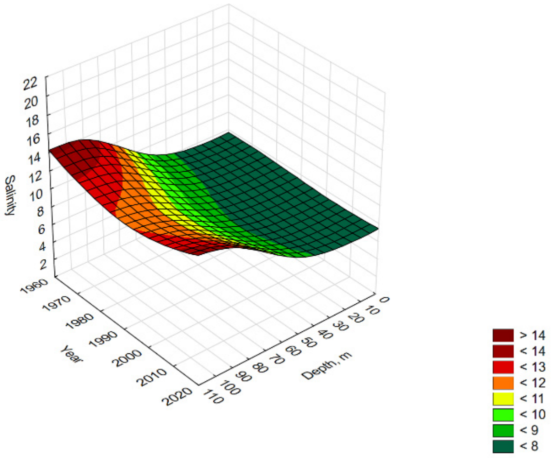

Figure 3. Salinity changes in the water column of the southern Baltic in 1959-2019

4. pH

An increase in the concentration of CO_2 in the air can lead to the acidification of marine waters. However, in inland seas such as the Baltic Sea, the effects of atmospheric CO_2 on pH are masked by the local effects of runoff, eutrophication, and mineralization. An increase in primary biological production is associated with increased CO_2 consumption and O_2 production, leading to the rise in pH in the surface layers and possibly the acidification in bottom waters due to mineralization. Our research, based on data from the period 1959 – 2019, confirmed the influence of these processes on the shaping of the pH value in the water column (Fig. 5). The study of trends and changes taking place in the discussed period showed that taking into account the data from the entire Baltic area and the data characterizing the whole water column, the average increase in pH per decade was 0.011 (Fig. 6). In the surface layer, this increase amounted to 0.052. Below 20 m depth, a decrease in pH of 0.018 per 30 m is observed to the maximum value of the decrease - 0.065 observed at a depth of 70 m. Below this level, the decline is smaller again.

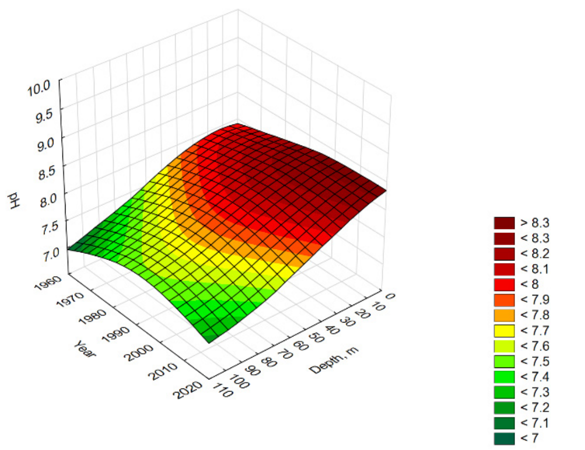

Figure 4. pH changes in the water column of the southern Baltic in 1959-2019

Figure 5 Change of pH in the water column per decade in the southern Baltic in 1959-2019

5. Correlations between physicochemical parameters and air temperature

As indicated, statistically significant changes were recorded for all parameters in the period from 1959 to 2019. As expected, the strongest correlation was found for sea water and air temperature, which was reflected in the Spearman's rank correlation coefficient of 0.926 (Tab. 1). The dependence of salinity on temperature was inversely proportional (r = -0.228). For pH, the correlation coefficient was 0.309. A relatively strong, inversely proportional relationship was found in the case of salinity and pH (r = -0.583). The dependence of salinity and pH on air temperature is described by the correlation coefficients -0.252 and 0.470.

Topic 9

Comparing marginal seas

Ancient land-sea connections in Mpondoland, on the South African Wild Coast

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1. Rationale

The South African continental shelf and adjacent coastal plain comprise the submerged and emergent portions of a continuous landscape that has waxed and waned over millennia in sync with changing sea levels and global climates. For 90% of the evolutionary history of the genus *Homo*, climates have been cooler and sea levels significantly lower than today. These exposed landscapes have provided plant and animal resources key to early hunter-gatherer survival. The Mpondoland Paleoclimate, Palaeoenviroment, Paleoecology, and Paleoanthropology (P5) Project is an international and multidisciplinary collaboration of scientists that have worked in Mpondoland for over a decade, in the Eastern Cape of South Africa (Figure 1). P5 research leverages the region's exceptionally narrow continental shelf—maximally 9 km wide—that constrained the outward movement of coastlines during prior glacial periods ensuring that records of coastal foraging are preserved in sites along the modern coastline. Our excavations along Mpondoland's coastline have revealed evidence for human occupation spanning the last 300,000 years in a persistent coastal context. At Waterfall Bluff (Figure 2), P5 has recently documented the first directly dated evidence for coastal foraging during the Last Glacial Maximum anywhere in Africa. Mpondoland's rare archaeological records, therefore, provide important and unique records about how hunter-gatherers adapted to coastlines during and across glacial-interglacial phases.

2. Results so far

The archaeological deposits are characterized by well-preserved stratigraphy, faunal, and botanical remains alongside abundant stone artifacts and other materials. A comprehensive dating programme consisting of five optically stimulated luminescence ages and fifty-one accelerator mass spectrometry ^{14}C ages shows that the record of hunter-gatherer occupations at Waterfall Bluff persisted from the late Pleistocene to the Holocene, spanning the last glacial maximum and the transition from the Pleistocene to the Holocene.

These records include the first direct evidence of hunter-gatherer coastal occupation and foraging during a glacial maximum (Fisher et al. 2013; 2019). Coupled with high-resolution, multi-proxy records of palaeoenvironments (Esteban et al. 2020), the excavations at Waterfall Bluff provide a window into hunter-gatherer behavior across a glacial/interglacial phase in a persistent coastal context, which has never before been studied in southern Africa. These findings hint at a diverse pattern of coastal exploitation at Waterfall Bluff where the site's centralized location between the land and the sea—and their plant and animal resources—may have been the main draw for people amid regional climatic and environmental variability.

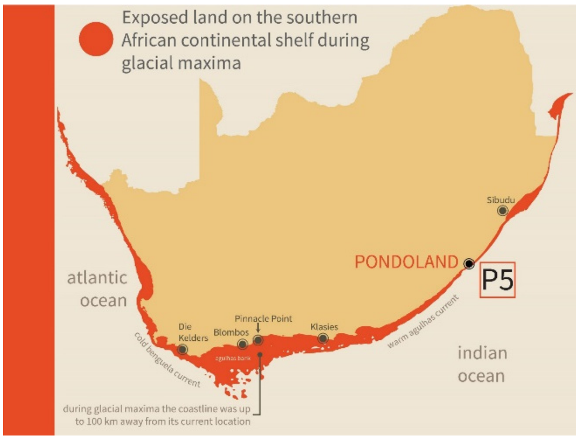

Figure 1. Aerial view of Waterfall Bluff and the Mlambomkulu waterfall, Mpondoland.

Figure 2. Aerial view of Waterfall Bluff and the Mlambomkulu waterfall, Mpondoland.

3. Ongoing geoscience research

In order to address research questions about how early humans used Mpondoland's coastal landscapes, by reconstructing specific ancient coastlines and obtaining paleoenvironmental data linked to coastline-environment interactions, geoscience context is necessary. The geoscientific elements of work in Mpondoland range from low-resolution landscape-scale investigations, to micromorphology on sediment layers from the cave stratigraphy. Continental shelf stratigraphy is being addressed using boomer sub-bottom profiles that illuminate submerged geologies. Thus far, the continuity of the basement quartzite rocks is clear, and locations of incised river channels from times that the shelf was exposed as a terrestrial landscape, are evident. These waterways are anticipated to have been important conduits for people and animals, linking the hinterland to the coast when sea levels were low, as the modern analogue provides in the present-day configuration of this coast.

We are compiling an isoscape map across the landscape, from the coast to the Drakensberg Mountains, ~200 km inland to Waterfall Bluff, in order to generate a geochemical base from which to compare isotopic data from archaeological records and test hypotheses of mobility and exchange in hunter-gatherer groups. We obtained plant, soil and rock samples every ~12 km across an area of 15,000 km^2 and preliminary results will be presented.

4. Outreach

Alongside primary research objectives, P5 researchers have invested in new ways to record and communicate our work among members of the research team, to other research teams, and to the general public. One of these methods is the development of web-based virtual field trips using interlinked spherical panoramic photography (https://p5project.org/virtual-tour/). The panoramas are embedded with multimedia content to highlight data and findings within a virtual environment of the research sites.

Our project has also collaborated with science communication specialists Jive Media Africa to produce a bilingual (English/isiXhosa) series of free comic materials to reach the South African rural populations. The comics communicate information about archaeology to South African primary and high school students. We have recently developed a radiocarbon dating worksheet (Figure 3) and are in the process of disseminating >10,000 copies of the worksheet through Jive Media Africa's Science Spaza programme with further dissemination programs for physical copies in Mpondoland and elsewhere planned in the future (https://p5project.org/public-outreach/).

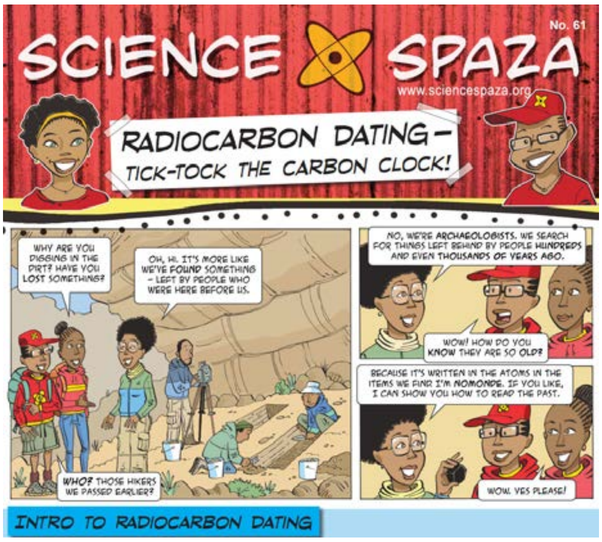

Figure 2. Snapshot of the radiocarbon dating comic.

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A National "Urban Sea" Initiative: *Full Characterization Leading to Integrated, Long-term Stewardship Strategies*

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1. Introduction

"Urban Seas" are coastal embayments, estuaries, or marginal seas that host large, industrialized port cities. These heavily urbanized settings are usually located at a key nexus of land-based transport networks interfacing with regional/global shipping lanes. They form essential elements of many national economies. Yet, industrial and shipping activities, and the inherent population densities, commonly result in progressive decline of ecosystems both on-shore and in adjacent waters.

Adverse impacts, both natural and anthropogenic, within **Urban Sea** basins can include: major fires, earthquakes, massive storms, tsunamis, unregulated logging, fertilizer runoff, floods, sea level rise, urban pollution, bio-toxic buildup in food chains, sound pollution, shipping accidents, oil spills, and ineffective waste management.

Actions to enhance **Urban Sea** vitality and resilience will require insightfully balancing ecological, economic, and security concerns with planned growth scenarios and multi-cultural inclusivity across all facets of such industrialized coastal enclaves. *Near-term efforts to select limited numbers of representative urban coastal settings for in-depth study could provide strategic and adaptable guidelines for improvement of many such communities across the country (Figure 1), and around the globe.*

2. Goals

Defining and resolving many **Urban Sea** issues will require extensive characterization of all essential, interactive processes operating within the entire drainage basin including the sea itself. Insightful acquisition of real-time data from comprehensive sensor suites could foster creation of next generation models for use in assessing, implementing, testing, and refining optimal management designed to deliver sustainable outcomes. A national U.S. component of the *United Nations Decade of Ocean Science for Sustainable Development (2021-2030)* focused on **Urban Sea Issues** could include capabilities that:

- Arrest Ecological Decline,
- Balance Economy, Ecology, & Security,
- Implement Carbon-Neutral Economies,
- Utilize Novel Sensors & Real-time Data Collection,
- Pioneer Urban Sea Eco-System "Digital Twins",
- Educate & Engage All Citizens-Especially the Young,
- Ensure Just and Enduring Change-oriented Stewardship.

A long-term program built on existing and evolving community-wide efforts must be informed by novel data collection and A.I.-based modeling of entire subsystems within **all related** environments. These approaches must be married to tailored policy strategies based on goals of enduring, comprehensive stewardship with benefits for all.

Establishment of carefully coordinated interlinked working groups focused on pursuit of these Goals, is an essential early step toward responsible management of these crucial human-ocean dominated **Urban Seas.** Owing to the inherently complex nature of such ecosystems, the first phase of planning must focus on identifying key processes and their *interactions*. The idea involves assembling, carefully selected teams to *bridge disciplinary silos*, while developing "adaptable road maps" for what must ultimately become an enduring form of ***Urban Sea Stewardship***

3. Program Focus

Ultimately, **p**rogrammatic emphasis should be on delivery of long-term, sustainable contributions & oversight needed to characterize & wisely manage our nation's **Urban Sea** systems. **What *is new?*** Rates of change are ever-more rapidly evolving. Implementation of wide-spread, cutting edge autonomy empowering constant in-depth

Figure 1. Map of U.S. indicating locations of well known port cities located on either coastal embayments, rivers, or estuarine settings. These "Urban Seas" represent important economic centers that are often plagued with detrimental

documentation of all key processes, is now possible at levels never before possible. AI-assisted computational modeling of real time data from extensive sensor suites distributed throughout all dynamic system components is now feasible and will only become more wide-spread and powerful. Such capabilities can set the stage for novel forms of system oversight and insightful stewardship. With optimal guidance, leaders embedded within relevant communities can learn to employ next-generation models, or societally relevant "Digital Twins" to empower an entirely new era of "systems-level" **Urban Sea** oversight. It is urgent that societal sectors across the country, and the world, begin to understand and insightfully manage the complex, dynamic systems underpinning our productive **Urban Coastlines.**

4. Working Groups

Carefully selected, interactive National and Regional working group-networks can be configured within 3-6 months of program initiation. Membership should be drawn from indigenous groups, government experts, leaders from industry, knowledgeable scientists, engineers, and modelers, underserved communities, and next-generation leaders. Special efforts must be made to ensure these groups do not fall into classic silo-like architectures that plague efforts to make smart, timely decisions about managing complex, dynamic systems (Figure 2)

Figure 2. Diagram of many contributing complexities involved in Urban Sea Systems. Virtually all of these elements are bound together by arrays of feed-back loops.

Potential Working Group Categories:

- Shipping & Transport - Energy Resources
- Basin-scale Networking - Data Flow & Outreach
- Natural Hazards, Oil Spills & Industrial Accidents
- Agriculture, Aquaculture, Logging, Mining
- Pharma, New Drugs, Toxins, Bio-Accumulation
- Balanced Healthy Ecosystem Modeling
- Physical/Bio-Chem Ocean Sciences
- Ocean Culture: K to Gray Engagement
- Marine Tech-Novel Sensing, Quality Data-on-Cloud
- Adaptive A. I. Modeling: Creation of "Digital Twins"
- Human Behavior: Economics, Health, Leisure, Jobs
- Predicting & Responding to Tipping Points
- Homeland Security in All its Forms
- Supervisory Committee(s)

A follow-on document should define specific roles, responsibilities, rotations, and liaisons for these groups.

5. Long-term Deliverables

Globally connected large Urban Ports and manufacturing centers tend to develop a host of key infrastructural resources such as industrial centers, government labs and university research hubs with economic, scientific, and technological resources to readily address growing vulnerabilities facing entire Urban Sea communities. Effective engagement of entire populations with these capable, embedded assets could empower entire communities to become "modern laboratories for change". With initial support the most effective approaches to sustained stewardship can emerge and be shared widely once proven effective. Enduring deliverables may include:

- **Real-time Data Flow** from novel sensor arrays to open-source quality-controlled Cloud-like hubs.
- **A.I. Computing** of dynamic, non-linear processes operating within Urban Sea systems.
- **Creation of "Digital Twins" (DT)** to faithfully emulate critical, and complex behavior in eco-subsystems (Grieves and Vickers, 2016; Marr, 2017)
- **Assessment of the Complex Interplay** between Human Society and its Environment.
- **Ability to Design, Evaluate, and Implement** viable solutions that enhance resilience of all key system components.
- **On-going DT Use to Identify, Explore, & Test** novel solutions before & after implementation by continuing assessments using DT approaches.

During the **Urban Sea i**nitiative all activities should be openly shared with communities involved. On-going funding resources must be sought nationally, regionally, at State/Province level, within cities, and from citizen donations. However, Access to "community-nucleation" funds may be key to early establishment of optimally responsive stewardship frameworks.

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DDE Marginal Seas Task Group

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Abstract

Marginal seas as interface between land and ocean play a crucial role providing people with habitat, food, trade ways, and facilitated socio-economic networking. However, marginal seas are increasingly threatened by rising sea-level, floods, storms, tsunamis, coastal erosion and environmental hazards that endanger livelihoods (Harff et al., 2019). Effective strategies for sustainable development of marginal seas environment require a deepening the understanding of the geological past but also future developments in the view of climate change and anthropogenic pressure and are becoming a cross-bordering task for the international scientific community. Modeling approaches will help to master these challenges. A road is paved by the Deep-time Digital Earth (DDE) program of the International Union of Geological Sciences (IUGS) (Stephensen et al., 2020). Within the frame of the DDE program a Marginal Seas Task Group has been established with the mission of the development of a general strategy for describing the processes in marginal seas holistically as an interaction between geo-, eco-, climate-, and socio-economic systems during the late Pleistocene, Holocene and Anthropocene. This strategy based on big data analyses, functional numerical models and AI approaches will allow to answer three basic question:

- How did marginal seas of different climatic zones and tectonic settings change their paleo-geography, -oceanography, and -environment during the natural climate and environmental variation of the Last Glacial Cycle?
- What are the future expectations for the development of marginal seas and their coastal zones facing the challenge of climate change and increasing human impact on the environment for this century?
- What strategies for sustainable development of the marine and coastal realm can help to mitigate the major threats to marginal seas driven by rising sea-level, floods, storms, (meteo)tsunamis, coastal erosion, silting and environmental hazards.

Our **vision** is to contribute to keep balance between the protection of the natural environment of marginal seas and the economic use of their resources based on new data and new model driven cognition methods.

The main action of the Task Group in 2021 was the initiation of an DDE research project “Morphological Evolution of Coastal Seas – Past and Future” (PI: Dr. Wenyan Zhang) together with international partners with the goals:
a) Integrating interdisciplinary data describing the structure and evolution of three exemplary Eurasian marginal seas (North Sea, Baltic Sea and South China Sea) over the past 130 kyr;

b) Developing advanced numerical methods (“Big-data” driven & mechanistic) of complex geo-systems to generate environmental scenarios for Eurasian coastal areas on the global, regional and local level;
c) Application of these methods to three targeted Eurasian marginal seas (North Sea, Baltic Sea and South China Sea) in order to reconstruct the geological and environmental history and to generate future scenarios for the end of this century by applying results of climate modeling;
d) To develop strategies for sustainable management of the coastal zones based on numerical experiments.

The establishment of the DDE Marginal Seas Task Group marks a step forward to understand comprehensively the functioning of marginal seas as buffer zones between continents and oceans. This step will help to mitigate the threats of coastal environmental disasters and to promote planning for sustainable marine and coastal development by:

- Fostering the internal co-operation and scientific exchange with DDE Working and Task Groups and the external co-operation with natural scientists, socio-economists, modelers and IT specialists for harmonization and standardization and data sharing of marginal seas geo-data and AI /numerical model design.
- Developing the co-operation with International science programs and societal stakeholders to generate cause-effect scenarios with the goal of optimizing environmental management strategies for sustainable development of marginal seas and their coastal zones.
- Expanding the team's creativity by involving young scientists in particular by developing cooperation with the International Association for Mathematical Geosciences (IAMG).

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The Marginal Salish Sea as an Urban Sea – Comparisons with the Baltic Sea

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1. Introduction

Urban Seas are concentrated dense populations and hotspots of industrialization, commerce, dense populations, and cultural diversity. They are seas marginal to the global ocean, estuaries, and inland seas marginal to the global ocean, that connect the terrestrial environment to the oceanic environment. Many, like the tentacles of an octopus, reach well into the hinterland to reap products for trade that are distributed widely across the global ocean. Many waste products from these systems concentrate in the nearby seas, often making their way to the open ocean.

Marginal seas have served as transportation corridors with a long history of human migration starting well before the last glacial maximum. These patterns continue today and will do so in the future with on-going migration toward the coasts by climate refugees. Urban seas are manufacturing centers and transshipment hubs connecting multi-modular forms of transport globally. Many of these coastal settings offer a physiographic and ecological diversity that attracts human occupation dependent upon the living and non-living resources of the basin in which the seas are located. However, while the seas themselves are attractive to humans, the increased concentration of humans and their activities has significantly impacted the overall environment. These patterns, along with natural and anthropogenic processes, are bringing unpleasant consequences detrimental to the economy and the environment. Recognition and prediction of decline, and solutions to these effects, are needed to foster "sustainable development" of our and to support a "blue ocean economy" for the global ocean.

2. The Salish Sea

The Salish Sea, a heavily populated inland estuarine body of water located in the Pacific Northwest of the U.S. is an excellent example of an "Urban Sea. It covers about 18,000 km^2 (6,950 mi^2), a region consisting of three major marine physiographic basins: the Strait of Juan de Fuca (~4,400 km^2 [1,700 mi^2], with a maximum depth of ~250 m [820 ft.]), the Strait of Georgia (~6,400 km^2 [2,471], with a maximum depth of ~400 m [1,312 ft.]), and Puget Sound (~2,500 km^2 [965 mi^2], with a maximum depth of ~280 m [919 ft.]). A sinuous coastline of approximately 7,500 km (4,460 mi) in length, and hundreds of islands including the centrally located San Juan Archipelago. Inter-island passages covering an area of approximately 4,700 km^2 (1,815 mi^2) are common within the Salish Sea (Mullan, 2017).

Geologically, the Salish Sea occupies the forearc basin of the Cascadia Subduction Zone, the convergent margin locus of the Juan de Fuca and Explorer plates with the North American Plate. As a consequence the entire region can experience potential plate tectonic geohazards (e.g., earthquakes, tsunamis, vulcanism, landslides, floods). In addition, intense industrialization and urbanization have increased anthropogenic pressures that impact the entire environment, including both terrestrial and marine eco-systems. Locally within the Salish Sea, areas of near-pristine conditions exist, while elsewhere highly toxic, polluted, and restricted shoreline conditions directly impact the marine environment. These contrasting conditions provide a unique opportunity to examine past, present, and future changes within a well-documentable urban sea.

3. Salish-Baltic Seas Comparisons

The general geometry of the Salish Sea and the Baltic Sea bear some similarities. Both exhibit primarily one major outlet to another sea or ocean (See Fig. 1). The Salish Sea is

Figure 1. Physiographic settings of the Salish Sea (left) and the Baltic Sea (right) showing similar geometry of the seas and enclosing basins. Note the high terrestrial relief for the Salish compared with the low relief of the Baltic and the differences in the depths of both seas.

considered a young urban sea while the Baltic has experienced a long history of human activity. By comparison, the Baltic is a relatively shallow, wide, and branching body of water, while the Salish Sea is composed of relatively deep to shallow, narrow, branching tidal straights and basins. Both experience tidal activity, 24 cm for the Baltic compared to 3 to 4 m for the Salish. This difference leads to stagnation and eutrophication in the Baltic. But strong flushing exists in the Salish, except in a few dead-end sounds and bays. Both regions experienced the last major glacial advance (~15,000 to 10, 000 years ago) and share common glacial seascape and terrestrial geomorphologies. Industrialization is intense in both regions resulting in dense concentrations of populations and differing cultures. While the Salish Sea crosses one international boundary (U.S.-Canada border), multiple international boundaries are shared within the Baltic region. Both regions host military establishments. Maritime shipping intensity is high in both regions with expectations of future increases. Global warming and sea level rise will impact both regions in a similar manner, although by differing degrees.

4. The Initiative

Following the guidelines of the *U.N. Decade of Ocean Science for Sustainable Development (2021-2032)* we imagine that the Salish Sea might emerge as a candidate for consideration within a potential U.S. theme of "Healthy Urban Seas". Presently development of this initiative is in an embryonic stage. However, both national and regional interests exist as the geologic, industrial, economic, and cultural diversity of any region might lend itself to becoming a "natural laboratory" in which experiments, monitoring, data collection and modeling can take place.

The intent of such an initiative would be to establish multidisciplinary and cross-cutting approaches that focus on improvement of any environment through monitoring and prediction. This type of outcome would be accomplished by instrumenting the sea and coastline with evolving technologies for sensing and modeling changing physical and human processes to begin analyzing existing issues and predicting and mitigating future problems. In addition, data collected during the program will be open-sourced to be useful nationally and internationally as well as to contribute to the understanding of the influences that urban seas have on our global ocean. Examples of future changes that have the potential to impact both the Salish and Baltic seas consist of increased shipping, oil spills, global warming and sea level rise, sediment, and pollutant inputs, to mention a few. We address here below one of many the examples, Shipping and Oil Spills, that appear to be common between the Salish and Baltic.

5. Shipping and Oil Spills

The International Chamber of Shipping reported that commercial shipping accounts for nearly 91,000 vessels plying the oceans annually (UNCTAD, 2017), which represents 90% of the global trade. This level is expected to increase substantially in the near future along with numbers and sizes of ships, and increased propulsion power (Cominelli et al., 2018; McWhinnie et al., 2021). Locally, the Salish Sea is one of the busiest water ways in North America and accounts for more than 50% of commercial marine traffic nationally (Simrad et al., 2014).

Like many urban seas around the globe, today the Salish Sea is experiencing high concentrations of commercial ocean-going container ("box") ships, bulk carriers, and tankers. Larger and more powerful ships are being built to handle the increase of commodities within the global supply chains including cruise liners (tourism).

The central Salish Sea (the San Juan Archipelago) is particularly susceptible to shipping accidents including oil spills and pipeline ruptures. The shipping lanes that weave through the islands are narrow, rocky, and subjected to strong tidal currents. Commercial marine traffic has been increasing (McWhinnie et al., 2021). Green et al. (2016) reported that during the past half century considerable attention has been given to the potential ecological, economic, and societal impacts of oil spills.

6. Resolutions

In urban marginal seas, such as the Salish and Baltic, the vulnerability of communities and environments can be assessed in advance of known and predicted impacts and can become a key component of shipping and spill response planning. The types of environments, communities, and facilities that could potentially be impacted along with their sensitivities and vulnerabilities, can thus be identified in advance, which are essential elements of response planning.

Often, the physical characteristics of the subtidal seafloor and its associated benthic habitats are unknown along shipping lanes and pipelines. This lack of knowledge can be resolved by sustained and repeated mapping of critical marine benthic habitats. We suspect that lessons learned in the Baltic can apply to the Salish and that lessons to be learned in the Salish may in turn be helpful to the Baltic. Thus, we seek cooperation between communities involved with these two well-defined Urban Seas.

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Predicting extreme dry spell risk based on probability distribution in coastal region of Tunisia

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Abstract Event based analysis of dry spell phenomenon, from series of daily rainfall observations was conducted in order to predict extreme dry-spell risk. The case study is a coastal region northern Tunisia of Mediterranean climate. A dry spell is defined as a series of days with daily rainfall less than a given threshold. As this limit 3.6 mm j^{-1} has been selected, since this amount of water corresponds approximately to the expected daily evaporation rate, thus marking the lowest physical limit frequency in the region under the influence of a changing climate was studied. The identification of the longest dry and wet events on the history was carried out. For planning purposes, the longest dry spells associated with various statistical recurrence periods are derived on the basis of the fitted GEV type probability distribution functions. Dry spell lengths for return periods of 2, 5, 10, 25 and 50 years indicate the areas where drought phenomena might be more severe, as well as how often they might occur. This analysis is used to calibrate precipitation models with little rainfall records, the study of the effects of climate change on water resources and crops.

Key words: climate change, extreme dry event, risk analysis.

1. Introduction

Dry spell can be defined as a sequence of dry days including days with less than a threshold value of rainfall. A practical procedure to analyze rainfall event time series under semi-arid climatic conditions is the event-based concept. This design of analysis is favored over continuous type data generation method. It is to simulate wet and dry spells separately by fitting their durations to an appropriate probability distribution such as the negative binominal or geometric distribution (Semenov *et al.*, 1998; Mathlouthi & Lebdi, 2008), or empirical distribution (Rajagopalan and Lall, 1999). The characteristics of multi-day wet and dry spells is often important for investigating likely scenarios for agricultural water requirements, reservoir operation for analyses of antecedent moisture conditions (Mathlouthi & Lebdi, 2008), and runoff generation in a watershed. In virtue, this paper is focused on the modelling of rainfall occurrences under climate Mediterranean by wet-dry spell approach for operation dam with basis different from that of observations carried out with regular time's intervals. The event-based concept allow the synthetic rainfall data generation. This used, for example, for reservoir simulation studies, the estimation of irrigation

for considering rainfall that may produce utilizable surface water resources. Dry spells are separated by rainfall events from each other. Thus the rainy season is defined as a series of rainfall and subsequent dry events. Rainfall events are defined as the uninterrupted sequence of rainy days, when at last on one day more than a threshold amount of rainfall has been observed. The evolution of dry events and longest spells in duration and

water demand and the study of the effects of a climatologically change. This paper concentrates solely on the characterization of the events of the dry spell in a Dam North of Tunisia.

2. Data and method

The data used in this analysis are the daily precipitation records at coastal region Northern Tunisia. The rainy season starting at September and lasting until the beginning of May. The mean of annual rainfall is 680 mm. Except in occasional wet years, most precipitation is confined to the winter months in this basin. The dry season lasts from May to August. Daily values of precipitation are quite variable.

A rainfall *event* is an uninterrupted sequence of wets periods. The definition of event is associated with a rainfall threshold value which defines *wet*. As this limit 3.6 mm d^{-1} has been selected. This amount of water corresponds to the expected daily evapotranspiration rate, marking the lowest physical limit for considering rainfall that may produce utilizable surface water resources. In this approach, the process of rainfall occurrences is specified by the probability laws of the length of the wet periods (storm duration), and the length of the dry periods (time between storms or inter-event time). The rainfall event *m* in a given rainy season *n* will be characterized by its duration $D_{n,m}$, the temporal position within the rainy season, the dry event or inter-event time $Z_{n,m}$ and by the cumulative rainfall amounts of Hn,m of Dn,m, rainy days in mm:

$$H_{n,m} = \sum_{i=1}^{Dn,m} h_i \qquad (1)$$

Where h_i is positive and represent the daily precipitation totals in mm. Note that for at least one *hi* >3.6 mm.

3. Results and concluding remarks

Independent events are separated by a time period t which follows an exponential distribution (Fogel and Duckstein, 1982):

$$f(t) = b.e^{-bt} \qquad t > 0 \qquad (2)$$

where *b* parameter of the exponential distribution, can be estimated as the reciprocal mean *t* of the sample of times observed:

$$b = \frac{1}{t} \qquad (3)$$

If the waiting time is measured in days, the exponential distribution can be replaced by the equivalent discrete distribution, namely the geometrical distribution:

$$f(n) = p.q^{n-1} \qquad \text{for n = 1, 2, …} \qquad (4)$$

where the *p* parameter is estimated by the reverse of the expectation of the average duration n of waiting between two successive events.

$$p = \frac{1}{\bar{n}} \quad ; \qquad \text{and} \quad q = 1 - p \qquad (5)$$

However, if the series of successive precipitations do not form independent events, the waiting time follows a gamma distribution with two parameters instead of an exponential distribution (Fogel and Duckstein, 1982). Consequently, if the time is discretized in days, the distribution of time separating two events is represented by the negative binomial distribution (Mathlouthi and Lebdi, 2008) which is the equivalent discrete distribution of the gamma distribution:

$$f(n) = \frac{(r + n - 1)}{n!(r - 1)!} . p^r . q^n \qquad (6)$$

where *n* = 0, 1, 2, … , and *r* et *p* are estimated by the variance and mean of the dry event duration.

Approximately 33% of the events last at most one day. The persistence of uninterrupted sequences of rainy days sometimes lasting nearly two weeks (the maximum observed duration is 13 days). However, the frequency of such long-duration events decreases rapidly with increasing duration. An arithmetic mean of 2.79 days and a standard deviation of 1.87 were obtained. The geometric pdf appears most adequate for the fitting.

The regression analysis display that the dry event can be assumed to be independent from the rainfall event and the rainfall depth per event. Thus the distribution of the dry event (interevent time), which can only assume integer values, follows an unconditional probability distribution function. The negative binomial pdf has been found as best fitted to describe the distribution of the dry event (Fig. 1). The shortest interruption (one day) is the most frequent one. Almost a fifth of the observed dry events are only one day long. Dry periods up to 30 or even more days may be recorded (a 56 days maximum is recorded). The arithmetic mean and the standard deviation for the dry event are respectively 7.3 days and 7.9; for the longest dry event there are 30.2 days and 3.6.

Figure 2 shows the best fitting of the beginning of the first rainfall event during rainy season. It was concluded that the first rainfall event occurs in the mid-September, whereas the probability of surpassing this value is 0.52 (a biennial return period). For extreme case, the hydrological year starts about the first decade of October.

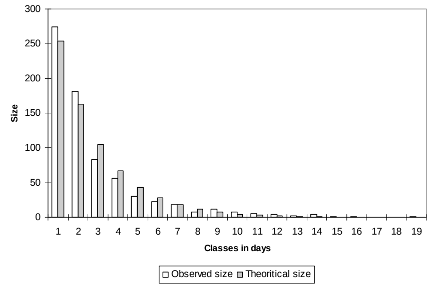

Figure 1. Distribution of the time elapsed between rainfall events (dry events).

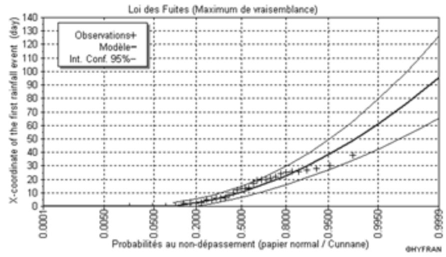

Figure 2. Fitting leaks law for the chronological position of the first rainfall event in rainy season.

The case study confirms the concept of the independence of rainfall and dry event duration. The dry spell phenomenon in this region seems to be particularly well described by fitting a pdf to the length of the interevent time. The negative binomial pdf provides an excellent fit for the prolonged dry periods between subsequent rainfall events. Conceptually, in a true Poisson process, the time "without event" should follow the exponential pdf or, in a discrete case, the geometric pdf (Fogel and Duckstein, 1982). It is relevant to note that this "flaw" could be eliminated by defining the interevent time as the dry event. Consequently, the present role of the interevent time would be taken over by the rainfall events duration. The theoretical requirements of the fitted geometric pdf are satisfied.

Event-based analysis has been used to generate synthetic rainfall event time series. By coupling this with a rainfall-runoff model, one obtains synthetic streamflow series to be used for reservoir simulation studies and design flood estimations. As another application, the study of the effects of a climatologically change.

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Concept of Marginal Seas Database Inventory (MSDI)

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Abstract

Within the frame of the Deep-time Digital Earth program (DDE) of the IUGS (Stephenson et al., 2020) a Marginal Seas Task Group has been established in 2021. The first research project *"Morphological evolution of coastal seas – Past and Future"* aims by comparative study of selected Eurasian marginal seas to reconstruct the evolution of the coasts during the Last Glacial Cycle and to generate future scenarios using modeling techniques (Zhang et al., 2020) and big-data science methodologies (Chen et al, 2019). These scenarios shall provide the base for management strategies of the coastal zones in order to diminish the threats because of climate change and increasing anthropogenic pressure. Morphodynamic modeling of marginal seas requires fast and convenient access to existing databases containing necessary geological, oceanographic, ecological and climate data characterized by specific spatial and temporal resolution and satisfactory quality. However, the process of searching for the appropriate database is time-consuming and the outcome may not meet the scientific targets. Therefore, a new concept of Marginal Seas Data Inventory (MSDI) was developed. MSDI is a user-friendly tool to support searching and downloading required data, that provides the opportunity to be applied for the solution of generalized scientific tasks (Miluch et al. 2021). The "Inventory" is designed as an interactive user-oriented hierarchically structured algorithm serving as "pathfinder" to lead the user to the most suitable platforms for data download. The presented version is a first approach (prototype) to generate inventories for the exemplified processes and areas. One of main targets of the prototype is to develop a new approach in data searching by emphasizing the processes to be investigated and filtering databases using universal keywords system (Raskin and Pan, 2005), in parallel maintaining data according to FAIRness principles (Tanhua et al. 2019). Potential future steps in MSDI development would involve expanding the inventory to generalized tasks and areas as well as an application of highly sophisticated programming tools.

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The Impact Matrix: A simple method to assess human pressures and their interrelations in different marginal seas

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Anthropogenic climate change has been regarded as a major driver for environmental changes since the industrial revolution, however, a multitude of of human-induced factors in addition to climate change affect the environments of coastal seas. In a recent paper (Reckermann et al. 2022), the different interrelations of different factors of the regional Earth system of the Baltic Sea region are assessed, using a simple approach of literature review and a simple ranking system aligned in a matrix to visualize the major factors affecting others, and, vice versa, being affected by others.

To allow this comprehensive and straightforward approach to the problem, we introduce a matrix in which we show at a glance the impacts of the various factors on each other. This matrix is the core of our analysis (Table 1). This analysis represents a critical review of the literature with the aim of identifying linkages between the different factors: is there evidence in the scientific literature for a connection or impact, or not? The extensive descriptions in Reckermann et al. 2022 provide brief characterizations of the current knowledge of the factors, followed by bullet lists of potential interrelations for each factor according to the matrix and describing the linkages in detail, as far as feasible in this context. References from the scientific literature are provided for the found linkages between factors (plus sign "+"). We also speculate on potential links (question marks, "?"), which have not (or sparsely) been confirmed in the scientific literature but which may be plausible, not to rule out a connection that has not yet been described.

These items represent potential connections, which may be worth considering further. Connections with no apparent or plausible linkages are marked with a minus sign ("–") and not discussed further in the text. The bullet lists in the paper are followed by a brief consideration of knowledge gaps, based on this analysis and authors' expert assessment. This assessment is based on literature review, and expert judgement but does not claim to make judgements on the severity or urgency of the described connection or circumstance. This assessment is incomplete and largely subjective, despite all efforts to support any claims by references and reflects the large uncertainties and low evidence in many of the described relationships.

This simple method could be potentially used to compare the anthropogenic pressures on other coastal systems or marginal seas, including respective influences of the factors on each other. It further has the potential to be further elaborated, also using more quantitative indicators rather than or in addition to literature-review derived subjective expert judgment.

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impact by↓/on→	Fisheries	Marine ecosystems	Agriculture Nutr. loads	Coastal management	Chem. Contamin.	Acidification	Offshore wind farms	Tourism	Shipping	Climate change	Coastal processes	Hypoxia	Land cover and use	Aquaculture	River regulations	Marine litter	Subm. Groundw. Disch.	Non-inig. species	Dumped militiary
Climate change	+	+	+	+	+	+	+	+	+		+	+	+	+	+	?	?	?	?
Shipping	+	+	+	+	+	+	?	+		+	+	-	-	?	-	+	-	+	-
Land cover and use	+	?	+	+	+	+	?	+	-	+	-	+		-	+	-	+	-	-
Agriculture/Nutrient loads	+	+		?	+	+	-	-	-	+	-	+	+	+	+	-	+	-	-
Coastal processes	?	?	+	+	?	?	+	-	+	-		?	+	?	+	+	+	-	?
Offshore wind farms	+	+	?	+	?	-		+	+	+	+	-	?	+	-	?	-	-	?
Aquaculture	?	+	+	+	?	-	+	?	-	-	-	+	+		-	?	-	+	-
Tourism	-	?	+	+	-	-	+		+	+	-	-	+	-	-	+	-	-	-
Hypoxia	+	+	+	-	+	+	-	-	-	-	-		-	?	-	-	-	-	+
Coastal management	+	?	?		-	-	+	+	+	-	+	-	?	?	?	?	?	?	+
Marine ecosystems	+		-	-	-	+	-	+	-	-	-	+	-	-	-	-	-	+	-
River regulations	+	+	?	+	?	+	-	-	-	-	+	?	?	?		?	?	-	-
Non-inigenous species	+	+	-	?	+	-	-	-	+	-	-	-	-	-	-	-	-		-
Fisheries		+	?	+	-	-	+	?	?	-	-	?	-	?	-	+	-	?	-
Chemical contaminants	+	+	+	-		-	-	-	-	-	-	-	-	+	-	-	-	-	-
Dumped militiary material	+	?	-	?	+	-	+	-	-	-	-	-	-	-	-	-	-	-	
Subm. Groundw. Disch.	-	?	+	-	+	?	-	-	-	-	-	?	-	-	-	-		-	-
Marine litter	+	?	-	?	?	-	-	+	-	-	-	-	-	?	-		-	-	-
Acidification	?	?	-	-	?		-	-	-	-	-	-	-	?	-	-	-	-	-

Table 1. The Impact Matrix for the Baltic Sea region

Integrated water vapor transport in a tropical-like cyclone over the Black Sea

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1. Introduction

The moisture content in the atmosphere column is a major characteristic that determines the potential of precipitation formation. In the atmosphere, horizontal air flows dominates, therefore, a water vapor can be redistributed inhomogeneously due to its horizontal advection. For precipitation, physical processes, which lead to lifting air mass and moisture condensation, are needed. If there is a large amount of water vapor in a significant layer of the troposphere, heavy precipitation can occurred. These cases include the so-called 'atmospheric rivers'.

Atmospheric rivers are often associated with extreme winter storms and heavy rainfalls along the west coast of continents, including the US and Western Europe. In some cases, atmospheric rivers penetrates inland and causing intensive precipitation and flash floods (Lavers and Villarini. 2015). The term 'atmospheric river' was introduced in 1998 (Zhu and Newell, 1998). Further, atmospheric rivers have been defined as anomalous moisture content and strong horizontal moisture transport, which are concentrated into long narrow corridors, typically 400–600 km wide (but ≤ 1000 km) and more than 2000 km long (Gimeno et al., 2014). Vertically integrated horizontal water vapor transport (IVT) is used as a physical threshold of the atmospheric river, in which IVT ≥ 250 kg m^{-1} s^{-1}.

Atmospheric rivers are associated with the processes of cyclogenesis, where the horizontal flow of water vapor get ascending movement and turn into precipitation. In the basins of the Mediterranean and Black Sea, intense mesoscale cyclones are sometimes observed, with characteristics and development mechanism similar to tropical cyclones. These cyclones have been named as "medicanes" (Mediterranean Hurricanes) or Tropical-Like Cyclones (TLC) (Miglietta, 2019). Medicanes are characterized by the development of intensive convection and convective phenomena, such as strong winds, heavy precipitation and flooding on coastal areas. The main process of medicanes intensification is the release of latent heat of condensation associated with convection processes and interaction of sea surface with the atmosphere. But in the early stages of development, the main mechanism is a baroclinic instability of the atmosphere, since these cyclones are developing under the deep upper-level cutoff low, in which contains a large amount of moisture (Emanuel, 2005).

The purpose of this study is to analyze the integrated water vapor transport in a tropical-like cyclone, which formed over the Black Sea in August 2021, and led to strong rainfalls with flooding in the northern regions of Turkey and in the Krasnodar Krai of the Russian Federation.

2. Data and Methods

To calculate the fields of integrated water vapor transport (IVT), the ERA5 reanalisys was used, with a grid step of 0.25°, on terms 00, 06, 12, 18 UTC, for the period 10-14 August, 2021, on pressure levels 1000, 850, 700, 600, 500, 400, 300 hPa: zonal (u) and meridional (v) wind components, specific humidity (q). The calculation area is restricted by coordinates 38-50° N, 28-45° E. Initial data was obtained from Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels).

The integrated water vapor transport (IVT) is computed according to the formula:

$$\mathrm{IVT}=\frac{1}{g}\int_{P_0}^{P_f} q\cdot\mathbf{V}\cdot dp \qquad (1)$$

In this equation, g is the acceleration due to gravity; P_o is the surface air pressure (1000 hPa); P_f is the upper limit of the integral (300 hPa); q is the specific humidity; **V** is the horizontal wind.

3. Results

In August 2021, a cyclone formed above the Black Sea, with characteristics from the size and cloud system to the thermal structure similar to tropical cyclone. The Black Sea basin in early August was very warm: sea surface temperature (SST) reached 25-27 °C, with positive anomalies throughout the basin. In the eastern part of the Black Sea, where cyclone originated, positive SST anomalies exceeded 4 °C (Figure 1).

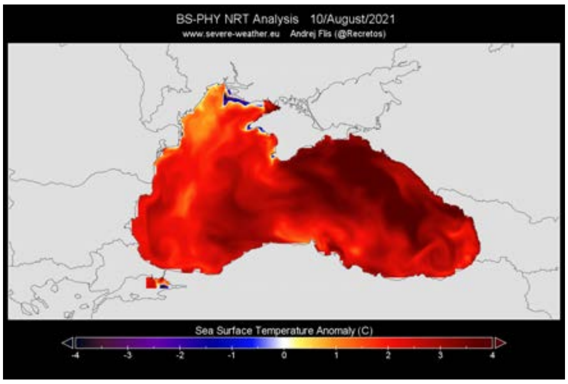
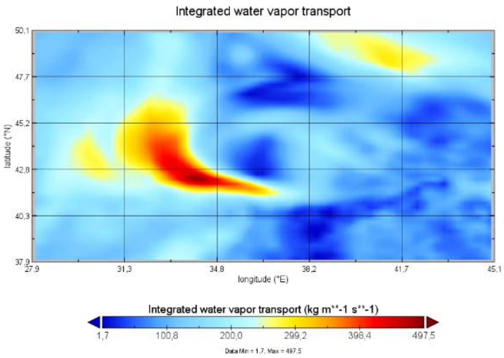


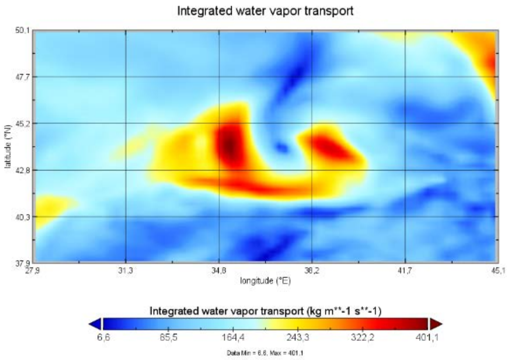
Figure 1. SST anomalies in the Black Sea basin 10 August 2021 Baltic.

Low-pressure zone formed over the central part of the Black Sea on August 10, 2021 was classified by the Mediterranean cyclone Center Center (https://medicanecentre.org/wiki/index.php/main_page) as Medistorm Falchion. In the period from 10 to 12 August, the cyclone affected the Black Sea coast of Turkey, causing significant losses through flash floods and landslides. At the same time, at least 81 people died and about 228 were injured in the floods. On August 12, the cyclone deepened and shifted to the northeast, to the coast of Krasnodar Krai (Russia). On August 13, the cyclone speed declined, and next day the cyclone filled.

Analysis of the calculated fields of IVT during the evolution of cyclone showed that the most intense transport reached and exceeded the intensity of atmospheric rivers, were observed on the southwestern periphery of the cyclone in the first three days (Fig. 2, a-b). Last days intense IVT had spread through the cyclone area, taking the like-ring form (Fig. 2, d).



(a)



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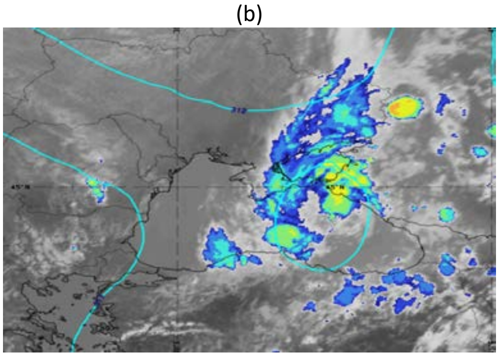
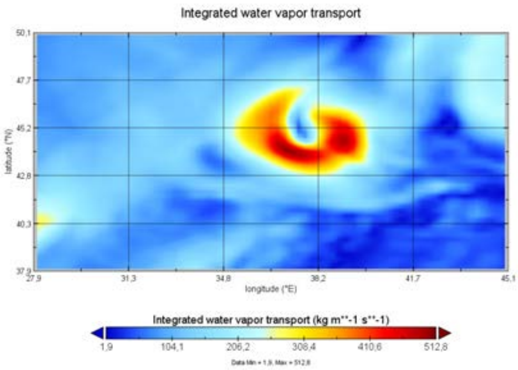


(c)



(d)

Figure 2. (a), (b) and (d) – IVT fields (kg m^{-1} s^{-1}) in cyclone area on 10, 12 and 13 August, 2021 (12 UTC), respectively; (c) - IR enhanced satellite image with isolines H-700, 12 August, 2021 (12 UTC).

During the evolution of cyclone over the Black Sea, there was an intense IVT, associated with the circulation of the cyclone, that is large reserves of the tropospheric water vapor had local origin and were formed before the surface cyclogenesis.

Position of the areas with maximum values of IVT coincides with highest convective cloudiness (Fig. 2, b and c), which means that the mechanism of conversion of a water vapor in the horizontal flow to precipitation was caused by convective instability of the atmosphere. In this case, the local source of water vapor was an evaporation from a superheated sea surface.

4. Conclusions

The case of cyclone over the Black Sea in August 2021, which formed and evolved within the sea basin, showed some elements of its structure, which are similar to tropical cyclones, namely, the ring-shaped temperature of the convective cloud tops, the absence of clear frontal cloud bands in the maximum stage of cyclone development.

Intensive vertically integrated water vapor transport, which reached the criteria of atmospheric rivers in this cyclone, turned out to be the main source of moisture in the implementation of convective instability and the formation of heavy precipitation, which was observed during the passage of this cyclone on coastal areas.

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Benthic Alkalinity fluxes from coastal sediments of the Baltic and North Seas: Comparing approaches and identifying knowledge gaps

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1. Motivation

In the shallow, coastal waters of the western Baltic and southern North Sea, benthic processes play an especially important role in shaping the direction and magnitude of air-water CO_2 exchange (Pätsch et al., 2018; Thomas et al., 2009). This is encouraged by bioturbation (Neumann et al., 2021) and persistent wind and tidal mixing, which together strongly couples this CO_2 uptake/release with sediment-water Total Alkalinity (TA) and Dissolved Inorganic Carbon (DIC) exchanges. However, the magnitude of sediment-water TA/DIC fluxes often depend on the method used to assess them, in part due to the combination of diffusive and advective processes.

In this study, we expand on prior work (Gogina et al., 2018; Lipka 2017; Lipka et al., 2018) and use new and archived data from the western Baltic and southern North seas to model net sediment-water fluxes across a broad range in sediment types. We investigate (bio)geochemical processes shaping net fluxes which are poorly represented in regional carbon budgets, as well as the coupled physical and biological drivers of net sediment-water exchange. Our study applies a broad suite of independent approaches to quantify sediment-water flux, including direct measurements, modeling, and Ra-based budgets. Each method has its own advantages and disadvantages, emphasizing advection, diffusion, or bioirrigation to varying degrees, such that differences among measured/modelled fluxes can indicate real differences between physical and biological drivers.

2. Key findings

We found relatively high ^{224}Ra activities (Burt et al 2014; 2016) in surface water and infer from this greater exchange between porewater and surface water than previously assumed. We also provide a new estimate of the porewater ^{224}Ra endmember, revised upwards by a factor of approximately 2, which may be import for future Ra-based budgets, which are highly sensitive to endmember quantification (Garcia-Orellana et al., 2021).

Modeled sediment-water TA fluxes were small in comparison with previous estimates in the coastal North Sea (Voyanova et al., 2019; Burt et al., 2014), and in fact imply a substantial sink for TA in North Sea sediments, which we associate with: 1) denitrification fed internally by nitrification, rather than "new" NO_3 (very low net sediment-water NO_3 flux), indicating no net TA production, 2) minimal net sulfate reduction, with gross SO_4 reduction balanced by oxidation in well-ventilated upper sediments. Small residual TA fluxes are associated with Si release, pointing towards silicate weathering as a new TA source in sandy North Sea sediments.

Although excess TA was greater in muddy sites (and close to equilibrium in silty and sandy sites) in the Baltic Sea than in the North Sea, the resulting modeled fluxes were also rather small. While modeled fluxes were positive (in direction of sediment to water) in Baltic muddy sites, they were negative in sandy sites, implying a sink in surficial sediments, which we attribute to: 1) Re-oxidation of sulfide and Fe(II) , 2) Minimal net denitrification, as in North Sea sites, and 3) Reverse weathering / mineral re-precipitation. At the few Baltic sites with small positive TA fluxes (muds/silt), we infer net TA production resulting from net sulfate reduction and pyrite burial.

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Marginal seas under threat: The emerging pollutant perspective

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1. Motivation

Continental shelves, accounting for only 7% of the ocean's surface and less than 0.5% of the oceans volume, are highly productive regions providing up to 14% of total global ocean production along with up to 90% of the new production. Their immediate proximity to the land masses makes them globally important in terms of transferring energy and material, controlling anthropogenic and terrestrial fluxes, transporting and trapping pollutants and primary production to and from the open ocean. Marginal seas respond very quickly to environmental changes on various time and space scales and are important areas for biogeochemical fluxes, with a carbon turnover time from days to weeks. As one of the main global fixers of CO_2, phytoplankton is crucial for oceanic carbon fixation which in turn has an impact on the atmospheric CO_2 content and acidification and is hence fundamentally important for the functioning of marine ecosystems. Depending on the region, the amount of organic matter reaching the bottom and hence its burial is higher in shelf seas compared to the open ocean and important for sedimentary chemical redox reactions (e.g. denitrification, trace metal reduction) with implications for the C, N, P and Fe cycles. However, the consequences rising from climate change on one side and human driven drastic changes within the coastal areas on the other side, are only fragmentarily known. In the recent past, large metropolitan areas have emerged along the coasts, which have drawn on the resources of the hinterland and catchment areas and are exerting steadily increasing pressure on the coastal environment due to the industrialization of the regions.

2. Aims of the study

Here results from three joint cruises within the Sino-German project "Megacity's fingerprint in Chinese marginal seas: Investigation of pollutant fingerprints and dispersal (MEGAPOL)" focusing on the Pearl River and the northern shelf of South China Sea as well as the MARGINS initiative are presented.

The pollution status is analysed using examples based on established organic pollutants (e.g. polycyclic aromatic hydrocarbons (PAH, dichlorodiphenyltrichloroethane (DDT), and polychlorinated biphenyls (PCB)) and emerging pollutants like natural and synthetic estrogens as well as microplastics, pharmaceuticals and personal care products (PPCP) and UV filters. The following questions are explored:

(1) To what extent is the "fingerprint" of the megacities in coastal seas mapped and/or modified by the prevailing hydrographic conditions on the shelf and within the estuaries?

(2) What is the function of the sediments in these regions with respect to anthropogenic pressure, in particular the introduced pollutants?

The results are used to assess the risk for the environment regarding individual compound's and are put into wide perspective by comparing our findings with other studies from different marginal seas e.g. Baltic Sea highlighting the need for action on the global scale.

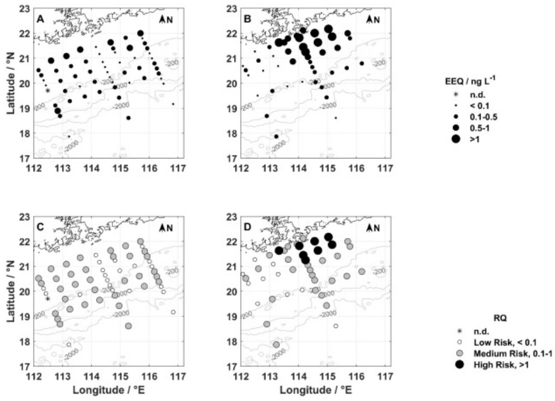

Figure 1. Calculated estradiol equivalent concentration (EEQ) in the working area in the northern South China Sea a) in 2018 and b) in 2019. The size of ● is related to the detected concentration. Bathymetry lines are based on ETOPO1. The calculated risk quotient in the region in 2018 (c) and 2019 (d). The colour refers to the level of risk (Deich et al., 2021).

3. South China Sea

The South China Sea (SCS), a marginal sea of the western Pacific, is oligotrophic in its distal parts and even on the shelf close to the coast, as it is a mostly stratified tropical region (Wu et al., 2003; Dai et al., 2013). Enhanced productivity occurs seasonally and is regionally limited to the upwelling areas off Vietnam, Luzon and Hainan, and off the river mouths, especially of the large rivers such as the Mekong in the southwest and the Pearl River in the northern SCS. The Pearl River is the largest river by volume discharged, delivering 326 billion m^3 of freshwater and 86 million tons of sediments into the SCS (Zu et al., 2014). Its catchment is population by 168 million inhabitants – a so-called megacity – and hosts among the biggest industries in China. The Pearl River is thus a conduit for wastewater from agriculture, industries and humans to the coastal SCS and potentially also to deeper parts of the SCS.

4. Environmental status

Our measurements of organic pollutants indicate that the concentrations of PAHs, DDT, and PCBs are below established sediment quality guidelines, suggesting no environmental risk. However, their concentrations increase from the shelf to the deep northern SCS, and are higher in the east of the study area. Their composition indicates that PAH were mainly derived from pyrogenic sources, and mostly degraded DDT and PCB were seen. However, in the deep northern SCS, considerable contribution of petrogenic PAH, low chlorinated PCBs and p,p'-DDT suggest more recent input from different sources compared to the shelf. We have measured rather uniform PCB concentrations in the nearshore area. A comparison with measurements from a cruise carried out in 2018 shows that the distribution and PCB concentrations in the aqueous phase in the SCS does not exhibit much interannual variation, with the Pearl River Estuary acting as a sources of PCBs into the South China Sea, contrasting the results of Kaiser et al (2018), who identified the water SW of Taiwan as their source. The DDT compounds had a different distribution pattern than the PCBs, with higher concentrations in the water column on the shelf than in the open South China Sea compared to 2018. As for the PCBs, the Pearl River Estuary is a major input source for the DDT compounds in the aqueous phase. Distribution patterns differ in the sediment compared to the water phase. Both PCBs and DDTs were detected in higher concentrations on the slope than on the shelf, indicating the strength of the observed resuspension leading to a considerable downslope redistribution of pollutants.

Our combined results (2018 & 2019) provide a first insight into the transport of PPCPs to the open sea and their different behaviour in the marine environment. Caffeine (CAF, alkaloid), phenylbenzimidazolesulfonic acid (PBSA, UV filter), octocrylene (OC, UV filter), and nonylphenoxyacetic acid (NP1EC, metabolite) were detected most abundantly in surface waters with different distribution patterns. High concentrations of the metabolite NP1EC were measured on the western shelf of the sampling area with decreasing concentrations towards the open sea. CAF exhibits a similar pattern to NP1EC, but the decrease was less pronounced allowing its detection in the open South China Sea. Highly elevated CAF concentrations were detected in the nearshore area off Hong Kong, indicating a land-based source. PBSA and OC had different distribution patterns, with the water-soluble UV filter PBSA detected at some stations and the poorly water-soluble OC almost everywhere in the area.

Synthetic and natural hormones estrone (E1), 17-estradiol (E2), 17-ethinylestradiol (EE2), genistein (GEN), daidzein (DAI), and zearalenone (ZEN) were used as indicators for human impact. Of those, mainly the naturally occurring hormones E1 and E2 as well as the synthetic EE2 were detected. Of the phytoestrogens and mycoestrogens, only GEN was detected at one station in August 2019 (1.2 ng L^{-1}, SCS-14; Deich et al., 2021a,b). Elevated concentrations of the E1 and EE2 were seen at nearshore stations in both years, with E1 up to 1.1 ng L^{-1} and EE2 up to 0.6 ng L^{-1}. The natural hormone E2 was detected up to 0.7 ng L^{-1} in August 2019. Because hormones and hormone-like substances can interfere with the endocrine system of living organisms and cause lasting damage (Adeel et al., 2017), an initial risk assessment was carried out by calculating ratios between measured and predicted no effect concentrations (PNEC) following Hernando et al., (2006). In SCS the calculated risk quotients for the natural hormone E1 (PNEC = 6 ng L^{-1}, Caldwell et al., 2012) range from <0.1 to <1, indicating low to moderate risk. In comparison, concentrations of the natural hormone E2 (PNEC = 2 ng L^{-1}, Caldwell et al., 2012) may pose a moderate risk to aquatic organisms. The synthetic EE2 generally shows a very strong estrogenic effect, which is also reflected in the low PNEC (PNEC = 0.1 ng L^{-1}, Caldwell et al., 2012) leading to a comparatively high risk with quotients well above 1 (Deich et al., 2021). Since the estrogenically active substances are not present individually in environmental matrices and can thus act together on the endocrine system of organisms, the estrogenic activity was determined as well using the measured concentration and the substance-specific estrogenic potency (Fig. 1). Estrogenic activity is considered in relation to the natural E2 and consequently expressed as estradiol equivalent quotient (EEQ). In 2019 EEQ up to 1.4 ng L^{-1} were observed (Deich et al., 2021). Hereby EE2 accounted for a large part of the estrogenic activity due to its high estrogenic potency.

5. Summary

In summary the organic and emerging pollutants are of moderate concentrations and exert moderate to high pressure on the environment of northern SCS. Their distribution in sediments evidently exceeds the region under direct land and river impact. Resuspension of sediments on the shelf and slope is an important process as shown by amino acids and lead to the redistribution of contaminants supplied by the Pearl River into distal areas allowing for considerable downslope transport of pollutants. It should be noted however, that conclusions about any synergistic, antagonistic, or competitive effects between individual compounds were currently not assessed and the effect of the contaminants mixtures on the environment are entirely unknown. Our MARGINS initiative allow for in-depth comparative studies of selected Euro-Asian marginal seas highlighting the anthropogenic stressors in ecosystems exposed to climate change.

6. Acknowledgements

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Modeling Regional Sedimentary Sequence in the North of South China Sea in Late Pleistocene

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1. Abstract

The South China Sea (SCS) is one of larger marginal seas in the west Pacific Ocean strongly impacted by global scale climate change. In the late Pleistocene the continental shelf of North South China Sea (SCS) was shaped frequently by sea-level fluctuation, following the glacial cyclicity. Regional marine geoscientific surveys have collected geophysical data including single channel seismic profiles and sediment data from coring campaigns in different spatial scales. These surveys allow to combine geoscientific data sets to model structure and genesis of sedimentary sequences in order to understand the interplay of global change impact on the SCS shelf with regional drivers. On the regional level, the continental shelf of the northern SCS is remarkably influenced by series of rivers discharging to the sea terrestrial matter particularly the Pearl River, Red River. Exemplified by top three river in China (Yangtze River, Yellow River and Pearl River), the Pearl River's paleo-channels and their changing patterns on the continental shelf have been investigated. The results show that during the post-glacial history the sea-level rise plaid the dominant role driving the shift of paleo-river channels and coastline migration. This data interpretation contributes to a more comprehensive insight into the history of sediment accumulation at the northern continental margin of the SCS and the global and regional drivers.

2. Key words:

South China Sea, Sedimentary Sequence, Pearl River, Late Pleistocene

Reconstruction of morphological evolution of the Baltic Sea and the North Sea during the Last Glacial Cycle

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1. Introduction

Coasts are constantly changing their shape due to multiple physical and biological interactions that lead to sediment erosion and deposition and are very sensitive to climate change and anthropogenic environmental impacts. Coasts of marginal seas composed of soft material (sands, mud and till) are most variable in this context. They are constantly shaped by winds, tides, waves and, on a longer time scale, they can shift landward or seaward due to oscillations of sea level, vertical crustal movements, ice-cover dynamics and variations in the sediment supply.

A research project "Morphological evolution of coastal seas – Past and Future" dedicated to better understand coastal morphological evolution driven by climate change, ocean dynamics and humans has been initiated by the Deep-time Digital Earth (DDE) program. One of its key objectives is reconstruction of coastal shelf morphology, paleo-coastline and hydrodynamics of the three exemplary Eurasian marginal seas (Baltic Sea, North Sea and South China Sea) during the Last Glacial Cycle (last 130 kyr) and in particular in the post-glacial period (last 20 kyr) based on compilation/analysis of existing published large datasets and numerical modelling.

The methods used in the reconstruction are elucidated in Zhang et al. (2014, 2020), Xiong et al. (2020), and Miluch et al. (2022) for applications to the Baltic Sea and the South China Sea. In this presentation, we will introduce the latest progress of the project.

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Posters on

Baltic Earth Assessment Reports (BEAR)

Helcom/Baltic Earth Climate Change Fact Sheet

The Baltic Earth Assessment Reports (BEAR): Making knowledge available on the regional Earth system of the Baltic Sea region

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[4]https://baltic.earth/bear

One of the goals of Baltic Earth when it inherited BALTEX, was the establishment of assessment reports of the current state of the science in different research fields in the Baltic Earth context, similar to the BACC approach for climate change. Now, 9 years after the founding of Baltic Earth, various international conferences, workshops, seminars, sessions, summer and winter schools later, a series of extensive assessment reports, called BEAR (Baltic Earth Assessment Reports), is published.

For each of the Baltic Earth Grand Challenges, a team of experts from the Baltic Earth network has wrapped up the current state of knowledge in the respective research fields, including uncertainties and gaps in knowledge. For each report, a lead author (mostly from the corresponding Working Group) has been responsible for the coordination of the writing process, but many co-authors contributed to the respective reports. In addition to the Grand Challenges, more topics are assessed, due to the great relevance for current research in the Baltic Sea region.

See below the list of BEAR papers, published in *Earth System Dynamics*:

Salinity dynamics of the Baltic Sea; Grand Challenge 1 (Andreas Lehmann et al.)

Biogeochemistry of the Baltic Sea; Grand Challenge 2 (Karol Kulinski et al.)

Natural hazards and extreme events in the Baltic Sea region; Grand Challenge 3 (Anna Rutgersson et al.)

Sea level dynamics and coastal erosion in the Baltic Sea region; Grand Challenge 4 (Ralf Weisse et al.)

Human impacts and their interactions in the Baltic Sea region; Grand Challenge 6 (Marcus Reckermann et al.)

Global climate change and the Baltic Sea ecosystem: direct and indirect effects on species, communities and ecosystem functioning; Baltic Earth topic (Markku Viitasalo and Erik Bonsdorff)

Coupled regional Earth system modelling in the Baltic Sea region; Baltic Earth topic (Matthias Gröger et al.)

Atmospheric regional climate projections for the Baltic Sea Region until 2100; Baltic Earth topic (Christensen et al.)

Oceanographic regional climate projections for the Baltic Sea until 2100; Baltic Earth topic (Meier et al.)

Climate Change in the Baltic Sea Region: A Summary; Baltic Earth topic (Meier et al.)

The latter report by Meier et al. is the update to BACC II, which had been published as a book in 2015. The upcoming report will add new knowledge and possibly challenge old knowledge, while summarizing but not repeating the valid information from BACC II and BACC I.

The reports have been established following the BACC principles, "by synthesis of material drawn comprehensively from the available scientifically legitimate literature (e.g. peer reviewed literature, conference proceedings, reports of scientific institutes). Studies whose results and conclusions cannot be reconciled with a consensus view but which are of a good scientific and technical standard should be taken into account. The assessment should thus encompass the knowledge about what scientists agree on but also identify cases of disagreement or knowledge gaps".

As for the previous two BACC endeavours, there is a close collaboration with HELCOM, the intergovernmental organization for the protection of the marine environment of the Baltic Sea. HELCOM will integrate climate change aspects into their work, e.g. into the update of the HELCOM Baltic Sea Action Plan. Moreover, HELCOM has published an easily accessible climate “Fact Sheet” for practitioners, decision makers and the public. Baltic Earth scientists are part of the joint expert network on climate change by HELCOM and Baltic Earth (EN CLIME) which is responsible for the scientific information of the fact sheets. EN CLIME largely draws its information on BACC, BACC II and the BEAR reports.

esd.copernicus.org/articles/special_issue1088.html

Figure 1. The BEAR logo

Climate Change in the Baltic Sea: HELCOM/Baltic Earth Fact Sheet 2021

HELCOM/Baltic Earth Expert Network Climate (EN Clime)[1], Marcus Reckermann[2], Jannica Haldin[3], Petra Kääriä[3], H.E. Markus Meier[4], Jonas Pålsson[5], Dominik Littfass[3]

[1]https://helcom.fi/helcom-at-work/groups/state-and-conservation/en-clime/
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Climate Change in the Baltic Sea
2021 Fact Sheet

The HELCOM/Baltic Earth Climate Change Fact Sheet 2021

Climate change effects on the Baltic Sea environment are manifold. It is for example expected that water temperature and sea level will rise, and sea ice cover will decrease. This will affect ecosystems and biota; for example, range shifts are expected for a number of marine species, benthic productivity will decrease, and breeding success of ringed seals will be reduced. The impacts will hence affect the overall ecosystem function and also extend to human uses of the sea; trawling will follow the fish towards southern areas, aquaculture will likely face a shift towards species diversification, and the value of most ecosystem services is expected to change — to name a few.

The Fact Sheet is a state-of-science overview over the current knowledge on climate change and its impacts in the Baltic Sea. The information is subdivided into three main sections: Direct Parameters, Indirect parameters – Ecosystem, and Indirect parameters – Human use. A map shows some projected impacts for the subbasins of the Baltic Sea.

The complete 45 page Fact Sheet can be downloaded from the HELCOM website: *https://helcom.fi/media/publications/Baltic-Sea-Climate-Change-Fact-Sheet-2021.pdf*

or here directly via QR code.

The Expert Network on Climate Change - EN CLIME

The Climate Change Fact Sheet was elaborated by the Baltic Sea Expert Network on Climate Change - EN CLIME

In 2018, the Baltic Sea Environment Protection Commission (HELCOM) and Baltic Earth formed a joint Expert Network on Climate Change in the Baltic Sea region (EN CLIME). This Expert Network involves more than 110 scientists from around the Baltic Sea. The purpose of the network is to function as a coordinating framework and a platform to harness the expertise of leading scientists on both direct and indirect effects of climate change on the Baltic Sea environment and ecosystems and make this expertise available to and open up for closer dialogue with policy makers.

Eine deutsche Übersetzung des Fact Sheets liegt vor und kann abgerufen werden unter

https://baltic.earth/projects/en_clime/

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International Baltic Earth Secretariat Publications

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No. 1 Programme, Abstracts, Participants. Baltic Earth Workshop on ”Natural hazards and extreme events in the Baltic Sea region”. Finnish Meteorological Institute, Dynamicum, Helsinki, 30-31 January 2014. International Baltic Earth Secretariat Publication No. 1, 33 pp, January 2014.

No. 2 Conference Proceedings of the 2nd International Conference on Climate Change - The environmental and socio-economic response in the Southern Baltic region. Szczecin, Poland, 12-15 May 2014. International Baltic Earth Secretariat Publication No. 2, 110 pp, May 2014.

No. 3 Workshop Proceedings of the 3rd International Lund Regional-Scale Climate Modelling Workshop ”21st Century Challenges in Regional Climate Modelling”. Lund, Sweden, 16-19 June 2014. International Baltic Earth Secretariat Publication No. 3, 391 pp, June 2014.

No. 4 Programme, Abstracts, Participants. Baltic Earth - Gulf of Finland Year 2014 Modelling Workshop ”Modelling as a tool to ensure sustainable development of the Gulf of Finland-Baltic Sea ecosystem”. Finnish Environment Institute SYKE, Helsinki, 24-25 November 2014. International Baltic Earth Secretariat Publication No. 4, 27 pp, November 2014.

No. 5 Programme, Abstracts, Participants. A Doctoral Students Conference Challenges for Earth system science in the Baltic Sea region: From measurements to models. University of Tartu and Vilsandi Island, Estonia, 10 - 14 August 2015. International Baltic Earth Secretariat Publication No. 5, 66 pp, August 2015.

No. 6 Programme, Abstracts, Participants. International advanced PhD course on Impact of climate change on the marine environment with special focus on the role of changing extremes. Askö Laboratory, Trosa, Sweden, 24 - 30 August 2015 International Baltic Earth Secretariat Publication No. 6, 61 pp, August 2015.

No. 7 Programme, Abstracts, Participants. HyMex-Baltic Earth Workshop ”Joint regional climate system modelling for the European sea regions”, ENEA, Rome, Italy, 5- 6 November 2015. International advanced PhD course on Impact of climate change on the marine International Baltic Earth Secretariat Publication No. 7, 103 pp, October 2015.

No. 8 Programme, Abstracts, Participants. A PhD seminar in connection with the Gulf of Finland Scientific Forum: "Exchange process between the Gulf of Finland and other Baltic Sea basins". Tallinn, Estonia, 19 November 2015. International Baltic Earth Secretariat Publication No. 8, 27 pp, November 2015

No. 9 Conference Proceedings. 1st Baltic Earth Conference. Multiple drivers for Earth system changes in the Baltic Sea region. Nida, Curonian Spit, Lithuania, 13 - 17 June 2016. International Baltic Earth Secretariat Publication No. 9, 222 pp, June 2016

No. 10 Programme, Abstracts, Participants. Baltic Earth Workshop on ”Coupled atmosphere-ocean modeling for the Baltic Sea and North Sea”, Leibniz Institute for Baltic Sea Research Warnemünde, Germany, 7- 8 February 2017. International Baltic Earth Secretariat Publication No. 10, 24 pp, February 2017

No. 11 Baltic Earth Science Plan 2017. International Baltic Earth Secretariat Publication No. 11, 28 pp, February 2017

No. 12 Programme, Abstracts, Participants. MedCORDEX-Baltic Earth-COST Workshop ”Regional Climate System Modelling for the European Sea Regions”. Universitat de les Illes Baleares, Palma de Mallorca, Spain, 14 - 16 March 2018, International Baltic Earth Secretariat Publication No. 12, 96 pp, March 2018

No. 13 Conference Proceedings. 2nd Baltic Earth Conference. The Baltic Sea in Transition. Helsingør, Denmark, 11 - 15 June 2018. International Baltic Earth Secretariat Publication No. 13, 216 pp, June 2018

No. 14 Programme, Abstracts, Participants. Baltic Earth Workshop "Multiple drivers for Earth system changes in the Baltic Sea region". Tallinn, Estonia, 26-27 November 2018. International Baltic Earth Secretariat Publication No. 14, 58 pp, March 2018

No. 15 Programme, Abstracts, Participants. Baltic Earth Workshop "Hydrology of the Baltic Sea Basin: Observations, Modelling, Forecasting". St. Petersburg, Russia, 8-9 October 2019. International Baltic Earth Secretariat Publication No. 15, 44 pp, October 2019

No. 16 Programme, Abstracts, Participants. Baltic Earth Workshop "Climate projections and uncertainties in the northerb Baltic Sea Region". Helsinki, Finland, 19-20 November 2019, International Baltic Earth Secretariat Publication No. 16, 38 pp, November 2019

No. 17 Anders Omstedt: 45 years of wandering - from processes to systems, through outer and inner seas. An interview by Hans von Storch and Marcus Reckermann with foreword by Jüri Elken, 63 pp. International Baltic Earth Secretariat Publication No. 17, 63 pp, February 2020

No. 18 Conference Proceedings. 3rd Baltic Earth Conference. Earth system changes and Baltic Sea coasts. To be held in Jastarnia, Hel Peninsula, Poland, 1 - 5 June 2020. Held online 2-3 June 2020. International Baltic Earth Secretariat Publication No. 18, 209 pp, June 2020

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No. 20 Programme, Abstracts, Participants. EMS2 Conference Marginal Seas – Past and Future, Online, 16-17 December 2020. 60 pp, December 2020

No. 21 Conference Proceedings. 4th Baltic Earth Conference. Assessing the Baltic Sea Earth System. To be held in Jastarnia, Hel Peninsula, Poland, 30 May - 03 June 2022. International Baltic Earth Secretariat Publication No. 21, 201 pp, May 2022

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