International Baltic Earth Secretariat Publication No. 23, May 2024

5th Baltic Earth Conference

New Challenges for Baltic Sea Earth System Research

Jūrmala, Latvia 13 -17 May 2024

Conference Proceedings

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Impressum

International Baltic Earth Secretariat Publications
ISSN 2198-4247

International Baltic Earth Secretariat
Helmholtz-Zentrum Hereon GmbH
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Front page photo: with kind permission of visitjurmala.lv

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Acknowledgments

We thank our local partner institution, the Latvian Institute of Aquatic Ecology in Riga, in particular Prof. Juris Aigars, for co-organizing this conference. Also from the same institute, we would like to thank Elina, Sanda, Sandra and Valentina for helping in various issues during the conference.

Silke Köppen of the International Baltic Earth Secretariat at Hereon put together this abstract volume. Christin Menneking of Hereon and Berit Recklebe of IOW 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 Monta, Rasa and Alisa of Con-Ex in Latvia for helping with registration and fee collection issues and the local organization, and Elīna and Kārlis of Hotel Jūrmala Spa for taking care of us at the Conference Hotel.

Preface

The scope of this 5th Baltic Earth Conference is "New Challenges for Baltic Sea Earth System Research". The completion of the Baltic Earth Assessment Reports (BEARs) marks the termination of the first phase, ten years after the launch of Baltic Earth. The BEARs provide a retrospect of Baltic Earth related research, current knowledge and knowledge gaps, and wrap up Baltic Earth activities.

It is now time to move on and update research challenges, and define new ones. The updated and new research foci will be presented and discussed by scientists, students, managers and other stakeholders at this conference.

The updated set of research topics are reflected in the thematic fields below and are described in the updated Baltic Earth Science Plan 2024, which will be available later this year.

A Biogeochemistry of the Baltic Sea – Linking observations and modelling
B Natural hazards and extreme events
C Sea level dynamics, sediment dynamics, coastal processes and impacts on coasts
D Human impacts, interactions and management options
E Modeling past and future climate changes and teleconnections
F Small scale processes not yet resolved and their impact on the large-scale dynamics and patterns
G Comparing marginal seas worldwide
H Philosophical aspects of Baltic Sea Earth system research

We have received 107 abstracts, which subdivides into 63 oral and 44 poster presentation, but as usual, no discrimination is made in this volume regarding poster or oral presentation; they are all sorted alphabetically within topics.

The conference is an on-site event, not a hybrid meeting; however, there are some exceptions for the global session on *Comparing Marginal Seas worldwide*, and some keynotes.

Participants from 17 countries have registered to the conference, among them many countries outside the Baltic Sea region. However, the strongest participation is again from the Baltic States, which emphasizes the central importance of this region for the scientific research landscape of the Baltic Sea region.

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, Juris Aigars, Andris Andrusaitis, Markus Meier and Karol Kuliński

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Managing marine resources sustainably – but how do we know when marine management has been successful?

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Abstract
Marine environmental management is more correctly termed managing people and their activities rather than managing the environment per se although the latter can be achieved through eco- and geo-engineering. Marine management requires the need to define who requires a successfully managed environment and who is responsible for it, what are the tools and indicators for that management, what are the indications of success in management and how do we know that the environment has been successfully managed. The analysis here tackles these issues using information gathered especially from the European and North American areas but with relevance to all maritime states. A detailed case-study, of the Nervion Estuary and Coast (Basque Country, Spain) and another of the EU Marine Strategy Framework Directive are used as examples of the successful implementation of these aspects in marine management.

Understanding the what, the how and the why: the role of science in informed decision making.
- Cooperation between Baltic Earth and HELCOM, today and in the future.

Jannica Haldin[1]

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1. The role of science in informed decision making

Science provides the foundation for informed decision making in environmental policy, It does this by supplying the knowledge, tools, and methodologies needed to understand, address, and manage environmental challenges effectively. Ignoring or sidelining scientific evidence in policymaking can therefore lead to ineffective or counterproductive policies that fail to protect the environment and safeguard public health and well-being.

Environmental issues often involve complex ecosystems and interactions between various factors. Science helps policymakers understand these complexities by providing insights into the interconnectedness of ecological processes, the dynamics of natural systems. Science also enables policymakers to assess environmental impacts associated with human activities and the pressures resulting from these. By understanding the potential impacts and uncertainties, policymakers can develop strategies to manage and mitigate these risks effectively.

Environmental challenges, such as climate change, biodiversity loss, and pollution, have long-term implications that extend beyond political cycles. Science provides the long-term perspective needed to evaluate the sustainability of different policy options and their impacts on future generations.

Science not only identifies environmental challenges but also offers potential solutions. Through research and innovation, scientists develop technologies, strategies, and best practices that can inform policy decisions aimed at addressing environmental issues.

Many, if not most, environmental issues transcend national borders and require coordinated efforts at the international level. Science serves as a common language that facilitates collaboration and information sharing among countries, enabling the development of global solutions to global challenges.

2. Importance of understanding the what, the how and the why in policymaking

Evidence-based decision making should be the core of any policy process. Environmental policies should be grounded in scientific evidence to ensure their effectiveness and should have a clear understanding of what is happening, why it is happening and how to address it. Science provides the empirical data needed to understand the current state of the environment, predict future trends, and assess the potential impacts of policy interventions. Informed environmental policies are also more likely to garner public trust and support. By relying on scientific evidence, policymakers demonstrate their commitment to making decisions based on objective data rather than political ideology or special interests, enhancing transparency and accountability in the policy-making process.

3. The science-policy interface: cooperation between Baltic Earth and HELCOM, today and in the future

Cooperation between Baltic Earth and HELCOM has a long history, reaching back to Baltic Earth's predecessor Baltex. This cooperation has historically involved sharing scientific research, data, and expertise, primarily in relation to climate change, with HELCOM relying on Baltic Earth's expertise and research findings to inform its policies and initiatives and BalticEarths work benefitting from an improved understanding of the needs of decision makers and increase uptake of science and research results in policy.

In 2018 it was agreed that, as a next step in HELCOMs efforts to integrate climate change in the organizations work, HELCOM needed to focus on a long-term, multi-disciplinary approach to understanding and communicating the implications of climate change for the marine and coastal environment. Simultaneously the lag time in transferring the quality assured science to the policy level, including providing clear guidance on the levels of confidence, needs to be reduced to ensure that the most current information is accessible to support decision making. At the same time it was inherently recognised that other organisations and institutions around the Baltic Sea, and on the international stage, work closely with climate change related issues and policies at different levels and subsequently synergies should be established where possible. This was the starting point for a strengthened cooperation between the two organization and has resulted in the establishment of the shared HELCOM-BalticEarth Expert Network on Climate Change, and the development of the first Baltic Sea Climate Change Factsheet.

As the triple planetary crisis exacerbates, science for decision-making is becoming ever more important, driven by the increasing complexity of issues and the urgency of action. This has direct implications for the already highly valued cooperation between BalticEarth and policy institutions such as HELCOM.

In addition to inter-organizational cooperation there is an increasing emphasis on regional collaboration to tackle the increasing challenges associated with anthropogenic pressures. Here both BalticEarth and HELCOM are strategically placed as regionally relevant transboundary entities. As these challenges do not acknowledge anthropogenic borders, aaddressing them requires coordinated action across local, national, and regional levels. Here science serves as a common language that facilitates collaboration, knowledge sharing, and information exchange among stakeholders, including governments, scientists, civil society organizations, and the private sector. International scientific-poliy cooperation can help mobilize resources, foster innovation, and scale up solutions to address the shared challenges of climate change, biodiversity loss, and environmental degradation.

The urgency for policymakers to address climate change, pollution and biodiversity loss, comes with an increased need to mitigate risks and uncertainties, and the triple planetary crisis is characterized by significant risks and uncertainties, including unpredictable environmental feedbacks, tipping points, and potential cascading effects on ecosystems and societies. Science helps policymakers assess these risks, evaluate potential impacts, and develop risk management strategies to minimize adverse consequences. Evidence-based decision-making can help navigate uncertainties and reduce the likelihood of unintended consequences.

As the Baltic Sea ecosystem needs to contend with global level pressures, in addition to local and regional pressures, there is, at the policy level, an enhanced focus on maintaining and enhancing the resilience of the Baltic Sea. Here science can provide valuable insights into the resilience of ecosystems, communities, and infrastructure to the impacts of the triple planetary crisis. By understanding the underlying dynamics and vulnerabilities, decision-makers can then design policies and interventions aimed at building resilience and enhancing adaptive capacity. This may involve strategies such as ecosystem restoration, climate-smart infrastructure, and community-based adaptation measures informed by scientific research and data.

In conclusion, the threat imposed by a combination of climate change, biodiversity loss and pollution are multifaceted issues influenced by multiple factors such as human activities, natural processes, and feedback loops and represent interconnected environmental challenges that require a deep understanding of scientific principles and processes. Science provides the tools and knowledge needed to unravel these complexities and develop effective strategies for addressing them. Science therefore plays a crucial role in mitigating, and adapting to, the triple planetary crisis, especially through assessing the current state of the environment, predicting future trends, and identifying the most pressing priorities for action. By relying on scientific evidence, policymakers can then prioritize interventions and allocate resources efficiently to address the most critical challenges. By leveraging the scientific evidence and expertise provided by BalticEarth, HELCOM can help develop effective strategies to address these interconnected environmental challenges. Together, BalticEarth and HELCOM can work towards the common goal of understanding, protecting and preserving the Baltic Sea environment, both now and in the future.

Regime shifts as an archetypal phenomenon of climate and climate change

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1. Introduction

The classic perception of climate change is that it is a slow, gradual, usually irreversible process that becomes evident more or less consistently in large areas. The core shortcoming of this perception is the implicit supposition that climate change can be to a certain extent linearized, that is, characterized by a sufficiently large set of various trends.

The climate system, however, is fundamentally nonlinear and thus naturally involves a multitude of phenomena that are intrinsic to complex systems. It is therefore much more natural to interpret both climate and its change as a fascinating variety of interacting nonlinear processes, phenomena and feedbacks that melt the multitude of inputs to the climate system into an environment that has been pretty much designed by the Earth's ecosystem into conditions in which we feel comfortable.

2. Questioning spatial and temporal scales

Many marvels of the climate system become evident both in space and time, be it North American cooling on the background of global warming, the interplay of El Niño and La Niña, or a shift in the North Atlantic storm track. Whether or not they are interpreted as an intrinsic part of basically (statistically) stationary climate or evidence of climate change often depends on the particular researcher's perception of spatial and temporal scales as well as on the length and extent of the relevant observations.

One of the classic ways that nonlinear systems respond to changes in forcing is by regime shift. It is a natural reaction of threshold-governed processes, from mechanical and ecosystem fatigue, to the reshaping of major teleconnection patterns. This is a common behaviour of systems whose internal feedbacks stabilize the reaction of the system to external impacts. Systems of this kind often evolve slowly, adapting themselves to the new situation, until a certain threshold is exceeded, after which the system is rapidly reorganized.

Such phenomena have been observed at radically different scales, from a step-like decrease in the thickness and deformation rate of Arctic sea ice around 2005–2007 (Sumata et al., 2023) down to substantial changes in small ecosystems (Biggs et al., 2018). Their common feature is that they occur abruptly, at time scales that are at least by an order of magnitude shorter than the common climatic periods. It is often speculated that the frequency of climate change driven regime shifts will increase with the increasing magnitude of climate change (Cooper et al., 2020). This conjecture is only partially justified as even the fundamental relationships between the spatial-temporal scales of shifts and their underlying mechanisms are poorly understood (Cooper et al., 2020). Moreover, abrupt changes do not necessarily imply discontinuous dynamics or collapse of the affected (eco)system (Blöcker et al., 2023).

3. Conceptualising regime shifts and tipping points

Cooper et al. (2020) conceptualize regime shifts as large, persistent, and generally unexpected changes in relatively stable features, patterns and systems, including ecosystems and socio-ecological systems (Biggs et al., 2018). Some such occasions involve reinforcing feedback loops that accelerate the change beyond so-called tipping points (Ditlevsen and Ditlevsen, 2023). The notion of tipping points is coined in Gladwell (2000) to denote "the moment of critical mass, the threshold, the boiling point" in a somewhat different frame to explain and describe the "mysterious" sociological changes that often mark everyday life.

This notion is often expanded in natural sciences to denote the point of no return of some process that can be uniquely identified and forecast (Ditlevsen and Ditlevsen, 2023). This extension of the concept of tipping points is often applied in a more restricted context to describe abrupt changes in the systems that involve hysteresis or even irreversible behaviour driven by (usually concealed) non-stationary functional relationships (Blöcker et al., 2023).

The characteristic feature of regime shifts is that they occur abruptly (but not necessarily immediately after the relevant tipping point). The duration of a regime shift is the time to transition to another stable but functionally different system state. The perceived time scale of such changes is from 1–2 years (Sumata et al., 2023) down to a few months (Soomere et al., 2015).

The impact of major regime shifts is not necessarily globally devastating. For example, a potential collapse of the Atlantic Meridional Overturning Circulation (Ditlevsen and Ditlevsen, 2023) may stabilize eastern Amazonian rainforests (Nian et al., 2023). However, cascading regime shifts, with multiple domino effects and hidden feedbacks, may lead to unprecedented cumulative effects and dire consequences (Rocha et al., 2018).

Regime shifts are usually well explainable retrospectively but extremely hard to forecast even though some advanced mathematical methods are giving promising results. The core obstacle is that the models of stochastic processes used to describe the evolution of systems in the proximity of such events are overly simplified. Such models do describe properly the mechanistic aspects, such as the presence of several stable versions of the system dynamics or the loss of stability of the system in terms of, e.g., a bifurcation or rolling towards another stable status. On some occasions such models may provide delicate information about how close the system is to a tipping point (Ditlevsen and Ditlevsen, 2023). However, increasing the prognostic value of such models is still a major challenge.

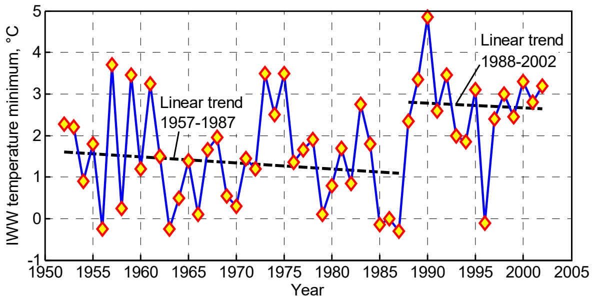

Figure 1. Time history of annual temperature minimum (°C) in the intermediate winter water (IWW) in the Baltic Sea. Redrawn from Mohrholz et al. (2006) using data kindly provided by Volker Mohrholz.

4. A small selection of identified regime shifts in the Baltic Sea

Not unexpectedly, the research pool of regime shift analyses in the Baltic Sea includes >200 papers in international journals. They start from the description of a regime shift in ice properties in 1877 (Omstedt and Chen, 2001), include a massive comparison of observed regime shifts in the Baltic Sea and North Sea (Dippner et al., 2012), touch on the possibility that regime shifts are an intrinsic constituent of the dynamics of the Baltic Sea (Kudryavtseva et al., 2018), expand the analysis of "marine" tipping points into the framework of social-ecological systems (Riekhof et al., 2022), and address events that happened thousands of years ago (Weiss et al., 2022)

Perhaps the most well-known regime shift in the Baltic Sea basin, among a multitude of similar marvels in the research literature, is the shift in trajectories of deep cyclones in the north Atlantic and the widening of the North Atlantic storm track to the north-east (Lehmann et al., 2011). This feature becomes evident locally as a rotation by about 90° of the average air-flow direction in the north-eastern Baltic Sea in January (Keevallik, 2011).

At a larger scale, geostrophic air-flow direction over the southern Baltic Sea abruptly turned by 40° at the end of the 1980s (Soomere et al., 2015). This feature reached the Gulf of Finland latitudes (Keevallik and Soomere, 2014), may have affected the formation of intermediate winter water (IWW) in the Baltic Sea (Fig. 1) and apparently resulted in a multitude of regime shifts in various observed phenomena in Estonia around 1990 (Kotta et al., 2018).

Acknowledgements

The underlying research was supported by the Estonian Research Council (grant PRG1129).

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Session A

Biogeochemistry of the Baltic Sea – Linking observations and modelling

Variability of the carbonate system in the coastal zone of the southern Baltic Sea.

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1. Introduction

The pH decrease caused by the rising atmospheric CO_2 concentrations, a mechanism called Ocean Acidification, has been recognized as one of the greatest threats for the marine environment. Its understanding requires knowledge about the structure and functioning of the marine CO_2 system, which is a complex interplay between four measurable variables: Dissolved Inorganic Carbon (DIC), Total Alkalinity (TA), CO_2 partial pressure (pCO_2), and pH. We know quite well how the CO_2 system works in the open ocean (Wesslander et all, 2011; Dickson et al., 2007), where ratio of TA and salinity is relatively constant, however, in coastal areas, the alkalinity is much more variable, due to the influence of many processes such as river runoff, photosynthesis, respiration or its release from sediments (Middelburg, 2020).

The Baltic Sea has been studied for decades now, however, so far the functioning of the marine CO_2 system has been studied mostly in the open Baltic Sea waters (Bełdowski et al., 2010; Kuliński et al., 2017). Little is known about shallow coastal regions, highly influenced by both freshwater input from land and processes occurring in sediments. Especially under-sampled in that respect are southern and south-eastern parts of the Baltic Sea influenced by the large continental rivers identified as a net source of TA to the Baltic Sea (Stokowski et al., 2021) Thus, the main goal for this study was to identify seasonal and interannual variability of the marine CO_2 system in a very dynamic, coastal environment (Gulf of Gdansk, southern Baltic Sea).

2. Monitoring system

We established our own monitoring on the pier in Sopot (the coastal part of the Gulf of Gdansk) as presented in Figure 1. This area is characterized by the influence of smaller rivers and also by the neighborhood of the second largest river draining to the Baltic Sea, the Vistula River, which with specific wind direction and wave propagation can influence the study area (Wielgat-Rychert et all, 2013; Szydłowski et all, 2019). The sampling spot is only around 3m deep, highly influenced by mixing, biological processes (both organic matter production and remineralization) and processes occurring in sediments.

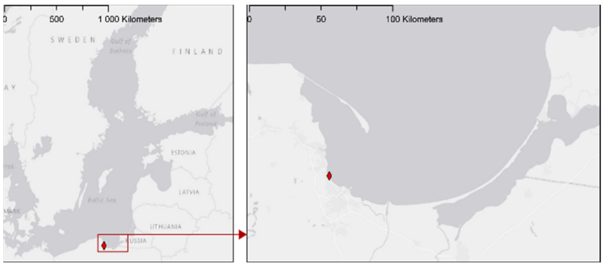

Figure 1. Sampling area.

Since the end of 2016, we have been collecting seawater samples once a week. Sampling includes parameters like temperature, salinity, DIC, TA, and pH. Additional samples measured are the dissolved organic carbon, particulate organic and inorganic carbon, metals (Ca and Mg), nutrients PO_4, NH_4, TON, NO_3+NO_2, SiO_2, and chlorophyll *a* concentration.

Collected samples are measured at IOPAN using the following methods: DIC is measured using the Apollo SciTech system equipped with Li7815 CO_2 detector. Alkalinity concentration is measured with an open-cell titration system developed by Prof. Andrew Dickson (University of California) and pH analyses are performed using a HydroFIA pH spectrophotometric system (4H Jena Engineering GmbH).

3. Results

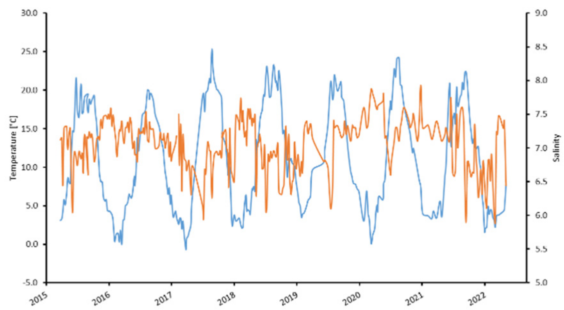

Figure 2. Changes in time of temperature (blue line) and Salinity (orange line).

We observed a strong seasonal variability in seawater temperature, with the highest values measured in August

2018 (maximum 25.3°C) and the lowest in March 2018 (minimum -0.7 °C) (presented on Figure 2). Salinity was relatively constant within the range between 5.9 and 7.9, with the occasional freshening due to the stronger influence of the Vistula River.

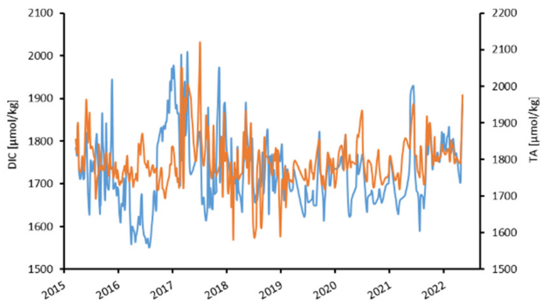

Figure 3. Changes in time of DIC (blue line) and TA (orange line).

As mentioned before there are four measurable parameters, which describe the marine CO_2 system. In this study we focused on two variables: DIC and TA (Figure 3). Obtained results are characterized by high temporal variability with no clear seasonal patterns as would be expected based on our knowledge from the open sea. DIC and TA results ranged from 1539 µmol/kg and 1525 µmol/kg to maximum 2007 µmol/kg and 2118 µmol/kg, respectively. Comparing the DIC and TA results with salinity, we can observe an increase of both parameters with a decrease of salinity, indicating that the Vistula River is an important source of TA and DIC to the Gulf of Gdansk.

4. Conclusion

This is the very preliminary interpretation of data that have been collected for the last 8 years. As this is the first such extensive report on the CO_2 system variability in this coastal region, we believe these results will be of key importance to validate biogeochemical models, which still lack information about the dynamic shallow coastal zone.

The observed high variability of the measured parameters poses a challenge for further interpretation of the results. As first, we plan to apply a two endmember approach (seawater + freshwater) to decouple from the dataset and quantify the influence of the Vistula River. Secondly, taking into account nutrient and chlorophyll *a* data we would like to quantify the contribution of primary production to the CO_2 system variability. And finally, we plan to obtain pCO_2 estimations from TA and DIC and approximate, for the first time, the CO_2 exchange through the air/sea interface in this coastal area.

Acknowledgements

This study was financially supported by the National Science Centre, Poland (UMO-2023/49/B/ST10/02690). ALKALIS - Transport and transformation of total alkalinity from continental rivers – the missing components for understanding pH variation in the Baltic Sea.

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Development of a Gas Equilibrium-Membrane-Inlet Mass Spectrometer (GE-MIMS) for continuous N_2, O_2 and Ar measurements to quantify nitrogen fixation in the Baltic Sea

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1. Introduction

Nitrogen fixation by cyanobacteria is a common phenomenon in the Baltic Sea. It is of particular importance in the context of eutrophication, as it promotes biomass production in the absence of dissolved inorganic nitrogen (DIN). Its contribution to the N budget is of the same order of magnitude as the combined sum of riverine and airborne DIN input, varying between 300 kt-N/yr and 800 kt-N/yr (Wasmund et al. 2005, Rolff et al. 2007). The vast range is due to internal fluctuations and significant uncertainties in the various techniques used to determine N_2 fixation (^{15}N incubation, total N budget, pCO_2 records, phosphate excess) and in extrapolating local studies to entire basins. To overcome some of the limitations we introduce a new approach based on large-scale records of the surface water N_2 depletion during June to August when the probability of a cyanobacteria bloom is high (Wasmund et al. 1997). Additionally, Ar measurements are performed to account for the air-sea N_2 gas exchange. Furthermore, the biological oxygen saturation ΔO_2/Ar can be utilized to further characterize the biological production.

For our studies we developed an Gas Equilibrium-Membrane-Inlet Mass Spectrometer (GE-MIMS) designed for deployment on a ferry line, enabling repeated transects along the same route and providing high temporal and spatial resolution data for N_2, O_2 and Ar gas concentrations in the surface water.

Our objectives are to identify various factors that initiate and potentially limit the growth of cyanobacteria, including temperature, phosphorus availability, solar radiation and meteorological/hydrographic conditions. The final goal is the determination of the N_2 fixation capacity of the entire Baltic Proper.

2. Gas Equilibrium-Membrane-Inlet Mass Spectrometer

The fundamental principle of a GE-MIMS involves an equilibration process between the partial pressures of a water side and a gas side (headspace) that are separated by a gas-permeable membrane. In Figure 1, the whole setup is shown.

We used the Liquicel mini-module cartridge containing porous hollow fibers, which create a membrane surface area of 0.9 m^2. When seawater is sampled, a filtration prior to the membrane is necessary to protect it from clogging with particles. Accurate temperature measurements are provided by temperature probes located at the inlet and outlet of the membrane.

The headspace of the membrane-equilibrator is connected with a pressure sensor and a mass spectrometer (MS). The latter is the commercially available Quadrupole-MS (QMS) GAM 2000 (InProcess Instruments, Bremen, Germany).

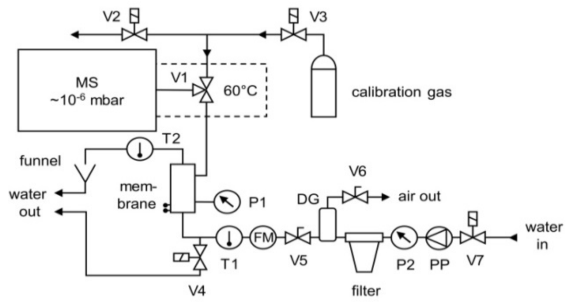

Figure 1. Schematic Diagram of the GE-MIMS.

Through calibration of the MS with a well-defined standard gas composition, the detected ion currents of the investigation gases (N_2: m/z = 28, O_2: m/z = 32 and Ar: m/z = 40) can be converted into their molar fractions x. Together with the recorded total pressure p_t in the headspace, the partial pressures of the respective gases p_i can be calculated by applying Dalton's Law. Since water vapor was not measured, the total pressure is corrected by subtracting the saturation partial pressure of water p_{H2O}.

$$p_i = x'_i \cdot (p_t - p_{H2O})$$

The impact of other gases on the total pressure is minimal, and therefore, they can be disregarded in this analysis. Finally the concentration of dissolved gases is determined by applying Henry's Law, using the Bunsen coefficient β and the molar Volume V_m.

$$c_i = \frac{\beta \cdot p_i}{V_m}$$

3. Measurement performance

To assess the accuracy and precision of concentration measurements, we conducted several laboratory experiments. We coupled the GE-MIMS with a thermostat filled with distilled water. The thermostat was set to a constant temperature (20 °C) and was open to the atmosphere in order to generate equilibrium with atmospheric gases. The respective saturation concentrations were calculated according to Hamme and Emerson (2004) and Weiss (1970). And the concentrations of N_2, O_2 and Ar were determined as described above. The accuracy is given by the difference between the measured and the saturation value: N_2: 0.2%, O_2: 0.2%, and Ar: 0.03%. The precision or detection limit was determined by calculating double the standard deviation, with the following results: N_2: 0.29 µmol/L, O_2: 0.32 µmol/L, and Ar: 0.02 µmol/L.

These results show that the performance of the GE-MIMS is sufficient enough to detect and quantify nitrogen fixation, where we anticipate a N_2-deficit of up to 5 µmol/L. Another important parameter of the GE-MIMS, which describes the kinetical aspect of the equilibration process, is the e-fold equilibration time τ. By conducting laboratory experiments with a flow rate of 2 L/min, we empirically determined τ, which ranges from 4.8 minutes for N_2 to 5.0 minutes for Ar.

4. Deployment on a cargo ship

In June/July of 2023 the GE-MIMS was deployed on the voluntary observing ship (VOS) "Finnmaid", where an automated measurement system for recording the surface partial pressures of CO_2, CH_4, O_2 and N_2O is already installed (Gülzow et al. 2011). Therefore, the existing infrastructure could be used to obtain a continuous water supply from a depth of approximately 3.5 meters.

Figure 2. The transect of VOS "Finnmaid" with indicators for the distance from Helsinki.

The VOS "Finnmaid" is travelling 2-3 times per week over a distance of about 1000 km between the Mecklenburg Bight and the Gulf of Finland (Figure 2). Therefore, we were able to create large scale concentration time series of N_2, O_2 and Ar with a temporal resolution up to 3 days and a spatial resolution of about 1 km.

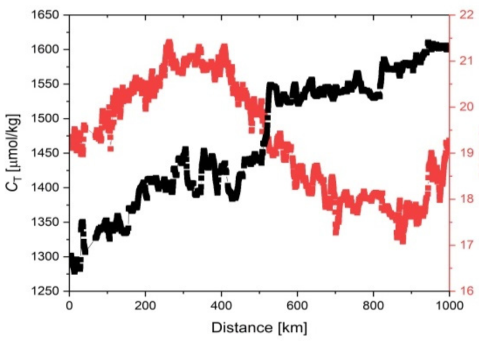

Figure 3. Total CO_2 concentration (C_T, black line) and sea surface temperature (SST, red line) measured on the VOS "Finnmaid" from 29th of June 2023 during the high productive phase of a cyanobacterial bloom. The distance is indicated from Helsinki.

At the end of June 2023, a high productive phase of a cyanobacterial bloom occurred north of Gotland, as shown by the low total CO_2 concentrations (C_T) in Figure 3. This event was likely influenced by calm weather conditions and relatively high sea surface temperatures (SST, Figure 3).

In order to detect biogenic changes of N_2 and O_2 concentrations, the Ar concentration can be used to separate the abiotic variability. The following equation represents the change in N_2 (ΔN_2) concentration due to biogeochemically induced changes (nitrogen fixation), where the element symbols represent the measured concentrations and the subscript "sat" refers to the saturation concentration (Schmale et al. 2019).

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

Based on this equation, also biogenic change in oxygen concentration (ΔO_2) can be calculated.

In Figure 4, the opposing trends of ΔN_2 and ΔO_2 can be clearly observed. In the highly productive area north of Gotland (0-200 km), very high ΔO_2 values are evident due to increased photosynthetic activity. Since this primary production by cyanobacteria is fueled by nitrogen fixation, the same area exhibits the lowest ΔN_2 values. In the southern part of the Baltic Sea, where minimal primary production was observed at that time (refer to C_T, Figure 3), the values for ΔO_2 decrease accordingly, and the ΔN_2 values increase.

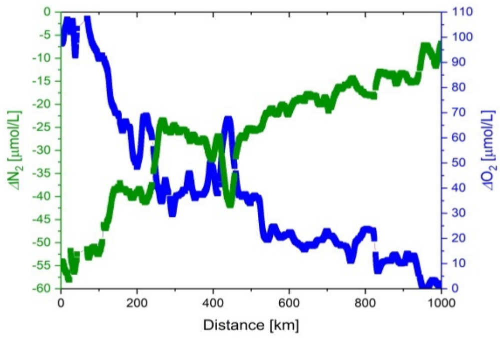

Figure 4. ΔN_2 values (green line) and ΔO_2 values (blue line) measured on the VOS "Finnmaid" from 29th of June 2023 during the high productive phase of a cyanobacterial bloom. The distance is indicated from Helsinki.

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Transport of total alkalinity from Vistula River to the Baltic Sea – seasonal and interannual variability (2016-2023)

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1. Introduction

In the Baltic Sea, the understanding of the Ocean Acidification mechanism requires knowledge of not only the atmospheric forcing but also the buffer capacity of seawater. The latter, as expressed by total alkalinity (A_T; defined as an excess of proton acceptors over proton donors), can be highly variable in space and time which makes the functioning of the marine CO_2 system substantially different from what is known for the open ocean (Kuliński et al., 2017; Dickson et al., 2007). The Baltic Sea is one of the largest brackish water bodies, with a mean surface salinity of about 7 in the central part, which clearly shows the predominant role of the freshwater component in shaping the chemical composition and properties of the Baltic surface water. However, the knowledge about the role of freshwater input in shaping the A_T fields and thus also pCO_2 and pH variability in the Baltic Sea remains still insufficient. Therefore, the main goal of this study was to identify long-term trends and seasonal variability of total alkalinity concentrations and loads from continental rivers to the Baltic Sea. For our study area, we chose the Vistula River - the largest river draining the continental part of the Baltic Sea catchment that is rich in limestone and thus can be an important source of bicarbonate and carbonate ions to the central Baltic Sea.

2. Material and Methods

Samples are collected biweekly (since 2016, up to now) at the station located in the lower section of the Vistula River in Kiezmark - 11 km inland from the mouth (Figure 1).

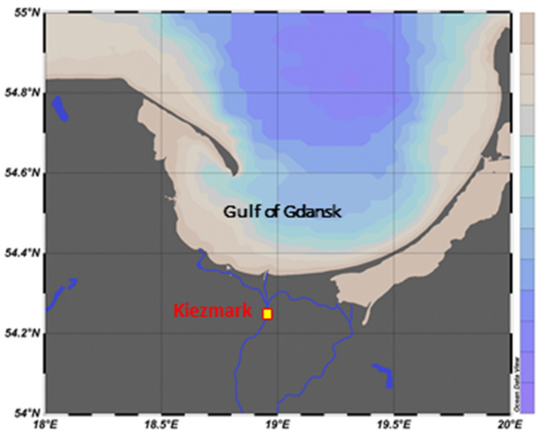

Figure 1. Sampling station

Although this study focuses on A_T specifically, sampling, performed according to the commonly used procedures by Dickson et al. (2007), includes also S, T, dissolved inorganic carbon (DIC), particulate inorganic carbon (PIC), and pH. Additionally, the study is supported with the water flow data obtained from IMGW. All the chemical analyses are performed at IO PAN based on the methods listed below:

- A_T is measured using a precise open-cell potentiometric titration system designed by Prof. Andrew Dickson (University of California San Diego).
- DIC measurements are performed using the Apollo SciTech system equipped with Li7815 CO_2 detector.
- PIC is determined from the double analysis as a difference between total and particulate organic carbon using the Elemental Analyzer Flash EA 1112 Series combined with an Isotopic Ratio Mass Spectrometer Delta V Advantage (Thermo., Germany).

3. Results

We observed a significant seasonal variability of total alkalinity, with the lowest mean concentration during the summer season (2790±272 µmol/kg in July) and the highest in winter (3812±200 µmol/kg in December; Figure 2a).

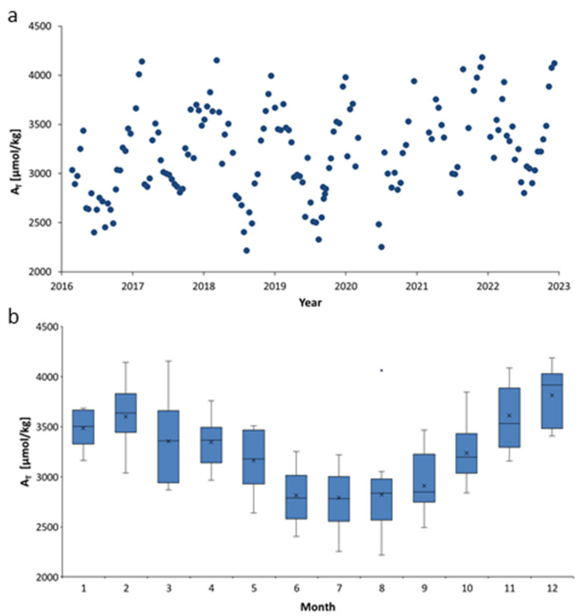

Figure 2. Seasonal (a) and daily (b) variability of total alkalinity in the Vistula River.

During the 8-year monitoring period, values ranged from 2217 to a maximum of 4186 µmol/kg (Figure 2b). This indicates that the Vistula River is an important source of A_T to the Baltic Sea, as the obtained values strongly exceed this measured in the Baltic Proper (A_T oscillates around 1650-1800 µmol/kg; Bełdowski et al., 2010). Moreover, the dataset revealed a clear increasing trend of A_T concentrations of 46 µmol kg^{-1} $year^{-1}$.
Based on alkalinity concentrations and water flow, we also estimated monthly loads of A_T from the Vistula River to the

Baltic Sea, which ranged from about 2.6 to 15.9 x 10^9 mol, with the lowest loads being observed in summer and the highest in winter and early spring. Although a clear long-term trend has been identified for A_T concentrations, it was impossible to detect such for A_T loads due to high interannual variability in water flow.

4. Conclusions

The obtained results, based on an 8-year time series, provide valuable insights into the role of freshwater input in shaping the total alkalinity in the coastal Baltic Sea. Moreover, a clear seasonal pattern in A_T concentrations has been identified, which in turn has a great potential to contribute to the development and improvement of biogeochemical models.

5. What next? New project - ALKALIS

The results obtained from the monitoring brought a lot of information, as well as scientific questions about the role of continental rivers in shaping the carbonate system in the Baltic Sea. We hope the research planned in the new project ALKALIS (more information below) will provide answers to at least some of them.

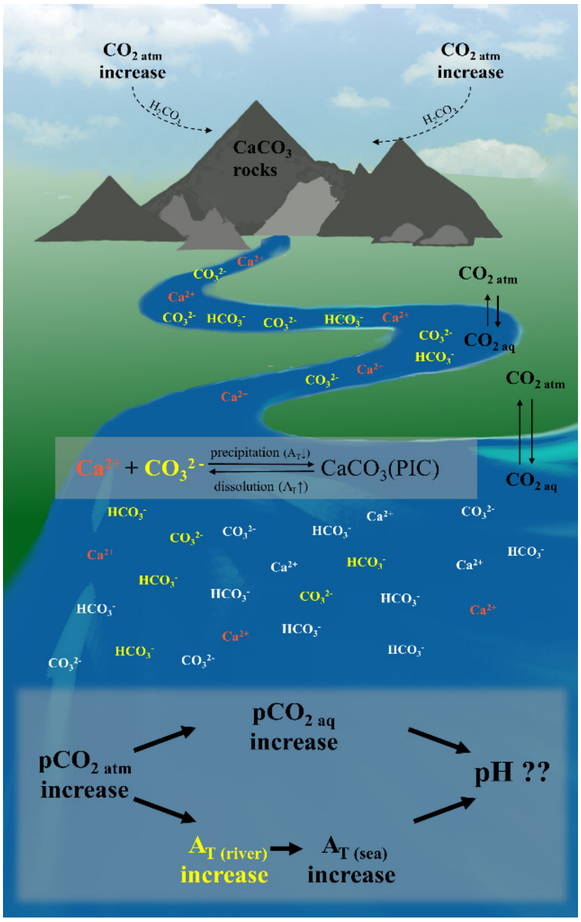

Figure 3. Conceptual scheme showing the scientific problem to be solved in the project (prepared by L. Bromboszcz).

Title: Transport and transformation of total alkalinity from continental rivers – the missing components for understanding pH variation in the Baltic Sea.

Project funded by National Science Center, Poland (UMO-2023/49/B/ST10/02690).

Project Leader: Institute of Oceanology Polish Academy of Science (PI: Karol Kuliński)

Partners: Institute of Meteorology and Water Management - National Research Institute (IMGW) and Adam Mickiewicz University in Poznań.

Duration time: 2024-2028 (48 months)

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Marked recent declines in boron in Baltic Sea cod otoliths – a bellwether of incipient acidification in a vast hypoxic system?

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1. Introduction

Ocean acidification is spreading globally as a result of anthropogenic CO_2 emissions, but the Baltic Sea is relatively well-buffered by alkalinity (AT) increase. Nevertheless, pH in the Baltic Sea is highly variable in space and time with its recent tendency to decline at greater depths (Kuliński et al., 2022). This decline is associated with the ongoing eutrophication and higher vertical export of organic matter that also leads to worsening deoxygenation (Kuliński et al., 2022).

The population of the eastern Baltic cod (Gadus morhua, hereafter referred to as EBC) has been severely impacted by a number of factors, including past overfishing, hypoxia, parasite infections, and seal predation, leading to reduced growth and age at maturity (Eero et al., 2020). Recent studies that reported links between hypoxia exposure and EBC body condition have relied on the measurement of trace elements in fish otoliths (ear stones). Briefly, otoliths, the calcified structures that form part of the hearing/balance system in teleost fishes, are sectioned with a diamond saw, polished smooth, and then analyzed by ablating microtransects along the major growth axis and analyzing by using mass spectrometry. The resulting elemental data are lifetime concentration histories, being incorporated at the time of exposure. The use of otolith manganese to track hypoxia exposure is one of the emerging biomarkers in fisheries ecology (Reis-Santos et al., 2022). Recently, with acquisition of more sensitive instrumentation, we began to experiment with quantifying elements having sub-ppm concentrations in cod otoliths, including the trace element boron. Boron is noteworthy because it is an indicator of salinity. Specifically, boron in seawater generally correlates with salinity (Kuliński et al., 2017) predominantly in the form of weak boric acid (H_3BO_3) at standard seawater salinity (35 PSU) and pH of 8. However, the dissociated anion borate $B(OH)_4^-$ is positively, nonlinearly correlated with pH (Yu and Elderfield, 2007).

In this study (Limburg et al., 2023), we explored the extent to which otolith B: Ca varied through time and whether its values were correlated with pH, salinity, or other otolith-derived values that are proxies for environmental or physiological factors. Specifically, in our study we posed the following questions:

1. What are the temporal trends in otolith boron (as B:Ca ratios)?
2. How do B:Ca ratios correlate with trends in water chemistry, particularly salinity and pH?
3. If pH declines are associated with hypoxia, do we see a correlation of B:Ca with our hypoxia proxy, Mn:Mg?
4. If there are any physiological influences, do we see a correlation of B:Ca with elemental ratios known to be physiologically controlled, e.g., P:Ca?

2. Material and Methods

Otoliths of Baltic cod (N=156) were obtained from both fishery-independent and fishery-dependent surveys conducted by the Swedish Fisheries Board and its successor, the Department of Aquatic Resources, Swedish University of Agricultural Sciences. Fish were collected from ICES subdivisions (SD) 24, 25, 27, and 28 (Fig. 1), spanning the period 1988–2021.

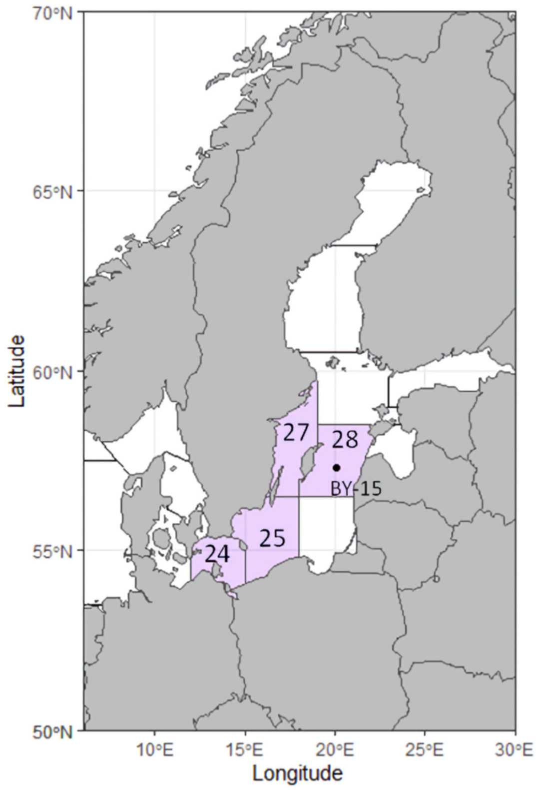

Figure 1. Map of the Baltic Sea region, showing the ICES subdivisions from where otoliths were sampled in purple. The black dot marks water monitoring station BY-15, located in the Gotland Deep.

Chemical analyses were performed with laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) by the Analytical and Technical Services group at the College of Environmental Science and Forestry, State University of New York. Otoliths were ablated with a 192 nm laser ablation unit (Teledyne Cetac Excite 2) along transects as illustrated in Fig. 2; the ablated material was transported via an Ar–He carrier gas mixture into a Thermo iCAP TQ plasma mass spectrometer, where isotopes were quantified.

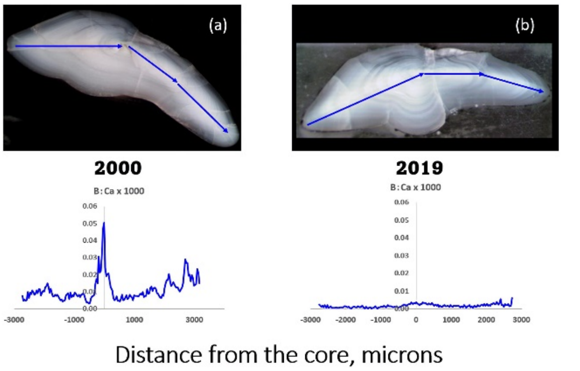

Figure 2. Comparison of transect analyses of boron (in its ratio to calcium, mass basis) in sectioned Baltic cod otoliths. (a) Fish captured in March 2000, age 3, length 46 cm. (b) Fish captured in November 2019, age 2, length 40 cm. Both came from the same part of the Baltic Sea (ICES subdivision SD25, see Fig. 1)

Water property data (temperature, salinity, dissolved oxygen, pH, and total alkalinity were downloaded from the Swedish Meteorological and Hydrological Institute's database, SHARKWeb (https://sharkweb.smhi.se/). Station BY-15, Gotland Deep, was selected as being representative of the central Baltic (Fig. 1) and having one of the longest and most detailed time series. We selected depths that corresponded to where cod had been found in fishery-independent surveys. Between 1985 and 1995, we averaged water data from 30 to 60m and from 1996 onward, between 40 and 75 m. Annual mean water values were computed and matched to corresponding otolith chemistry data (annual means of element : Ca data parsed to calendar years as described above).

3. Results

Examination of the long-term time series of data from station BY15 shows that while temperature generally increased, the other water variables showed very nonlinear patterns. Alkalinity is in part a function of salinity; dividing AT by S produces a time series showing a dramatic state change around 1990, particularly in the water layers occupied by cod. Despite the increasing AT, pH has declined more or less monotonically at midwater depths (40–75 m). Over the period 1985–2019, box plots of B:Ca by year show a pattern of increase toward a maximum, albeit with great variation, in the late 1990s, followed by gradual decline (Fig. 4). Visual comparisons with salinity and pH show that neither explain all the variation in B:Ca, but since 2000, pH and B : Ca have both trended downward whereas salinity has increased.

4. Conclusions

Baltic cod showed variable patterns of otolith B:Ca over a 35-year period, with maximum values in the late 1990s, a gradual decline in B:Ca thereafter, and an all-time low in 2019–2020. These trends are imperfectly related to water chemistry data but showed strong correlations that varied by decade. Otolith B:Ca ratios and relationships in the 2010s were suggestive of environmental changes in pH and total alkalinity that could be coupled to deoxygenation.

Undoubtedly, some of the relationships found could be due to the choice of samples, and a more focused study might select otoliths from areas where trends in acidification are clear. Future work could also examine otoliths from other species, as well as determine, if possible, the form of boron (borate or boric acid) taken up by otoliths. Complex interactions notwithstanding, we suggest B:Ca in cod otoliths as a prospective variable in the palette of important and available tools used to look into the environmental changes through the lens of otolith chemistry.

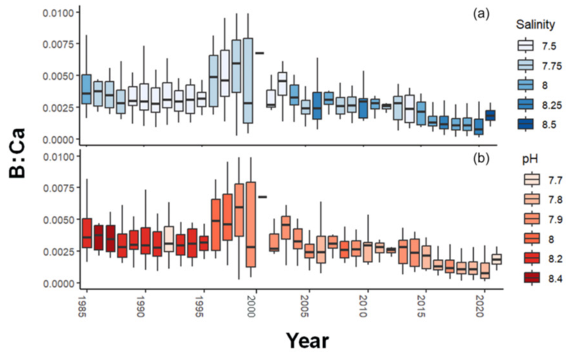

Figure 4. Annual B:Ca in Baltic cod otoliths, colored by salinity (a) and pH (b). Boxes represent the upper and lower quartiles, vertical lines show the maximum and minimum values, and the horizontal lines are the median values. Salinity has been increasing and pH declining. Since the late 1990s, there has been a general decline =in B : Ca.

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Dissolved organic matter cycling in the southern and central Baltic Sea: results from sediment porewater sampling and incubations

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1. Abstract

Recent studies suggested that sediment pore waters may serve as a source of bioavailable DOM to the overlying water column, which may stimulate microbial activity in the near bottom waters. In this study, we aim to assess the bioavailability of DOM, released by sediments, and whether it may stimulate an increase in heterotrophic cell number. For this, we conduct the measurements of dissolved organic carbon (DOC) and DOM molecular weight and optical properties, such as chromophoric (CDOM) and fluorescent (FDOM) DOM, from the sediment pore waters of the Baltic Sea Deeps and in the water column in order to evaluate the initial supply flux (return flux) to the bottom waters and provide essential insights on the starting composition of DOM. We combine those measurements with the temporal changes of DOC, CDOM and FDOM during ex-situ incubations of the sediment cores with overlying water to infer quantitative and qualitative transformations of DOM during the incubation time. We discuss those data in combination with microbial abundance as a proxy for sedimentary DOM bioavailability.

2. Study area and Incubation setup

Our sampling was carried out in three distinct depositional areas of the central and southern Baltic Sea, which are influenced by either permanent or temporary oxygen deficit, that is, Bornholm Basin (54.9-55.7°N/15.0-16.5°E), Gdansk Basin (54.3-55.0°N/18.5-20.0°E), and eastern Gotland Basin, further referenced to as Gotland Basin (56.0-57.5°N/18.5-21.0°E) (Fig.1). Pore-water samples were collected using Rhizon samplers (0.2µm pore size; Rhizosphere Research Products B.V.) immediately after recovery of sediment cores by GeMax gravity corer (Winterhalter, 2001) during six cruises from 2020-2021 onboard of RV Oceania (Poland).

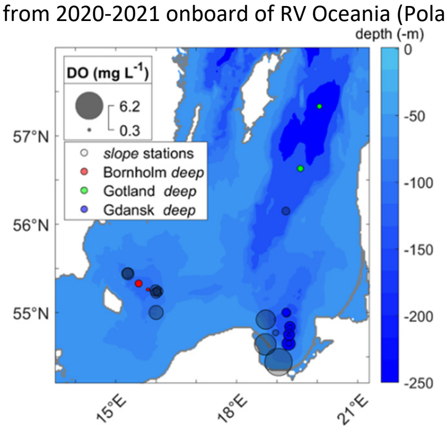


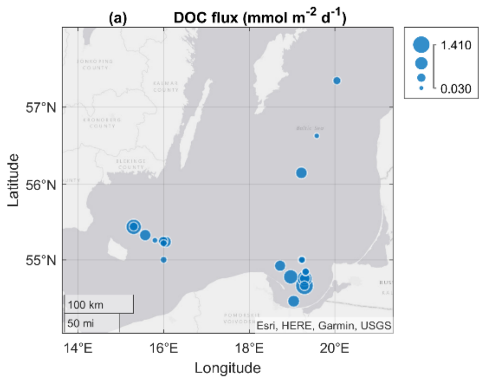
Figure 1. Study area Sampling locations are presented as circles, i.e., Bornholm, Gdansk, and Gotland deep stations are marked in red, blue, and green color, respectively. Grey circles represent reference stations referred to as slope stations. The size of circles is referred to the DO concentration (in mg L-1) measured in the near-sediment water at the time of sample collection. Baltic Sea bathymetry and landmark files were obtained from www.io-warnemuende.de (i.e., iow2_z_water and iow2_landmask) and are marked as the background color and grey line on the figure.

We referred to as "deep" stations (or "deeps") to stations that were deepest and were characterized by the minimal concentrations of dissolved oxygen (DO) in the near-sediment waters. Shallower stations, which obtained slightly higher to higher ambient DO, we referred to as "slope" stations (or "slopes").

Furthermore, six ex-situ incubations were performed for stations located at the three *deeps* (3x) in Spring and (3x) in Fall 2022 during three cruises onboard of RV Oceania (Poland) and one cruise onboard of RV Aranda (Finland). For this, recovered by GeMax gravity corers were incubated enclosed gas-tight with overlying bottom water at 8°C in the dark. Regular subsampling of the overlying water was performed over the course of 60-72hrs of incubation.

3. Results and discussion

Although highly variable fluxes of DOM (Fig.2, a, b), did not



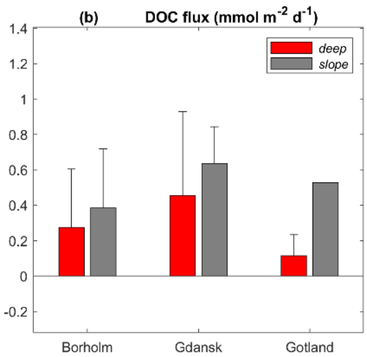


Figure 2. Sediment DOC release DOC diffusive fluxes (JDOC) in the investigated area (a) and mean flux distributions in Bornholm, Gdansk, and Gotland deep (red) and slope (grey) stations (b). The error bars represent the standard deviation of the JDOC in the corresponding area.

allow us to infer statistically significant differences between investigated areas, apparent differences in sediment release (Fig.2 b) and in the pore water DOM quality (Fig.3 a, b, c) supported the notion that microbial utilization of organic matter and the resulting DOM quality (particularly within pore waters) is largely co-determined by the characteristics and quality of the settling organic matter (e.g., Le Moigne et al., 2017).

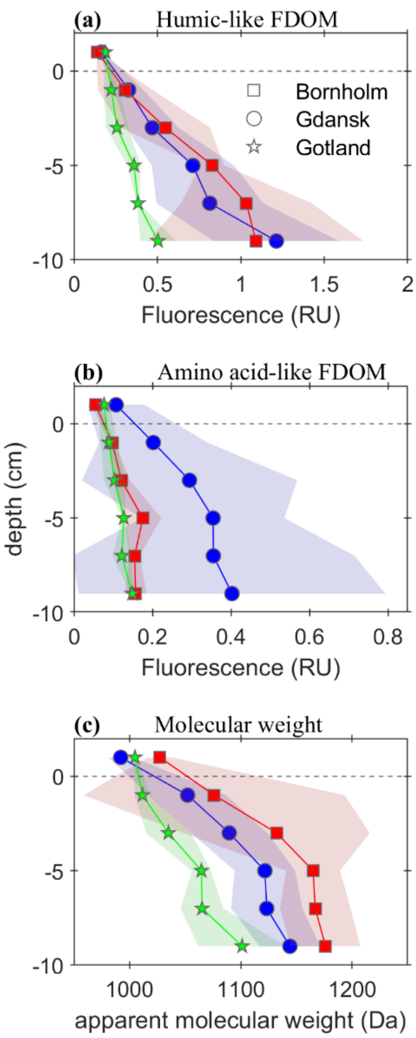


Figure 3. FDOM and AMW pore water distribution in Bornholm, Gdansk, and Gotland Deeps. Mean depth distribution of FDOM intensity in Raman Units (RU) components resulted from PARAFAC analyses (a, b) and weighted averaged apparent molecular weight (c). The colored lines present the mean value calculated for all stations referred the corresponding deeps. The shaded areas of the corresponding color represent the standard deviation of the average estimates. The dotted grey line represents the sediment surface.

The amino acid-like DOM fraction (Fig3.b) of low molecular weight (not shown) accumulated with depth, suggesting encapsulation of bioavailable amino acid-like oligomers by humic substances within pore waters (Tomaszewski et al, 2011), and therefore, indicating potential supply source of labile DOM to the microbial communities in the overlying waters by sediments (also see Reader et al., 2019).
During our incubation experiments, we noticed seasonal variability in the starting DOM composition (not shown), coinciding with the magnitude of microbial abundance response (Fig.4). Despite mentioned variability, microbial communities seemed to be stimulated by the sediment release of DOM, as the net number of heterotrophic bacteria increased in all the incubations (Fig. 4)

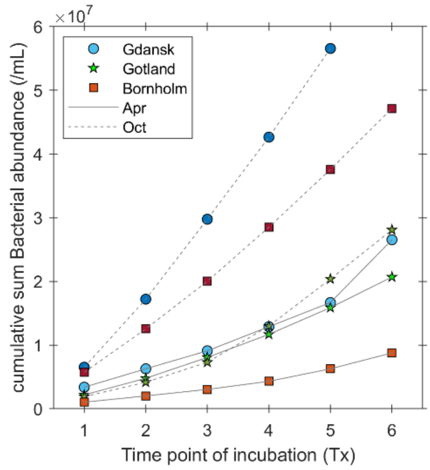


Figure 4. Cumulative sum of abundances of heterotrophic bacteria at the ex-situ incubations. Time points (Tx) represent the time identification numbers of sampling, where T1=2hrs after the start of the incubation and T6=72hrs after the incubation setup. Light marker colors and solid lined represent the bacterial abundancies measured in incubations that took place during Spring cruises at Gdansk (blue circles), Gotland (green pentagrams) and Bornholm (red squares) deeps. Dashed lines and darker symbols are stated for incubations in the corresponding areas during Fall cruises.

This agreed with the changes in the DOM optical properties development in the incubations (not shown), supporting the idea that DOM released from sediments serves as a substrate for bottom water heterotrophic communities to respire.

5. Funding

Research leading to these results has received funding from the Norwegian Financial Mechanism 2014-2021 project DOMUSe (2020/37/K/ST10/03018) granted to ANL and the Polish National Science Foundation (NCN) OPUS17 project DiSeDOM (2019/33/B/ST10/01232) granted to PK, it was partly supported also from NCN project PROSPECTOR (2019/34/E/ST10/00167) granted to KK.

6. Data availability

The study on the sediment DOM release and pore water DOM properties is submitted to *Nat Sci Rep* under the title "Porewater Dissolved Organic Matter: Diagenetic Alteration and Sediment Release in the Baltic Sea" and the corresponding data are registered at PANGAEA® (both in review). The data from incubation experiments are under preparation.

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Baltic Sea oxygen dynamics under reduced nutrient input scenarios

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1. Introduction

World Ocean's oxygen loss is a growing environmental problem that affects both the open ocean and the coastal zones and leads to the expansion of hypoxia (dissolved oxygen concentrations less than 2 ml O_2 l^{-1}) and anoxia (the total absence of dissolved oxygen in the water). Coastal zones worldwide are most sensitive to changes in external forcing. They are experiencing an increase in hypoxia, connected to climate change and elevated nutrient input from land (Breitburg et al., 2018). One example of such a coastal system is the Baltic Sea.

The Baltic Sea is a semi-enclosed sea located in Northern Europe. Due to its natural features, e.g., limited connection to the World Ocean, which leads to the long residence time (around 30 years) or positive water balance across the catchment area, which results in the estuarine circulation with permanent halocline, the Baltic Sea is naturally prone to hypoxia (Leppäranta and Myrberg, 2009).

Hypoxia in the Baltic Sea was already present long before modern times, which is visible in the, e.g., sediment profiles (van Helmond et al., 2018). However, the hypoxic area in the Baltic Sea has been rapidly extending during the last few decades due to the elevated nutrient loads from land (Carstensen et al., 2014). To mitigate the Baltic Sea eutrophication, the Helsinki Commission (HELCOM) introduced the Baltic Sea Action Plan (BSAP) in 2007 (HELCOM, 2007), which introduced the Maximum Allowable Input (MAI) of phosphorus and nitrogen for each sub-basin of the Baltic Sea. The BSAP was last time revised in 2021 (HELCOM, 2021). Despite the continuous reduction of nutrient loads since the 1980s, no significant decrease in hypoxic area in the Baltic Sea has been observed so far. Moreover, the structure of the oxygen budget has been consistently changing since the 1940s, with the main pattern of moving the oxygen consumption from the sediments to the water column (Naumov et al., 2023). The delayed Baltic Sea response to reduced nutrient input is linked to the "vicious circle" of the Baltic Sea eutrophication (Vahtera et al., 2007).

The question of how the Baltic Sea would react to further reduced nutrient loads from land and whether it is possible to return the system to its initial state is still actual. To answer this, we extend the oxygen budget studies started by Naumov et al. (2023) to the case of reduced nutrient forcing.

2. Materials and methods

To study interannual oxygen dynamics of the Baltic Sea under reduced nutrient input, we used a 3-dimensional coupled Modular Ocean Model (MOM) (https://www.gfdl.noaa.gov/mom-ocean-model) – Ecological ReGional Ocean Model (ERGOM) (ergom.net). MOM simulates ocean dynamics by solving primitive equations of motion. ERGOM models biogeochemical cycles in the ocean. This includes the cycles of nitrogen, phosphorus, carbon, oxygen, and hydrogen sulfide. Phytoplankton in ERGOM is split into three functional groups: large phytoplankton, small phytoplankton, and cyanobacteria, which is only limited by phosphorus. The three nautical miles setup of the model was applied in this study. More details on the setup, including validation, can be found in Naumov et al. (2023).

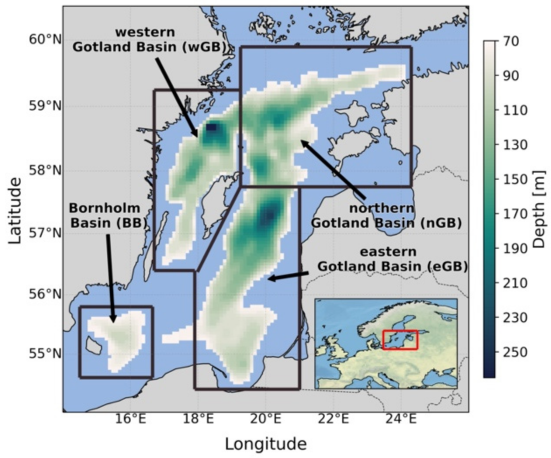

Figure 1. Model topography at a depth of 70 meters and the four defined sub-basins (black lines).

Four regions were considered in the study. They include the Bornholm Basin (BB) and the three areas of the Gotland Basin (eastern Gotland Basin, or eGB; northern Gotland Basin, or nGB; and western Gotland Basin, or wGB). All four studied sub-basins extended vertically from 70 meters down to the bottom. For more details, see Figure 1.

In total, three model experiments were analyzed. The reference run (ref) is the run that has already been presented in Naumov et al. (2023). It employs the observed nutrient loads. In the two nutrient reduction scenarios – BSAP and 0.5 BSAP, the yearly input of N and P was assumed constant and corresponds to the BSAP MAI and half of BSAP MAI, respectively. The initial conditions for all biogeochemical variables were taken from the reference simulation. Neither initial conditions for other variables nor atmospheric forcing were modified. All three simulations spanned 71 years (1948-2018 for reference simulation and 2019-2089 for nutrient reduction scenarios).

3. Results

Under both nutrient reduction scenarios, the Balt Sea demonstrated pronounced reoxygenation, leading to the oxidation of the previously deposited organic material and H_2S and the reduction of hypoxic and, especially, anoxic areas. Under the more drastic 0.5 BSAP scenario, the reoxygenation of the Baltic Sea happened faster.

Figure 2 shows the oxygen consumption in the water column and the sediments and oxygen supply by the advection and diffusion in the four studied sub-basins. It is visible that the remote basins (nGB and wGB) demonstrate a pronounced reaction to the changed forcing. The pattern there is the opposite of the previous pattern observed during the reference run, namely, the shift of oxygen consumption from the sediments to the water column.

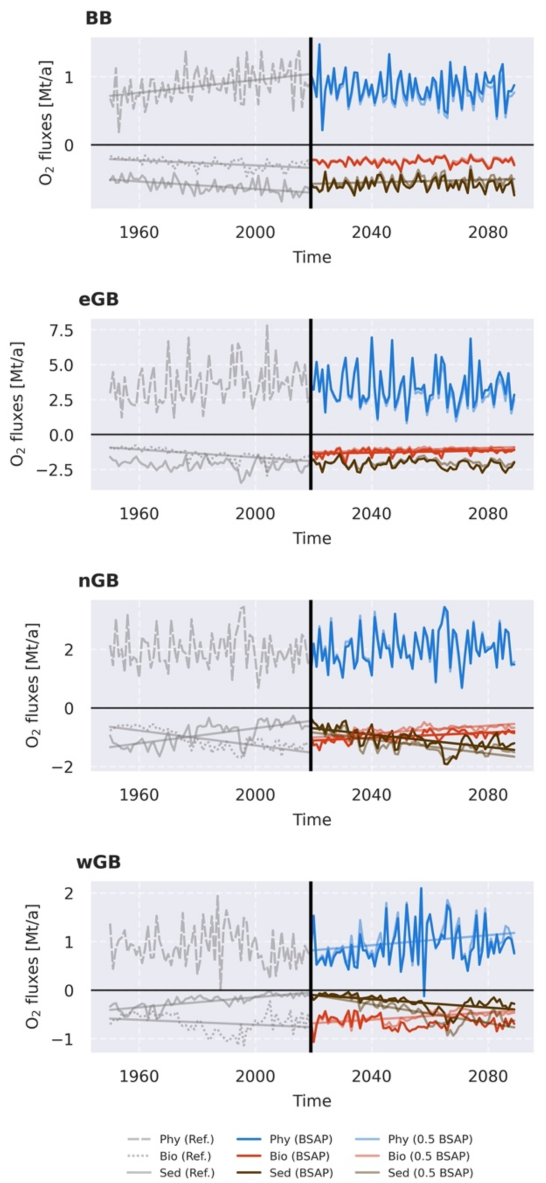

Figure 2. Oxygen consumption in the water column and sediments (bio and sed, respectively) and oxygen supply via advection and diffusion (phy). Grey lines represent reference simulation. Colored lines represent the BSAP (vivid colors) and 0.5 BSAP (translucent colors) scenarios. Only statistically significant linear trends with the 95% confidence level are shown.

In the nGB, under both scenarios, oxygen consumption in the sediments exceeded oxygen consumption in the water column after 30 years of the simulation, and more oxygen was consumed in the sediments than in the water column at the end of the study period. In the wGB, the oxygen consumption in the sediments becomes comparable to the oxygen consumption in the water column after 50 years of simulation. It exceeds it at the end of the simulation only under the 0.5 BSAP scenario. In addition, in the wGB, the positive trend in the advection of oxygen is observed, indicating improved ventilation by the inflows. The same general pattern of oxygen consumption applies to the eGB and BB but is less visible since those sub-basins lost less oxygen compared to the nGB and wGB. Since the consumption in the nGB at the end of the study period has returned to its initial values (the beginning of the reference simulation), it can be concluded that the system is still reversible and no noticeable hysteresis effect is observed, at least on the timescale of the study.

To examine how important nutrient load reduction is, we applied an EOF analysis to the 3-dimensional spatial-temporal matrix of annual mean anomalies of oxygen consumption by different groups of processes (not shown). The first three EOFs explain around 90% of the variability. The first EOF, associated with nutrient reduction, explains 56% of the variability. This makes nutrient reduction a necessary measure to improve the oxygen conditions in the Baltic Sea.

4. Conclusions

Under both BSAP and 0.5 BSAP scenarios, the Baltic Sea demonstrated visible reoxygenation within the simulated 71 years. No visible hysteresis effect was observed, at least within the simulated time. Nutrient loads reduction governs the interannual variability of the oxygen sources and sinks in the Baltic Sea.

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Seasonal changes in chlorophyll *a* concentrations, phytoplankton biomass and primary production in the Baltic Sea based on monitoring and glider data.

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Phytoplankton respond rapidly to changing environmental conditions, influencing energy and carbon transfer to higher trophic levels, removal of carbon dioxide from the atmosphere and biogeochemical cycles. Phytoplankton are recognized as an important bioindicator of changing environmental conditions by different legislations, including the Marine Strategy Framework Directive. Ongoing monthly monitoring programs which estimate primary production are logistically difficult, expensive, time-consuming and suffer from the low spatial-temporal resolution. Satellites also provide these estimates but are limited to the surface mixed ocean so they can underestimate the contribution of deep chlorophyll maxima to primary production (PP). We combined data collected at the BOOS BY5 station with sustained observations from an ocean glider for a full annual cycle in the Bornholm Basin. We showed that gliders can provide information at very small spatial and temporal scales across long periods. However, it needs to be supplemented by key *in situ* information such as phytoplankton biomass (PB), community composition and photosynthetic yield parameters collected by SMHI within the Swedish National Monitoring Program to provide a deeper understanding of ecosystem functioning. These new estimates revealed a decoupling between chlorophyll *a*, PB and PP was found in the southern Baltic Sea. Higher chlorophyll *a* concentration was measured in early spring (March, 3.7 mg m^{-3}) when PP was lower, while this pattern was reversed in summer. This decoupling is explained by variability in the light-saturated maximum rates normalized to chlorophyll a concentration ($P^{B}{}_{max}$) which correlated to phytoplankton size-structure. In summer, under stratified conditions, a Deep Chlorophyll Maximum (DCM) occurred (19.6 mg m^{-3}) and contributed disproportionately to the total annual production. Our project demonstrated that gliders could improve existing monitoring in the Baltic Sea by revealing features hidden to ships and satellite at the current resolution but require continued collection of *in situ* data.

Evidencing the Impact of Sea Ice on Eutrophication in the Baltic Sea using new Eutrophication Indicators

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1. Introduction

The Baltic Sea, a unique semi-enclosed brackish sea with a large-scale gradient from a temperate marine to a subarctic climate, is vulnerable to global change. Eutrophication, caused by excessive nutrients, poses a significant threat to the sea's biodiversity (HELCOM, 2018a). This phenomenon leads to elevated algal blooms, plant growth, increased turbidity, oxygen depletion, and altered species composition, ultimately reducing the ecosystem's resilience, and increasing its vulnerability to climate change (HELCOM, 2021). The Baltic Sea faces substantial anthropogenic pressure, highlighting the need for a comprehensive understanding of its ecosystem processes. Despite efforts to reduce nutrient loads, the ecosystem's recovery has been slow, with persistent deep-water anoxia and cyanobacterial blooms (Elmgren et al., 2015; Reckermann et al., 2022). Climate change exacerbates eutrophication, further threatening the sea's health. Therefore, it is essential to address these factors and implement sustainable management initiatives to protect the Baltic Sea.

Sea-ice conditions demonstrate the strongest correlation with summer chlorophyll-a levels in coastal waters, highlighting the significant role of ice in shaping the trends of summer chlorophyll-a concentrations in the Baltic Sea (Vigouroux et al., 2021). Light and stratification are pivotal influences governing the phytoplankton spring bloom (Kari et al., 2018). Sea ice affects underwater light conditions by limiting the amount of light transmitted through the surface and modifying water mixing and nutrient circulation beneath the ice (Katlein et al., 2015). Furthermore, attenuation caused by snow cover on the sea ice significantly reduces underwater light. The albedo of freshly fallen snow can be as high as 0.9, whereas that of melting bare ice is only 0.4—considerably higher than that of the open sea (<0.1) (Vihma and Haapala, 2009). The seasonal ice cover plays a crucial role in establishing time frames for the growth of phytoplankton, the primary producer, thereby influencing the seasonality of ecological processes. The duration of the ice season in the northern Baltic Sea can extend up to 7 months (Vihma and Haapala, 2009; Siitam et al., 2017), with the maximum ice extent typically occurring in late February and early March (BACC II Author Team, 2015).

This study, conducted as a model experiment, delves into the impact of sea ice, a climate change indicator, on the marine ecosystem's capacity for nutrient consumption. Initially, the study assesses the potential effects of sea ice on marine eutrophication indicators outlined in the Marine Strategy Framework Directive Descriptor 5—namely, dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorous (DIP), chlorophyll-a (CHL), and bottom O_2. Subsequently, the investigation explores the influence of sea ice on the transition from diatom prevalence to dinoflagellate dominance in the Baltic Sea, utilizing the Dia/Dino index. To further evaluate the impact of sea ice on eutrophication a novel indicator, the Trophic Transfer Index (TTI), is employed. The TTI was recently proposed (Polimene et al. 2023) as a method to assess eutrophication by considering trophic fluxes instead of biogeochemical concentrations. More specifically, the TTI assumes that a given location is in healthy conditions if primary production is consistently transferred towards higher trophic levels. Areas affected by eutrophication are then identified where a mismatch between PP and zooplankton grazing is present.

The marine ecosystem is modeled using the GETM-ERGOM model (Macias et al., 2018; Pärn et al., 2021) from 1953 to 2017, and indicators are derived from the model outputs. The reference simulation (ICE) incorporates sea ice, while the comparative simulation (NO-ICE) without sea ice maintains identical meteorological conditions and terrestrial influences, such as nutrient inflow and river runoff, but does not include sea ice formation. This study aims to provide insights into the intricate relationship between sea ice dynamics and the eutrophication processes in the Baltic Sea ecosystem.

2. Methodology for Calculating the Ice Impact Factor

The "ice impact" on marine eutrophication indicators is computed as relative difference between the scenario without ice and the simulation with sea ice as reference. To track the temporal evolution of these relative changes, we initially calculated spatial averages for each indicator for both simulations over a 1-month period. Subsequently, we computed the temporal average over the entire simulation period and determined the relative differences ("ice impact factor") using the formula (ICE – NO-ICE)/ICE × 100.

3. Results

The sea ice exerted a substantial annual influence on the Baltic Sea ecosystem. In simulations comparing scenarios with and without sea ice, the average impact factor of ice was 15%, 8% and 9% on DIN, DIP and CHL, respectively, while on average oxygen concentration it was only 1%. Additionally, the average ice impact factor for the Dia/Dino index during the spring from 1953 to 2017 was 16%.

According to the calculated TTI values, nearly half of the Baltic Sea's area was classified as a "no problem area" until the early 1970s (Fig 1). During this time, the ice factor was ~5%. However, thereafter (and up to about 2015), there was a rapid decrease of no-problem areas, suggesting a substantial increase of eutrophication in the basin. During this period, the sea ice factor reached -60%. Starting from 2015, the percentage of "no problem areas" increased again, signaling a reduction in eutrophied regions. Likely as the result of implemented nutrient load reduction measures, the proportion of regions with a healthy ecosystem in the Baltic Sea has increased from 15% to 30%.

Figure 1. Ice impact factor in TTi and "no problem" area, as TTI>0.7. Black dots represent the results of simulations with sea ice (ICE), whereas '+' symbols represent the results of simulations without sea ice (NO-ICE).

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Acidification in the Baltic Sea: Science, monitoring perspectives, and future governance within HELCOM

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1. Scientific Background

Rising atmospheric CO_2 concentrations in connection to increasing temperatures foster the increase of the partial pressure of CO_2 (pCO_2) in surface waters and consequently, ocean acidification. This phenomenon, sometimes referred to as "the evil twin of global warming" or "the other CO_2 problem" is well understood for the open ocean and predictable under a given future climate (and atmospheric CO_2) scenario (Doney et al., 2009), leading to a decrease in pH in open ocean surface waters of ~0.002 a^{-1} over the last 3 decades (PMEL, 2024). In coastal waters like the Baltic Sea, other processes affecting the acid-base dynamics of seawater complicate or even impede such predictions (e.g. Carstensen and Duarte, 2019). For the Baltic Sea, it has been shown that an increase in alkalinity partly compensates atmospheric-driven acidification (Müller et al., 2016). Other drivers such as eutrophication and oligotrophication, as well as the input of organic bases, might interfere as well (e.g. Kuliński et al., 2017). As an example, pH increased in the surface waters of the major basins of the Baltic Sea from the 60th to the mid-80th (Carstensen and Duarte, 2019, Kuliński et al., 2022), likely as a result of eutrophication. This trend could be revealed from sparse data of moderate quality, mainly due to the fact that the signal is way stronger (and in opposite direction) than the expected trend due to rising atmospheric CO_2 levels. For the future, however, model results suggest that "regular" acidification due to higher atmospheric CO_2 will be the dominant driver (Gustafsson and Gustafsson, 2020). The threat of future acidification on marine biota in the Baltic Sea is hard to predict, as responses and thresholds vary strongly between species, and potential effects have to be evaluated in the framework of various other stressors (e.g. Gustafsson et al., 2023 and references therein).

2. Monitoring acidification in the Baltic Sea

Detecting long-term acidification trends in the Baltic Sea is a challenging task. Large productivity and a low and spatially varying buffer capacity lead to large seasonal variability in pH, requiring precise long-term stable measurements at high spatio-temporal resolution. High quality measurements of pH are further hampered by the sensitivity of electrochemical measurements to salinity, while the more precise spectrophotometric method has until recently not been applicable for brackish waters (Müller and Rehder, 2018). Since a few years, these hurdles have been overcome, and high resolution long-term traceable measurements of pH in the Baltic are scientifically possible and on the horizon of being operational (Müller et al., 2018, Müller and Rehder, 2018). Alkalinity measurements with high accuracy at the other hand are available since at least 1995, but a lack of data exists in the southern regions of the Baltic (e.g. Müller et al., 2016). Another access to operational long-term tracing of acidification in surface waters at very high spatiotemporal resolution is through the use of the infrastructure for pCO_2 measurements in the framework of the Integrated Carbon Observation System (ICOS) RI. While continuous measurements between Lübeck and Helsinki are operational since 2003 (SOOP FINNMAID), lines running from Umea to Lübeck and from Stockholm to Helsinki recently became part of the ICOS network.

3. Governance within HELCOM

Right in time for the 3rd HELCOM assessment of the Baltic Sea (HOLAS 3), an indicator report on acidification was drafted and *Acidification* was adopted as an *Element Indicator* (HELCOM, 2023). An element indicator is a new category of indicators within the HELCOM indicator scheme. It is meant to chronicle important processes, may not specifically address human activities, may not be specifically required as indicator of good environmental status, but offers important contextual information. The indicator report summarizes the main existing knowledge on acidification in the Baltic Sea. It builds an important stepstone towards a strategic approach to ocean acidification. The HELCOM Contracting Parties committed in the Baltic Sea Action Plan 2021 to the development of such a strategic approach, with first steps to be taken until 2025 under the remit of HELCOM WG GEAR.

With these boundary conditions, a growing interest in carbon system parameters, acidification indicators and consequences, and enhanced capacities for carbon system measurements in various countries in the pan-Baltic area, the time is right for a concerted observational framework on acidification. This concerted effort would largely support the commitment given in the BSAP 2021, but at the same time offers high potential for advancing our knowledge base on ecosystem functioning of the Baltic Sea.

4. Summary

This presentation will give an overview of some scientific aspects of past and present acidification in the Baltic, review the existing monitoring possibilities for biogeochemical parameters related to acidification, and the new interest on acidification within HELCOM. It will use this background to venture into potential opportunities and a vision for the scientific and strategic steps ahead.

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Seasonal investigation of nitrogen removal pathways in the Baltic Sea water column.

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1. Introduction

The Baltic Sea with an area of 415,000 km^2 (including the Kattegat) is the second largest brackish water globally (Leipe et al., 2011) and is well known for its hypoxic condition (Kulinski et al., 2021). The Baltic Sea has a limited shallow connection to the North Sea, resulting in little water exchange (Reissmann et al., 2009). It is also characterized by high river water flux and stratification. Due to the significant catchment area, the Baltic Sea receives high nutrient loads from land that enhance primary production and eutrophication (Savchuk, 2018). The strong vertical salinity gradient controls the mixing in the water column and the supply of oxygen to the bottom water layers. The presence of suboxic and anoxic conditions favors the main nitrogen (N) removal pathways, which are denitrification and anammox. Denitrification refers to the microbiologically mediated process in which nitrate (NO_3^-) is sequentially reduced to N_2, while anammox is the anaerobic microbiological process in which NO_3^- and ammonium ions (NH_4^+) are also converted to N_2. Both processes are primarily controlled by substrate availability and oxygen concentration (Bonaglia et al., 2014; 2016). In the Baltic Sea, these processes have not been fully understood. Spatial variability was not adequately covered, and still little is known about seasonal changes. We hypothesize that N removal processes change seasonally due to variable oxygen concentration, dissolved organic carbon (DOC) and substrate availability such as, NO_3^-, NO_2^-, and NH_4^+. The main objective of the study was to assess the seasonal removal rate of nitrogen from the water column in oxygen-deficient zones.

2. Methodology

Seawater samples were collected from the Gdansk Deep, Baltic Sea (at sites P1 and P1a) during the r/v Oceania Cruise in 2021 (January, April and September).

The water samples were collected at 6-10 depths using the Rosette sampler equipped with twelve 10 L Niskin bottles. The depths of the samples were selected based on the salinity and oxygen profiles. Temperature, salinity, and oxygen (O_2) concentration were measured in situ using a Sea-Bird Scientific SBE 911 Plus profiler.

The samples for nutrients, dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), alkalinity (A_T), and N_2/Ar measurements were collected directly from Niskin bottles. Samples for nutrient analysis were filtered (cellulose acetate filters with a pore size of 0.45 µm), collected in polyethylene bottles and stored at -20 °C for further analysis. The samples for the DIC analysis were transferred to the precombusted glass bottle and poisoned with 50 µL of $HgCl_2$. The samples for the DOC analyses were filtered with 0.45 µm MN GF-5 filters transferred to the precombusted glass bottle and acidified with 50 µL of $HCl_{conc.}$ (pH=2) to stop mineralization and remove carbonates.

Incubation experiments followed the method suggested by Dalsgaard et al. (2003, 2013) and Bonaglia et al. (2016) and were carried out at in situ temperature. In general, seawater was collected in 2 L glass bottle (without contact with the atmosphere) and placed inside a glove box (prefilled with helium). In the glove box, the low oxygen concentration (below 5 µmol/L) during the experiments was monitored by an oxygen-sensitive spot optode (PreSens precision sensing). In addition to the control experiment (in situ seawater), the additions of $^{15}NO_3^-$ to calculate denitrification rates and $^{15}NH_4^+$, $^{14}NO_2^-$ to investigate the anammox rate were used. After preincubation subsamples for nutrients, DIC, DOC, AT, and N_2/Ar from the glass bottles were collected and incubated at in situ temperature. The experiment was carried out for 24 h. (Jan.) and 108 h. (Apr., Sep.) depending on the oxygen consumption (monitored in vials dedicated for N_2/Ar measurement using spot sensors).

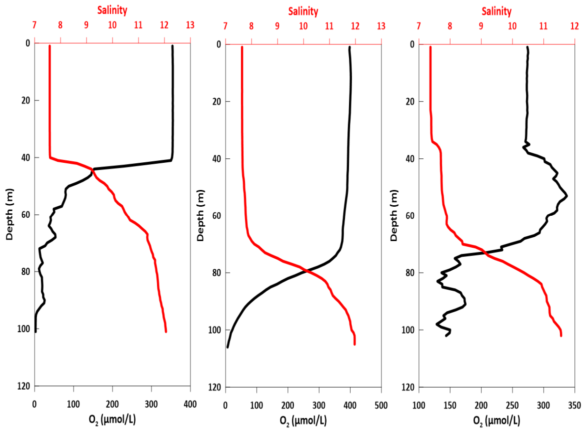

Figure 1. Salinity and oxygen (O_2) depth profiles at Gdansk Deep (P1).

N_2/Ar was measured using the membrane inlet mass spectrometry technique (MIMS) (Kana et al. 1994). Data were collected using QuikDATA software. The precision (coefficient of variation) was determined as <0.5% for N_2 and Ar concentrations and the concentrations of the concentrations of the concentrations of dissolved gases were assumed to be of the order of 0.1%. Nutrient concentrations in seawater samples were determined using the SEAL AA500 AutoAnalyzer (Seal Analytical) applying standard photometric methods (Grasshoff, 1983). The precision for nutrients NO_3^-, NO_2^-, NH_4^+ and PO_4^{3-} was 0.7%, 1.1%, 0.6% and 0.5%, respectively. AT was measured by precise potentiometric titration using a semiautomatic total alkalinity analyzer (Dickson et al., 2007). The methodology used was verified using certified reference material (Andrew Dickson Laboratory, San Diego, USA). The DOC analysis was measured on a TOC-L analyzer (Shimadzu) using the high temperature (680 °C) oxidation method with a Pt catalyst. The DIC analyses were performed based on the infrared detection of CO_2 formed during the acidification of a seawater sample (module for inorganic carbon analysis analysis analysis in TOC-L, Shimadzu). The methodology for the DIC and DOC measurements was checked using certified reference material (seawater from Andrew Dickson Laboratory, San Diego, USA) and provided satisfactory accuracy and precision.

3. Preliminary Results

During all sampling campaigns, salinity increased from 7.4 to 12 PSU while oxygen concentration decreased from 401.6 to 2.4 µmol/L (Figure 1). The halocline, depending on the season, was located at different depths. Below the halocline, we observed an increase in excess nitrogen concentration. The excess nitrogen concentration is an anomaly of the N_2/Ar ratio at equilibrium with the atmosphere (N_2/Ar saturation with in situ temperature and salinity) and the measured ratio. The highest excess N_2 concertation was observed in winter. The observed increase in excess N_2 concertation was most probably due to 1) water column denitrification and 2) accumulation of N_2 over time due to mixing with different water masses and diffusion from the sediment (Sivasamy et al., unpublished data). In terms of the incubation experiments, we observed changes in concertation of all investigated parameters over time such as increase of A_T, N_2, DOC, DIC and decrease of NO_3^- and NH_4^+. The results of the incubation experiments are still under interpretation; therefore, it is still unclear if the rates were significantly different seasonally.

4. Acknowledgements

The results were obtained within the framework of the statutory activities of the Polish Academy of Sciences Institute of Oceanology and the research project: 2019/34/E/ST10/00217 funded by the Polish National Science Centre. The authors thank the crew of r/v Oceania.

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Decoding Trends: Coastal Water Darkening in the Gulf of Riga with In-Situ, Model, and Remote Sensing Data Analysis

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1. Context and environmental dynamics

The light conditions play a critical role in shaping the freshwater and marine ecosystems, thus influencing submerged vegetation distribution. Consequently, changes in water optical properties profoundly affect photoautotroph communities and their capacity to supply ecosystem services.

Decreased water transparency is often associated with eutrophication, as a result of human activities leading to the nutrient enrichment of water bodies (Dupont and Aksnes, 2013). However, recent observations are drawing attention to significant changes in color of the coastal waters, described as a darkening and manifested by a transition to a browner hue (Monteith et al., 2007). The shift happens most likely due to changes in the interaction between land and coastal ecosystems caused by the climate change (Canuel et al., 2012). In the Baltic Sea, colored dissolved organic matter (CDOM) significantly contributes to light attenuation of the coastal waters (Ferrari et al., 1998), whereas phytoplankton contributes only 13–17% (Fleming-Lehtinen and Laamen, 2012).

2. Problem statement

In-situ measurements of Secchi depth and water color in the Forel-Ule (FU) scale are part of the National Monitoring Program in the Gulf of Riga. A limited number of observations at predetermined sampling sites and times results in data with insufficient temporal and spatial resolution. The constrained variability prevents definitive conclusions about whether observed changes in the light attenuation are uniform along the Gulf. Modern technologies enable the examination of "optically complex" waters using remote sensing of reflectance to classify optical water types and the hue angle to calculate FU through established algorithms (Pitarch et al., 2019a). This study integrates traditional marine monitoring with algorithmically processed remote sensing data (Pitarch et al., 2019b) and an oceanographic model of the Gulf, offering broader coverage at significantly higher resolution than in-situ data alone.

3. Data sources

In-situ data including Secchi disk depth, water color, salinity and chlorophyll-a were obtained from the national monitoring database (LIAE).

Remote sensing data of Secchi depth and water color derived from the ESA-OC-CCI v4.0 multi-sensor merged remote-sensing reflectance provided by Pitarch et al. (2019b) through The World Data Center Pangea.

Sea surface salinity was obtained from the oceanographic reanalysis using output from the UL HIROMB-BOOS model (Frishfelds et al., 2023).

Monthly estimates of chlorophyll-*a* values were extracted from downscaled projections of key marine variables in the Baltic Sea, publicly available in the Zenodo repository (Kristiansen and Butenschön, 2022).

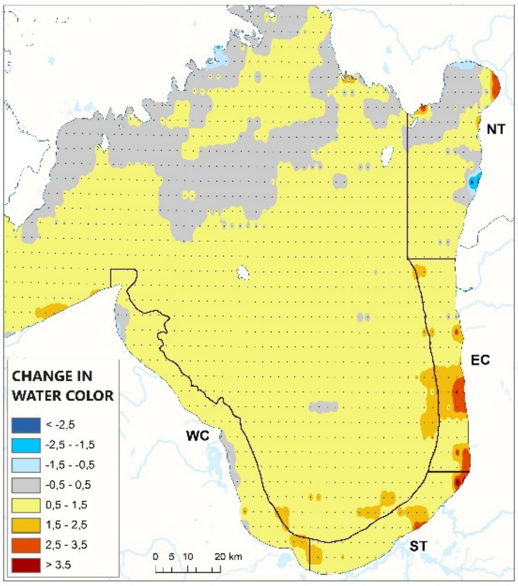

Figure 1. Average sea water color change (FU scale) comparing decades 1998-2007 and 2008-2018 derived from remote sensing data (Pitarch et al., 2019b); WC – Western coast, ST – Southern transitional waters, EC – Eastern coast, NT – Northern transitional waters.

4. Results and conclusions

Supplementing in-situ observations with remote sensing and modeling proved crucial for validating long-term trends interpolated due to data gaps. However, it was determined that the 20-year data series, derived from computed data, were insufficient to encompass the full spectrum of changes obtained from field observations spanning at least five decades.

In-situ data facilitated the identification of decreasing trends in Secchi disk depth in the most frequently observed months and sampling stations only. Simultaneously, the modified remote sensing data enabled a spatial examination and statistical confirmation of a significant shift in water transparency and color towards brownification along the coast. This shift might have been missed if only traditional marine monitoring data were used. Moreover, the most affected hotspots on the Eastern coast were identified (Figure 1). Based on the results, it can be speculated that CDOM is a significant cause of darkening in the Gulf of Riga.

In conclusion, the study underscores a need to investigate the connections between water browning in coastal waters and the ecosystem processes affecting it. Moreover, it emphasizes the need to explore the climate change consequences reflected in the distribution of light-sensitive species and alterations to habitats, which play a crucial role executing functions in the ecosystem service supply.

Funding

The study was supported by the Joint Project Initiative Ocean grant "Downscaling Climate and Ocean Change to services: Thresholds and Opportunities - CE2COAST", contract numbers 23-11.17e/20/176 and 23-11.17e/20/246 and "AquaINFRA" project funded from the European Commission's Horizon Europe Research and Innovation programme under grant agreement No 101094434.

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Integrating Earth Observation and Modeling for Monitoring the Vernal Diatom–Dinoflagellate Bloom in Finnish coastal waterbodies

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1. Introduction

In 2024, Finland is set to introduce a national indicator to monitor and assess the vernal diatom–dinoflagellate bloom in the Baltic Sea. This initiative by the Finnish Environment Institute (Syke) leverages satellite-based Earth Observation (EO) and biogeochemical modeling. The proposed Vernal Bloom Indicator and its core metric, the Vernal Bloom Index (VBI), are founded on EO data gathered over Finnish coastal water bodies. The index's baselines are established through simulations from the Finnish Coastal Nutrient Load Model (FICOS).

The vernal diatom-dinoflagellate bloom, also known as the *spring bloom*, occurs from late April to early June and is a period of intense biological activity in the Baltic Sea and the most significant phytoplankton bloom event by biomass. Monitoring this bloom is useful for understanding the ecological health of coastal water bodies since it is expected to react promptly to land-based nutrient load reduction measures. This stands in contrast to many other eutrophication indicators used in marine management in Finland such as cyanobacterial surface blooms and summertime chlorophyll, which are not projected to reach a Good Environmental Status (GES) in the near future.

Syke is a state research institute playing a central role in Finland's environmental management and monitoring. It collaborates with other relevant national entities to establish and execute monitoring programs, develop and maintain information systems, coordinate marine planning activities as well as manage and report environmental data. Syke conducts specialized monitoring programs such as EO-based monitoring of chlorophyll-*a* levels and collaborates in the national implementations of EU's Water Framework Directive (WFD) and Marine Strategy Framework Directive (MSFD).

2. Methodology

For monitoring the vernal bloom, we utilize EO data from the Sentinel-3 OLCI instrument, which has an intermediate resolution of 300 m and provides detailed spectral information with ten relatively narrow (7.5–10 nm) bands in the visible wavelength range. The satellite constellation's multiple daily overpasses provide a good coverage of the dynamic nature of the bloom. We employ the FUB-CSIRO Coastal Water Processor (Schroeder et al. 2022) to translate OLCI top-of-atmosphere radiance data into chlorophyll-*a* concentrations. The processor has a history of successful usage at Syke (Attila et al. 2018) and can produce stable spring chl-*a* estimates for Sentinel-3 OLCI data (see Fig. 1).

The VBI is calculated from the daily regional chl-*a* statistics extracted over coastal water bodies, by integrating the chl-*a* time series over the bloom periods. Bloom periods are defined by the date range in spring when chl-*a* concentrations are at or above type-specific limits (ranging from 5 to 15 µg/L). Such an approach was originally introduced by Fleming and Kaitala (2006) and yields a single VBI value for each coastal water body per year. For the years 2003 to 2011, when Sentinel-3 mission had not started, we utilized Envisat MERIS data from the same processor. The years in-between (2012 to 2015) form a well-known gap in the availability of intermediate-resolution EO data (see, e.g., Anttila et al. 2018).

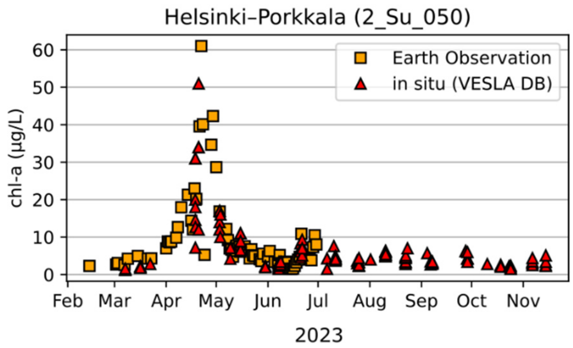

Figure 1. Chlorophyll levels during the vernal bloom from Sentinel-3 OLCI EOs (yellow squares) and Finnish environmental administration's water quality database (VESLA) shows an excellent match between the two in Helsinki–Porkkala coastal water body in yearly 2023. EOs indicate chlorophyll-*a* levels as high as 60 µg/L during the spring, values almost, but not quite, reached by the frequent coastal station sampling. Contains modified Copernicus Sentinel data.

FICOS is utilized to simulate nutrient consumption, algal biomass, and chlorophyll content in Finnish coastal waterbodies. This model incorporates various data sources, including catchment loads, atmospheric deposition, and local point sources, and it can be used to simulate both hypothetical and real-life cases. We ran FICOS under two scenarios: (1) a contemporary loads scenario, and (2) a hypothetical 'natural loads' scenario where all human-caused loads are eliminated on land, and open-sea boundary conditions for nutrients are reduced to natural levels, taken to be 33 % below the current Baltic Sea Action Plan (BSAP) targets. The contemporary loads scenario was used to calibrate FICOS results against EO, and the natural-loads scenario was used for baseline setting (see next section).

3. Baseline setting with FICOS

FICOS 'natural loads' simulations were used to represent the Finnish coast in an idealized state, unaffected by eutrophication. This was done to establish GES thresholds for the Vernal Bloom Index. The GES threshold is also used to represent the boundary between 'good' and 'moderate' ecological status in the 5-step classification of the WFD.

The baseline-VBIs for each coastal water body were computed from simulated daily surface chlorophyll concentrations under the FICOS 'natural loads' scenario, using a limit of 1 µg/L for the start of the bloom. The end of the bloom was determined by the depletion of the limiting nutrient (usually nitrogen), with an additional one-week allowance to account for the bloom's decay phase. When neither limiting nutrient ran out during the simulation, the spring bloom was terminated when sea surface temperature rose above 10 °C (see Fig. 2).

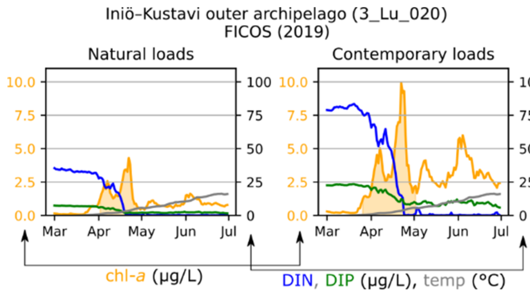

Figure 2. Method used for determining the VBI from chl-*a* time series data. The left figure shows a natural loads simulation (used for baseline setting) and the right figure a contemporary loads simulation (used to calibrate FICOS results against EO) in an example water body. The curves show the evolutions of chlorophyll (orange), nutrients (dissolved inorganic nitrogen (DIN), blue; dissolved inorganic phosphorus (DIP), green) and temperature (gray). The spring bloom index is calculated as the integral of chlorophyll concentration (shaded area).

Before establishing the GES thresholds, the discrepancy between FICOS and EO was addressed by adjusting the FICOS VBIs (natural loads) to the range of the EO data using the observed ratios between EO and FICOS VBIs (contemporary loads) for each coastal water type. Subsequently, the GES threshold in each water type was obtained as the 95th percentile of the adjusted FICOS VBIs (natural loads) for the constituent water bodies within that type. The thresholds obtained this way are the same order of magnitude than thresholds obtained with a 50 % acceptable deviation, which is in use, e.g., for several HELCOM indicators (HELCOM, 2015).

4. Results

Finnish coastal waters comprise 276 water bodies, categorized into 11 types. The Quark and Bothnian Bay do not display distinct spring and summer blooms, making the indicator inapplicable there. Additionally, the autonomous region of Åland is excluded from the indicator results because its coastal waters are managed by local authorities. After also excluding smaller inner waterbodies that are beyond Sentinel-3 OLCI's resolution, we are able to report indicator results for 109 coastal water bodies, spread across 7 types.

The Vernal Bloom Indicator indicated a poor status in all coastal water types where the indicator is relevant. The worst situation was observed in the Southwestern inner and middle archipelagos (EQRS < 0.4) and in the Gulf of Finland's inner and outer archipelagos (EQRS = 0.43). The spring bloom has not declined in any of the coastal water types since the early 2000s. It has intensified especially in the outer coastal waters of the Gulf of Finland and the inner and outer coastal waters of the Gulf of Bothnia during the same period.

5. Discussion

The match between FUB-CSIRO EO chlorophyll levels and in-situ observations (Fig. 1) shows potential. However, the accuracy of the highest chlorophyll concentrations indicated by EO is an area that warrants further investigation since the highest chlorophyll levels are usually missed by even the most regularly sampled stations. It has been recognized that some municipalities and cities possess valuable monitoring time series for springtime chlorophyll concentrations, but these datasets are not always accessible to environmental administration.

The integration of EO data with FICOS model outputs requires addressing the observed discrepancies between them. Our approach of calibrating FICOS scenario results against EO data is one way to make them compatible but does not yet explain where the differences arise from. They are possibly related to the generalizations required by the biogeochemical model and will be subject to further analysis.

6. Conclusion

The state of Finnish coastal waters in terms of springtime chlorophyll concentration was assessed for the first time. The status was indicated as poor in all coastal water types where the indicator is relevant.

The integration of Earth Observation and modeling represents a significant advancement in monitoring the vernal bloom, offering a comprehensive and timely assessment of the bloom's intensity and its ecological implications. Such methodologies are essential for future environmental monitoring and management under policies like the MSFD and initiatives like the BSAP.

The synergy between EO data and model outputs enables a more accurate and robust monitoring of the bloom. This integrated methodology proves crucial for understanding the impact of nutrient reduction measures along the coast and enhances the national capability to monitor eutrophication and manage the coastal waters more effectively.

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Session B

Natural hazards and extreme events

Impact of atmospheric low pressure trajectories on extreme wind waves in the southern Baltic region

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1. Introduction

Extreme sea events, such as strong high waves and elevated sea levels, are associated with strong winds. In the Baltic Sea, a semi-enclosed sea with a complex shoreline, the wind's direction and its rapid changes can significantly influence hydrodynamic processes. The highest atmospheric pressure gradients and strongest wind over the Baltic typically result from low pressure systems moving across or near the sea (Averkiev & Klevannyy, 2010). Specific trajectories of these systems influence various hydrodynamic processes, like Major Baltic Inflows, storm surges, and sea levels (Lehmann et al., 2017; Suursaar et al., 2006). These events are closely linked to large scale atmospheric circulation in Northern Hemisphere, often originating over northwestern Atlantic.

In this study we examine meteorological conditions associated with high waves in the Gulf of Gdańsk (Fig. 1), southern Baltic Sea. The coasts of Gulf of Gdańsk, mainly sandy beaches, undergo erosion and accumulation from highly dynamic processes like storms. Additionally, this densely populated area is characterised by heavy marine traffic making understanding of conditions influenced by storm events vital for human safety.

2. Datasets and methods

This study utilised modelled wind wave and atmospheric data from the HIPOCAS project. The meteorological dataset was produced using the REMO atmospheric model based on NCEP reanalysis data (Jacob & Podzun, 1997). The wind wave dataset was created with the WAM wave model (see Cieślikiewicz & Paplińska-Swerpel, 2008). In the study, 34 extreme storm events were selected in five different locations within the Gulf of Gdańsk, based on the significant wave height (SWH) from years 1958–2001 (points W1–W5 in Fig. 1). A detailed analysis of these events will be presented in a separate publication.

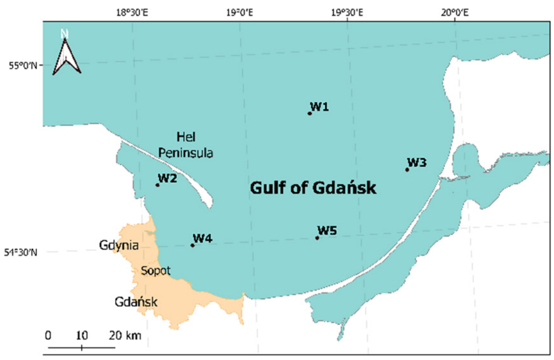

Figure 1. Gulf of Gdańsk with 5 locations with distinct characteristics (W1–W5).

We traced the trajectories of low pressure centres for each storm event based on 1-hour atmospheric pressure fields over northeastern Europe. These trajectories were subsequently classified based on their characteristics and the impact they exert on the wind wave field in the region.

3. Results

We identified and analysed four cyclone paths: two representing the most common trajectories (P1 and P2) associated with extreme wind wave conditions in the Gulf of Gdańsk, and two unique trajectories (P3 and P4) that occurred only once during the analysed period. Trajectories P3 and P4 are atypical for storm events in the area.

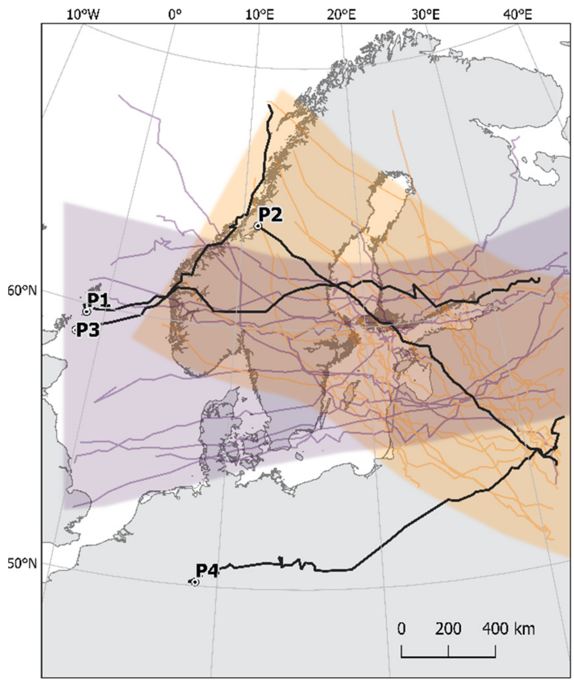

Figure 2. Trajectories of low-pressure systems' centers generating severe wave events in the Gulf of Gdańsk. In black, paths P1–P4 are shown. Their IDs are marked at the first hour when low-pressure system was recorded in the study area. Semi-transparent are the trajectories of lows resulting in the remaining 30 storm events. Overlaid are most common areas of trajectories similar to P1 (purple) and P2 (orange).

Figure 2 illustrates the trajectories of low-pressure systems' centres that resulted in 34 severe wind wave events in the Gulf of Gdańsk during the study period. Paths described here are shown in black. Overlaid in purple and orange are areas over which storms, crossing the Baltic

Sea, moved similarly to the paths P1 and P2, respectively. These two paths represent two specific extreme events: the storm of 20–22 November 1981 (P1) and the storm of 28 November–1 December 1988 (P2).

Path P1 is characterised by a low pressure centre moving from west to east across Scandinavia and through the Baltic, a pattern arising from zonal circulation that dominates the region.

Path P2 represents a low originating over the Norwegian Sea and following a NW-SE trajectory across the Baltic. Storms generated by lows travelling along this path are among the most severe in the Gulf of Gdańsk, with SWH reaching up to 9 m. This path infrequently considered in relation to wind waves in the southeastern Baltic, is more commonly associated with storm surges along the eastern Polish coast.

P3 features a low pressure system moving northward in the Atlantic, along the western coast of the Scandinavian Peninsula. During this particular storm (12–14 January 1984) in the Gulf of Gdańsk, the lowest SWH of all 34 events analysed in this study was recorded. However, the modelled SWH in the open part of the Gulf during this storm was still nearly three times higher than the average. Maximum wind speed was modelled at about 17.8 m/s and the lowest atmospheric pressure was 947 hPa.

The low pressure system following path P4 (9–12 April 1986) moved south of the Baltic Sea along the W-E trajectory. Its relative position to the Gulf of Gdańsk resulted in the rarely extreme NE winds. At point W4, northeastern winds have the longest fetch. Therefore, it is not surprising that this storm, with a maximum wind speed of 18.2 m/s, generated the highest significant wave height at this location during the entire study period. The lowest modelled atmospheric pressure was 993 hPa.

4. Conclusions

Low-pressure systems are the primary source of extreme wind wave events in the Baltic Sea. Given the complexity of the shoreline and variability in fetch lengths, the trajectories of lows are key drivers of variability in these events. The trajectory of low-pressure systems not only governs wind direction but also its rate of change, sometimes within a short time period.

We presented four cyclone paths associated with extreme wind wave events in the Gulf of Gdańsk. Paths P1 and P2 characterise several storms from the second half of the 20th century in the Gulf. P1 is known for causing severe wind wave conditions as well as storm surges and extreme sea level in various Baltic Sea locations (Suursaar et al., 2006), while P2 has not been comprehensively described in the context of southern Baltic storm events. The atypical paths P3 and P4 warrant further study. Further research will compare these findings with more contemporary data to assess temporal variability and the rarity of trajectories P3 and P4.

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Characteristics of marine heatwaves in the SE Baltic Sea based on long-term in situ and satellite observations

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1. Introduction

One of the effects of climate change is the increasing frequency and intensity of heat waves not only on land, but also in the aquatic environment, such as seas, lagoons, or lakes. The aquatic heatwaves are characterised by relatively short (lasting from days to weeks) but extreme water temperature anomalies. Marine heatwaves (MHW) can pose risk of serious and, in some cases, irreversible negative effects on aquatic ecosystems, and can have many-sided effects on coastal communities (IPCC, 2014; Pachauri & Meyer, 2014).

Our research, therefore, is motivated by the need to gain better knowledge of MHW patterns, which is important for predictability and deeper understanding of the direct and indirect impacts of marine heatwaves in the environmentally sensitive Baltic Sea.

2. Methods and Results

For this, we have analysed marine heatwave events (e.g., number of events, MHW days, mean, maximum, and cumulative intensity of MHWs) in the coastal waters of the SE Baltic Sea during warm (April-September) season using long term (1993-2023) in situ data from three coastal monitoring stations, i.e., Nida, Klaipeda, and Palanga, also measurements from oceanographic surveys, and Terra/Aqua MODIS satellite sea surface (SST) temperature data for the period of 2000-2023.

Our results revealed that in the latest decade, marine heatwaves have become more frequent across the coastal areas of the SE Baltic Sea, typically occurring about 1-2 times per warm (April-September) season, however, in recent years marine heatwave occurrence up to 6 times was recorded. An increased duration of MHWs was also observed and even though the majority of the events lasted for around one week, more than 16 % of marine heatwaves were recorded to last for more than two weeks, reaching even up to 26 days of duration. In addition, satellite SST measurements and data from oceanographic surveys demonstrated that the impact of MHW events is affecting both, the coastal and the open waters, heating not only surface waters but the deeper parts of the sea as well.

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Effects of extreme storms on coastal erosion in non-tidal seas (the Baltic, Black, and Azov Seas)

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Introduction

The Baltic, Azov, and Black Seas are isolated basins with regional tidal variations, ranging from a few millimeteres to a few centimeteres.

These variations do not impact the morphodynamics of the coastal zone of the aforementioned seas. This is why these seas are called non-tidal (Zenkovich, 1946; Longinov, 1963; Gudelis, 1993).

In these non-tidal isolated seas, coastal processes are driven by storm waves and short-term weather fluctuations (Jarmalavicius et al. 2016; Davydov et al. 2019).

With global climate change and sea level rise, the importance of meteorological hydrological phenomena for coastal development is increasing significantly (Fox-Kemper, B. et al. 2021).

In this context, within the coastal barriers of non-tidal seas, there is an intensification of coastal processes that can be catastrophic in some areas (Vousdoukas, et al. 2020).

In the coastal zone of inland seas, storm surges are important for the development of morphodynamic and lithodynamic processes. Storm surges are the result of the simultaneous occurrence of wind, wave, and anemobaric components. Storm surge parameters are determined by the morphological conditions of the coastal zone, namely the dissection of the coastline and the slope of underwater and subaerial coastal areas.

Within the Black Sea, the most significant storm surges occur in the north-western part of the Black Sea, along the shallow inland coasts of Tendrovsky and Dzharylgachsky bays (maximum sea level rise of about 3.0 m) (Davydov et al., 2019).

Along the coast of the Azov Sea, maximum surges are recorded in the Taganrog Bay (up to 4.5 m) and the Utlyuk estuary (up to 3.0 m) (Davydov et al., 2019).

The southeastern sandy coasts are the most sensitive areas to the storm surge in the Baltic Sea. In Lithuania, for example, storm surges can reach 3 metres or more during extreme storms.

The aim of this paper is to evaluate the frequency and impact of storm surges on coastal barriers in non-tidal seas. To achieve this goal, the meteorological data during the major storm events in 2022–2023 and topographic surveys, as well as aerial images of sandy barriers on the Baltic, Black, and Azov seas, are analysed.

Results

On 25 November 2023, a cyclone (974 hPa) appeared in the southwestern part of the Black Sea. This depression gradually moved northeast towards central Ukraine. Wind speeds reached up to 40 m/s and contributed to the development of storm swell and storm surge across the northern Black Sea.

Along the coastal system of Tendra-Dzarylgach (Black Sea, 26-27 November), the height of the waves (based on the data of the observatory research system Poseidon) was between 3.3 and 3.7 m. At the same time, the water level along the frontal coast of the system was raised by 1.1–1.3 m, while along the rear coast it was lowered by 0.35–0.5 m. As a result, the difference in water levels between the adjacent water areas exceeded 1.5 m. The average surface height of the Tendra-Dzharylgach coastal barrier does not exceed 1.0 m, so the described storm surge favoured active overwashing and breaching.

As a result of the described storm and storm surge, multiple breakthroughs occurred within the studied barrier (Fig. 1). It should be noted that these multiple breakthroughs are the most severe for the entire observation period

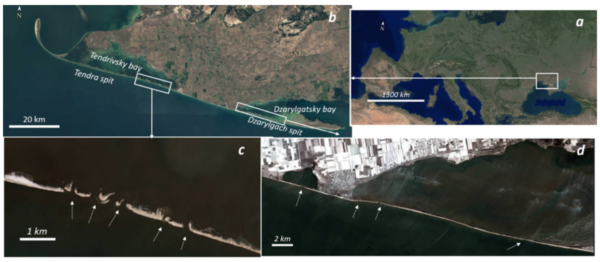

Fig. 1. Consequences of the storm 25-27 November for the Tendra - Dzharylgach coastal system: a - location of the system; b - structure of the system; c - breaches within the Tendra barrier; d - breaches within the Dzharylgach barrier and the barrier of Ustrichne Lake

In early 2022, an unusual meteorological event occurred on the Lithuanian coast. From mid-January until the end of February, multiple deep cyclones had been passing across the Lithuanian seacoast, causing a rise in sea levels. On 30 January, Cyclone Malik, reached the Lithuanian coast, producing winds gusting up to 35 m/s from the WNW direction and causing sea level to rise to 124 cm. On 17 February, another powerful cyclone, Dudley, hit the Lithuanian coast, leading to winds gusting up to 24 m/s in the SW-W direction and causing sea levels to rise to 120 cm. On 19 February, Eunice struck the Lithuanian coast, bringing gusty SW winds of 31 m/s and causing the sea level to rise to 143 cm. Two days later, on 21 February, a weaker but still powerful cyclone named Franklin occurred, accompanied by SW winds gusting up to 30 m/s and causing the sea level to reach the mark of 121 cm. The wave height at sea reached 4 m during each storm. Observations have shown that the capacity of different coastal stretches to withstand extreme storms varies significantly. This capacity depends not only on the irregularity of the wind field during storms, the different storm tracks, and storm surges, but also on the morphometric characteristics of the coastal zone. In general, the losses caused by these storms were the highest in the 21st century. Compared to previous storms, the losses on the mainland coast were relatively similar to the effects of Ervin in 2005 (Žilinskas et al., 2005). However, the losses on the coast of the Curonian Spit were comparable to those caused by Anatolia in 1999 (Žilinskas et al., 2000).

Conclusions. The results based on the analysis of the extreme meteorological events and their impact on three non-tidal seacoasts allow us to state the following:

- Major storms and significant storm surges are the phenomena with the highest impact on the coastal zone of non-tidal seas;
- the frequency of the described phenomena is not characterised by an increase in their temporal frequency, but by the higher energy level than on a multi-annual time scale;
- the major storms and storm surges are relief-forming and determine the further development of the coastal barriers of non-tidal seas;
- within the coastal barriers, where natural forms of man-made coastal protection measures are present, these natural phenomena do not cause catastrophic consequences.

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Recent extreme water level events in the southwestern Baltic Sea in a climate perspective

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1. Introduction

In the recent years three significant storm surge events took place at the southwestern Baltic Sea coast (2017, 2019 and 2023). Whereas in most cases such surge events come along with high wind speeds, these three occurred by relatively moderate wind speeds. Using a numerical simulation the events are analyzed, compared with observations and decomposed to their contributing factors, such as direct atmospheric effects but also the effect of pre-filling of the Baltic Sea, and are put in a climate perspective.

2. Experimental setup

The simulated water level is derived with the hydrodynamic model TRIM-NP (Casulli and Stelling, 1998) in a three-way nested mode, with the finest resolution of 1.6 km for the southwestern Baltic Sea. The atmospheric forcing for the water level simulation originates from a long hindcast simulation with the COSMO-CLM (Geyer, 2014).

3. Climatology of total water level

Using the classification from the Federal Maritime and Hydrographic Agency (BSH) for the time series of extreme water level events at Travemünde, Warnemünde and Flensburg, no clear trends could be detected. However, the recent extreme events are one of the highest in the analyzed period and in the case of the 2023 event in Flensburg even the highest one.

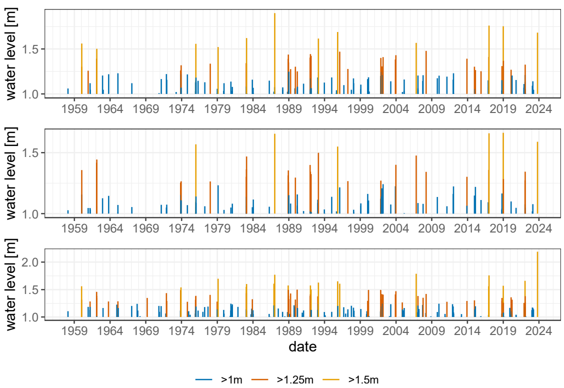

Figure 1. Simulated time series of storm surge events above 1m (blue) above 1.25m (red) and above 1.5m (orange) mean sea level at Travemünde (top), Warnemünde (middle) and Flensburg (bottom) for the years 1958 to 2023.

4. Contributing factors

Analyzing the corresponding wind fields, only moderate to high, but no extreme wind speeds occurred during these recent events. Another contributing factor for extreme water levels could be the prefilling conditions of the Baltic Sea (e.g. Mudersbach and Jensen (2009)). The analysis on the effect of the prefilling the Baltic Sea Volume (BSV) is derived from model data and is put in relation to the water level during the extreme surge events. First results show that for certain events, especially for the 2017 event at Travemünde (Fig. 2), the prefilling contributed a substantial part to the total water level. In detail, the Baltic Sea Volume was about 0.45m above long term mean and thus contributed about 25% to the total water level of the 2017 event at Travemünde. For the 2019 event, the contribution was about 10%, whereas for the most recent extreme event in October 2023 the contribution of the Baltic Sea Volume was negligible. For the latest event other effects, such as wind and especially wind direction were more important.

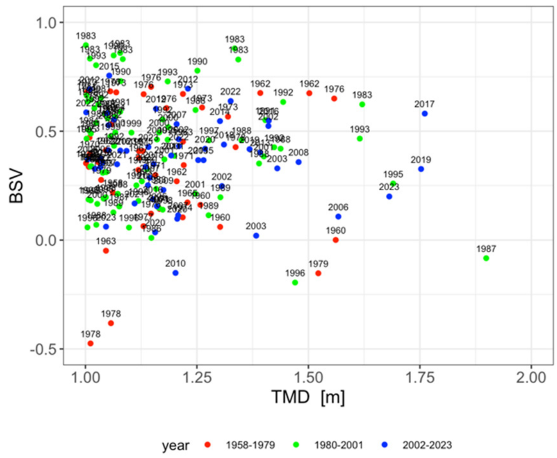

Figure 2. Scatterplot for the event maximum of BSV and total water level at Travemünde. Colored dots indicate three different periods, events are annotated by the year of occurrence.

5. Outlook

Further analysis will compare the recent events and their contributing factors within the last decades. Possible trends will be discussed, and single events will be put in a climate perspective.

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The very strong storm surge of October 2023 in the southwestern Baltic from the perspective of an operational forecast and warning service.

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1. Storm surge 19.-21.102023

Strong easterly winds lead to a strong storm surge in the southwesterly Baltic in the time October 19th to 21st. The peak values of the surge were reached on in the night from October 20th to 21st with +227cm above NN at Flensburg (22:40) and +231cm at Schleswig (1:14). Further east the values were not as high, but also reached values over +180cm in the Bay of Lübeck. The sturm surge caused massive damages at shore and in harbors and even lead to the breaking of dikes. Some gauges did not deliver actual values (but could be recovered afterwards) but some gauges were also fully damaged. In the whole western part of the German coast this storm surge was the highest surge after the 1872 storm surge.

2. Warnings

Already Monday, October 16th the operational models showed a storm surge for the 20th with maximum values of around 135cm above NN with a smaller peak on the 19th. As time progressed, the expected peak values increased. The BSH gave a first surge warning on the 17th for the time from the 19th to the 21st. Several warnings with increasing peak values followed until, with water levels falling below 100cm, the end of the storm surge was declared on the 21st on 10:45.

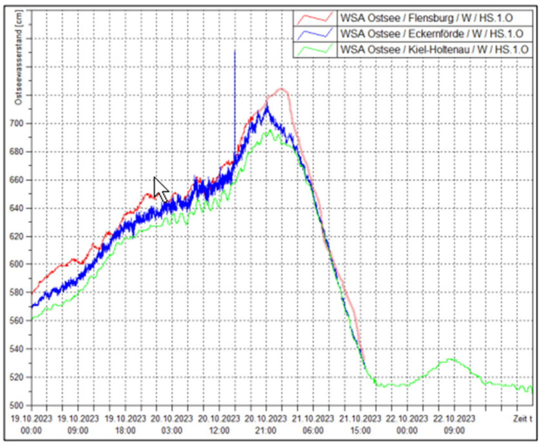

Figure 1. The water level (raw values) during the storm surge at Flensburg, Eckernförde and Kiel-Holtenau.

3. Recurrence and Duration

The expected recurrence period for such a storm surge was about 100 year and the recurrence periods also did not change in considerable amount after including this surge in the calculations. A surge of similar magnitude (only slightly lower) occurred on 31.12.1904, which also fits the 100year recurrence period. The surge of 1872 was considerably higher, but this surge is also considered a 1000year surge.

The duration of the storm surge was also exceptional, this also contributed to the damages. At Flensburg the water level surpassed +100cm for more than 54 hours. Since the time we have hourly data (1955) the longest duration was also 54hours (28.12.1978), the second longest was 47hours (14.2.1979) and all other storm surges last less or equal 31 hours.

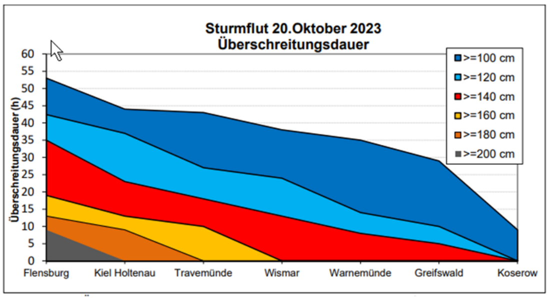

Figure 2.Duration (time were water levels surpassed certain values given by the colored areas) of the October 20th storm surge for several gauge stations along the whole German Baltic coast.

4. Schlei

The Schlei is a narrow inlet/fjord of the Baltic and being so narrow is not included in the standard operational forecast models. Compared to most previous storm surges the October 20th surge showed some peculiarities. The peak values was higher than in Flensburg, which is not the case in standard storm surges (100 year recurrence at Schleswig is also 223cm compared to 238cm at Flensburg). First examination hints to strong precipitation as the main cause; this will be discussed in more detail.

5. Future warnings

Although the actual warnings were overall considered timely and adequate, some ideas on how to improve the warnings were discussed after the event with several stakeholders. Some of the improvements involve only a better communication of the available information (for example the expected duration). Others need some modelling effort (Schlei) or some scientific advances, which hopefully will come out of the Baltic Earth conference.

Compound late-spring frost and drought events in the eastern part of the Baltic Sea region

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1. Introduction

Droughts and late frosts, occurring in spring, after the growing season has already started, are dangerous meteorological phenomena that have negative impact on vegetation, agriculture, and the economy (Chamberlain et al., 2019). To date, these phenomena have mostly been studied separately. However, in recent years, it has been observed that risk and negative impacts are often more severe when late-spring frost and drought are recorded simultaneously (Li et al., 2022). Such events, where multiple physical processes or hazards act together to cause social or environmental risks, are referred to as compound climate events (Zscheischler et al., 2018). One of these events – compound late-spring frost and drought (CLSFD) events, are investigated in this study.

To date, CLSFD events have not been analysed in the study area. Both late-spring frosts and droughts have been studied only as individual phenomena. Therefore, the main objective of this study is to identify compound late-spring frost and drought events in the eastern Baltic Sea region during the period of 1950–2022 and to assess the recurrence and intensity of these events.

2. Data and methods

The study area covered the eastern part of the Baltic Sea region from 53.5° to 59.5° N and from 20° to 28.5° E. To identify late-spring frost events, the date of the start of the growing season (SGS) and the day of the last spring frost (LSF) were first determined at each point of the study area for each year of the study period. Daily mean air temperature (t_{avg}) data were used to determine the SGS date. In this study the SGS date at a particular grid point was defined as the first day in a period of six consecutive days when the t_{avg} was higher than 5 °C. This method for determining SGS is used by the Swedish Meteorological and Hydrological Institute (SMHI) and has been applied in other scientific studies in this region (Graczyk, Szwed, 2020; SMHI, 2022). LSF date was defined using daily minimum air temperature (t_{min}) data. LSF at a particular grid point was then determined as the day when t_{min} fell below 0 °C for the last time during the March–June of the corresponding year. Late-spring frosts at every point of the study area were distinguished when LSF was recorded later than SGS.

Standard Precipitation Index (SPI) was used to identify droughts. 1-month SPI values were calculated for each day of the study period. Drought was identified if the SPI value at a given grid point was less than -1. Extreme drought was recorded if SPI < -2. Daily precipitation data, used for SPI calculation, along with the data of t_{min} and t_{avg} were obtained from the European Centre of Medium-range Weather Forecast ERA-5 reanalysis database. The data grid size was 0.25 x 0.25°.

Finally, compound late-spring frost and drought event was distinguished when, on the day of identifying late-spring frost, the SPI value at the respective point was less than -1. Not only the recurrence, but also the intensity of these phenomena was evaluated in the entire analysed territory and in each grid cell separately. The intensity of each CLSFD event was determined by assessing three different variables: the SPI value on the day of CLSFD event; the sum of growing-degree days (GDD), accumulated up to the day of CLSFD event (t_{base} = 5 °C); and the value of t_{min} on the day of CLSFD event. Terciles of these variables were calculated and the values of SPI, GDD and t_{min} were divided into three categories (Table 1). Then, based on intensity, CLSFD events were distributed into 27 classes.

Table 1. Categories used to define the intensity of compound late-spring frost and drought events. The letters D, GDD and F stand for the intensity of the drought, the sum of growing-degree days accumulated until CLSFD event, and the severity of the frost, respectively. The numbers 1, 2 and 3 denote different intensity categories, with 3 being the highest intensity category.

Variable	Category	Threshold values
Intensity of drought	D1	-1 > SPI > -2
	D2	-2 > SPI > -3
	D3	SPI < -3
GDD, accumulated until CLSFD event	GDD1	0 °C < GDD < 80 °C
	GDD2	80 °C < GDD < 160 °C
	GDD3	GDD > 160 °C
Intensity of late-spring frost	F1	0 °C > t_{min} > -2 °C
	F2	-2 °C > t_{min} > -4 °C
	F3	t_{min} < -4 °C

3. Results

Over the study period of 1950–2022, a total of 6156 compound late-spring frost and drought events were distinguished at separate grid points. At least one such event occurred in 71.2% of the study years. The highest number of CLSFD events was observed during the period of 2000–2009, while the lowest occurred in the ninth decade of the 20th century. During the analysis of such events in a single year, the highest number of CLSFD events were found in 2019. In that year, these events were identified in 76.3% of the analysed territory (Fig. 1), with such events not occurring only in the northern part of the study area and the northwestern part of Latvia. Moreover, slightly more than half of the CLSFD events in 2019 were identified when extreme drought was recorded (SPI value was lower than -2). Higher number of such events was found only in 1974 when late-spring frost during extreme drought was identified in 56.5% of the grid cells (Fig. 1). It was also found that the number of CLSFD cases slightly increased over the study period. However, this change was not statistically significant (when $p < 0.05$).

The highest number of CLSFD events were identified in northern Lithuania and southern Latvia. In these areas 14-15 such events were recorded over a 73-year period (Fig. 2). In total, at least one CLSFD event was detected in almost all grid cells (99.1%).

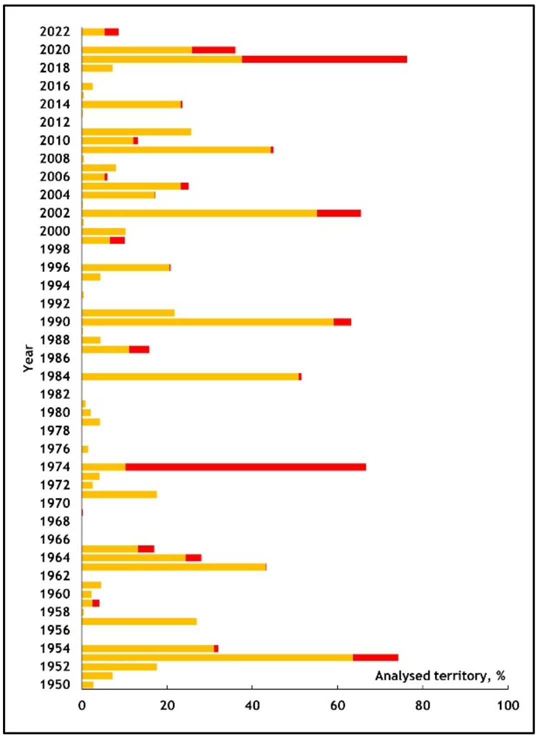

Figure 1. The part of the analysed territory (%) in which compound late-spring frost and drought events were recorded during different years of the study period. Orange bars indicate events, when late-spring frost occurred during drought conditions (SPI < -1) while red bars indicate events when late-spring frost occurred during extreme drought conditions (when SPI was lower than -2).

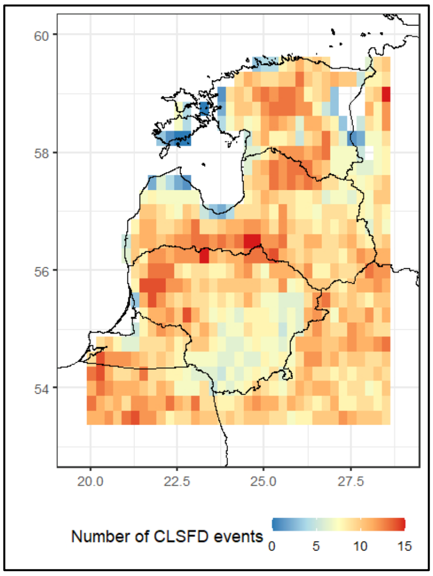

Figure 2 The number of compound late-spring frost and drought events over the study period (1950–2022).

At least one event when late-spring frost occurred during extreme drought (when SPI < -2) was identified in 80.7% of the study area. The largest number of such events over the 73-year period, five, was identified in two grid cells near the border of Poland–Kaliningrad region.

To assess the intensity and severity of a specific CLSFD event all such occurrences were distributed into 27 classes and at least one event fell into 15 of them. The majority of CLSFD events (45.5%) in terms of intensity belonged to the first class, which included the categories of the weakest drought (D1 category); the lowest amount of GDD, accumulated until the CLSFD event (GDD1 category); and the mildest frost (F1 category) (Fig. 3).

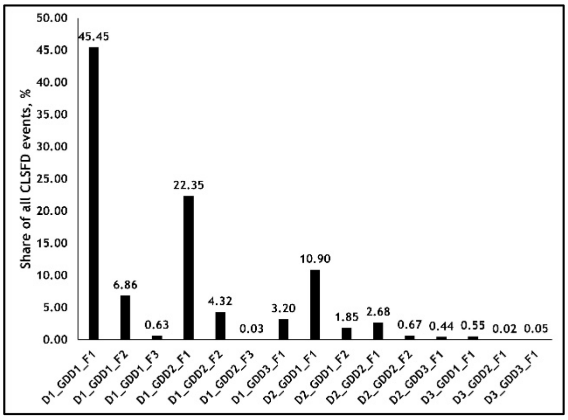

Figure 3. Share of compound late-spring frost and drought events (%) belonging to each intensity class. More details about intensity categories can be found in Table 1.

Overall, only 4.9% of all CLSFD events belonged to the classes where at least one variable in terms of intensity reached the highest, third category. However, 63.0% of CLSFD events belonging to these classes were recorded between 2000 and 2022, with the highest number of such events identified in 2004, 2014, and 2019, respectively. Additionally, in 2019, three CLSFD events were identified in central Lithuania that were the most intense, reaching the third category in terms of both drought severity and sum of GDD.

4. Conclusions

Over the period from 1950 to 2022, at least one compound late-spring and drought event occurred in 71.2% of the study years. The largest number of CLSFD events was observed in southern Latvia and northern Lithuania, while along the shores of the Baltic Sea and Lake Peipus, such events rarely occurred. At some points here, no CLSFD events were observed in the 73-year period. Of all the years in the study period, 2019 was the most notable. In that year, the CLSFD events not only covered the largest part of the study area but were also the most intense, especially in the central part of Lithuania.

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Baltic Sea Surface Temperature Analysis 2022: A Study of Marine Heatwaves and Overall High Seasonal Temperatures

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1. Summary

Over the summer and autumn months of 2022, large parts of the Baltic Sea surface experienced the third-warmest to the warmest temperatures since 1997. Warm temperature anomalies can lead to marine heatwaves (MHWs), which are discrete periods of anomalous high temperatures relative to the usual local conditions. Here, we describe the overall sea surface temperature (SST) conditions observed in the Baltic Sea in 2022 and provide a spatio-temporal description of surface and subsurface MHW events based on remote sensing, model reanalysis and in-situ station data.

Locally, the western Baltic Sea and the Inner Danish Straits saw the most MHWs. Maximum MHW intensities reached values of up to 4.6 °C above the climatological mean during up to seven MHW events there. The northern Baltic Proper and the Gulf of Bothnia were affected mainly by two MHWs at maximum intensities of 7.3 °C and 9.6 °C, respectively.

Model data reveal that MHWs in the upper layer occur at a different period and are likely driven by different mechanisms than those at the bottom layers. Model data and long-term mooring data from two exemplary stations, 'Lighthouse Kiel (LT Kiel)' and 'Northern Baltic', show a significant increase in MHW occurrences of +0.73 MHW events per decade at LT Kiel and of +0.64 MHW events per decade at Northern Baltic.

2. Data and methods

We employed satellite data, model reanalysis data and mooring data to analyze 2022 temperatures and MHWs. MHWs refer to discrete periods of unusually high seawater temperatures. While several definitions describe MHWs quantitatively, the most commonly used method defines them as periods of temperatures exceeding the 90th percentile of the local, daily climatology for five days or more (Hobday et al., 2016). We use open-source python and matlab packages to detect MHWs in station and model data (Oliver, 2016; Zhao and Marin, 2019).

Since 1990, the German Federal Maritime and Hydrographic Agency (BSH) has been compiling daily maps of SST data from radiances by the Advanced Very High Resolution Radiometer (AVHRR/3) at a spatial resolution of 1.1 km. The operational weekly SST analysis for the Baltic Sea started in autumn 1996. The analysis of the BSH SST dataset presented here is therefore limited to the period from 1997–2022.

The Baltic Sea physics reanalysis product is a model dataset based on the ocean model NEMO v4.0 (Panteleit et al. 2023). The model system assimilates satellite observations of SST and in-situ temperature and salinity profile observations from the ICES database. The spatial coverage is 1 nautical mile or approximately 1.8 km. This multi-year product covers the reference period from 1993 up to 2022.

In-situ temperature time series from mooring stations located in the Baltic Sea are used for 1) model validation and 2) cross-validation of MHW computations from model data. Two mooring stations, Lighthouse Kiel (LT Kiel, In Situ TAC partners, 2022) and Northern Baltic, were chosen for cross-validation of MHWs. LT Kiel lies in the far western part of the southern Baltic. The station Northern Baltic is located in the northern Baltic Proper.

3. Sea surface temperature anomalies in satellite data

Based on the BSH SST analysis, large parts of the Baltic Sea featured strong warm anomalies in the summer of 2022. The highest values were up to 3 °C above the long-term mean (1997–2021) in the Bothnian Sea in June and in the Bothnian Bay in July. In August, however, these areas were neutral or exhibited cold anomalies while the Baltic Proper as well as the Gulf of Finland and the Gulf of Riga showed the warmest anomalies of +1.5 °C to 2.5 °C. In November, the whole Baltic Sea featured strong warm anomalies, again with peak values above +2 °C around Southern Sweden.

To provide climatological context for the observed SST anomalies, we ranked SST anomalies from the summer and autumn months of 2022 against the same months in previous years starting in 1997 (Fig. 1). The warm anomalies across large parts of the Baltic Sea during summer and autumn of 2022 are among the warmest eight on record for the respective months. In September, coastal upwelling led to cold anomalies along the eastern shores, but the other five months of the summer and fall of 2022 (June, July and August as well as October and November) show large areas of the Baltic Sea with warm anomalies that are among the four most pronounced on record. In August and November, we see several large areas along the coastlines of the Baltic countries as well as off the Polish coast and around Gotland that according to the BSH SST analysis dataset featured highest-ever surface temperatures.

4. Surface MHWs in model data

We used daily SST output from the Baltic Sea physics reanalysis to detect MHWs (not shown here). The Inner Danish Straits and the Western Baltic saw the most MHWs during 2022; four to five (and localized up to seven) MHWs were detected there. A maximum of 94 total days of MHW conditions were recorded in the Western Baltic. The mean and maximum intensities of all MHWs in the Western Baltic reached 3.8 °C and 4.6 °C, respectively. The highest mean and maximum intensity values were reached in the northern Baltic Proper and in the Bothnian Sea and

Bothnian Bay. The maximum intensity in the Bothnian Bay even reached 9.6 °C, the highest within the entire studied period from 1993 to 2022.

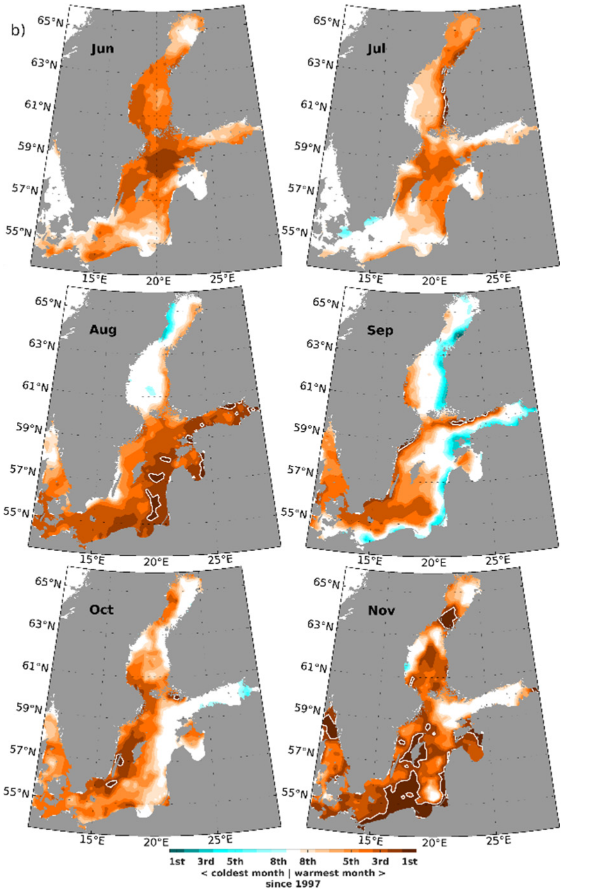

Figure 1. Ranked anomalies (2022 difference to climatology of 1997-2021) of SST for the Baltic Sea according to the BSH SST analysis during the summer and autumn months. Brownish (cyan) colors denote anomalies belonging to the warmest (coldest) eight anomalies found since 1997. Record warm anomalies (rank 1) are highlighted by white contours.

5. Multi-year evaluation of MHW metrics

Finally, we assess the frequency and other characteristics of the 2022 MHWs in a climatological context based on both observations and model data for two long-term stations.

Shown here are the results from LT Kiel (based on the overlapping climatology period 1993–2021, Fig. 2a–h), where five MHWs (four in the reanalysis) occurred throughout 2022 (Fig. 2a). Though none of the ones at LT Kiel was extraordinarily long or intense, the time series of yearly MHW metrics shows that the number of MHW occurrences based on observational data in 2022 was the second highest there since 1989 (Fig. 2a). The time series of MHW frequencies per year suggests that the occurrence of MHW events has increased over the last three decades (Fig. 2a). The trend computed from model data is +0.73 MHWs per decade for the period 1993–2022.

The number of MHW events per year is positively correlated (R=0.76) with the increasing annual mean SST at this mooring station (Fig. 2b). The maximum (Fig. 2c) and cumulative intensities (Fig. 2e) of observed MHWs show no clear trend and do not correlate with warming annual mean temperatures (Fig. 2d and Fig. 2f). There is no significant trend in the total number of MHW days (Fig. 2g) at LT Kiel, but there is a positive correlation (R=0.71) with rising average temperatures (Fig. 2h).

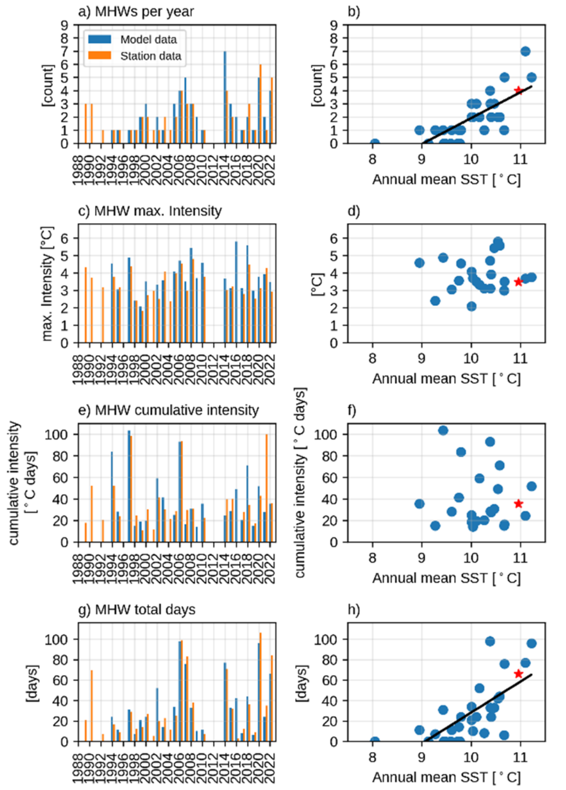

Figure 2. Comparison and time series of annual MHW metrics (a: MHW events; c: maximum intensity [°C]; e: cumulative intensity [°C days]; g: MHW days) for station data (orange bars) and model data (blue bars) at the LT Kiel station, for which MHW metrics from the model are plotted against annual mean SST, with 2022 marked in red. Statistically significant (95 %) correlations are indicated by a black line.

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This study is currently in review at *State of the Planet* for the 8th edition of the Copernicus Ocean State Report (OSR8).

More frequent and longer marine heatwaves in the Baltic Sea

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Abstract

Various data sets such as satellite observations, in situ measurements and gridded reanalysis data sets indicate that marine heatwaves have globally occurred more frequently and for longer periods over the past century (Oliver et al., 2028). The increase in water temperature extremes is a direct consequence of global warming and has devastating and long-term impacts on marine ecosystems such as coral bleaching. While many studies have investigated the changes in marine heatwaves in past and future climates for the global ocean in recent years, there have not yet been many studies for the Baltic Sea (e.g. Goebeler et al., 2022; Rutgersson et al., 2022; Meier et al., 2022a; 2022b; Gröger et al., 2022; 2024). In this talk, we will present three new studies analysing marine heatwaves in the Baltic Sea in past and future climates.

Firstly, we will present and discuss different definitions of marine heatwaves commonly used in the literature. The different definitions are intended for different applications and produce very different results. It is therefore important to know the exact definition of marine heatwaves of a study before comparing the results with other studies. We will use reanalysis data to illustrate the difference in the temporal and spatial distribution of marine heatwaves based on a simple threshold approach and the commonly used approach by Hobday et al. (2018). According to the latter approach, marine heatwaves of class I are temperature extremes for a period of five days that exceed the 90th percentile for any day of the year relative to a fixed baseline.

Secondly, we will present trends in past and future climates in sea surface and bottom marine heatwaves based upon reanalysis data and climate model simulations. We will present maps of trends and we will analyse the drivers of marine heatwaves in the Baltic Sea during past climate.

Finally, we will discuss the impact of marine heatwaves on the marine ecosystem in the Baltic Sea by analysing the impact of such extreme events on dissolved oxygen concentrations at the seabed.

In conclusion, marine heatwaves during both summer and winter have become more frequent and longer since the 1980s and the marine heatwave annual maximum extent at the seabed of shallow coastal waters has increased. During such events, the concentration of dissolved oxygen on the seabed decreases, which increases the risk of episodic hypoxia events. Furthermore, projections of future climate until the end of the century suggest a further increase in frequency and duration of marine heatwaves at a rate depending on the global warming level.

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What causes the port of Klaipeda to be closed at every storm?

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1. Introduction

Coastal regions face significant threats from extreme water levels induced by long waves of different origins (Monserrat et al. 2006; Vilibić 2008; Pellikka et al. 2022), with Traukunas phenomena in the Port of Klaipeda posing a particular hazard (Nesteckyte et al 2023). The Port of Klaipėda is vital to Lithuania's economy, according to Lithuania's (Ministry of Transport and Communications)generating around 6% of the country's gross domestic product. It is also essential geographically as the northernmost non-freezing port on the Baltic Sea. However, the port is notorious for the recurring long waves that enter the port during storms, creating hazardous conditions inside the port to the extent that ships are banned from entering the port during storms or even taken out to sea, as it is safer to be at open sea than in the port. In extreme scenarios, a long wave trough could create a critical situation by causing the sea level on the sea side of the barrier to fall below the sea level on the lagoon side. This potential scenario could lead to the failure of the storm surge barrier. The primary purpose of the barrier is to protect against high water levels on the seaside. Measures were taken to safeguard the Port of Klaipeda from storm-wave-induced hazards, including the extension of the port entrance channel and changes to its configuration (Šakurova et al. 2022); however, such cases still occur (Nesteckytė et al. 2023).

Whenever the wind speed reaches 20 m/s and the wave height at the harbour gate reaches 3 m, port operations are restricted or even stopped. We analyze the wave characteristics in the Port of Klaipeda during these situations. The attention is primarily directed toward the long waves responsible for significant disruptions in the port's operational work.

2. Methods and data

The Lithuanian Hydrometeorological Service obtained data on Klaipėda strait water level fluctuations. SWL changes within a period of 1 minute. Sea level pressure and wind data were also obtained from Klaipeda meteorological stations, gathered from the Lithuanian Hydrometeorological Service (Figure 1) for November-December 2023.

For determining the origin of waves recorded in Klaipėda harbour, the record underwent de-meaning and de-trending, and then it was converted into a time series of water levels by employing linear wave theory (Kelpšaitė-Rimkienė er.al. 2018). Power density spectra analysis was applied to the resulting water level data to identify the predominant frequencies and periods of recorded oscillations. Bandpass filters were applied to water level time series to extract oscillation bands with the highest energy. Cut-off frequencies were set to wind waves – 0.1 <f < 0.3 Hz; harbour oscillation – 0.03 < f <0.01 Hz and seiche 0.001 < f < 0.0006 Hz according to the Gailiušis 2010 proposed main wave frequencies at the Port of Klaipeda.

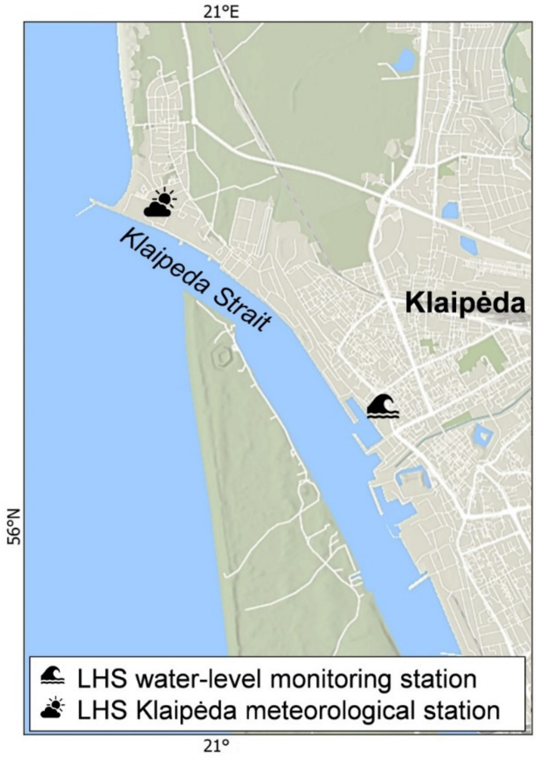

Figure 1. Klaipeda Strait and the Port of Klaipeda.

3. Results and conclusions

On the morning of 22 November, Klaipėda experienced the persistence of elevated atmospheric pressure, registering a sea-level pressure of 1027.4 hPa. Despite this, preliminary signs of an approaching cyclone had already become apparent. At 03:00 Coordinated Universal Time (UTC) on 22 November, a sudden reduction of 1.1 hPa in atmospheric pressure was documented, giving rise to a meteotsunami-like soliton with an amplitude of 17 cm (referred to as a medium-sized "traukūnas" in Lithuanian (Fig. 2).

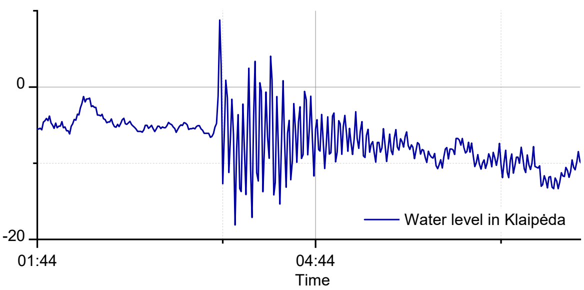

Figure 2. Traukūnas in Klaipėda Port on 22 November 2023

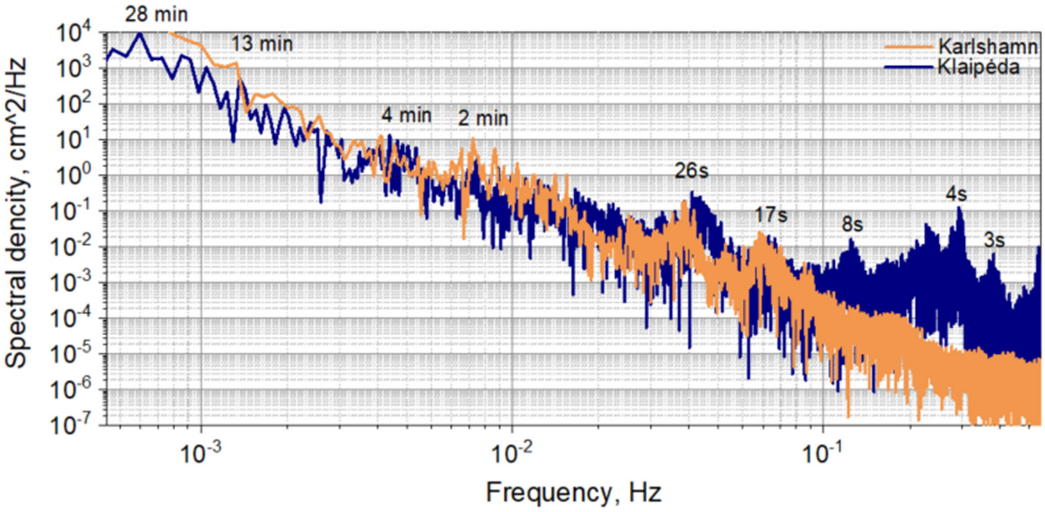

Figure 3. Power density spectra showing the dominant frequency peaks

By the evening of 22 November, specifically at 23:00 local time, port operations in Klaipėda were halted due to adverse weather conditions. Wind gusts reached 27.4 m/s, and wave heights exceeded 3 m at the port entrance. A rapid decline in atmospheric pressure commenced, reaching its maximum at 23 UTC and decreasing by 2.5 hPa every 10 minutes.

The analysis of power density spectra was employed to examine the waves generated by the November storm in the Baltic Sea. The spectra for the recorded signal revealed distinct frequency peaks (Fig. 3). Notably, at Klaipėda port, elevated peaks at 4 s and 8 s periods indicated the influx of storm waves or swell from the Baltic Sea into the harbor.

Conversely, water level analysis fot the Karlshamn, Sweeden did not exhibit these peaks, attributed to the cyclone's northwest-to-southeast trajectory, prevailing southwest winds, and the geographical positioning of the port hindering the generation of high wind waves. While wind waves were absent in both ports, seiches with periods ranging from 2 minutes to 28 minutes were observed in Klaipėda and Karlshamn (Fig. 3), consistent with the presence of long waves in the system. Although frequency band analyses did not reveal substantial oscillation amplitudes, it is evident that the seiche propagated across the Baltic Sea from Karlshamn to Klaipėda.

The closure of the Klaipėda port extended beyond 24 hours, and even after the decrease of winds, unsafe navigational conditions persisted in the port.

In conclusion, as detailed in this study, the observed meteorological and oceanographic phenomena during the November storm in the Baltic Sea, underscore the complex interplay of atmospheric pressure changes, wind patterns, and coastal geography in shaping localized impacts.

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Flood risk assessment on the rivers of the Vistula basin within Ukraine

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1. Introduction

Studies of dangerous hydrological phenomena, which include floods of various origins, in particular rain and spring floods, remain extremely relevant due to the possible catastrophic consequences of such phenomena. To minimize the consequences, assessing and managing flooding risks is of great practical importance.

In the process of implementing Directive 2007/60/EC of the European Parliament and the Council of October 23, 2007 (European Union Directive, 2007), regulatory documents were developed in Ukraine, such as the Methodology for preliminary assessment of flooding risks, the Methodology for developing flood threat and risk maps, and the Procedure for developing a flood risk management plan, the main purpose of which is to reduce consequences of flooding, life and health of people, economy, cultural heritage (Resolution of the Cabinet of Ministers of Ukraine, 2018).

In the study, was the collection, preparation, and analysis of hydrological, meteorological raw data and data of remote sensing, used in the calculations of the maximum runoff of spring and rain floods in the studied basin, as well as further hydrological modeling of the flooding of individual catchment areas, which have potentially significant risks of flooding.

The flood risk assessment was carried out for individual areas of the catchment, that have potentially significant flooding risks (APSFR), which was determined according to the Flood Risk Management Plan in individual territories within the Vistula River Basin District for 2023-2030.

2. Data and methods

Calculations of the maximum runoff were carried out using the operator model developed by scientists at the Odesa State Environmental University (Ovcharuk, Hopchenko, 2018). The characteristics of the maximum runoff of the rare probability of exceeding both spring and rain floods were calculated. The result of the calculations is the maximum runoff modules, geographically generalized by the territory of the studied basin (Ovcharuk, Martyniuk 2020, 2021, 2023). Thus, the method allows us to determine the characteristics of the maximum runoff of the rare probability of exceedance in the absence of hydrological observation data in the territory of the studied basin.

The hydrologic modeling of flood zones was performed using HEC-RAS software developed by the U.S. Army Corps of Engineers (USACE). The constructed digital evaluation model, data of measuring works and calculated hydrographs were used as input data for modeling (Yalcin, 2020).

A Digital evaluation model (DEM) of the study area was developed using QGIS software based on SRTM images obtained from the Earth Explorer resource, as well as data from the Hydro SHEDS project conducted by the U.S. World Wildlife Fund to create digital data layers to support large-scale hydroecological research (Martyniuk, Ovcharuk, 2023).

Estimated hydrographs were built for spring and rain floods according to the methodology given in SNiP 2.01.14-87 and improved by E.D. Gopchenko.

3. Flood risk assessment

Determination of the inundation area was carried out on the example of the WGS Rata River – Volitsa. Modeling was carried out for spring and rain floods, as well as on actual and calculated (Q1%) hydrographs to compare the areas of flood zones (Fig.1).

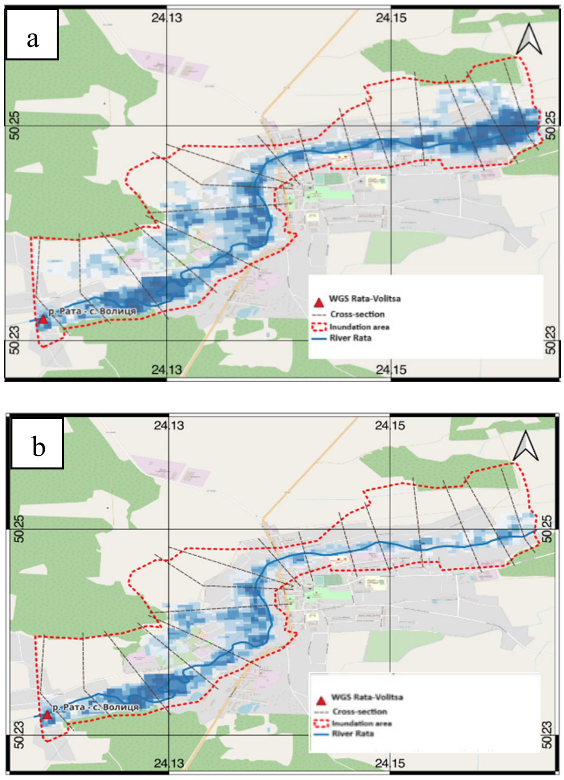

Figure 1. Flooding zone during the passage of spring flood (a) and rain flood (b) in the area of the WGS Rata River - Volitsa according to the calculated hydrograph (Q1%)

A comparison of the inundation area during the passage of the maximum runoff of spring and rain floods was performed according to the calculated and actual hydrograph. The total area of inundation according to the estimated hydrograph of spring flood was 7.40 km^2, and rain floods - 6.55 km^2. Since the maximum observed water consumption for typical years for the studied hydrological post was not one percent (the reliability of the maximum observed water consumption of spring flood was 3.2%, of rain floods - 3.8%), the flooded area was smaller - 4.05 km^2 for spring irrigation, 3.90 km^2 for rain floods. The study showed a significant dependence of the flooded area on

the relief of the area and the nature of the underlying surface.
An assessment of the flood risks was carried out for the APSFR of WGS Rata - Prystan in the absence of observations of the river runoff. In fig. 2 shows a part of the DEM relief of the studied area with the prepared two-dimensional flow model. The studied perimeter with 7 cross-sections, as well as a network of calculation cells, is displayed.

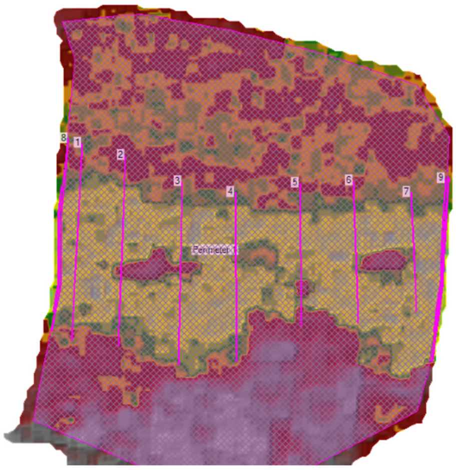

Figure 2. Two-dimensional flow model taking into account cross-sections (Rata river - Prystan village)

The total area of flooding was 2.21 km^2 (Fig.3). The number of objects that fell into the flood zone was determined, including buildings, residential buildings, cultural monuments, industrial facilities, agricultural areas, roads, and bridges.

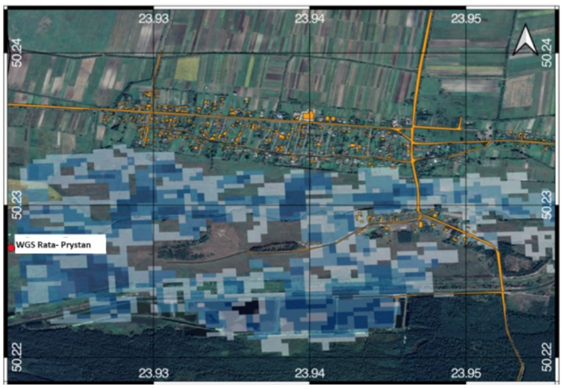

Figure 3. Flooding zone during the passage of spring flood in the area of the WGS Rata River - Prystan according to the calculated hydrograph (Q1%) in the absence of observations of the runoff

The flood risk assessment was carried out according to the Methodology of preliminary flood risk assessment developed by the Ukrainian Hydrometeorological Institute.
Such criteria as the nature of the consequences of flooding and the nature of the probability of flooding were determined, and, in accordance with them, the magnitude of the risk of flooding was determined.
The nature of the consequences of flooding is calculated as moderately significant based on data on the area of flooding and the number of flooded objects.
The probability of flooding, in turn, is determined as average, since the characteristics of the maximum runoff with a 1% probability of exceedance, 1 time in 100 years, were used in the modeling.
The magnitude of the flood risk is defined as moderate by the Methodology of preliminary assessment of flooding risks.

4. Conclusions

A methodology for determining the area of inundation zones during the passage of rain and spring floods in areas with the availability of observations of the runoff has been developed.
With the use of prepared maps of the characteristics of the maximum runoff for the Vistula River basin, a method for determining the areas of flood zones without runoff observations is also given.
The presented method can be used for other rivers of the Vistula River basin in order to determine the magnitude of the risk of flooding of the APSFR and is recommended for the purpose of further implementation of the EU Flood Directive in Ukraine and the implementation of the flood risk management plan in certain territories within the Vistula River Basin District for 2023-2030.

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Estimating frequency of extreme temperature events in Latvia based on skewed probability distribution.

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1. Introduction

Heatwaves are defined as periods when air temperature significantly exceeds climatological normal. Heatwaves are a major threat to both society and ecosystems. Heatwaves negatively affect human health. During heatwaves drought risk increases, which can cause forest fires or crop failure. Heat can cause infrastructure damage. Railroad tracks expand due to heat, which can lead to their damage. Air conditioning use during heatwaves increases, which can lead to electricity grid overload.

Longer and more intensive heatwaves have a higher impact on society. Due to climate change, frequency and severity of heatwaves is expected to increase. Therefore, it is important to estimate frequency of extreme heat events in the changing climate to minimize their adverse impact.

2. Statistical model

In this work, a statistical model is developed that estimates the return period of extreme heat events in Latvia. The model was used to estimate probability distribution of temperature related variables. Temperature related variables chosen in this work were daily mean temperature, highest and lowest daily maximum temperature, highest and lowest daily minimum temperature. As air temperature is autocorrelated in time, calculating return periods of heatwaves is different than calculating return periods of air temperature. Therefore, return periods of these air temperature related variables were calculated for periods with length between 1 and 30 days.

Usually, the probability distribution of temperature is calculated based on historical observations during a 30-year reference period. However, such method has downsides, which were addressed during this work. First, the classical approach assumes normal distribution of daily temperature. However, during the summer, the daily mean temperature distribution in Latvia is skewed towards higher temperatures and during the winter the distribution of daily mean temperature is skewed towards lower temperatures. Therefore, in this work skewed Student-t distribution was used to model daily probability distribution of temperature.

Second, due to climate change temperature has increased in the last decades. By using a 30-year reference period it is assumed that the mean air temperature during the period was constant. In this work the issue is addressed by assuming that the mean of the temperature distribution has increased during the study period. Such an approach allowed to calculate probability distribution of air temperature for each particular year. In Figure 1 estimated daily mean temperature distribution for the year 2024 is shown.

3. Identifying extreme events

Based on yearly probability distributions of air temperature return period of historical heat waves was estimated. Return periods of extreme heat events were strongly dependent on the analyzed temperature variable.

For example, during June 2021 heatwave on 21st of June record for the highest nighttime temperature in Latvia was broken. Such high lowest daily air temperature on June 21st has a return period of 4300 years. However, daily mean temperature on June 21st has a return period of 186 years and daily maximum temperature has return period of only 41 years. Based on the probability distribution most intense historical heatwaves were identified to examine their physical causes.

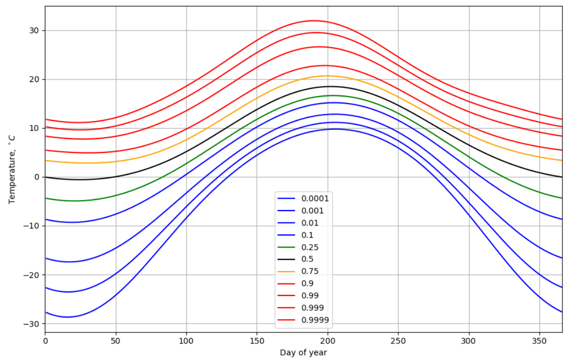

Figure 1. Probability distribution of daily mean temperature for 2024 in Latvia as a function of the day of year. Median (0.5), 25th, 75th percentiles (0.25, 0.75) and events with 10, 100, 1000, 10000 year return period are shown with the colored lines. 10-year return period is shown with line labeled 0.1 for coldest temperatures, and 0.9 – for warmest, and similarly for 100 year return periods (0.01-0.99), and so on.).

4. Causes of heatwaves

Heatwaves are caused by interaction between different processes in the atmosphere. These processes include advection, adiabatic heating due to air subsidence and diabatic heating due to solar radiation or moisture condensation. Knowledge about physical mechanisms behind heatwaves will allow to improve their modelling.

To identify mechanisms behind most extreme heatwaves in Latvia trajectories of air masses that bring warm air into the region were traced. By tracing air temperature, potential temperature, and humidity along the trajectories, contribution of different mechanisms in warming were identified.

5. Modelling of heatwaves

Using WRF atmosphere modelling software, mesoscale numerical modelling of historically most extreme heatwaves in Latvia was performed. Model results were compared to the historical observations to identify issues that arise when forecasting extreme heat events.

Large Scale Atmospheric Conditions related to Storm Surges in the North and Baltic Seas and possible Future Changes using a CMIP6 GCM Ensemble

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1. Introduction

Storm surges can seriously affect shipping as well as shoreline infrastructure. Strong onshore winds can lead to extremely high water levels that endanger waterfront structures, may severely restrict transportation along the waterways, and could therefore lead to economic losses. Further, the dewatering capacities of low-lying coastal areas may be reduced and could lead to flooding of critical infrastructure.

Climate Change will not only lead to further *sea level rise* (SLR) but also to changes in the large-scale atmospheric circulation that drives weather conditions in the North and Baltic Sea regions. In this study, we analyse these large-scale meteorological conditions, which lead to coastal storm surges and possible future changes thereof in climate change scenarios.

2. Data

Following the definition of the *German Federal Maritime and Hydrographic Agency* (BSH), storm surges at the German North Sea coast are defined as an exceedance of the *Mean High Water* (MHW) of at least 1.5 m. For the German Baltic Sea coast, this threshold is 1 m above *Mean Water* (MW).

Our study is based on water level observations during storm surges at the stations Cuxhaven (located in the German Bight of the North Sea), as well as Koserow, Warnemünde, Kiel, and Flensburg at the German Baltic Sea coast. For the analysis of past meteorological conditions related to the storm surges, we use ERA5 and NCEP R1 reanalyses *sea level pressure* (SLP) fields as input for the objective classification of circulation types.

In order to analyse potential future changes in the meteorological conditions favoring storm surges in the North and Baltic Seas, we extracted daily mean SLP fields from 23 model runs from seven different CMIP6 global models. For the analyses, we examined the four Tier1-scenarios of ScenarioMIP, namely SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. These span a wide range of socio-economic narratives and greenhouse gas concentration pathways for the remainder of the 21st century.

3. Methods

A general characterization of the large-scale atmospheric circulation is possible using defined circulation patterns or weather types (e.g. Lamb, 1950). At BSH, the automatic classification method developed by Jenkinson and Collison (1977) to objectify the "*Lamb Weather Types*" (hereafter LWTs) is an important part of the operational analysis of the state of the North and Baltic Seas region.

This method uses daily mean values of the SLP fields over the extended North and Baltic Seas regions (Figure 1), respectively, to calculate the vector components of the geostrophic wind and the vorticity.

The geostrophic wind is a good approximation of the large-scale wind conditions above the boundary layer. The LWTs are derived from the relationships between the geostrophic wind components and the vorticity. A reduced set of six characteristic weather types is classified to assure reliable and robust statistics: *Anticyclonic* (A), *Cyclonic* (C), *North-East* (NE), *North-West* (NW), *South-East* (SE), and *South-West* (SW).

Furthermore, the SLP data is used to categorize the gale strength (G) into four classes ("NUL" = *no gale*, "G" = *gale*, "SG" = *severe gale* and "VSG" = *very severe gale*). On top of that, the geostrophic effective wind speed (v_eff) – the part of the wind vector that has the strongest effect on the water level at a specific location – is estimated.

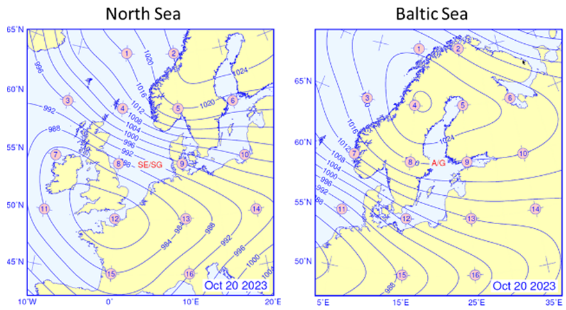

Figure 1. Sea level pressure fields for the North (left) and Baltic (right) Seas for 20 October 2024 with the respective LAMB weather types and gale indices derived from daily averages of NCEP sea level pressure (North Sea: SE\G, Baltic Sea: A\G); the grid points used for the LWT classification are marked as well.

4. North Sea

Our investigations show that the LWTs NW, C, and SW are the atmospheric drivers during storm surges in Cuxhaven (Figure 2), representing the German Bight.

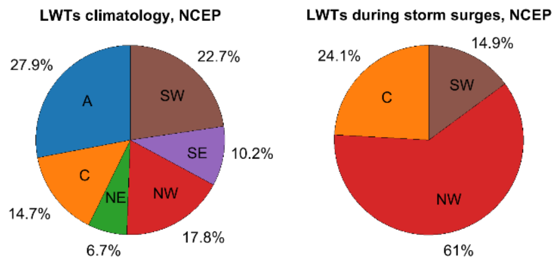

Figure 2. Left: Mean distribution of LWTs determined from daily means of NCEP sea level pressure for the entire period from 1951 to 2022. Right: Mean distribution of LWTs during storm surges at Cuxhaven between 1951 and 2022.

In addition, the distribution of v_eff projected at 295° for storm surges in Cuxhaven is clearly distinct from the climatology (Figure 3, orange bars): v_eff is always positive and higher than 10 m/s for most cases. The climatological probability distribution (blue bars) spreads from about -23 m/s to 31 m/s with a mean value of approx. 2.4 m/s. The 95th percentile of 13.3 m/s is close to the modal value of the distribution during storm surges (14 m/s). For the investigation of future climate projections, we use this 95th percentile of v_eff as a proxy for storm surge prone situations in order to assess potential changes of storm surge risk in the future.

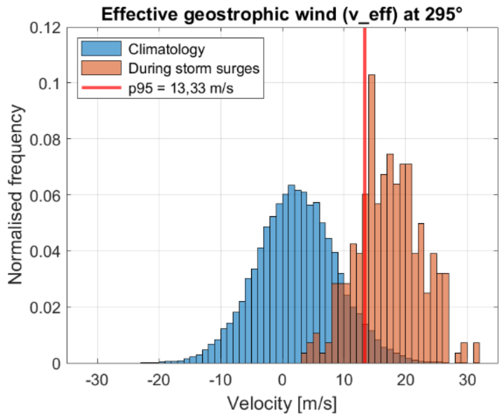

Figure 3. Distribution of the effective wind at 295° at the station Cuxhaven for the whole period 1951–2022 (climatology, blue) and during storm surges (orange). The red line indicates the 95th percentile of the climatology

Figure 4a shows the distribution of the occurrence of the derived LWTs SW, C, and NW per year for NCEP, ERA5, and the CMIP6-ensemble for the historical period (1971-2000) and the far future (2071–2100) in SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, respectively:

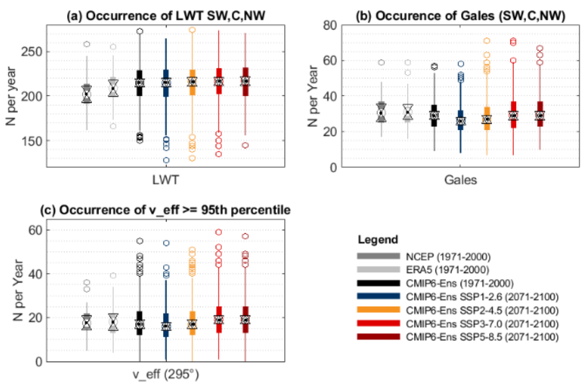

Figure 4. Boxplot of the yearly occurrence of (a) the Lamb Weather Type (LWT) SW, C, NW, (b) Gales, and (c) effective wind speeds >= 95th percentile for ERA5 (light grey) and the 23-member CMIP6 ensemble (black) for the historical period (1971–2000) and respective runs for each of the SSP-Scenarios 1–2.6 (blue), 2–4.5 (orange), 3–7.0 (light red), and 5–8.5 (dark red) for the far future (2071–2100). The Boxplots display the median (black dot), the interquartile range (25–75th percentile, box), the extremes, i.e., approximately ±2.7 sigma and 99.3% coverage, of the distribution (whiskers), and outliers (circles). Notches, depicted as triangles around the median, correspond to q2 - 1.57 (q3 - q1)/sqrt (n) and q2 + 1.57 (q3 - q1)/sqrt (n), where q2 is the median (50th percentile), q1 and q3 are the 25th and 75th percentiles, respectively, and n is the number of observations.

Despite the almost unchanged yearly mean occurrences in the sum of relevant LWTs and gales for the higher scenarios, we find an increase in the mean occurrence of days with v_eff ≥ 95th percentile (see Figure 4c). This results from the reduced occurrence in LWT C, and increased occurrence in the westerly LWTs SW & NW (not shown). Therefore, our ensemble projects an increase in the likelihood of atmospheric conditions favoring storm surges in the German Bight for the far future (2071-2100) under the scenarios SSP3-7.0 and SSP5-8.5.

It should be noted that the ensemble also projects a similarly strong opposite signal under the SSP1-2.6 scenario, indicating the chance of a decrease in the likelihood of atmospheric conditions favoring storm surges if global warming can be kept below the respective thresholds.

5. Baltic Sea

Essentially, we use the same data and methods as described for the North Sea on a slightly shifted 16-point grid over the Baltic Sea region (see Figure 1, right). The directions for v_eff are different for the Baltic Sea stations. Here, we show the first results for the station Koserow on the island of Usedom: Apparently, the driving LWTs are not as clearly determined as for Cuxhaven, i.e. storm surges occur during all LWTs. Yet, the favorable LTWs are NE and C (Figure 5, right).

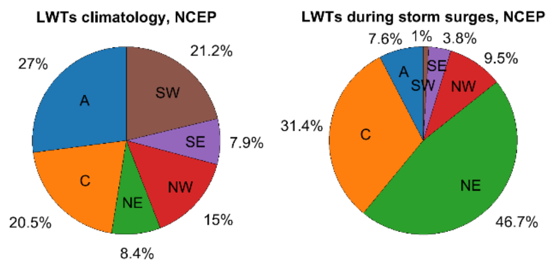

Figure 5. See Figure 2 but results for the Baltic Sea station Koserow between 1951 and 2022.

6. Outlook

Investigations for Koserow and the other stations in the Baltic Sea (Kiel, Flensburg, and Warnemünde) are ongoing; results are expected to be ready for the Baltic Earth Conference. Furthermore, this method could be applied to all stations within the North and Baltic Seas region and could prove beneficial for various implementations (e.g. investigations of negative storm surges; Jensen et al., 2022).

LWTs and gale days over the North Sea since 1948 are freely available for download at the *World Data Center for Climate* (WDCC, Loewe, 2022) and are updated yearly. Data for the Baltic Sea is currently being processed and will be available at the WDCC as well soon.

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The weather patterns favoring flash floods in southern Ukraine: a case study

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1. Introduction

Flash floods are one of the most dangerous and destructive phenomena that lead to high economic and human losses. Research shows that these events have become more frequent in Europe in recent decades, which may be caused by ongoing climate changes (*Meyer et al., 2022*).

Flash floods usually result from intense rainfall when deep convection systems develop under strong atmospheric instability. High antecedent soil moisture and landscape features can contribute to an extremely rapid rise in water level. In addition to the intensity of precipitation, its quantity and duration are important. The slow movement of precipitation zones is determined by weak-gradient low-pressure systems, which ensure the convergence of moist and warm air in the lower layers and weak flows at the middle troposphere. These conditions are favorable for the development of mesoscale convection systems (*Emanuel, 1994*).

The paper examines the synoptic conditions of several cases when intense precipitation was observed, causing a sharp local rise in water levels in rivers and settlements in southern Ukraine.

2. Data and methods

In this study, a modified Jenkinson and Collison classification, which takes into account the pressure field structure at sea surface level and at the level 500 hPa, was used to describe the synoptic processes which generated flash floods (*Miró et al.*, 2020). This classification was adapted for the territory of Ukraine using a 16-point scheme and contains 14 types of circulation, reflecting the daily structure of the pressure field and the advection of air masses in the lower half of the troposphere (*Semenova, 2023*). Data for daily pressure at the sea surface level (SLP) and heighs of 500 hPa pressure level from the NCEP/NCAR-1 reanalysis were used to determine circulation types.

Three cases of heavy rainfall that occurred in the southern regions of Ukraine (Odesa and Mykolaiv oblast`s) were selected for analysis. These regions are located in the Northern Black Sea Region, the climatic conditions of which are characterized by relatively low annual precipitation (350-450 mm). Information on the amount of precipitation and the maximum runoff of rivers was obtained from regular observations of the Hydrometeorological Service of Ukraine. Data about precipitation is present over a longer period than runoff. Mass observations of river flow in the study area of Ukraine began in 1925-1930 and are currently ongoing.

3. Flash flood cases

The formation of rain runoff is quite complex as a result of the interaction of meteorological factors that vary over time and territory, which determine the rainfall patterns (their intensity, duration, irrigation area) and soil and physical characteristics of the surface of river catchments that determine the amount of infiltration losses, speed, and time water running down slopes and channels (*Ovcharuk et al., 2020*). Examples of significant floods and their consequences in the study area are presented below.

August 2019. During August 3-4, 2019, extremely unfavorable weather was observed, moderate to heavy rains fell everywhere, and wind gusts up to 12-13 m/s were observed during thunderstorms. Heavy rainfalls covered the entire southern Ukraine, where the amount of precipitation significantly exceeded monthly norm. Abnormal rains were fixed in the Kherson region (Khorly, 105 mm; Bekhteri, 69 mm), Zaporizhzhia region (Kyrilovka, 88 mm), Zaporizhzhia, 121 mm and Mykolaiv, 100 mm. But the highest rate are noted for the Odesa region, where an extraordinary rain was observed at the Bilgorod-Dnistrovskyi weather station - 121 mm in 6 hours. As a result, the mudflow formed in the Mologa village (Bilgorod-Dniester district, Odesa region), and flash flood was in Odesa. On August 4, 2019, traffic was disrupted in the city of Bilgorod-Dnistrovskyi; agricultural and basement premises of buildings as well as some areas were flooded; sewer manholes were destroyed, and trees were felled.

September 2013. From September 10 to 14, 2013, in the Odesa region as a result of a continuous rainfall, an abnormal amount of precipitation fell from 41 mm to 270 mm, which led to the formation of a flood in the basin of the Kogilnyk River, which passes through the settlements of Tarutyne, Berezino, Peremoga, Chervone, Borodino of the Tarutyn district, Vesely Corner of Artsyz district and agricultural lands of Tatarbunar district. Of the total length of 243 km, 122 km of the Kogilnyk River is located in the territory of Ukraine. During the specified period, torrential rain fell in the amount of approximately 250.0 million cubic meters, which according to the river's passport data is 5.5 times more than the average annual flow of the river, which is 45.5 million cubic meters of water. According to to the information from districts, the area covered by precipitation amounted to 141.74 thousand hectares (1400 km^2), which corresponds to 35% of the total catchment area of the Kogilnik River (3910 km^2).

June 1955. In the third decade of June 1955, it rained very often in the South of Ukraine (daily from June 23 in Mykolaiv city). The rainfall on June 30, 1955, near Mykolaiv was catastrophic. During 2 hours, the precipitation rate was of 1.33 mm/min, with the highest intensity 2.92 mm/min for 5 minutes and 2.07-2.10 mm/min for other 14 minutes. The total amount of precipitation was 190.2 mm. The rain was accompanied by a strong thunderstorm, with hail, squalls, and tornadoes. But the area flooded by the rain was relatively small, about 1200 km^2. This rainfall caused a lot of material damage to the city. On the small dry stream Yaltinka with a catchment area of 1.2 km^2, located east of Mykolaiv, a powerful flow with a depth of 5.5 m formed. This stream destroyed adobe residential buildings in the densely populated dully. The 1.5 km long railway track near the Mykolaiv station was washed away, and train traffic was suspended.

4. The weather patterns

August 3-4, 2019

Circulation type NORTH ADVECTION (N_AD). The situation was characterized by the formation of a cyclone over the south of the Odesa oblast` on August, 3, and its rapid movement to the eastward (Fig. 1, a). Compared to the composite fields for the N_AD circulation type, the SLP throughout Ukraine was lower by 7-10 hPa, and in the cyclone area by 15 hPa. The tropospheric trough was deeper to the northeast of Ukraine, but in the rest of the territory geopotential heights at AT-500 were higher than average. Analysis of satellite images showed the presence of an active deep convection zone over the south of the Odesa oblast`, which formed in the warm sector of the cyclone (Fig. 1, b).

September 10-14, 2013

Circulation types SOUTH ADVECTION (S_AD)-EAST ADVECTION (E_AD)-SOUTH ADVECTION (S_AD)-EAST ADVECTION WITH CUT-OFF LOW ABOVE (E_AD_CL)-CYCLONIC (CYC). The situation was characterized by a low pressure with stationary fronts over the Carpathian region, followed by the formation of a cyclone over the south of Ukraine on September, 13 (Fig. 1, c). There was a change in circulation types during the study period as a result of the formation and slow movement of the cyclone, but most of Europe the process of anticyclone strengthening was observed.

Over the flash flood area, the SLP relative to the composite field for each type of circulation was predominantly lower. At the level of 500 hPa, with different types of circulation, significant positive height anomalies were observed, which characterized the strengthening of the ridge over all of Europe and as a result the localization of cyclone over the south of Ukraine. Analysis of satellite images showed the frontal cloud band over the flood area, which enhanced during the cyclon deepening (Fig. 1, d).

June 30, 1955

Circulation type EAST ADVECTION (E_AD). The SLP over Ukraine was lower by 5-10 hPa compared to the composite field of the E_AD circulation type. In the middle troposphere, on the contrary, the heights of AT-500 were above average over the entire Eastern Europe and corresponded to the blocking ridge. At base of this ridge the cut-of-low was formed over the Black Sea (Fig. 1, e). In the south of Ukraine, on the southern periphery of the anticyclone the high humidity (>60%) and strong instability was observed in troposphere (Fig. 1, f), which contributed to the occurrence of heavy rainfall.

5. Conclusions

Analysis of circulation types during periods of three extreme precipitation events in southern Ukraine, which caused local flash floods, showed their diversity, but all cases are associated with cyclogenesis over the flooding area, which occurs on the periphery of an anticyclone which is strengthening. These areas contain air flow convergence in the lower levels and convective instability in the upper layers, favorable for the development of deep convection systems and intense precipitation.

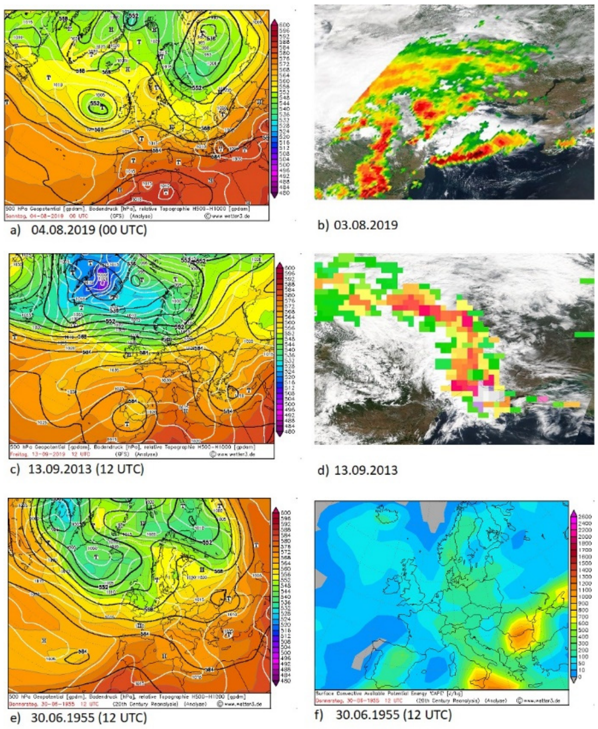

Figure 1. Maps of SLP and geopotential heights of 500 hPa (a, c, e) based on 20th Century Reanalysis; satellite images with precipitation rate intensity (b, d); map of CAPE (f)

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Negative emission technology carbon capture and storage

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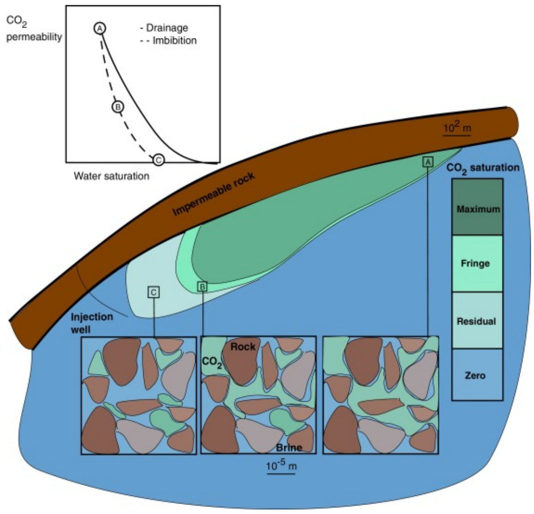
Negative emission technology carbon capture and geological storage CCS, mineral carbonation co2 injecting in basal rock, carbon capture utilisation and storage, CCUS,etc. Prohibition to avoid geohazards- CCS Continetal shelf, vertical water column seabed stratification, gashydrate continental slope instability geohazards, etc. Residual trapping mechanism geological carbon storage, intermittent geological carbon storage, carbon storage in depleted oil and gas reservoir, saline aquifer, seabed Geological CCS , CCS onshore & offshore, abandoned coal mine, underground coal gasification coal mine ,etc. CO2 storage in geological reservoirs ; CO2 plume location ; 2D ,3D and 4D seismic reflection surveys, 4D Seismic datasets (time lapse 3D seismic) for Seismic subsurface imaging of hydrocarbon reservoirs ,CO2 injection velocity pushdown effect, tuning effect, electrohydrodynamic effect on Seismic reflections, etc. New technology CCS geological hydrocarbon reservoir surveillance 4D Seismic time lapse 3D, Spot seismic focused seismic reflected seismic energy stacking over seismic trace and time.Carbonate reservoir carbon capture storage and utilization hydrogen production, hydrogen subsurface geological storage projects,etc.The trapping of CO_2 by capillary forces in the pore space of rocks is a key process for maximising capacity and ensuring the integrity of CO_2 sequestration at industrial scales. When CO_2 is injected into a deep subsurface geologic formation it will displace the resident fluid, generally brine and in some cases hydrocarbons, and migrate in response to buoyancy and pressure gradients. As the reservoir brine imbibes back into the pore space pursuant to the migrating CO_2 plume, small isolated blobs of CO_2 will be trapped by capillary forces: this is known as capillary or residual trapping. The isolated blobs are of the size scale of the pores of the rocks, tens to hundreds of micrometers, and the process is controlled by fluid physics and interfacial forces at the micron scale. Because the trapping, however, is pervasive over the hundreds of meters to hundreds of kilometres of the plume extent it plays a major role in plume migration, immobilisation, storage security and ultimately the capacity for storage resources to safely contain injected CO2 . Image Processing flow of fluid in porous rock edge detection GPU graphic processing unit gradient filter sobel filter edge detection 3D visualization rendering immersive technology virtual reality and visualization, etc.Capture and storage or utilization of *biogenic* CO2 is sometimes abbreviated as "BECCS/U", sometimes as "BECCUS" and sometimes as "*Bio-CCUS*". Biogenic carbons refer to all those which are stored in, sequestered by and emitted through organic matter. The most common biogenic feedstocks include trees, plants and soil biochar, which absorb carbon as a natural part of their life cycle. Glaciology Carbon Capture And Storage: glacial rock flour from Greenland show that it can capture significant amounts of CO2 and provide a wider array of nutrients than commercial organic fertilizers, resulting in improved crop growth. In the long term, the glacial rock flour can be of great importance in stopping climate change. Rock "flour" produced by the grinding under glaciers can trap climate-heating carbon dioxide when spread on farm fields,.Natural chemical reactions break down the rock powder and lead to CO_2 from the air being fixed in new carbonate minerals. Scientists believe measures to speed up the process, called enhanced rock weathering (ERW), have global potential and could remove billions of tonnes of CO_2 from the atmosphere, helping to prevent extreme global heating.Soil fertility naturally depends on rock weathering to provide essential nutrients, so enhancing the process delivers an extra benefit.Innovative gas capture technologies with the objective to mitigate CO2 and CH4 - nanoparticles (NP) as sorbents of CO2 and CH4, which are the two most important global warming gases. The Fe3O4-graphene and the MOF-117 based NPs show the greatest CO2 sorption capacities, due to their high thermal stability and high porosity.nano materials absorbents to decrease the cost of capture and to scale-up the technologies to minimize large-scale power plant CO2 emissions.Metal organic framework MOF-177 is one of the most promising crystalline porous adsorbents for hydrogen adsorption , CO2 and CH4 Geosequestration is often assigned as carbon capture and storage (CCS), carbon capture and geological storage (CCGS), carbon dioxide capture and storage, or clean-coal technology-Under Ground Coal GasificationUCG,Hydrogen production from fossil fuel ,etc. Geological storage (Aquifer storage) Underground CO2 storage of any kind must take place in sedimentary rocks. Only they are porous enough to have storage capacity of interest. Storage of the CO2 in underground sites beneath a layer of impermeable rock (cap rock) which acts as a seal to prevent the CO2 from leaking out is the most popular option at present. There are three main types of proposed underground storage sites: Deep saline water-bearing formations (saline aquifers), Depleted oil and gas reservoirs , Oil reservoirs that may be used for CO2 Enhanced Oil Recovery (EOR) , Deep coal seems containing methane (Enhanced Coal Bed Methane Recovery (ECBM) , Deep ocean storage. Methane Hydrate(white gold) Reservoirs – CO2 hydrates are more stable and if CO2 is injected into a methane hydrate reservoir, it will displace the methane hydrate by capturing the water from the methane hydrate and releasing the methane. The issue is low permeability because the hydrates are solids filling the pore spaces . Microbial Enhanced Methane Production- Technology to enhance biogenic methane production, or methanogenesis, in deep unmineable coal beds. This would potentially have numerous benefits:accelerating methane production in naturally occurring coal bed methane reservoirs , converting sequestered CO2 to methane by injecting CO2 or flue gas into coal beds to enhance CBM recovery , increasing shale gas recovery. UCG in combination with CCS (CO2 capture and storage) shows considerable promise as a low cost solution to carbon abatement. The composition of the syngas is particularly suited to CO2 capture and the high pressure from deep UCG will require smaller and less costly plant. The possibility of storing CO2 in nearby coal seams is a further option. Geoengineering is the idea of applying planetary engineering to Earth. Geoengineering would involve the deliberate modification of Earth's environment on a large scale "to suit human needs and promote habitability". The global recovery of hydrocarbons from the subsurface using integrated geoscience and engineering technology has been termed 'petroleum geoengineering' as an activity with global impact. Geophysical techniques employed for the risks assessment of CO2 storage in geological reservoirs ; CO2 plume location ; 2D ,3D and 4D seismic reflection surveys, Wellbore to surface and cross wellbore seismic measurements, NMR (Nuclear Magnetic Resonance) ,Electroseismic(ES),Grond Probing RADAR, Electrical and electromagnetic methods ,Magnetotelluric,CCRI-Capacitively Coupled Resistivity Imaging, MASW-Multichannel Analysis of Surface Waves, SASW-Spectral-Analysis-Of-Surface-Waves, Land surface deformation using satellite imaging (InSar) or tiltmeters, Gravity, Reservoir pressure monitoring, Wellhead and formation fluid sampling, Natural and introduced tracers, Fiber optics sensor DAS-Distributed acoustics sensor, DTS- Distributed Temperature Sensor, etc. Geosequestration seismic data is analysed by SEISMICUNIX. GHG Green House Gas mitigation is controoled by geosequestration carbon capture & storage.



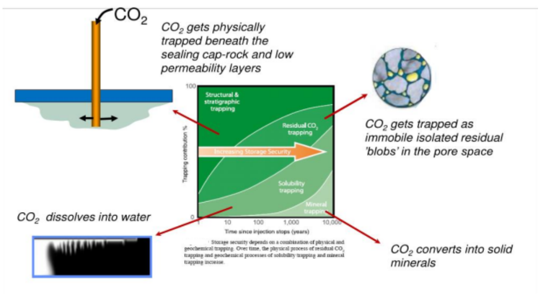


Fig1. A sketch of key processes governed by capillary trapping after CO_2 injection has ceased at a storage site. Plume migration is limited by the trapping as large fractions of the plume are immobilised. Capillary trapping is secure over long timescales and avoids buoyant stress on overlying cap rock layers.

Conclusion, Discussion and Perspectives:

By healthy observation of the present global warming situation of of our planet earth system , pertinent task before geoscientist & environmental technologists to control green house effect by employing Carbon Capturing & Storing Technolgy,Underground Coal Gasification, Underground Gas Storage. Geosequestration (carbon capture and storage (CCS), carbon capture and geological storage (CCGS), carbon dioxide capture and storage, or clean-coal technology) plays a pivotal role in mitigation of green house concentration. Use of fossil is a major source of excess CO2 that contributes to the increased concentration of greenhouse gases in the atmosphere. There is a compelling need to reduce the concentration of CO2; as a high concentration is likely to produce rapid climate change. Capturing and storing of CO2 by injecting it in geologic formations is a mitigation option. Proven and emerging geophysical technologies could assess the reliability and long term stability of CO2 storage to meet the challenge of monitoring CO2 sequestration. Monitoring and verification are the other challenges in geologic CO2 sequestration. Additional research and development efforts are needed in adapting currently proven and emerging geophysical tools applied for other applications and also in developing new innovative tools to CO2 sequestration application. The optimum site selection for geologic storage requires thorough analyses of data, integration of results and fully characterizing the subsurface formations. Bifurcation theory is employed for gemechanics of reservoir to carbon capturiing technologyCOMSOL is employed for computational fluid dynamics multiscale flow of fluid and geophysical metthods .

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https://co2datashare.org/dataset

Session C

Sea level dynamics, sediment dynamics, coastal processes and impacts on coasts

Reconstruction of post-glacial eustatic sea level in the south-eastern Baltic Sea

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There have been a number of attempts to reconstruct water level changes in the Baltic Sea during post-glacial time as a whole, as well as in individual sectors, including the Lithuanian coastal zone and adjacent offshore areas. As a result, a number of generally controversial relative sea level (RSL) curves of the south-eastern Baltic Sea have been published. The reason for such diversity and incompatibility of RSL curves is that the different authors have been guided by one or another concept of data interpretation, have given priority or, on the contrary, have ignored a number of geochronologically dated objects, have estimated or not estimated a factor of glacio-isostatic adjustment (GIA) and other neotectonic movements, etc. However, for paleogeographic reconstructions of the development of the Baltic Sea, the eustatic water level curve would be much more useful. The Lithuanian coast from the last glacial retreat to the present covers the transition zone between glacio-isostatic uplift in the northern part of the Baltic Sea and subsidence in the southern part. Thus, the Lithuanian coast and offshore could be a suitable polygon for the reconstruction of eustatic sea level (ESL).

The construction of an ESL curve on the Lithuanian coast is based on two main moments: (1) a strong selection of reliable dated objects indicating the water level position (key indicators), and (2) an estimation of the character and amplitudes of the GIA. It was found that a reliable reconstruction of the water level in different paleobasins is possible according to a very limited number of reliable key-indicators: a) rooted tree trunks (*in situ*) on the seabed, b) submerged footprints of human activities (in our case – wooden fishing fence), c) marine shells (*in situ*), d) some selected layers (*in situ*) of peat and freshwater gyttja. The key indicators were dated by methods of absolute geochronology: wood, peat, gyttja, marine shells – by radiocarbon (^{14}C) method (bulk samples only), marine and lagoon sand – by optical stimulated luminescence (OSL and IR-OSL) methods. The most important indicators of sea-level changes are dated rooted tree trunks (*in situ*) found on the seabed during underwater archaeological investigations.

The model of GIA for the Lithuanian coastal area is based on the estimation of the present positions and heights of ancient coastlines identified by onshore relicts of cliffs, terraces and recessional washout scarps, the age of which is confirmed by data from geochronological investigations. The results of the state geological mapping of the Quaternary sediments at the scale of 1:50 000, carried out for the entire Lithuanian maritime region, as well as the data of the Geological Atlas of the Lithuanian Coast at the scale of 1:5 000, served as a background for such an assessment. A few onshore points with dated peat and freshwater gyttja at different elevations were also considered. The primary (original) heights of the key indicators of sea level position were recalculated according to the presented model; the present sea level was taken as the "zero" point. As a result, a single ESL curve was constructed for the entire Lithuanian coastal zone, but it needs to be detailed in the future.

The plotted ESL curve shows that some shorelines in the southern part of the Lithuanian coast, located above the present sea level and formerly attributed to the Baltic Ice Lake (BIL), are most likely the relics of local ice lakes (i.e. meltwater basins), while the position of the BIL shoreline may have been a few metres below the present sea level. The lack of factual data from seafloor did not allow a reliable reconstruction, especially for the period from 11 to 8 ka BP. As a result, the reliable identification of the coastal positions and their heights during the Yoldia Sea stage and the beginning of the Ancylus Lake stage is still problematic. It can be argued that during the Ancylus Lake stage the water level was lower than in the World Ocean (WO). Thus, it can be assumed that some temporary influxes of seawater (transgression at the end of Ancylus Lake and the Early Littorina Sea transgression) occurred in this basin when the sea-level rise in the WO exceeded the amplitude of the GIA in the area of the Danish straits. According to this interpretation, it allowed only transgression of Ancylus Lake, but not drainage. A very rapid (catastrophic) influx of seawater into the Baltic basin around 7.7-7.6 ka BP can probably be explained only in one way – by a big difference between the sea level in the WO (at least about 20 metres) and the water level in the Baltic Basin during the Early Littorina Sea stage.

The assumptions made contradict a significant part of the existing views on the development of the Baltic Sea in the post-glacial period, so this study has to state the fact that the correlation of the constructed eustatic sea level curve for the south-eastern Baltic Sea with the eustatic sea level rise curve in the World Ocean is still problematic and needs further investigations and discussions.

Scour effect in Łeba, poland – Impact of submerged breakwaters

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1. Submerged breakwaters as a form of coastal protection

Coastal infrastructure is one of the most general forms of coastal protection. The most common structures, such as sea walls, breakwaters, and groynes, are generally well understood and extensively covered in literature in terms of their attributes and their negative (erosional) impacts on the coastal zone (Burchart et al. 2015, Ostrowski et al. 2016, Szmytkiewicz et al. 2022). One form of construction that needs to be considered is submerged breakwaters. The purpose of these structures is similar to the others, as the mechanism of submerged breakwaters involves dissipation of incoming wave energy and, as a result, reduced erosion in the area near the coastline. An additional effect of breakwaters is stopping sediments from escaping the area alongside seaward currents. The advantages of using underwater structures include improved seawater exchange (improving water quality in the beach area), preventing the creation of sand spits (Na'im et al. 2015), and no visual pollution, which is especially important in locations with heavy tourism.

Figure 1. Submerged breakwater. Author: Oleg Kovtun

However, there is an inherent risk of structural subsidence associated with the construction of submerged breakwaters. Subsistence is a result of erosion around the foundations of the structure, also known as the scouring effect (Mutlu Sumer et al. 2001). Wave-induced vibrations of the breakwater can also influence this effect. The resulting coastal erosion that can follow the formation of a scour is a topic that has not been extensively covered before. For that reason, an attempt was made to analyze the potential relationship between submerged breakwater, scour generated around this structure, and beach and dune erosion. Using an example from the South Baltic Sea, interesting phenomena are presented, and mechanisms generating beach erosion are discussed.

2. Area of analysis

The place of interest is situated near the port of Łeba, located on the east coast of Poland. Łeba is a port town, one of the biggest in the region, and its beaches are a popular tourist attraction.

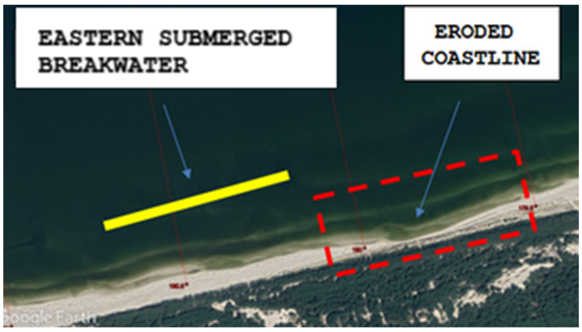

Figure 2. Location of the breakwater and eroded coastline east of the Łeba Port.

A set of submerged breakwaters is located about 3 km east of the Łeba port and was constructed in 2016. It consists of two segments containing eight elements with a total length of 2300 m. They are located about 200 m from the shore, at a depth of around 2,5 m. In the near vicinity of the breakwater, part of the coastline has suffered from significant erosion (Fig. 2). The cut segment is about 300 m long and it is deep enough that the sea is now reaching the base of the dune.

3. Link between the breakwater and erosion – methods of analysis

The investigation of the relationship between the breakwater and the area of erosion involves multiple steps. It is necessary to examine the documentation from the construction company managing the project and the reports from the months following the placement of the breakwater.

Furthermore, the mechanics of sediment transport in this particular area of the Baltic Sea need to be fully understood by a review of existing knowledge related to coastal morphodynamics in the region. Works of researchers such as Furmańczyk and Musielak (1974), Baraniecki and Racinowski (1989), Rożyński et al. (2018) and Szmytkiewicz et al. (2022) were used in the analysis.

Additionally, changes in the coastal zone need to be translated into a sediment transport model to follow the evolution of the shoreline on a step-by-step basis. LIDAR data from the years between 2013 and 2022 was used as a point of comparison between two different periods.

4. Results

Between 2013 and 2022, there was a noticeable retraction of the shoreline in the analyzed segment of the coast. The steepness of the dune near that area markedly increased as well. Around the year 2018, sediment accumulation was becoming noticeable on the coast segment parallel to the breakwater, while the erosion on the eastern side of the beach was increasing. The scour around the breakwater started forming within a year after its construction in 2016.

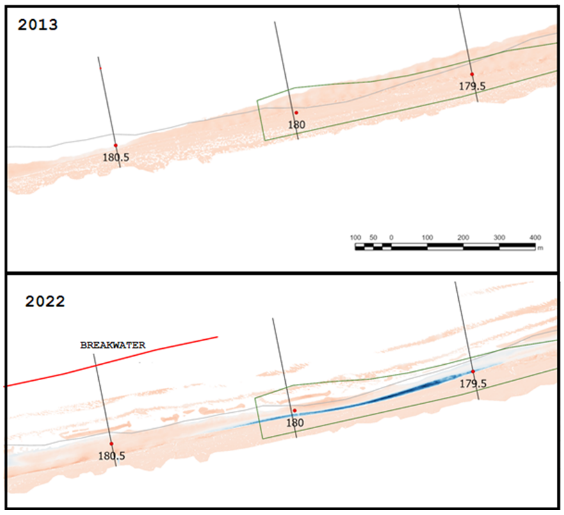

Figure 3. Shoreline evolution, 2013 -2022. The blue line represents the lost coastal sediments.

Between 2013-2018 the shoreline receded by nearly 40 m. In the years 2021-2022 the shoreline receded by about 20 m. In some parts, the dune lowered by about 5 m. Total recession amounts to 60 m in a nine-year period.

It has been concluded that the scour formed around the eastern part of the breakwater extended tens of meters in the eastward direction. The depth in parts of the area changed from less than 3 m to around 7 m. This resulted in higher waves being able to approach the coast during storm events, and the energy dissipation from wave breaking started occurring nearer to the coastline, which caused a destructive effect on the sediments.

All the results indicate that the process of severe erosion in the area was caused by the scour around the breakwater. This will likely continue in the future unless measures are undertaken to address this process. Beach nourishment is a proposed method of slowing down the erosion and ensuring the beach doesn't completely wear away in the future.

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Modeling volumetric changes of sandy coast during various hydrodynamic conditions (case study Dziwnów Spit)

Natalia Bugajny

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1. Introduction

Sea level rise and increased number of storm events have recently become real hazards in coastal areas, especially those with low dune berms as their first line of defense. If coastal parameters are insufficient to resist these phenomena, the continuous dune berm may be breached, leading to inland flooding. Therefore, to mitigate the adverse effects of coastal hazards, it is necessary to develop a tool that would allow emergency units to be ready to launch specific procedures to mitigate these hazards.

Coastal zone studies are increasingly supported by numerical models that determine shoreline displacement and volumetric changes induced by extreme events. On the other hand, the global literature includes only a few papers focused on deployment of numerical models to moderate and weak hydrodynamic conditions.

Coastal models can be used in process of crisis management in form of an early warning systems and for coastal zone modeling systems that are convenient tools for coastal zone management (Barnard et al., 2014 ; Furmańczyk et al., 2014; Haerens et al., 2012). However, it should always be kept in mind that models have limitations in reflecting the natural processes that occur in coastal zones. These limitations result from simplified assumptions or equations that describe coastal processes and from insufficient availability of up-to-date datasets; hence, these models may generate errors. It is essential from the perspective of forecasting changes of the coast in short-term scale and its development tendencies in the long-term.

The goal of this study is to asses volume changes in dune coast induced by extreme, moderate and weak hydrodynamic conditions using XBeach model (Roelvink et. al., 2009) in 1D and 2D mode and to answer the questions about the validity of pre-storm data and the transferability of calibration parameters in space and in various model operation modes.

2. Data and methods

The studies were carried out on a dune coast of Dziwnów Spit located on the western coast of the southern Baltic. This spit is well protected by diverse coastal engineering structures such as groynes, seawalls and beach nourishment that modify the course of natural processes (Dudzińska-Nowak, 2006), which makes this area quite a complex coastal system.

In the research numerous datasets that diverge from each other in terms of form and accuracy were used. The morphological data included bathymetric-topographic profiles delivered by the Maritime Office in Szczecin as a part of the annual monitoring program of the coastal zone. (Bugajny et al., 2013; 2015). In addition, cross-shore profiles were surveyed using GPS RTK (Bugajny and Furmańczyk, 2014) and data from an airborne laser scanner (Dudzińska-Nowak and Wężyk, 2014) was used. Moreover, two sheets of orthophotograph were also applied to the study and digitalized to comply with the PUWG 1922/19 coordinate system. Resultant orthoimages were saved as uncompressed TIFFs, with a pixel size of 0.15 m.

Hydrodynamic data in form of time-series of water level were registered by a tide gauge located in the Dziwna mouth from station of Institute of Meteorology and Water Management – National Research Institute.

Basic wave parameters were derived from the WAM model (WAMDI Group, 1988), shared by the Interdisciplinary Centre for Mathematical and Computational Modeling, University of Warsaw (ICM UW). For the Baltic Sea verification tests of the WAM model proved very good correlation between modelled and measured wave parameters (Paplińska, 1999).

To simulate coastal changes caused by extreme storm events, the profile (1D) mode of the XBeach model was adapted to 19 cross-shore profiles located along the Dziwnów Spit. The model was calibrated with a storm event in 2009 that caused significant changes to dunes and beaches. To simulate moderate and weak hydrodynamic conditions that do not cause changes in the dune system, yet only at the beach and in the nearshore, the model was applied in 2D mode for timeframes in 2012 which were classified means of hierarchical cluster analysis using Ward's method by Bugajny and Furmańczyk (2014). An evaluation of model performance was made based on the Brier skill score (BSS), the visual match of the profile shape (VMS), the absolute volumetric change error (m^3/m) and the relative volumetric change error (%).

3. Results

3.1. Extreme events

The calibration of the model in 1D mode for particular profiles led to a good coherence between the real and the modeled volume changes, as the mean absolute error was ca. 4 m^3/m, and the mean relative error amounted to ca. 20% for a single profile. The worst results were obtained for profiles located near coastal engineering structures. The absolute error there reached as high as 10 m^3/m, while the relative error reached 60% (Bugajny and Furmańczyk, 2022).

Another aspect analyzed in the research was the impact of the adopted set of calibration parameters on the predicted volumetric changes on the coast. The most common approach for 1D modeling is to determine the optimum model parameters for one profile and to apply them to the selected coast section as long as the alongshore characteristics are sufficiently uniform. The research showed that among the most favorable profiles in this respect, their location nor any other criterion do not provide the answer which profile should be representative. It seems reasonable to use a set of averaged parameters from all profiles simultaneously because the relative error rate of these sets varies between 20 and 40%. (Bugajny and Furmańczyk, 2022).

The last issue of the application of the 1D XBeach model consisted of an investigation of how the bathymetry data recorded before the storm influence the volumetric changes determined by the model. This aspect is crucial due to the substantial difficulty of obtaining data just before and after storm events and updating the bathymetric data exported to operational online early warning systems. This study revealed that the impact of the bathymetry on modeling volumetric changes was evident up to 100 m off the shoreline and to a depth of 2 m. A change in the seabed slope of 1-2% within the first 40 m off the shoreline, and hence a change in the nearshore volume of 20-30 m^3/m in the first 60 m, may increase the difference between the real and modeled changes in the volume of the subaerial part in profile by ca. 6-8 m^3/m (Bugajny and Furmańczyk, 2022).

3.2. Moderate and weak hydrodynamic conditions

An analysis of accuracy in determination of volumetric changes in the dune coast, with XBeach applied, provided an average absolute error of 1.5 m^3/m in a 2D model calibration process. For modeling morphological changes for 7 timeframes classified into 3 groups of hydrodynamic conditions (Bugajny and Furmańczyk, 2014), the same input data on bathymetry and topography had been accepted to all these timeframes.

Within a validation process in the 2D mode, the average absolute error in a determination of volumetric changes in the beach induced by moderate and weak hydrodynamic conditions was ranging from 0.64 m^3/m to 2.42 m^3/m depending on the group of hydrodynamic conditions.

An analysis of balance of volumetric changes (m^3/m) revealed a high value of correlation coefficient (R) between real and modelled balance for all timeframes – 0.79 and for the ‘strongest’ group – 0.91. For the remaining groups of hydrodynamic conditions, no such correlation was observed.

Furthermore, the temporal analysis of the sum of beach volumes proved that a rising trend was observed over 4 months. Thus, moderate and weak hydrodynamic conditions caused the accumulation within the area of study. XBeach reflected this trend well, producing a difference between measured and modeled sum of volumes of 7.27 m^3/m at the end of the timeframe, which is close to the volume determination error by the model.

4. Conclusions

The application of the XBeach numerical model to determine the volumetric changes caused by various hydrodynamic conditions (form extreme events to weak hydrodynamic conditions) to the southern Baltic dune coast using the example of the Dziwnów Spit allowed us to define:

- the calibration parameters of the 1D and 2D mode of the model;
- the absolute and relative errors of determination of volumetric changes of the dune coast;
- the possibility of using a set of parameters for all profiles at the same time with the determination of related errors;
- the impact of prestorm bathymetry on the modeled volumetric change.

Results obtained in the studies seem to be particularly important in assessment of extension of XBeach application in warning systems and inventory control of effects and hazards in the coastal zone driven by different hydrodynamic conditions.

Acknowledgments

This research was conducted and financed as part of two projects: ‘Satellite Monitoring of the Baltic Sea Environment’, contract No. POIG.01.01.02-22-011/09 funded by the European Union through the European Regional Development Fund and ‘The Oceanographic Data and Information System eCUDO.pl’ - contract No. POPC.02.03.01-00-0062/18-00 funded by the European Union through the Operational Programme Digital Poland 2014–2020 Fund.

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Major changes to directional forcing of sediment transport along the eastern Baltic Sea coast

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1. Introduction

Sediment transport in the nearshore is predominantly driven by wind waves. In the Baltic Sea waves are almost fully driven by local wind fields. This feature gives rise to spatially and temporally intermittent wave fields. Most of annual wave energy brought to the Baltic Sea coasts is supplied by relatively short and steep wind-seas. Such waves often arrive the shore at a large angle with respect to the shore normal. Consequently, the wind direction and thereby the propagation direction of waves during the strongest storms in the year play a key role in the formation of alongshore sediment transport.

Changes in weather patterns in the Baltic Sea region may have led to modifications in the directional structure of wave fields, particularly in the stormiest months of the year (Soomere et al., 2015) when most of the annual sediment transport takes place. These changes are particularly concerning for eastern coast of the Baltic proper that develops mainly under the impact of two predominant systems of strong waves driven by south-western (SW) and north-north-western (NNW) winds (Soomere, 2003). These wave systems produce a delicate balance of alongshore transport (Soomere and Viška, 2014). In such situations even a small change in the predominant storm wave approach direction, can lead to significant modifications in alongshore sediment transport patterns (Flor-Blanco et al., 2021) and drastic results on the coast.

This study focuses on the changes in the wave-driven longshore sediment transport along the eastern coast of the Baltic Sea. Ultimately, this analysis enables the identification of coastal areas at risk of significant change or threatened by large-scale erosion.

2. Study area and methods

The analyses cover the entire nearshore of the eastern Baltic Sea from the northern tip of Hiiumaa, Estonia, to Sambian Peninsula. The calculations of alongshore sediment transport utilize a recent reconstruction of the wave climate of the eastern Baltic Sea, with a spatial resolution of 0.5–1 nautical mile. Wave time series with 1 h resolution are replicated using a triple-nested high-resolution version of the SWAN model forced for the years 1990 to 2021 by ERA5 winds (Giudici et al., 2023).

The time series of wave-driven directional alongshore sediment transport in about 1–1.8 km long coastal segments are estimated using the Coastal Engineering Research Centre (CERC) approach (USACE, 2002). This application requires wave properties at the wave breaker line that are evaluated based on the joint impact of refraction and shoaling processes resolved in the frame of linear wave theory (Soomere et al., 2015).

Changes to the alongshore sediment transport caused by possible alterations of wave approach directions are analysed with a resolution of 30°. This resolution allows to specify the prevailing wave direction(s) that drive(s) the majority of alongshore transport at each coastal section, and subsequently to quantify the contribution of waves from different prevailing directions to the annual net transport in this section. These directions are identified for both positive (counter-clockwise) and negative (clockwise) transport directions. Doing so makes it possible to also highlight coastal areas where a bi-directional sediment transport pattern exists and to evaluated changes to longshore sediment transport created by changes in these patterns.

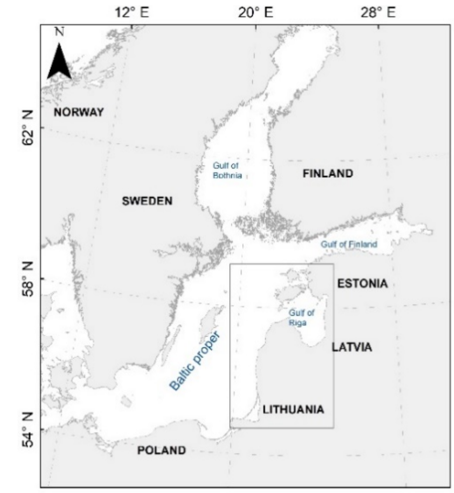

Figure 1. Study area. Box indicate coastal areas covered by longshore sediment transport analyses. The model grid points are chosen in the nearshore at a depth about 10–25 m.

3. Directional distribution of longshore sediment transport

The majority of annual alongshore sediment transport is driven by waves approaching from a narrow directional range within 30°. The contribution of wave fields from such a range is up to 80–90% in certain coastal sections (Fig. 2). This feature highlights almost unidirectional nature of wave fields that create intense sediment transit in many coastal sections (Soomere and Viška, 2014). Reasonable changes in the properties of driving wind and wave fields may affect the magnitude of sediment transport in such sections but do not alter its direction.

The situation is more delicate in sectors where two prevailing wave systems jointly form sediment transport. Alterations in these wave fields are likely to significantly impact on the relevant coastal sector.

The predominant wave direction responsible for the majority of the annual net alongshore sediment transport varies significantly (Fig. 2). The primary driving force on the coasts of Hiiumaa and Saaremaa are usually waves from

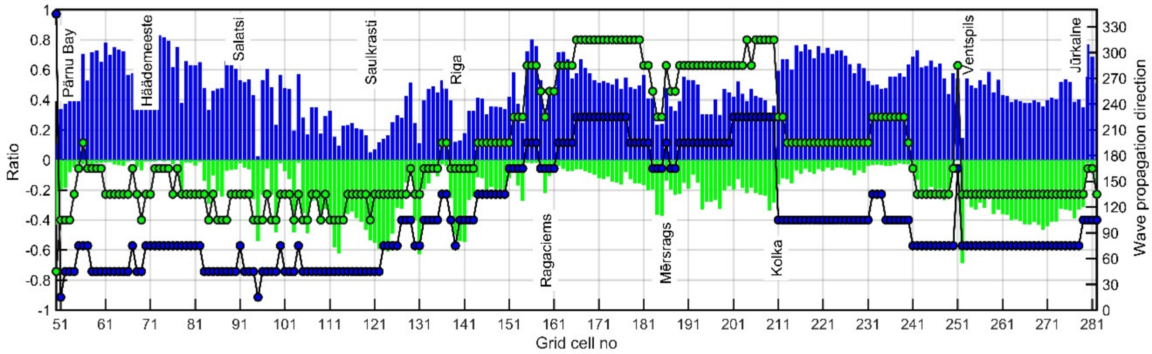

Figure 2. Properties of prevailing annual alongshore net sediment transport from Pärnu Bay in the Gulf of Riga up to Jurkalne, Latvia, on the open Baltic proper coast. Blue bars: ratio of positive to total net annual transport driven by waves within the prevailing 30° range. Blue circles: wave direction driving positive sediment transport in the given coastal section. Green bars: ratio of negative to total net annual transport driven by waves within the prevailing 30° directional range. Green circles on a black line: directional range of waves driving negative direction sediment transport in the given coastal section. Y-scale on the right: wave propagation direction (±15°).

the SW but in some sections waves from the NNW. The alongshore sediment transport from Pärnu Bay to Skulte is predominantly driven by waves from directions 210°–240° (Fig. 2).

The western shore of the Gulf of Riga up to the Cape Kolka is sheltered against waves from the SW and the alongshore sediment transport is predominantly driven by waves from the north and northeast. The Baltic proper shore of Latvia reveals an interesting bi-directional pattern: waves from two prevailing directions drive almost entire longshore sediment transport in this region. Transport to the north is driven by waves approaching from 240°–270°, contributing about 40–50 % of the total annual sediment flux. Sediment flux to the south forms 30–40% of this transport. It is driven by waves approaching from 300°–330° that mostly represent the contribution of storms to the alongshore sediment transport.

4. Changes in the alongshore sediment transport

Significant changes have occurred to the directional distribution of alongshore sediment transport driven by waves from these directions. The alongshore sediment transport driven by the waves from the NW–NNW has decreased over 31 stormy seasons (June to May) in 1990–2021. These alterations are specifically highlighted by variations in the transport driven by waves within a narrow directional range. This implicitly reflects certain shift in the wind patterns in the Baltic Sea region, including alterations in the storm wave fields.

The described feature reflects a considerably changed balance of these two wind and wave systems in the bi-directional alongshore sediment transport regime on the Latvian shore of the Baltic proper. This change may have led to substantial alterations in coastal processes.

5. Conclusions

This analysis reveals that the majority of alongshore sediment transport along the north-eastern Baltic Sea shores is governed by waves from one or two narrow directional ranges. Such wave systems contribute about 80% of sediment transport in many coastal sections. We have identified considerable changes in the relative role of waves from these prevailing wave directions on the net alongshore sediment transport. Most importantly, the contribution by waves from the NW has significantly decreased for a large part of the study area.

This change is apparently already reflected in the course of coastal processes, particularly in the observed increase in erosion rates in many coastal areas (Weisse, et al., 2021). It may also affect potential changes in recovery conditions after storms and joint impact of several drivers. For example, wave systems from different directions are synchronised with background sea level variations (Eelsalu et al., 2022). The complex interplay between wave driven sediment transport and other coastal drivers demands thorough investigation.

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Towards a user friendly coastal modeling tool for North Sea – Baltic Sea

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1. Introduction

Development and tuning of a coastal oceanographic model may take months even for experienced oceanographic user. Nowadays, there are many situations where an easily producible, user-friendly and still reliable oceanographic coastal tool is desirable. Here, we discuss the possibility to build a user friendly platform for developing highly resolved coastal oceanographic setup with an easy to use tool. For this reason, a high resolution domain is attached to the base setup of open seas.

2. Methods

Coastal oceanographic tool is developed basing on the oceanographic circulation model HIROMB BOOS Model (HBM), which implements a two-way nesting technique to ensure a seamless transition from open seas to coastal waters. EmodNET bathymetry together with OpenStreetMap is used as the source for the base bathymetry and the land sea-mask with resolution of 2 arc seconds. Discrete lower resolution bathymetries are derived from the basis bathymetry. The bathymetries at each resolution are processed beforehand to ensure that users can apply them directly. Vector layer of waterways is used to ensure connectivities between water bodies. Similarly, vector layer of dams ensures narrow land forms.

Weather forcing for user applications will be provided either by Harmonie model (2.5 km) or Hirlam model (11 km resolution before 2017) of Danish Meteorological Institute. Boundary conditions with Atlantic Ocean are provided by 2D NOAMOD storm surge model, together with tidal forcing and climatological conditions for boundary temperature and salinity in connection with northern Atlantic Ocean.

It may take considerable effort to properly tune an oceanographic setup for specific seas and coastal areas. Quality of coastal setup largely depends on the quality of open sea model to which the coastal domains are nested. Therefore, we have tuned the open sea model for North Sea – Baltic Sea to have similarly good behavior as existing reanalysis products for North Sea and Baltic Sea. The idea is that user attaches coastal high resolution domain to existing setup of open seas. This dramatically minimizes possible inconsistent choices for the user, as underlying open sea model with correct forcing, boundary conditions and freshwater inflow is properly settled.

3. User interface

It is challenging for the user to understand specific oceanographic software. Also, there may be limited documentation how to use the software for coastal high resolution studies. Therefore, we are developing a Graphical User Interface (GUI) in order to make the problem easier for the end user that does not require knowing the oceanographic software.

As the HBM is written in Fortran an automatic setup configuration is made with Fortran tools to create necessary setups. It addresses also the automatic nesting procedure. Geospatial tasks of bathymetry generation at each of the resolutions are made using GDAL and other libraries in Python scripts.

The user interface should be as simple as possible and still compatible with super computer systems. Therefore we have chosen Python Tkinter library to build the user interface.

The user at the starts selects the starting template for the setup which properly resolves the open sea area. Some of the templates already contain high resolution sample costal domains, but user can select the base template with only open sea configuration.

When the basis setup is selected, user can start to modify the model and add or modify additional coastal domains, see Figure 1. Using graphical tools the selection of domains is made easy. The graphical tools also help to set the properties of each coastal domain such as resolution, nesting, bottom friction maps, time stepping, exclusion maps, etc.

When the geometry is specified, user selects the parameters defining the period and output variables. The simulation can be started right after. The proper weather forcing and boundary conditions are set up automatically using the DMI weather data. An available period of reanalysis will start from year of 2013.

As the first hours of modeling are finished, the user can check results in the prost-processing part of the GUI. The post-processing part consists of viewers of 2d and 1 d fields. The 2d fields include 2d or 3d fields at different depth as well as vector fields. Viewer for 1d fields includes results for specific locations including vector fields. User can also pick a sea level station from the list with more frequent output frequency.

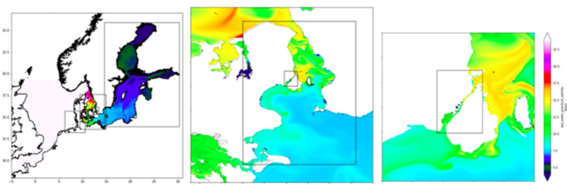

Figure 1. Inserting high resolution domains with two-way nesting. Left: North Sea-Baltic Sea, middle – Øresund domain, right – Copenhagen domain

4. Discussion

Because the quality of the coastal domains integrated into the base setup primarily results from quality of the base setup of open seas, the idea of on-demand modeling is to fix the open sea configuration with the tested starting template. The user has just to append high resolution coastal domains to it. The stability and quality of the resulting two-way nested coastal setups can be enhanced by implementing a cascade of two-way nestings instead of using nesting with high ratios. The GUI demonstrates that creation of on-demand coastal oceanographic applications by attaching highly resolved coastal domains to existing base setups for open seas with few user actions is achievable task.

Long-term sea level rise impacts upon the southern Baltic Sea coast, derived from numerical modelling

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1. Rationale

Observed climate change, glacial melting and global mean sea-level rise (GMSL), the development of mass wasting processes (including landslides) on coastal cliffs, as well as the increasing impact of storms on urbanised areas located in the coastal zone of seas and oceans, should be considered as key issues challenging coastal researchers to identify in the 21st century.

2. 4F MODEL application area (southern Baltic Sea)

The impact of sea level rise on the Polish coast, expressed in terms of shoreline position changes and erosion dynamics, was determined by applying numerical modelling utilising functional programming within the 4F MODEL in Desmos and GIS environments. Long-term predictions of potential shoreline position and transgression dynamics in the *Anthropocene* were presented on a general spatial and temporal scale.

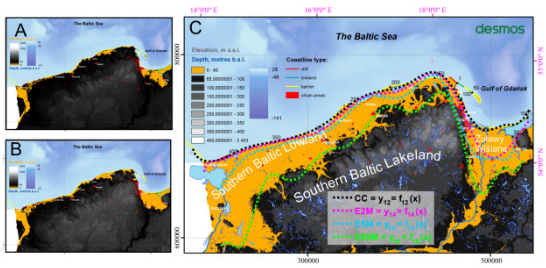

Figure 1. Fig.4 Projection of the SBS extent in the *Anthropocene* based on gmsl-rise RCP8.5 and RCP2.6 scenarios: (A) sea-level rise (SLR) by 2 m by 2190–2720 CE; (B) SLR by 5 m by 2400–3800 CE; (C) SLR by 65m (ice sheet–free Earth); consecutive functions marked with dotted lines correspond to each scenario: (A) purple; (B) blue; (C) green; dotted black line represents the current coastline, modified from the 4F model, coordinate system ETRS 1989 PL-1992 (EPSG 2180) (Frydel, 2022)

3. 4F MODEL operational formula

The model utilises formulae derived from Frydel (2022):

$$C_{t_{m-1}\to t_m} = A_{(t_{m-1})t_m}/tB = \frac{\int_{x_l}^{x_u}\left(\sum_{i=0}^{n} a_i x^i\right)dx - \int_{x_l}^{x_u}\left(\sum_{i=0}^{n} b_i x^i\right)dx}{|x_u - x_l| * |t_{m-1} - t_m|}$$

$C_{t_{m-1}\to t_m}$ – averaged shift dynamics (ice sheet retreat or advance / marine transgression or regression / coastal erosion or accretion / accumulation), expressed in m/yr,

$A_{(t_{m-1})t_m}$ – the area between t_1 and t_2 (projected on the XY plane), expressed in m^2,

t_1 – time moment for the first data series,

t_2 – time moment for the second data series,

t – number of years (interval) between t_1 and t_2, expressed in years, yr,

$B \in < x_u, x_l >$ – base line length (integral limit) expressed in meters, m.

4. 4F MODEL inputs, results and areas of application

Extrapolations made under the assumption of a linear rate of sea-level rise were carried out for projections in the range <RCP8.5, RCP2.6>, approximating both the nature and spectrum of expected scenarios. Consequently, the application of GMSL rise scenarios, with reference to the hypsometry represented by the digital elevation model (DEM, 100 x 100 m) derived from GUGIK, suggests that a 2 m rise in global ocean level by 2190–2720 AD is likely to be associated with coastline transgression dynamics in the range 24–38 m/year. As a result, approximately 684,000 people, including 3,400 km2 of land, could be exposed to inundation. The 4F MODEL also indicates the most vulnerable areas (Fig.1) of the Polish coastal zone. Among the largest in terms of area and most at risk are the Żuławy Wiślane, a vast area of the alluvial Vistula delta, including depressed areas that are still habitable owing to an extensive drainage system and structures related to coastal engineering. Inflows of saline Baltic waters can reach up to 40 km inland. The Hel Peninsula may be subject to periodic storm breaks in its western part, with simultaneous accumulation of erosional material near the south-eastern part of the promontory (Frydel, 2022). The model applied here, which utilises variables including time, space, dynamics and analyses scope (integral limits), is also relevant for other nontidal seas.

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https://www.desmos.com/calculator/tyfe60bhw6 – projection of the southern Baltic Sea extent in the *Anthropocene* based on GMSL rise RCP8.5 and RCP2.6 scenarios, sea-level rise of 2 m by 2190–2720 CE

Analysis of wave properties in the Baltic Sea: integrating findings from the Gulf of Finland, Gulf of Riga and Western Baltic Coasts.

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1. Introduction

The Baltic Sea is a semi-enclosed marine region with a unique history and appearance, and diverse coastal environments, the management of which require the best available understanding of the wave properties, and their extremes, especially in semi-sheltered regions (Monbaliu et al., 2014). Despite wave models have become better at resolving wave properties in areas of complex shape, and the increasing availability of measurements, certain areas of the Baltic Sea, such as the Gulf of Riga and the western coasts of Latvia and Lithuania, are characterized by particularly scarce availability of wave data, compared to more studied regions like the Gulf of Finland. The knowledge of long-term information on wave climate is nevertheless of key importance to safety and sustainability (Cooper and McKenna, 2008).

This research utilizes the SWAN wave model with a nested, high-resolution (up to 260 m) grid system to hindcast wave properties. Previous steps focused on the replication of several parameters of wave fields, such as significant wave height (SWH) and wave period, their stability with respect to different input wind datasets, and their spatio-temporal variations. Validation is achieved against measured wind data and the available wave measurements.

The aim of this work is to provide better insight into the regional and seasonal variations of wave properties, as well as the interplay between wind patterns and wave dynamics. This insight may prove useful towards a better understanding of coastal erosion, alongshore sediment transport, and the extreme events which, due to climate change, may be of increasing frequency and intensity. Additionally, this work opens the door to future steps, towards better wave modeling techniques and the application of Machine Learning for model fine-tuning.

2. Methods

The SWAN wave model version 41.31A was employed to analyze wave properties in the Baltic Sea, focusing on the Gulf of Finland, the Gulf of Riga, and the western coasts of Latvia and Lithuania. The model uses a three-level nested grid system (Fig. 1), designed to achieve iteratively higher-resolution, adequate to resolve most wave properties in the nearshore. This approach is well suited for accurately capturing the wave climate specific to each region, as the model parameterization is specific for each grid. Wind input data is provided by ERA5, by the European Centre for Medium-Range Weather Forecasts. The model is run under idealized ice-free conditions. The timeframe covered is 1991-2022, and the wave spectrum is computed with a resolution of 10°, with periods ranging from 1 to 20s.

To validate the model, simulated wave properties and the input wind were compared with in-situ measurements from various sources to assess the accuracy of the model and input dataset. In addition to the in-situ data, historical visual wave observations were also considered for a more comprehensive validation. The overall average correlation coefficient and RMSE for SWH were 0.92 and 0.32 m, respectively.

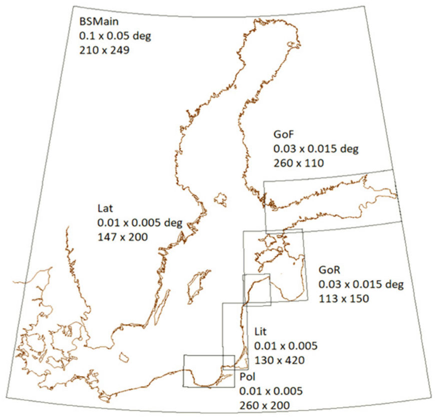

Figure 1. The grids used in the model. BSMain – Baltic Sea, GoF – Gulf of Finland, GoR – Gulf of Riga, Lat – western Latvia, Lit – Lithuania, Pol – Gdańsk Bay.

To further strengthen the model setup from an engineering and management point of view, an additional validation step was done to verify the accuracy of the simulations during 28 extreme events (SWH>7 m), which resulted in an overall average correlation coefficient and RMSE for SWH under extreme conditions of 0.98 and 0.32 m, respectively.

3. Dataset Extension for Latvia and Lithuania

In the most recent iteration of this work, the wave simulations were extended to also include the coasts of Latvia and Lithuania (corresponding to "Lit" and "Lat" in Fig. 1). The data extracted at three locations (Irbe, Pavilosta, and Klaipėda) on the grid Lit grid showed that the average SWH during the winter and summer seasons was of (1.29 m; 1.13 m; 1.04 m) and (0.74m ; 0.65 m; 0.61 m), respectively. The average wave direction showed small (<10%) seasonal variability and was 225°, 238° and 250° respectively. The highest recorded wave heights were of 4.1m, 5.5m and 6.5m respectively.

Fig. 2 displays the distribution of frequency of calculated wave heights which expectedly follows a Weibull or a Rayleigh distribution for narrow-band processes like the sea surface in fully developed conditions. The statistical wave properties resulting from the calculations on these grids agree with the previous results shown in (Björkqvist et al., 2018), where a lower space and time resolution was used. Spatial distributions of the highest percentiles of SWH like shown in Fig. 3 support this feature.

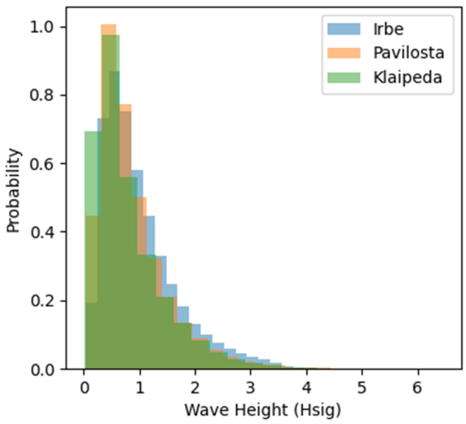

Figure 2. Histogram displaying the frequency distribution of wave heights at three locations on the second-level grids belonging to the western coasts of Latvia and Lithuania.

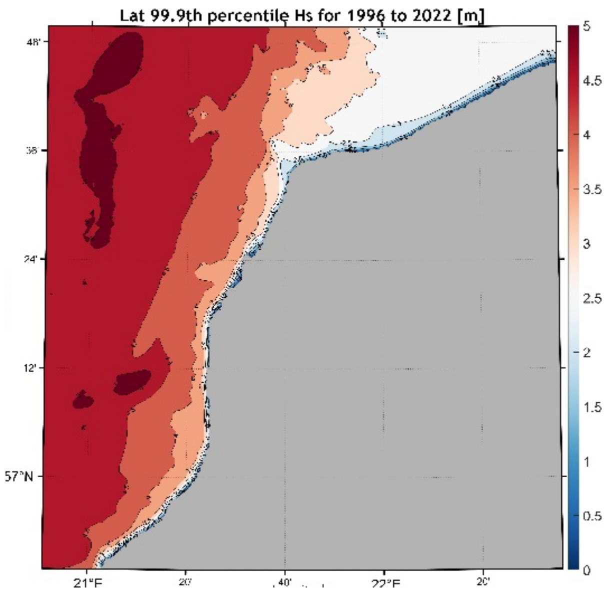

Figure 3. Spatial distribution of the 99.9th percentile of SWH on the second-level "Lat" grid, covering the western coast of Latvia.

4. Wave Data Online Repository

The modeled wave data generated (including the latest extension to Lithuanian and Latvian grids) are available for download through the online repository called "Tsunami" (https://tsunami.taltech.ee). This online resource provides access to the dataset of all calculated wave parameters, for all the grids and in different formats, together with the documentation necessary to retrieve it.

5. Main findings

The findings of this work so far revealed distinct spatial and temporal variations in wave properties across the Baltic Sea, in agreement with previous perceptions in the literature. In the Gulf of Finland, the model simulations indicate a weaker North-South asymmetry in wave properties than previous research. The central part of the gulf expectedly records the highest wave intensity, with average SWH gradually decreasing towards the coastlines and from west to east (Giudici et al., 2023).

In the Gulf of Riga, the wave climate is milder compared to that of the Baltic proper. SWH is consistently higher in the central and eastern parts of the gulf, in alignment with the predominant wind patterns in the region. The highest wave heights are observed in areas in the northern and north-eastern regions of the gulf, particularly during extreme events, highlighting the exposure that these regions have to such high-energy wave events (Najafzadeh et al., 2024).

This study's findings also highlight the efficacy of the SWAN model in replicating extreme wave events (even at lower resolution than the one achieved in this work), a fundamental aspect for coastal management and engineering applications. The model accurately reproduced SWH during extreme events. Across all the grids, the model's output showed a strong correlation and adequate RMSE.

6. Conclusion and future steps

This work has produced a high-resolution dataset describing the wave climate in the Baltic Sea, with a focus on the Gulf of Finland, the Gulf of Riga, and the western coasts of Latvia and Lithuania. The data is made available online through the "Tsunami" portal. The successful replication of extreme wave events and the strong correlation of model outputs with in-situ measurements highlight the accuracy of the model setup in simulating wave dynamics under varying geographical and meteorological conditions.

The findings are useful for coastal management strategies, enhancing the safety of maritime activities, and contributing to the field of marine and environmental engineering in the context of the changing climate. This study provides a detailed portrait of the wave climate including lesser-studied areas of the Baltic Sea, but also makes a step forward in the direction of high-resolution wave modeling efforts in similar semi-enclosed marine environments.

Future steps will involve further extension of the dataset, and the application of Machine Learning techniques to programmatically tune the model.

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The Impact of Baltic Sea Level Rise on Estonian Coastal Areas

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Abstract

The rate of sea level rise is a critical parameter, the understanding of which is essential for the economy, environmental protection, and overall safety of maritime and coastal areas. This phenomenon has garnered particular attention in recent decades due to the impact of climate change, leading to an acceleration in sea level rise. Estonia, being a coastal country on the Baltic Sea, faces similar challenges associated with sea level rise. Therefore, it is imperative to conduct comprehensive studies to understand the rate of sea level rise and its impact on Estonia's coastal areas.

This study investigates the impact of sea level rise on the coastal areas of Estonia by using tide gauges and satellite altimetry data. Sea level rise is a well-documented consequence of global climate change, posing significant threats to coastal regions worldwide. Estonia, with its extensive coastline and low-lying coastal areas, is particularly vulnerable to these effects. Coastal areas of Estonia are no exception, and the purpose of this research is to analyze data from tide gauges to determine the rate of sea level rise in the coastal area of Estonia. By using long-term measurements, it is possible to provide valuable knowledge to local and regional decision makers to help them adapt to future changes.

The postglacial land uplift has a significant impact on the relative sea level rise in the coastal area. Therefore, it is important to consider postglacial land uplift when studying sea level changes, as this will help to understand the significant sea level change in the coastal area. The link between land uplift and sea level rise has also become relevant due to climate change and the associated acceleration of global sea level rise. It`s known that the postglacial land uplift in the Baltic Sea region is quite different. For example, the official land uplift model NKG2016LU of the Nordic Commission of Geodesy (NKG) for northern Europe shows a maximum absolute uplift of about 10 mm/yr near the city of Umeå in northern Sweden and a zero-line that follows the shores of Germany and Poland. Sea level rise rates from 2 to 6 mm/yr have been detected in the Baltic Sea from the German and Danish coasts to the Bay of Bothnia, respectively.

The aim of the study was to find the sea level rise of the Estonian coastal area of the Baltic Sea during the last three decades. Different sea level rise models from ESA and data from Estonian tide gauges were used in the study. Two land uplift models, the NKG2016LU land uplift model and Estonian land uplift model EST2020VEL, were used to eliminate post-glacial land uplift from absolute sea level rise and find out the relative sea level rise. In addition, different models provide an opportunity to analyze sea level rise in more depth.

The study confirmed that the sea level rise along the coastal area of Estonia is influenced by land uplift rates. The study affirmed that in many parts of the Estonia the relative sea level is rising due to different rates of land uplift. There were few areas where relative sea level rise was minimal.

The results of the study indicate that the rate of sea level rise has not been uniform across the entire coastal area of Estonia over the past three decades, due to land uplift. Along the Estonian coastline, sea level has risen up to 4 mm/yr over the last three decades, but there are also areas where sea level has decreased by -1 mm/yr. Nevertheless, this is a concerning rate, especially considering the vulnerability of coastal areas to sea level rise.

The results of this study are important for both scientists, policymakers, and local communities whose lives and economies depend largely on the future condition of Estonia's coastal areas. Through thorough analysis and presentation of data, we hope that this research article will help raise awareness of the rate of sea level rise in Estonia's coastal areas and promote further investigation and implementation of measures to address this significant challenge.

The BALTEX Hydrological dataset of GRDC – A unique archive for river discharge data of the Baltic Sea catchment

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1. Introduction

River systems are an integral part of the global water cycle, which are linked to many processes on local, regional and global scales. Terrestrial monitoring of rivers is fundamental for the sustainable management of available water resources on regional or catchment scale. It adds value to the scientific understanding of regional catchments and provides a basis for climatological and hydrological models and it contributes to the calibration and validation of satellite-derived earth observations. To serve the scientific community during research projects, the monitoring data needs to be stored and made publicly available to preserve and share the data with interested user groups.

2. The GRDC

The Global Runoff Data Centre (GRDC, grdc.bafg.de) operates under the auspices of the World Meteorological Organization (WMO) at the German Federal Institute of Hydrology (BfG). It holds the most substantive collection of quality assured river discharge data on global scale. Established in 1988 to support the research on global and climate change and integrated water resources management, GRDC has been a key partner in a number of data collection and data management projects. It connects national meteorological and hydrological services, the primary providers of river discharge data and associated metadata, and the scientific research community utilizing this unique data collection. The GRDC is an international archive of data up to 200 years old, and fosters multinational and global long-term hydrological studies. The constantly growing database currently holds daily and monthly discharge data of 10,730 stations from more than 160 countries and is regularly updated (Figure 1). Since 2020, the data can be downloaded for free, but with identified access from the GRDC Data Portal (https://portal.grdc.bafg.de/).

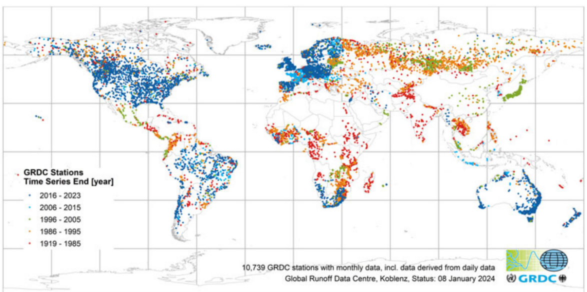

Figure 1. Global coverage of GRDC stations

3. The BALTEX Hydrological dataset

The Baltic Sea Experiment (BALTEX) was launched in 1992 as a Continental-scale Experiment (CSE) of the Global Energy and Water Exchanges Project (GEWEX) within the World Climate Research Program (WCRP) and was active until 2013. Its primary focus was the hydrological cycle and the exchange of energy between the atmosphere and the surface of the earth in the huge catchment region of the Baltic Sea.

Hydrological data relevant to BALTEX were collected at the BALTEX Hydrological Data Center (BHDC) operating at the Swedish Meteorological and Hydrological Institute (SMHI) since 1995. Until 2015 BHDC collected data of daily and monthly discharges of around 600 stations in the Baltic Sea region. In 2015, the BALTEX Hydrological Dataset moved from SMHI to the GRDC in order to ensure sustainable operation and regular updates as an integral part of the Global Runoff Database (Figure 2). By release and on behalf of the national hydrological services, the former BALTEX stations and flow data were integrated in the Global Runoff Database.

Figure 2. Catchment area of GRDC stations in the Baltic region.

4. Current status of BALTEX dataset

Currently, there are only 398 of more than 660 original stations of the BALTEX dataset available for download (Table 1). The data can be received from the GRDC Data Portal. The average daily time series length is 42 years, with the longest time series reaching 198 years.

Table 1. Current station distribution per Country.:

Country	Number of stations
Belarus	50
Denmark	18
Estonia	44
Finland	67
Latvia	61
Lithuania	75
Poland	24
Sweden	59

In the course of GRDC's data acquisition activities, the BALTEX stations are regularly updated in cooperation with the national hydrological services.

Sensitivity of wind forcing data to the wave energy in the Baltic Sea

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1. Introduction

Renewable energy, including the wave energy, has become attractive to the scientific community and policymakers, especially in recent years due to the crisis in the energy sector. One of the first steps in implementing wave energy converters is to thoroughly study the wind waves and provide a detailed wave energy map for a particular region.

Wave energy in the Baltic Sea has been studied for several decades, and significant progress has been made in recent years regarding wave climate and wave energy resources (Jakimavičius et al., 2018; Nilsson et al., 2019). However, the wind forcing is sensitive and could strongly influence the wave parameters (Van Vledder and Akpınar, 2015), especially in the Baltic Sea where the bathymetry is highly complicated and the basin includes many small islands. As a result, the wave energy map could be altered differently. Therefore, the main objective of the present study is to investigate the impact of the spatial resolution of the wind data on the wave energy map for the Baltic Sea.

2. Methodology

The spectral wave model WAM Cycle 6, package ST4 is used in the present study (WAMDI Group, 1988; Ardhuin et al., 2010; Staneva et al., 2017). The computational domain covers the Baltic Sea, Kattegat and Skagerrak with a spatial grid resolution of 1 nautical mile, where the bathymetry is based on the EMODnet Bathymetry. The wave spectrum is discretized in 24 directional bins at 15° each and 30 frequencies logarithmically spaced from 0.042 to 0.66 Hz at intervals of $\Delta f/f = 0.1$. At the open boundary in Skagerrak, the model uses the 2D spectrum information derived from the model for GCOAST domain (Bonaduce et al., 2020).

Two different sources of wind data for the driving forces is employed, including the ERA5 reanalysis of the ECMWF (Hersbach et al., 2020) and the ICON-EU reanalysis of the DWD (German Weather Service). The temporal resolution of the 10 m wind fields is hourly for both datasets. However, the spatial resolution of the ERA5 data is 0.25° x 0.25°, while the ICON-EU data have a finer resolution (0.0625° x 0.0625°). Ice cover is included in the model based on ERA5 data.

The potential wave energy is estimated from the hourly wave parameters of the WAM model as,

$$P = \frac{\rho g^2}{64\pi} H_s^2 T_e \qquad (1)$$

where ρ = water density, g = gravitational acceleration, H_s = significant wave height, T_e = wave energy period.

3. Preliminary Results

Two experiments, for the period from January 1 to December 31, 2020, were performed using the ERA5 and ICON-EU data and validated against the in-situ measurements and satellite data. The ST4 package with β_{max} = 1.42 has been used for both experiments. Several error metrics, skill scores and correlation coefficient were used for validation.

Figure 1 shows the comparisons between the calculated H_s and the observations in 2020 from the eight wave buoys (top panels) and seven satellites (bottom panels), taking into account the wind forcing by the ERA5 and ICON-EU data. In general, both experiments reproduce observations well, and the performance with ERA5 was even slightly better. For in-situ data, the indexes such as bias, rmse, si, and hh are somewhat smaller when using the ERA5 data, whereas the skill score, correlation coefficient and quantile curve are slightly better when using ICON-EU. For satellite data, the calculated H_s slightly underestimate the observations using ERA5 data with the bias is approximately -2 cm. In contrast, the calculated H_s using ICON-EU are more pronounced than the observations.

Figure 2 illustrates the annual energy maps in 2020 and the absolute and relative energy differences using ERA5 and ICON-EU. The energy patterns are similar, but the differences in magnitude between the two experiments are clearly visible. This is mainly due to the higher waves obtained by the ICON-EU. Furthermore, the maximum energy is obtained in the northern Baltic Proper, a higher latitude compared to that found in Nilsson et al. (2019). The relative differences indicate that the energy is significantly higher near the coast, especially in the Bothnian Bay, the Gulfs of Finland and Riga, and the Danish Straits when using ICON-EU data.

4. Concluding Remarks and Outlook

The sensitivity of the spatial resolution of the wind forcing data to the wave energy in the Baltic Sea was investigated using two different reanalysis wind datasets. Validations against wave buoy and satellite data showed that both experiments reproduce observations well. However, the wave energy using ICON-EU data is significantly higher than that using ERA5 data. Particularly, near the coasts of the northern Baltic Sea, the Gulfs of Finland and the Danish Straits, the relative differences are significant (> 40%).

Longer runs of both experiments will be conducted to investigate the variability of wave energy in the Baltic Sea.

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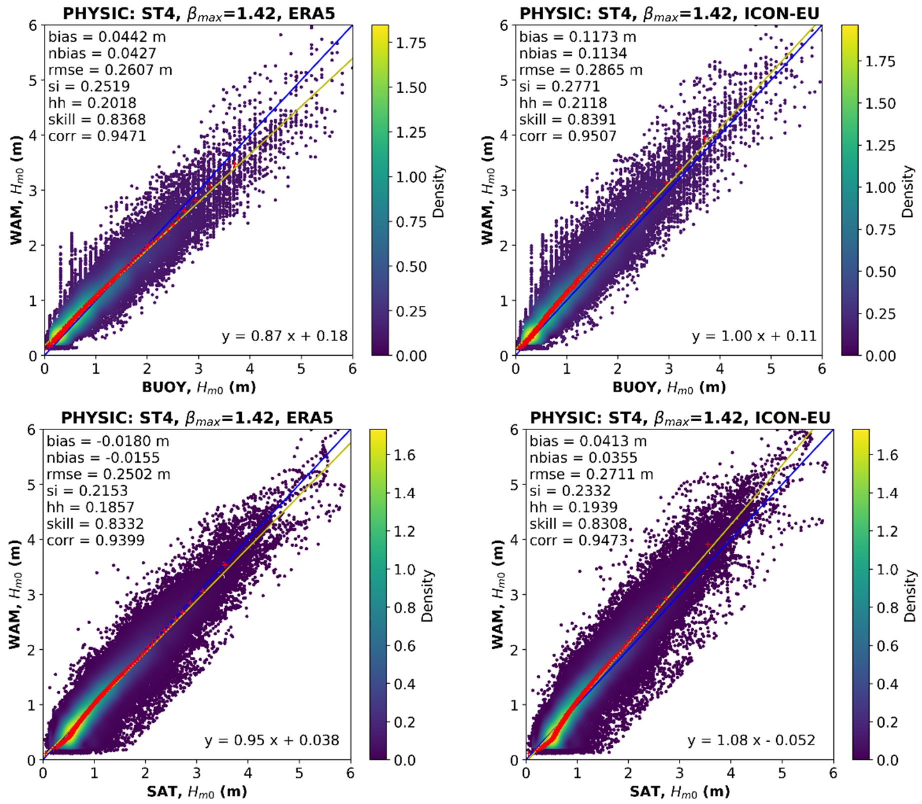

Figure 1. Validations of significant wave height based on ERA5 and ICON-EU data against wave buoys (top panels) and satellite data (bottom panels)

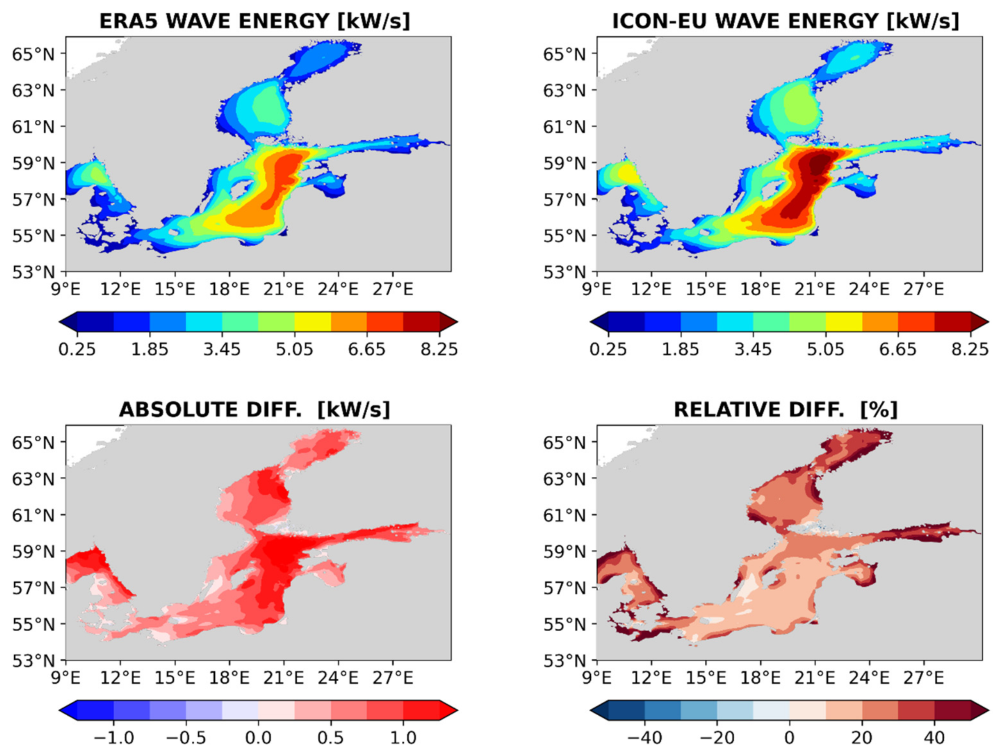

Figure 2. Annual wave energy in 2020 based on ERA5 and ICON-EU data (top panels) and their differences (bottom panels)

Diving marine birds as Baltic oceanographers: a novel method to collect data on water parameters

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1. Introduction

Oceanographers face the lack of in-situ environmental data to investigate marine features' changes, particularly in some specific habitats or inaccessible areas (Boehme et al. 2009). Collecting measurements on marine environments can be challenging and limited with traditional methods.

Oceanographic data collection with diving birds using transmitters with integrated sensors has been already started in different places of the World, however, with still few studies mostly related to foraging behavior of birds (Peck-Richardson et al. 2018, Fijn et al. 2021).

In this work, we will present the application of diving marine bird telemetry as a novel approach to collect data in different depths on water parameters (e.g. temperature, salinity) for oceanographic research in the Baltic Sea.

2. Material and methods

The deployment of GPS/GSM transmitters on diving marine bird species provides the opportunity to survey the coastal and offshore environment of the Baltic Sea.

GPS/GSM transmitters with integrated temperature and pressure sensors have been deployed on the breeding and wintering diving marine birds since 2019 at the Klaipeda University (Figure 1).

Great Cormorant is a pursuit diving seabird, and, due to the daily high-frequency dives, it provides an excellent chance for data collection. One individual as an example for this study was selected. It was deployed with GPS/GSM transmitter with solar panel and different sensors in May 2019 at the seacoast colony in Lithuania. The different of sensors recorded diving depth (each second underwater) and water temperature.

Figure 1. Great Cormorant *Phalacrocorax carbo* (on the top) and Red-throated Diver *Gavia stellata* (on the bottom) – species fitted with GPS/GSM transmitters with depth and environmental data sensors in the Baltic Sea.

3. Results and conclusions

Here we present data collected by the one individual of Great Cormorant on the 12th of August 2020. During one of the five of this day diving occasions. The individual started this dive at the 56.51735 Latitude 20.95065 Longitude coordinates, what corresponds to the Baltic Sea in front of the Liepaja (Latvia). Data on the water temperature were collected up to the 14 m, during 5 short dives (Figure 2).

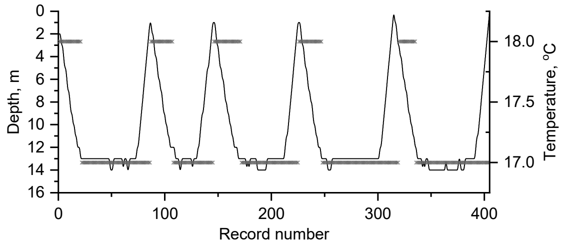

Figure 2. Record of the depth and temperature data collected by selected Great Cormorant during its one dive, 12 August 2020.

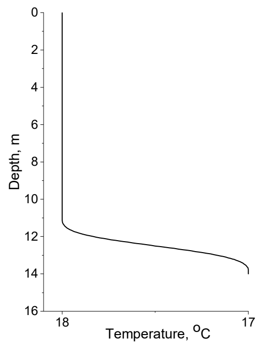

Figure 3. The median temperature measurements at various depths during the one dive of selected Great Cormorant deployed with GPS/GSM transmitter with sensors for depth and water temperature, 12 August 2020.

On the 12th of August, a well-mixed water column was observed up to 12 meters, where the temperature remained uniform at 18 ºC. Beyond this depth, a gradual decrease in water temperature was observed, with a decline of 1 degree per meter. Subsequent dives conducted by studied individual of Great Cormorant on the same day, reaching depths of 16 meters, revealed water temperatures of 16 ºC. Notably, during bird dives within the Port of Liepaja, water temperature measurements in the upper 3 meters indicated a higher value, reaching up to 20 ºC.

Marine bird telemetry emerges as a potential tool, furnishing high-frequency data that promises to deliver fresh qualitative and quantitative insights into water's physical characteristics' temporal and spatial dynamics.

This real-time information enhances our understanding of marine processes. Moreover, the utilization of marine bird telemetry holds the potential for validating hydrodynamic models, reinforcing its significance in advancing our knowledge of dynamic aquatic systems.

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Mapping Elevation and Elevation Changes in the North and Baltic Sea

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The Federal Agency for Cartography and Geodesy (BKG) is the central service provider of topographic data, cartography, and geodetic reference systems for the German government. As the marine sector is constantly gaining importance, e.g. for the transport of goods or energy security, BKG aims to improve the quality of the fundamental geodetic information in the North and the Baltic Sea for the benefit of public and private users. In this context we provide the official national and international vertical reference datum for height and depth measurements and monitor elevation changes over time.

We use satellite altimetry to map and monitor the sea surface heights of the North and the Baltic Sea. As a reference for the altimetric measurements we use the geoid model of the recently released internationally unified Baltic Sea Chart Datum 2000 (BSCD2000). This avoids otherwise evident sampling problems when using a mean sea surface from altimetry. We validate the satellite observations using measurements on the offshore research platform FINO2 as well as from shipborne field campaigns. In order to improve the spatial and temporal resolution of the altimetry data, we combine the observations with the output of a regional ocean model from Leibniz Institute for Baltic Sea Research (IOW). The high degree of agreement between products from satellite altimetry and the results of the hydrodynamic model documents the quality of both datasets and could help to improve both datasets in future. Here we present the first results of these activities. Furthermore, we also present our strategy of combining satellite altimetry with different other observation techniques of sea level changes and land uplift to map and monitor elevation and elevation changes in the German coastal zone and the surrounding seas.

Intriguing interannual variations of sediment transport in the Gulf of Riga

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1. Introduction

The properties of wave-driven sediment transport often serve as a trustworthy indicator of subtle climate change driven alterations in the atmospheric forcing, such as changes in the air-flow (Soomere et al., 2015) or in the directional structure of moderate and strong winds (Bierstedt). We explore possibilities of this indicator to characterize changes in the wind fields and associated wave generation conditions along sedimentary shores of the Gulf of Riga in the eastern Baltic Sea.

2. Sedimentary shores of the Gulf of Riga

The observations of R. Knaps (1966) highlighted a complicated pattern of erosion, transitional and accumulation areas on sedimentary shores of the Gulf of Riga (Fig. 1). This perception is supported by simulations of wave-driven alongshore potential sediment transport (Viška and Soomere, 2013b). They both signal that the western, southern and eastern shores of the Gulf of Riga form an extensive partially interconnected sedimentary system that extends from the Cape Kolka to the Estonian-Latvian border. The system is largely fed by sand transported along the Baltic proper shore of Latvia to Cape Kolka. This sand is predominantly transported along a counter-clockwise path in the gulf interior (Fig. 1).

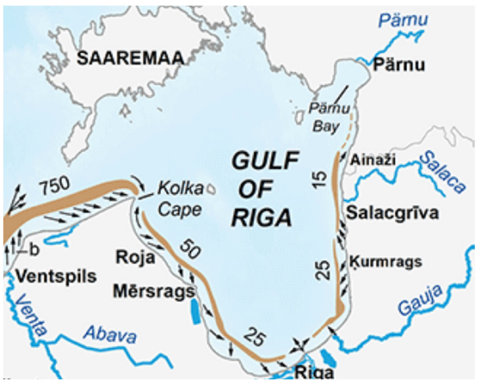

Figure 1. Sediment transport into the Gulf of Riga and along its western, southern and eastern shores evaluated from in situ observations (Knaps 1966; Ulsts 1998). Numbers indicate the magnitude of transport in thousands m^3/yr, arrows – its direction. Background map by M. Eelsalu, graphics by K. Ehlvest.

To analyse interannual, decadal and long-term changes to this pattern of sediment transport, we employ time series of wave height, period and direction replicated using a three-level nested SWAN wave model forced by ERA5 wind fields (Giudici et al., 2023) for 1990–2022 with a spatial resolution of about 0.32 nautical miles (about 600 m), for the coastal areas of the Gulf of Riga (Najafzadeh et al., 2024). The time series and long-term values of bulk and net potential sediment transport are evaluated using the Coastal Engineering Research Centre (CERC) approach (USACE, 2002). While intense sediment transit prevails on the western shore of this water body, the southern shores mostly serve as accumulation areas (Jankowski et al., 2024). The south-eastern coast serves as an end station of the counterclockwise sand transport, contains several small sedimentary cells, and hosts a longer segment where clockwise transport predominates.

3. Variations in alongshore sediment flux

The intensity of wave-driven potential alongshore sediment transport is largest on the eastern shore of the Gulf of Riga (Fig. 2). As this coastal stretch suffers from deficit of fine sediment (Knaps, 1966; Ulsts, 1998), actual sediment transport evidently is only a small fraction of potential transport. Sediment transport is almost by factor of 2 less intense on the western shore and by factor of 3 on the southern shore. Interestingly, the potential bulk transport systematically decreases on the eastern and western shores 1990–2005, and exhibits no explicit trend 2005–2022.

The average bulk transport over all three coastal segments also shows a certain decrease 1990–2005. This outcome is consistent with the conjecture of Viška and Soomere (2013a) who noted qualitatively similar behaviour of bulk sediment transport integrated from Cape Kolka to Pärnu Bay, with maxima around the years 2004 and 2007.

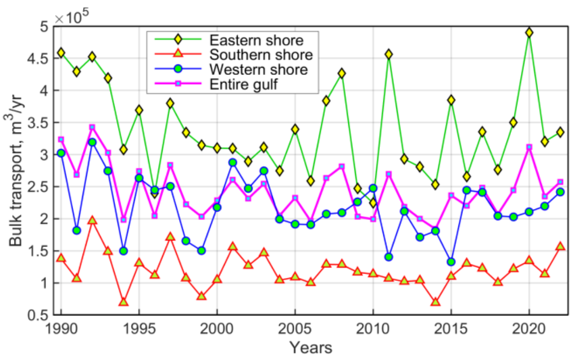

Figure 2. Average potential bulk sediment transport per wave model grid cell along western, southern and eastern shores of the Gulf of Riga in single years 1990–2022. Magenta line shows the average over the entire study area.

Bulk sediment transport on the eastern and western shores of the gulf exhibits extensive interannual variations, with no explicit trend 2005–2022. On the contrary, this transport on the southern shore had relatively large interannual variations 1990–2005 but remained at an almost constant level since then. This feature signals that interannual variations in wind properties differently affect differently oriented segments.

Consistent with Viška and Soomere (2013a), average potential net sediment transport over the entire study area exhibits almost no long-term and decadal changes, and contains fairly limited interannual variations (Fig. 3). Also, net transport on the southern shore has a relatively low level of interannual variations.

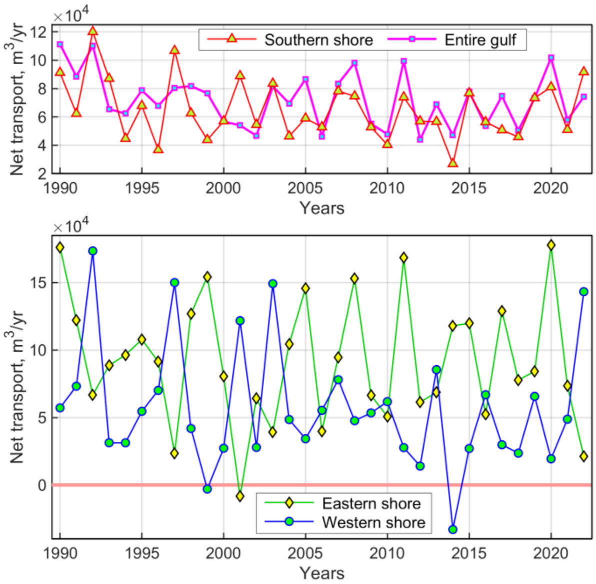

Figure 3. Average potential net sediment transport per wave model grid cell along western (blue), southern (red) and eastern (green) shores of the Gulf of Riga in single years 1990–2022. The magenta line shows the average over the entire study area.

Different from the above, potential net transport rates on the western and eastern shores have extensive interannual variations with amplitudes that, by an order of magnitude, exceed the average level. These variations are generally not in phase with similar (but much smaller) variations on the southern shore. Interestingly, most of the large variations of this kind are exactly in counter-phase on the western and eastern shores. As a consequence, the average net transport over the entire study area has fairly limited interannual variations with amplitudes comparable to those for net transport on the southern shore.

4. Discussion and conclusions

An obvious reason for the described pattern of interannual variations is the interplay of the specific bi-directional structure of moderate and strong (south-western, SW, and north-north-western, NNW) winds in the region (Soomere 2003) and orientation of the shoreline in the selected three coastal segments.

On the one hand, SW winds have only a short fetch for the southern shore of the gulf and thus do not excite any strong waves in this segment. On the other hand, waves driven by NNW winds may be much higher but they approach this segment at a small angle with respect to shore normal and thus usually do not generate intense alongshore transport. It is thus natural that both bulk and net transport are relatively weak on the southern shore.

The situation is radically different on the eastern and western shores. Large sections of both these segments are often impacted by waves excited by NNW winds. The northern part of the eastern shore is often impacted by waves driven by SW winds. Both these wave fields approach these shores at a large angle and thus create relatively intense alongshore sediment transport.

The level of bulk transport incorporates the joint non-directional impact of both wave systems. The magnitude of net transport expresses the changing role of these wave systems in directional transport in different years. A year with stronger than average NNW waves means a stronger than average transport to the south in both segments. This feature is translated into more intense than usual counter-clockwise (positive net) transport on the western shore but into more intense than usual clockwise (negative net) transport on the eastern shore.

Therefore, large interannual fluctuations in potential wave-driven net transport on the eastern and western shores of the Gulf of Riga first of all represent the relative role of waves excited by northerly winds on sediments of these segments. Their role varies greatly but relatively regularly and with an almost constant amplitude, and with a time scale of 3–4 years. This kind of periodicity in atmospheric forcing is a highly interesting feature.

Acknowledgements

The underlying research was supported by the Estonian Research Council (grant PRG1129) and the European Economic Area (EEA) Financial Mechanism 2014–2021 Baltic Research (grant EMP480).

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Classification of soft cliff dynamics using remote sensing and data mining techniques

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1. Introduction

The factors influencing coastal cliffs and their adjacent beaches have been investigated using diverse quantitative numerical methods, ranging from basic correlation matrices to stochastic simulations and numerical modeling. Given the potential for future increases in SLR and storm activity, it is crucial to continue investigating spatiotemporal patterns of cliff erosion to address existing knowledge gaps related to the processes leading to cliff erosion.

2. Methods

Initial task was to establish a methodology for describing cliff morphology using various indicators to facilitate subsequent statistical analysis. Therefore, we implemented an automatic methodology using the Coastal Cliffs Morphology Analysis Toolbox (CCMORPH v2.0). CCMORPH comprises Python scripts and a JavaScript tool designed to generate georectified information tailored for the creation and quantitative analysis of coastal cliff morphology.

Having prepared all geomorphological variables, our second task involved generating hydrometeorological predictors to elucidate different cliff classification types. In this study, we analyzed a total of 34 variables, including various parameter calculations related to wave, wind, water level, temperature, and precipitation.

Finally we utilized high-resolution in-situ monitoring datasets and applied various data mining methods tailored to the study's objectives, including classification, grouping, and correlation analysis. To this end, we employed six distinct methods, namely: (1) multivariate regression trees (MRTs), (2) component analysis, (3) correspondence analysis (CA), (4) canonical CA (CCA), as well as (5) multivariate analysis (MVA) and (6) multivariate random forests (MRFs).

3. Features controlling coastal morphology changes

Divergent hydrometeorological conditions observed over 2 years at three distinct test sites allowed for the analysis of morphological changes and the identification of major forces influencing the beach-cliff system. All three investigated test sites underwent significant morphological changes between surveys.

According to correlation analysis, the highest associations were observed with wave direction during the storm period and maximum water levels. These parameters highlight the importance of storm surges in the process of beach lowering and shortening during the initial phase of the storm season. Their influence has been confirmed by the results of MRT analysis.

Surprisingly, neither shoreline nor beach width correlated with wave heights. Those are more related to wave direction, as the highest association was observed with both wave direction during the storm period and average wave direction. Nevertheless, their average and maximum values, together with maximum water levels, are controlling complex mechanisms regulating beach and cliff volumes. While water levels are considered preparatory factors for erosion processes, waves are responsible for erosion volumes. These variables, along with maximum wave power and storm energy, showed the highest correlation with cliff foot changes.

4. Seasonal coastal cliff dynamics

Morphological features such as cliff volume, beach width, cliff slope, and cliff top retreat mainly elucidate the variance of the two axes in MRT, splitting the data into different classes of the most frequently occurring types of coastal profiles. This data-driven machine learning erosion model allowed us to determine six schematic types of cliff dynamics. Descriptively, they can be characterized as follows: (i) Stable, wide beach, and gentle cliff slope; (ii) Stable, wide beach, and steep cliff slope; (iii) Narrow beach, gentle cliff slope with low cliff balance and low top retreat; (iv) Narrow beach, gentle cliff slope with high cliff balance and low top retreat; (v) Narrow beach, steep cliff slope with low top retreat; (vi) Narrow beach and high cliff top retreat. How the types evolve over time during the intensive transformation and stabilization periods is clearly visible in Fig. 1.

Finally, a statistical analysis using CCA was performed to uncover the relationship between the different identified types of coastal dynamics and measured hydrometeorological conditions. Based on previous results, we expected heavy rainfall to be responsible for weakening the beach structure and increasing erosional material flow. Precipitation, including both maximum values and rainfall during the storm season, emerged as the most significant variables for explaining seasonal cliff dynamics. They surpassed the importance of storm energy and wave action (direction and period). Furthermore, average temperature can be considered a valuable seasonal indicator corresponding to the seasonality of coastal dynamics, i.e., the different periods of beach erosion and accumulation.

5. Discussion and conclusions

This research, with erosion rates reaching 12, 24, and 36 m3 per meter of cliff length per year in Międzyzdroje, Bansin, and Wicie, respectively, falls on the higher end of this magnitude. Comparatively lower erosion volumes were recorded on the shores in Germany (Schleswig-Holstein), estimated at 1.5 m3 per m of shoreline (Averes et al., 2021). Similar studies, utilizing LiDAR, on the Baltic Sea shores in Poland indicate erosion rates of 6.6–17.3 m3 per meter of shoreline on Wolin Island (Winowski et al., 2022) and 11–26 m3 in the central Polish coast (Frydel, 2022).

Recent studies have emphasized the significant impact of extreme waves and water levels on coastal cliff erosion (Earlie et al., 2018; Young et al., 2021). This study reaffirms the importance of these two key factors in influencing erosion rates. However, while wave height has a direct correlation with erosion volumes, it does not significantly contribute to changes in beach width. Beach width is primarily controlled by variations in water levels. Consequently, a high baseline sea level can allow even small waves to reach the cliff, contributing to cliff erosion. This explains the strong correlation between this type of erosion and the average wave indicator.

In this study, heavy rainfall episodes were identified as one of the explanatory variables through CCA. It is expected that heavy rainfall not only affects the cliff face but, when combined with other extreme conditions, also intensifies beach erosion and the redeposition of colluvial sediments. It is worth noting that, according to another study, precipitation is a major source of errors in hydrological models, so its influence should be carefully analyzed (Bárdossy et al., 2022).

Interestingly, the results also highlight precipitation as a crucial factor influencing seasonal coastal cliff dynamics. While rainfall has previously been considered a significant factor in cliff top retreat, it has not been widely acknowledged as suitable for investigating intra-annual (seasonal) analysis. However, these results suggest that rainfall can also be considered a force governing not only event-based, short-term cliff dynamics but also season-term cliff recession and fronting beach reconstruction processes.

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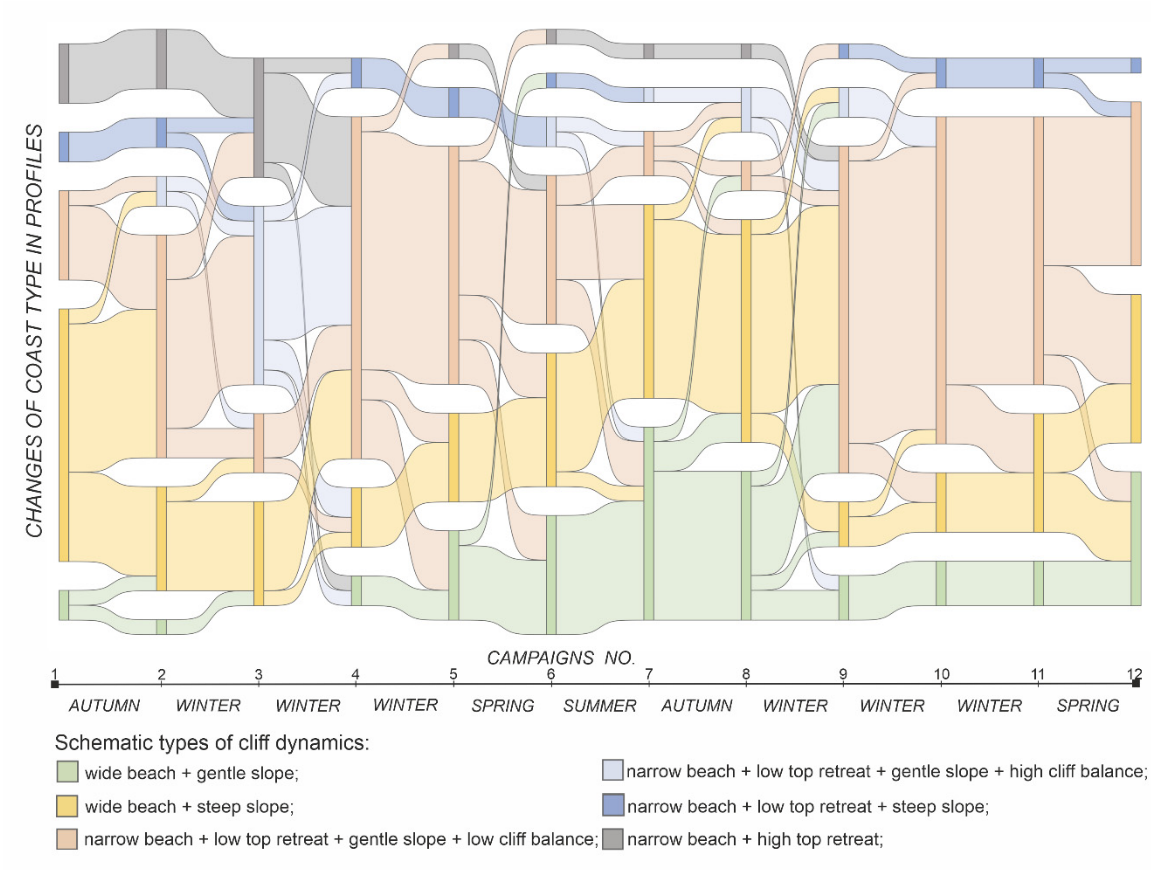

Figure 1. Seasonal coastal cliff dynamics.

Hydrodynamic modeling of the intrusion of the transformed seawater from the Dniester Estuary to the mouth part of the Dniester

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1. Introduction

An important problem faced by the population in the estuarine areas of many rivers is occupied by the deep penetration of saline seawater into the river mouths, which poses a risk to the stable fresh water supply for drinking, communal, and agricultural purposes. The papers (Eslami et al., 2021; Cotta & de Jesus, 2021; Al-Aesawi et al., 2021; Lončar et al., 2020) consider various aspects of prevention from significant saline water intrusion into river estuaries or mitigation of its consequence by artificial river flow control, or the building dams of various designs with the possibility to change the depth of their upper boundary.

Four big European rivers are flowing into the north-western Black Sea: Danube, Dniester, Dnipro, and Pivdennyi Bug. The waters of the three last-mentioned rivers enter the sea through the Dniester Estuary and the Dnipro-Bug Estuary which are formed in their mouth areas.

The purpose of the work is to establish, using hydrodynamic modelling, the hydro-meteorological conditions under which the transformed sea water from the Dniester Estuary could enter the mouth part of the Dniester River and impact the quality of water used for drinking and irrigation.

2. Data and methods

To solve the task a simplified variant (disregarding thermal factor) of the numerical non-stationary 3-D hydrodynamic MECCA model (Model for Estuarine and Coastal Circulation Assessment) (Hess, 1989; 2000) was used. A characteristic feature of the model is the possibility to use it for calculation of water dynamics and component transport in water bodies, some areas of which have a smaller (sub-grid) size in one of the horizontal directions than the step of the selected calculation grid (for example, river mouths, canals, etc.)

The model is based on a complete system of hydrothermodynamics equations in the Boussinesq approximation, incompressibility, and hydrostatics, which includes the equations: of motion for the horizontal components of the flow velocity vector, hydrostatic approximation, continuity, state, conservation of heat and salts. For the simulation of currents and transport of substances on sub-grid scales in channels, rivers, and their branches the source system of equations was integrated across the flow (i.e. in the direction normal for the flow in the horizontal plane). The new system of equations used in the model is obtained as a result of combining the equations integrated across the flow and the original equations in such a way that in the absence of a channel (three-dimensional flow), the original system of equations is in the traditional form, while in the presence of the channel - the equations averaged across the flow (two-dimensional flow). The numerical implementation of the obtained system of equations is performed in a vertically curvilinear coordinate system using the implicit finite-difference schemes.

The method of solving the hydrodynamic task involves splitting the full velocity of currents into the depth-averaged velocity (barotropic component) and a deviation from it at each calculated level (baroclinic component). The vertical turbulent viscosity is described based on the semi-empirical theory of turbulence as a function of water column stability and the local vertical shift of the current velocity. Horizontal turbulent exchange coefficients are calculated based on the value of the local horizontal shift of the barotropic component of the current velocity and the spatial step of the horizontal finite-difference grid.

A detailed description of the model equations, parameterizations, and boundary conditions used is presented in the works (Tuchkovenko et al., 2012).

During calculations, the estuary's water area together with the adjacent estuarine section of the Lower Dniester was covered with a horizontal calculation grid of 35x90 nodes, its step was 500 m. Six vertical calculation levels in the - coordinate system were used.

3. Results

The amplitude of the Black Sea tides is very low and is therefore categorized as non-tidal. A dominant role in the formation of the level fluctuations in the coastal zones on the time scales of a natural synoptic period is played by the wind-induced up and down surges (Simonov & Altman, 1991). Water exchange between the Dniester Estuary and the adjacent north-western Black Sea is determined by the wind regime and the Dniester River discharge volume.

The first set of numerical experiments with the model has shown that the strongest surges in the Dniester Estuary happen at southern and south-eastern winds (Fig. 2). At south-eastern wind, in case of its force growing during three days from 5 to 25 m/sec, the difference in level between the southern and the northern parts of the estuary reaches 170 cm.

When the speed of a storm surge wind stays the same or gets somewhat weaker, as the result of water level increases in the place where the main flow of the Dniester River splits into two arms, the Glybokyi Turunchuk and the Dniester, due to the river water backing up by the estuarine, the flow from the estuary into the Glybokyi Turunchuk Arm first gets weaker and then changes for the usual, in direction to the estuary, but its intensity is lower than before. In the estuarine arm of the Dniester, the usual hydraulic current directed from the estuarine arm to the estuary is maintained all the time.

So, the transformed sea water penetrates the estuarine arms and further, the Dniester River main channel from the estuary through the right estuarine arm, the Glybokyi Turunchuk, and then, having reached the point where the Dniester River channel divides into two estuarine arms, the water from the estuary is drawn into the left branch, the

Dniester, by the discharge flow and returns via the Dniester branch back to the estuary. It should be pointed out that in case of southern and south-eastern storm winds that cause the highest surge in the upper part of the estuary the water level mark at the

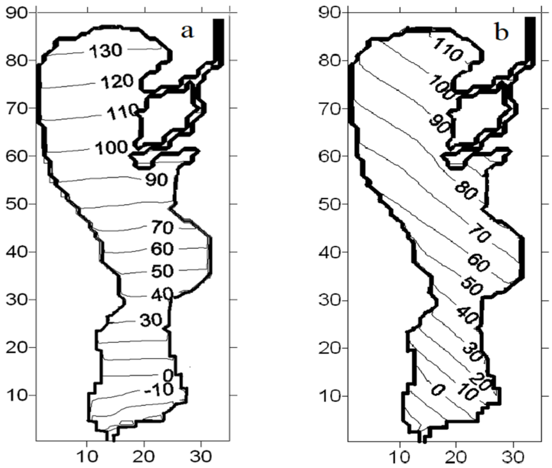

Figure 2. Denivellation of water level in the Dniester Estuary (cm) with strengthening of the south-eastern (a) and southern (b) winds up to 20-25 m/sec.

the outlet of the Dniester Arm is always lower than those of the Glybokyi Turunchuk Arm and the place where the main river channel divides into the two arms. At the same time, in different temporal periods of wind surges development, the level in the Glybokyi Turunchuk Arm can be both higher and lower than that at the point of the main river channel division into the two mouth arms.
The variability of salinity spatial distribution obtained for the hydrometeorological conditions described above using the model is presented in Fig. 3.

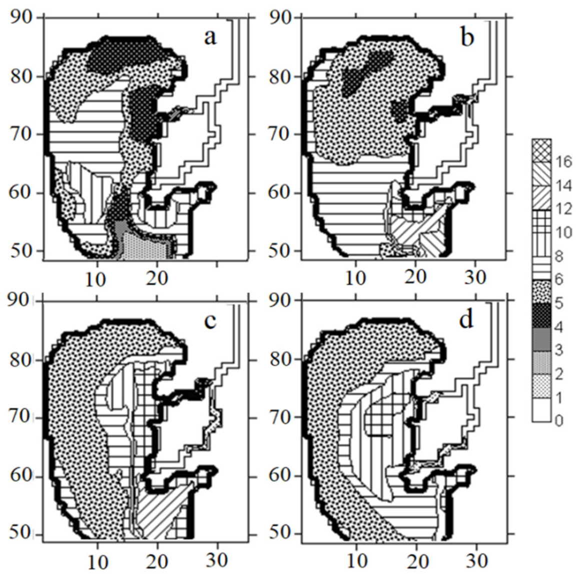

Figure 3. Variability of water salinity (ppt) spatial distribution obtained from the model at growing southern wind speed from 5 to 25 m/sec and the Dniester discharge of 75 m3/sec: a) in 1 day at 10-15

As the southern and south-eastern surge winds intensify, the transformed sea water of higher salinity rises along the estuary's eastern shore to the mouthes of Glybokyi Turunchuk and Dniester Arm. Penetration of waters having a salinity of 4-7 ppt into the Glybokyi Turunchuk is visible. The front of estuarine brackish water penetrates this branch up to the point where the Dniester main channel divides into two branches, the Glybokyi Turunchuk, and the Dniester Arm, after which the brackish estuarine water mixes intensively with the fresh river water and returns to the estuary through the Dniester Arm with the river flow.

4. Conclusions

Since water level in the estuary at the entrance to the Glybokyi Turunchuk Arm at surge winds from the sea will always be higher than at the entrance into the Dniester Arm, is unlikely that estuarine water of higher salinity (up to 7 ppt) could penetrate the main channel of the Dniester River (that is higher than the place where the river divides into two estuarine arms) even with flow rate going below 100 m3/sec, as evidenced by the scheme of estuarine water distribution in the Dniester River mouth area.
The case described could be used by experts as an example when identifying effective hydro-engineering measures to prevent transformed sea water penetration in river mouth by the building of a second estuarine canal (arm).

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Wave- and current-induced sediment resuspension in the Bothnian Sea

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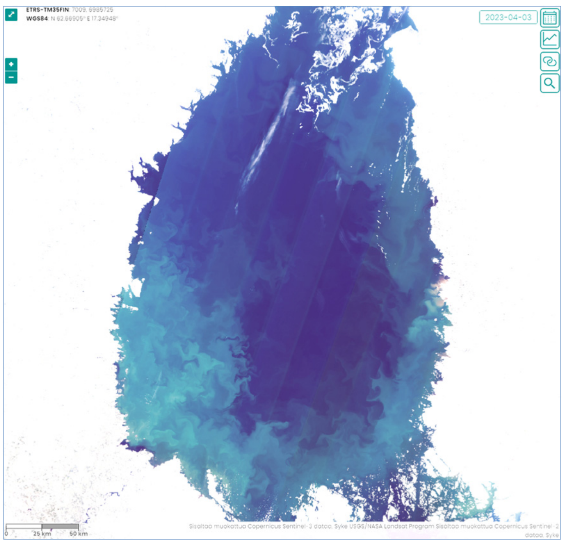
1. Abstract

Waves and bottom currents are the main drivers of sediment resuspension. In the Bothnian Sea the wave climate can be quite severe, the measured maximum value of significant wave height is 8.1 m, with the highest individual wave of 15 m, is of same order of magnitude as the records from the northern Baltic proper. The coastal areas, with shallow water depths, are more prone to wave-induced sediment resuspension. Earth observations (EO) data reveals several occasions where the resuspended sediments reach the surface layer. Linking these events to different wind, waves and current conditions can bring us valuable information about the conditions inducing sediment resuspension and enable us to evaluate the extent of this phenomenon.

We will use EO data (Copernicus programme and Landsat) to identify cases of sediment resuspension. In-situ measurements and reanalyses data will be used to study the wind, wave and current conditions linked to identified sediment resuspension cases. With the combined information we will evaluate the temporal and spatial extent of these events and identify the main physical forcing inducing these events. This will enable us to estimate where and how often these events take place. This will enhance our understanding of the sediment dynamics in the Bothnian Sea and enable us to estimate the changes in it related to climate change and human pressures (e.g. offshore wind farms).



Resuspension during spring in the Gulf of Bothnia (3.4.2023). Contains modified Copernicus Sentinel-3 and USGS Landsat data.

Coastal vulnerability of the eastern Baltic Sea with respect to extreme minima of sea level

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1. Introduction

The course of local water level is an important factor for coastal management and engineering applications. Mostly the hazards associated with extreme water levels are linked with their maxima and possible coastal flooding. However, extreme water level dropdowns influence a number of applications, such as shipping safety in shallow waters (Männikus et al., 2020), harbour design and management, nuclear power stations (Gordeeva and Klevannyy, 2020), or fish and wind farms. Unusually low water levels also have an important role in coastal processes as in such occasions storm waves may erode the seaward end of the beach profile and move sediments out of the equilibrium system.

Water level minima in the Baltic Sea are mostly driven by anticyclones and persistent offshore winds. Low water levels have remarkably longer time-scale than positive surges. Extremely low water levels are normally formed slowly and last for longer time. Water level minima occur less often and have smaller dropdowns compared to the frequency and magnitude of elevated water levels (Männikus et al., 2020). The increase in the magnitude of extreme water level dropdowns is much smaller than the similar increase in water level maxima in the Baltic Sea (Barbosa, 2008).

In this study we analyse the parameters of Generalised Extreme Value (GEV) distribution for extreme water level dropdowns based on the block minima of the annual lowest water level extracted from the output of two different circulation models. The aim is to develop an option to use the shape parameter of GEV distribution to characterise the vulnerability of coastal segments in terms of the likelihood of having a much deeper water level dropdown in the future compared to the existing records. We build an ensemble of 8 projections to estimate an extreme water level dropdown with 50-year return period.

2. Data and methods

We study properties of extremely low water levels along the 1400 km long coastline of Samland (Kaliningrad District of Russia), Lithuania, Latvia and Estonia (Figure 1). We apply recorded water level data from six Estonian and eight Latvian sites. To obtain a continuous projection for the study area, we employ the sea surface height time series from the Rossby Centre Ocean (RCO) model covering 1961–2005 with a temporal resolution of 6 h with a grid step of 2 nautical miles (nmi) (Meier et al., 2003) and the RCA4-NEMO model with hourly output covering 1961–2009 (Hordoir et al., 2013). We rely on these data because several newer circulation model runs seem to have problems with replication of extreme water levels in the eastern Baltic Sea (Lorenz and Gräwe, 2023).

The block maxima (minima) method is applicable to describe extreme water levels and their return periods if data sets can be split into sections so that the minimum (or maximum) values within these blocks are identically distributed and statistically independent (Coles, 2004). If these requirements are fulfilled the water level minima follow a GEV distribution. In the Baltic Sea conditions short term variations of water level are highly correlated (Soomere et al., 2015; Männikus et al., 2020). As water level lows in this region usually occur during the spring or summer season (Männikus et al., 2020), we apply the annual minima as independent block minima.

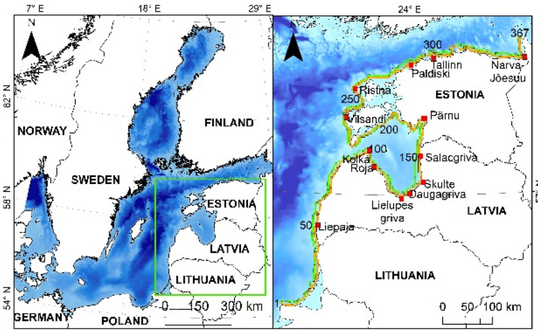

Figure 1. Study area in the eastern Baltic Sea (left panel). Grid cells of RCO (orange) and RCA4-NEMO (green) models used in the analysis (right panel). Red squares indicate water level measurement sites in Latvia and Estonia applied in the study.

The family of GEV distributions consists of the (three-dimensional reversed) Weibull, Fréchet and Gumbel distributions. The main difference is the rate of decay of the tails of these distributions. A GEV distribution is described by the shape, location and scale parameter. The sign of the shape parameter indicates the nature of the respective distribution. If it is 0, the extremes are governed by a Gumbel distribution that predicts a modest growth of future extremes. When shape parameter is positive the respective Fréchet distribution projects a rapid growth of extremes. With the negative shape parameter, the GEV distribution is a 3-parameter Weibull distribution, and the growth of extremes in time is smaller and limited (Coles, 2004).

We evaluated the shape parameter of GEV for two data sets with four different methods: the maximum likelihood method in *Hydrognomon* (Kozanis et al., 2010) and *Matlab* environments, and the biased (population based) and unbiased (sample-based) method of moments.

3. Results

The shape parameter of a GEV distribution based on water level minima (Figure 2) is negative in the entire study area. The estimates form two clearly separated sets. The values found from the output of the RCA4-NEMO model vary from –0.2 to –0.05. Smaller values occur along the open areas at the Samland and coast of Lithuania, inside the Gulf of Riga and in the eastern Gulf of Finland. The values of this parameter are closer to zero at the open shores of Latvia and the West Estonian Archipelago.

The estimates of shape parameter based on the RCO model output are consistently smaller, in the range of –0.38 to –0.2. Their spatial variation is very modest. The lowest values are at the coast of Samland, Lithuania and at the eastern part of Gulf of Finland. The largest examples are in the Gulf of Riga.

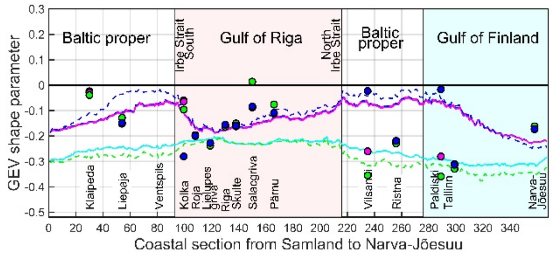

Figure 2. Alongshore variation of the GEV shape parameter of water level minima. The upper cluster (magenta and dark blue) represents estimates calculated from the output of the RCA4-NEMO model. The lower cluster (cyan and green) contains estimates based on the RCO model. Single circles, represent the values found from recorded data with different methods.

The commonly occurring negative values of shape parameter signal that extreme water level dropdowns follow a 3-parameter Weibull distribution in the entire study area. Consequently, much deeper dropdowns of future water level minima compared to the existing records are unlikely.

The estimates of location parameter from the RCA4-NEMO model output are systematically larger than the ones based on the RCO model. The overall alongshore courses of location parameters of the two datasets are qualitatively similar, with larger values along shores of Samland and in bayheads of Gulf of Riga and Gulf of Finland.

The values of scale parameter estimated based on the RCO model data have only small alongshore variations. In contrary, similar values estimated based on the RCA4-NEMO model have remarkable alongshore fluctuations. Notably, the match between the values of all parameters evaluated from measured and modelled data is poor.

The projections of water level minima that occur once in 50 yr based on the RCO and RCA4-NEMO model data (Figure 3) exhibit remarkable differences. The projections relying on the RCA4-NEMO model host values in range –0.8 to –1.15 m. These are considerably deeper than the ones based on the RCO model that stay in the range from –0.65 to –0.92 m. The difference between the two groups of projections is ~10 cm on the shores of Latvia, the West Estonian Archipelago and in the western part of Gulf of Finland, larger on the shores of Samland, and around 30 cm in the eastern Gulf of Riga and eastern Gulf of Finland.

The projections that rely on the RCA4-NEMO data match considerably well the all-time measured minima of water level in all locations along the study area, except in Gulf of Riga. This signals that the RCA4-NEMO model is more adequate in describing water level minima in the study area and can eventually replicate both, single values and statistics better while the RCO model seems to be capable of reproducing the majority of the water level maxima in this region (Soomere et al., 2015).

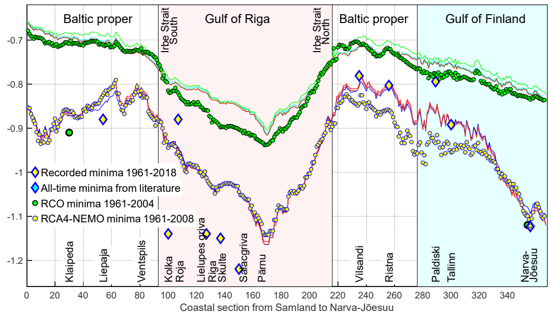

Figure 3. Projections of return values of water level minima once in 50 years based on modelled data and the GEV distribution. The parameters of this distribution are evaluated using the maximum likelihood method implemented in *Matlab* and *Hydrognomon*) for RCA4-NEMO (lower cluster) and RCO model data (upper cluster). The recorded minimum in 1961–2018 at Riga is –1.32 m and at Pärnu –1.29 m.

4. Conclusions

The analysis demonstrates that extremely low water levels in the eastern Baltic Sea commonly follow a 3-dimensional Weibull distribution. It is therefore unlikely that much lower water level extremes than already recorded will occur in this region.

The results also indicate that different hydrodynamic models may be appropriate for the estimations of extremely high and of extremely low water levels.

Acknowledgements

The research was supported by the Estonian Research Council (grant PRG1129). The authors are deeply grateful to the SMHI for providing the RCO and RCA4-NEMO model data.

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Coastal dynamics of the Daugavgriva Island beach in the Gulf of Riga, Latvia

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1. Introduction

One of the tasks of coastal engineering and management is to develop the coastal zone and protect the coast and the hinterland. A situation becomes more complicated if coast is prone to erode and choice between management strategies (retreat, accommodate, protect) must be made. In order to be successful, engineers must have a good knowledge about coastal dynamics over a long period. Case studies from other locations serve as a vital starting point for generating ideas and approaches.

We are focusing on the area near the mouth of the river Daugava in Latvia (location called Daugavgriva), in the Gulf of Riga, eastern part of the Baltic Sea. Sea (Figure 1). This is typical gentle sloped sandy beach with foredunes covered with grass, bushes and trees. Rapid accumulation in this area occurred after building the western breakwater in the 19th century, turning the area from marshy islands to sandy beach areas (Eberhards, 2003, Bertina et al. 2015). This area is also facilitated by the accumulation of sand from river Lielupe on the left side of Daugavgriva island.

Figure 1. Gulf of Riga and the location of Daugavgriva.

Unfortunately, this coastline is experiencing beach erosion. Almost 30 years ago, a rock revetment was built approximately 650 meters south-west from the western breakwater (Figure 2). This has also some sections of concrete plates. Although this structure effectively protects the land and facilities behind the coastline from further erosion and flooding threats, it fails to preserve the sandy beach in front of it. Namely, this rock revetment acts as a bounce-wall for waves and enhances the erosion (scour) of soft sediments. Beach to the south from the rock revetment is a part of nature park "Piejura". This area has very high anthropogenic load during the recreational season.

Figure 2. Study area in Daugavgriva (denoted with read oval)

This rock revetment was not built till the western breakwater and the problems with erosion have persisted. In 2023, a local municipality ordered a study to evaluate the situation and, if necessary, propose protection measures. We are describing here briefly our work which covered the analysis of coastal dynamics and proposed ideas for further protection. To start with, we describe shortly previous studies in the neighbouring area and local wave climate based on the modelling and water level measurements at Daugavgriva. Then we assess shoreline changes and sediment movements in 20 years and try to predict what happens with the beach in the future. Finally, we model a possible solution as a combination of beach nourishment and jetty which should keep the sand in the area.

2. Site conditions

Historically, the main sediment transport direction has been along the eastern coast of Gulf of Riga to the north (Eberhards, 2003), sometimes small amounts of sediments are also moving towards south. According to Ulsts (1998), eastern part of the Daugavgriva island is strongly affected during storms and in last 40-50 years the retreat could be around 240-250 m. Intensive washing of the beach and foredune is documented on Daugavgriva island during strong storms when the maximum water levels reach 2 m or even more above the sea level, large amounts of sediment material is removed from shoreline. The area to the south of the coastal protection consists slightly more than 50% of fine-grained sand 0.125–0.24 mm and below 50% of medium coarse sand 0.25–0.5 mm. Coarser sediment in the area closed to the jetty indicates greater intensity of water energy causing the coastal erosion.

Najafzadeh et al. (2023) modelled waves in the Gulf of Riga for 1990–2021 with a spatial resolution of 3 nautical miles (nmi) forced by the wind field of ERA5, to the Gulf of Riga and its entrance area with a resolution of 1 nmi, and to nearshore areas of this gulf with a resolution of 0.32 nmi. The calculations were performed for idealised ice-free climate. We extracted the wave parameters 3 km away from the study site. It showed that high waves come always from NWW.

Near the study site, there is a high-quality water level Daugavgriva measurement station (Figure 1) in terms of length and frequency (Männikus et al., 2021). We used this data together with wave data to calculate wave run-up with Hunt formula:

$$R = \frac{H_0 tan\beta}{\sqrt{H_0/L_0}},$$

where R is wave run-up, β denotes the slope of the beach (here 1:50), H_0 is significant wave height in deep water and L_0 is a wave length.

In order to assess the change of influence of storms on the beach of Daugavgriva, monthly and stormy season maxima of wave run-up were analysed. Stormy season starts in July and ends in June in the following year. No clear trend neither to decreasing nor increasing was to be seen. This indicates that the impact of the storms at Daugavgriva has not changed during the last 30 years.

3. Analysis of coastal processes

The rock revetment has changed coastal processes significantly. Figure 3 shows the simplified scheme. Main sediment transport is still from south to the north. Depth of the sea in front of this hard defence measure, as a result of more than 20 years of erosion, has increased significantly and almost every storm is able to move the sediments to the deeper sea. Basically, sediment flow from the south is no longer moving to the north but is directed to the deeper sea by the defence structures. The beach between the Daugavgriva jetty (western breakwater) and defence structure is now like a pocket beach – no more sand is coming from the south. Moreover, sometimes the storm waves from NW are carrying sediments towards the south, where they reach close to the defence structure and then larger waves are taking these sediments also to the deeper sea – out from this pocket beach system.

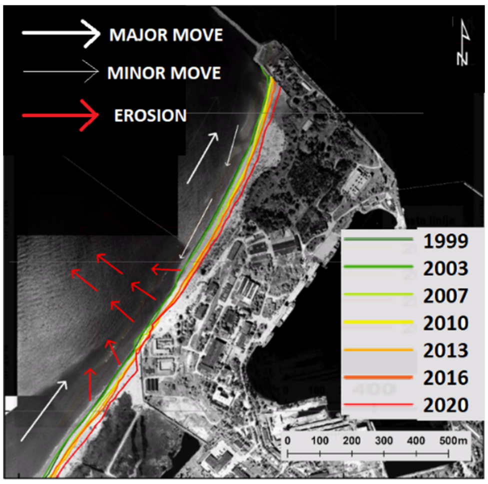

Figure 3. Shoreline changes (coloured lines) and scheme of the sediment transport after the rock revetment was built ca 650 m south from the breakwater.

We have digitized shorelines from all available orthophotos since 1999 and have seen gradual retreat of the shoreline (Figure 3). The maximum extent of the erosion between western breakwater and defence structure is 43 m, while it is up to 45 m, just south from the defence structure. We estimate that the beach in total lost ca 30 000 m^3 of sand. When examining at earlier beach profiles, it can be seen that large amount of the sand has been accumulated in foredunes and dunes.

4. Modelling beach nourishment

Delft3D 4.04.01 coupled modules WAVE and FLOW were used to model the sediment transport. WAVE grid was forced with dominating wave data from Najafzadeh et al. (2023). This data was sorted into different classes and according to the calculated wave energy, dominating conditions were found.

Sediment transport was modelled in FLOW grid which was nested into the WAVE grid. It had boundary conditions of Neumann and water level. Sediment thicknesses and spatial distribution were assessed from boreholes and orthophotos. Morphological factor 10 was used to speed up the processes. The results of separate simulations of dominating conditions were assessed. It was found that beach nourishment combined with an additional jetty (Figure 4) decreases the erosion.

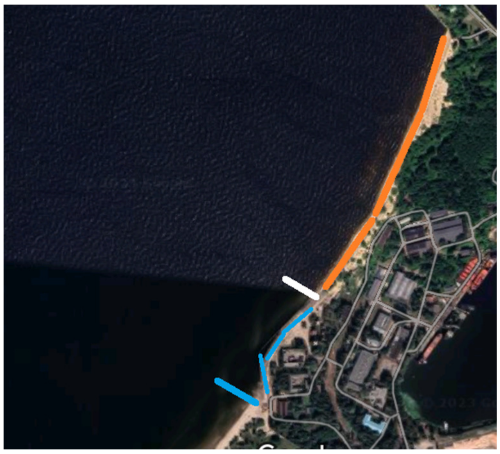

Figure 4. Scheme of the proposed solution. First step: jetty (white). The second: beach nourishment with sand (orange). The third: another jetty (blue) The lengths are schematic and need to be determined in the second part if this option is chosen.

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Application of the probability of extreme sea levels at selected Baltic tide gauge stations

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1. Introduction

Currently, about 220 tide gauges are deployed on the coasts of the Baltic Sea, whose network carefully monitors the processes of sea level fluctuations. Extreme sea levels that occur during storm surge and storm floods contribute to catastrophic changes in the coastal zone (abrasion, erosion processes, destruction of infrastructure). The complex nature of the phenomenon of extreme sea levels makes the forecast of this process complicated. In addition to hydrometeorological and anthropogenic factors, local conditions have a large impact on changes in sea level: coastline configuration, morphology and bathymetry of the shallow-water coastal zone. Therefore, in order to analyze the hydrological risk of the coastal area, probabilistic forecasting of maximum and minimum sea levels is commonly used. Probabilistic analysis determine the so-called theoretical sea levels (theoretical water) i.s. the highest and lowest water levels that can occur every certain number of years, e.g. once every 10, 20, 100 or 500 years. These numbers of years are called the return period. It is extremely important to prepare the longest possible observation series of maximum and minimum annual sea levels for the long-term probabilistic forecast. Only then can the obtained results be considered credible and practical.

The aim of this study is to analyze the probability of the occurrence of extreme water levels along the entire Baltic Sea coast from 1960-2020.

In the work lists the critical sea levels in the Baltic States. These levels are related to the height of the breakwaters and are determined on the basis of probabilistic methods. In the next section of the work, the heights of the theoretical water in the entire quantile range was determined. The calculated levels were visualized on maps of the Baltic Sea and the geographic distribution of theoretical water heights with a 200-year return period was analyzed. The next part of the analysis concerns the variability of theoretical water levels over the last 120 years and a comparison of water levels from two 61-year periods: 1900-1960 and 1960-2020. Thanks to this, it is possible to see how the return period has changed and what were the trends of the theoretical and observed sea level in the last few decades. In the last part of the analysis was checked how the size of the sea surface and the length of the coastline change, which correspond to different heights (ranges of sea levels) of theoretical water for 1-year, 50-year, 100-year, 200-year return period.

2. Material and methods.

The research material contains two ranges of sea level data with different resolution and different period. The first one contains hourly observations of sea levels from 42 tide gauge stations located along all the coasts of the Baltic Sea from the period 1960-2020 (Fig.1). The second type of research material is the maximum and minimum annual sea levels from the period 1900-1960 (or slightly shorter) from 21 Baltic tide gauge stations. Both ranges of measurement data were selected as the longest possible sea level observation periods available from the national hydrological and meteorological institutes of the Baltic states.

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. Selected results and discussion

Some of the obtained maximum and minimum theoretical water levels results are shown in Figure 1.

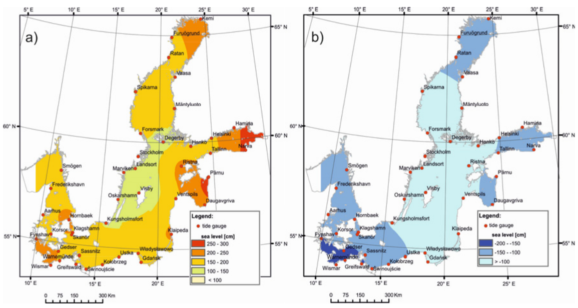

Figure 1. The distribution of theoretical water with a 200-year return period: a) theoretical maximum sea level, b) theoretical minimum sea level.

The results in Figures 1 indicate that the theoretical water levels at individual tide gauges are related to the distance of these tide gauges from the open waters of the Baltic Sea. In Visby, the 200-year maximum sea level was 98,1 cm, and its annual minimum was –71 cm, the smallest range in the whole Baltic Sea for the 200-year period. The range is so small because the station is located on the coast of the open waters of the Baltic Sea. (Central Baltic, Gotland), where the water level fluctuations are the smallest. For the remaining tide gauges, away from the open waters of the Baltic Sea and located in Baltic gulfs and bays, the ranges of extreme water levels are much higher- for Narva (Gulf of Finland) the range was from 256 cm to -114 cm, for Wismar (Western Baltic, Meklemburg Bay) from 220.5 cm to 199.3 cm, and for Kemi (Bothnian Bay) from 237.3 cm to –143,7cm. The theoretical, maximum and minimum sea levels analyzed in this work are similar in nature to the actual, observed water levels of the Baltic Sea. The occurrence of these extreme sea levels is consistent with the so-called a geographical pattern about which the authors have already written in previous research works (Wolski and Wiśniewski, 2020 a,b).

The next-stage analysis compare (calculation of differences) height of the maximum theoretical water levels between two 61–year periods, 1900-1960 and 1960-2020, for selected tide gauge stations. From the comparison of the 2 periods height of the theoretical water results in a shortening of the return period in the Baltic Sea. For example, for Świnoujście (Southern Baltic), after 61 years, the 100-year water level shifted to the 73-year water level (Fig. 2a), and in Hanko (Northern Baltic), it shifted to about the 15-year water level (Fig. 2b).

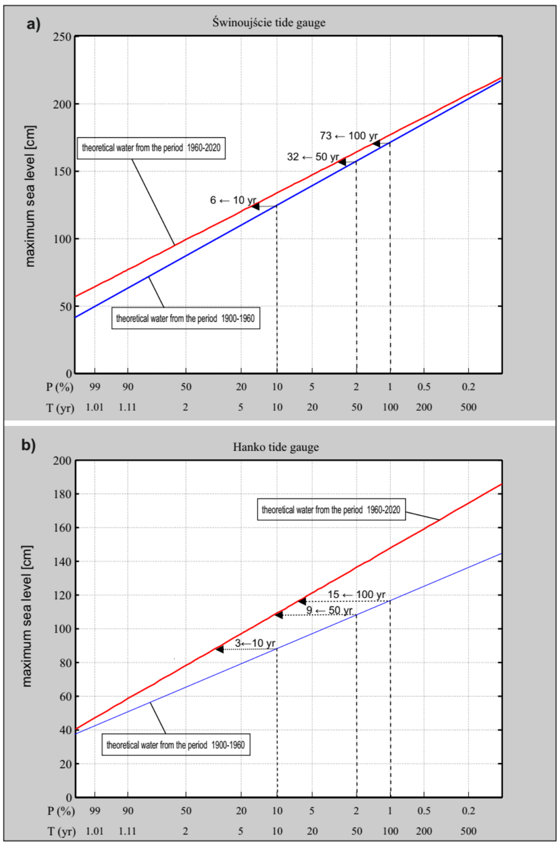

Figure 2. Differences in the theoretical water levels between 1960–2020 and 1900–1960 in Świnoujście (Southern Baltic)(a) and Hanko (Northern Baltic)(b).

The above analysis was performed for 21 water gauge stations located along the coast of the Baltic Sea. Comparison of theoretical water levels from two periods: 1900-1960 and 1960-2020 showed that over the last 60 years, a stable trend of increasing both the theoretical and the observed maximum water level in the Baltic Sea has been visible. The sea level rise averaged for the entire Baltic coast was 15.6 cm (2.6 mm/year). This increase sea level shortened the return period for the Baltic Sea tide gauge stations an average about 50%.

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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Coastal erosion assessment for Latvia using Sentinel-2 data

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1. Introduction

Change of sandy coasts, particularly due to rising global sea levels, is a problem observed both worldwide and in the Baltic Sea IPCC (2023), Luijendijk et al., (2018). Coast of Latvia is almost 500 km long, and generally composed of loosely consolidated, sandy sediments Eberhards (2003). The coastline changes due to water level and sea wave dynamics in Latvia is a long-known issue and has been monitored by *in-situ* methods for more than 30 years i.e. by Lapinskis and Grīna, (2014). However, the *in-situ* monitoring does not cover the entire coastline homogeneously and is costly both financially and human labor hours. As an alternative, satellite remote sensing has been used for coastal change detection in multiple global and regional studies as outlined inn Konstantinou et al. (2023), Vos and Harley, et al. (2019) and Luijendijk et al. (2018). Thus, we propose the use Copernicus Setinel-2 data to infer about coastal changes near Baltic Sea in Latvia for the five-year period of 2017-2022, with a perspective of creating a stable remote monitoring system with an ever-increasing archive of Sentinel-2 satellite data in the future.

2. Research area

Latvia is in northern Europe, in the south-eastern part of the Baltic Sea, between Lithuania and Estonia. Morphologically, the coast is composed of sandy, quaternary sediments, mainly formed after regression of Littorina sea. Beaches of Latvia are wide, with gentle slope profiles and dunes not exceeding 15 m in height. While beaches are very well pronounced over almost the entire coast, there are areas where wave breaking currents are slow, allowing the growth of meadows into the sea (see fig. 1).

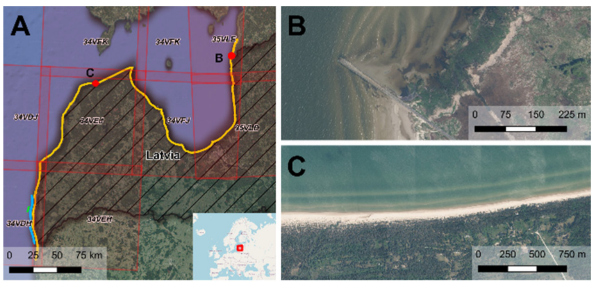

Figure 1. A - Latvia in the context of Europe. Yellow color outlines the study area, green and blue – verification area of unmanned aerial vehicle and high-resolution satellite date, respectively. Red polygons indicate the Sentinel-2 tiles used in the study. B, C – typical aerial images of Latvian coast

3. Materials and methods

Our methodology can be divided into four distinct parts – **data preprocessing, water line extraction, shoreline analysis** and **water line verification** (see fig. 2).

3.1. Data preprocessing

We first download Sentinel-2 data from 2017-2022, for each tile outlined in fig. 1. We download the L1C version of data and perform atmospheric correction locally with ACOLITE processer by Vanhellemont and Ruddick (2018). Each scene is then coregistered to a single location with AROSICS processor by Scheffler et al. (2017). We mask the clouds by sen2cloudless algorithm by Zupanc, (2020).

3.2. Water line extraction

We use the thresholding algorithm by Otsu (1979) on the band-8 (near infrared channel) of Sentinel-2 data to extract land-water classes for each scene. We then remove classification artifacts with dilation-erosion process in saga GIS and perform vectorization by marching squares algorithm. Lines are simplified by Douglas-Pecker (1973) algorithm with a tolerance of 10 m. Then, a comparison with water level measurements from LEGMC is made, removing all coastlines at the time when water level was +- 0.2 m above 1991-2020 sea level climate normal. We also remove waterlines from November to March, due to errors that are introduced by snow and ice in the classification data set. Finally, we perform manual quality control, removing a few erroneous lines still in the data set. From more than 12000 Sentinel-2 scenes we are left with 1139 lines describing the Latvian coast.

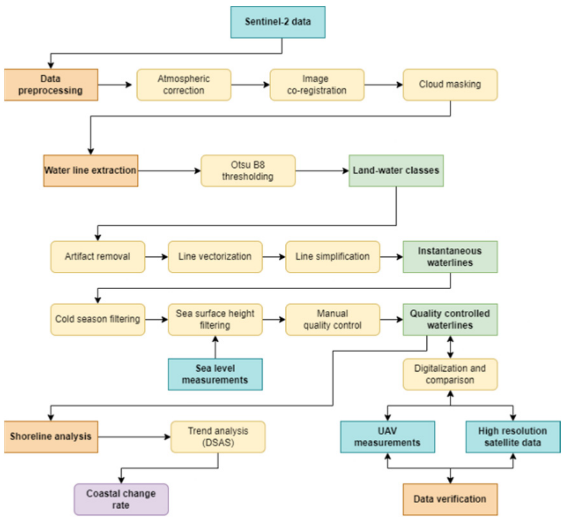

Figure 2. Data processing flowchart

3.3. Shoreline change analysis

We perform shoreline analysis using Digital Shoreline Analysis system by United States Geological Survey and Himmelstoss et al. (2021). Shoreline change rate is determined every 50 meters on transects parallel to the coastline. Linear regression rate for water line retreat is then calculated. For better visualization, we extract the moving average retreat rate with a step of 1 km along the coastline.

3.4. Water line verification

We performed unmanned aerial vehicle (UAV) survey near Bernāti, Latvia on 26th of July 2021 and used high-resolution satellite scene on 9th of June, 2021 from Airbus Pleiades constellation to infer about coastline detection error (fig. 1 green and blue lines respectively). The results are digitalized and compared with extracted waterlines from Sentinel-2 scenes around the same time. We get the RMSE classification error of 5.36 m and 4.96 m for UAV and Pleiades data, respectively.

4. Results

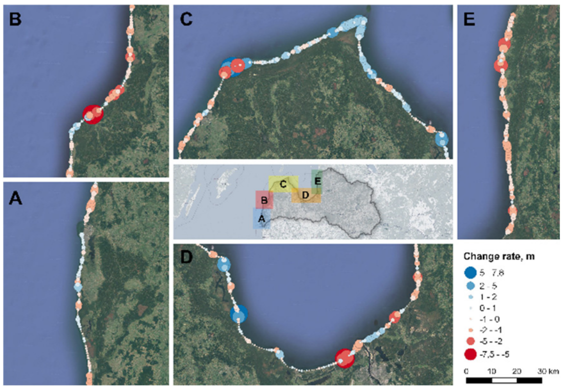

Figure 3. Moving average coastline change rate in 2017-2022. Blue color indicates coastline advance, red – retreat. Circle size denotes the retreat rate, with larger circles indicating larger changes.

As seen in fig. 3 we can see that overall, the coastline change rate is Latvia is relatively small. Larger changes tend to be located at a few key locations, reaching the highest values near Pāvilosta (fig. 3B), with retreat rates up to 7 m/year), Oviši cape (fig. 3C northwest cape), where fast coastal advance of 7.8 m/year is observed close to shoreline retreat of 3.8 m/year, key locations near river mouths and harbors in the Gulf of Riga (fig. 3D) with both shoreline advance and retreat and the northeastern part of the Gulf of Riga (fig. 3E), where mainly shoreline retreat is observed.

Preliminary comparison with previous monitoring efforts of Lapinskis and Grīne (2014) show good alignment with our results. Satellite data observations every 50 meters highlight the advantages of better spatial coverage, however, at some locations, our method performs with high uncertainty. One of such areas is the northernmost part of the Gulf of Riga near Ainaži (fig. 3E north), which geomorphologically indicates prevailing accumulation processes, however, our results indicate relatively large coastal erosion (of about 2 m/year).

5. Conclusions

Our results show that in the five-year time span most of the coastal changes can be attributed to the human-induced processes. While we observe naturally occurring coastal dynamics, they are generally of lower amplitude than human driven processes. We also see that the time span of five years is appropriate to monitor short-term changes in the coastline but does not represent the full extent of the coastal dynamics in Latvia. With the measurement data from Sentinel-2 mission in the future, we predict that our monitoring system will provide increasing value.

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Session D

Human impacts, interactions and management options

Air pollution and it's dispersion in the city of Klaipeda: the influence of meteorological conditions of the Baltic Sea Region

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1. Abstract

Climate change and air pollution is one of the crucial and unresolved issues in the world, and all countries put considerable efforts into identifying major pollutants in their cities and the sources where this pollution comes from because it affects many different natural and social subjects, such as landscape, surface, soil, and most importantly human health. The World Health Organization (WHO) identified air pollution as the greatest environmental threat to human health – around 800,000 premature death each year, and this is the 13th leading cause of death worldwide. Even though many studies show that the link between air pollution and public health are much deeper and much more complex than originally thought. The main pollutant found in cities is particulate matter and nitrogen dioxide (NO2). The size of the city, demographic trends, urban development, economic activities, climatic conditions, and some other minor factors play an enormous role in impacting air pollution. The main aim of this research is to measure the air quality in the functional areas of the city of Klaipeda using passive solid particle collectors and nitrogen dioxide sorbents. Functional areas in which air quality is studied and compared: industry zone, green area, residential area, transport hub and the port area.

Are pollution measurements for this research are carried out once a season in order to determine not only the spread of pollution in the city territory by measuring pollution in functional zones, but also the impact of Baltic sea region's meteorological conditions on air quality . For comparative evaluation, passive air pollution tests are also carried out in resort areas.

2. Methodology

To achieve the main aim of this research - to identify hotspots of contaminants in Klaipeda city the total suspended particulates and nitrogen dioxide were measured in 19th sites by using original passive samplers (Figure 2.) and palmes passive diffusion tubes (Figure 3.). Measurments are caried out in the following periods: 8 weeks period in each season for particulate matters (PM) and 2 weeks period for nitrogen dioxide (NO_2).

For this research the Kernel density tool was chosen to show the concentrations of pollution in the Klaipeda portcity by categorizing results into levels between low and high.

Kernel density estimation is used to identify the location, spatial extent, and intensity of pollution hotspots. The kernel density (KD) function estimates the intensity of events across a surface by calculating the overall number of cases situated within a given search radius from a target point. This feature of KD smoothing is especially beneficial for empirical studies in which individual observations are represented by geographic coordinates only and have no other attributes, required by more commonly used smoothing techniques, such as spline and kriging.

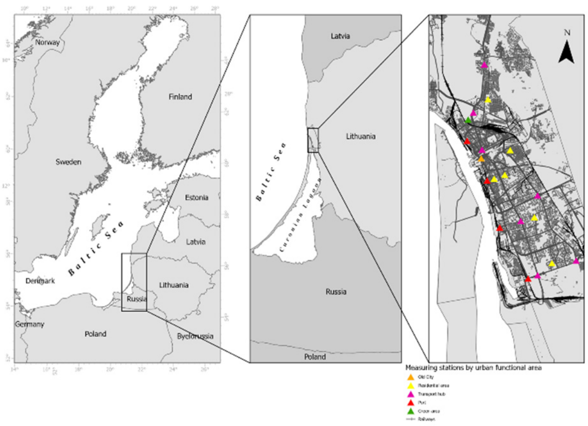

Figure 1. The study area: southeast part (SE) of the Baltic sea (a); Klaipeda city (b); air pollution measuring stations (MS) by urban functional area (c)

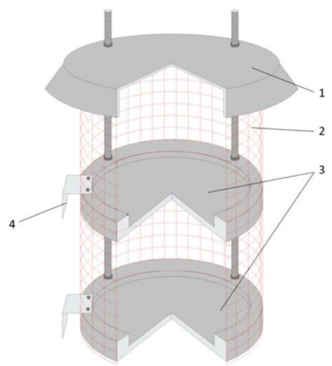

Figure 2. Passive sampler for particulate matter. Roof (1), protective net (2), collection plates (3), fixing bracket (4).

(Paulius Rapalis, 2021, Geochemistry of the Dust Collected by passive Samplers as a Tool for Search of Pollution Sources: The Case of Klaipeda Port.)

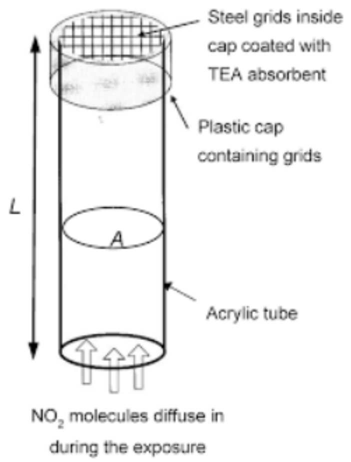

Figure 3. Nitrogen dioxide (NO_2) palmes passive diffusion tubes.

(Mathew R. Heal, Duncan P.H. Laxen, Bend B. Marner (2019) Biases in the Measurement of Ambient Nitrogen Dioxide (NO_2) by Palmes Pasive Diffusion : A Review of Current Understanding, *Atmosphere* 2019, *10*(7), 357)

Results

The result of measuring air pollution using passive samplers in Klaipeda city shows that the biggest quantities of total suspended particulates are located close to the main transport hubs and the most polluted area is the Western side of the city.

Result shown that the residential area close to the port is very polluted and it's value is very high.

Klaipeda is a city by the sea, where the west direction winds prevail in summer time, so the activities of the port companies can be felt in the city areas further away from the port.

Estimated result of this whole research is to show the main air pollution hotspot by the kernel density and the differences of air quality in each seasons. Impact of the Baltic sea region climate on the air pollution in portcity will be analyzed.

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A method for optimizing the location of measurement stations and its application to the Baltic Sea area

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1. Introduction

Evaluating the human impact on the natural environment involves closely monitoring different environmental parameters and indicators. This requires establishing monitoring networks capable of effectively covering specific area. One of the key issues in designing such networks is optimal selection of the location of measurement stations and assessment of their representativeness for a given area. So far, there is no well-established and commonly recognized reference procedure of optimal determination a measurement network or assessment of the spatial representativeness of the existing network. Different approaches are used depending on the quantities being studied, the research goal and the type of data available for analysis (ex. Piersanti et al. (2015); Araki et al. (2015); Lu et al. (2011)). In most cases, however, the choice of the location of measurement stations is based on the researcher's intuition.

In this work we present a method for optimizing the location of measurement stations that minimizes the error in determining the average value of the parameter under study for a given area. The method will be described in the following section and its practical application will be shown for the Baltic Sea area, for two parameters: sea surface temperature (SST) and chlorophyll-a concentration.

2. Methodology

Assuming that the purpose of the measurements is to optimally determine the spatial average value of a given parameter, we adopted a linear regression model, where the explanatory variables are the measurements at individual locations and the dependent variable is the mean value for a given area. This relation can be written as follows:

$$\langle\tilde{Q}\rangle = \sum_{i=1}^{N} b_i Q_i + b_0,$$

where:
N – number of measuring stations,
Q_i – measured value of quantity Q at i-th measuring station (i-th location),
$\langle\tilde{Q}\rangle$ – estimated average value of quantity Q,
b_i – coefficient of the linear combination corresponding to the i-th measuring station,
b_0 – free term.
In the equation above the coefficients b_i can be treated as weights showing the contribution of the measurements at individual locations to the mean value. Minimization of the model's root mean square error (RMSE) was adopted as the optimization criterion, ie. for a given number of measuring sites (N) locations resulting in lower RMSE were regarded as more favorable.

Our analysis, ie. determining the b_i coefficients and RMSE for various combinations of stations locations in search for their optimal arrangement, was based on data provided by the *System SatBałtyk* (https://www.satbaltyk.pl/). It contains satellite data for the Baltic Sea area complemented with the results of numerical models, Konik et al. (2019). The SatBałtyk service provides data on SST four times a day and daily surface chlorophyll-a concentrations at a spatial resolution of 1 km with full coverage of the entire Baltic Sea.

It should be mentioned that in practical calculations examining all possible arrangements of measurement stations in search of the one that minimizes the RMSE would be very time-consuming in most cases. Therefore, it is necessary to use approximate methods. In our study an optimization method based on genetic algorithms was used for calculations.

3. Results

The first part of the analysis was performed for a set of 60 measurement stations being a part of the HELCOM (Helsinki Commission) and ICES (The International Council for the Exploration of the Sea) monitoring (Fig. 1). The optimal stations (i.e those with the best locations) out of the full set were determined for each given number of measurement stations (N). As an illustration, we show results of analyses conducted for daily and for monthly average of chlorophyll-a concentrations at individual locations and for the whole Baltic Sea. The RMSE and coefficient of determination (r^2) of the linear model for the optimal locations found by our procedure are presented in Tab. 1 for different N. One can see that the RMSE quickly diminishes and r^2 improves with increasing number of measurement station. Clearly, a few properly selected stations are sufficient to estimate the average value of chlorophyll-a concentration for the Baltic Sea area with reasonable accuracy.

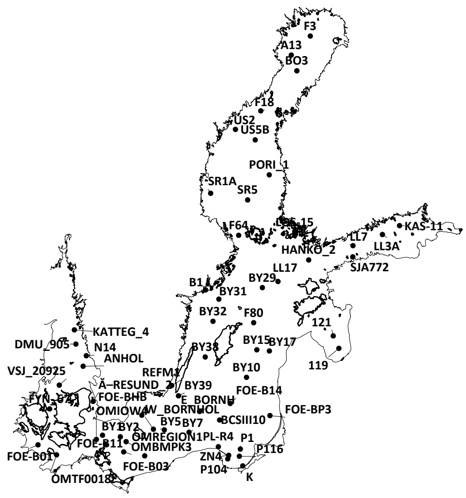

Figure 1. Location of the measurement stations (HELCOM & ICES).

Table 1. The RMSE and coefficient of determination r^2 of the linear model used to determine the daily and monthly average value of chlorophyll-a concentration for the Baltic Sea depending on the number of optimal measurement stations (N).

N	daily average		monthly average	
	RMSE	r^2	RMSE	r^2
1	0.55	0.7206	0.40	0.8236
2	0.43	0.8266	0.29	0.9032
3	0.36	0.8773	0.22	0.9447
4	0.30	0.9142	0.18	0.9645
5	0.27	0.9314	0.16	0.9697
6	0.25	0.9422	0.15	0.9741
10	0.19	0.9659	0.11	0.9863
20	0.14	0.9830	0.083	0.9923

It should be emphasized that the results (optimal station locations and related statistics) will vary depending on whether a daily average or a monthly average is taken into consideration.

In the second part of the study, the adopted algorithm was used to determine the optimal positions of a given number of measurement points, assuming full freedom of their location (i.e not restricting to any predefined set of locations, as it was done in the first part of the research). Thus, the analysis carried out is an attempt to find an answer to the question: "How to optimally design a network of N measurement stations/points in the Baltic Sea in relation to the measured parameter?" As an illustrative example we show results for SST for the case N=3 and N=6 measuring sites: their optimal locations together with corresponding b_i values (weighting factors) are presented in Fig. 2.

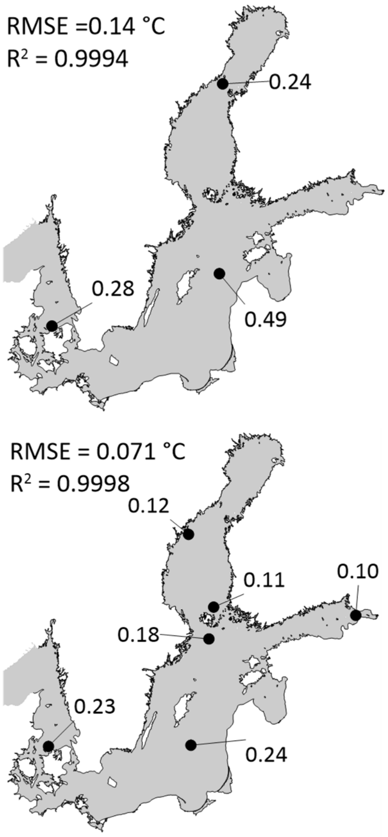

Figure 2. Location of optimal measurement points and corresponding regression coefficients (weights) determined for monthly average SST. Case of N=3 and N=6 measurement stations.

4. Summary

We developed a method, that can be used both to test the representativeness of measurement stations in the case of an existing monitoring network (by identification of the most important and redundant ones), and to determine the optimal network of measurement stations when designing a new one. Assigning the weights (coefficients b_i of the linear combination) to measurements from individual stations when determining the spatially averaged value of the parameter (together with its uncertainty) is a noteworthy additional advantage of the proposed methods. It is also worth noting that in contrast to some other methods for determining the optimality of measurement networks and the representativeness of measurement stations, in our method there are no additional parameters whose values must be arbitrarily adopted (such as threshold values present in the method used in (Piersanti et al., 2015). The presented method is convenient and relatively simple, but its limitation is that in its current form it is suitable only for determining the spatial average of the analyzed characteristics, for other applications it should be modified accordingly. This, however, requires additional studies and is beyond the scope of present work.

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Knowledge Transfer Platform FindFISH – Numerical Forecasting System for Fisheries for the Marine Environment of the Gulf of Gdańsk

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1. Introduction

The FindFISH Knowledge Transfer Platform aims to tackle the primary challenge facing the fisheries sector: the declining profitability of fishing operations. This challenge is accompanied by several concerns, including rising operational costs for fishermen, the need for longer and more distant fishing trips to find fish, catching low quantities or low-value fish, engaging in activities that barely break even due to increasing costs, complying with fishing quotas, and dealing with associated difficulties.

Currently, the Polish fishing industry is searching for effective strategies in response to these challenges. Increased awareness of the nutritional benefits of fish among the Polish population has led to a rise in fish consumption (European Commission, 2009). While new technologies help meet this growing demand, they also add pressure on fishing resources. As a result, many fish stocks are being overexploited, posing a threat to the marine ecosystem of which fish are a crucial part (Fousiya et al., 2023; Kemp et al., 2023; Laghari et al., 2022).

2. Methods

The work within the FindFISH project was divided into five main stages and implemented in three blocks: environmental research, numerical work, and IT tasks (Fig. 1) (Dzierzbicka-Głowacka et al., 2018).

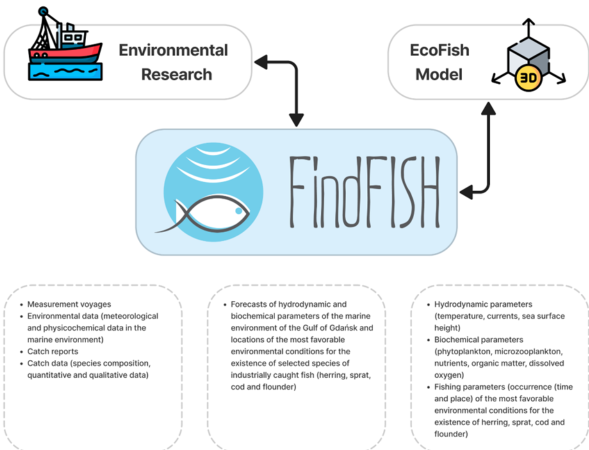

Figure 1. Structure of the FindFISH platform.

In the first stage, an assessment of the Gulf of Gdańsk's environmental condition was conducted, focusing on chemical and ecological aspects, particularly the ichthyofauna, utilizing existing and newly acquired data (Kuczyński et al., 2023; Zaborska et al., 2023, 2019). The second stage involved fishing expeditions where physicochemical measurements were taken, including water temperature, salinity, and dissolved oxygen levels, to determine habitat preferences of selected fish species and validate the EcoFish model (Krzemień and Wittbrodt, 2023). Analysis of the data from these expeditions allowed for identifying habitat preferences for commercially harvested fish species in the Gulf of Gdańsk (Pieckiel et al., 2023). The third stage saw the development of the EcoFish model, comprising hydrodynamic, biochemical, and Fish Module components, enabling the monitoring and prediction of changes in the marine environment (Janecki et al., 2023c, 2023b; Janecki and Dzierzbicka-Głowacka, 2023; Nowicki et al., 2023b, 2023a). The Fish Module, employing fuzzy logic, was created to interpret environmental parameters and determine optimal conditions for fish habitat (Janecki and Dzierzbicka-Głowacka, 2023). Additionally, the FindFISH Platform was designed to visualize measurement data, forecasts, and environmental conditions for fish habitat in real-time (Biernaczyk et al., 2023). Testing of the FindFISH numerical system aimed to assess its functionality and potential benefits for fishermen, scientists, and fisheries administrators (Dzierzbicka-Głowacka, Wittbrodt, et al., 2023).

3. Results

The FindFISH Platform represents a significant leap forward in fishing technology, presenting a comprehensive solution that integrates historical data, environmental observations, and user feedback to optimize fishing operations. This platform holds the potential for substantial economic and ecological advantages:

- Fuel Savings and Operational Cost Reductions: Drawing from operational data, the FindFISH Platform has the capacity to curtail overall operational expenses by 5-15%. This reduction is realized through the implementation of more efficient fishing routes and strategies, leading to significant fuel savings, particularly for vessels engaged in extended voyages.
- Time Efficiency and Enhanced Fish Quality: The platform stands to decrease trawling time by approximately 25%, facilitated by precise location predictions that enhance fishing efficiency. This translates to a roughly 20% reduction in the time

from catch to port, consequently improving the freshness and quality of the catch.

- Environmental Benefits: The FindFISH service contributes to mitigating the environmental impact of fishing activities. Reduced trawling time translates to diminished disturbance to marine ecosystems and a decrease in bycatch.
- Profitability and Compliance: By facilitating targeted fishing, the platform ensures adherence to fishing quotas while enhancing the profitability of catches, as fishermen can concentrate on commercially valuable species.

These projections are derived from the experiences and input of fishermen who have utilized the platform, coupled with an analysis of diverse factors influencing the costs of fishing operations. The precise impact of the FindFISH Platform on cost reductions will become more apparent in the coming years, as a growing number of fishermen embrace the system and provide feedback on its efficacy.

4. Summary

In summary, the FindFISH Platform offers a suite of benefits encompassing cost savings, enhanced efficiency, improved catch quality, and environmental sustainability, all contributing to a more lucrative and conscientious fishing sector.

Designed with fishermen in mind, the FindFISH Platform aims to elevate fishing efficiency and minimize environmental impact. As a pioneering tool, it employs numerical methods to forecast marine conditions in the Gulf of Gdańsk, facilitating the identification of optimal fishing grounds. Addressing a diverse market, FindFISH pledges profitability and decreased operational costs for the fishing industry, while upholding sustainability and environmental conservation. Developed through collaboration between scientific institutes and a fishermen's association, the platform integrates real-time data and ecohydrodynamic models, with anticipated benefits not only for fishermen but also various stakeholders, promoting sustainable fishing practices and aiding in marine environment protection.

5. Acknowledgments

Scientific work financed from the state budget under the programme of the Minister of Education and Science (Poland) entitled "Science for Society" No. NdS/546027/2022/2022, amount of funding PLN 1 702 130.65, total value of the project PLN 1 702 130.65

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Good eutrophication status is a challenging goal for coastal waters

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This research has been published (open access) by Ambio (2023). https://doi.org/10.1007/s13280-023-01965-7

1. Background & motivation

Coastal ecosystems are hotspots of marine biodiversity and multiple human interests. They act as an interface between the terrestrial environment and the open sea and are prone to eutrophication caused by excess nutrients from various sources. Coastal states bear the responsibility of developing environmental legislation, policies, and institutions necessary for safeguarding its coastal waters.

However, many pollutants, including chemicals, microplastics, and nutrients, readily dissolve in water, disperse, and become diluted across expansive bodies of water. Consequently, pollution originating in other countries and regions further impacts the condition of coastal waters, compounding the pollution stemming from local sources such as cities, industries, and agricultural land located on or near the coast or within the watershed.

2. Research questions

To what extent can local communities and regions manage the eutrophication status of their adjacent coastal ecosystems? How much do coastal water conditions depend on pollution levels and mitigation efforts happening in other areas? How do local water conservation practices, along with actions taken in other locations, impact the timing and geographical spread of pollution-induced damages? These are questions addressed in this paper.

To study these questions, we developed a modeling framework for the Archipelago Sea (Figure 1), conducted what-if analyses for various ambition levels of nutrient abatement, and studied the long-term consequences at the sea basin scale.

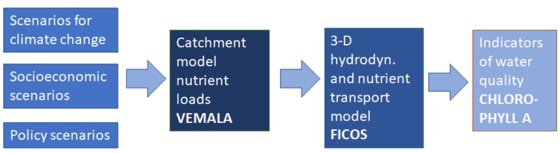

Figure 1. Modelling framework

3. Materials and methods

We combined exploratory and target-seeking scenarios with spatially and temporally explicit models for a coastal sea area and its catchment area to study the effectiveness of local water protection measures for protecting a highly heterogenous archipelago.

At first, we chose a set of exploratory and target-seeking scenarios addressing the research question and reflecting alternative future conditions in the society, climate, and policy environment. We extended the computations to 9 scenarios including different levels of mitigation effort, technological development, and societal development, both in the catchment area of the Archipelago Sea and in other regions sharing the Baltic Sea catchment.

As the next step, we translated scenario narratives and assumptions as inputs to the catchment model, which describes the soil and aquatic processes and provides the spatially and temporally explicit projections of nutrient loading from agricultural land, forests, built land, and point sources. We used the catchment-scale modeling system VEMALA (Water Quality Watershed Model) to simulate run-off processes, nutrient processes, leaching, and transport on land and in rivers and lakes in Finland (Huttunen et al. 2021).

Thereafter, we used the outputs from the VEMALA catchment model as inputs in a spatially and temporally detailed coastal model that describes the transport and biogeochemical processes in the Archipelago Sea. We used the coastal water quality model FICOS (Miettunen et al. 2020) to simulate the nutrient and chlorophyll-a concentrations in the Archipelago Sea.

4. Results

We demonstrate that a good ecological status can be achieved in most parts of the Archipelago Sea through well-coordinated multilateral load reductions and joint actions across those countries that share the Baltic Sea catchment (Figure 2).

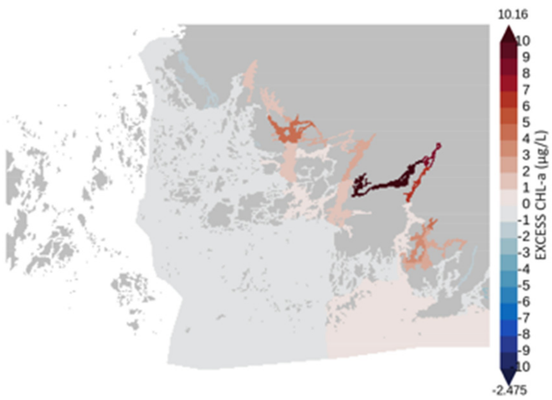

Figure 2. Excess chlorophyll-a (µg/l) to the threshold level indicating good ecological status after implementing the Baltic Sea Action Plan. The concentrations are measured as the average summertime concentration.

Inner coastal areas are an exception, as current goals for phytoplankton biomass levels in these areas can be reached only through extreme water protection efforts in the catchment area and through the large-scale application of yet untested ecological engineering methods to control phosphorus stocks in the sediments.

Achieving such an outcome would require substantial investments in research and development, and infrastructure both on land and at sea – and willingness of the local society to largely adopt those measures that are found to be effective and are suited for the area. It also eventually requires societal readiness to accept failures and to continue searching for better cost-effective measures.

This result calls for carefully considering the relevance of current threshold values for phytoplankton and the need for additional monitoring effort to better understand the true state of coastal food webs.

5. Conclusion

Our simulations support the general understanding and demonstrate that both local water protection measures and measures conducted elsewhere are necessary to achieve improvements in local water quality even in a relative closed Archipelago Sea. Obtainable synergies encourage co-operation across regions and between neighboring countries sharing the coastline of coastal seas. Achieving good eutrophication status (including in the archipelago and the country's own territorial waters) will only succeed if neighboring regions and countries commit to reductions.

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A Prognostic Tool for Modeling the Optimal Environmental Conditions for Fish in the Gulf of Gdańsk – the Fish Module

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1. Abstract

The "*Fish Module*" is a cutting-edge tool designed for predicting optimal environmental conditions for fish species in the southern Baltic Sea, with a focus on the Gulf of Gdańsk. This tool integrates the EcoFish ecohydrodynamic model with fuzzy logic and extensive fish preference data to calculate the Habitat Suitability Index (HSI). The study meticulously analyzes data from 587 fishing expeditions, correlating physicochemical sea parameters with fishing success to establish HSI threshold values for sprat, herring, cod and flounder. The research findings provide actionable guidance for selecting efficient fishing routes and challenge traditional notions about the relationship between fishing duration and catch size.

2. Introduction

The global fishing industry, a critical component of the world's food supply, faces increasing challenges due to overfishing, climate change, and environmental degradation, Godfray et al. (2010), Lotze et al. (2019), Hilborn et al. (2003). These challenges not only threaten marine ecosystems but also the economic stability and food security of communities reliant on fishing. In response to these pressing concerns, innovative approaches combining ecological knowledge with advanced technology are essential.

The *Fish Module*, developed as part of the "*Knowledge Transfer Platform FindFISH – Numerical Forecasting System for the Marine Environment of the Gulf of Gdańsk for Fisheries*" project, Dzierzbicka-Głowacka et al. (2018), Dzierzbicka-Głowacka et al. (2024, In Press) emerges as a pivotal solution in this context. It is a tool designed to optimize fishing practices in the southern Baltic Sea, particularly in the Gulf of Gdańsk. The *Fish Module's* development was motivated by the urgent need to balance the economic necessities of the fishing industry with the imperative of environmental conservation. This tool represents a synergistic approach, melding traditional fishing expertise with cutting-edge scientific research and technological advancements.

3. Methodology

The *Fish Module* employs a novel approach by integrating data from the EcoFish ecohydrodynamic model with fuzzy logic and fish preference data (Figure 1).

We focus on temperature, salinity, oxygen, and depth as key input parameters as they represent critical abiotic factors in aquatic ecosystems, playing pivotal roles in shaping fish behavior and influencing overall habitat suitability, Gerhard et al. (2023). Our research in the Gulf of Gdańsk focuses on four fish species, and the selection of these parameters is grounded in their significant impact on the ecological dynamics of the region.

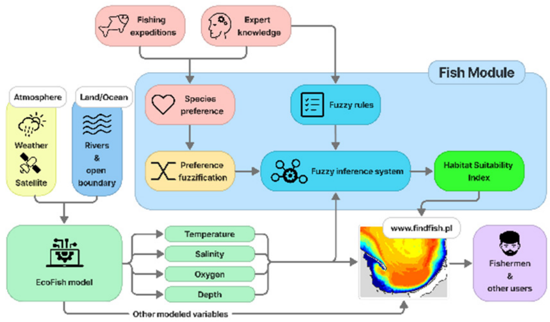

Figure 1. The general outline of the Fish Module algorithm along with the interdependencies between the elements implemented in the FindFISH project. Source: Janecki & Dzierzbicka-Głowacka (2024, In Press).

4. Results

The analysis of data from 587 fishing expeditions reveals compelling insights into the operational effectiveness of the *Fish Module*. The key finding is the establishment of specific Habitat Suitability Index (HSI) thresholds for targeted fish species - sprat, herring, cod, and flounder. These thresholds have shown a correlation with successful fishing expeditions, indicating that the *Fish Module* can effectively guide fishermen to areas with favorable environmental conditions (Figure 2).

Additionally, it has been demonstrated that for pelagic fish the main examined factor, that influenced both, fishing strategy and the increase in catch per unit effort throughout each year, was temperature, Pieckiel et al. (2023).

Further, a significant insight emerged regarding the relationship between fishing duration and catch size. The study found that longer fishing times do not necessarily translate into larger catches. This revelation underscores the critical importance of selecting fishing routes based on optimal environmental conditions rather than just duration at sea.

In addition to these findings, a pivotal aspect of the project is the presentation of this data through a dedicated web portal. This online platform serves as a dynamic and user-friendly interface for accessing the *Fish Module's* data and analyses. The portal not only provides real-time data to fishermen but also acts as a repository of historical data, allowing for in-depth analysis and study over time. It serves as an educational and decision-making tool for both the fishing community and researchers, enhancing the accessibility and applicability of the *Fish Module's* insights.

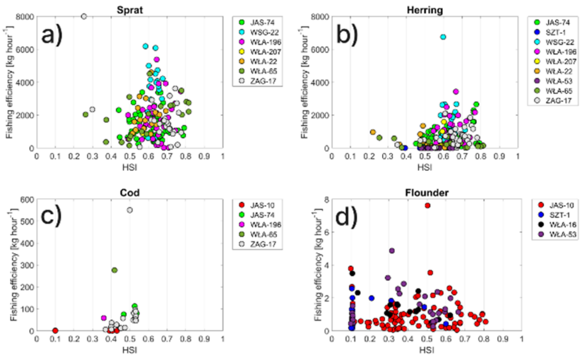

Figure 2. Fishing efficiency for a) sprat, b) herring, c) cod, and d) flounder related to the mean HSI value along the fishing route. Source: Janecki & Dzierzbicka-Głowacka (2024, In Press).

5. Summary

The *Fish Module* stands as a groundbreaking tool in sustainable fishing, offering data-driven guidance to fishermen on optimal fishing locations. Its implementation is poised to enhance fishing efficiency, contribute to environmental conservation, and support the sustainable management of fish resources in the Gulf of Gdańsk. The study emphasizes the *Fish Module's* potential as a model for future innovations in the fishing industry.

6. Acknowledgments

Partial support for this study was provided by the project "*Knowledge transfer platform Find-Fish Numerical Forecasting System for the Marine Environment of the Gulf of Gdańsk for Fisheries*", funded by the European Union through European Regional Development Fund Contract RPPM.01.01.01-22-0025/16-00.

Some elements of the EcoFish model (i.e., river runoff data) are based on the solutions developed during the *WaterPUCK* project funded by National Centre for Research and Development of Poland within the BIOSTRATEG III program BIOSTRATEG3/343927/3/NCBR/2017.

Computations were carried out using the computers of *Centre of Informatics Tricity Academic Supercomputer & Network*.

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Finnish-Estonian Collaborative Research Project: Utilizing Passive Samplers in Pharmaceutical Research in the Gulf of Finland

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1. Pharmaceuticals in the Marine Environment

The primary purpose of pharmaceuticals is to influence human life processes. Due to their biologically active nature, they may also have adverse effects on other organisms. Although most pharmaceuticals are not persistent in the environment, their continuous use in society results in their constant release into the environment. Oceans act as a sink for pharmaceutical loading of societies and, due to the significant dilution effect in the sea, low but biologically significant concentrations may be challenging to detect using only traditional environmental sampling methods.

The environmental risk generated by pharmaceuticals depends on their concentrations. However, the data concerning the presence and concentrations of pharmaceuticals in the Baltic Sea is scattered and mainly relies on results of individual grab samples collected in a few studies. Most of the peer-reviewed studies conducted in the Baltic Sea region focus on the southern marine areas (Figure 1). Regarding the northern marine areas, such as the Gulf of Finland and the Gulf of Bothnia, information on the occurrence of pharmaceuticals is limited or non-existent. At the same time international conventions and organizations crave information to support environmental status assessments and action plans.

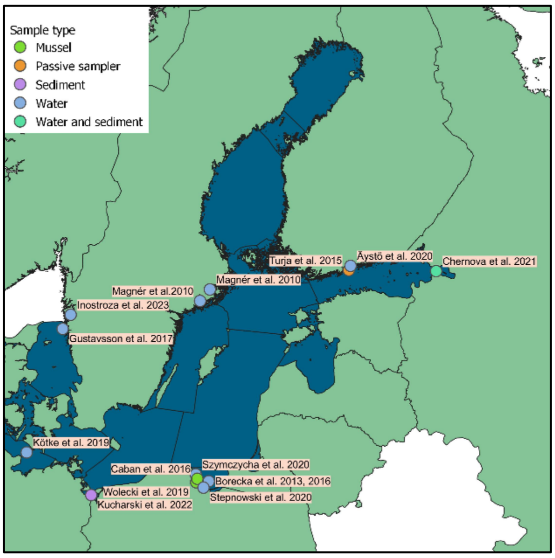

Figure 1. Peer reviewed studies concerning pharmaceuticals in the marine environment of the Baltic Sea.

2. Passive Samplers in Marine Research

Passive samplers are an underutilized research instrument which can be used in generating valuable information about prevailing concentrations of pharmaceuticals in the marine environment. Passive samplers are deployed in the marine environment where they accumulate contaminants from the surrounding water over extended periods. As a result, they provide information about longer term average concentrations of the studied compounds. Moreover, the presence of different classes of pharmaceuticals in the marine environment can be studied more comprehensively.

In our presentation, we illustrate the utilization of passive samplers in a screening study of pharmaceuticals in the coastal waters of Finland and Estonia. In our ongoing research project, passive samplers are deployed at differently polluted marine sites in front of Helsinki and Tallinn (Figure 2). Additionally, one deployment is also conducted in the open sea of the Gulf of Finland to supply information about background levels of pharmaceuticals. Almost 200 active pharmaceutical ingredients are analyzed from the samplers, and their concentrations are compared to threshold values of harmful concentrations. The produced data will be used in pharmaceutical risk assessment and in generating good practices for passive sampler use in further environmental research activities.

Figure 2. Passive sampler deployment sites. WWTP = wastewater treatment plant.

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Implementing Nature-Based Solutions: Types of Actions, Addressed Challenges and Received Benefits

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1. Nature-based Solutions as an overarching framework

The term Nature-based Solutions (NbS) is a central concept that helps to connect the natural environment, society, and human well-being. It was coined in the late 2000s by the World Bank (MacKinnon et al., 2008) and IUCN (2009) to emphasize the significance of biodiversity conservation in addressing climate change through both mitigation and adaptation measures.

NbS is frequently regarded as a comprehensive term encompassing a broader array of ecosystem-based approaches, such as ecosystem-based adaptation (EbA), forest and landscape restoration (FLR), ecosystem-based disaster risk reduction (eco-DRR) and others (Welden et al., 2021). These transformative actions intend to jointly address biodiversity loss and climate change as well as deliver more benefits in solving societal and economic challenges and minimise possible trade-offs (Pauleit et al., 2017)

Integration of nature-based concepts into environmental problem-solving by various stakeholders and decision-makers requires a collaborative and interdisciplinary approach, fostering a shared understanding of the ecological, social, and economic dimensions involved, as well as a commitment to sustainable practices and conservation principles. Such an approach, however, is not necessary understood by all parties and adapted when actual NbS measures are implemented locally. The question remains as to what type of NbS are adapted locally, what challenges they address and if expected benefits were received. This work presents an integrative framework for the assessment of NbS implemented locally in Lithuania. Eight cases were identified using a literature review and their analysis was developed using the framework.

2. NbS as problem-solving multifunctional action

European Union (EU), with its diverse ecosystems and commitment to sustainability, acknowledges the pivotal role of NbS in achieving its policy goals. NbS is integrated into the European Green Deal, the Biodiversity Strategy for 2030, the EU Forest Strategy, the EU Soil Strategy, the EU's Strategy on Heating and Cooling, the Zero Pollution Action Plan for Air, Water, Soil, and the revised EU Sustainable Blue Economy, along with the Climate Adaptation strategy. NbS is also integrated within the Horizon 2020, Horizon Europe, and European Commission (EC) Framework Programme for Research and Innovation. By embracing NbS, the EU aims to create a more resilient society that would be capable of adapting to environmental challenges while maintaining economic growth. NbS positively affects the economy by reducing water and energy costs and creating environmentally friendly employment opportunities (green jobs) and business prospects. Furthermore, NbS align with the EU's commitment to the UN Sustainable Development Goals (SDGs), providing a pathway to achieve several of these goals simultaneously (El Harrak et al., 2023).

As outlined in the initial comprehensive publication from the EC on NbS, solutions are deemed effective when they are locally adapted, resource-efficient and systematically verified (Bauduceau et al., 2015). Additionally, NbS should address at least one of the societal challenges outlined by the IUCN (2020) including disaster risk reduction, climate change adaptation and mitigation, ecosystem degradation and biodiversity loss, human health, socio-economic development, food and water security. Nevertheless, the prevailing literature on NbS predominantly addresses climate-related challenges, emphasizing the potential alterations in ecosystems and their service provision due to changing climate (Sowińska-Świerkosz & García, 2022).

NbS provides solutions to problems detected *a priori* and this aspect is crucial for distinguishing it from other green interventions (Albert et al., 2019). There is a tendency to intertwine or mix established, interconnected activities, such as green-blue infrastructure (GBI), EbA, FLR and implementation of ecological/environmental engineering projects, with the NbS concept. Occasionally, these measures might fall under the criteria of NbS, yet there is no assurance that such alignment will occur in every case. To be classified as NbS, a solution must provide simultaneous benefits to both the environment and human well-being. Considering the current biodiversity crisis, NbS should actively maintain, preserve, or enhance biodiversity to effectively address this issue. (Bauduceau et al., 2015, IUCN 2020). Nonetheless, green interventions that lack a specific design to tackle identified issues through a transparent process involving all affected stakeholders should not be categorized as NbS—examples include creating national reserves or buffer zones around high-value areas without stakeholders' consent. Another key factor that distinguishes NbS from other green and blue solutions lies in the adaptive management of trade-offs throughout the life cycle of NbS. In addition, striking a balance between costs and benefits is essential—implementation and management expenses for NbS should be reasonable, comparable to, or lower than those associated with alternative solutions aimed at addressing the same issue (Sowińska-Świerkosz & García, 2022).

Considering the increasing demand to implement NbS and evaluate their outcomes, this assessment thoroughly analyzed different aspects of selected NbS cases in Lithuania as problem-solving multifunctional components.

3. Case studies identified and assessed

This study identified and analysed 8 potential instances of locally implemented NbS in Lithuania using the established framework (fig. 1). This framework includes indicators that have been specifically chosen for the territory of Lithuania from the set of recommended indicators by the EC (European Commission, 2021). To equally assess the NbS types of action and identify benefits, an expert-based assessment utilizing a binary system was chosen: indicators were evaluated as either providing a noticeable benefit or not within each case study. This approach prevents the underestimation of NbS caused by a lack of quantitative data. Additional evaluations were included based on the existing data.

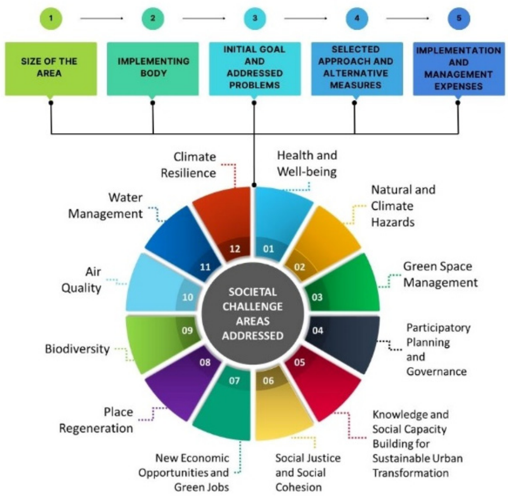

Figure 1. Framework developed for assessing local NbS. Societal challenge areas addressed evaluation part is based on EC recommendations (European Commission, 2021) and adapted to Lithuania.

During the selection of cases for the study, it was verified whether the following conditions were met: the project is inspired by nature and uses at least one nature-based solution, the area is larger than $100m^2$, and it was implemented with the initial goal of addressing at least one problem. In addition, the selection of different types of NbS was attempted. Areas selected for analysis are a rainwater storage pond in Vilnius (1), a green roof at Vilnius University Botanical Garden (2), Senvagė Valley in Šnipiškės, Vilnius (3), a ravine with aquatic plants in Plungė (4), the Creative Center "inTegra House" (5), a green roof at the "Žali" shopping mall in Vilnius (6), the Japanese Garden Park in Vilnius (7), and Pastauninkas Park in Kretinga (8).

The assessment was conducted based on publicly available information, detailed implementation project information, and aerial photography sourced from Geoportal.

4. Results

The study shows that in Lithuania, the prevalent adoption of NbS includes greening of roofs, rainwater management through artificial ponds or micro-relief adjustments, and the restoration of urban green spaces.

The majority of examined cases make substantial contributions to well-being, social justice and social cohesion, and the preservation and enhancement of biodiversity. However, in most cases, local communities and citizens are rarely involved in the NbS planning and implementing processes. It is also noticed that in the analysed cases, greater positive outcomes are achieved when both green and blue spaces are integrated into NbS. In addition, during NbS implementation, it's vital to prioritize adapting and enhancing the existing ecosystem, but this principle wasn't consistently followed in all analysed cases.

Not all studied NbS cases were able to attain the expected benefits, with some still grappling with engineering issues and experiencing high maintenance and adjustment costs. Furthermore, the absence of public involvement in certain cases led to dissatisfaction regarding the perceived ineffectiveness of NbS or a lack of comprehension regarding the implemented measures.

5. Conclusions

As the concept of NbS is not yet widely embraced by the public, it might be challenging to identify NbS cases. This raises concerns about the potential misuse of the term and the allocation of financial funds to measures that do not genuinely qualify as NbS. Additionally, the consideration of implementation and management expenses in NbS projects is not yet widespread. It is crucial to assess the financial aspects before implementing NbS to ensure that costs remain proportionate or lower than the benefits obtained. For an accurate evaluation of the benefits, it is advisable to conduct a thorough assessment of the area before NbS implementation, ensuring effective monitoring and a clear understanding of success afterwards.

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Changes in water optical properties: Gulf of Riga and River Daugava use case (AquaINFRA project)

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1. Scope of the AquaINFRA project

The main goal of the AquaINFRA project is to establish a research infrastructure that facilitates seamless data discovery and processing through a unified interface. The project specifically aims to address the unique requirements of researchers in both marine and freshwater domains, promoting collaboration and cooperation across these two scientific communities. To achieve this, the project will develop and implement a series of strategic use cases, drawing insights from cases conducted in the Baltic, North and Mediterranean Seas. A Pan-European use case will also be established to serve as a broader context for the co-design and testing services within the targeted research communities. Through these endeavors, the project strives to contribute to advancing the European Open Science Cloud (EOSC) as a comprehensive and inclusive research infrastructure.

Use cases will be examples of open data applications demonstrating connections between freshwater and marine domains. It will highlight the interdependencies between land use in the catchment area and processes within the connected marine waterbody and, therefore, links between terrestrial and marine policy. It will also show the potential of FAIR data usage principles in addressing issues that arise from transboundary collaboration.

2. River Daugava and the Gulf of Riga continuum

The Daugava River (1005 km long) begins in western Russia, flows through Belarus and Latvia and discharges into the Gulf of Riga, Baltic Sea. The main land use in the Daugava River catchment area is agriculture (51%). The rest of the area is covered by forests (40%), grasslands (6%) and urban areas. The freshwater inflow of the Daugava River largely defines the state of the Gulf of Riga as it is the main contributor of nutrients, organic matter and pollution load to the Gulf of Riga. Heavy freshwater input defines the Gulf of Riga as optically complex waters with low transparency and high turbidity.

3. The story behind the use case

The Secchi depth data for the Gulf of Riga indicate a consistent decline over the past five decades (Fig.1), signifying an ongoing change in littoral and pelagic ecosystems. This diminishing water transparency poses potential risks to underwater habitats and biota. This particularly impacts perennial macroalgae growth—an essential component of various ecosystem services and a vital nursery for numerous fish stocks (e.g., Luhtala et al. 2016, Kraufvelin et al. 2018). Changes in the optical properties of the water column can be expected to have important implications on aquatic ecosystem functioning and ecosystem service supply. This use case will explore this link and provide a knowledge base to guide ecosystem-based management and future actions for protecting biodiversity and maintaining an ecosystem service supply.

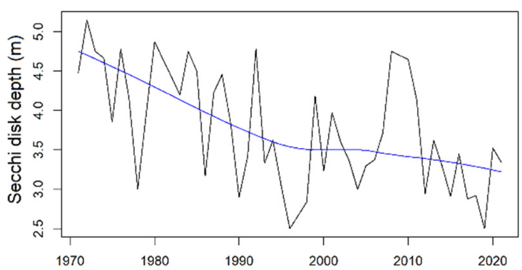

Figure 1. Monthly mean value of Secchi depth (m) in the open waters of the Gulf of Riga in August.

4. Study design and the preliminary results

The Gulf of Riga waters are recognized as optically complex due to their high absorption and scattering properties. The optical dynamics of these waters are predominantly governed by three key biogeochemical variables: chlorophyll-a, various suspended particulate matter (SPM), and colored dissolved organic matter (CDOM). Understanding the interplay of these variables is crucial for comprehending the optical complexity of the Gulf of Riga and its ecological implications.

Long-term monitoring data and Earth Observation products, utilizing satellite data from spectral instruments, are employed to identify changes in the optical properties of the Gulf of Riga waters. The primary focus lies on finding relationship between satellite-derived products, such as CDM and KD (Copernicus Marine Environment Monitoring Service), and in situ parameters, including dissolved organic carbon (DOC), water transparency, and water color. The analysis also aims to examine the composition of phytoplankton functional groups and their respective pigments in the context of changes in water optical properties. Concurrently, biogeochemical parameters of the River Daugava undergo long-term analysis, with their trends compared to those observed in the Gulf of Riga.

The comparative analysis of trends will be utilized to indirectly describe impacts of ongoing processes in the catchment area, influenced by human activities and climate change, on processes within the Gulf of Riga.

5. Conclusion

This study will draw attention to the optical dynamics of the Gulf of Riga and the interconnected biogeochemical patterns in the River Daugava. The preliminary results provide insights that can guide more in-depth research into the links between marine and coastal ecosystem states and drivers of change in subsequent stages of the study. Furthermore, it supports analysis of the effectiveness of management measures and measures for mitigating and adapting to climate change.

Funding

The "AquaINFRA" project funded from the European Commission’s Horizon Europe Research and Innovation programme under grant agreement No 101094434.

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Macrophytes Identification Algorithm based on Žuvintas Lake satellite data

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1. Introduction

Macrophytes are aquatic plants that grow along the shores of water bodies and in the shallow parts. Three main groups of macrophytes are distinguished as emergent (reeds and bulrush), submerged (pondweeds and elodea), and floating-leaves (water lilies). These plants are an important part of the water body overgrowth process, each thriving at its own depth and under specific conditions, thereby serving as an indicator of the ecosystem's health (Bornette & Puijalon, 2009). Monitoring macrophytes is typically conducted through field observations, utilizing transect methods (Regarding the Approval of the Methodology of Macrophyte Research in Lakes and Ponds, 2013), or establishing a network of key sampling sites. However, such methods may not always ensure a comprehensive understanding of the entire picture, and large-scale field measurements require substantial human and financial resources.

With the use of satellite data possessing high resolution and necessary imagery update frequency, it is possible not only to recognize macrophytes but also to classify them into types and track their dynamics (Edvinas Tiškus et al., 2023). Considering the relatively stable spatial distribution of plants in the short term, having one cloud-free image per month is sufficient to capture various vegetation types in a water body. This allows the utilization of optical Earth observation satellites, such as Sentinel 2 with a resolution of 10 m for visible and infrared ranges.

This study aims to develop an algorithm for macrophyte identification using Sentinel 2 satellite data. With such an algorithm, it becomes possible in the future not only to identify macrophytes but also to categorize them by type, track their dynamics, and assess the distribution of this type of vegetation on a larger scale, based on satellite image data.

2. Materials

To build a robust model, a substantial amount of initial data is necessary. In this context, Lake Žuvintas, one of Lithuania's most macrophyte-rich lakes representing various types of aquatic vegetation, was chosen as the study area.

The process of searching for a macrophyte identification algorithm can be divided into three stages: pre-processing, clustering or label creation for modeling, and algorithm development, including machine learning model training, testing and application.

For macrophyte identification algorithm creation, we used reflectance data on April 19, May 11, June 18, July 10, September 8, and 26, and October 31, 2021 - in the snow-free period, in the visible and near-infrared ranges (b2 – b8) from the Sentinel-2 MSI satellite (Level-1C). The area of interest was manually delineated along the Lake Žuvintas border, including the shoreline vegetation, using a special mask to exclude cloud scenes on the Google Earth Engine platform. The data were downloaded and prepared for the next stage.

3. Algorithm creation

Without field data and acknowledging that only macrophytes and water surface could be identified on the lake territory, we employed cluster analysis to identify areas with similar seasonal reflectance dynamics in one cluster.

To determine the optimal number of clusters, we applied Gap statistic, Silhouette score, and Within-Cluster Sum of Squares metrics on two principal components of the entire dataset, representing 90.17% of data variance. Principal component analysis helped reduce the data dimensionality, and we also applied the gap statistic method to random samples from the overall dataset.

Considering the metric results and empirical considerations, we decided to divide Lake Žuvintas into four clusters.

We used the CLARA method for clustering, as it is less demanding in terms of memory and suitable for such large datasets. The input data for clustering were normalized reflectance data in the visible and infrared ranges (b2 – b8) during the snow-free period. Clusters were validated through visual analysis using higher-resolution data than satellite imagery - aerial photography data. Validation was performed by aligning the clustering results with aerial photography and Google Satellite Imagery. Ultimately, four clusters were identified: two emergent macrophyte clusters, submerged macrophytes, and water surface (Figure 1). Two clusters of emergent macrophytes may represent distinct plant species or groups of species sharing similar reflectance dynamics.

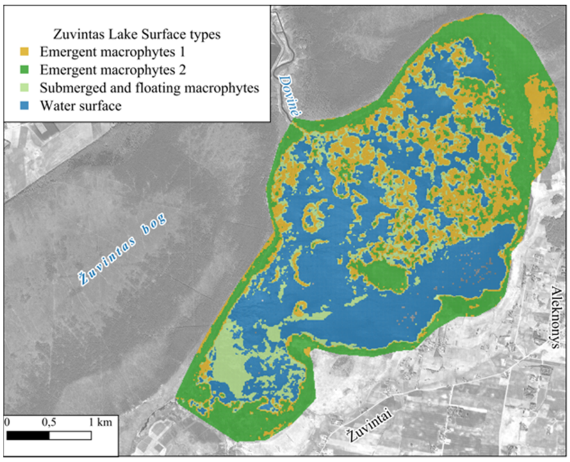

Figure 1. Žuvintas Lake is divided by emergent (1 and 2), submerged, and floating (3) macrophytes, 4th cluster is the water surface. The surface area under water is 39.9% of the area of interest, submerged and floating macrophytes are distributed on 15.2% of the surface. The rest of 45% is occupied by two types of emergent macrophytes.

The model creation process was based on using data obtained as a result of clustering as target labels. We utilized the Recursive Partitioning and Regression Trees (RPART) method to build the model and applied cross-validation to evaluate how the model would perform on independent data.

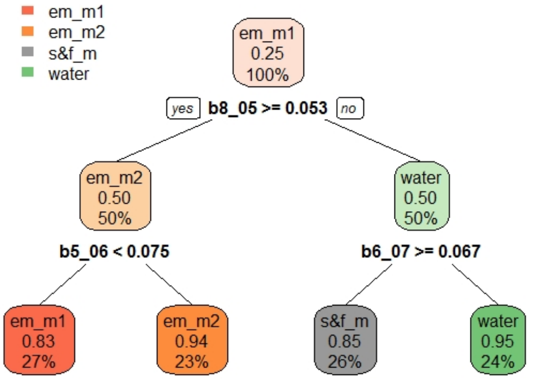

Figure 2. Žuvintas Lake macrophytes detection model. For identifying emergent (em_m1 and em_m2), floating and submerged (s&f_m) macrophytes and water surface (water) need to have data in the near-infrared range (842 nm) of May – b8_05, two in vegetation red edge (705 nm and 740 nm) in June and in July respectively – b5_06 and b6_07. Each node shows a surface type label, probability of identification, and a portion of the data set.

The training dataset was carefully selected to constitute 20% of the total Žuvintas Lake data volume. The training process involved splitting the data into distinct sets for training and testing. Approximately 70% of the dataset was allocated for training the model, allowing it to learn patterns and relationships within the data. The remaining 30% was reserved for testing the trained model's performance. This partitioning strategy is essential for evaluating how well the model generalizes to new, unseen data and helps assess its effectiveness in real-world scenarios.

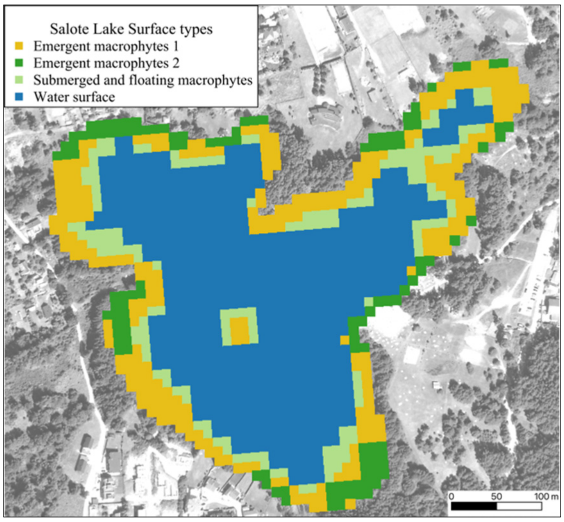

Figure 3. Algorithm applying on Lake Salote Reflectance data in 2021.

The initially obtained model demonstrated an accuracy of 70 %. However, the application of a complexity parameter (cp) significantly increased the accuracy to 89 %. In this context, a parameter with a value of 0.256 was employed. It is noteworthy that utilizing a lower parameter value could have further improved the accuracy of identification; nevertheless, such an approach might have led to increased complexity of the entire model and necessitated a larger volume of information. Therefore, the decision was made that the parameter value of cp = 0.256 was deemed optimal in this particular context.

In the end, a model was built that can determine macrophytes in the lake based on three variables. The use of this model reduced the amount of necessary information for identification. While 49 variables were used for clustering, only three are needed when applying the model—May's variable of the near-infrared range (b8_05), two variables in the vegetation red edge in June and July, respectively (b5_06 and b6_07) (Figure 2). Applying the model to the 2021 dataset identifies macrophytes and water surface with 89% accuracy that validated model application. Applying the model to the 2022 data achieves 86% accuracy, the 2022 data is completely new for the model.

For a more accurate understanding of the model's performance, it was applied to entirely independent data—macrophytes from another lake, Lake Salotė (Figure 3). The obtained results were consistent with real-world conditions, successfully identifying various features such as islands populated with macrophytes, emergent macrophyte zones along the lake's shoreline, and areas submerged with macrophytes. However, it is worth noting that occasional misclassifications were observed, particularly around the beach and island. This misclassification could potentially be attributed to limitations in the spatial resolution of the data, underscoring the importance of considering such factors when interpreting model outcomes. Despite these minor discrepancies, the model demonstrated a commendable capacity to generalize across lakes, showcasing its robustness in identifying diverse macrophyte habitats.

4. Conclusion

The algorithm, based on Sentinel 2 satellite data, was developed to identify macrophyte types and water surfaces using three variables: the near-infrared range in May (before submerged vegetation appears), and two variables in the vegetation red edge in June and July, respectively. The developed algorithm demonstrates high accuracy in identifying macrophytes and their distribution. The obtained results not only contribute to a deeper understanding of aquatic plant dynamics but also provide a practical foundation for the effective management and conservation of aquatic ecosystems.

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Monitoring seasonal maritime traffic from Sentinel-2 RGB imagery with YOLOv8

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1. Introduction

Indicators of pressures caused by human activities at sea are needed to estimate their effects on marine habitats and in the planning and management of existing and future marine protected areas (MPAs). Pressures caused by commercial maritime traffic can be quantified and localized via their Automatic Identification System (AIS) positioning data. However, the quantity and occurrence of leisure and recreational boats remain largely unknown as AIS is not required for them. Yet, these vessels often move in shallower areas and cause disturbance to marine habitats by anchoring, resuspension of suspended sediment due to propeller currents, coastal erosion by boat waves, and underwater and above-water noise (e.g., Sagerman et al. (, 2020)). In addition, grey water, harmful substances from antifouling paints, and litter, may be introduced to sea areas via leisure boating. Moreover, submerged aquatic vegetation (SAV) communities, which provide several high-value ecosystem services (Waycott et al. (2009), Santos et al. (2022)), thrive in these shallow areas. SAV habitats are threatened by several human activities (Crain et al. (2009), Virtanen et al. (2022)), and they have been steadily disappearing worldwide for a long time (Waycott et al. (2009)). The impact of leisure boating pressure on these habitats has been largely missing due to lack of spatio-temporal information on boating pressure.

During the last decade, computer vision has been revolutionized by deep learning methods, and they have been increasingly applied to remote sensing tasks (e.g. Ma et al. (2020)). These methods have been increasingly adapted also to remote sensing tasks, and they have proven to be successful in marine vessel detection from optical satellite imagery (e.g., Ciocarlan et al. (2022); Patel et al. (2022); Prete et al. (2023)). While several studies utilize very high resolution (VHR) imagery (Kanjir et al. (2018)), which have a resolution of fewer than three meters, these data typically do not have sufficient spatial or temporal coverage to be usable for monitoring maritime traffic over long timeseries or large areas. There is a knowledge gap on how useful satellites with a slightly coarser resolution, such as Sentinel-2 (10 m), are in monitoring recreational boating. The main advantage of using Sentinel-2 imagery is that they offer both high revisit time (two to three days in Finland) and large spatial coverage, making them suitable for large-scale monitoring.

In this work, we demonstrate how YOLOv8 (Jocher et al. (2023)), a state-of-the-art deep learning-based object detection method developed by Ultralytics., can be used to monitor and quantify marine traffic in broad geographical areas and over long time periods. We use openly available Sentinel-2 optical imagery, chosen for its high revisit time and sufficient spatial resolution, as well as free availability. Our results can be used to detect the temporal and spatial hotspots, and the results have several uses in monitoring the status of the shallow coastal areas, as well as in planning the management efforts of marine protected areas.

2. Materials and methods

We selected five Sentinel-2 tiles to use as the training and testing locations (Figure 1). For each of these locations, we acquired three separate images to capture scenes with varying cloud coverage and environmental conditions (algae blooms, differences in the color of water), and converted them into true-color mosaics. Next, we manually annotated all visible marine vessels from each of these images by drawing bounding boxes around them. We used 2 × 2 pixels (20 × 20 m) as the minimum area an object needed to cover to be annotated. While most of the recreational boats are smaller than this, our annotations also contain the wakes of the moving vessels, making it possible to detect objects smaller than the spatial resolution of the data.

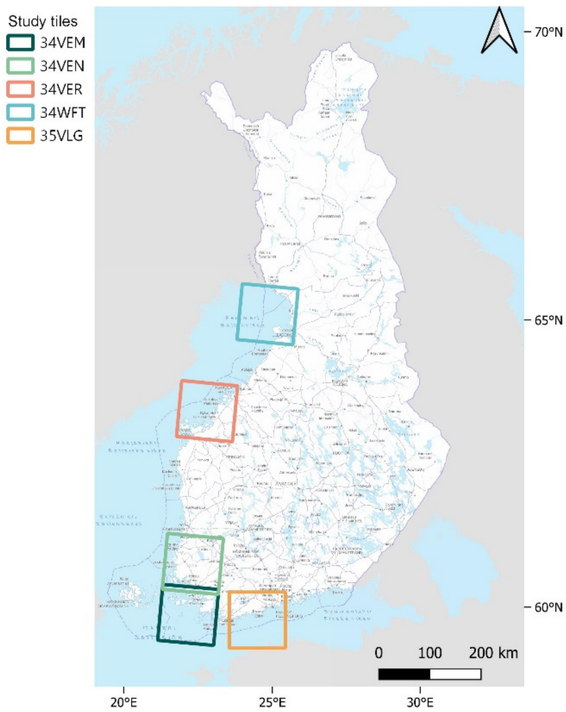

Figure 1. Locations of the study areas in the Finnish coast. Background map: The National Land Survey Finland (CC BY 4.0).

We evaluated the suitability of YOLOv8 for marine vessel detection by fine-tuning the different sized backbones to our task. The models were trained with

320 × 320 pixel image chips, which were upscaled to 640 × 640 pixels to improve the detection rate of the smallest objects.

3. Results

The results indicate that YOLOv8 models are suitable method for detecting marine vessels, including leisure boats, in coastal areas. The best performing model achieved cross-validation precision of 0.85, recall of 0.874, and mean Average Precision with Intersection-over-Union threshold of 0.5 (mAP50) of 0.81, and test set precision of 0.825, recall of 0.874, and mAP50 of 0.810 (Figure 2). To improve the accuracy of results, we applied post-processing steps to filter out stationary objects that are easily confused with small vessels, such as sector lights, wind power plants and above water rocks.

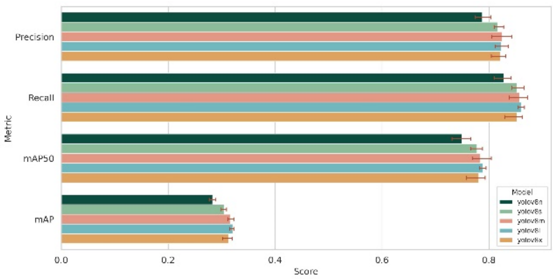

Figure 2. Test set results for each model architecture

As a demonstration of using the models to quantify maritime traffic in Finnish regional territorial waters, we used the best performing model to generate a marine traffic map from May-September 2022 for the Archipelago Sea. Even though we had to discard most of the available images due to too high a cloud coverage or too rough sea conditions, we were able to use 21 images to generate marine traffic maps for the Archipelago Sea. These data were then aggregated as yearly traffic heat map, shown in Figure 3.

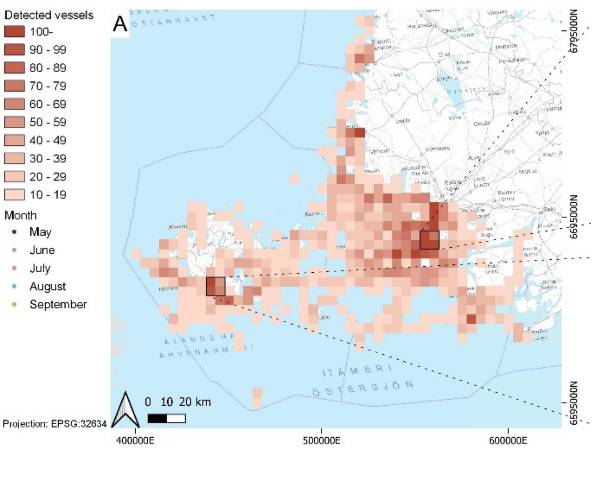

Figure 3. Detected vessels from the Archipelago Sea from May-September 2022, aggregated to a 5 km grid.

4. Discussion

The proposed method of utilizing YOLOv8 for marine vessel detection achieved good results, with overall precision and recall being both higher than 0.8. These results indicate that this type of approach is viable for detecting marine vessels from satellite imagery, even with data of 10 m resolution. While these data have their limitations (spatial resolution, clouds), their large spatial coverages and dense temporal resolutions and operationality make them a viable cost-effective solution for marine traffic monitoring.

In the future, we aim to build a framework which enables yearly monitoring of maritime traffic in the Finnish coast and utilize the produced data to further assess the human pressures and disturbances in shallow coastal areas, as well as evaluate the trends and amount of maritime traffic over multiple years.

Acknowledgments

This study was supported by Enhancing the marine and coastal biodiversity of the Baltic Sea in Finland and promoting the sustainable use of marine resources (LIFE-IP BIODIVERSEA (LIFE20 IPE/FI/000020)).

The authors wish to acknowledge CSC -- IT Center for Science, Finland, for computational resources.

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Evaluating ecological connectivity in the Archipelago Sea

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1. Introduction

Recent conservation agreements, such as the Kunming-Montreal Global Biodiversity Framework and EU Biodiversity strategy, have aspirational goals to increase the global coverage of marine protected area (MPA) networks to 30%. While the main goal of marine protected areas is to safeguard specific habitats and species, understanding how ecological connectivity influences the resilience of MPAs has become imperative. Ecological connectivity in marine systems refers to how species move, disperse, or spread among habitats. Well-designed and strategically located MPAs can act as stepping-stones, fostering the connectivity between distinct habitat patches.

While ecological connectivity is a crucial element of metacommunity persistence, the importance of connectivity varies depending on dispersal traits of species and marine system in question. In regions where connectivity is determined by somewhat unidirectional, strong currents, the inclusion of connectivity in MPA design may be quite simple, if suitable data on currents in the region exist. In topographically complex regions, such as archipelagos with fragmented habitat mosaics, that have weak currents with wide directional distribution, accounting for connectivity turns out to be complicated.

2. Study area

In this study, we aim to demonstrate how ecological connectivity could be accounted for in a complex coastal area, using the Archipelago Sea in the northern Baltic Sea as an example region. It is a topographically complex archipelago area with over 50,000 islands and skerries, narrow inlets, and steep bathymetry variations. There is a lot of variation in the current speeds and directions, and the connectivity between the different parts of the archipelago depends on wind conditions (Miettunen et al., 2020).

Species communities within the study area can broadly be categorized to 1) hard substrate habitats, characterized by perennial algae or aquatic moss, and 2) soft sediment habitats, with a variety of vascular plant species.

3. Modelling connectivity

We use a Lagrangian particle tracking model OpenDrift (Dagestad et al., 2018) to simulate connectivity between selected areas in the Archipelago Sea. We run the OpenDrift simulations using current velocity data produced with a NEMO hydrodynamic model configuration that covers the Åland Sea–Archipelago Sea region with the horizontal resolution of 0.25 nautical miles (Westerlund et al., 2022).

Species inventory and habitat type data are available for the Finnish coastal areas in a very high resolution. The Finnish Inventory Programme for Underwater Marine Diversity, Velmu, has mapped habitats since 2004. However, trying to include all available data on species and habitats in the particle tracking simulations would be computationally heavy and produce huge amounts of data. To keep the simulations feasible and the size of output manageable, we choose the areas to be modelled based on species-groupings rather than habitats of specific species.

Among the areas of interest, we select representative locations as seeding locations for the tracer particles. The drift of tracers is then simulated separately for each year and for each source location. The tracer particles represent, e.g., spores, seeds, or eggs of organisms. The different dispersal traits of selected key species can be accounted for by choosing, e.g., different seeding periods and simulation periods and lengths.

From the modelled trajectories, we calculate potential connectivity (Watson et al., 2010) between the seeding locations, i.e., the percentage of particles released from a source area *j* that reach a destination area *i*. The resulting connectivity matrix can then be used to identify the areas which are connected and to evaluate the importance of each of them in maintaining connectivity.

4. Expected outcome

To assess how well the present Finnish MPA network connects ecologically important sites, and to identify where MPAs should be placed to maximize ecological connectivity, we will use the spatial conservation prioritization tool, Zonation 5 (Moilanen et al., 2022). The software can include information on species, communities, threats, costs, as well as connectivity parameters. Following Virtanen et al. (2020), we will demonstrate the theoretical and technical options to include ecological connectivity in marine conservation design, based on the results from the trajectory simulations.

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Long term observations and modeling of dissolved methane from Nord Stream leaks

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1. Background

This study presents measurements and mapping of elevated CH4 levels in the the Baltic Sea, attributed to leaks in the Nord Stream 2 natural gas pipelines. Methane concentration data, gathered by autonomous gliders and a ship of opportunity system (SOOP, Gülzow et al., 2011), were processed and combined, highlighting the agreement between the two platforms. Utilizing these measurements and a lagrangian tracer analysis tool (Aghito et al. 2023) together with a regional ocean model (SMHI et al., 2022), the study predicts the subsurface dispersion of methane in the water column from the leak sites.

2. Key findings

The spread and concentrations of methane in the Baltic Sea is modeled and presented aggregated by month, and affected basin or Marine Protected Area (MPA). We estimate the initial amount of dissolved methane from the leaks to approximately 10.9 kt, constituting a substantial fraction of the total emitted methane that escaped into the atmosphere. In the glider observations, the dissolved methane is found predominantly in intermediate depths, positioned above a local halocline and below the seasonal mixed layer, and it spread predominantly controlled by advection. Increased dissolved CH4 levels in 23 MPAs, varying by factors of 2 to 100 times natural levels were found. Some dissolved methane that was initially observed below the autumn mixed layer is later entrained into the deeper winter-time mixed layer and released into the atmosphere.

3. Impact

The potential impact of heightened dissolved methane levels in the Baltic due to the leaks is not yet fully understood. However, the majority of dissolved methane outgassed to the atmosphere within 3 months time, where it is known to act as a potent greenhouse gas. The study underscores the benefit of swift and continuous marine environmental assessments in a distinctive socio-political landscape, that can be reached by autonomous systems such as gliders and SOOP.

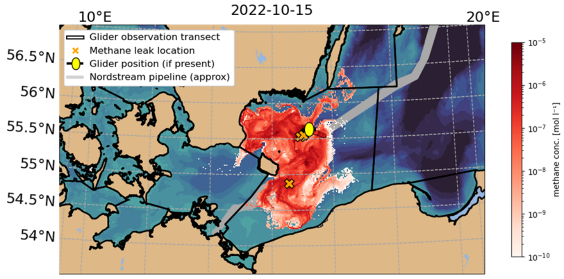

Figure 1. Snapshot of column averaged dissolved methane concentration in the Baltic Sea, from Glider observations and a dissolved methane fate and spread model for one time step (15 October 2022).

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The impact of meteorological conditions on diseases transmitted by tick in Lithuania

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1. Introduction

The climatic and environmental conditions in Lithuania provide an ideal habitat for ticks to flourish, resulting in a significant public health concern. Lithuania is one of the countries with the highest number of cases of tick-borne encephalitis (TBE) in Europe (Radzišauskienė et al., 2018). According to data from the National Public Health Centre of Lithuania, the country records hundreds of cases of tick-borne encephalitis and thousands of Lyme disease cases each year. Even more, the national authorities have officially declared the risk of contracting these diseases within country territory as high. Even new tick species recently identified in the Lithuanian territory (Paulauskas et al., 2020). Increasing ambient temperature due to climate change is primary driver of tick population changes, including increased maturation and decreased mortality (Elmieh, 2022). This poses an increased threat to the population, particularly during the summer months when people are actively engaged in outdoor activities, coinciding with the peak activity periods of these dangerous tick species. It is known that ticks need specific meteorological conditions to be active and spread. Mainly those conditions are temperature and precipitation (humidity), while climate change is amplifying the impact of tick-borne diseases. Some research shows that relationship between climate change and tick-borne diseases is critical (Voyiatzaki et al., 2022). Warmer winters and hotter summers probably will change tick seasonal activity (Gray et al., 2009).

This study aims to investigate how meteorological conditions influence tick behavior in Lithuania and whether there is a correlation between meteorological conditions and the registered cases of Lyme disease and tick-borne encephalitis. Additionally, we seek to explore potential variations between different years attributable to changing climate patterns. Through this research, we aspire to contribute valuable insights into the dynamic interplay between meteorological factors and the incidence of tick-borne diseases, aiding in the development of effective preventive measures and public health strategies.

2. Data and methods

For this research we used monthly data on Lyme disease and tick-born encephalitis in Lithuania, along with the corresponding monthly average temperature and precipitation data. Data sets were obtained from The National Public Health Center and from Lithuanian Hydrometeorology Service. Research covers period from 2003 to 2022. Only from 2003 we have detailed monthly statistics on thick-borne diseases. The year 2020 was excluded from calculations because of COVID-19 and strict isolation which interrupted normal data collection.

Firstly, we examined the dynamics of tick-borne disease case numbers across various months in different years (Figure 1). It becomes apparent that there is an annual pattern in the registered cases. This pattern is closely tied to the tick life cycle, as ticks behave differently in various life stages and seek hosts of different sizes. After reaching the nymph stage, ticks are sufficiently mature to begin questing for humans as hosts.

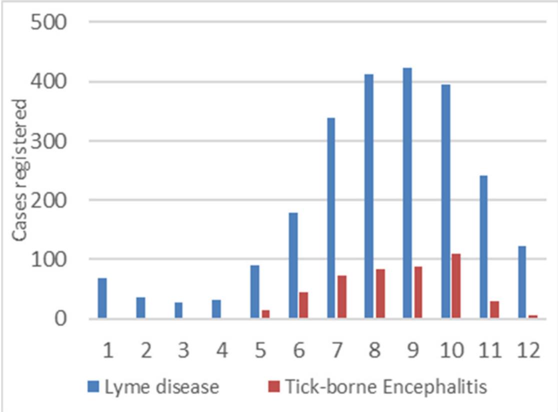

Figure 1. The average number of tick-borne disease cases registered during the research period (2003-2022) in Lithuania.

Secondly, we try to find connection between number of registered tick-born disease cases and average temperature and precipitation sum. To achieve this, we computed the correlation between the datasets and conducted multiple regression analyses using SPSS software. A statistically significant correlation is indicated when $p < 0,05$. Furthermore, we analyzed the influence of meteorological conditions of previous months since the symptoms of the diseases often manifest later and the number of ticks and their developmental stage are determined by meteorological conditions in the previous months.

3. Results

The link between the registered number of tick-borne disease cases and meteorological conditions (average temperature and precipitation) is quite weak. Assessing the relationship with the average monthly temperature, a positive correlation with the number of Lyme disease cases was identified in spring and early summer, but only in June the correlation is statistically significant ($p<0,05$). A warmer start of year leads to earlier tick activity; moreover, people spend more time in places where they can get infected. In October, an opposite relationship is observed: the lower temperature, the more cases of Lyme disease and tick-borne encephalitis are recorded. This situation is likely due to the tick's life cycle and preparation for the winter period, which begins when the temperature drops to 4 °C. If October is cold (during the period of investigation the average temperature of this month ranges from 4,4 to 10,2 °C) the ticks, sensing the temperature drop, become highly active in seeking hosts for feeding and subsequent reproduction.

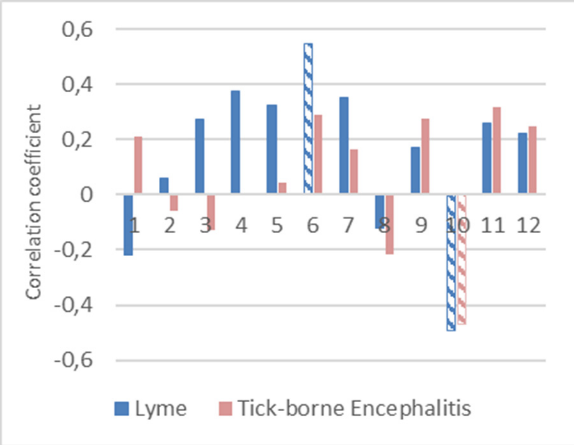

Figure 2. Pearson correlation coefficients between tick-borne diseases and air temperature (2003-2022) in Lithuania. Stripped columns show a statistically significant correlation (p<0,05).

Examining the correlation between the number of tick-borne diseases and the average temperature of the preceding and current months, slightly stronger correlation was determined during the spring and early summer (r=0,5-0,6). At the beginning of the year, the size of the tick population depends significantly on both the spring transition over a 4 °C date and the air temperature of the following period.

The correlation between precipitation amount and tick-borne disease incidence isn't strong and, in most cases, statistically insignificant. It has been observed that the quantity of rainfall in the previous month has a greater impact on the number of diseases. The correlation is positive and more pronounced at the first half of the year. With less rainfall and drier conditions, ticks tend to move closer to the ground in vegetation, reducing the probability of tick bites on humans.

By employing multiple regression, combining air temperature and rainfall, a stronger correlation with the number of diseases is obtained. In many cases, the correlation coefficient exceeds 0,5. The annual number of infections the most strongly depends on hydroclimatic conditions of October and November. The proximity of this month's temperatures to the critical value makes the largest impact on annual sum of tick-borne diseases.

Conclusion

There is a weak but statistically significant connection between number of cases of tick-borne diseases registered and meteorological conditions (air temperature, precipitation) in Lithuania. In majority of cases, it depends on a combination of meteorological conditions over several months. Correlation analysis has shown that sufficient precipitation amount at the beginning of the warm season, higher than normal air temperature at February-May, as well as temperatures close to the critical threshold (4 °C) in autumn, contribute to increased tick activity and the number of cases of diseases they cause. During these months, ticks either encounter favorable conditions to thrive or must actively seek a host for their survival.

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Impact of River Catchments on Baltic Sea Heavy Metal Contamination and Natural-Based Solution Remediation Strategies: A Pilica River Case Study

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1. Introduction

Due to the rapidly progressing industry in the catchment area population estimated at 85 milion people living in this field, Baltic Sea is constantly expose and supply with hazardous compounds. The almost enclosed location of the Baltic Sea, which makes the complete water replacement last 25-40 years, and its brackish water conditions create a unique ecosystem that make it especially sensitive to the results of androgenization processes. What is more, the Baltic Sea is supplied with freshwater flowing from the area of nine highly industrialized and well-developed agricultural Baltic countries. All these factors affect the contamination of Baltic Sea with toxic substances such as heavy metals and contribute to the fact that the Baltic Sea is considered one of the most polluted waters in the world (Kiedrzyńska et al., 2014a; Dobrzycka-Krahel & Bogalecka, 2022; HELCOM, 2021; Lodenius, 2016; Borecka et al., 2015).

One of the most dangerous pollutants entering the Baltic Sea ecosystem are heavy metals (HELCOM, 2021). Among the sources emitting their greatest amount are i.a. mining, metallurgy, the exploitation of minerals and fossil fuels, energy production, industry and transport, the use of pesticides and fertilizers, as well as wastewater discharges from sewage treatment plants (Paul, 2017; Rodríguez Martín et al., 2015; Verma & Dwivedi, 2013).

According to the HELCOM data (2019), only in 2014 at the catchment area of the Baltic Sea 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).

Among the main routes of heavy metal emissions from highly industrialized areas to the Baltic Sea are atmospheric deposition and river runoff (HELCOM, 2021). A large freshwater inflow from around 200 rivers provides about 400-500 km^3 of freshwater annually (Köhn, 1998). The annual average inflow of river waters to the Baltic Sea is 14 000 m^3 (Kanwischer et al., 2021). In years 2013-2018, total amount of heavy metals (cadmium, ledad, mercury) entering the Baltic Sea was 2175.6 tons (t) (no data for Pb in 2018). Load of cadmium (Cd) was 6.16% of the total amount, load of lead (Pb) was 92.57% and load of mercury was 1.27%. 107 t of Cd, 1261 t of Pb and 9.2 t of Hg entered the Baltic Sea via riverine waters. In the same years, 2.38 t of Cd, 13.66 t of Pb and 1.01 t of Hg entered the Baltic Sea from point sources (HELCOM 2021). Rivers having the biggest influence on the Baltic Sea contamination are Neva, Vistula, Oder, Nemunas, Dauguva, Kemijoki, Gota (Dobrzycka-Krahel & Bogalecka, 2022). Nevertheless, it is worth to remember that the contamination of big rivers is affected by smaller rivers such as Pilica River, which is the left largest tributary of the Vistula River (Figure 1).

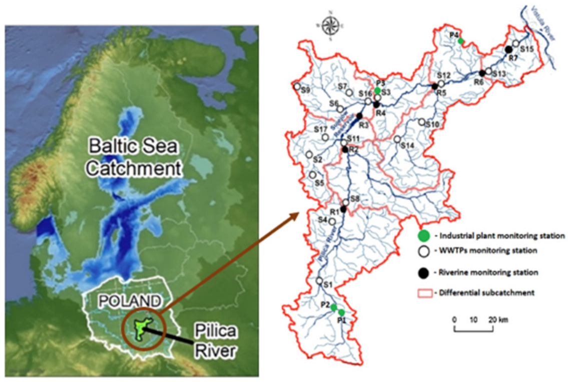

Figure 1. The catchment area of the Baltic Sea and the Pilica River (source: Kiedrzyńska et al., 2014b; modified).

The goal of the presented research is (1) holistic analysis of the point sources located throughout the catchment area, contributing to Pilica River contamination with selected heavy metals, and thus, indirectly, in the pollution of the Baltic Sea (2) to present examples of ecohydrological remediation activities in the field of nature-based solutions (EH Nature Based Solutions) (Zalewski 2020, Kiedrzyńska et al. 2017) to remediate fields contaminated with heavy metals and to reduce their transfer from the catchment area to the sea.

2. Sampling and methods

The research was carried out in the Pilica River catchment, which is located in central Poland. Catchment area is 9258 km² and the length of the river is 342 km (Kiedrzyńska et al., 2014b). There are 143 municipal sewage treatment plants and numerous industrial plants in the catchment area, therefore the river is polluted from numerous anthropogenic sources (Kiedrzyńska et al., 2014b; Harnisz et al., 2020; Szklarek et al., 2021).

Samples were taken at 28 points during fourth seasons: Spring, Summer, Autumn 2022 and Winter 2023. Water quality monitoring of the Pilica River was carried out at seven points located along the continuum from the source to the mouth. The analyzes also included 17 municipal wastewater treatment plants (WWTPs) divided in terms of population equivalent (p.e.) into class I (0-1999), class II (2000-9999) and class IV (15,000-99,999), and 4 industrial plants. The points were located throughout the catchment area. The analyzes include seasonal sampling. Sewage samples were collected directly at the point of sewage discharge into the Pilica River or its tributaries. Analyzes of heavy metals in the tested samples were carried out using inductively coupled plasma mass spectrometry (ICP-MS) in accordance with the PN-EN ISO 17294-2:2016-11 standard.

3. Results

Seasonal analyses (2022/2023) showed the presence of toxic substances from the group of heavy metals i.a. Chromium (Cr), Barium (Ba) and Copper (Cu) in almost all tested samples. The highest concentrations of heavy metals were detected in class I sewage treatment plants. The presence of heavy metals in the analyzed samples was most often detected in the summer and winter seasons of 2022 yr. The most commonly detected heavy metal was Cr with the winter's highest concentration of 14.0 mg/L for WWTP class I. Nevertheless, in wastewater samples from WWTPs and industrial plants there was also detected heavy metal from the group called *toxic trio* (because of their highly hazardous characteristics) (Pambudiono et al., 2018) - Lead (Pb). The highest concentration of this metal was 14.0 mg/L, which has been detected in small WWTP (class I). Pb was the most commonly detected in samples collected in summer.
According to literaturę, effective and low cost methods of the environment's remediation are Nature-Based Solutions, which are the preferred approach in various programs of the European Commission (e.g. Horizon Europe) and under the activities of the IX phase of the UNESCO Hydrological Program (UNESCO, 2022). Among the methods suitable for heavy metals' elimination there can be distinguished i.a. constructed wetlands, hybrid biofiltration systems and buffer zones (Kiedrzyńska et al., 2017; Izydorczyk et al., 2015).

4. 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). Developing an effective methods for preventing surface water pollution with heavy metals and maintaining it in good condition, requires a clear understanding of the emission sources and migration routes. To minimize the risk of contamination with heavy metals, it is necessary to limit their emissions to the environment. Approaches based on Ecohydrological Biotechnologies and Nature-Based Solutions are inexpensive and socially-acceptable approaches for the safe, non-invasive and effective elimination of heavy metals, thus mitigating the effects of anthropogenic pressure on the environment.

5. Acknowledgments

The research was supported by the National Science Centre, Poland (Project No. 2021/43/B/ST10/01076) and the National Center for Research and Development, Poland (HYDROSTRATEG1/000E/2022).

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Distribution of pyrogenic organic matter in the southwestern Baltic Sea

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1. Background

The Baltic Sea is one of the most polluted seas worldwide, with shipping emissions strongly contributing to the eutrophication and acidification of the seawater. Recent research has reported and estimated loads of inorganic and organic pollutants from the atmosphere to the Baltic Sea (Kanwisher et al., 2020; Ytreberg et al., 2020; Jalkanen et al., 2021; Kanwisher et al., 2022; Siudek, 2022; Ytreberg et al., 2022; Rosewig et al., 2023) and the fluctuations of their concentrations and sources. Regulations and mitigation strategies were adopted to decrease air pollution and its impact on the marine environment.

The incomplete combustion products released from ship exhausts already undergo fast physical and chemical changes before reaching the aquatic system. Due to their low solubility, these aromatic compounds including black carbon (BC) and polycyclic aromatic hydrocarbons (PAH) potentially accumulate at the interface between the atmosphere and seawater, the sea-surface microlayer (SML). Here, they are prone to further transformation, e.g., solubilization via abiotic factors such as UV radiation or adsorption to particles, which govern their subsequent transport in the environment. Different fractions of combustion-derived compounds thus should be used to track the fate of anthropogenic emissions in marine systems to improve our understanding of how emissions not only add nutrients (niltrogen and sulfer) to the dissolved and particulate organic matter pool, but also play an essential role as long-lived components in the organic carbon cycle.

2. Sampling area and collection

This research is part of the project PlumeBaSe, which aims to understand the fate of incomplete combustion from shipping emissions into the Baltic Sea water since the transformation of pollutants during this transport is not yet well understood.

The water sampling for this study was done in April 2023 in the southwestern Baltic Sea (10º0' E to 54º3' N and 14º5' E to 54º0' N; Figure 1). 84 water samples distributed in the water column (SML, SSW, and deep water) were taken during cruise EMB315 using RV Elisabeth Mann Borgese's CTD rosette for deep water, as well as its working boat for SML and SSW sampling. Water samples were filtered (GF/F) to separate dissolved and particulate fractions. A collection of atmospheric aerosols and single-particle measurements were performed simultaneously.

3. Analytical tools

Environmental data, such as wind direction and speed, distance from the shipping lane, salinity and dissolved organic carbon (DOC) were considered in order to understand the contribution, source, and distribution of the pyrogenic organic carbon fractions in the dissolved organic matter (DOM) pool.

A combination of targeted (PAH and BC) and untargeted (DOM molecular composition) approaches was used to give more insight into the composition, quality, and transformation of the combustion-related products in the seawater. The 16 PAHs listed in the priority pollutant list were assessed, while BC content was determined by the concentration of its molecular markers. DOM characterization was done using Fourier-Transform Ion Cyclotron Resonance mass spectrometry (FT-ICR-MS).

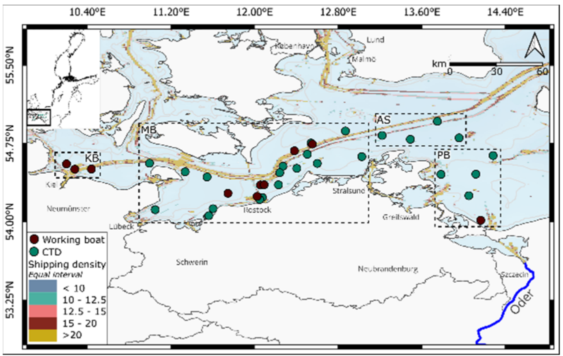

Figure 1. Sampling locations in the southwestern Baltic Sea: 25 stations were occupied, covering a salinity gradient from 8.2 to 17.6 and located near the major shipping lanes, including the Kadetrinne. A total of 84 samples were taken (Kiel Bay, KB [*n* = 11]; Mecklenburg Bight, MB [*n* = 56]; Arkona Sea, AS [*n* = 6], and Pomeranian Bight, PB [*n* = 11]). Shipping density is defined as the number of ships (times a thousand) crossing a 1 x 1 km grid cell (HELCOM AIS [Automatic Identification System] data).

4. Preliminary results

Wind direction and speed varied between 7.15 and 354.2 ° (mainly easterly) and 0.9 and 14.7 m s^{-1} during the cruise, and salinity ranged from 8.2 to 17.6. The SML thickness average was 64.7 ± 2.6 µm.

DOC concentrations ranged from 161 to 337 µM (270 ± 34 µM). PAH concentrations ranged from 2.35 to 29.69 ng L^{-1} (16.05 ± 4.44 ng L^{-1}) with a significant contribution of low molecular weight (LMW; 12.615 ± 3.89 ng L^{-1}) PAH compared to the high molecular weight (HMW; 3.44 ± 1.02 ng L^{-1}) PAH to the samples. The evaluated parameters were not significantly enriched in the SML. PAH concentrations in the SML were 17.81 ± 5.51 ng L^{-1}, with a majority contribution of LMW accounting for 14.52 ± 4.97 ng L^{-1}.

6913 molecular formulae were assigned during DOM characterization, with 415 molecular formulae assigned as aromatic compounds – PAH and BC. Those molecular formulae were attributed mainly to the CHO and CHON groups, accounting for 94.5 % and 86.3 % of the relative intensity and the number of formulae in the samples, while compounds with sulfur (CHOS and CHONS) had a smaller contribution to the intensity and number of formulae overall with 5.5 % and 13.7 %, respectively.

5. Spatial distribution and sources

DOC concentrations were higher in the Pomeranian Bight, with a gradient decreasing towards Kiel Bay. This was likely due to the higher influence of the Oder River on the Baltic

Sea, transporting high concentrations of terrestrial matter to the seawater via its estuary, which can also explain the negative linear relationship between DOC and salinity for the SSW (R^2 = 0.39, p < 0.001) and deep water (R^2 = 0.60, p < 0.001). No relationship was observed between DOC and PAH concentrations. Even though the PAH concentrations were not significantly different between the areas (one-way ANOVA, p > 0.05), the diagnostic ratios (i.e., ratios between single PAH commonly used for identifying and assessing the sources of pollution) revealed a variation of source for this group of pollutants, with a major contribution of fossil and petrogenic sources and, in a minor proportion, pyrogenic combustion (e.g., wood, grass, and coal combustion). In Kiel Bay, HMW PAH decreased with increasing proximity from the shipping lane; the opposite was observed for Arkona Sea. Wind direction and speed related to concentrations of HMW PAHs, potentially denoting different source regions. The high spatial variability of concentrations emphasizes the importance of local sources and complex atmospheric and aquatic processes governing the transport.

PAHs were not enriched in the here analyzed dissolved fraction of the SML. To our knowledge, the only study addressing PAH concentrations in the SML in the Baltic Sea was done by Witt (2002) and found higher concentrations of PAH in the SML compared to the SSW and deep water using whole-water samples, with concentrations decreasing from the Mecklenburg Bight to the Gulf of Finland. Particle adsorption of the PAHs in this layer is likely and will be assessed in the future.

PAH concentrations were not related to the fraction of aromatic compounds detected in the DOM pool via ultrahigh resolution MS, indicating a minor contribution of these combustion-derived products to the high natural background. The relative contributions of CHO, CHON, and CHOS compounds were similar between the study areas, while the presence of CHONS compounds was slightly less in the Arkona Sea (one-way ANOVA, p = 0.065), with S:C ratio varying in the same way between the areas. A moderately positive correlation was found between the aromatic compounds with DOC concentration in the Pomeranian Bight (r_S = 0.65, p = 0.031), indicating that the Oder River is a primary source of thermogenic organic matter in this area, which is in agreement with the literature, evidencing the importance of riverine transport of thermogenic material.

6. Conclusion

Overall, the study investigated the distribution of thermogenic pollutants and their contribution to the DOM pool in the Baltic Sea. The results indicated high spatial heterogeneity of PAH concentrations, with higher levels in the Pomeranian Bight attributed to the influence of the Oder River. PAH concentrations were similar along the Kadetrinne shipping lane but likely originated from different sources, including fossil fuel combustion on land. While the in-depth comparison to the simultaneously performed atmospheric aerosol sampling is ongoing, our study already highlights the complexity of pollutant distribution in the land-locked sea and emphasizes the role of local factors, such as riverine input and wind conditions, in shaping environmental patterns.

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Use of Artificial Neural Networks as a tool for port pollution control

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1. Introduction

Over past decade increasing air pollution became a serious problem that affects many areas, especially ports and cities near ports. While global shipping traffic in recent years, more specifically in 2019-2020 took a serious reduction due to the Covid-19 pandemic (European Maritime Safety Agency, 2022; Gavalas et al., 2022; Millefiori et al., 2021; United Nations Conference on Trade and Development, 2021), however recent statistics show that shipping traffic have been restored to pre pandemic levels (Review of Maritime Transport, 2022). Ensuring efficiency and keeping with ecological requirements are important for ports, especially in cases where port is close to the city and pollutants from port can reach urban areas and be a significant source of air pollution (Kim et al., 2022; Ma et al., 2021; Mamoudou et al., 2018).

Despite of effort being made to reduce air pollution from ships such as international laws like International Convention for the Prevention of Pollution from ships – MARPOL Convention (International Maritime Organization, 1973) pollution from ships still are a big issue. There is also a lot of direct and indirect ships pollution measurements methods and the variety of them growing by the year. However, monitoring shipping emissions remains a challenge, since statistical methods, that are reliable in evaluation of cruising operations, have low accuracy in low-speed conditions (Topic et al., 2021). Furthermore, they usually provide emissions evaluation but not dispersion parameters that are important for keeping with local regulations of pollutant concentrations. Direct measurement of air pollutant concentration is good solution widely applied in most ports that allows the port to monitor air pollutant levels and take actions if needed, but it has its limitations primary financial – maintaining a large network of measurements stations can be costly, it might not cover all port areas or provide information on sources (Shen et al., 2022; Smailys et al., 2009). In addition, products exist that combine some of these solutions together, to provide both the integration of measurement station data and simplified dispersion evaluation from cargo and stationary pollutant sources (Air Quality Monitoring | Ambient Air Quality Monitoring, n.d.; AQM 65, n.d.). However, these solutions usually don't cover shipping emissions that make up a large percentage of in port pollutant emissions. The reason for that is that with different technical characteristics of every ship and dynamic port conditions its prohibitively complicated to evaluate pollutant dispersion from every ship using traditional methods. This is where neural networks and machine learning can help.

Artificial neural network (ANN) models can be chosen for pollution from ships evaluation to avoid major calculations errors. Most of the ANN's models are used for air quality determination in cities and or wide areas (Ding & Zhu, 2022; Jiang et al., 2022; Kujawska et al., 2022; Qiao et al., 2022). Hong et al., 2022 study shows that ANNs can be effectively used to evaluate air pollution in wide areas. This study attempts to use an ANN model to accurately evaluate individual ships' plumes in port. Obtained results showing that ANN models can effectively be used to evaluate dispersion of pollution without data required by existing models such as AERMOD, GRAL (GRAL, 2023; US EPA, 2016).

2. Materials and methods

The data for artificial neural network model was collected from several sources (figure 1). Exhaust gas plume measurement data was taken from existing measurement station AQM 65 in port. Ship technical data was collected from IHS Fairplay database. Meteorological data was taken from available archives online. And ship position and movement data were collected from AIS station which was provided by the Lithuanian transport safety administration.

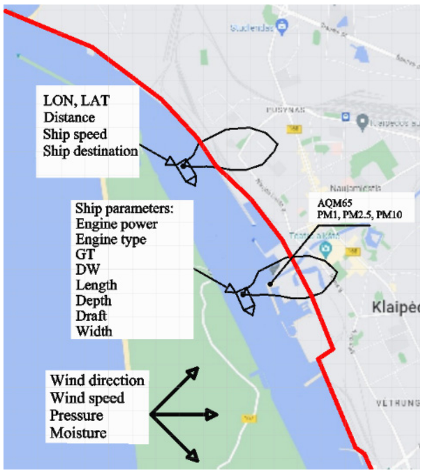

Figure 1. Data used for model creation.

Data was additionally filtered by adding limitations to wind direction so all data points would be with wind direction between 180° and 360° interval. Wind direction limitation is shown as red line in figure 1. By adding this filter model was feed only data which allowed evaluate pollution in shipping without pollution coming from port infrastructure or city. Also, data array was filtered from all negative or zero values in AQM station measurement's part when the station was undergoing maintenance. All methodology used for ANN creation were published in detail in authors previous publication (Šilas et al., 2023).

3. Model use in ports

For port control office it is imperative to have a good monitoring capabilities for all port facilities, that's why online pollution measurement services like Envirosuite, (2024) are popular. However, in most cases pollution from shipping is still difficult to predict. As mentioned before evaluation is usually done on the bases of emission coefficients, however statistical emission coefficients can't represent the current pollution conditions. An evaluation of dispersion is necessary, that is difficult to do for a moving object with insufficient initial data. The presented model allows the evaluation of dispersion of air pollutants from ship at real time.

Created model by using ship technical properties, meteorological and detailed ship location data predicted the concentrations of particulate matter (PM) at different distances from the ship at any given time. Model was able to find connection between all inputs and can adjust predictions if any of parameters change. Data correlation between predicted and know data is quite high and varies from 0,9 to 0,83 depending on the PM fraction size (1 µm, 2.5 µm and 10 µm). Trained model also lets user to use it to predict pollutants concentration changes when ship change speed. Predicted data results of pollutants concentration change at different ship speed are shown in Figure 4. The data shows that trained model can evaluate particulate matter dispersion as well as any other existing models like AERMOD or GRAL. However, this model does not require initial data about the emissions, gas temperature, chemical composition, release speed and many others which are very difficult to obtain without direct measurements onboard the ship.

In this way, based only on limited data, the estimation of air pollutant plume of ship operating in port can be evaluated and appropriate actions can be initiated. Furthermore, this model could be included in other system to operate together with evaluation of other sources for a full picture of port environmental conditions.

4. Conclusions

In the port environment, the simplest way to estimate ship emissions is from statistical models. However, most of the times they generate remarkably high errors and can lead to overestimation or underestimation.

Prediction of dispersion of air pollutants from ships in real time is also big challenge due to different technical characteristics of ships, consistent weather conditions changes and multiple different objects (ships) operating at once. Moreover, real emission from ship is usually unknown, making it difficult for traditional dispersion models. This is where artificial neural network models can be chosen for pollution from ships evaluation. ANN's models are already used for air quality determination in cities. As it is shown in this study, neural networks can be trained based on real ship operation and pollutant concentration data to develop a model for online prediction of air pollutant plumes from ships in ports based only on data that is already available for port operators.

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In search for suitable parameters quantifying the contribution of water level variations into coastal vulnerability index of microtidal seas

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1. Introduction

Gradually increasing hydrodynamic loads to sea shores owing to climate change combined with increasing concentration of people and infrastructure in the coastal areas have rendered the assessment of vulnerability of sedimentary shores of the Baltic Sea a significant coastal management challenge (Bagdanavičiute et al., 2015).

Coastal vulnerability incorporates exposure, sensitivity, and resilience. The common exposure parameters are land surface elevation, beach slope, underwater slope, shoreline change, closure depth, extreme water level, relative sea level change, and wave loads. The usual sensitivity parameters are geomorphology, sediments or population density. Resilience parameters relate to coastal protection structures and coastal setback.

The classic version of quantification of vulnerability of open ocean shores (Gornitz et al., 1991) includes only five parameters: geomorphology, relative sea level change, shoreline displacement, tidal range and wave heights. Of these, tidal range is irrelevant in the microtidal Baltic Sea and relative sea level change may vary insignificantly at the scale of a small country, such as Lithuania. The further increase in the set of parameters (Bagdanavičiute et al., 2015, 2019) in the wake of (Gornitz et al., 1994) does not compensate for the missing contribution of the impact of local and regional water level variations into the coastal vulnerability index. This contribution forms the core component of many coastal hazards.

We explore the potential of several quantities that reflect various features of local water level variations to characterise the contribution of water level into estimates of coastal vulnerability. The focus is on quantities with potentially predictive capacity, such as statistical parameters of water level distributions, rather than basically diagnostic variables, such as recorded water level maxima or minima.

2. Projections of extreme water levels

The classic parameters to characterise vulnerability of a coastal sector with respect to high or low water levels are extremely high and low water levels in the past. A natural generalisation of these quantities is the projection of extreme water levels for a certain return interval. Similar to the limitations of the use of tidal range for this purpose, interpretation of alongshore variations of this parameter is not straightforward. Namely, sedimentary beaches and shores with thick vegetation (e.g., mangrove forests) that regularly host very high water levels may have already adjusted to such (storm) conditions and may be much more resilient than coastal sectors where water level variations are smaller but sediment is mobile. This conjecture generalises the perception that many beaches with large tidal range are resilient to large variations in the water level.

In is thus not unexpected that the use of classic indicators of coastal vulnerability, including an ensemble-based projection of extreme water levels (Fig. 1) leads to controversial results for the entire shoreline of Estonia. On the one hand, several sections of the shoreline that are characterised as vulnerable (e.g., on Saaremaa) are naturally protected either by pebble, cobble and boulder pavement, or by thick and resilient vegetation. On the other hand, historically most sensitive bayheads and beaches, such as the interior of Pärnu Bay or sandy beach of Narva-Jõesuu on the north-eastern coast, have been categorised as having moderate vulnerability (Fig. 1).

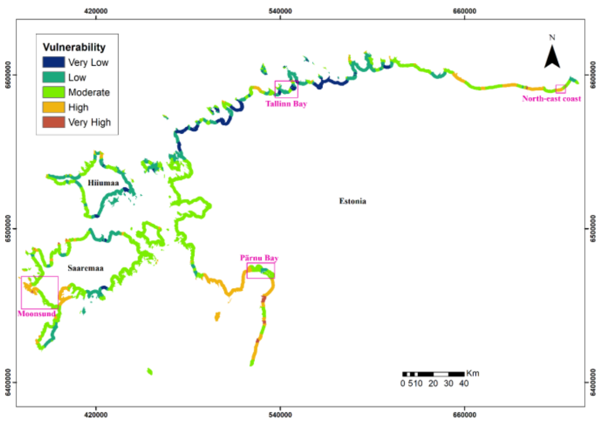

Figure 1. An example of coastal vulnerability map of Estonia based on three most important parameters (extreme water level, shoreline change and geomorphology).

3. Intensity of local storm surges

A natural parameter that makes it possible to evaluate to some extent the magnitude of future extreme events is the scale parameter of the exponential distribution of local storm surges. It appears as a natural measure of severity of very low or high water levels with respect to the current level of the entire Baltic Sea (Soomere et al., 2015).

For a suitable averaging procedure of water level time series, the probability distributions of low and high water levels converge into a standard exponential distribution $\sim\exp(\lambda x)$. The scale parameter $1/\lambda$ (with a suitably chosen sign) characterises the slope of this distribution and thus provides a first order estimate of both past and future severity of local water level extremes (Soomere et al., 2015).

The largest values of this parameter for positive surges occur in eastern bayheads that regularly host very large water levels while the smallest values are characteristic to shore segments that are open to the Baltic proper (Fig. 2). A natural limitation of this parameter is that it ignores the preconditioning, that is, situations with considerably elevated or depressed level of the entire Baltic Sea.

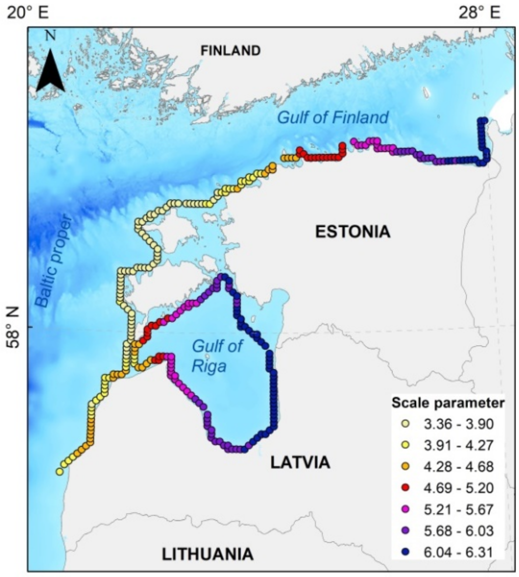

Figure 2. The scale parameter of the exponential distribution of the frequency of occurrence of positive storm-driven surges in the eastern Baltic Sea. Adapted from (Soomere et al., 2015).

4. Shape parameter of the GEV distribution

A possibly richer in content measure that to some extent incorporates the preconditioning effect is the shape parameter of generalised extreme value (GEV) distributions for extremely high and extremely low water levels evaluated using the block maxima approach (e.g., based on annual water level maxima or minima).

This parameter essentially defines the appearance of the GEV distribution for a particular coastal sector. Clearly positive values of this parameter signal that extreme water levels may rapidly increase in the future as the GEV distribution is represented by a Fréchet distribution. If the shape parameter is zero, the future water level extremes are governed by a Gumbel distribution that predicts a modest growth of future extremes. The most favourable situation occurs in coastal sectors with negative values of shape parameter. In this case the GEV distribution is represented by a 3-parameter Weibull distribution and the growth of extremes is much slower (Coles, 2004).

Similar to the above-discussed scale parameter of the exponential distribution, clearly positive values of the shape parameter of the GEV distribution (and thus higher levels of danger) typically occur in the eastern Gulf of Riga and Gulf of Finland (Fig. 3). The shores of the Baltic proper have these values either close to zero (and thus moderate increase in flooding risk in the future) or clearly negative (and therefore modest future risks).

5. Discussion and conclusions

The maps of water level extremes in the past and the projections of extreme water level mostly rely on past events and thus have basically diagnostic value. This situation motivates a search for prospective quantities of water level variations with certain prognostic value. Obviously, there exists no perfect quantity of this kind. The scale parameter of the exponential distribution of local storm surge heights follows accurately the geometry of the coast but does not take into account variations in the background water level. The shape parameter of the GEV distribution eventually has a larger prognostic merit but its values are noisy and contain substantial uncertainties depending on the particular method of their evaluation (Soomere et al., 2018).

Figure 3. Alongshore variation of the GEV shape parameter calculated from the stormy season (from July to June of subsequent year) maxima of the Rossby Centre Ocean (RCO) model for 1970–2005.

Acknowledgements

The research was supported by the Estonian Research Council (grant PRG1129). The authors are deeply grateful to the SMHI for providing the RCO and RCA4-NEMO model data.

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Overview of alien species introduction pathways in the Baltic Sea

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1. Introduction

The aim of this work was to review the data on alien species that spread due the ballast water, after analyzing the data, we assessed their distribution trends and identify their countries of origin, and provide guidance for further research on ballast water. Currently, various ballast water treatment systems are already being developed, tested and applied in the world. According to the International Convention on the Control and Management of Ships' Ballast Water and Sediments (IMO, 2007), all ships from 2024 ballast water treatment systems will have to be installed, the operation and quality of which will have to meet IMO standards.

2. Methods

The data analyzed in the work are collected in the database of alien and cryptogenic species AquaNIS, which collects data on the occurrence events of the species, their origin, method of propagation, and biological properties. All geographic information is arranged in a hierarchical order ranging from oceans, ocean sub-regions, LMEs, sub-regions of LMEs to smaller entities. In addition, AquaNIS gathers and disseminates information on environmental tolerance limits, availability of molecular data for identification, habitats. Moreover, the information system is equipped with a structured "search" function that allows for retrieving and organizing data by multiple and complex search criteria.

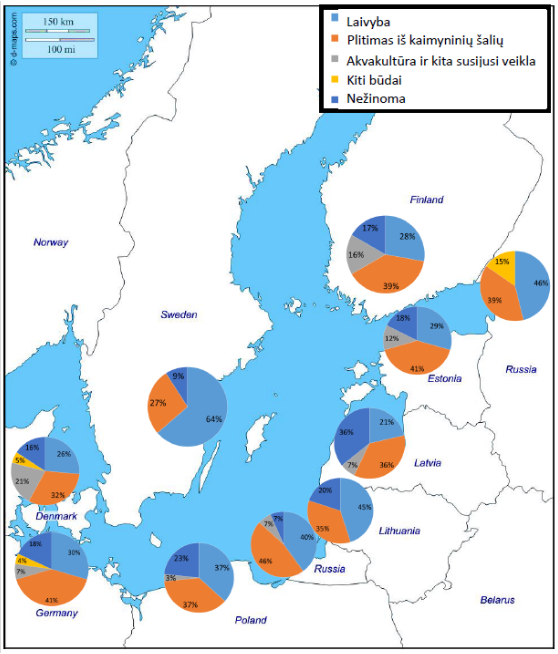

Figure 1. Fig. 2. The percentage distribution by pathways of non-indigenous species introduction into the Baltic Sea since 2000

3. Results

The results of this research allowed us to identify and describe the dynamics of the distribution vectors of species introduced in the Baltic Sea region. According to the analysis of non-indigenous species on their native origin, the results showed that in the last 20 years non-indigenous species from Ponto – Caspian region were dominating. 33% of non-indigenous species had either the Black or Caspian Sea as their native region. The second dominating origin was the Northwest (NW) Atlantic (24%), Northwest (NW) Pacific (19%), while Northeast (NE) Atlantic origin constituted only 6% of the non-indigenous species origin. For some species, the origin was unknown (11%) and in the case the native region was different (different from Ponto-Caspian, NW Atlantic, NW Pacific) they were assigned as "Others" (5%). The spread from the neighboring countries and shipping from the North Sea can be considered to be responsible for most of the currently widespread non-indigenous species. Other possible pathways include canals, culture activities and aquarium trade. The number of alien species that could spread through ballast water has been declining over the past decade.

During the international project COMPLETE (2017 - 2020), which was carried out together with other countries of the Baltic Sea region, the structure of the early warning system was discussed and harmonized. The purpose of such a system is to provide timely warning of critical biological conditions when HAOP occur in ports and surrounding waters. The warning signal must be received by ships and environmental and health authorities. Vessels are advised not to take ballast water in certain areas due to the likely entry of HAOP into ballast tanks (Magaletti et al., 2017).

4. Conclusions

The results of this research allowed us to identify and describe the dynamics of the distribution vectors of species introduced in the Baltic Sea region in relation to different periods. The number of alien species that could spread in ballast water has been declining over the past decade. However, if harmful organisms and pathogens are detected, an especially important step in considering the ballast water management strategy is to signal the detection of the detection to the responsible authorities (Early et al., 2016).

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Changing Marine Lightscapes

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Light profoundly influences marine life, driving evolutionary daptations in response to its intensity, color spectrum, and natural cycles. However, contemporary challenges have altered marine lightscapes in two significant ways. Firstly, factors like runoff, increased nutrients, rising temperatures and melting ice, darken certain marine areas, altering primary production and phytoplankton rhythms. Conversely, coastal regions are experiencing brighter nighttime environments due to urbanization and industrial activities, exacerbating light pollution. Despite these contrasting changes, they are connected by their impact on marine ecosystems' natural light conditions. This presentation aims to provide insights into the emerging topic, focusing on the North-West-European Shelf and the Baltic Sea. It will present recent trends, highlight gaps in our understanding of changing marine lightscapes and their effects on biodiversity and ecosystem structure.

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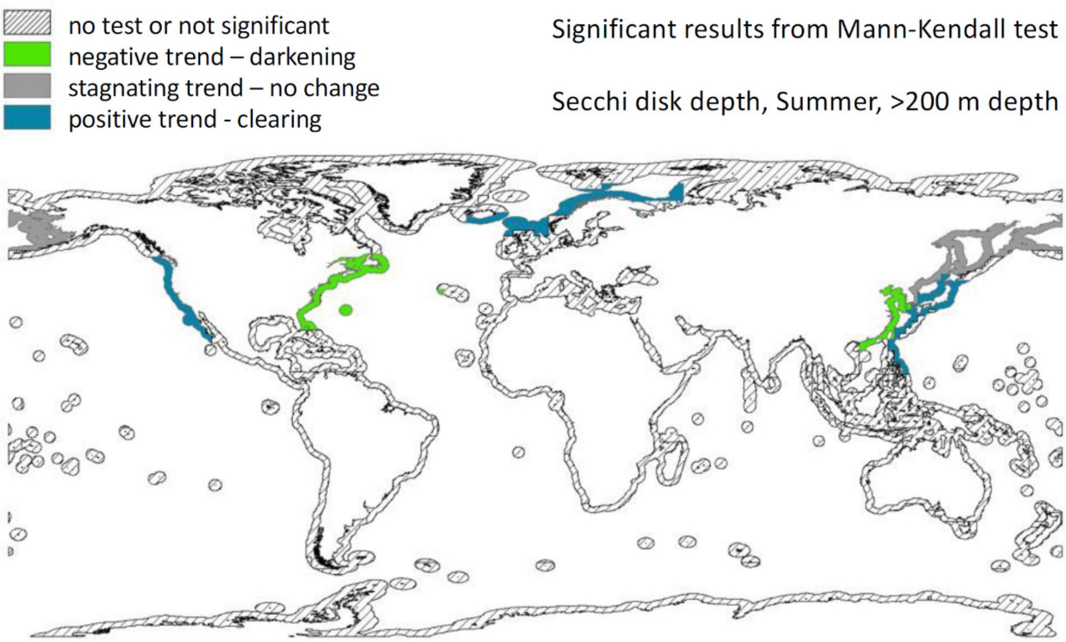

Trends in Secchi disk depth, data selected {summer, >200m water depth} from a global coastal ocean dataset (N>300.000). Mann-Kendall trend analysis per Longhurst region.

Session E

Modeling past and future climate changes and teleconnections

Exceptional warming and intensified oxygen depletion due to warm saltwater inflows in the western Baltic Sea

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1. Introduction

Hypoxia is considered a major environmental threat for coastal seas all around the world, including the Baltic Sea. With its pronounced haline stratification, it is naturally prone to oxygen deficiency, as the vertical oxygen supply to deep water layers is very limited. Their main sources of oxygen are sporadic saltwater inflows from the North Sea.

Between the 1950s and 1980s, nutrient input from anthropogenic sources (nitrogen and phosphorus) to the Baltic Sea has increased tremendously (Gustafsson et al., 2012). This led to eutrophication and therefore to the development of one of the largest hypoxic areas worldwide (e. g., Krapf et al., 2022). Since the 1980s, nutrient loads have decreased, but the oxygen content of deep water layers did not measurably improve (Hansson et al., 2019). One important reason is that phosphorus bounded in the sediments is again released to the water column under anoxic conditions (Vahtera et al., 2007).

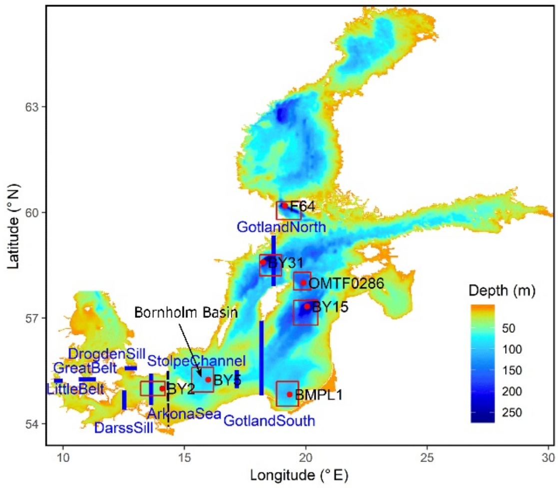
The impact of rising water temperatures due to global warming on the oxygen concentrations is still considered small relative to that of eutrophication (Meier et al., 2019), although several studies have shown a connection between bottom water temperatures and oxygen content (e. g., Krapf et al., 2022). An exceptionally high warming trend over the 20th century has been detected in the deep water layers of the Bornholm Basin (e. g., Dutheil et al., 2022). As they mainly receive heat laterally via saltwater inflows from the North Sea, the hypothesis arose that these inflows got warmer during the last decades, due to a shift in their seasonality (Mohrholz et al., 2006). Very large inflows happen mainly in winter (e. g., Matthäus and Franck, 1992), but since 1990, several pronounced inflows of warm water in summer and autumn were registered (e. g., Mohrholz et al., 2006).

In our study (Barghorn et al. 2023, Barghorn et al.), we analyzed hindcast simulations ranging from 1850 to 2008 to explore the linkage between the seasonality of saltwater inflows, the deep-water temperatures in the Bornholm Basin and its oxygen content. We conducted several sensitivity experiments to disentangle different drivers of changes in salinity dynamics and temperature.

2. Data and Methods

We used model output from three different regional ocean models: GETM (Burchard and Bolding, 2002), RCO (Meier et al., 2003) and MOM (Griffies, 2004). RCO and MOM were additionally coupled to biogeochemical models: RCO to SCOBI (Eilola et al., 2009) and MOM to ERGOM (Neumann et al., 2022). The model domain and bathymetry of the GETM setup are shown in Figure 1. It has a horizontal resolution of 1 nm and uses adaptive vertical coordinates (Hofmeister et al., 2011). RCO has a horizontal resolution of 2 nm and a vertical resolution of 3 m. The horizontal resolution of MOM amounts to 3 nm and in the vertical domain, z* coordinates with layer thicknesses ranging from 0.5 m at the surface to 2 m at larger depths were implemented.

Figure 1. Model domain and bathymetry of the GETM setup



(taken from Radtke et al. (2020) and modified). Blue lines denote transects for salt transport calculation. The thin dashed line indicates the eastern boundary of the Arkona Basin for the salt content calculations (S17). Red squares show areas around selected stations from which observational data was taken for the model validation.

All model runs were forced with the HiResAFF data set (Schenk and Zorita, 2012), which was constructed based on the analogue method, and with the river runoff data described in Meier et al. (2019).

We extracted the salt content in highly saline water masses (salinity of at least 17 g/kg) in the Arkona Basin (S17) as a proxy for the salt import via saltwater inflows. For the boundaries of the Arkona Basin, we used the DarssSill and DrogdenSill transects in the west and the beginning of the Bornholm Channel (approximately the thin dashed line in Figure 1) in the east. For GETM, we also deduced the salt import by inflows directly from the salt transport across the DarssSill and DrogdenSill transects which is part of the model output.

To investigate how different drivers affect the inflow seasonality, we conducted sensitivity experiments in GETM with climatological runoff (RUNOFF), with climatological plus interannually variable runoff (RUNOFF2), without sea level rise (noSLR) and with high-pass filtered wind (WIND). Additionally, an RCO experiment without global warming (TAIR) was used to disentangle the impacts of rising air temperatures and inflow seasonality on the temperature trends in the Bornholm Basin.

3. Selected results

For all three models we compared time series of annual and seasonal means of S17 (and salt import in case of GETM). As seasons, we chose summer (June – August; JJA) and early autumn (September and October; SO). We found that from 1920 onward, the SO means of S17 / salt import increased significantly while annual and JJA means decreased or did not change noticeably (Figure 2). We plotted the same time series and trends for the GETM sensitivity experiments to identify the drivers between the observed changes. We found the largest differences compared to the reference simulation (REF) in the RUNOFF/RUNOFF2 experiments, indicating that changes in the runoff seasonality might have affected the inflow seasonality.

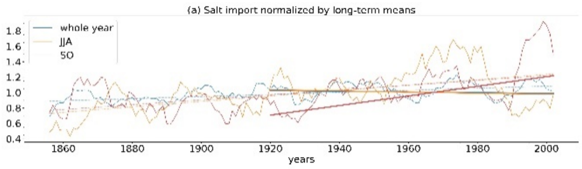


Figure 2. 11-year running means of salt import per year, June–August (JJA) and September– October (SO) with linear trends from 1851 and 1920. All values were normalized by respective long-term means.

To investigate the impact of warm inflows on the temperatures in the Bornholm Basin, we correlated the summer and early autumn (JJASO) S17 / salt import with the annual temperature maximum below the seasonal thermocline (Tmax) at station BY5 (see Figure 1). In all models, the correlations are high (Figure 3, top). Since the trends and correlations do not change much for the experiment TAIR, the exceptional warming in the Bornholm Basin must have been mainly caused by the changes in inflow seasonality and not by global warming. For RCO and MOM, we also compared annual means of temperature and oxygen concentration below 60 m at the same station and found very high correlations (Figure 3, bottom). Hence, the warm inflows seem to deteriorate the oxygen conditions on an interannual scale.

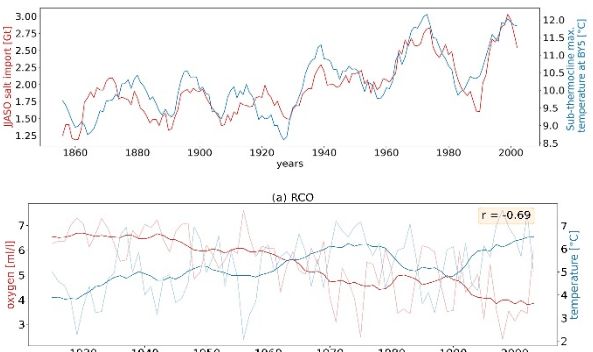


Figure 3. Top: Smoothed time series of JJASO salt import and Tmax at BY5 for GETM. Bottom: Annual and smoothed time series of oxygen content vs temperature averaged between 60 m depth and the bottom at station BY5, for the reference simulation of RCO. The yellow box displays the Pearson correlation coefficient between the non-smoothed and detrended time series.

4. Conclusions

By comparing long hindcast simulations of three regional ocean models, we identified a shift in saltwater inflow seasonality during the 20th century. It was the main driver of the exceptional warming in the Bornholm Basin, which deteriorated the oxygen conditions.

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The impact of Atlantic Multidecadal Variability on Baltic Sea temperatures limited to winter

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Börgel, F., Gröger, M., Meier, H.E.M. et al. The impact of Atlantic Multidecadal Variability on Baltic Sea temperatures limited to winter. npj Clim Atmos Sci 6, 64 (2023). https://doi.org/10.1038/s41612-023-00373-8

1. Abstract

We analyze multidecadal temperature fluctuations of the Atlantic Ocean and their influence on Northern Europe, focusing on the Baltic Sea, without a priori assuming a linear relationship of this teleconnection. Instead, we use the method of low-frequency component analysis (LFCA) to identify modes of multidecadal variability in the Baltic Sea temperature signal and relate this signal to the Atlantic climate variability. Disentangling the seasonal impact reveals that a large fraction of the variability in Baltic Sea winter temperatures is related to multidecadal temperature fluctuations in the North Atlantic, known as Atlantic Multidecadal Variability (AMV). The strong winter response can be linked to the interaction between the North Atlantic Oscillation and the AMV and is maintained by oceanic inertia. In contrast, the AMV does not influence the Baltic Sea's summer and spring water temperatures.

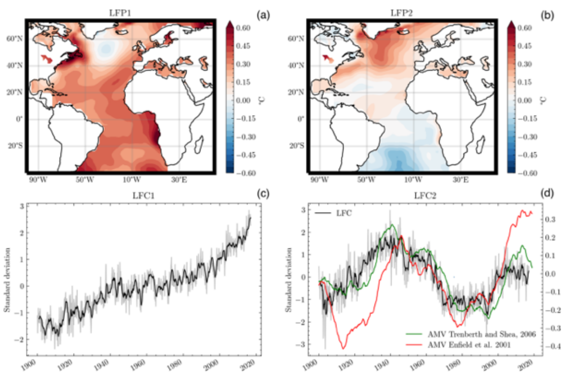

Figure 1. The first and second low-frequency patterns (a, b) (LFP) and low-frequency components (c, d) (LFC) retaining 30 EOFs and a 10-y low-pass cutoff are shown. LFC1 (global warming in the Atlantic) shows a 1-y running mean in black, whereas the gray line shows monthly fluctuations. LFC2 (Atlantic Multidecadal Variability, AMV) shows a 1-y running mean in black and monthly changes in gray. The AMV definitions of Enfield et al. (2001) and Trenberth and Shea (2006a) have been added in red and green, respectively.

2. Overview

The study explores the influence of multidecadal sea surface temperature (SST) fluctuations in the North Atlantic Ocean, known as the Atlantic Multidecadal Variability on Northern European temperature, particularly in the Baltic Sea region. The AMV, characterized by anomalous warm and cold SST phases, is linked to climate variations in Europe, impacting temperature and precipitation patterns. This article focuses on the dynamic coupling between the North Atlantic Oscillation (NAO) and the AMV, highlighting their interconnected influence on atmospheric and oceanic conditions. The study employs a method called low-frequency component analysis (LFCA) to analyze the seasonal impact of the AMV on temperature variability in Northern Europe, focusing on the Baltic Sea region. The LFCA method is employed to capture non-linearities and assess low-frequency signals within the Baltic Sea region without assuming linearity in teleconnections.

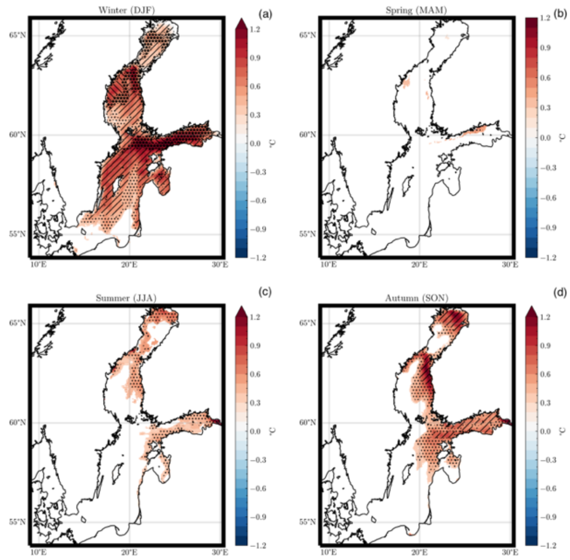

Figure2: Linear regression of seasonal sea surface temperature anomalies onto the seasonal component of the BMV (winter (a), spring (b), summer (c), and autumn (d)). The hatching indicates the explained variance. Dots (.) correspond to >5%, side hatching (/) to >10%, stars (*) to >20%, and backward side hatching (\) to >30%, explained variance. Only statistically significant changes are colored ($p < 0.05$; Student's t-test).

3. Findings

This study investigates multidecadal fluctuations in regional climate systems. Using the LFCA, the study identifies multidecadal sea surface temperature (SST) fluctuations in the Baltic Sea (BMV) closely resembling the AMV. During winter, the BMV significantly impacts Baltic Sea SST, explaining up to 40% of the variance, while its influence diminishes during spring and summer. The study attributes the winter influence to the NAO's out-of-phase relationship with the AMV, leading to North Atlantic warming. The warming effect extends to the Baltic Sea, impacting sea ice cover and snowfall. The study suggests that oceanic inertia, coupled with reduced ice/snow albedo, amplifies the warming effect in the North Atlantic and Baltic Sea. The LFCA reveals a stronger seasonal response from BMV compared to AMV, highlighting the importance of considering both in analyzing regional climate variations.

Future wind conditions over the South-Western Baltic Sea for the forcing of a high-resolution hydrodynamic numerical model chain

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1. Introduction

For the development of strategies and options for the adaptation to climate change in coastal protection, detailed information about possible future changes of the coastal hydro- and sediment transport dynamics are needed. One of the most important input variables for the modelling of possible future hydrodynamic conditions are spatially and temporally high-resolution wind fields over the Baltic Sea.
These wind fields were derived using an innovative extended delta approach based on high-resolution reanalysis wind data and detailed analysis of large sub-ensembles of regional climate projections for the forcing with RCP8.5, RCP4.5 and RCP2.6.
One of the advancements of this approach is that it accounts for the seasonal variability of the future climate change signals. Moreover, the approach enables the simulation of hydro- and sediment transport dynamics at high temporal and spatial resolution ($\Delta t \leq 0{,}2$ s and edge lengths down to 10 m at the coastline in selected focus areas) along the German Western Baltic Sea Coast (Figure 1).

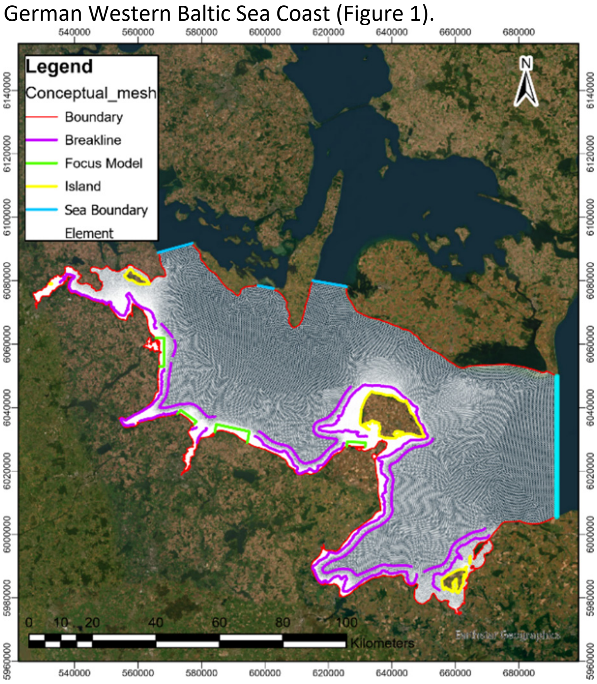

Figure 1. Domain and unstructured computational mesh of the coupled regional hydrodynamic model

2. Methods

An extended delta approach was used for analyzing possible future changes in hydro- and sediment transport dynamics. This involves carrying out a large number of demanding numerical simulations for the current state (hindcast of hydrodynamics) and possible future scenarios that describe relative changes in possible future wind conditions and sea level. The current state is described for the average conditions by a selected representative wind year 2016/2017 and for extreme events by selected storm events, which are characterized by different high water levels (storm surges) and/or by higher wave heights on the coast.
High-resolution wind data from the COSMO-REA6 reanalysis (Bollmeyer et al. 2015) was used as the basis for driving the hydrodynamic models for the past and future. The high-resolution wind data from COSMO-REA6 cover the European CORDEX EUR-11 domain with a spatial resolution of 6 km x 6 km and a hourly temporal resolution. Possible future changes of both 10 m wind speed and direction have been derived based on regional climate projections from the CORDEX-EUR11 ensemble (Jacob et al. 2020) with a spatial resolution of ca. 12,5 km and a hourly to daily temporal resolution. A comprehensive analysis was conducted on a total of 69 climate simulations spanning the period from 1950 to 2100. This included 38 simulations corresponding to the RCP8.5 forcing, 14 simulations for the RCP4.5 forcing, and 17 simulations for the RCP2.6 forcing. The wind data has been spatially averaged over different local domains and a larger domain covering the South-Western Baltic Sea area. A novel spatial weighting approach (Dreier et al. 2021) has been applied that takes into account the land fraction as weighting factor, which gives more weight to the wind speeds over sea than over land areas. The changes of the wind conditions have been finally derived from the comparison of long-term averages of the spatial averages for two future time periods 2071-2100 and 2021-2050 to the values for the reference period 1971-2000. In addition, changes of extreme wind speeds have been calculated for the different higher percentiles, e.g. the 95th to 99.9th percentile (see Figure 2).

3. Results

One result of the study is that, in order to correctly evaluate the changes in wind direction, the evaluations must be carried out separately for westerly and easterly wind directions for statistical reasons.
The changes of wind events for the forcing with RCP8.5 and from westerly directions show that up to the middle of the 21st century (2021-2050) there is no clear trend for the changes in wind directions, while the wind speeds tend to increase slightly (annual average value of the median changes ca. +1.2% and monthly median changes up to +4%).
At the end of the 21st century (2071-2100), however, there are major median changes in wind direction of more than +3° (maximum +6°) towards more westerly directions in May and July to November. At the same time, there is an increase in wind speeds for the same months (annual

average value of the median changes ca. +2.8% and monthly median changes up to +9%).

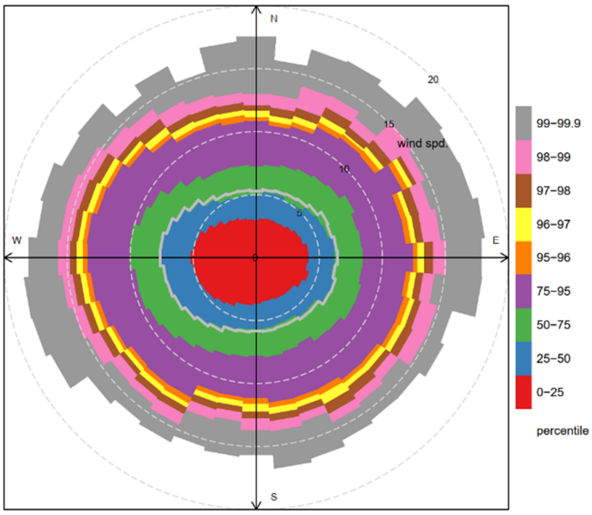

Figure 2. Percentiles (colored) of spatially averaged hourly 10 m wind speed (radial axis, in m/s) and direction in intervals of 10° in the reference period 1971-2000 from REMO forced by MOHC-HadGEM2-ES and the first realization of RCP8.5

For easterly wind directions, no clear trend was identified for the changes in wind speed and wind direction in the middle of the 21st century (2021-2050). At the end of the 21st century (2071-2100), relevant changes in wind direction occur in the months of July to September, with a shift of ca. 3° towards more easterly directions. In these months, there is also a decrease in wind speeds (annual average value of the median changes ca. -3.7% and monthly median changes down to -5%).

In agreement with previous assessments (Dreier et al. 2021) it was found that mean and extreme wind speeds exhibit different climate change signals, which also vary seasonally. For the period 2071-2100 and averaged over the storm surge season at the German Baltic Sea coast (September to April), the 99.9% percentile showed an increase in wind speed of ca. +5% for events from westerly directions and a decrease of ca. -2% for events from easterly directions.

In the chosen representative year of 2016/2017, the wind vector components of COSMO-REA6 were finally adjusted by incorporating monthly median changes in wind speed and direction for the 2071-2100 period.

In contrast, the wind vector components during the separately simulated storm events were modified with monthly median changes averaged over the storm surge season for the 99.9% percentile of the wind speed for the period 2071-2100.

The modifications took into account different climate change signals for westerly and easterly wind directions to derive scenario-based high-resolution wind fields which were subsequently employed to force scenario simulations with the coupled regional hydrodynamic numerical model.

4. Acknowledgements

This research was funded by state research grants from the Ministry of Energy, Agriculture, the Environment, Nature and Digitalization (MELUR) of the federal state of Schleswig-Holstein. We would like to thank the Climate Service Center Germany (GERICS) of the Helmholtz-Zentrum Hereon for performing and providing the REMO regional climate model simulations, the Deutscher Wetterdienst (DWD) for the provision of the reanalysis data COSMO-REA6 and the local authority responsible for coastal protection in Schleswig-Holstein (LKN) for the bathymetric and hydrodynamic measurement data for the set-up and operation of the hydrodynamic numerical model.

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The dependence of the future climate of Estonia on the level of global warming

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1. Introduction

Climate projections are needed to increase readiness and capacity to adapt to the effects of climate change. We are updating the climate projections for Estonia to inform climate change adaptation in Estonia. Updated projections will include an analysis of various climate variables for both observed and future climates. Previous climate projections for Estonia utilised IPCC AR5 models with Representative Concentration Pathways RCP4.5 and RCP8.5 climate scenarios (Luhamaa et al., 2015). We follow IPCC AR6 and analyse the climate conditions in Estonia as a function of the Global Warming Level (GWL). This preliminary study is limited to analysing how temperature projections for Estonia scale with GWL.

2. Data and methods

Global climate projections CMIP6 and CMIP5 underpinning the IPCC AR6 Interactive Atlas from the Copernicus datastore (C3S, 2023) were used in this study. The ensembles were harmonised using regular grids with horizontal resolutions of 2° (CMIP5) and 1° (CMIP6).

This study used historical experiments and climate projections based on RCP = 2.6, 4.5 and 8.5 and Shared Socioeconomic Pathways SSP = 1-2.6, 2-4.5 and 5-8.5 scenarios.

A climate simulation reaches the defined GWL when its global near-surface air temperature change averaged over successive 20-year periods first attains that level of warming relative to 1851–1900 (IPCC, 2021). For each model and each RCP/SSP the 20-year long period was calculated for each GWL. The model was omitted if it did not reach the specified GWL for the selected RCP/SSP.

For calculating spatial averages over the continental area of Estonia, the data was initially regridded to 0.1°x0.1° grid, and after that, the land mask was applied.

3. Results

We compare the regional distributions of annual and seasonal temperatures between CMIP5 and CMIP6 (Fig 1.) The historical mean of CMIP5 is more than 1.5 degrees warmer in southern Norway in all seasons and more than 1 degree colder in the Gulf of Bothnia and in Skagerrak in autumn and winter, compared to CMIP6 (last column of Fig 1). All systematical biases cancel out for projections when using the GWL approach (Fig. 1 first 5 columns). At GWLs 1°C and 1.5°C, the difference between CMIP6 and CMIP5 temperature rise is less than 0.5°C in the whole region, while biases get stronger when the GWL increases. At GWL = 4°C, the CMIP5 is 0.5 – 1.5°C warmer in winter at the Gulf of Bothnia and higher latitudes, while 1 – 2°C colder in summer in the whole region.

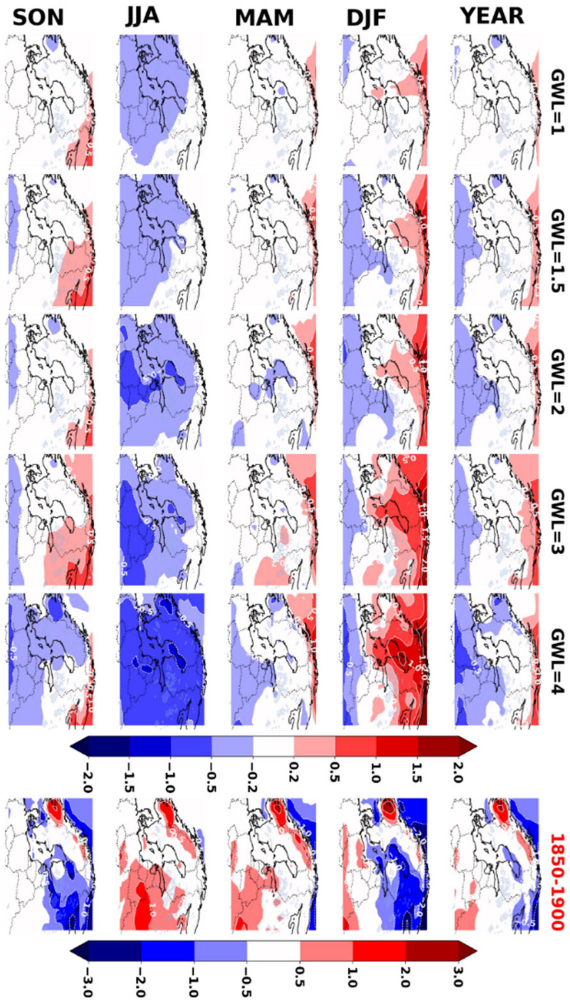

Figure 1. Difference between CMIP6 and CMIP5. Columns GWL = 1 to GWL = 4 represent annual and seasonal differences between CMIP6 and CMIP5 mean temperature rise at periods when the global warming level reaches specified levels. The last column shows the difference between CMIP6 and CMIP5 historical average temperatures (1850-1900).

The rise in the global average temperature produces an overall temperature rise in the area (Figure 2). Stronger warming occurs in winter in colder regions, and the standard deviation between different ensemble members is also the largest in the colder areas with higher GWLs. GWL=2°C will produce a 4–6°C temperature rise in Estonia in winter.

The seasonal mean (t), minimum (tn) and maximum (tx) daily temperatures respond similarly to the GWL increase. The warming is about 1.7 times faster in winter and 1.4 times in other seasons (Figure 3). Only in winter does the tn increase slightly more than t, while the tx warming rate is a bit smaller than t. Seasonal minimum of daily minimum temperatures (tnn) increases with GWLs much faster than the daily mean t, up to 16°C in winter with GWL = 4°C. As the txx increases at the same only 4°C, we can conclude that the maximum temperature amplitude in winter decreases by 12°C with GWL = 4°C.

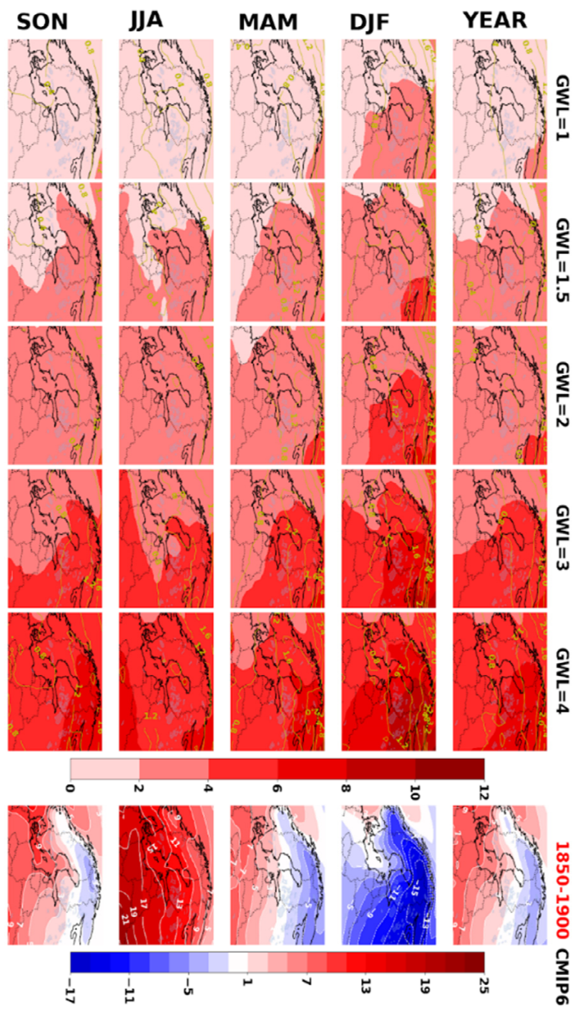

Figure 2. Seasonal and annual rise in mean temperature (°C) according to CMIP6 data. Rows are yearly and seasonal means. Columns GWL = 1 to GWL = 4 represent temperature change in periods when the global warming level reaches specified levels. Yellow isolines represent standard deviations between models. The last column shows the historical average temperature (1850-1900).

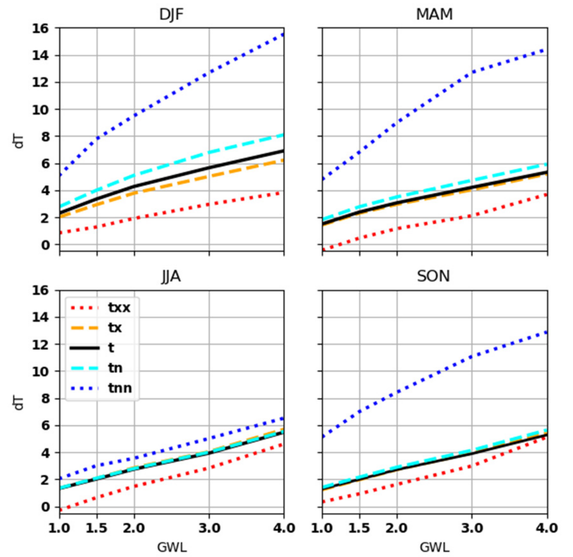

Figure 3. Seasonal differences from historical means of Estonia land area average temperature (°C), according to CMIP6 data. x-axes are global warming levels GWLs and y-axes are temperature differences from the historical (1850-1900) means. txx is the seasonal maximum of daily maximum temperature, tx is the seasonal mean of daily maximum temperature, t is the seasonal mean of daily mean temperature, tn is the seasonal mean of daily minimum temperature, and tnn is the seasonal minimum of daily minimum temperature.

4. Conclusions

- GWL-based regional climate projections are not directly affected by systematic differences between models. A good example is the systematic difference between CMIP6 and CMIP5 historical period averages in southern Norway, which are not present in GWL-based projections differences.
- GWL-based climate projections are not bound to specific SSP/RCP-s, so there is no need to justify why exactly one SSP/RCP has been selected.
- In winter, the Estonian average temperature is warming 1.7 times faster than the global average. For other seasons, the warming is about 1.4 times faster.
- Maximum temperature amplitude in winter decreases by 12°C with GWL = 4°C

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Changing impact of large-scale atmospheric circulation variability on the water mass exchange and circulation of the Baltic Sea for 1950-2022

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1. Introduction

This research builds upon previous studies that examined how the Baltic Sea circulation responds to climate variability between 1958 and 2008 (Lehmann et al., 2011). We have access to an extended time series ECMWF ERA 5 reanalysis (Bell et al., 2021) covering seven decades, providing insight into recent changes in atmospheric conditions over the Baltic Sea. Our primary objective is to identify the dominant large-scale atmospheric circulation patterns (North Atlantic winter climate regimes) that control the development of regional atmospheric weather types over the Baltic Sea area on a monthly/seasonal time scale. This, in turn, can be associated with different Baltic Sea circulation patterns and water mass exchange with the North Sea. Additionally, we will investigate long-term changes on an annual to decadal time scale, utilizing numerical modeling, statistics, and machine learning techniques such as PCA and clustering analysis.

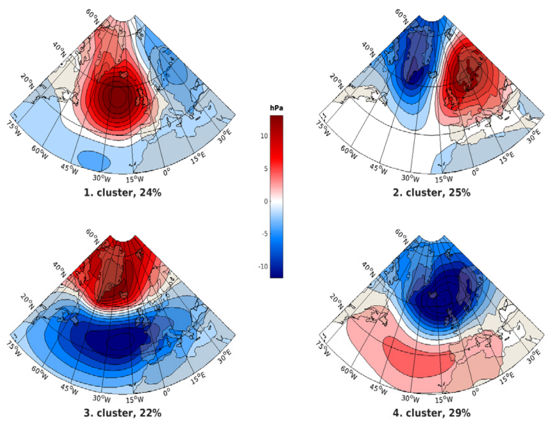

Figure 1. k-means climate regimes based on seasonal DJF MSLP anomalies (ERA5 1950/51-2021/22). 1. Cluster (EA/WR), 2. Cluster (SCAN), 3. Cluster (NAO$^-$), 4. Cluster (NAO$^+$).

2. Large-scale atmospheric circulation

The large-scale atmospheric circulation over the North Atlantic can be described by four dominant regimes (NAO$^+$, NAO$^-$ SCAN, EA/WR., e.g. Hurrel & Deser, 2009, Fig. 1). Different North Atlantic winter climate regimes force different circulation patterns in the Baltic Sea. Furthermore, as the atmospheric circulation, to a large extent, controls patterns of water circulation and biophysical aspects relevant to biological production, such as the vertical distribution of temperature, salinity and oxygen, 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 of the Baltic Sea, it is essential to investigate all climate system components, including the large-scale atmospheric circulation variability. Here, we focus on the link between changes/shifts in large-scale atmospheric conditions and their impact on regional scale variability over the Baltic Sea area from 1950 to 2022.

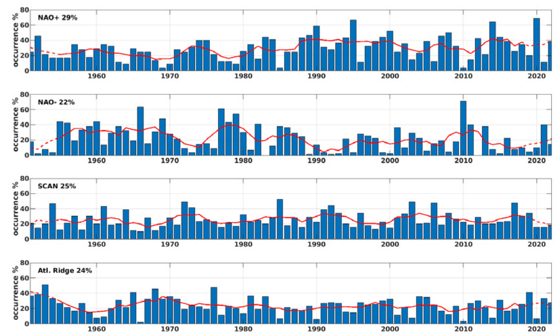

Figure 2. Time series of k-means climate regimes daily occurrences based on seasonal DJF MSLP anomalies (ERA5 1950/51-2021/22).

The time series of k-means climate regimes' daily occurrences based on seasonal DJF MSLP anomalies are displayed in Figure 2. There is a high interannual variability and opposing trends, especially between NAO+ and NAO-. For most years (DJF), all four climate regimes contribute to the daily occurrences, but in special cases (e.g. 2010), only one regime dominates.

3. Regional scale weather types

In the next step, we combined k-means climate regimes with regional scale weather types (Fig. 3). The Jenkinson-Collison weather type scheme can classify regional mean sea level pressure (MSLP) into a reduced number of typical recurrent patterns (Jenkinson & Collison, 1977). We used ten classes: eight directional types (W, NW, N, NE, E, SE, S, SW), a cyclonic and an anticyclonic type (C, AC).

From the weather types, the predominant weather situation over the Baltic Sea area can be deduced and further related to the corresponding barotropic circulation of the Baltic Sea.

4. Barotropic circulation of the Baltic Sea

For typical climate regimes, we calculated the monthly mean stream function of the barotropic circulation of the Baltic Sea (Fig. 4). Prevailing weather/climate regimes result in specific circulation patterns.

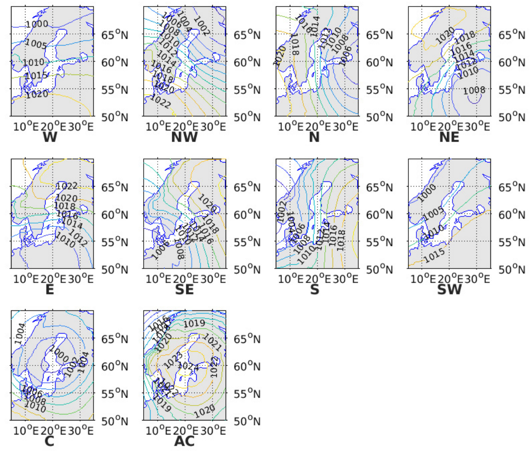

Figure 3. MSLP fields (hPa) for 10 Jenkinson-Collison weather types (JCT).

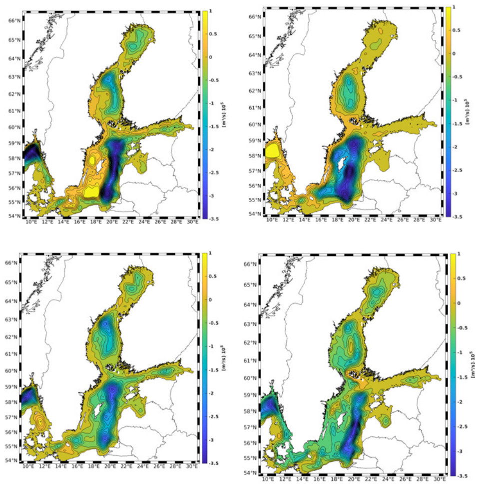

Figure 4. Baltic Sea Ice Ocean Model (BSIOM): Stream function of monthly mean barotropic circulation. Upper left: NAO+, December 2011; upper right: NAO-, February 2010; lower left: SCAN, December 1984; lower right: EA/WR, December 1975,

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Possible mechanisms of anthropocentric strengthening of the wintertime jet stream in the Atlantic sector: from the ocean to the stratosphere

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1. Introduction

Wintertime variability of both the strength of the jet stream and the North Atlantic Oscillation (NAO) index have been correlated in decadal time scale. Both have positive trends since the 1960s which have been recently proposed to be connected to anthropogenic global warming (Blackport and Ftyfe, 2022). At the same time there is a rich literature explaining both the observed variability and also the discrepancy with circulation models in which the variability is usually much smaller. Among the proposed mechanisms were "tug-of-war" between the tropics and the Arctic lower troposphere and surface temperatures, Arctic amplification, polar vortex strength. However, none of those forcing can not explain the trends in all the studied period.

2. Motivation

Wintertime jet stream strength and especially the sign of the NAO index control the storminess and temperatures in the Baltic Sea region between December and March. The motivation behind the present study is to find a mechanism which can explain the variability and trend in the whole period of accelerated global warning, that is since the middle of the previous century. One possible candidate can be warming of the troposphere and cooling of the stratosphere, both well established results of the increase in greenhouse gas forcing. Together with the lowering of the tropopause altitude with increasing latitude, this results in warming south of the jet stream and cooling north of it, increasing the very gradient which sustains a thermal wind such as the jet stream.

3. Results and Discussion

The results of early analysis show that the greenhouse related tropospheric warming / stratospheric cooling is a plausible candidate for the driver of changes in the wintertime jet stream strength and related NAO changes supporting the notion that NAO may head towards constant positive values. This confirms the proposed mechanism of direct global-warming related mechanism of the jest stream strengthening (Lee et al., 2019). However the question remains why such changes are only visible in the Atlantic sector and not elsewhere in the mid-latitudes of the Northern Hemisphere. The multidecadal wintertime NAO changes seemed related with the AMO/AMV variability of North Atlantic SST values at least until the 1990s (Latif et al., 2006) with the position of the Gulf Stream influencing the sign of NAO (Joyce and Zhang, 2010) and the pattern of summer North Atlantic SST values used to predict winter NAO for over 20 years now (Rodwell et al., 1999) This leaves the possibility that both Atlantic SSTs and greenhouse gas forcing are drivers of the variability in the wintertime jet stream strength.

4. Conclusions

The result support the notion of the increase of the wintertime strength of the Atlantic sector jet stream and more positive values of the NAO index due to greenhouse gas induced changes in troposphere and atmosphere temperatures. At the same time it is known that the pattern of SST values on the North Atlantic and the position of the Gulf Stream affect the value (and sign) of wintertime NAO. This suggest that both mechanism, compete in controlling the zonal circulation of the Atlantic sector affecting directly winter storminess and temperature of the Baltic Sea region.

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Analysing the occurrence and duration of periods with low wind speeds and high cloud cover in the Baltic Sea area: Insights from a renewable energy perspective

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1. Motivation

In the upcoming years, wind and solar energy are expected to play a more prominent role in Europe's energy mix. European Renewable Energy Directive raises the EU's binding renewable target for 2030 to a minimum of 42.5% of the region's total energy demand by 2030 (European Commission, 2023). The North and Baltic Sea regions have been pivotal in driving this expansion of renewable energy.

As the energy sector increasingly relies on renewable sources, long-term climatic shifts could significantly impact the future capacity of renewable energy. In this context, the winter months emerge as a critical period in the region, characterised by low solar power output and reliance primarily on wind power. An examination of the monthly ERA5 dataset indicates no substantial long-term alterations in overall wind speed over Scandinavia (55N-72N, 0-42E) annually and during the winter months (December-February) from 1991 to 2020, with the standard reference period being 1961-1990.

However, regarding energy security, the frequency and duration of concurrent low wind speed and surface solar radiation levels are crucial considerations. Nevertheless, the increasing dependence on variable wind and solar generation presents challenges for power production, particularly during adverse weather conditions. We specifically focus on a meteorological phenomenon known as 'Dunkelflaute,' characterized by calm winds and overcast skies (Li et al., 2021). Understanding and predicting such extreme weather events is essential for effective power production planning.

2. Data and Method

This study investigates the connections between unfavourable meteorological conditions for renewable energy production based on climate and energy indicators provided by the Copernicus Climate Change Service (2020). The analysis spans from 1979 to the present

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Innovative approaches to understanding ocean dynamics: Unveiling coherent variability and trends by data-driven methods and Koopman operator theory

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1. Introduction

We introduce the key findings and contributions of our work centered around operator-theoretic techniques applied to dynamical systems, particularly in the context of climate dynamics. The essential ingredient are kernel methods for machine learning and transfer/Koopman operators theory to identify and analyze persistent cyclic modes of variability in climate systems, as well as trend associated with climate change.

2. Pattern extraction and internal variability across a range of spatiotemporal scales

We introduce a framework that models the evolution of climate observables using transfer and Koopman operators. The dominant eigenfunctions of these operators reveal fundamental modes of climate variability, while their corresponding eigenvalues reflect the intrinsic timescales of these modes. We validate the approach through theoretical arguments and numerical analyses of idealized systems, comprehensive climate models, and reanalysis data. Notably, these eigenfunctions offer several advantages over conventional methods, including the ability to construct composites in the original observation space and providing rectified coordinates for the state of the given oscillation. Additionally, these extracted cycles exhibit self-consistency under forward evolution, making them valuable for prediction purposes.

3. Objective identification of trend and impact of trend

We also extend the application of operator-theoretic techniques to non-autonomous dynamical systems, addressing the challenge of analyzing systems influenced by time-dependent exogenous factors. The approach combines concepts from time-series delay-embedding geometry, Markov diffusion processes, spectral theory of transfer/ Koopman operators, and kernel-based regularization of dynamical operators. Spectral decomposition of the regularized operators further uncovers product eigenfunctions capturing the modulation of fundamental cycles by nonstationary trends.

4. Applications

We illustrate their methodology with idealized models representing non-autonomous dynamics in real-world problems, including climate change over the industrial era and the mid-Pleistocene transition of Quaternary glaciation cycles. The results demonstrate the ability of transfer operators to recover trends in systems undergoing drifts in mean and amplitude of oscillatory dynamics, as well as delineate non-autonomous frequency switching in systems with oscillatory dynamics.

We also apply the techniques to Indo-Pacific sea surface temperature (SST) and δ18O radioisotope concentration data, revealing nonparametric representations of climate change trends and associated product modes capturing the response of seasonal cycles to trends. These methods provide valuable insights into regional changes in South American seasonal precipitation and the long-term trend of δ18O concentration over the past 3 million years, including fundamental glaciation cycles before and after the mid-Pleistocene transition.

In conclusion, we propose a powerful framework based on operator-theoretic techniques with the ability to extract trends and cycles from certain classes of nonautonomous systems. These autonomous methods require only a single time series, making them applicable in natural science domains where repeated experiments are infeasible. The research offers a bridge between autonomous and non-autonomous methodologies for data-driven analysis of dynamical systems, with promising applications in climate dynamics and beyond.

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ROPEWALK (Rescuing Old data with People's Efforts: Weather and climate Archives from LogbooK records) - a digitization project for three centuries of weather observations on board of Danish ships

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1. Introduction

The project ROPEWALK, funded by the AP Møller Mærsk Fund, is a joint initiative of the Danish National Archive and the Danish Meteorological Institute over the period 2023-2026. The aim of the project is to digitize and transcribe all weather observations in ship journals and logbooks stored in the Danish National Archive.

A huge amount of data (more than 750 shelf meters) is stored in the archive, beginning as early as the 1680s. With the exception of the Napoleonic wars and the Danish state bankruptcy in 1814, the data is complete. In the archive, ship journals and logbooks from Danish ships sailing over large parts of Northern Hemisphere are found.

2. Unique data

Of particular interest are observations from two regions, the Øresund and Greenland:

In connection with levying 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 (Fig. 1). These ships had to ensure that no one passed without paying the duties.

Figure 1. Sound (top right) and Belts (middle and left). Millions of weather observations were taken on board of war ships positioned near Helsingør (1), Copenhagen (2) and Nyborg (3). Map: Frederick de Witt: Insularum Danicarum ut Zeelandiæ, Fioniæ, Langelandiæ, Lalandiæ, Falstriæ, Fembriæ, Monæ aliarumq. in Mari Balthico sitar. Amsterdam 1670. Royal Library Copenhagen.

Weather observations on board of these ships were tabulated starting as early as the first half of the 18th century, and in several cases, observations were conducted every time the ship bell was struck, resulting in as many as 48 observations in the course of one day (see an example of half-hourly observations in Fig. 2). For the oldest logbooks, which are in free text rather than in tabular form and go back to the Little Ice Age, we could locate transcriptions in the library of the Danish Defence College, which are much easier to read than the original data.

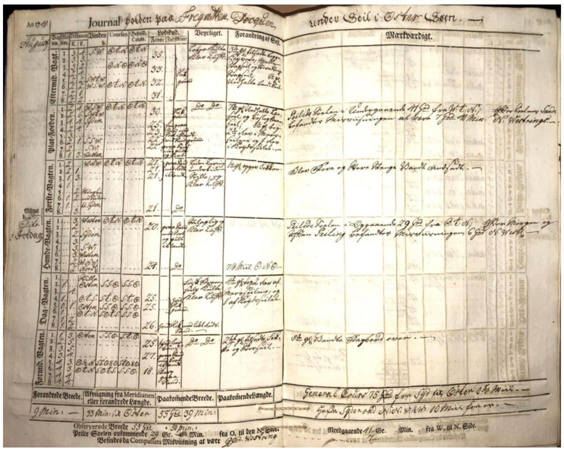

Figure 2: A page from the logbook of Frigate Docquen, under sails in the Baltic Sea in August 1748. Note the pre-printed tables.

The other group of logbooks which are of particular interest are from voyages to the colonies, in particular to (western) Greenland. The Greenlandic Trade Company had the monopoly for commerce with Greenland for nearly 200 years, and foreign ships would not be allowed to call a port. These "Greenland Voyages" were conducted several times per year and date back to the 1720s (Fig.3).

In many cases, detailed sea ice observations, both from the Øresund region and the Greenland voyages, have been conducted.

In addition, many journals are available from merchant ships during the 19th and 20th century, which have not yet been digitized so far either.

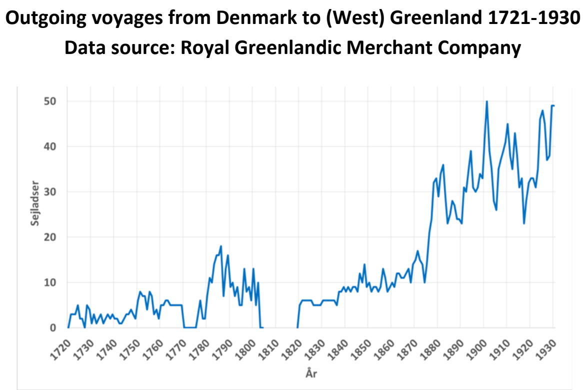

Figure 3. Number of outgoing Greenland voyages from Copenhagen 1920-1930. Return voyages are not shown in this graph, so that the total number of voyages is twice as large.

3. Scanning and transcription

All documents need to be scanned first, and the correct metadata and a unique identifier are assigned. The next step is transcription. Many logbooks have one of only a few designs, so we solve this task by means of a machine learning approach. Where this is not possible, we use the help of volunteers, as has been done in many other digitization projects.

As a novelty, we involve pupils in the final grade of Danish primary schools. They will be given real data, which they can transcribe by means of a mobile app, possibly in a mass experiment (to be negotiated).

The scanning of the original logbooks and journals by the National Archive in highest possible resolution is now almost complete. We have therefore initiated the transcription of the scanned documents by means of machine learning. Starting with logbooks which are relatively easy to read, first results (example in Fig. 4) are very encouraging, and we will present them here.

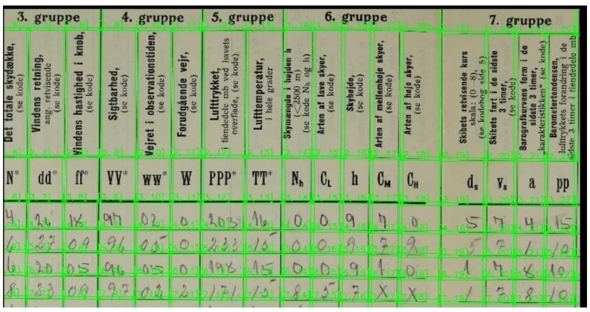

Figure 4. Excerpt from the logbook of M/S Bolivia, en route from Copenhagen to Godthaab (Nuuk) at the beginning of October 1953. Individual cells are labelled with numbers, so that the machine learning algorithm "understands" that data in a column belongs together.

All transcribed data will be made publicly available and can be used for future research or as input for reanalysis projects.

Information flow and multivariate causality estimates between measured and modelled forcing and temperature time series.

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1. Introduction to causality

Causality analysis is an important problem of science and is of specific importance in geophysics, data science and machine learning. Stips et al (2016) demonstrated the causal relationship between Green House Gases (GHG) concentration and Global Mean Surface Temperature (GMTA) based on the Information Flow (IF) methodology. Critics on the application of the Information Flow concept as developed by Liang (2008, 2015) has focused on the underlying assumption of uncorrelated residuals (noise). However, this assumption can only make sense for a system with two components, as for multi-dimensional system unobserved noise may well exist. Fundamentally, there can be no such thing like correlated noise at all. It can seemingly only appear because of some hidden process(es). For this purpose, a multivariate information flow analysis has been developed (Liang, 2021). We will show that in our tests using processes with correlated noises, the preset causalities can be well reproduced. The main focus of the presentation is on the application of the multivariate information flow methodology to disentangle causal interferences in global radiative forcings and global temperature response from measured data and from model output data.

2. Correlation and causality multi-dimensional estimates

The selected radiative forces are based on Meinshausen et al. (2011) comprise total forcing, greenhouse gas (GHG) forcing, CO2 alone forcing, forcing from aerosols, cloud albedo effect and land use albedo effect among others. Global mean surface temperature (GMTA) is based on Cowtan and Way (2014) modified HADCRUT4 time series. These series have been selected for comparing the previous bivariate results from Stips et al. (2016) to the new multi-variate results. The results from the multi-variate correlation analysis confirm the well-known significant high positive and negative correlations between the different forcings and the global mean temperature. The correlation matrix in Fig. 1 visualizes the calculated numbers. All chosen forcings are not only correlated with GMTA but exhibit also a high correlation between each other.

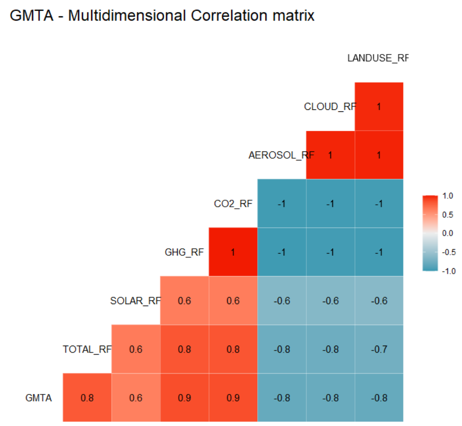

Figure 1. Correlation matrix between Global Mean Temperature and different major forcing components.

The application of the new multi-variate causality estimation gives, however a rather different picture. From the data visualized in Fig. 2 we find that GMTA is mainly driven by GHG, CO2 and aerosol radiative forcing, all other components show only minor or insignificant contributions. Further it is evident that these 3 components are also the main contributors to the total forcing. The application of this methodology to temperature data from global models confirms basically these findings.

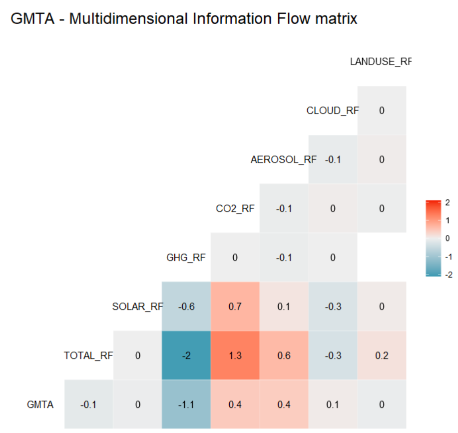

Figure 2. Multidimensional causality estimation between Global Mean Temperature and different major forcing components.

Finally, we question the critics against the Liang information flow theory based multi-variate causality method and the validity of a proposed alternative measure based on vector autoregression, as in this method causal directions can be reversed by reordering. A physically faithful causal measure should be independent of ordering.

3. Conclusions

Using the new multi-variate information flow concept, we were able to confirm the inherent one-way causality between human activities and global warming, as during the last 150 years the increasing anthropogenic radiative forcing is driving the increasing global temperature, a result that cannot be inferred from traditional time delayed correlation or ordinary least square regression analysis. Natural forcing (as solar forcing and volcanic activities) contributes only marginally to the global temperature dynamics during the last 150 years. Investigation of the temperature simulations from the CMIP5 ensemble is largely in agreement with the conclusion drawn from the observational data.

We conclude that the Liang information flow theory provides a strict non-parametric causality measurement which can identify causality between any given time series. Especially in its multi-variate form it provides a powerful tool for causal inference in complex multi-variate systems. However, basic assumptions as stationarity of the time series need to be considered for achieving statistical confidence.

Other causality estimates based on vector autoregression, seem not to respect basic physical assumptions.

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Projections of future drought in Australia using CMIP6 downscaled projections

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1. Abstract

Droughts are recurring natural hazards throughout the Australian continent, with their impacts affecting society and the environment. Under climate change, there is potential for more frequent and severe drought events. However, the ability of global climate models to generate regionally relevant insights into future droughts is limited. As such, regional projections of droughts are required to inform decision makers on the likelihood of these hazards across the different regions of the continent.

In this study we employ the 12-month standardised precipitation index (SPI; including only precipitation) and the 12-month standardised precipitation-evapotranspiration index (SPEI; including precipitation and temperature/evaporation) to investigate changes to future meteorological droughts.

We used an ensemble of 15 CMIP6 simulations downscaled using the Conformal Cubic Atmospheric Model (CCAM) to a 10 km resolution for the whole of Australia. Simulations of precipitation and potential evapotranspiration were bias corrected against observational and reanalysed data using the MBCr bias correction approach developed by Cannon. We assess the changes to 12-month SPI and SPEI in two future periods (2041-2060 and 2081-2100) and compare them with the historical baseline (1995-2014) for three Shared Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, and SSP3-7.0, representing low, high-emissions pathways, respectively). Three metrics (frequency of occurrence, duration, time in drought) are used to evaluate the impacts of climate change across different drought severity categories. The insights generated from these results are of importance to a range of stakeholders across Australia and may be adopted to help inform future adaptation strategies.

Assessing bias correction approaches for analysis of climate extremes and hazards

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1. Abstract

Evaluations of downscaled climate projections have shown they generally add value over host models, especially over coastal and mountainous regions. However, downscaled simulations also carry systematic biases inherited from global models and generated by regional models that must be adjusted otherwise they are propagated into the calculations of climate extremes and hazards.

Here, we performed a series of numerical experiments assessing different bias correction approaches with the goal of defining the methodology for the CMIP6 cycle of downscaled simulations of the Queensland Future Climate Science Program. We used our previous CMIP5 downscaled projections under RCP8.5 over Queensland with the Conformal Cubic Atmospheric Model (CCAM).

The bias correction was applied to two downscaled simulations with ACCESS1-0 and ACCESS1-3 and three variables: precipitation, minimum and maximum temperatures. After a preliminary assessment of a broader list, we selected the two best performing methods (quantile delta mapping and non-parametric transfer function) with and without seasonal calibrations (seasonal and monthly) and wet/dry day frequency correction.

We also assessed the performance of the three Cannon's multivariate bias correction approaches: MBCn, MBCp and MBCr. We used the periods 1980-2000 and 2001-2020 as calibration and validation, respectively. The assessment criteria were bias in climatological spatial patters, impact on the future climate change signal (2079-2099) and impacts on climate extremes – assessed using an adaptation of the Perkins skill score applied to the lower and upper tails of the distributions. The results revealed important insights to inform bias correction strategies of climate modelling programs and impact assessments.

Session F

Small scale processes not yet resolved and their impact on the large scale dynamics and patterns

Unraveling Ocean Dynamics with Glider Profiling and ship-based Microstructure Observations in the Slupsk Furrow.

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1. Abstract

We present a thorough examination of the small-scale dynamics within the Slupsk Furrow, employing a dual-pronged approach that integrates glider profiling operations and microstructure measurements from the ship. This investigation is a part of the Glider Mission to Resolve Mixing in the Southern Baltic (LISTEN) project funded by the European Commission – H2020 Framework Programme, JERICO-S3.

Initially, comprehensive CTD profiles, dissolved oxygen, and ocean current measurements were conducted during the IO PAN cruise of RV Oceania within the Slupsk Furrow on May 9, 2023. These measurements were taken at stations spaced at 5 nautical-mile intervals, strategically scheduled one day prior to the initiation of glider profiling operations (Figure 1).

Subsequently, on the following day, the research vessel positioned itself approximately 3 kilometres behind the glider to mitigate any potential collision risks. The vessel adopted a westerly drift with a velocity of 1 kilometre per hour, mirroring the course of the glider. Continuous ocean current measurements were carried out using a 150 kHz vessel-mounted Acoustic Doppler Current Profiler (ADCP). Concurrently, microstructure measurements were conducted from rv Oceania at hourly intervals, corresponding to 1 kilometre separation, utilizing a Vertical Microstructure Profiler (VMP250) from Rockland Scientific. This VMP data collection spanned approximately 3 hours (or 3 km) to the east of the glider, encompassing the time frame from 10:00 AM on May 10, 2023, to 10:00 PM on May 11, 2023, (36 hr) and again from 12:30 PM on May 12, 2023, to 4:00 AM on May 15, 2023 (63.5hr). The VMP successfully recorded 294 profiles distributed across 98 stations, each separated by 1 km, with a minimum of 3 profiles performed at each station. Due to temporal and logistical constraints, the VMP measurements were concluded on May 15, 2023, after covering the deepest segment of the basin.

Despite challenges with the oxygen sensor limiting the glider's profiling capacity to a single extended section along the Slupsk Furrow from May 10 to May 18, 2023, an Argo float, concurrently traversing the Furrow, measured CTD and dissolved oxygen. Merging a variety of collected data we present more holistic description of ocean dynamics within the Slupsk Furrow. The findings encompass diurnal variability in chlorophyll-A concentrations, spatial and temporal fluctuations in water temperature and salinity, and discernible patterns in turbidity and turbulence intensity. This integrative approach provides a nuanced understanding of the interplay between physical and biogeochemical parameters in the coastal environment.

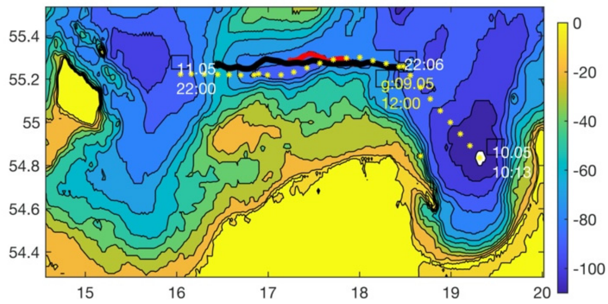

Figure 1.Location of the measurements of: glider (black), VMP-250 (red) , ship CTDO (yellow).

2. Funding

This Research has received funding from the European Union's H2020 Framework Programme (H2020-INFRAIA) under grant agreement n°871153, JERICO-S3" and was supported by the Tallinn University of Technology TalTech as the infrastructure facility provider and by "Turbulent mixing in the Slupsk Furrow (Southern Baltic) SUFMIX " project funded by the National Science Centre (NCN) Poland [2019/33/B/ST10/02189], and the "Argo-Poland" project funded by the Polish Ministry of Education and Science [2022/WK/04].

Marine Organisms at Work: Biomixing in the Baltic Sea

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1. Abstract

Small-scale ocean turbulent mixing plays a pivotal role in shaping the physical and biogeochemical processes, as well as ocean circulation. While the significance of this phenomenon is acknowledged, the mixing induced by marine organisms, commonly known as biomixing, remains inadequately observed and understood. This study presents an exploration, revealing the substantial impact of biomixing within the highly-stratified coastal waters of the Baltic Sea.

Employing continuous microstructure measurements using VMP-250 (Rockland Scientific) and a vessel mounted ADCP during the fieldwork spanning 6.5 days we analyse a centimeter-scale turbulence dynamics in the Slupsk Furrow—a key channel connecting the western and eastern Baltic Sea, thus exerting profound influence on the entire Baltic Sea dynamics. We observe elevated turbulent eddy kinetic energy dissipation rates by 2-3 orders of magnitude every night at sub-surface waters of about 20-30 m water depth. While the swimming activity aggregations of small fish (sprout or herring) are implicated as a potential source of the observed increased mixing. We approach our findings with cautious speculation. It remains uncertain whether these small fish or perhaps zooplankton, though less likely, are responsible for the observed turbulence. We advocate for further research endeavors to unravel the intricate interactions between marine organisms and turbulent mixing dynamics.

2. Funding

This research was supported by the following projects: “Turbulent mixing in the Slupsk Furrow (Southern Baltic)” funded by the National Science Centre (NCN) Poland [2019/33/B/ST10/02189] and the state budget under the program of the Minister of Education and Science (Poland) entitled "Science for Society" [NdS/546027/2022/2022], project funded by the and Infrastructure Sustainability and Enhancement (EA-RISE) funded by the European Union [82431].

Seasonal Variability and Long-Term Winter Shoaling of the Upper Mixed Layer in the Southern Baltic Sea.

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1. Abstract

The upper ocean mixed layer plays a crucial role in regulating the exchange between the ocean and the atmosphere. The Mixed Layer Depth (MLD) is a key parameter affecting the air-sea exchanges of momentum and heat and determining the upper ocean temperature. Numerous previous studies have investigated MLD variability in the global ocean or regional seas but no such studies were carried in the Baltic Sea. In this study, we present the first observational assessment of the MLD and its properties in the Southern Baltic Sea including quantification of its seasonal and long-term changes and identification of the multi-year winter shoaling. We calculated monthly maps of MLD in the southern Baltic Sea using a large number of historical CTD profiles collected in 1995- 2021 from a combination of different data sets. To test the robustness of the results we compared the MLDs calculated using different threshold methods. Throughout the southern Baltic Sea, across its three basins, a distinct seasonality is evident in the MLD, with values varying from 12 m in July to 60 m in December-March. During winter the water column is well mixed down to the upper halocline depth and the MLD reaches about 45 m in the Bornholm Basin, 50 m in the Slupsk Furrow, and 60 m in the Gdansk Basin. The observed global warming and decadal changes in the salty inflows from the North Sea to the Baltic have had an impact on stratification by increasing water densities in the intermediate and deep layers. Consequently, density gradients have strengthened with depth while the upper ocean mixing has weakened during the winter season. The results reveal a significant winter shoaling of the mixed layer by 4 meters per decade, driven by the increased stratification due to rising temperatures and salinity. These changes could have significant impacts on the dynamics and productivity of marine ecosystems

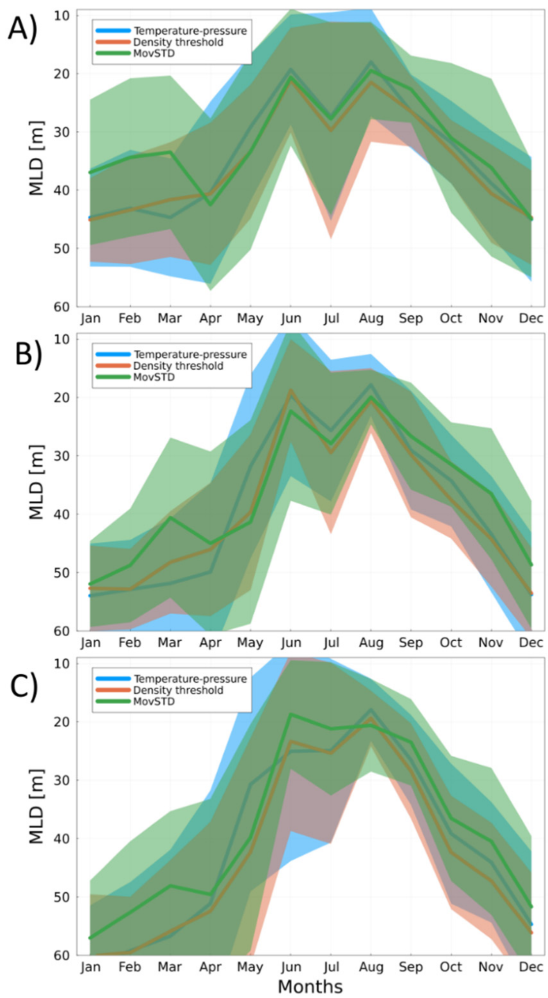

Figure 1. Mean seasonal MLD changes in the Bornholm Basin (A), Słupsk Furrow (B) and the Gdańsk Basin (C) in 1995-2021 obtained using three different algorithms with shadows representing one standard deviation.

2. Funding

This research was supported by the following projects: “Turbulent mixing in the Slupsk Furrow (Southern Baltic)” funded by the National Science Centre (NCN) Poland [2019/33/B/ST10/02189] and the state budget under the program of the Minister of Education and Science (Poland) entitled "Science for Society" [NdS/546027/2022/2022], the Argo-Poland project funded by the Polish Ministry of Education and Science [2022/WK/04], the Euro-Argo Research and Infrastructure Sustainability and Enhancement (EA-RISE) funded by the European Union [82431].

3. Acknowledgments

We would like to thank the crew of *RV Oceania* and Piotr Wieczorek for their support in collecting CTD data and help at sea. Numerical calculations were carried out using computers from the Academic Computer Centre in Gdańsk.

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Detection of marine eddies based on high-resolution model data

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1. Introduction

Marine eddies play a crucial role in ocean circulation, affecting various environmental and climatic processes. Accurate detection of these features is essential for understanding their dynamics and impact on marine ecosystems.

Kahru et al. (1995) laid the foundational groundwork with meticulous analysis of satellite data, elucidating the seasonal patterns and spatial variability of sea-surface temperature fronts and offering fundamental insights into the thermal dynamics of the Baltic Sea.

Zhurbas et al. (2003) conducted numerical experiments, providing a detailed exploration of the mechanisms governing the generation of cyclonic eddies in the Eastern Gotland Basin, thus affording a quantitative understanding of the response to dense water inflows.

In 2012, Gurova and Chubarenko (2012) expanded the observational scope, employing advanced remote-sensing techniques to probe the characteristics and spatial distribution of coastal sub-mesoscale eddies, enriching the understanding of these phenomena in the coastal context.

Lagrangian descriptor used by Vortmeyer-Kley et al. (2016) for the detection and tracking of eddies through the use of the modulus of vorticity, providing a Lagrangian perspective that augmented comprehension of their spatiotemporal evolution within oceanic flow fields.

Building upon this advancement, in 2019, Vortmeyer-Kley et al. (2019a) conducted a comparative analysis, systematically evaluating disparities in Eulerian and Lagrangian approaches for conducting an eddy census, refining methodologies employed in understanding the complex circulation patterns of the Baltic Sea.

Vortmeyer-Kley et al. (2019b) presented a case study, adeptly intertwining fluid dynamics and ecological considerations, delving into the intricate roles of eddies to discern whether these fluid dynamical features predominantly serve as ecological niches or act as primary transporters.

2. Methods

Our approach involves the utilization of state-of-the-art high-resolution hydrodynamic model CEMBS-PolSea. CEMBS-PolSea model simulate ocean dynamics with high accuracy, allowing for the identification of (not only) mesoscale features such as eddies.

The detection algorithm, inspired by Graftieaux et al. (2001), takes advantage of vorticity and velocity fields, providing both qualitative and quantitative characteristics of marine eddies. This method, with its automatic detection capability, enhances the precision of our eddy detection process, enabling a more detailed analysis of their spatiotemporal distribution.

The automated eddy detection tool has been developed to precisely determine the location and characteristics of these dynamic phenomena. It utilizes data from a netCDF file containing modeling results to compute mathematical functions Γ_1 and Γ_2. These functions aid in identifying areas with particularly intense water movement, indicative of the presence of eddies.

The algorithm analyzes spatial and temporal data, identifying areas with Γ_1 values surpassing a predefined threshold. Subsequently, through the grouping of points with similar properties, clusters are formed, representing potential marine eddies.

For each identified eddy, the algorithm calculates additional parameters such as eddy size and duration. This information is then aggregated, creating a comprehensive dataset regarding the located marine eddies.

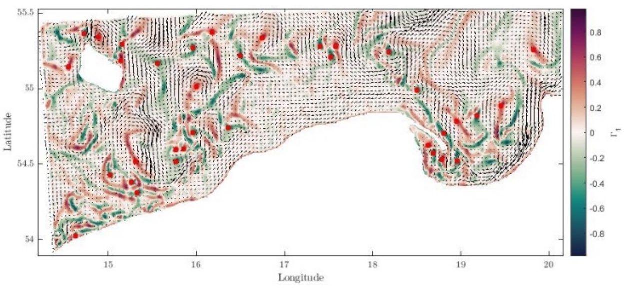

Figure 1. Map of the Γ_1 scalar field distribution (color bar scale) with an overlaid vector field of the surface current distribution and marked places of localized eddies (red dots).

3. Results

Preliminary results indicate the successful automatic identification and tracking of marine eddies using the high-resolution model data and the adapted algorithm based on Graftieaux et al. (2001). The tool not only determines the expected location of the eddie but also provides information on its size and duration.

The example result of detection process is graphically represented in Figure 1, where red points symbolize cluster centroids, indicating areas of potential eddy occurrence. This methodology effectively allows for the monitoring and characterization of dynamic marine phenomena, with significance for both oceanographic research and practical applications. The incorporation of this algorithm enriches our methodology, aligning it with established techniques and providing a robust basis for eddy detection, both qualitatively and quantitatively.

The findings derived from the CSI-POM tool, as illustrated in Figure 1, specifically pertaining to the characteristics of the marine eddies, are conveniently accessible to the public through an online portal (https://csipom.pl/en/). This portal functions in an operational mode, ensuring that the data remains both current and easily reachable for researchers, maritime professionals, and interested members of the public.

By presenting CSI-POM products on an interactive platform, the project effectively closes the gap between sophisticated scientific research and practical, real-world applications. This approach not only facilitates the widespread dissemination of vital oceanographic data but also promotes collaborative initiatives and knowledge exchange within both maritime and scientific communities. This, in turn, cultivates a deeper understanding of the dynamic marine environment within the Baltic Sea.

4. Summary

The CSI-POM initiative was established to address challenges in the maritime sector, aiming to develop reliable tools for monitoring changes in the marine environment. This includes planning for projects, making informed decisions across maritime sectors, and improving safety and efficiency in marine operations. The novel tool developed under CSI-POM represents a significant advancement in understanding and predicting water mixing dynamics in the Baltic Sea. Its implementation contributes significantly to various aspects of maritime operations and research.

In conclusion, our study contributes to the advancement of marine science by providing a robust methodology for the automatic detection of marine eddies based on high-resolution model data.

5. Acknowledgments

Scientific work financed from the state budget under the programme of the Minister of Education and Science (Poland) entitled "Science for Society" No. NdS/546027/2022/2022, amount of funding PLN 1 702 130.65, total value of the project PLN 1 702 130.65

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Baltic Sea Water Dynamics: The Role of the CSI-POM Project in Understanding Thermocline, Halocline, and Pycnocline

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1. Abstract

This presentation introduces a tool developed under the CSI-POM project (Digital Information System for Polish Maritime Areas), playing a pivotal role in examining the water mixing phenomena in the Polish maritime areas of the Baltic Sea. The tool is designed to detect and forecast the top, bottom, and thickness of the thermocline, halocline, and pycnocline layers, using the data from the hydrodynamic numerical model CEMBS-PolSea.

2. Introduction

The existence of a well-mixed surface layer where temperature, salinity, and density are almost homogeneous is a characteristic and almost universal feature of water bodies such as seas and oceans. Wind-driven interactions and heat flux exchange at the water–atmosphere boundary cause strong turbulent mixing processes within this layer.

The depth of this mixed layer shows high seasonal variability. It may be located close to the surface or not present at all during the warm summer months. However, in winter, due to the deep convection stimulated by surface heat loss, the boundary of the mixed layer is observed at great depths. In selected ocean locations, it can reach 2000 m, Marshall and Schott (1999), while in shallow seas, an example of which is the Baltic Sea, it is observed at depths of tens of meters, Leppäranta and Myrberg (2009).

The correct determination of the mixed layer depth (MLD) is of key importance in oceanographic research. This knowledge is used in the development, parameterization improvements and validation of ocean general circulation models (OGCMs), which are used to simulate the physical and thermodynamic processes that occur in the ocean, Chen et al. (1994), Masson et al. (2002), Noh et al. (2002), Kara et al. (2003), Zhang and Zebiak (2002). Furthermore, since a significant proportion of biological activity occurs in the upper ocean (in the euphotic zone), the mixed layer is also important for work related to biological processes, Longhurst (1995), Polovina et al. (1995).

3. Results

Leveraging data from the high-resolution (575 m horizontal resolution) CEMBS-PolSea numerical model, we created the system that works in an operational mode, generating 48-hour forecasts of critical parameters that describe the properties of the mixing layer.

A noteworthy aspect of this tool is the use of the algorithm called the "MovSTD" algorithm (Figure 1). This algorithm was developed as part of a recently published study, Janecki et al. (2022), and introduces a novel approach for determining the top, bottom, and thickness of the thermocline (TTD) and halocline (THD), potentially serving as a powerful tool in shallow sea basins globally. It calculates a moving average of the short-scale spatial variability of the ocean's vertical profile (standard deviation) and then processes it to determine the potential depth at which temperature or salinity changes rapidly. This method was calibrated using an extensive dataset from the ecohydrodynamic model. The calibration resulted in setting input parameter values that accurately determine TTD and THD, confirmed through validation on *in situ* profiles collected by the research vessel S/Y Oceania during statutory voyages in the southern Baltic Sea. The "MovSTD" algorithm was subsequently used to analyze the seasonal variability of the vertical structure of waters in the Gdańsk Deep in terms of temperature and salinity. The thermocline deepening speed was also estimated in the region analyzed.

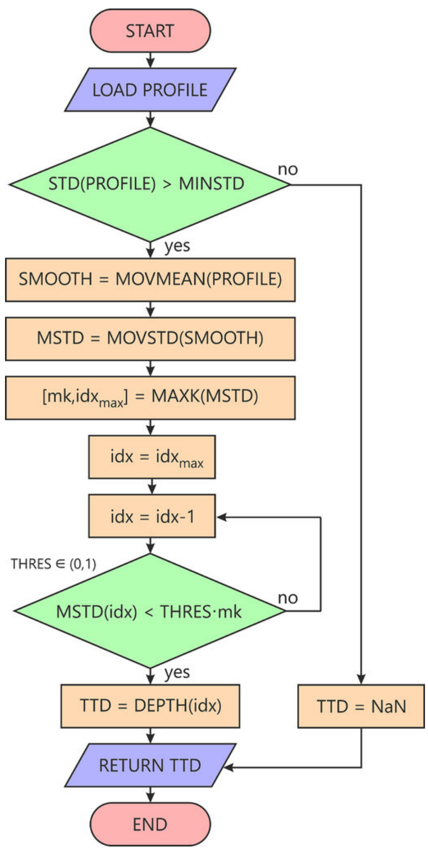

Figure 1. The flow diagram of the "MovSTD" algorithm, source: Janecki et al. (2022).

The results obtained from the CSI-POM tool (Figure 2), particularly concerning the top, bottom, and thickness of the thermocline, halocline, and pycnocline, are readily accessible to the public through an online portal (https://csipom.pl/en/). This portal operates in an operational mode, ensuring that the data is not only up-to-date but also easily accessible to researchers, maritime professionals, and interested members of the public. By providing these insights on an interactive platform, the project bridges the gap between advanced scientific research and practical, real-world application. This approach not only facilitates the dissemination of crucial oceanographic data, but also enhances collaborative efforts and knowledge sharing within the maritime and scientific communities, fostering a deeper understanding of the Baltic Sea's dynamic marine environment.

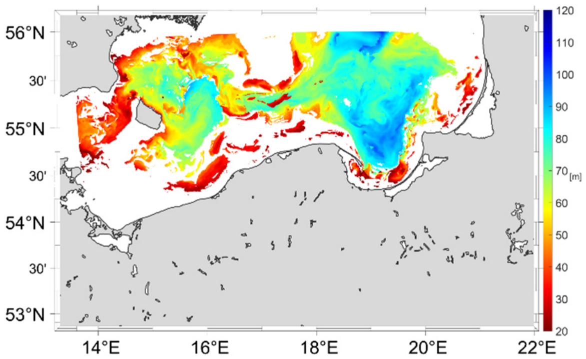

Figure 2. Sample result for the bottom of the thermocline depth on February 5, 2022 from CSI-POM tool.

4. Summary

The CSI-POM project itself is a response to challenges in the maritime economy, which require reliable and precise tools for monitoring changes in the marine environment. This includes planning and assessing optimal hydrodynamic conditions for projects, making informed decisions in various sectors of the maritime economy, and enhancing the safety and efficiency of marine operations.

This innovative tool, developed under CSI-POM, offers significant advancements in understanding and predicting the dynamics of water mixing in the Baltic Sea, contributing immensely to various aspects of maritime operations and research.

5. Acknowledgments

Scientific work financed from the state budget under the programme of the Minister of Education and Science (Poland) entitled "Science for Society" No. NdS/546027/2022/2022, amount of funding PLN 1 702 130.65, total value of the project PLN 1 702 130.65

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Central Baltic Sea Circulation Experiment – first results

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1. Introduction

Central Baltic Sea Circulation Experiment (CABLE) was designed to address the knowledge gap regarding the prevailing subsurface circulation patterns in the Central and Northern Baltic Proper.

Although there are no stable or permanent currents in the Baltic, lateral flows play an important role in distributing the properties of the water.

Thermohaline circulation, superimposed by atmospheric forcing, determines so called Baltic Sea Haline Conveyor. Part of this overturning circulation is up-estuary flow in the deep layers. There is a high short-term variability in the current dynamics in the Baltic. However, recent observations have revealed that under stable atmospheric forcing, highly persistent current structures occur at the coastal slope of the Baltic Proper (Liblik et al. 2022).

Subsurface layer circulation in the Baltic Sea has been rigorously studied by numerical modeling. Most of the simulations were not validated against in-situ current measurements or have been validated to a very limited extent. The reason for the latter is a relatively small number of available in-situ measurements of currents in most of the Baltic Sea. An international current measurement experiment was conducted to reveal the details of the circulation in the Central Baltic Sea.

The first aim of the work was to capture the current dynamics in the subsurface part of the Baltic Sea Conveyer Belt at the time scales from days to months. Specifically, we aimed to investigate the lateral structure of quasi-steady circulation features observed at the coast (Liblik et al., 2022). Secondly, we aimed to capture the connections between circulation dynamics in the Central Baltic Sea and changes in the water properties in the Northeastern Baltic Sea. Preliminary results of the CABLE will be presented at the Baltic Earth conference.

2. Data

Ship time of RV Aranda was successfully applied from the Eurofleets+ project for the activities at sea. Five moorings carrying current meters were deployed to the sea from RV Aranda in April 2022. The moorings were recovered in October 2022. Water sampling in both cruises along the zonal section from Saaremaa Island towards Farö Island and from the Gotland Deep towards the central Gulf of Finland was conducted. Three moorings were deployed from RV Elisabeth Mann Borgese in May 2022. One of them was recovered by RV Oceania in November 2022, and the other two by RV E. M. Borgese in March 2023. The deployed moorings formed a zonal array between Saaremaa Island and Farö Island (Figure 1). Voice of the Ocean (VOTO) Foundation and SMHI in the frame of the JERICO-S3 project transnational access mechanism provided by FMI conducted glider observations in the western part of the mooring array. All moorings carried acoustic Doppler profilers except the one at M10, which had a point current meter installed at a dept of 10 m. Not all the acoustic profilers covered the full range of the water column. Gliders operated by VOTO also had downward-looking current profilers installed.

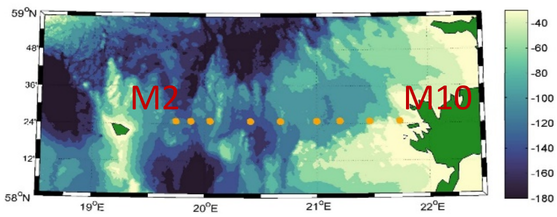

Figure 1. Location of the mooring array. The westernmost mooring station is M2 and the easternmost M10.

3. Preliminary results and discussion

Generally, the mean current velocity in June- September ranged from 10-13 cm/s near the sea surface to 4-5 cm/s in the deep layer. Currents had rather low persistency (see, e.g. Liblik et al. 2022 for the equation); in many areas/layers, it was below 30%. Exceptionally strong and rather persistent flow was observed in the deep layer at the Farö Sill at station M3.

The mean current field from June to September revealed cyclonic circulation with northward flow at the Saaremaa coast and southwestward flow in the western part of the array (Figure 2). The latter is consistent with earlier observations and simulations (e.g. Jędrasik and Kowalewski, 2019; Placke et al., 2018). A similar mean basin-scale structure was identified in the cold intermediate layer, although the mean velocities were weaker and less persistent there. The mean zonal current component was positive (i.e. northward) in the deep layer of most of the stations. An outstanding, strong mean zonal component towards the north was observed at the thalweg of the Farö sill. However, the mean flow was towards the south on the western flank of the sill.

The current structure under prevailing northerly winds consisted of southward flow and westward flow in the upper at the eastern coast and at the westward part of the array, respectively. Strong flow towards northerly directions occurred in the deep layer. Onshore flow was observed in the intermediate layer at the coastal slopes (stations M2, M9).

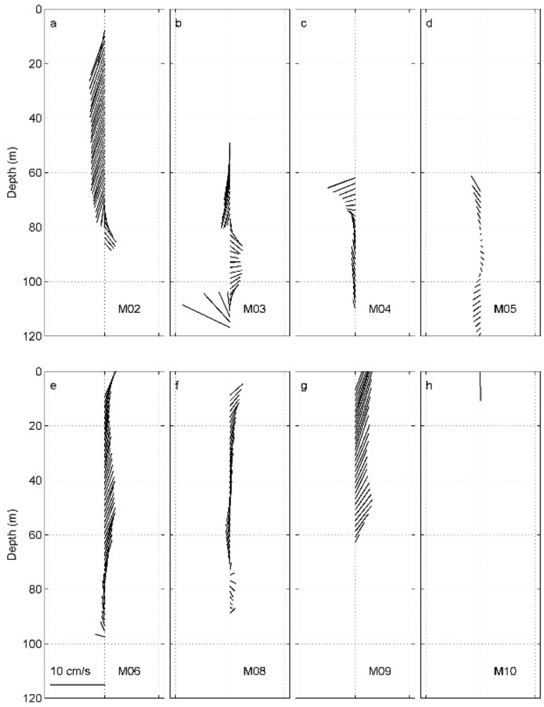

Figure 2. Mean profiles of current velocity from June to September 2022.

Southwesterly winds stimulated the basin-scale cyclonic gyre in the upper layer: strong northward current occurred near the eastern and southward current near the western end of the section. The flow to the north was halted or even reversed in the deep layer during southwesterly winds prevailing.

The time series of the upper layer currents in the eastern and western edge of the section were quite often negatively correlated, but not always. Thus, hinting at the complexity of the current field due to mesoscale and other activity.

Northerly zonal component was more frequent in the time series of the deep layer. Only one remarkable reversal event of the prevailing northerly current in the deep layer in the Farö sill caused by the southwesterly wind impulse was observed from April to September. Otherwise, northward flow prevailed during the period, which is well aligned with the suggestion of the existence of quasi-permanent flow towards a northerly direction there (Liblik et al. 2022). More reversals occurred in winter, which is likely related to the more frequent southwesterly winds in that season and potentially also to the absence of the seasonal thermocline. Flow reversals were strongly accompanied by the drops in salinity and temperature in the deep layer. The glider data showed that isotherms and isohalines were lowered up to 25-30 m at the sill during reversals.

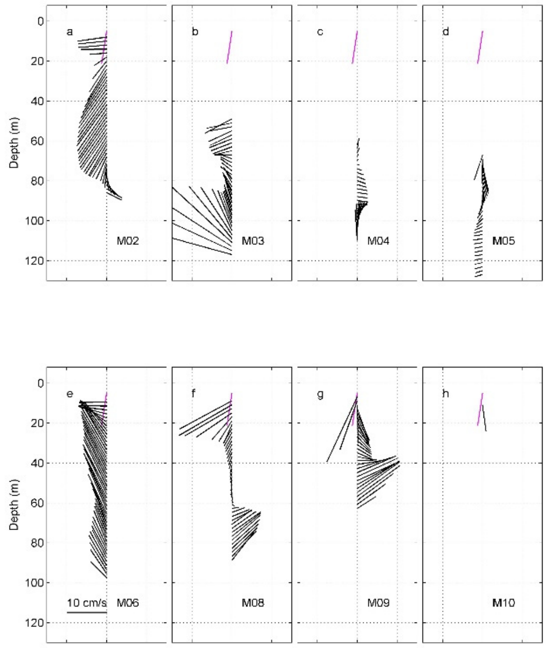

Figure 3. Mean profiles of current velocity from 29 August to 4 September 2022. The mean wind velocity vector, but in m/s, during the same period, is shown as a pink line.

4. Acknowledgments

We thank our colleagues and crews of research vessels who assisted with operations at sea. This work was supported by the Estonian Research Council (grant no. PRG602). Ship time was provided by Eurofleets+. Some infrastructure assets used in the current study are part of the JERICO infrastructure supported by the JERICO-S3 project under the European Union's Horizon 2020 research and innovation program with grant no. 871153. The mooring operations M2-M4 and the contribution of IOW is funded in frame of the IOW Baltic Long-Term Observation Program.

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Energy Fluxes and Vertical Heat Transfer in the Southern Baltic Sea

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Abstract

This research explores the dynamics of thermal energy exchange in the Southern Baltic Sea, underlining the dicothermal layer's significant influence on thermocline penetration and thermal energy propagation. A notable finding is the time lag between solar energy absorption peaks and the Vertical Integral of Total Energy (VITE), further extended before reaching peak Sea Surface Temperature (SST). This delay highlights the intricate process of energy redistribution and the water's high heat capacity.

The study uncovers considerable spatial variability in VITE across the region, affected by latitude, upwelling events, coastal topography, halocline level, and advection processes. These factors critically influence the thickness of the dicothermal layer and the seasonal thermal signal's propagation.

Moreover, the Southern Baltic is identified as a net energy sink, with a mean energy budget of 5.48 W m^{-2}, contributing significantly to oceanic heat storage and potentially impacting larger-scale climate processes. The research also notes distinct differences in the rate of maximum temperature propagation across different basins, highlighting the local basin characteristics' influence on the area's thermal structure.

1. Introduction

The Baltic Sea's heat transfer mechanisms are essential for its ecosystem's health. Restricted by its semi-enclosed nature, the sea's thermal environment is isolated, making understanding heat transfer processes crucial for addressing climate change impacts. This research examines factors like maximum short-wave energy, surface heat flux and further transport of heat into the deeper layers of the Baltic.

2. Data Collection

Data were collected from various sources, including 93 R/V Oceania monitoring cruises using a towed CTD technique, Argo floats from the Argo-Poland project, and reanalysis data from ERA5 and NEMOv4.0.

3. Results and conclusions

This research highlights how heat moves and changes in the Southern Baltic Sea, showing important effects on our understanding of ocean heat flow and climate changes. The main findings are:

The Southern Baltic Sea absorbs an average of 5.48 W m^{-2}, acting as a major heat collector that stores energy.

Mostly, the sea takes in heat during daylight hours from 8 AM to 4 PM. However, from September to February, it releases more heat than it captures.

There's a delay of 59 days between the highest solar energy received and the VITE, plus another 6 days before the highest sea surface temperature is reached (Figure 1).

The VITE varies greatly across different areas, influenced by geographic location, water movements like upwelling and downwelling, and water from rivers.

A layer called the dicothermal layer controls how deep the heat goes into the sea and how fast it moves, causing a delay in temperature change by 15 days for every 10 meters of depth, which increases to 35 days further north and central in the Baltic.

The way heat is transferred in the Southern Baltic depends on the depth of the thermocline and halocline, with water movements affecting the mixed upper layer and the dicothermal layer. Below the halocline, the pattern of seasonal temperature changes varies by location, being strong in the Bornholm Basin, moderate in the Slupsk Furrow, and missing in the Gdansk Deep.

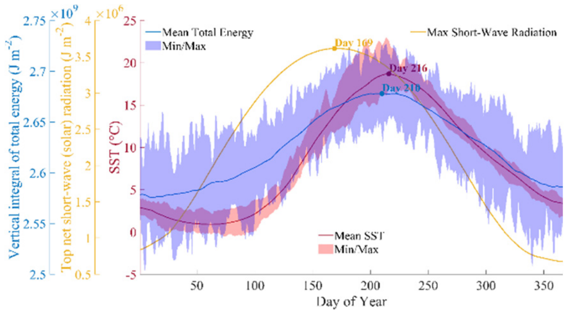

Figure 1. Annual variations of Vertical Integral of Total Energy, Top Net Short-Wave Radiation, and Sea Surface Temperature in the Southern Baltic Sea, based on data ERA-5 from 1987 to 2023

Funding and References

The research is supported by projects like Argo-Poland, CSI-POM, and SufMix.

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On the coastal-offshore exchange in the Baltic Sea: a high-resolution modelling study

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1. Introduction

The objective of this study is to analyze the coastal-offshore processes in the central Baltic Sea using numerical modelling and additional idealistic Eulerian tracers to track the freshwater and the seawater age.

2. Materials and Methods

A three-dimensional, primitive equation model GETM (General Estuarine Transport Model; Burchard & Bolding, 2002) has been applied to simulate the circulation and density field in the Baltic Sea with two different spatial resolutions. The high-resolution setup of the model has a submesoscale permitting horizontal grid spacing of 250 m and 60 vertically adaptive layers (e.g. Gräwe et al, 2015) covering the Baltic proper, Kattegat, Gulf of Finland and Gulf of Riga (Fig. 1), while the low-resolution model is eddy-permitting with a grid spacing of 1 nautical mile only. The latter covers the entire Baltic Sea. Results from the low-resolution model have been used as boundary conditions for the high-resolution model.
Both setups are driven by atmospheric forcing fields from the UERRA dataset for 2010-2018 and river runoff prepared for the BMIP project (Gröger et al, 2022). Two additional prognostic tracers have been added to the models – one prescribing the freshwater concentration and other describing the age of the freshwater.
More details about the high- und low-resolution model setups can be found in Väli et al (2024) and Radtke et al (2020), respectively.

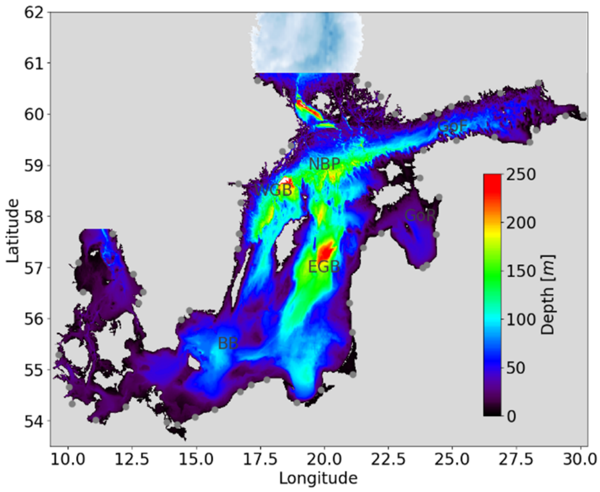

Figure 1. The bathymetry and the model domain (coloured area) for the high-resolution simulation of the central Baltic Sea. The locations of the river mouths are shown with grey dots.

3. Results

The temporally averaged riverine origin tracer concentrations from low- and high-resolution simulations are shown in Figure 2. The highest concentrations are found in the eastern part of the Gulf of Finland and the semi-enclosed Gulf of Riga because of the influence of the large rivers Neva and Daugava.

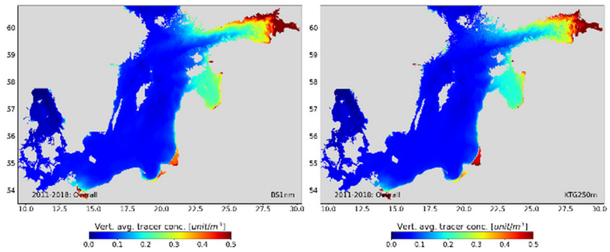

Figure 2. 8-year mean vertically averaged riverine tracer concentration from low- (left) and high-(right) resolution simulations.

The riverine origin tracer concentration time-depth maps at 3 different monitoring stations (BY5, BY15 and BY31) are shown in Figure 3. The tracer concentrations in the surface layers are highest in BY15 and BY31. The distinctive barrier between the surface and deep layers is the halocline as the concentrations below the 60-70 meters are increasing significantly slower compared to the surface layers.

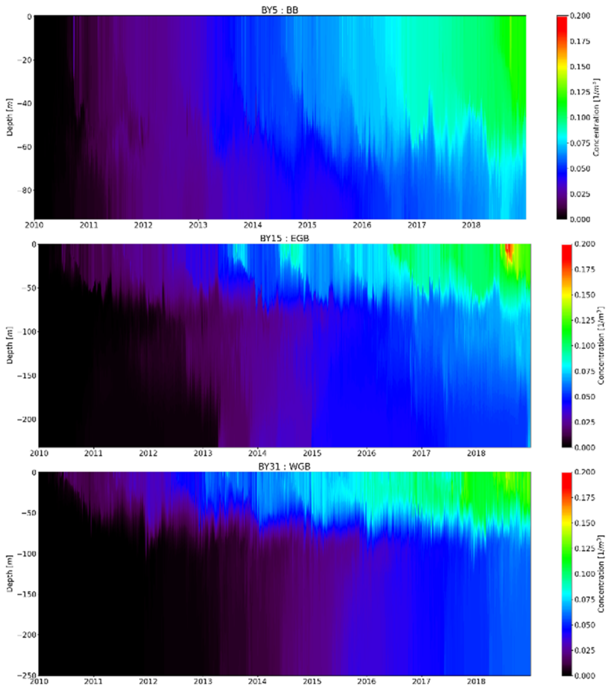

Figure 3. Time-depth distribution of riverine tracer in BY5, BY15 and BY31 from high-resolution simulations.

The temporally averaged ages from low- and high-resolution simulation are shown in Figure 4. As the freshwater tracer concentration, the general patterns are similar in both simulations. The water age is much smaller in the areas, where the riverine tracer concentrations are higher. The age is large in deep areas, where the amount of riverine origin water is small.

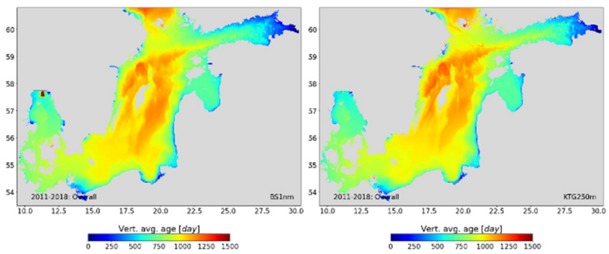

Figure 4. 8-year mean vertically averaged ages of freshwater tracer concentrations from low- and high-resolution simulations.

The water age time-depth maps at 3 different monitoring stations are shown in Figure 5. Similarly with the riverine origin tracer, the halocline is a visible separatore between the surface and bottom layers – the water age below 60-70 m at BY15 and 90-100 m at BY31 is increasing faster compared to the waters above these depths. At BY5 the water age is increasing slightly slower, whereas the highest values are somewhere between 40-60 m depth.

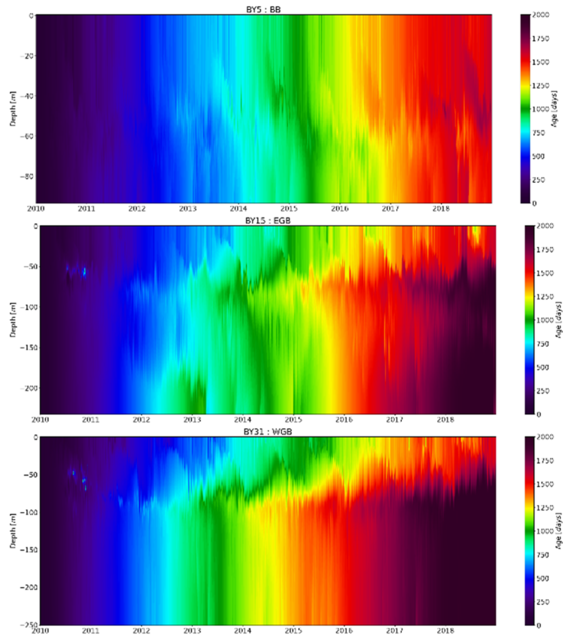

Figure 5. Time-depth distribution of riverine tracer in BY5, BY15 and BY31 from high-resolution simulations.

4. Summary and conclusions

Multi-year high-resolution simulation permitting submesoscale with additional tracers for riverine freshwater and its age has been carried out for the central part of the Baltic Sea. The increase in the resolution enables us to study the impact of the model resolution in coastal-offshore processes in more detail compared to previous studies.

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Deep mixing observed by Argo floats in the Gdansk Basin during the winter of 2023.

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1. Introduction

Vertical mixing is an extremely important process for the Baltic Sea. Inflows of salty, oxygenated water from the North Sea propagate along the bottom, leading to the formation of a strong halocline and the associated pycnocline between the near-bottom layer with a salinity of several PSU and the freshened surface layer. The salinity of the Baltic Sea's surface layer is maintained through vertical salt exchange by the halocline. The vertical salt transport into the entire surface mixed layer is estimated to be around 30 kg/(m² a), as noted by Reissmann et al. (2009).

Mixing processes occur throughout the advection of salty water from west to east and further north. According to Reissmann et al. (2009), in the initial phase, to the west of Bornholm, entrainment processes predominate. In the central Baltic, the advection of bottom water is accompanied by turbulent vertical transport through the halocline into the surface layers. The energy required for mixing is derived from both water movement and wind. In a tideless sea environment, the breaking of internal waves is a significant mechanism for transferring wind energy into the deeper layers. Upwelling, often observed in the Baltic Sea, plays a crucial role in the coastal zone. Phenomena occurring on a smaller temporal and spatial scale are much less studied.

2. Observations

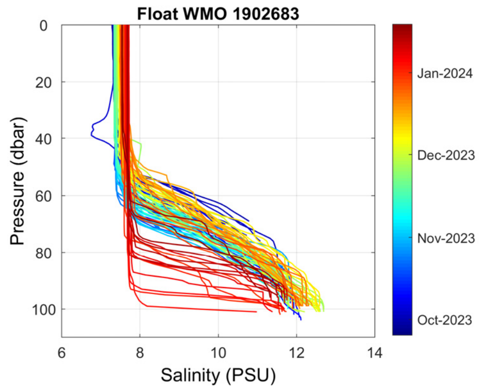
The Institute of Oceanology Polish Academy of Sciences investigates processes related to the transport and mixing of deep waters in the Bornholm Basin, the Slupsk Channel, and the Gdansk Deep. Since the deployment of Argo floats in the Southern Baltic, we have obtained a new tool (Walczowski et al., 2020). The application of the 'parking on the bottom' technique has reduced the mobility of the floats, allowing for the acquisition of long time series data from limited area with profiling frequency every 1-2 days (Merchel et al., 2024).

In late 2023, we succeeded in observing the phenomenon of almost complete mixing of the water column in the Gdansk Deep. Over the last days of 2023, there was a rapid change in the water column structure. The original haline structure consisted of a mixed surface layer with a salinity of 7.6 PSU, a halocline at a depth of 60-90 m, and a thin near-bottom layer with a salinity of up to 12.0 PSU (Fig. 1a). According to Bulczak et al. (2024), a halocline beginning at a depth of 60 m is typical for the winter period in the Gdansk Basin. On December 24th, the peak of the halocline lowered to a depth of 75 m, and by December 30th, it reached 98 m, 3 m above the seabed. The nearly homogeneous layer above the halocline reached a salinity of 7.7 PSU, while the bottom salinity dropped to 11 PSU. The evolution of the temperature field was also interesting: from the original structure with a thermocline at a depth of 50-60 m, the temperature of the upper layer about 6.3°C, and a temperature inversion up to 8.7°C at a depth of 100 m, it transformed into a homogeneous, 93-meter column with a temperature of 6°C and a temperature inversion of 8.4°C at the bottom (Fig. 1b). The dissolved oxygen content in the deep water also increased abruptly (Fig. 2a). Up to a depth of 93 m, the dissolved oxygen content in the water was 365 micromoles/kg.

After two weeks, the halocline rose to a depth of 60 m, and the dissolved oxygen content in the water returned to a value of 25 micromoles/kg at a depth of 95 meters.

This phenomenon was recorded by two Argo floats launched by the Argo-Poland consortium. WMO 1902683 is the first Polish biogeochemical float (BGC) with an additional set of sensors. The presence of two floats allows for determining the minimum spatial scale of this deep ventilation event. The sequence of events observed on the second Argo float, located 20 km southeast of the first one, was similar to BGC float. The culmination of mixing occurred on December 30th, with the halocline top at a depth of 90 m. The water column was not entirely homogeneous, showing a slight jump in salinity and temperature at a depth of 67 m.

(a)



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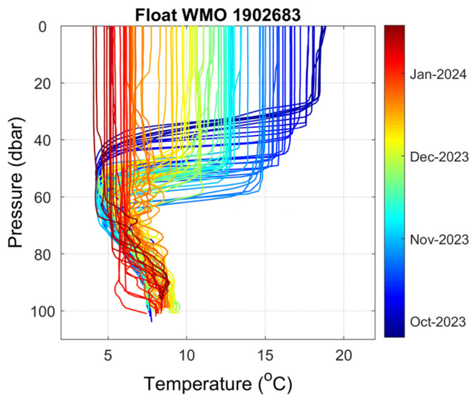
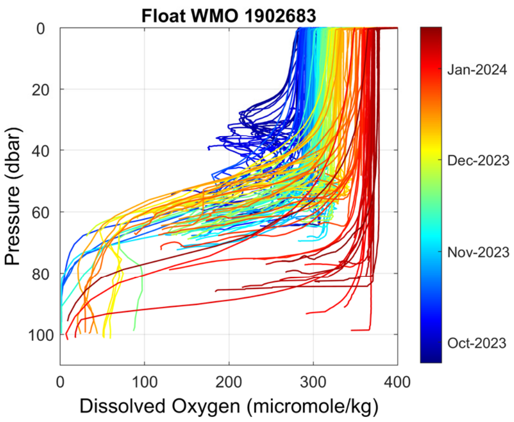


Figure 1. Series of (a) salinity and (b) temperature profiles collected by float WMO1902683 in the Gdansk Deep.

(a)



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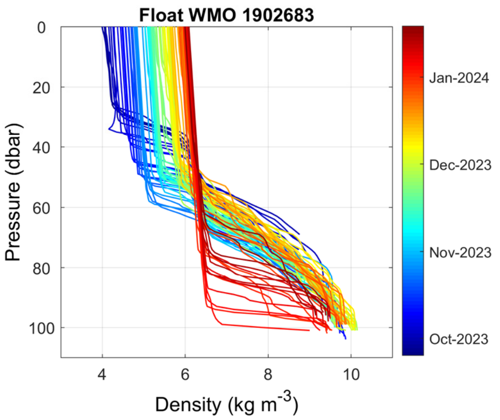

Figure 2. Series of (a) dissolved oxygen content and (b) density profiles collected by float WMO1902683 in the Gdansk Deep.

3. Discussion

At this stage of the study, it is challenging to definitively answer the question of what mechanisms caused such deep mixing. Thermal convection is ruled out, as the water density was significantly lower than that previously resting in the bottom layer (Figure 2b), with a temperature reaching 6°C. Most likely is, that the energy required for such deep mixing was supplied by the stormy winds prevailing during this period. However, wind-induced mixing extends to depths of several tens of meters, insufficient to mix the entire water column in the Gdansk Deep. There likely occurred an interaction of different phenomena. At that time, a very strong current was observed along the Hel Peninsula. This phenomenon is often associated with the generation of eddies that propagate towards the central part of the Gdansk Deep. A cyclonic eddy or another surface currents configuration conducive to the convergence of the surface layer may have triggered Ekman pumping phenomena, pushing surface water to greater depths.

Assuming that the increase in salinity in the mixed layer resulted from the transport of salt through the halocline, the total transport over 8 days had to exceed 9 kg/m^2. The instantaneous salt flux could therefore be 14 times greater than the average salt flux through the halocline (30 kg/m^2 a).

However, adopting a different approximation: the freshening of the bottom layer with a thickness of 35 m from an average salinity of 9.8 PSU to 7.7 PSU, these fluxes increase significantly. Over 8 days, the salt transport to the upper layer should be 73.5 kg/m^2, which is more than twice the estimated average annual salt transport through the halocline. The instantaneous salt flux during this phenomenon: 3354 kg/m^2 a, is 111 times greater than the estimated average annual flux to surface layer of the Baltic Sea. These are already significant values, indicating that the Gdansk Deep is one of the vertical mixing "hotspots" in the Baltic Sea.

The deep, rich in oxygen layer, persisted for several days. After two weeks, the fresh, oxygenated water was replaced by oxygen-depleted during the stagnation period, saline bottom water. Therefore, it does not seem that the observed phenomenon has substantial implications for the ecology of this part of the Baltic Sea. However, it may be significant for mixing processes and the supply of salt to the upper layers, which are freshened by the waters of the Vistula River.

4. Conclusions

Mesoscale and submesoscale phenomena play an important, yet not entirely recognized role in shaping the environment of marginal seas. However, their observation is challenging as they not only exhibit small spatial scales but also are short-lived. Regular measurements with high frequency are therefore necessary. Additionally, such processes often occur during stormy weather, making the use of research vessels difficult. In this situation, autonomous research devices prove to be very useful. Independent instruments placed on buoys, moorings with profiling instruments, and gliders have been used for a long time in the Baltic Sea. Experiences of Finnish and Polish oceanographers indicate that Argo floats, despite being designed for the deep ocean, perform exceptionally well in the conditions of the Baltic Sea.

Funding

This research was supported by the “Argo-Poland” project funded by the Polish Ministry of Education and Science [2022/WK/04], and “Turbulent mixing in the Slupsk Furrow (Southern Baltic)” funded by the National Science Centre (NCN) Poland [2019/33/B/ST10/02189]

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Continuous Baltic Sea Glider Observatories; two case studies

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1. Background

Voice of the Ocean Foundation acts to make the oceans more accessible to all sectors of society. Within the Ocean Knowledge division, we focus on the marine science community, testing new methodologies, providing high quality data, and supporting research projects with marine infrastructure and knowledge exchange. All the data is open access and uploaded to the VOTO ERDDAP server and mirrored to the EMODNet physics portal. Ocean Knowledge operates 5 different glider observatories with continuous measurements. The sites locations are planned in order to capture the small-scale variabilities in water basins with importance to the circulation of the Baltic Sea. The aim is to have a consistent fleet of gliders equipped with a standard setup of sensors. The observatories will deliver parameters such as salinity, temperature, oxygen, current and several biological parameters, depending on the site.

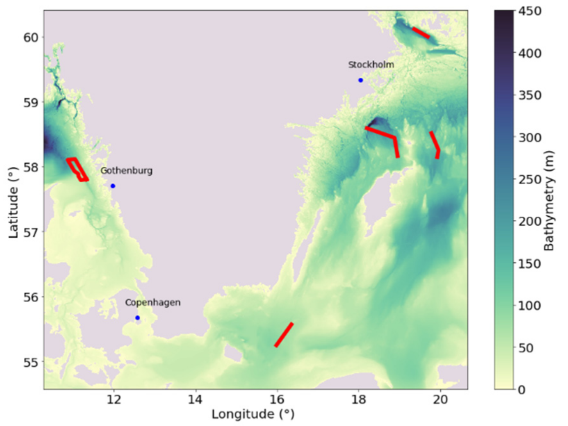

Figure 1. Positions of the VOTO glider observatories.

This poster takes a closer look at two sites of specific interest:

2. Åland Observatory

A first glider was deployed in the Åland Sea in November 2023, and this observatory is planned to be a long-term observation site. The high-resolution data provided gives us new information about the small-scale processes that is continuously ongoing.

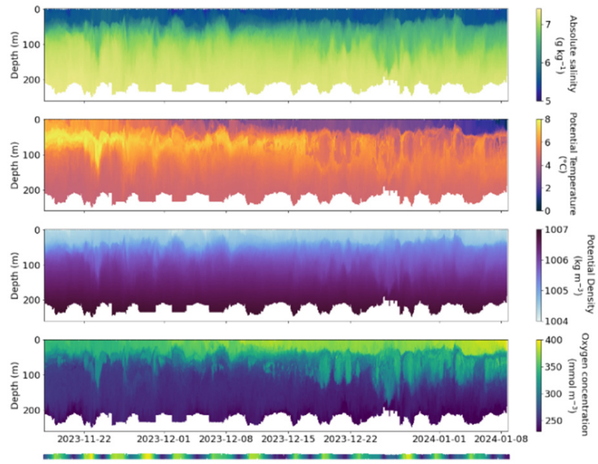

Figure 2. Åland Sea transect from November 2023 to January 2024. The bar on the bottom shows latitude in yellow as the glider goes north and in blue as it travels south.

3. Bornholm Observatory

The observatory in the Bornholm basin has delivered near real time data since March 2021 and has produced a unique time series. The observatory was strategically placed to be able to capture an inflow event from the North Sea through the Danish Straits and to monitor the extension of the anoxic areas in the southern parts of the Baltic Sea. Together with data from moored stations, Argo floats and monthly monitoring, the inflow can be well observed and captured.

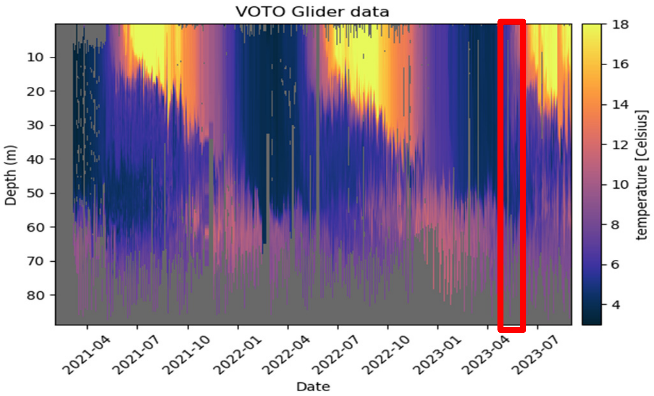

Figure 3. Data from the Bornholm Observatory from March 2021 to July 2023.

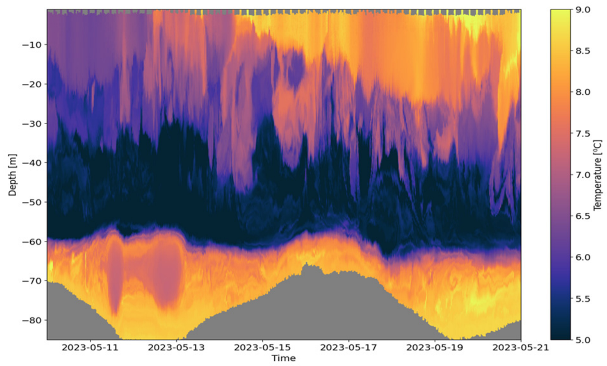

Figure 4. High light of a shorter period from the Bornholm observatory; May 11 -21 2023

Figure 3 shows a 2.5 - year continuous temperature data series from Bornholm Basin with typical warmer periods in the summer and periods of cold water in the wintertime. Figure 4 has zoomed in on 10 days in May 2023 where the variability of the temperature and how the warm water enters the deeper parts shows nicely.

4. Summary

Gliders can be used for long time monitoring of different water basins in the Baltic Sea. The high frequency profiles create a data set not only for monitoring purpose but also for research of fine scale variability of the water masses. We test the abilities of the glider platform, and work to understand their place within a future ocean monitoring infrastructure, since high resolution, profile measurements is a good combination with the long-term monitoring, done by several countries around the Baltic Sea

Session G

Comparing marginal seas worldwide

Comparing Baltic and North Sea coastline using remote sensing and machine learning

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1. Coastline change identification

Marginal Seas are lying at the transition zone between land and ocean and are thus subject to extensive human activities and stressor (pollution, land reclamation, tourism, shipping, fisheries, offshore wind farms) and multiple natural drivers (tides, waves, winds, storm surges, sea level change) which are impacting the marine environment and ecosystem. These drivers will feedback with geological properties of the coastline and thus determine its appearance which will be unique for all marginal seas. The coastline is highly dynamic and may react to regime shifts in climate or hydrodynamic conditions or changes in human activity by accretion or erosion of sediments, growth or decline of vegetation or composition change.

Acquiring data on coastline changes may serve as a proxy for regime shifts and may deepen the understanding of different drivers acting within marginal seas. Therefore, in this presentation we will present our analysis on the coastline change in the North- and the Baltic Sea using multispectral satellite images (sentinel-2). The general difference in coastal morphology between both Seas will be shown. For this purpose the coastline will be classified into different classes such as tidal flats, salt marshes, cliffs, sandy beaches, human constructions etc. Finally, hotspots of changes among those classes will be identified in the past 8 years (at a later stage up to the past 40 years).

For the classification of the coastline, deep learning methods are used. The main challenge is to create and label an encompassing dataset, covering a large variety of different coastline types in space and time. In order to reduce this effort we are developing an *active learning* framework to select the images which are suited for a fast learning progress. In combination with a semi-supervised method these images are labeled with minimum effort. This framework will be shortly presented alongside the coastline changes in North- and Baltic Sea.

Human use of ancient and now-submerged coasts in South Africa

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1. Introduction

Marginal seas and open oceans that border the world's coastlines fringe submerged continental shelves that have been drowned for at least 20,000 years, since the Last Glacial Maximum. These areas are repeatedly exposed and submerged in accordance with fluctuating sea levels. In certain areas these now under-water landscapes hosted rich ecosystems and attractive habitats for humans and can be associated with archaeological records where humans were present in the past.

Where geological deposits are preserved on these continental shelves, they can be mapped and sampled and form elegant, complementary, proxies for investigating the meaning of coastal archaeological records.

South Africa has a long record of human use of these ancient coasts, and here, we provide a comparison between two strongly contrasting areas that are more than 1000 km apart. These regions are the Cape South Coast in the vicinity of the archaeological site Pinnacle Point, and the East Coast / Mpondoland coast in the vicinity of the Waterfall Bluff rock shelter.

2. Methods

At both localities, high-resolution archaeological excavations have been undertaken. In parallel with analysing these fine-scale and site-specific records, landscape surveys have been conducted to contextualise the archaeological records. Landscape surveys have included studies on sources of raw materials, palaeoenvironmental reconstruction from sediment cores to compare to palaeobotanical remains from cave strata, and different levels of offshore surveys aimed at mapping the continental shelf.

Geochronological control has been established by radiocarbon and optically stimulated luminescence dating.

3. Cape South Coast

Pinnacle Point provides one of the oldest records (up to Marine Isotope Stage / MIS 6) of coastal foraging since the emergence of Homo sapiens. The offshore landscape has been called the Palaeo-Agulhas Plain.

Unlike the deeply dissected, undulating landscape of the modern-day coastal foreland, the Palaeo-Agulhas Plain on the Cape South Coast was relatively flat, with wide meandering rivers. Palaeocoastlines of this plain, dominated by beaches and aeolianite reefs, lacked the rocky cliff coasts typical of much of the area today and overlie Mesozoic sediments that are not commonly exposed onshore. This Cape South Coast shelf is broad and low-gradient in relief, and with the sea-level fluctuations experienced in the Pleistocene the coast was often positioned more than 100 km seaward of its present elevation.

Only a remnant of the marine sediments and alluvium that characterized the Palaeo-Agulhas Plain exist on the modern coast today, and the largely fertile soils of the now offshore shelf contrast with the impoverished soils of the contemporary coastal platform. The physiographic regime of the Palaeo-Agulhas Plain comprised ecosystems very different from the modern contemporary coastal lowlands, including vast areas of nutritious grassland and savanna, numerous wetlands, and a soft and highly dynamic coastline. This is because the geological substrate offshore differs markedly from now-onshore to now-offshore. The productivity of the terrestrial ecosystems supported a diverse and abundant plains fauna that included several megaherbivores not known from the region today. The emergent picture of this missing part of the landscape has provided a new window into the context of early modern human evolution as well as the evolution of the modern Cape Floristic Region.

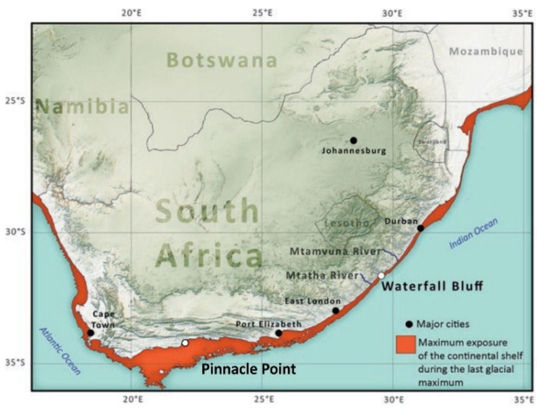

Figure 1. Locality map of South Africa showing the exposed shelf during the Last Glacial Maximum and other Pleistocene ice ages (in red) and the positions of Pinnacle Point and Waterfall Bluff, on the Cape South Coast and Mpondoland shelves, respectively.

4. East Coast

The Waterfall Bluff deposits preserve the first direct and clear evidence of coastal foraging (shellfish and estuarine fish) during a glacial maximum and across a glacial/interglacial transition in southern Africa. These records extend back to MIS 3.

Waterfall Bluff is situated adjacent to a continental shelf which is steep and narrow. During Pleistocene glacial maxima, the coast never shifted more than 8 km seaward of its present position. Preliminary seafloor mapping has revealed a similar geological record on the shelf to the modern coastal environment and we surmise that the submerged shelf's landscape likely represented a continuation of the presently exposed portion. This may be a function of its remarkably narrow width and a lack of accommodation space for Mesozoic sediments to accumulate.

Mpondoland's coastline therefore remained a stable and predictable point on the landscape over the last glacial/interglacial transition being well positioned for hunter-gatherers to access resources from the nearby coastline, narrow continental shelf, and inland areas.

5. Broader thoughts

If in one global region, strongly contrasting variability exists between two archaeological sites and these records can shed light on nuances of the past environments and ecosystems, then the potential for further studies of archaeological sites adjacent to marginal seas is an exciting prospect. Palaeo archives that are now submerged by the sea can provide a different perspective on traditionally-excavated caves and rock shelters containing traces of ancient human populations.

The South African continental shelf was never glaciated in the Pleistocene ice ages, and hence the geological deposits remnant of this time are generally well preserved. Erosion occurred on Pleistocene seafloor sedimentary deposits, but this was erosion by wave action associated with rising sea level on the post-glacial marine transgression. Because of this geological and environmental setting, South Africa has provided an opportunity to carry out palaeoscape-style projects.

Classification of the morphodynamics of the coast - a tool for comparison of the marginal seas

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1. Introduction

The shape of the marginal seas coast is an overlap result of complex of geological settings and processes affecting lithosphere, hydrosphere, atmosphere as well as biosphere and anthroposphere, which occur in various temporal and spatial scales from millennia to hours and in spatial scale from kilometers to centimeters (Musielak et al. 2017). The results of the interference is visible as a morphology pattern of beach and dune / cliff as well as a nearshore area.

Morphodynamic coastal processes of the southern Baltic Sea are determined by a complex interplay of the geological setting, eustatic sea-level change, glacio-isostatic adjustment, wave driven sediment dynamics, storm surges and aeolian processes (Harff et al. 2017, Dudzińska-Nowak 2019).

In terms of presently occurring climate changes, an increase of number and intensity of observed storm events, which pose a threat to the coast, the determination of the future scenario of coast development is of particular importance for broadly defined coastal safety (Dudzińska-Nowak 2019).

This study present the method of the classification of the morphodynamics of the coast which can be useful for prediction of the coastal changes as well as a tool for other marginal seas comparison.

2. Methods

To be a complex and allow the marginal seas comparison the scientific classification of the coast should meet the following conditions: (1) cover all morphological types of the coasts, (2) take into account the processes and factors determining the type of shore development, and reflect the relationships between different types of shore and (3) it should reflect the contemporary dynamics of the shore as fully as possible.

Use of remote sensing, mainly high resolution aerial photographs and laser scanning data, allow to indicate precisely the characteristic features of the morphology of the terrain, which if repeated, can be treated as indicators of the changes.

Presented research shows the methodology and results of conducted classification of the coastal dynamics of the southern Baltic Sea, focusing not only on direction of movement and rate of change but also on dynamic of change in different time scales. The main criterion for this classification is the determination of two numerical indicators for each examined section of the coast, synthesizing the image of registered changes in the dune / cliff base line.

3. Results and conclusions

The spatial distribution of individual classes of shore dynamics indicates a great diversity and variability of morphodynamic processes along the entire studied section and even on adjacent sections of the shore. Changes with medium and high dynamics of both accumulation and erosion processes dominate. The sections with low dynamics of the processes taking place constitute only less than 20% of the studied area. The coast in dynamic equilibrium cover less than 10%. Spatial distribution of individual classes of shore dynamics proves a large diversity and space and time variability of morphodynamic processes along the entire investigated section of the shore, which may substantially bias of the future scenarios.

Further interdisciplinary studies based of measured and modeled 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.

Presented classification can be treated as an open classification which makes it possible to complete the picture of the contemporary dynamics of the coast of any non-tidal marginal seas and any time intervals.

The location of specific dynamic shore classes may change over time depending on the variability of hydro-meteorological conditions.

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Long term monitoring of the coastline changes, for future use in modeling (example from Southern Baltic Sea, Poland)

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1. Introduction

The character of the Baltic Sea, a post glacial marginal sea with a small inlet to the Atlantic Ocean, its lack of tides, the varied composition of cliffs, dunes, spits, and barriers and lagoons, and addition of many anthropogenic engineering structures, makes an interesting model research site.

Morphogenetic processes of this coasts are determined by a complex interplay of the geological setting, eustatic sea-level change, glacio-isostatic adjustment as well as wind, waves, sediment dynamics, storm surges and eaolian processes, acting on different time scales (Musielak et al. 2017, Harff et al. 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, Viska 2013). The most important erosional coastline changes occur during extreme conditions (Furmanczyk, 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, which allow to accurate future scenario which is of particular importance for broadly defined coastal safety (Dudzińska-Nowak 2019).

This study aimed to determine the relation between the geological and geomorphological settings and their influence on coastal morphodynamics and future development of the coast.

2. Materials and methods

An analysis and comparison of selected sites along the west Pomeranian Polish coast of the Baltic Sea, based mainly on photogrammetrically processed remote sensing datasets, historical and modern aerial photographs and sea level data allows for long term morphological changes to be determined.

Additionally, geological maps and cores as well as the samples of in situ organic materials, particularly tree trunks and peat, makes possible the calculation of C14 dates and RSL curves were used for palegeographical reconstruction as well as to determine the relation between the geological and geomorphological settings and their influence on coastal morphodynamics using GIS spatial analysis.

Here, we inquire what lithologies and geological structures between the investigated sites are most resistant to erosion, and or support the acceleration of erosion or accretion. Obtained results will be discussed in relation to sea level changes, geological setting and coastal development tendencies for more reliable future projections necessary for coastal protection and safety.

The method used, allows to discuss the geographical regionalization based on geological settings and dynamic driving forces, which is very important in case of comparison results with other marginal seas.

3. Results and conclusions

Conducted analyses show the considerable temporal and spatial variability as well as high dynamics of the coastal changes taking place in neighboring, geomorphologically and geologically uniform coastal segments which are similar also in terms of evolutionary trends.

This suggests the necessity of selecting representative sites used to forecast the magnitude of coastal changes. The selection of time periods for analysis is of the same importance as site location. This is confirmed by the high variability of morphodynamic effects in the periods analyzed.

An accidental location and too short a period of observations, not accounting for the geological settings as well as hydrometeorological variability, may substantially bias the forecast. This bias may pose a threat for the planned infrastructure at such sites.

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The Ganges-Brahmaputra-Meghna delta systematics

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The arcuate Ganges-Brahmaputra-Meghna (GBM) river delta is represented by an extensive tract of subaerial and subaqueous to deep sea fan complex located at the northern apex of Bay of Bengal. It harbors a low-lying flood plain covering ~ 100,000 sq. km of which 62% area falls within Bangladesh and 38% in India.

The delta experiences tropical monsoonal climate and this coupled with Himalayan source area sediment flux, contributes to one of the world's largest tropical riverine sediment loads (1.8–2.4 billion tons annually) passing through the GBM dispersal system [Rahman et al. (2018)]. The total catchment area of these river systems is 1.55 million sq. km. The rivers are dominantly tidal with maximum tidal range up to 6.7 meter. Based on the relative importance of river, wave, and tidal process in shaping their morphology and internal facies, GBM delta undoubtedly represents a tide dominated, macrotidal delta [Goodbred and Saito (2012)].

The delta outbuilding of GBM was initiated between Cretaceous to Neogene period. The deltaic arcs or lobes are reported to have been developed about 50,000 YBP with south and eastward progradation. However, the present location of the mega delta was attained not more than 10,000 years back (Pleistocene to Recent). The geological formation covering the island system belongs to the so called 'Bengal Alluvium' [Hazra et al. (2002)].

While the subaerial part of the delta is strongly influenced by tectonics, resulting into development of uplifted Holocene and Pleistocene terraces, subsiding basins etc. the subaerial delta has been prograding seaward with 'S' shaped clinoform across the shelf. Offshore delta is intercepted by "Swatch of No Ground"- a submarine canyon that regulates sediment distribution from east to west. Changing river discharge, basin filling, and delta-lobe migration have been common during Holocene evolution of the delta [(Kuehl et al. (2005)].

Since, past few centuries, this composite macrotidal deltaic tract (~ 260 kms from Hooghly River in the west to Meghna river in the east) generally showed a continuous trend of shoreline retreat, although rate of retreat varies from one sector to other.

The northern part of the delta is facing drainage failure resulting into, rapid siltation in the delta plains. For example, the upper reaches of Saptamukhi River got disconnected from the Adi Ganga, the original thalweg of Ganges River in this part of the delta [Kumar et al. (2010)]. Except the major rivers, the smaller rivers/creeks in the delta had changed their nature from fresh water to saline due to tidal surge in the river mouths and siltation in the upper reaches, thus restricting the river within the tidal domain only. These had resulted in changes in riverbank morphology, agricultural crop pattern and aquaculture activities of the surrounding areas thus imposing further difficulties in the livelihood of the local inhabitants. The mitigation of such issues is a cause of major concern to all the geoscientists engaged in coastal zone management in the area. A ready reckoner is pattern of changes in river morphology, water quality of Saptamukhi creek, one of the river of Sundarbans Delta System.

This densely populated deltaic plain (with over 100 million inhabitants) is proven to be vulnerable in view of climate change and being exposed to multi- hazardous events like relative sea level rise/sea level rise, tropical cyclones, coastal floods, erosion, landward prograding salinity front etc. Thus, an in depth understanding of the geological-geomorphological, hydro-meteorological, coastal and shelf processes including sea level rise in the changing backdrop of anthropogenic practices (land reclamation, deforestation, irrigation etc.), is of paramount importance to deduce the future course of evolution of GBM delta. The offsetting of the geomorphic equilibrium in this delta system is attributed to a large extent to the increasing human-environment interaction. An evolved conceptual framework in this regard is proposed.

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E^6 – A Short-Hand Expression for Six Key Elements to Characterize Urban Sea Systems

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Many marginal seas lie within an Urban Sea System. We define an Urban Sea System as interactive networks of all activities, natural and human-generated, operating within entire watersheds flowing into proximal coastal waters harboring one, or more, major port cities. Natural and man-made hazards, in combination with long-term human-induced alterations, can plague urban seas. These and other threats must be comprehensively understood if the **economy**, the **energy** potential, the physical **environment**, **ecology**, **education,** and cultural **empathy** (**E^6**) of these regions are to be optimized, improved, and sustained. We use **E^6** as a short-hand expression of the six key elements that must be balanced to foster enduring, responsive stewardship of these critical coastal enclaves that so powerfully serve our international trade supply chains. To explore approaches and guide further discussion, we focus herein on the Salish Sea, located on the west coast of the North American Continent and extending into both the Canadian province of British Columbia and the state of Washington, in the US. It is a useful exemplar for illustrative purposes of an Urban Sea System. Although each Urban Sea System is unique, and while **E^6** for the Salish differs from other marginal urban seas, characterizing and contrasting these six elements among the many such systems can lead to enhanced insight and more broadly focused ocean-land problem solving. It can also provide key frameworks relevant to the analysis of other urban sea systems.

Understanding change is dependent upon the knowledge of the altering processes that bring about change. Urban Sea Systems are point sources that introduce toxins, waste, and other materials into the global ocean. Consequently, without a focus on the roles that such systems play in the production of conditions leading to an uncomfortable and inhospitable planet for human occupation, little or nothing will change. Quantifying contributions that Urban Sea Systems make to the decline of the global ocean need to be undertaken to assess what might be optimal solutions and mitigation for change. We start with appraisals of change brought about by energy resources, food, and economic sustainability, security declines, and adverse effects from natural and anthropogenic impacts. Of immediate concern is the identification and development of the **energy** that will be needed to maintain a healthy **economy** along with the ability of an Urban Sea System to sustain itself as a significant global trade hub. We focus on these two potentials for the Salish Sea here.

Marginal Seas – Diversity and Comparison

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1. Why generalization?

As highly sensitive areas of the ocean, the marginal seas are particularly exposed to the effects of climate change, but also to anthropogenic pressure due to the increasing economic use of the seas and their coasts and catchment areas. This makes it all the more important to protect these fragile ecosystems and habitats while ensuring the sustainable use of valuable marine resources. These are the goals that are generally integrated into the UN program "Decade of Marine Sciences for Sustainable Development" (2021 – 2030). The goals require new holistic approaches comprehensively describing management strategies of marginal seas including coasts and catchment areas. This is not about individual solutions, but rather about approaches to solutions that can be derived from a generalization of individual cases' diversity. One way to achieve this is to classify individual cases by a marginal seas taxonomy to be developed. This has to consider not only the differentiation through natural parameters and influences, but also the increasing interaction with users of resources and anthropogenic drivers.

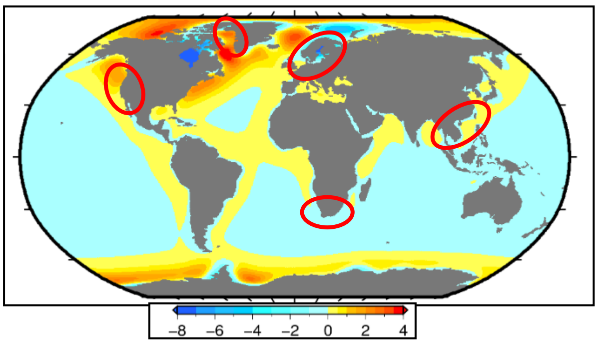

Figure 1. Global relative sea level change (mm/a). Marginal seas compared from west to east: Salish Sea, Western Greenland shelf, Baltic Sea, South African shelf (Agulhas Bank), South China Sea (modified from Groh and Harff, 2023)

2. Spatial – temporal frame, variables and data

The spatial framework is set by the shelf seas, their coastal zones and drainage areas. The time frame is determined by the last glacial cycle, but especially the postglacial period of global transgression on the continental shelf. Influencing factors are determined by the dynamics of climate, geosystem and ecosystem as well as increasingly by socio-economic developments. On the one hand, the question of variables and their values (data) is historically determined by developments in measurement and monitoring techniques and ranges from local and regional monitoring programs (sometimes real-time data registrations) to global satellite observations. On the other hand, for the long-term development (trends) of the human-nature relationship over thousands of years, data are need that cannot be directly measured. This data can only be provided indirectly by deciphering proxy data from natural archives of basin fill sediments. In addition to numerical functional models, AI and ML methods are available for the complex evaluation and interpretation of this data. The mentioned tasks require direct collaboration between natural, human and social scientists, modelers and IT/data scientists.

3. Examples

The concept is illustrated by comparisons of the glacio-isostatically controlled Baltic Sea and the West Greenland shelf with the isostatically stable South African shelf (Agulhas Bank), South Asian marginal seas controlled by monsoons and the geohazard threatened Salish Sea at the north-western American coast (Figure 1). Using the example of the Baltic Sea, a generally applicable correlation methodology is proposed that illustrates the connections between various driving natural and anthropogenic forces as a base to compare marginal seas.

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Disko Bay – a uniquely complex environment in the West Greenland shelf area

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Disko Bay is the largest bay along the coasts of Werst Greenland. It is characterized by complex geology, topography, hydrography, and rich marine biodiversity including rare observations of Vulnerable Marine Ecosystem species. The freshwater runoff from melting glaciers and icebergs during summer further contributes to the hydrographic complexity and diverse Arctic marine ecosystem.

Disko Bay is considered a biodiversity hotspot, identified as the Ecologically and Biologically Significant Area by the International Union for Conservation of Nature. Besides that, it is a highly economically relevant area with commercial shrimp fishery affecting the integrity of seafloor, and marine traffic.

A better understanding of Disko Bay environment can help the classification system of the subpolar marginal seas. Our presentation will focus on the climate, geological setting with benthic habitats and natural hazards, and a brief note on the (glacio-) morphodynamics of Disko Bay to support the systematic search for tools to protect the Arctic marine environment.

Coastal processes and erosion with and without swell waves and tides in marginal seas

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1. Introduction

Drivers of coastal erosion and the morphological outcomes vary by environment. In this paper the processes that result in erosion on the sedimentary shorelines of three marginal seas are compared. While many of the concepts apply to all coastal sedimentary environments that are impacted by wind generated waves (by definition, beaches), particular emphasis is given to the North Sea, the South China Sea (north-western continental margin) and the Baltic Sea, marginal seas (Zhou, 2016) that are the subject of investigation by the DDE Marginal Seas Task Group (https://marginalseas.ddeworld.org/) (Figure 1).

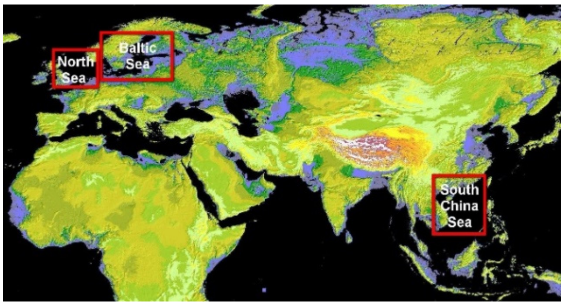

Figure 1. Baltic Sea, North Sea and South China Sea

2. Coastal processes

Two of the main drivers of coastal processes are waves and tides. Tidal range is the most significant tidal parameter, with a common classification being micro- (<2 m), meso- (2-4 m) and macro- (>4 m) tidal range. Wave height is often regarded as the most important wave parameter, but with respect to the active wave zone at the coast, landward of closure depth, wave period is in many respects the most influential parameter. This is because wave period determines how deep intense wave-induced water motions penetrate in the water column, where waves start to interact with the seabed, where sediment transport is initiated, where wave breaking occurs, and the refraction properties that govern the angle of wave approach to the shore. Due to the extent of wave refraction as a wave gets into intermediate and shallow water depths before breaking, it is the most important determinant of sediment transport direction and quantity. Simple application of the so called 'wave limiting parameter' at break point, $H/h = 0.78$ (Munk, 1949) (in reality normally in the range 0.6–1.6 depending primarily on beach slope), where H is wave height and h is water depth, means that wave height is limited by water depth, so that even very big waves in deep water, are limited in height when they approach the shoreline. The same is not true for wave period, which remains constant throughout the shoaling process.

Water depth is therefore an important parameter, both before and after wave break. It is obvious that the most severe coastal erosion occurs during storm events, but 'big waves' cannot be the primary cause. There must be drivers, the effects of which are weighted towards the shoreline, where we see erosion taking place (Holman, 1983). Such drivers are tides, storm surge (pressure setup and wind setup), infragravity and edge waves, wave setup and wave runup.

Wind waves are usually considered in two groups. 'Swell' is the term generally given to waves that have left the area in which they were generated, with wave period lengthening over time due to wave-wave interactions, and with longer waves leading due to dispersion. 'Sea' is the term used for waves still being formed by the wind blowing across the water surface, with wave periods being affected by fetch length, and wind intensity and duration. Both swell and sea may exist at the same time (with different directions). There are various methods for separating sea and swell (e.g. Portilla *et al.*, 2009) in a wave record, but a typically used value is around 8 s. For most purposes, however, this classification is not needed.

3. Coastal erosion

Coastal erosion is the landward translation of the active beach profile. It is not movement within the beach profile as is often misinterpreted. Erosion is the result of a deficit in the sediment budget, either in the long term (which leads to systematic erosion), or short term during an extreme event, where there is insufficient sediment in the active beach and dissipation of energy requires 'reserves' from the sediment store. Such erosion events may be unexpected or unusual.

Where tidal range is not negligible, the length of time that very high water levels can exist is limited. It is certain that the water level (and therefore the height to which waves will reach on the upper beach) will drop after a certain time. Attack by waves, and therefore erosion, at the upper beach will be limited to a few hours, even when other drivers are still causing elevated water levels. In cases of very small tidal range, extreme water levels may be maintained for much longer, determined only by the progress of the storm event, and erosion can occur for the duration of storm conditions. The magnitude of the elevated water level is important in all cases.

When the wave energy spectrum is dominated by long period waves, erosion is likely to be independent of the direction from which the waves are coming, because wave refraction will cause waves reaching the middle to upper beach to arrive almost shore normal. Where shorter period waves dominate, wave refraction is delayed leading to higher angles at the shoreline and therefore high alongshore sediment transport. On a shoreline that has complex morphology, refraction may cause long wave energy to penetrate apparently protected locations, whereas on shores with short period waves, such beaches remain relatively unaffected.

4. Marginal Seas

Classifications of marginal seas can be made based on tidal range and characteristic wave periods. With three interacting amphidromic nodes, the tides of the North Sea are complex. With the exception of the western coast of Denmark (typical tidal ranges <1.2 m) and the (non-sedimentary) southern coast of Norway, the North Sea coasts are meso- to macrotidal. With a complex interaction of amphidromic nodes, the South China Sea is mainly micro- and mesotidal, but with areas in the north around Taiwan, and the south (Mekong Delta) having macrotidal range. Almost all of the area experiences some tidal variation. For the most part, the Baltic Sea is effectively tideless, with ranges in the order of 2–5 cm with slightly higher tides, 10-30 cm, in specific locations in the western sea area (Leppäranta and Myrberg, 2009).

Despite dominant winds being from the west and southwest, being open to the northwest, the North Sea is well known for its high (even extreme) and long period waves, which impact the coast. Both sea and swell are significant, but beaches are mostly adapted to the long-period swell. In the South China Sea, winds and sea are typically southwesterly in summer and northeasterly in winter. While swell waves occur in the South China Sea, dominant periods of sea waves are in the order of 5–7 s. However, the coastal effects are most significant during the passage of frequent typhoons. In the Baltic Sea, long-period swell waves are virtually non-existent, with wave periods typically less than 5 s. Periods greater than 8 s are rare.

5. Erosion drivers in different environments

The qualitative analysis in Table 1 does not consider erosion trends caused by long term changes to the sediment budget, or trends caused by long-term changes to climatic variables (particularly wind strength and direction). Such trends are important everywhere, but may be particularly significant in the Baltic Sea, where sea waves dominate.

The assessment in Table 1 is subjective and is meant to indicate the relative importance to coastal processes of the particular driver in that environment. Beaches in the North Sea and in parts of the South China Sea have high tidal ranges and are likely to be in equilibrium with frequently occurring high waves on spring tides. With characteristic long wave periods, the wave direction offshore is of little consequence.

An equivalent equilibrium condition for low and very low tidal range conditions is a frequently occurring (not tide driven) water level, with moderate waves from a common direction. In the Estonian part of the Baltic Sea, for example, water levels 0.5–0.7 m above MSL, with moderate (<1 m) waves from the NW or SW is a common condition that may be maintained for many days. Under such conditions, some locations may receive no wave energy at all, even though water levels are elevated. Higher elevated water levels (caused by basin-wide and sub-regional effects) combined with high winds from an unusual direction, however, may lead to extreme coastal change.

In the South China Sea, conditions are highly variable, with the passage of typhoons being of extreme significance. In such conditions, extreme storm surges combined with high waves that may be (relatively) short period can cause massive erosion (You, 2019). The recovery interval between events will determine the natural equilibrium condition.

Table 1: Qualitative assessment of erosion drivers. North Sea (NS), South China Sea NW margin (SCS), Baltic Sea (BS). Low (1), Medium (2), High (3) influence in that environment. Onshore/offshore (O), Mixed (M), Alongshore (A) sediment transport dominates.

Erosion Driver	NS	SCS	BS
Tidal range	3	2	-
Extreme water level	3	3	3
Storm surge	2	3	2
Infragravity and edge waves	3	1	?
Wave setup	3	2	2
Wave runup	3	2	1
Wave period	3	2	3
Wave direction	1	2	3
Shoreline shape and orientation	1	2	3
Other considerations			
Dominant sediment movements	O	M	A
Erosion in unexpected locations	1	2	3

6. Discussion and conclusions

Understanding the process drivers that maintain coastal equilibrium, and conversely those that cause significant or unexpected erosion, can assist in preparedness and response. Even though the extent of erosion may be greater in high tidal range and high energy environments (such as the North Sea), its unusual expression in a location that has never experienced it before can be a bigger coastal management problem. Such a situation in the Baltic Sea may be sustained high water levels accompanied by winds from an unusual direction.

When trying to understand marginal seas as a particular type of marine environment, a suitable classification of process drivers can assist interpretations of coastal change.

Acknowledgements

The research was co-supported by the Estonian Research Council (grant PRG1129) and the European Economic (EEA) Financial Mechanism 2014-2021 Baltic Research Programme (grant EMP480).

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Compound events triggering coastal flooding: Results from the WAKOS project

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1. Introduction

Risks emerging from the coincidence of multiple hazards have gained increasing attention in recent years for several reasons: First, a hazard can act as a trigger for another one or may change its probability of occurrence or its magnitude. Second, the co-occurrence of both hazards may have a considerable impact even if the magnitudes of the individual hazards themselves are not extreme. When coastal flooding is considered, high sea levels co-occurring with high river discharges are frequently discussed.

We review results from the WAKOS project (https://hereon.de/wakos) within which a consistent analysis of compound high sea levels and river discharge along European coastlines was carried out (Heinrich et al. 2023a, b). From this analysis, similarities and differences in the drivers of compound events along different coasts could be determined. Based on an example from the North Sea we further elaborate on other drivers that may cause compound flooding in low-lying areas (Borman et al. 2024) and discuss potential relevance for Baltic Sea coasts.

2. Compound coastal flooding: High sea levels and river discharges

Using two different daily river runoff data sets 1950/1979-2018/2019 and hourly data from several corresponding tide-surge reconstructions, Heinrich et al. (2023a) analyzed co-occurring events of high sea level and river discharges along European coasts. Two robust results that emerged from their analysis were:

1. For most rivers, compound events did not occur more frequently than would be expected by chance (Figure 1).
2. Exceptions are westward-facing estuaries and river mouths. Here in particular rivers with smaller catchments show more compound events than expected by chance (Figures 1, 2).

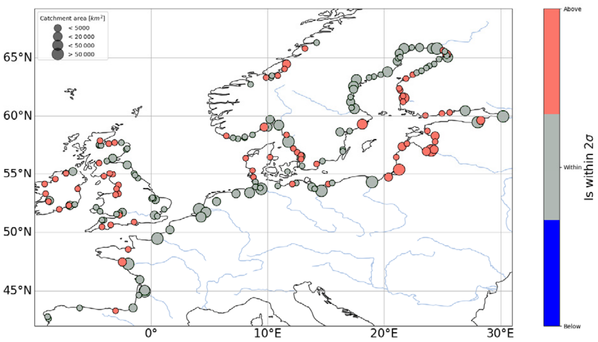

Figure 1. Locations of estuaries and river mouths considered in Heinrich et al. (2023a) for which the number of compound events does (red) or does not (grey) exceed the number that would be expected by chance (after Heinrich et al. 2023a).

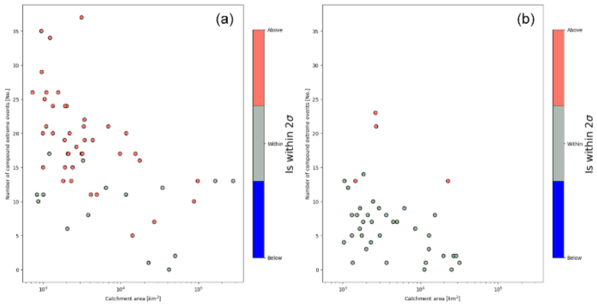

Figure 2. Number of compound events with high sea level and high river discharge over 24 years as a function of catchment size and for the rivers considered in Heinrich et al. (2023a). (a) westward-facing and (b) all other estuaries and river mouths. Rivers for which the co-occurrence is larger than would be expected by chance are colored in red (after Heinrich et al. 2023a).

Heinrich et al. (2023a) further showed that most of the compound events at western-facing coasts were associated with cyclonic westerly atmospheric conditions that are usually associated with strong winds and precipitation. This makes westward-facing coasts comprising river mouths with smaller catchments more susceptible to compound flooding, a situation that is expected to intensify towards the end of the century, primarily because of mean sea level rise (Heinrich et al. 2023b) and increasing frequency of westerly atmospheric conditions (Heinrich et al. 2024).

3. Compound coastal flooding: Drainage system overload

While most of the presently existing studies on compound coastal flooding concentrate on co-occurring high sea levels and river discharges, there are further mechanisms that may drive compound coastal (inland) flooding. Many low-lying coastal areas, for example along the Netherlands and German North Sea coastline, have developed efficient drainage systems consisting of tidal gates and pumping stations to convey the excess water from the hinterland to the sea (e.g., Bormann et al. 2020). While such systems are widespread along the southern North Sea coastlines, they are less frequent but still exist on some Baltic Sea coasts. They are usually highly efficient during average weather conditions but become less effective during long periods of high coastal water levels and/or long-lasting precipitation events.

Studying historical data from a part of the German North Sea coastline, Bormann et al. (2024) showed that mainly moderate storm series in combination with large-scale precipitation led to an overload of the inland drainage systems, while severe storm tides or heavy precipitation events alone could be handled well. The latter is important as it suggests that the coincidence of moderate extremes may have larger impacts than individual larger extremes.

Future climate projections further suggest that the intensity of compound events of rainfall and storm tides will increase consistently against the background of mean sea level rise increasing the risk of drainage system overload (Bormann et al. 2024). These findings are important as such types of compound events are considered explicitly neither in current risk management nor in long-term planning of climate change adaptation in Germany.

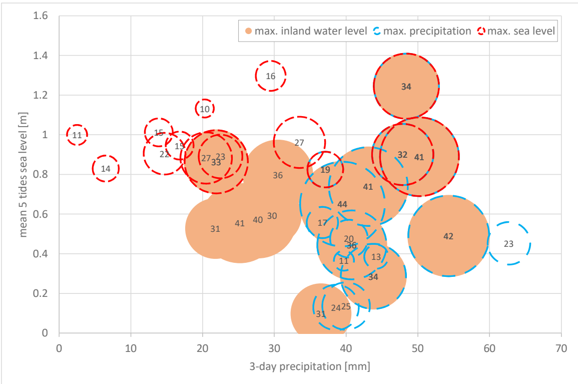

Figure 4. Observed inland water levels (maximum daily value; orange circles), sea levels (maximum sea level over a 5-tides period; red circles), and precipitation (antecedent 3 days precipitation sum; blue circles) for the 15 largest events each in the period 2000 to 2019 for a coastal section in the southern North Sea. The diameter of the bubbles is proportional to the anomaly of the high inland water level from the regulated inland water level [cm]. The anomaly is a measure of potential drainage system overload (after Bormann et al. 2024).

4. Summary

Risks and impacts from compound (extreme) events have gained increasing attention over recent years. Results from the WAKOS project suggest that compounding high sea levels and river discharges may pose a substantial threat along westward-facing coasts in Europe, a situation that is expected to intensify in the future due to mean sea level rise and changing frequency of cyclonic westerly atmospheric circulation. Against this background, results from the North Sea suggest that the risks of drainage system overload may increase along low-lying coasts and that already co-occurring events with moderate magnitude of the individual drivers may constitute an important source of inland flood risk.

Acknowledgments

Research carried out in the WAKOS project has been supported by the German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, grant no. 01LR2003A).

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Comparative studies on the river mouth system development and sedimentary environment changes between Pearl River and Oder River

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1. Abstract

In order to understand the climate change impact on river mouth systems in high latitude and low latitude marginal seas with different geological backgrounds, a comparative study is targeted to the Pearl River Estuary in the northern of the South China Sea and the Oder River Estuary in the southern Baltic Sea, mainly in aspects of the sedimentary environment, sea-level, coastline and climate change, and human being actives influence, after the last glacial stage, especially since past 8000 years in Holocene. Through sedimentary sequences comparison, the documents show two estuaries underwent rapid transgression after the last glacial period, but developed different sedimentary sequences, forming their own distinctive estuarine systems. To compare the sea-level changes in these two estuaries in postglacial, the obvious discrepancies had been happened. The Pearl River Estuary was mainly controlled by fluctuations in global sea level and regional hydrodynamic processes (e.g., Xiong et al., 2018), while the Oder River Estuary is significantly superimposed by the crustal rise or fall caused by the melting of the Scandinavian ice sheet around Baltic area (e.g., Harff et al., 2017). These two estuarine displayed the notable cases of eustatic sea-level changes under global ice mass controlling to marginal sea in low latitude zone and the glacioeustatic sea-level change under crustal movement in term of glacial isostatic adjustment in high latitude zone.

In the past 3,000 years, there have a great difference in sedimentation and shoreline changes between these two estuaries, although both of them had been in a global sea-level retreat period, resulting in the expansion of land area and obvious seaward of the coastline. The migration of the Pearl River Estuary is much higher than that of the Oder River Estuary. In historically, the role of human activities had been continued to affect the shape of estuaries and harbors construction, but the impact on the Pearl River Estuary is stronger.

In the past 100 years, the artificial disturbance of the Pearl River Estuary, especially the land reclamation activities, significantly affected the shoreline change and the natural development of the estuary, while the migration of the coastline in the Oder River Estuary was mainly caused by the erosion and accumulation of sandy coastline in natural processes under local tide, wind and coastal current system. In addition, from the sedimentary records, the 4.2 ka climate cold event and the Medieval warm event were also documented in the Pearl River Estuary, that were widely recorded in Baltic area, in term of transhemispheric scale linkage.

2. Acknowledgement

This work was supported by the international collaboration project between GMGS/CGS, China and USZ, Poland. Deeply thanks to Prof. Ryszard Borowka, Andrzej Witkowksi, Andrzej Osadczuk, Joanna Dudzinksa-Nowak, Jan Harff from USZ, Poland who contributed constructive advices. Part of the communication was supported by the Guangdong Basic and Applied Basic Research Foundation (No. 2021A1515011746).

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Session H

Philosophical aspects of Baltic Sea Earth system research

The Geography of the Baltic Sea and the Philosophical approach to its interdisciplinary nature

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1. Introduction

Geography is the science that studies Earth's surface, its physical properties, its people, their activities, and their interactions. It explores the structure, development, and processes of Earth's surface and the impact of human activity on Earth's surface.

The name of geography is composed of the Greek "*geo*," which means "Earth, " and "*graphein*," which means " to write." This name arose from the need to describe the area in detail, its place on the world scale, landscape, climate, natural resources, and population, and depict it on maps. Ptolemy, author of one of the discipline's first books, Guide to Geography (2nd century CE), defined geography as "a representation in pictures of the whole known world together with the phenomena which are contained therein" (Johnston, 2024). This expresses what many still consider geography's essence — a description of the world using maps.

For a long time, maps have been the human way to build a new world. Winther (2020) argues that map thinking is how we explore our thinking.

Along with geography, cartography was also developed, which helped summarize and visualize large-scale information. Undoubtedly, these days, Geographic information systems (GIS) tools are used as a basis for the visualization and presentation of knowledge of interdisciplinary results.

Visual geography, popular in research on the Baltic Sea Earth (region), is an important tool that can help us better understand the physical location and properties of the research subject and its society's needs. Interdisciplinary knowledge is important for its use. Therefore, maps are often created in cooperation between representatives of various specialties. In practice, we can see that when creating commissioned, thematic, target maps or interactive information maps, constant cooperation with the client is necessary both in the creative process and when using them in practical implementation. At the same time, with the intensive development of technologies and changes in the natural environment, the climate has the task of constantly updating models that partially reflect reality and their visualization.

This work aims to illustrate the understanding of the geography of the Baltic Sea from a philosophical approach needed for learning, applying, and visualization of multi-disciplinary research.

2. Geography of the Baltic Sea from various philosophical perspectives

The geography of the Baltic Sea and the history of its development can be interpreted from various philosophical points of view.

From the point of view of ecological philosophy, the Baltic Sea is a unique natural formation with great environmental value. It is an important habitat for many species of animals. However, the Baltic Sea ecosystem is vulnerable to natural processes, climate change, and unbalanced human activities. There is no doubt about the importance of protecting tools for the Baltic Sea ecosystems and environment. Due to the four seasons, phenology studies are relevant—phenology studies cyclic and seasonal natural phenomena, especially concerning climate and plant or animal life.

From the point of view of tourist philosophy, the Baltic Sea has exceptional natural beauty and diversity, including differences in four seasons. Due to its length from south to north, the sea has several climatic zones. Due to the different geological structures - different shores, rich in islands, due to the nine countries surrounding the sea - it has a different cultural heritage.

From the point of view of historical philosophy, the Baltic Sea is an important region of European history. It was an important crossroads of trade and culture. The Baltic Sea was also a place of struggle for power and influence.

From the point of view of political philosophy, the Baltic Sea is geopolitically important. It is an important place for international trade and cooperation. Nine European countries surround it. The Baltic Sea is the most important regional waterway. It is also important for the national security of many countries. It is to be regretted that in the 21st century, geopolitical ambitions regarding the Baltic Sea have not subsided. Issues regarding territorial waters, their resources, renewable energy resources, safe navigation, and sustainable management remain relevant among the Baltic countries.

From a philosophical view, scientific achievements should lead to more important things - preservation and transmission of scientific experience, progress, preservation of natural nature, reduction of pollution, communication, and collaboration between people, sustainability, to preserve a healthy natural environment on our alone Earth's planet.

3. Big data visualization

Geographic data models serve as the foundation for all geographic information systems. One of the main tasks of geography is to inform the public in a language they understand. As mentioned, one of the main examples of large or complex information presentation can be visualized through conceptual models like diagrams, maps, drawings, or paintings.

Understandably, big data is often used to illustrate and cluster, using in cartography the problem studied by making strong idealizations and realizing that a figure, colors, and special signs can say more than words. An example of the "simplified" and visualated content of a geographical map of the Baltic Sea (Fig. 1).

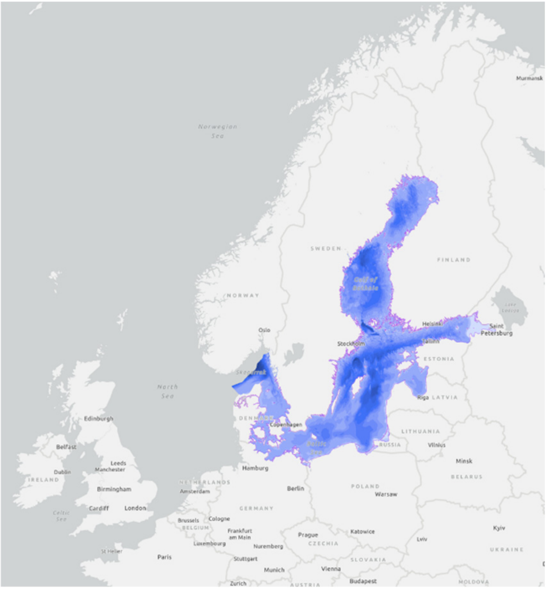

Figure 1. An example of a physical geographic map is intended to show: the location of the sea in Europe, its bathymetry (depth), the coast's line expositions, straits, main islands, and parts of the Baltic Sea, and the countries surrounding the sea.

The compositional elements cartography employs within semiotics have signs for design and perception, the symbolic meanings of those signs, and their interpretation. Geovisualisation is a knowledge-intensive art in which providers and users must possess a wide range of knowledge (Huang and Harrie, 2019). According to the same authors, however, geo-visualization knowledge is usually embedded implicitly in complex programs or rest in cartographers' minds, making the understanding difficult to transfer, interpret, expand, and reuse. All geographic information systems are built using formal models that describe how things are located in space. A formal model is an abstract and well-defined system of concepts. A geographic data model defines the vocabulary for describing and reasoning about the things that are located on the Earth.

Knowledge-based geovisualisation with Semantic Web technologies implies using geospatial linked data as underlying data (Huang and Harrie, 2019). Based on the same authors, such a knowledge base guides the visualization providers in producing satisfactory applications with formalized knowledge and semantic inference. It also enriches the knowledge represented to the users to ease their perception of map content, e.g., through a semantically enriched legend with links and relevant resources.

Soon, such powerful computer tools, currently called "artificial intelligence," will help use big data and create high-quality pictures, diagrams, maps, etc. The current success of AI techniques is equally caused by a new culture of data creation and sharing, but this was simply unthinkable just two decades ago (Janowicz et al., 2020). The use, content, and intended purpose of big data and geographical resources have recently depended on people's needs, interdisciplinary abilities, and the ability to interpret properly.

Understandably, this example in 1 figure is very simplified. However, anyone familiar with geographic information systems can modify it more according to needs. For example, the main data and tools are available on the HELCOM website Map and data service. Currently, there are many tools and programs that help visualize large arrays by combining data from ground-based measuring stations, remote sensing, and models. One of the most innovative tools is the ESRI World Imagery, HELCOM Map and Data Service (MADS), and Copernicus program services. Copernicus is the Earth observation component of the European Union's Space program, looking at our planet and its environment to benefit all European citizens. It offers information services that draw from satellite Earth Observation and in-situ (non-space) data. Copernicus services: atmosphere, marine, land, climate change, security, emergency. More opportunities to learn about the program and the use of its products: https://www.copernicus.eu/en/about-copernicus.

The Baltic Sea researchers in the Baltic Sea countries use these visualization tools for analysis of marine ecosystems, climate parameters, sea surface temperature (SST), sea level change, wave, wind, current, turbidity, Chlorophyll-a concentration, ice concentration, anomalies, and extreme events, marine heat waves, coastal upwelling freshwater content (FWC) of the Baltic Sea, etc. To investigate future warming trends scientists used climate simulation and IPCC data of scenarios. Climate models are one of the primary means not only for scientists but for all humans to understand how the climate has changed in the past and may change in the future.

4. Conclusions

Geographic data models serve as the foundation for all geographic information systems.

Geography is a much broader field, and many people realize it because geographers study the 'Earth's physical characteristics, landscapes, phenomena such as climate, the 'Earth's place within the universe, its people, as well as the impact of human activity on Earth's surface and climate.

The modern academic discipline of geography is rooted in ancient practice. It is concerned with the characteristics of places, particularly their natural environments and peoples, as well as the relations between the two (Johnston, 2024) and within the integration of GIS tools. Today, more possibilities are gained by developing conceptual drawings with large amounts of information and big data. It has become obvious that scientists must improve their skills in describing the big GIS informative visualization tools.

In summary, scientists and researchers in the Baltic countries widely use geographic visualization tools. Results of the Baltic Earth community and scientists are useful to better understand the historical and future changes of the Baltic Sea, but also in terms of the marine ecosystem and public management, and could thus be used for planning sustainable coastal development and adaptation for climate change.

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The reference list is available by request from the first author.

Mechanical energy balance in the Baltic Sea

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1. Introduction

Recent decades have manifested several man-made interferences in the mechanical energy of the sea. (1) **Ship-induced mixing.** In confined areas with intense shipping, added mixing may be considerable. Such an area can be Öresund. (2) **Waves and coastal erosion due to high-speed ships.** The problem has been actual in Tallinn Bay. (3) **Altering cross-sections and sill depths by construction.** The problem arises in many places due to construction of bridges, tunnels, artificial islands, laying pipelines. (4) **Oceanographic effects of wind farms.** There could be changes in the local wave and current regime. There are also likely changes in the wind field on larger scales that may have feedback on currents (change of wind stress), mixing (change of current shear generating turbulence), and ecosystem health. Note that The Marine Strategy Framework Directive has acknowledged that permanent alteration of hydrographical conditions must not adversely affect marine ecosystems.

The water and energy cycles have been the research focus within GEWEX and BALTEX/Baltic Earth programs. However, the energy cycle has mainly considered the heat balance. In this presentation, some aspects of mechanical energy balance are outlined, because it controls turbulence and stratification in the Baltic Sea and thus strongly influences the marine environment.

2. Mechanical energy concept

Mechanical energy, consisting from kinetic and potential energy at various scales, is naturally produced by **wind** (frictional agitation of surface drift currents, inertial and internal motions, large-scale sea level oscillations including seiche, generation of wind waves), **atmospheric pressure differences** (agitation of motions over a range of scales, from large-scale emptying and filling of the basins following inverse barometer approach, to small-scale agitation of surface capillary waves), **differential surface heat and freshwater fluxes** (formation of horizontal density differences and related potential energy), **freshwater discharge and saline water exchange** (creating estuarine-type density gradients and layered structures, depending on the flow and mixing balance guided by topography). The energy production by the wind and heat is modified by **ice cover**, e.g. by changing surface roughness and creating ice ridges. Mechanical energy is transferred by currents and waves and is dissipated mainly to heat, but a small part causes **mixing**, which has a unique critical role in the Baltic Sea physical system, e.g., in altering the **stratification and enabling a large-scale overturning circulation**. Part of the mechanical energy goes to **coastal and sediment dynamics**. For the physical system function, there are energy-sensitive areas where small changes in mechanical energy balance may lead to significant changes in circulation, volume transports, and stratification. Regarding saline water exchange, the sensitive areas are straits, deep channels, and sills.

3. Potential energy anomaly

Stratification of the sea is of primary importance for its hydrodynamic and ecosystem function. Possibility of full mixing of the water column is characterized by potential energy anomaly (PEA), calculated with a reference to the vertically mean density (Simpson, 1981). While PEA is generated mainly by the upper layer heating and sub-surface lateral salinity advection, then destratification occurs due to cooling and mixing of water masses, e.g in the surface and bottom mixed layers due to the influence of bottom friction, surface wind stress and surface wave breaking, and in the interior due to shear instabilities and dissipating internal waves.

PEA time series in the Gotland Deep and the deepwater downstream basins, calculated from the Copernicus Marine reanalysis data 1993-2021 (Fig. 1) revealed that all the selected deep locations exhibit significant seasonal cycle on the background of long-term variations. This background variation exhibits PEA decay in the Gotland Deep and its northward extension Northern Deep after Baltic Major inflows (1993, 2003 and 2015) that increase the mean PEA levels. While PEA levels decrease during the winter mixing, there has been enough PEA in the Gotland Deep to maintain saline stratification against the work by thermal convection and wind mixing. In some other areas of the Baltic, like the Gulf of Finland, PEA levels have been occasionally reduced to enable complete mixing during the winter (Elken et al, 2014). By recent investigations, complete vertical mixing occurred also in the Gotland Deep before the giant inflow in 1951 (Moros et al, 2023).

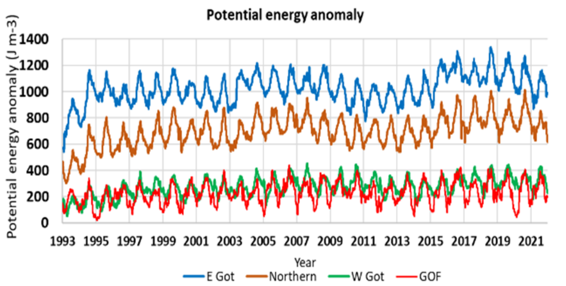


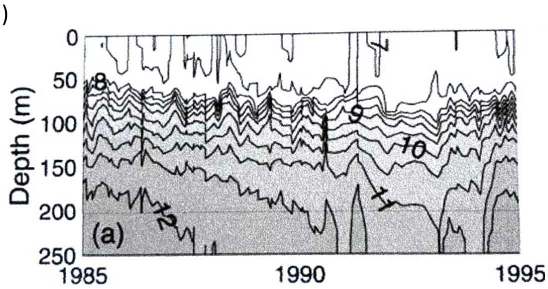
Figure 1. Time series of potential energy anomaly in the Gotland Deep (E Got), Northern Deep (Northern), Western Gotland Basin (W Got) and the Gulf of Finland near Tallinn (GOF). Data from Copernicus Marine reanalysis. https://data.marine.copernicus.eu/product/BALTICSEA_MULTIYEAR_PHY_003_011/description

Väli et al. (2023) studied mechanical energy components in the central Baltic, using a sub-mesoscale numerical model. They found that higher PEA values appear in the deeper areas where the halocline is present. Close relationship between the wind speed and the kinetic energy at the surface on one hand, and the vertically averaged kinetic energy on the other hand, was found. The complex relation of mechanical energy to internal waves, dissipation, and bottom topography are illustrated in, e.g., Muchowski et al. (2023) and Green et al., (2006).

4. Wind energy transfer and vertical mixing

Within the turbulence models based on balances of turbulent kinetic energy and its dissipation, dynamics of the mixed layer is usually properly simulated, but in the deeper layer, penetration of direct wind forcing tends to be too small to explain the observed changes of stratification. A common approach to overcome too low mixing is to include additional mixing term to the turbulence coefficient, due to breaking of internal waves. By Stigebrandt (1987) that additional term is proportional to the inverse of the Brunt-Väisälä frequency. As an example, simulating the end of the enhanced stagnation period 1985-1994, with only a few deep inflows (Fig. 2a), Axell (2002) obtained that the 1D model simulation (Fig. 2b) reasonably fits the observation only in case when mixing by internal waves is included. The same additional deepwater mixing is used also in 3D models (Meier, 2001).

a)



b)

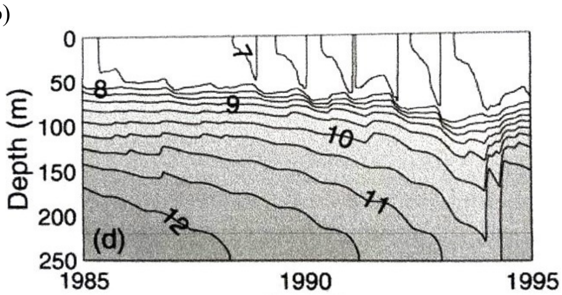


Figure 2. Observed salinities from the central Baltic Sea (a) and calculated salinities (b) by adding Langmuir circulation and internal wave energy (Axell, 2002).

The main forcing for the mechanical energy in the Baltic Sea is the wind. Surface layers are agitated by the wind stress and downward mixing of momentum. Regarding changes in stratification and potential energy, the wind energy flux to the ocean can be calculated by multiplying the wind stress to the ocean surface drift velocity (Axell, 2002), resulting approximately in the energy flux proportional to the wind speed cubed.

Suppose the energy flux from the wind is reduced with a decrease in energy to the internal wave energy. In that case, we may expect a stronger vertical stratification that will influence the marine environment differently, for example, by lowering the oxygen concentration. Extensive use of offshore wind farms in the Baltic Sea may have environmental impacts like what was reported by Daewel et al (2022) for the North Sea. More specifically, Akhtar et al. (2022) have shown that presence of wind farms reduces the 10 m wind speed by approximately 7% within a wake behind the farm structures during stably stratified atmospheric conditions. This causes changes to the stratification, but it is still uncertain how important these changes are to the ecosystems, and for the Baltic Sea this issue remains to be investigated.

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Philosophical Aspects of Marginal Seas

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1. Introduction

The ocean is one whole system connected to the land through the continental shelf with many seas. These marginal seas have enclosed islands, archipelagos, and peninsulas and are restricted through sills and channels. They are rich in marine life and human activities that strongly affect the local, regional, and global environment (e.g., Reckermann, 2022; World Ocean Review 5, 2017). There is a need to rethink and realize that scientific and humanistic perspectives can generate new knowledge necessary today with the many complex problems society needs to solve. Much work is concentrated on external phenomena, but the importance of the human's inner world is often neglected. (Ives et al 2020; Omstedt, 2020, 2023; Omstedt and Gustavsson, 2022a). The division between natural sciences and humanities or between knowledge from outside and inside has led to a division of the whole into two parts that often do not overlap (dichotomy). The philosopher Paul Ricoeur has linked these parts (Kristensson Uggla, 2011). From different perspectives, a common pursuit can achieve something third. Thus, natural science and human science could interact with different perspectives that carry a common quest for truth. This is also the argument behind transdisciplinary methods used to address the global challenges of the United Nations. Working together can generate an orchestra that gives something more than individual instruments.

The ocean, with its marginal seas, and humans are one system. There is a strong need to see the whole because fragmentation is so prevalent in today's society, and it is an illusion that the fragmented parts exist independently. This is similar to the Sustainable Development Goals by the United Nations, which include 17 goals that aim to create a better future for all. These goals should not be treated as individual; they are strongly interrelated (UN, 2018). Correspondingly, to improve and manage the ocean and its marginal seas sustainably, we must be able to see and work for the whole human and ocean system. An emphasis on harmony and beauty between humans and the ocean can strengthen a healthier and more integrated approach (Omstedt and Gustavsson, 2022a).

In this article, we will introduce analogies for philosophical reflections. Analogy means comparing an object in one domain (source domain) with another (target domain)Winther (2020). One classic example is the analogy between the solar system and an atom. Or the movement of the continents, which can be compared to sea ice breaking up and forming ice ridges. In Section 2, the analogy *"The human condition is an ocean"* reflects how the ocean has been used to process human conditions. In Section 3, the analogy *"The marginal seas are hospitals"* changes the perspective and addresses human and ocean health. Here, recovery from busy urban life and alienation from nature can be cured by the mental and physical experiences of the sea, where wonder and responsibility can stimulate attitude changes.

2. The human condition is an ocean

The ocean is a source for analysis of the human condition in all its complexity - emotion, freedom, sexuality, imagination, memory, political structures, and cultural conditioning (Döring and Winther, 2020). The oceans provide an analogical source for important philosophical reflections and questions. The Mediterranean Sea has, for example, been used by a variety of philosophers as an analogy or metaphor. Döring and Winther review some of these philosophers, starting with Thales. Thales (about 625 – 545 BC) was the first philosopher who taught sailors to find their way on the sea. One of Thales's students, Aniximander (610 – 546 BC), was the first to map the Mediterranean coastline. Heraclitus lived towards the end of the fifth century BC and argued for the truth through the unit of opposites, "the sea is the purest and most polluted water." Platon (428 – 348 BC) used the ship as a symbol for the city and the captain as the ruler. Seneca (4BC – 65 AD) was a Stoic philosopher of Rome and spoke about the Mediterranean Sea as Mare Nostrum (Our Sea). Nietzsche (1844 – 1900 AD) regarded the Mediterranean as a source of liberty and health. Camus (1913 – 1960 AD) wrote about the sea as a sensual being. Being at the seaside was of higher value than being in cities. These cases are each discussed in more detail in Döring and Winther (2020).

Figure 1. An image of how the goddess of the air, Ilmatar, becomes pregnant with the sea, the opening set in Kalevala (Omstedt, 2024).

Literature and stories create a prerequisite for understanding other people's living conditions and feelings. In the creation stories from, e.g., America (the Navajo myth) and Scandinavia (the Norse myths), much can be learned about the early humans' perception of the sea. *The Odyssey* by Homer, one of the greatest adventures in world literature, is another example. It began as an oral story and was later written down, perhaps by Homer, about 700 years before our era. This story has been interpreted and rewritten in many ways. It is a symbol and a starting point for a large part of Western

Culture, created through literature, art, and philosophy (Omstedt and Gustavsson, 2022b). The epic Finnish poem *Kalevala* originated in oral tradition, which in the 19th century was compiled into a whole by Elias Lönnrot, see preface in Kalevala (1999). The first chapter describes how it all began and how the great singer Väinämöinen was born (Figure 1). The philosophical interpretation of how the air becomes pregnant by the sea is discussed in Omstedt (2020) as an illustration of how changed perspectives can generate something new and unexpected. The oceans' creative and analogical power permeates human imaginations and thinking and deserves more explicit attention.

3. Marginal seas are hospitals

The human impacts on the ocean are easily visible in all plastic and waste transported into the sea. This risky behavior reflects humans' wasteful lifestyles and the need for an attitude change based on improved mental health. The ocean and humans are vulnerable, and people need inspiration to change their behavior. Today, the communication between the sea and humans occurs through many different voices, where science, art, and the extensive measurements of marine scientists call for attention (Omstedt, 2024). A vision and analogy are that *"the marginal seas are hospitals."* The most important aspect of a healthy ocean is healthy people who manage the sea carefully and sustainably. Coastal areas with growing populations may cause increased misuse of the sea. Instead, an attitude change could be based on using the marginal seas as a hospital for human physical and mental health.

Figure 2. Our inner ocean of rational thinking, feelings, thoughts, and values holds a powerful ability to find a new relationship with the sea, inspired by all the voices from many marine sources, observations, literature, art, and music (Omstedt, 2024)

Urban seas and coastal areas are important for humans for inspiration and involvement in efforts that build with the sea. Marine activity, such as increased marine protected areas and new marine wind farm plants, should be more holistic by promoting beauty and harmony for all living in coastal areas instead of fragmentation into sectors of interest. People need to be involved both for the ocean and for themselves and to recover with the help of the sea. The UN Ocean Decade aims *to safeguard the ocean we need for the future we want*. This vision is scientific, technical, and humanistic, seeking a changed relationship that promotes a caring mentality that generates health for the sea and humans.

4. Discussion

The ocean and its marginal seas have developed for four billion years into the blue planet we know today. Only in the most recent time of the earth's history have humans become a part of the sea that affects it, almost always negatively. The earth system and society always evolve dynamically, and there is no turning back. Some hope to restore nature and the sea to an earlier historical period, but this will not be possible. Instead, the future of the marine environment is closely linked to human activity. The idea that the sea will care for itself is fundamentally wrong. The effort to restore to the way it was before is impossible. Unlike our ancestors, however, today, we have access to much knowledge that allows us to change how we misuse the sea and instead create the future we want.

The complex interaction between humans and the environment requires serious philosophical reflections on how to develop improved and sustainable relations with our marginal seas. Geosciences and technical inventions are not the only solutions; humanities and philosophy have a key role to play. The added value of philosophy includes, e.g., analytical thinking and critical reflection, integrating plural pieces of knowledge, disciplines, and dichotomies, and imagining (Winther, 2020).

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The reference list is available by request from the second author.

Impactful Science-Policy Dialogues

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Fostering lasting science-policy-dialogues

Scientific evidence plays a central role in shaping policy on climate, environment, sustainability, and resources. Successful engagement between science and policy requires the alignment of scientific focus with the needs of decision-makers, ensuring policy relevance, scientific expertise, and timeliness. Face-to-face interactions are essential, fostering a mutual understanding. This approach not only ensures that the information provided to policymakers is accurate, but also actionable. In addition, the inclusion of different scientific perspectives and broad expertise enhances the credibility and impact of scientific information and provides a comprehensive view of complex issues.

Figure 1. Parliamentary Evening in the Käfer rooftop restaurant of the German Bundestag, Berlin. © Helmholtz Earth & Environment

The following elements are essential for bridging the gap between research and policymaking, establishing impactful connections:

- Highly motivated researchers, ready to customize their studies to align with policymakers' needs.
- Institutionalized knowledge exchange between the scientific and political communities, facilitated through e.g. advisory councils and expert hearings.
- Coordinated events in parliaments, delivering core messages tailored to current parliamentary processes, along with policy recommendations targeting specific policy areas.
- Establishment of trustful connections with policymakers through regular, face-to-face meetings between individual politicians and scientists.
- Implementation of targeted outreach initiatives, including site visits, to provide firsthand experience of research activities within the institute or in the field.

To give insights into national and international science policy activities conducted by Helmholtz SynCom, three examples (i-iii) are provided below.

Addressing policymakers with parliamentary events and aligning scientific evidence with policy processes

i) In October 2023, Helmholtz SynCom, together with scientists from Helmholtz Centres AWI, GFZ, GEOMAR, and Hereon, organized a parliamentary breakfast in the German Bundestag focused on sea level rise. The aim of the event was to inform political decision-makers about the causes, impacts, and significance of sea level rise for Germany, and to foster sustainable relations between Helmholtz experts and federal policymakers. In preparation for this parliamentary event, a close dialogue with the patron and other parliamentarians proved essential to tailor the content of the presentations to the specific needs of policymakers. Additionally, researchers from different disciplines and institutions worked closely together to ensure that their presentations told a coherent story. In summary, the parliamentary breakfast proved to be an effective tool for initiating and strengthening the dialogue between science and politics.

Figure 2. Parliamentary Breakfast in the breakfast restaurant of the Jakob-Kaiser-Haus of the German Bundestag, Berlin. © Helmholtz Earth & Environment

ii) In May 2024, Helmholtz SynCom, together with Helmholtz Energy, Helmholtz Climate, CDRterra, CDRmare, and DACstore, will host a parliamentary breakfast on Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture and Storage (DACS). Beside BECCS and DACS, the event will explore the opportunities and challenges of marine and terrestrial Carbon Capture and Storage (CCS). This event will address negative emissions from a holistic scientific perspective and discuss the socio-political relevance and the current need for action with policymakers in the German Bundestag.

Engaging Early Career Researchers in Science-Policy Dialogue

iii) Helmholtz SynCom involves early career researchers in the science-policy dialogue, as they not only bring a diverse perspective to the discourse, but also gain early exposure to interactions with policymakers. This has the potential to provide young policymakers with counterparts at their level and to establish a trusting exchange, which is essential for effective communication.

A notable case in point unfolded during a delegation trip of the Helmholtz Research Field 'Earth and Environment' to the European Parliament in December 2023, where seven early career researchers from seven Helmholtz Centres took center stage. This initiative, orchestrated at the invitation of Niklas Nienaß, Member of the European Parliament, underlined the commitment to fostering a robust dialogue between emerging researchers and policymakers.

The delegation's agenda focused on Earth observation and included strategic meetings with members of the European Parliament, representatives of the European Commission's Directorate-Generals for Defence Industry and Space (DG DEFIS) and Climate Action (DG Climate Action), and the European Space Agency (ESA). By actively participating in these discussions, the early career researchers gained valuable insights into the complex interplay between science and policy. This trip underlined the commitment to a vibrant interface between science and policy.

Figure 3. Delegation trip to the European Parliament. © Helmholtz Earth & Environment

The illustrated examples show how targeted and engaging parliamentary events can effectively bridge the gap between science and policy, fostering productive dialogues that are crucial for evidence-based policymaking.

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Philosophical views on Baltic Basin climate and environmental sciences

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1. Introduction

Human activities give rise to many factors exerting tremendous pressure on the marine environment. Simultaneously, social, political, and ecological environments are highly complex, with many competing interests. Therefore, marine science, management, and governance must integrate many perspectives incorporating human perception and behavior, e.g., Omstedt and Gustavsson (2022). The study applies a philosophical view of complex systems, which promotes increased understanding through idealizations without organizing science into hierarchies. The background is the climate and environmental research in the Baltic Basin (Baltic Sea and its drainage basin) during the past three decades that has gone from disciplinary research to much broader perspectives or from studies on closing the water and heat balances to human impact with multiple stressors, Omstedt and Von Storch (2023), Reckermann et al., (2022).

2. Complexity and simplifications

Our seas are highly complex for many reasons, such as their dynamics, climate or environmental changes, and human behavior. There are few universal laws, and the science practice differs from different fields, e.g., physics goes for mathematical laws, chemistry for molecules, biology for species, and policy for economic and judicial systems. Scientific laws and theories also have many approximations, such as earth system models. Therefore, science aims not for truth but for understanding and relies on simplifications. Different disciplines have their practice, and the most basic consequence of science practice is the extensive use of idealizations or assumptions made without regard for whether they are true and often with full knowledge that they are false Potochnik (2017).

Models often play significant roles. Maximum complexity models resolve as many details and degrees of freedom as computationally possible, allowing experimentation, data assimilation, forecasts, and scenarios of possible futures but do not provide immediate understanding. On the other hand, minimum complexity models, such as maps, budgets, conceptual views, process, mechanical, and system models, may represent understanding. In a sense, parametrizations are often such minimum complexity models. Models of different types are indispensable tools in the scientific process of constructing knowledge Hasselmann (1988); Müller and von Storch (2004). We will investigate scientific practices in the BALTEX/Baltic Earth program from 1993 to 2023. The aim is to illustrate the importance of addressing complex problems through simplifications.

3. Advancement of knowledge through simplifications

Knowledge development in the BALTEX/Baltic Earth program involves close interaction between observations and theoretical considerations. The region has diverse information from the last millennium—data of different styles and scales in time and space and with various qualities. A strong development has occurred in analyzing these data during the past three decades, including instrumental data and historical data proxy data such as tree rings, diaries, and written information. At the same time, many new instruments, including satellite data, are mixed with older ones, producing reconstructions many centuries back in time. Large efforts to build complex systems based on three-dimensional numerical modeling were undertaken during the program, while knowledge advanced through simplified approaches. Science is in the business of finding causal patterns (cause and effect), and idealizations play a particularly valuable role in representing causal patterns. However, causal patterns are often complex and hidden in the complex world. One example is the North Atlantic Oscillation index (NAO), an idea that just a number can describe the large-scale atmospheric circulation over the North Atlantic Ocean. This index has been applied in many Baltic Sea studies, illustrating the importance of atmospheric circulation for parameters such as ice, temperature, sea levels, inflows, wind, parameters of eutrophication, etc.

The drainage basin concept was launched by GEWEX and BALTEX and visualized through the BALTEX box is another example. The drainage basin concept combines the atmosphere, land, and sea into a system for evaluating climate models' water and heat balances. Furthermore, this simplification can be validated in just one control section, the entrance of the Baltic Sea. Similarly, the drainage basin concept has been applied for a long time in hydrology and during the BALTEX/Baltic Earth period, demonstrated by Bergström and Graham (1998) and Graham (1999) how the river runoff to the Baltic Sea could be modeled and validated. Land surface dynamics simplified the complex ecosystems by vegetation sub-models and the Leaf Area Index (LAI) that characterized plant canopies Smith et al. (2001) and incorporated them into different Regional ClimateModels.

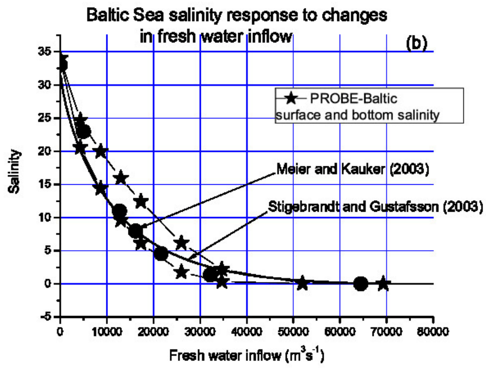

Figure 1. Steady-state Baltic Sea salinity with freshwater inflow.

Closing the water and heat balances was possible by introducing coupled ocean basins for the Baltic Sea, giving information on net outflow and properties such as net precipitation, temperature, and salinity (Gustafsson, 2000a, b, Omstedt 1987, 1990 a, Omstedt, and Rutgersson, 2000, Rutgersson, Omstedt, & Räisänen, 2002). The ocean models added two new validation parameters for evaluating climate models: the Baltic Sea heat and salinity content, Omstedt and Nohr (2004). An important aspect of using different model complexity is identifying dynamical aspects and checking if they work similarly. For example, there is a nonlinear relation between Baltic Sea salinity and freshwater input Omstedt and Hansson (2006) (Figure 1). Here, mechanistic models were compared with the three-dimensional model study by Meier and Kauker (2003), and both levels of complexity were able to reproduce the nonlinear behavior.

Using the closure concept, Climate Models (GCM and RCM forced by GCM) illustrated a large bias in water and heat transports Omstedt et al., (2000); Omstedt et al., (2012).

Similar problems were shown using Regional Climate Models (RCM) forced by GCM lateral boundary conditions. However, Bengtsson (2001) illustrated a reasonable fit using RCMs driven by reanalyzed data as lateral boundaries.

Sea ice is a highly complex material that, on a geophysical scale, is fragile, plastic, and viscous. The formation of ridges and leads illustrates that the plastic behavior in coastal seas is related to onshore and offshore winds. A simplified sea ice-edge one-dimensional model (Omstedt, 1990 b) for coastal seas was developed and validated with Baltic Sea data showing how major processes could be modeled. For example, the plastic behavior was investigated, illustrating that standard formulations from Artic Ocean do not hold. Later, this sea ice model was applied to the Baltic Sea, examining sea ice on different time scales Omstedt and Nyberg (1996). Strong knowledge achievements were gained in close contact with international work, e.g., Leppäranta (2011) and Åström, Haapala, and Polojärvi (2023).

Eutrophication is one of the major threats to a healthy Baltic Sea. It includes a complex mix of physical, chemical, and biological processes and knowledge about humans through external loads from land and atmosphere. Here, Savchuk and Wulff (2007) developed a decision system based on a model concept called SANBALT (Simple As Necessary Baltic Long-Term Large Scale). The model included detailed nutrient budgets. Gustavsson et al. (2017) extended this approach and calculated the P, N, and C budgets for the major sub-basins in the Baltic Sea. A striking property of C versus N and P cycling was that while internal removal processes largely balanced the external supplies of total N and P, the total carbon supply was mainly compensated by a net export out of the system. A result also calculated by Kulinski et al. (2011). Later, Stigebrandt and Andersson (2020) estimated the importance of phosphorous fluxes from anoxic sediments.

There are many other examples of how simplification has advanced the knowledge about the Baltic Basin. Here, we will finally only mention the work by Bernd Schneider, who, through careful studies of the Baltic Sea CO_2 system (Figure 2), could add new knowledge to ecosystem modeling, Schneider, Nausch, and Pohl (2010).

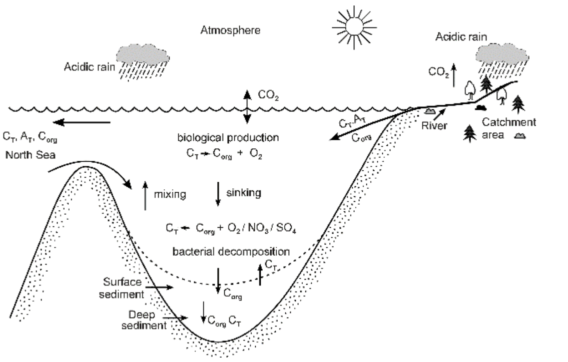

Figure 2. A conceptual illustration of the cycle of CO_2 in the Baltic Sea, redrawn from an earlier sketch by Bernd Schneider.

4. Summary and some conclusions

The BALTEX/Baltic Earth science work has been investigated during the past three decades using a philosophical view of complex systems, promoting increased understanding through idealizations without organizing science into hierarchies. The BALTEX/Baltic Earth pluralistic science practice has been successfully developed and generated new knowledge about dealing with climate and environmental changes in the region. Some of the major improvements in understanding are:

- Improved communication skills through more possibilities by developing conceptual views into drawings with large information contents and on different time and space scales.
- Improved knowledge based on increasing data and data product and the need for well-documented, homogenized, and open data sets. Training to characterize and detect climate and environmental changes in the region.
- Indices and statistical models have played an educational illustration of complex dynamics. We have learned that they also need consideration of homogeneities and often have severe limitations.
- Several new maps on the region have, in an easy visual way, opened up the understanding of the need for multi-disciplinary research.
- Improved knowledge of the atmosphere-ocean boundary layers.
- New knowledge has been achieved through water, heat, nutrients, and carbon budgets.
- Improved knowledge of mechanical and system models regarding water, heat, nutrients, and carbon cycling.
- Maxim complex models have been strongly developed as the computer capacity has grown and shown important results when attributing the causes for climate change and scenarios of possible future developments.
- Knowledge about assessment strengths and problems has improved our insights into multiple-discipline research and communication.

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The historical and cultural value of the Marine Protected areas: The island of Seili

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1. Introduction

We cannot live happily without a healthy Baltic Sea with its history, resources, transport, tourism, culture, and inspiration. However, the sea has been under strong human stress for decades (e.g., Reckermann, 2022). The decline in fishing stocks in general and herring and cod in the Baltic Sea send a strong warning signal that managing marine resources needs a new relationship between humans and the sea. Here, the field station and marine protected areas play a major role in observing and protecting marine habitats and as a base for a living archipelago.

Kristineberg Biological Station, located at the mouth of the Gullmar fjord, Bohuslän, Sweden, was founded in 1877 as one of the world's oldest marine stations for education and research. Similar field stations have been later established around the Baltic Sea. Here, we will outline the history and importance of the marine station at Seili island in the Turku/Åbo archipelago, Finland, Northern Baltic Sea.
Archipelago Research Institute (ARI) of the University of Turku (UTU) is celebrating its 60th anniversary in 2014. Started as a field base for biology and geography, ARI is today an environmental research institute concentrated on the ecological state of the Baltic Sea and the Archipelago Sea of Finland. Besides, it is a meeting point for all the faculties at UTU and serves as a resource for public relations development.

Figure 1. The Island of Seili and Archipelago Research Institute off Turku/Åbo, SW Finland.

2. The Island of Seili's history, from hospital to marine station

The rich historical past, local culture, and traditions of the Island of Seili formed a special point of interest. The state has had a presence on the island since the 1600s in the form of a hospital. The hospital activities included a leprosy asylum, then a mental hospital until 1962, after which the university founded the ARI. The institute used old hospital buildings and the archipelago milieu around it. Over the centuries, the island has been governed by three states: first, Finland was a part of Sweden (not called Finland, but Östermark), then there was a period of Russian government, and finally, since 1918, the independent Finland. All this has left traces on the island and forms a rich potential for history and culture researchers of UTU, e.g., archaeology.

Another basis has been the active interplay between visitors on the island and university visitors. The island has been the target of tourists since the 19th century. In the beginning, quite rudely, it was an attraction for "the funny farm" watching. With increasing tourism in the 1990s, it was clear that sustainable development, not only in the number of tourists but also in their visiting tracks, needed to be planned carefully. Therefore, we started to arrange the visitor's 15 to 30-minute introductions to the island's history and introduce the university's activities. Thus, a combination of local history and university activities connected to the ecological state of the Baltic Sea was made a narrative that served around 10 to 15 thousand yearly visitors. This would not have been possible without taking the humanities as a part of the developing program for the ARI. This development took place especially since 2011 when Turku/Åbo was chosen as the cultural capital of Finland. As a result of that year, several art projects were initiated in the archipelago of Turku with strong support from the ARI. Thus, the central features of humanities as a philosophy that is informed by science, inspired by art, and motivated by compassion (https://americanhumanist.org/what-is-humanism/definition-of-humanism/) have made it possible to reach a much wider audience than science alone could attract.

This development has not occurred in "a university vacuum" but simultaneously with other important changes in the developing discussion about the need for marine protected areas. Thus, the first Biosphere area of Finland was formed, with active support from the UTU, around the Seili Research base in the early 1990s. Some years later, the European Union program of Natura 2000 was added to the protection initiatives in the Seili Archipelago. The research was boosted when Finland joined the EU in 1997, adding to the financial base for research by opening international funding possibilities for Finnish environmental research in marine areas.

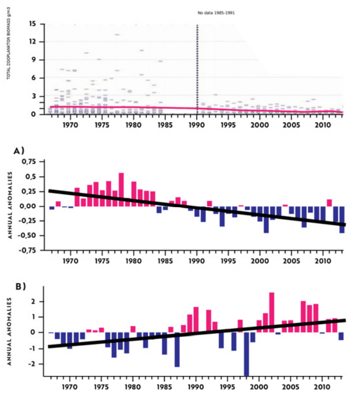
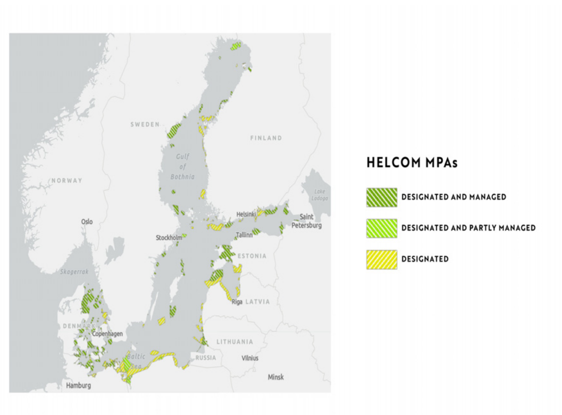


Figure 2. Time series of zooplankton, salinity and temperature at Seili (modified from Rousi et al. 2024 (submitted) and Mäkinen et al. 2019). Graphics Terri Vuorinen.

3. The environmental and climate importance

The background for this development has been a combination of scientific environmental research and the university's active pursuit of public outreach and increasing the scientific discussion and interchange inside the university. In that way, the former field base has been transformed into a cross-disciplinary institute and a place for public outreach. The Baltic Sea field stations and increased marine protected areas offer important options for developing a healthy Baltic Sea. Based on scientific evidence, they can be particularly effective when developed as part of a wider management solution. But also, the field stations provide an important source of reflection for all humans living around the sea with their different cultures. They work, Figure 4. therefore, as a guarantee for a living archipelago.

Figure 3. Marine Protected Areas in the Baltic Sea region (Map downloaded from the HELCOM website, modified by Terri Vuorinen).



Marine protected areas aim to protect valuable marine and coastal habitats. In the Baltic, we have around 13 percent of the sea area protected by national MPAs, while the international target is to cover at least 30% of the global ocean. However, the field stations and the protected areas can not be looked upon without considering the whole region with many treats, such as eutrophication, climate change, industrial overfishing, and building new constructions. Therefore, the expansion and design of marine protected areas will need research on the whole marine ecosystem. Many perspectives are needed here (e.g., Omstedt and Gustavsson, 2022) to create a healthy Baltic Sea and sustain its beauty.

Fig 4. An artwork in the archipelago. Raqs Media Collectiven 2011. Photo Stefan Krämer.

4. Summary and some reseach challenges

The countries around the Baltic Sea face a great challenge to develop science and a marine management that can protect and develop a living, healthy and beautiful Baltic Sea. Here the marine field stations and marine protected area will serve as important observation and information areas. Similar challenges are on highest political level where the United Nation has formulated an Ocean Decade, during the period 2021-2030, that provides a rare opportunity to show how working closely across disciplines and with societal actors to co-design innovative and transformative solutions can lead to a more sustainable marine enviroment. Below we list a number of research topics with relevance for the Baltic Earth community that involves questions related to:

- How will a degraded vs healthy marine environment influence climate change such as eg. the uptake/release of greenhouse gases?
- How should the Marine Protected Areas be connected to improve reproduction of key species of fish or e.g. Zoostera marina or the Bladder wrack?
- How could the voice of the Baltic Sea be better transformed and mediated for the urban citizen?

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international target is to cover at least 30% of the global ocean. However, the field stations and the protected areas

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