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Temperature driven coastal processes and their far reaching effects on deep Baltic Sea biogeochemical dynamics

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Abstract. The coastal zone of the Baltic Sea plays a critical role in shaping the biogeochemistry of the deep ocean mainly through the coastal filter. In this study, we investigated the role of temperature driven biogeochemical processes in the sediment and water column in defining the biogeochemistry of the nine distinct basins of the Baltic Sea using a coupled physical biogeochemical model MOM-ERGOM. In ERGOM, the temperature driven biogeochemical processes are represented by the q_{10} parameterization, which is uniform in space and time and neglects that temperature sensitivities may differ with depth. We conducted two sets of sensitivity experiments to examine the effect of enhancing the temperature driven biogeochemical processes by increasing the q_{10} parameter both basin wide and selectively in the coastal zone of the Baltic Sea. We found that detritus recycling in both sediment and the water column is the key process regulating basin scale biogeochemistry. A modest 10% enhancement in the q_{10} parameter for these processes caused disproportionately big changes in nitrogen and phosphorus cycles of the Baltic Sea, demonstrating a nonlinear system response. The results reveal significant spatial heterogeneity in system wide responses, with strong accumulation of ammonium and depletion of nitrate in the anoxic basins, indicating stronger denitrification over nitrification in warmer conditions. The rising nutrients from enhanced temperature driven remineralization indicate potential for higher primary productivity under a future warmer climate. Basin wide enhanced water column remineralization also caused increased phosphate concentrations in the Bothnian Bay, suggesting that the basin could potentially shift away from phosphate limitation under warming, with consequences for future productivity regimes. We introduced a non-dimensional metric of relative coastal sensitivity to assess the disproportional role of the coast in defining the biogeochemistry of the deep Baltic basins. The analysis shows that the nitrate cycle is disproportionately sensitive to coastal sediment recycling, with the Bothnian Bay displaying two to four fold stronger responses in nutrient cycles than basin wide perturbations, underscoring the disproportionate influence of coastal processes on basin biogeochemistry. In the Bothnian Bay, phosphate dynamics depend on the spatial scope of sediment recycling. When enhanced only in coastal sediments, oxic conditions trap much of the released phosphate as iron–phosphate, strengthening the coastal filter and limiting export to the deep basin. In contrast, basin wide enhancement releases phosphate from adjacent anoxic basins, which is transported northward, increasing phosphate availability in the Bothnian Bay. Accurately resolving coastal processes is therefore essential to capture the coastal filter and avoid misrepresenting nutrient transport and ecosystem responses under climate change.

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1 Introduction

Coastal oceans (9.7% of the global ocean by area) form a link between the land and the open sea, play an essential role in marine biogeochemical cycles (Holt et al., 2017). It acts as a buffer zone to mitigate the terrestrial and anthropogenic impacts in the deeper basins (McGlathery et al., 2007; Nelson and Zavaleta, 2012). The coastal ecosystems are highly affected by climate change and human activities (Steffen et al., 2015) and suffering from eutrophication and hypoxia (Almroth-Rosell et al., 2016). Despite its smaller area, the coastal ocean contributes significantly to the global marine productivity, supporting 10% of primary production and 30% of benthic production of the world ocean (Ducklow et al., 2001; Muller-Karger et al., 2005). These highly dynamic systems show strong benthopelagic coupling and receive significant inputs of land derived nutrients and organic matter, and support rapid turnover of nutrients. They also play an essential role in basin scale nutrient and carbon cycling (Salgado-Hernanz et al., 2022).

One of the key ecosystem functions of the coastal ocean is the coastal filter, a biogeochemical buffer encompassing processes that retain, remove, and transform land derived nutrients on the way to the open ocean (Asmala et al., 2017). It helps to mitigate eutrophication and reduce nutrient export to the open ocean. The Baltic Sea, one of the eutrophied regions in the world, has more than half of the land derived nitrogen and phosphorus being retained or permanently removed in its coastal zone (Almroth-Rosell et al., 2016; Edman et al., 2018). However, observational studies (Asmala et al., 2017) report lower retention than models, highlighting uncertainties in quantifying the coastal filter. These differences may arise from the way the key biogeochemical processes underlying the coastal filter, such as denitrification, remineralization, and burial (Duarte and Cebrián, 1996; Voss et al., 2005) are represented in models. As these processes are highly temperature sensitive, their accurate representation in models is vital under a changing climate (Edman et al., 2018). Wåhlström et al. (2024) show that the total retention in the entire Stockholm Archipelago is projected to increase under a future warming climate, resulting in a decreased net exchange with the open coastal sea (Meier et al., 2012). However, the overall effects of climate warming on the coastal filter remain highly uncertain (Meier et al., 2022).

Despite the vital role of coastal oceans in regulating the nutrient and carbon cycles, the accurate representation of the coast and the coastal filter in biogeochemical models (BGCMs) remains a grand challenge (Holt et al., 2017). The coastal oceans are crudely neglected in BGCMs (Laruelle et al., 2014; Gruber, 2015; Ward et al., 2020; Mathis et al., 2022), mainly due to the challenges in representing their complex dynamics and spatio-temporal heterogeneity (Renner et al., 2009; Holt et al., 2010; Ward et al., 2020). Many BGCMs either exclude or oversimplify the key biogeochemical processes that represent the coastal filter, bentho-pelagic coupling, and sediment interactions (Allen et al., 2010; Hauck et al., 2020). A common simplification in models is the use of constant process parameters, such as q_{10} temperature coefficient, remineralization rate, although biogeochemical processes can vary significantly between the coast and the offshore (McGuire et al., 2001; Ward et al., 2020). These oversimplifications can lead to underrepresenting the shallow coastal processes, especially in regions like the Baltic Sea, where

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the shallow water processes can strongly influence the biogeochemistry of the deeper basins.

To address these limitations, recent studies focused on improving the representation of coastal biogeochemical processes in models by adding more complex and detailed coastal processes (Reed et al., 2011; Butenschön et al., 2016; Sharples et al., 2017; Izett and Fennel, 2018; Radtke et al., 2019) and using higher temporal and spatial resolutions to capture the fine-scale coastal dynamics (Holt et al., 2009; Martyr-Koller et al., 2017; Mathis et al., 2022). However, detailed process representation can increase model complexity and uncertainty. As a trade off, the models often use constant process parameters (which themselves are uncertain and poorly known) to represent both coastal and deep sea processes. While this simplification helps to reduce model complexity, it overlooks the inherent biogeochemical differences between the coast and deep oceans (Platt et al., 1991; Hemmings et al., 2003; Losa et al., 2004; Geary et al., 2020; Singh et al., 2022). Since the parameters represent the unresolved processes which directly impact the resolved ones, such as the coastal filter (Luo and Schuur, 2020), any uncertainty or neglecting their spatio-temporal variability can lead to further uncertainty in the models.

Trying to improve the representation of the coastal zone in the models means addressing rather than ignoring these spatial differences. However, the model parameters and the corresponding process rates are mostly difficult to constrain by observations or experiments alone. The model parameters are often measured and calibrated in laboratory experiments, which often fail to reflect the large scale open ocean conditions (Singh et al., 2022). Many studies have proven that resolving space and/or time varying BGCM parameters is more relevant in the context of biogeochemical modeling (Losa et al., 2003; Tjiputra et al., 2007; Mattern et al., 2012; Roy et al., 2012; Doron et al., 2013). Singh et al. (2022) point out the need for an efficient method to tune the most sensitive model parameters and thereby reduce the parameter uncertainty. Moreover, many of these parameters depend on environmental conditions, which adds a layer of difficulty to deriving the parameters from the sparse observations. Therefore, the question of which of the many processes to observe and where to observe them to reduce model biases optimally is not easy. Research should focus on those processes and parameters that are most sensitive, that is, where the impact of ignoring an existing spatial difference in the system wide biogeochemical cycles is maximal. Here, state-of-the-art BGCMs and sensitivity experiments can play a vital role in identifying the parameters that are highly sensitive to the biogeochemical processes, and help us to come to a conclusion on which regions or conditions these parameters should be measured to reduce model biases. So, focusing on the key model parameters is highly important to reduce the model uncertainty and improve the representation of the coast in the models. In this way, models can effectively complement observations and can support accurate and more targeted data collection strategies.

In ecological modeling, the q_{10} temperature coefficient (a parameter representing the temperature sensitivity of a process rate) is identified as one of the parameters with considerable uncertainty (Yoshie et al., 2007; Post et al., 2008). The q_{10} parameters often have a relatively large range ($\pm 50\%$ from the mean value) (Gibson and Spitz, 2011; Laufkötter et al., 2017) and it can also change with temperature (Rasmusson et al., 2019; Mundim et al., 2020). Despite this, many of the community models (Kishi et al., 2001; Aumont and Bopp, 2006; Vichi et al., 2007; Shigemitsu et al., 2012; Buitenhuis et al., 2013; Dunne

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et al., 2013; Moore et al., 2013; Anju et al., 2020; Mundim et al., 2020; Neumann et al., 2022) have constant q_{10} both in space and time to represent the processes like growth rates, respiration, remineralization, nitrification, with a very few models which have at least two q_{10} for different temperature regimes (Hauck et al., 2013). Laufkötter et al. (2017) argued that the differences in the temperature dependent parameterization of remineralization are partly responsible for observed uncertainty in future projections of the biological pump. A temperature sensitivity study for the Baltic Sea ecosystem identified a high mineralization rate in a warming climate, and it suggests a revisit to temperature dependent mineralization in current climate projections (Börgel et al., 2023). The experts suggest that the biggest uncertainties in biogeochemical cycles in the Baltic Sea are due to the unknown current and future land and atmosphere derived nutrient loads into the sea (Meier et al., 2019). Meier et al. (2018) pointed out that the existence of large discrepancies in scenario simulations in the state-of-the-art BGCMs is due to the sensitivity of biogeochemical processes to the model assumptions. Misrepresenting the temperature-driven coastal processes in the model can cause uncertainty in the coastal filter, hence affecting nutrient export to the deep sea and its biogeochemical cycles.

In this study, we revisit the role of q_{10} parameterization (and thereby the temperature sensitivity on process rates) in the ecosystem model Ecological ReGional Ocean Model (ERGOM, (Neumann et al., 2022)) in defining the biogeochemical cycles of the deep basins of the Baltic Sea. As one of the oceanic regions strongly affected by the climate induced temperature changes (Meier et al., 2022), the Baltic Sea provides an excellent example for exploring the sensitivity of q_{10} parameterizations in marine ecosystem models. The long term trends of sea surface temperature show much greater warming in the Baltic Sea that exceeds the global mean by a factor of seven, with the strongest trends since the mid-1980s (MacKenzie and Schiedek, 2007; Belkin, 2009; Kniebusch et al., 2019; Barghorn et al., 2025a). In summer, this semi-enclosed basin exhibits pronounced spatial temperature ($> 10°C$ difference in temperature) gradients with warm conditions in the south and cold conditions in the north, with highly variable pelagic and benthic processes. Specifically, we investigate how spatial differences in temperature sensitivity influence nutrient cycling and ecosystem dynamics in the Baltic Sea deep basins. To address these questions, the main aims of the paper are as follows:

1. Examine the impact of both uniform and spatially varying temperature sensitivity (by increasing the q_{10} parameter) on the biogeochemical cycles in the deep Baltic basins.
2. Develop a methodology to assess the impact of coast-to-basin differences in q_{10} parameters and their associated process rates on the biogeochemistry of the deep Baltic basins.
3. Classify the deep basins of the Baltic Sea based on the extent to which their biogeochemical cycles are influenced by coastal versus whole-basin processes.
4. Determine whether parameter measurements should be prioritized in the coastal or deep basins to reduce model bias.

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While demonstrated for the Baltic Sea, the methodology can broadly apply to other coastal regions and model parameterizations, making it a valuable tool for understanding coastal-biogeochemical interactions in diverse marine systems. The rest of the paper is structured as follows: Section 2 describes the model details, data, and methodology. Results and discussions are presented in sections 3 and 4, respectively, followed by the Summary and Conclusions in section 5.

2 Model, Data and Methodology

2.1 Biogeochemical Model

2.1.1 Model structure

The ecosystem model used in this study is based on a Non-Redfield carbon model, the Ecological ReGional Ocean Model (ERGOM; (Neumann et al., 2022)), with elemental cycles of nitrogen, phosphorus, carbon, oxygen, and partially sulfur. The three phytoplankton functional groups (small cells, large cells, and cyanobacteria) are responsible for photosynthesis, which is driven by photosynthetically active radiation (PAR). Photosynthesis is limited by light (Steele, 1962) and nutrients (Monod, 1949; Neumann et al., 2002). The optical model uses the chlorophyll concentration derived from the phytoplankton functional groups and the CDOM concentration (Neumann et al., 2021). A bulk zooplankton group, the highest trophic level in the model, grazes the phytoplankton. The dead particles accumulate in the detritus variable. Detritus can sink in the water column and accumulate in the sediment layer along with large cell phytoplankton (which accumulates in the lowest layer of water). The particle sinking is parameterized by the Martin curve (Martin et al., 1987) to achieve a linear increase in sinking speed with depth. The detritus is remineralized (controlled by temperature and oxygen concentration) into ammonium, and further nitrification converts ammonium into nitrate in the water column and sediment. Oxygen is produced by primary production in the euphotic zone and consumed by metabolism and mineralization. Under oxic conditions, the phosphate-bound iron oxides remain in the sediment as particles, and under anoxic conditions, the dissolved phosphate is liberated from the sediment (Neumann and Schernewski, 2008).

The model maintains a Redfield elemental composition for phytoplankton with a non-Redfield elemental composition for dissolved organic matter (DOM) (Neumann et al., 2022). DOM can flocculate and form particulate organic matter (POM). The DOM is divided into three state variables: dissolved organic carbon (DOC), dissolved organic nitrogen (DON), and dissolved organic phosphorus (DOP). The temperature-dependent process rates (detritus recycling in the sediment, detritus recycling in the water column, recycling of DOC, and nitrification) are parameterized by the q_{10} parameter (Eppley, 1972), meaning a doubling of the process rate with a 10K increase in temperature. The complete model equations, parameters, and detailed processes are given in (Neumann et al., 2022).

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For the model sensitivity studies, we used a coupled physical-biogeochemical model. The circulation model is the Modular Ocean Model (MOM5.1; (Griffies, 2004)) with an integrated sea ice model (Winton, 2000), adapted for the Baltic Sea. The sea ice formation and its dynamics are based on Hunke and Dukowicz (1997). ERGOM is coupled with MOM5.1 via the tracer module, part of the MOM5.1 code.

2.1.2 q_{10} parameterisation in ERGOM

The temperature sensitivity on biogeochemical process rates (Figure 1) in an ecosystem model is traditionally represented by the q_{10} parameter (Neumann et al., 2002; Fennel et al., 2006; Eilola et al., 2009; Anju et al., 2020). The q_{10} parameter quantifies the change in the process reaction rate with a 10K change in temperature. Lower and higher values of q_{10} represent a slower and faster exponential increase in the reaction rates with temperature, respectively. Figure 1 illustrates the classical Q_{10} concept to provide a general understanding of the temperature sensitivity. In this classical formulation the rate is given as follows (Equation 1).

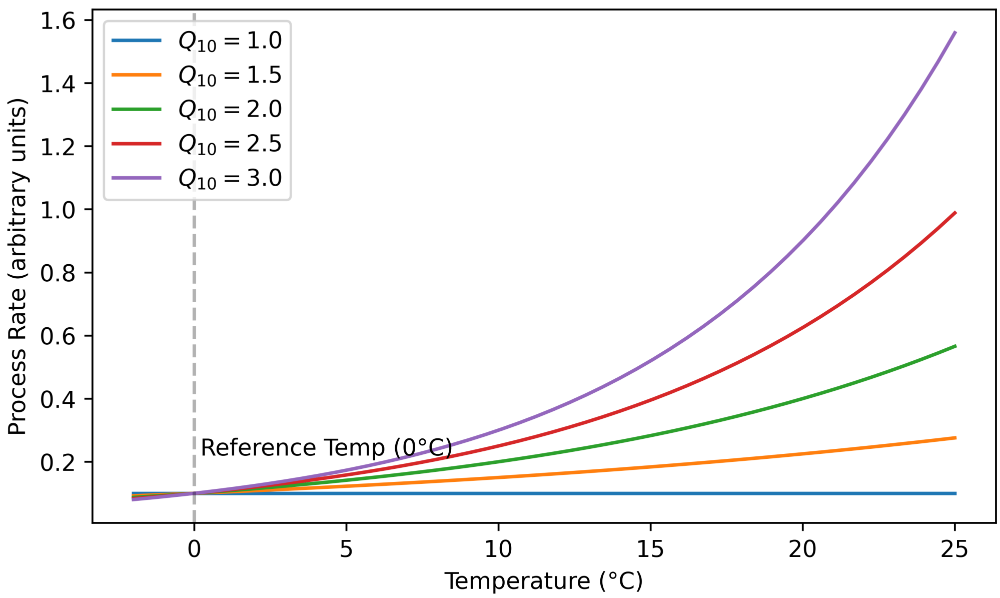

Figure 1. Effect of Q_{10} parameter on the reaction rate across temperatures. The curves represent reaction rates for Q_{10} values of 1.0, 1.5, 2.0, 2.5, and 3.0, showing how reaction rates increase exponentially with temperature relative to the reference temperature of 0°C, based on the classical Q_{10} formulation.

$$R = R_{\text{ref}} \cdot Q_{10}^{\frac{T - T_{\text{ref}}}{10}} \quad (1)$$

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R and R_{ref} are the reaction rate at temperature T and reference temperature T_{ref} respectively. Q_{10} the factor by which the process rate increases per 10°C. The implementation of temperature sensitivity of process rates in ERGOM uses an exponential formulation (Equation 2).

$$R = R_{\mathrm{ref}} \cdot \exp(q_{10} \cdot \mathrm{T}) \quad (2)$$

Here, R_{ref} and T are the reaction rates at the reference temperature and temperature, respectively. In ERGOM, the detritus recycling in sediment, detritus recycling in the water column, DOC recycling, and nitrification are formulated based on the q_{10} parameterization.

2.1.3 Model setup

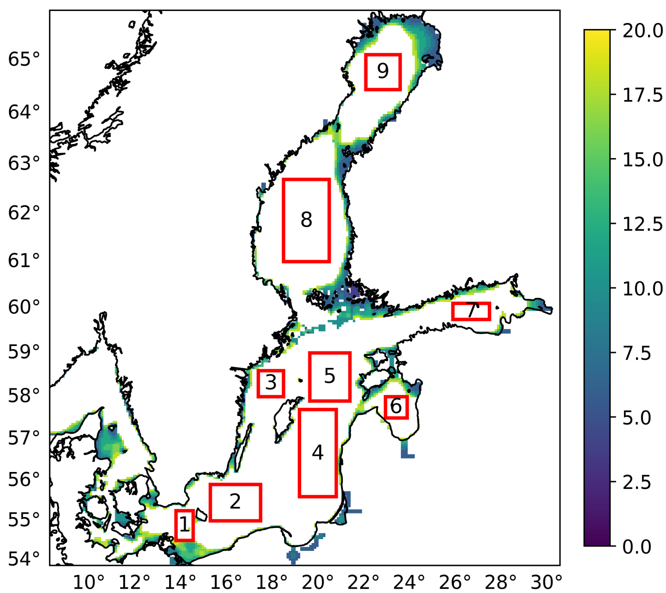

Figure 2. The study domain, the shaded region, represents the coastal zone with a depth less than 20m. The red boxes represent the distinct deep basins of the Baltic Sea (depth greater than 20m) from south to north as (1) Arkona Basin, (2) Bornholm Basin, (3) Western Gotland Basin, (4) Eastern Gotland Basin, (5) Northern Gotland Basin, (6) Gulf of Riga, (7) Gulf of Finland, (8) Bothnian Sea and (9) Bothnian Bay respectively.

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The coupled physical-biogeochemical model (MOM5.1-ERGOM) was applied to the Baltic Sea domain (Figure 2) with a horizontal resolution of 3 nautical miles (n.m., a relatively coarse resolution chosen as a trade-off between simulation costs and model accuracy). The model is resolved into 152 vertical layers, with a layer thickness of 0.5m at the surface and a gradual increase up to 2m with depth.

We simulated the model for 70 years (1950 to 2019) after a spin-up period of 50 years. Long simulation periods are necessary to ensure the reliability of the physical and biogeochemical processes in the Baltic Sea due to its high residence time (≈ 30 years). This is particularly important for phosphorus, which exhibits an even longer residence time than nitrogen (Radtke et al., 2012), due to its slower turnover. Therefore, extended simulation periods are necessary to represent biogeochemical cycling in the Baltic Sea accurately.

The model simulations were forced by the meteorological data from the coastDat-2 dataset (Geyer and Rockel, 2013). The nutrient loads from the riverine and atmospheric deposition are taken from the HELCOM assessments (Sonesten et al., 2018). The riverine alkalinity is taken from (Hjalmarsson et al., 2008) and assigned to the model rivers. A detailed model validation is given in Neumann et al. (2022).

2.2 Sensitivity experiments

Parameter	Value
Detritus recycling in the sediment	0.175 K^{-1}
Detritus recycling in the water column	0.15 K^{-1}
DOC recycling	0.069 K^{-1}
Nitrification	0.110 K^{-1}

Table 1. Details of the q_{10} parameters and the default value from (Neumann et al., 2022).

In this study, we focus on four biogeochemical processes parameterized using q_{10} as follows: (1) detritus recycling in the sediment, (2) detritus recycling in the water column, (3) DOC recycling, and (4) nitrification (the process details and equations are given in Neumann et al. (2022)). The corresponding q_{10} values for these processes are provided in Table 1. Our primary objective is to examine the impact of temperature sensitivity on biogeochemical cycling in the Baltic Sea. First, we assess the effects of uniformly increasing the q_{10} value for each process (i.e., one parameter at a time) across the entire Baltic Sea to understand its influence on the biogeochemical cycles of different basins shown in Figure 2. Next, we introduce a spatial contrast in the selected four process rates by increasing the q_{10} parameter only at the coastal ocean to reflect the observed

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higher process rates on the coast. Finally, we evaluate how these intensified coastal processes influence the biogeochemical conditions of the deeper Baltic Sea basins. The details of the sensitivity analysis are provided in Section 2.2.1.

Simulation	Parameter	Change
Base	All model parameters kept as default as in (Neumann et al., 2022).	
E1	Detritus recycling in the sediment	+10% for the entire Baltic Sea
E2	Detritus recycling in the water column	
E3	DOC recycling in the sediment	
E4	Nitrification	
C1	Detritus recycling in the sediment	+10% only in the coastal region
C2	Detritus recycling in the water column	
C3	DOC recycling in the sediment	
C4	Nitrification	

Table 2: Details of the q_{10} parameters and the corresponding changes in each sensitivity experiment.

In total, we conducted nine model simulations (one base simulation and eight sensitivity simulations) to investigate the role of coastal processes in defining the biogeochemical cycles of the deep Baltic basins (the nine boxes in Figure 2). The details of the model simulations are provided in Table 2. In the first four experiments (E1 to E4), we assumed an increase in the temperature sensitivity of the selected biogeochemical processes across the Baltic Sea, from the coast to the deep basins and from the surface to the bottom. It can be achieved by increasing the q_{10} parameter by 10% for the parameterizations of the selected processes. In the remaining four sensitivity simulations (C1 to C4), we imposed a higher temperature sensitivity for the selected processes in the coastal region (shaded region in Figure 2) while maintaining the default q_{10} values in the deeper regions of the Baltic Sea. Through this approach, we introduced a spatial contrast in the q_{10}.

2.2.1 Details of sensitivity analysis

A sensitivity analysis for an individual model parameter typically involves two model simulations, a baseline simulation and one with a modified parameter. For a model state variable V of interest (such as water column nitrate concentration in a selected station), the percentage sensitivity to a change in parameter P (i.e. ΔP) can then be defined as:

$$S = \frac{V_E - V_0}{V_0} \times 100 \tag{3}$$

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Where V_0 and V_E give the resulting state variable of interest in the baseline and the sensitivity run, respectively. If it leads to a 3% change, the sensitivity would be S = 3% for our chosen ΔP, which is $\Delta P = 0.1 \cdot P$ in our study. It should be noted that this sensitivity measure is not objective but depends both on ΔP and on subjective choices in the model formulation. In our example, it would depend on whether we give the temperature in Celsius or Kelvin. However, different but mathematically identical ways of writing the process equations will affect the value of S, such as using the square of a parameter rather than the parameter itself, or even logarithmic parameters. Therefore, a quantitative comparison between the S values for different parameters is not meaningful unless the exact formulation of the model equations is taken into account in the interpretation.

The same holds for a measure that we define as coastal sensitivity S_c. Here, we do a third model run where we change the parameter P, but only in the coastal zone (shaded region in Figure 2), which is the area where we suspect the parameter could differ in reality from its open-sea value. This run will give us a value V_C of our interested state variable. We can then calculate coastal sensitivity as follows:

$$S_c = \frac{V_C - V_0}{V_0} \times 100 \tag{4}$$

The coastal model run aims to simulate our suspicion that the biogeochemical processes differ in their rates between the coast and the basin. Here, we may assume that P (default parameter as per Neumann et al. (2022)) may be the correctly chosen value for the offshore area, while for the coastal zone, a value of "$P + \Delta P$" is closer to reality. The ratio between the two sensitivities, $\frac{S_c}{S}$, is independent of the specific formulation of the equations. This is at least true, as long as the magnitude of the ΔP is still in the linear range. Therefore, this ratio is the first objective measure comparable between the different model parameters. It allows us to assess the impact of a change in a specific parameter in the coastal zone compared to a change everywhere in the model domain.

We may typically assume that this ratio $\frac{S_c}{S}$ is smaller than one; In the coastal experiment, the parameter is only modified in a fraction of the model domain. If the ratio of the area of the coast to the total area of the Baltic Sea ($\frac{A_c}{A}$) is small, we may also expect the ratio to be small. Therefore it makes sense to normalize the ratio by the factor A_c, and we arrive at the relative coastal sensitivity as follows:

$$S_{cr} = \frac{\frac{S_c}{S}}{\frac{A_c}{A}} \tag{5}$$

The absolute (and dimensionless) value of S_{cr} now allows a direct interpretation. We assume that the quantity V is measured outside the coastal zone. A value of S_{cr} equal to zero means that the effect of changing the parameter in the coastal zone remains localized. A value of S_{cr} close to 1 means that the system likely reacts to changes in the parameter everywhere in the same way. So, ignoring a deviation of this parameter in the coastal zone from the open sea will have a small effect if the

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coastal area is small. If the value of S_{cr} is larger than one, this means we should make an effort to specifically constrain the parameter in the coastal zone, since the system reacts with a higher sensitivity to errors we make in the parameterization here. If the value of S_{cr} is substantially below zero, it indicates a mechanistic difference between the coast and the open sea. A strict thresholding is applied to ensure that the S_{cr} values reflect meaningful signals rather than numerical noise. The S_{cr} values are masked when the absolute value of S is less than 1%. This cutoff eliminates spurious signals that are not ecologically relevant.

To assess the impact of temperature sensitivity on selected biogeochemical process rates, we quantified the percentage sensitivities (S and S_c) and the relative coastal sensitivity (S_{cr}) as defined in Equations 3, 4 and 5, for five target biogeochemical variables V: nitrate (NO_3), ammonium (NH_4), phosphate (PO_4), phytoplankton (phyto) and oxygen (O_2). Here, the tracer hydrogen sulphide H_2S is considered as a negative O_2 concentration ($2H_2S$=-O_2). We assume that the biogeochemical variables are quantified outside the coastal zone (in the nine rectangles shown in Figure 2). This methodology helps us determine which model parameters should be explicitly constrained in the coastal region to reduce model biases.

3 Results

3.1 Impact of basin wide enhanced biogeochemical process rates

3.1.1 Response on nutrients

Nutrient dynamics show variable responses across different basins and different q_{10} parameters (Figure 3, Depth integrated tracer values were calculated by summing basin averaged tracer concentrations over depth. Values are for comparison between base and sensitivity simulations and are not converted to inventories. The same applies to all subsequent figures showing depth integrated tracer values). NH_4 displays both positive and negative sensitivity varying from -7 to 48%, particularly in Cases-E1, E2 and E4. The strong positive sensitivity is highly significant, as a 10% change in the q_{10} parameters for detritus recycling in the water and sediment results (E1 and E2) in a 30–45% change in water column NH_4, especially in the Gotland Basins (Figure 3). A strong negative sensitivity of NH_4 is evident in E4, which is a response to basin wide enhanced nitrification. A stronger positive sensitivity and accumulation of NH_4 is noted in the anoxic Gotland basin of the Baltic Sea compared to the oxic southern and northern basins. For instance, in the Northern Gotland Basin, NH_4 sensitivity to the enhanced detritus recycling in the sediment (i.e, E1) exceeds 48%, indicating that even a moderate increase in detritus recycling substantially increases the NH_4 concentration in the basin. The accumulation of NH_4 is observed with a significant decline in water column NO_3. In the oxic basins (southern and northern basins), the sensitivity of NH_4 (2 to 7%) is weaker (but still significant) compared to the Gotland Basin.

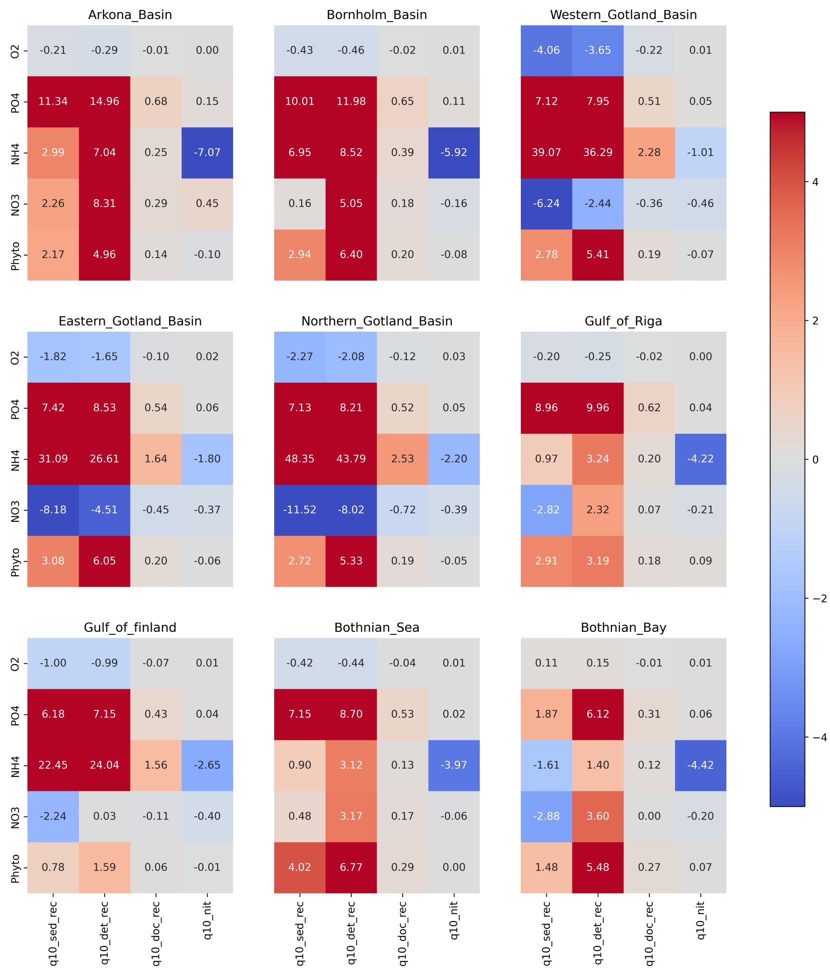

Figure 3. Percentage sensitivity on targeted ecosystem variables (Phytoplankton, NO_3, NH_4, PO_4, and O_2) to a 10% increase in biogeochemical parameters (q_{10} sed rec, q_{10} det rec, q_{10} doc rec, and q_{10} nit) across nine basins of the Baltic Sea. The targeted variables are depth integrated from surface to deep layer, basin averaged, and year averaged. Red shades indicate positive sensitivity, suggesting increased target variable values, while blue shades indicate negative sensitivity. Units are in %

Nitrate (NO_3) exhibits mixed responses to enhanced detritus recycling rates, showing a pronounced negative sensitivity in E1 for the Gotland Basin (-6 to -11%) as well as in the Gulf of Riga, Gulf of Finland, and Bothnian Bay (-2 to -3%). In E2, NO_3 increased/decreased in the northern basins (Arkona and Bornholm)/Gotland Basins, which is identical to E1. However, in the Gulf of Riga and the Bothnian Bay, a mechanistic difference is visible: NO_3 increases in E2 and decreases in E1. In the northern basins (Arkona and Bornholm), enhanced detritus recycling in the water column (i.e, Case-E2) increases both NO_3 and NH_4. The phosphate (PO_4) response is positive across all basins in all cases (E1 to E4), with significant sensitivity in E1 and E2, especially in the northern basins (Arkona and Bornholm).There are negligible effects on all five target variables in E3

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and E4 except NH_4.

3.1.2 Response on phytoplankton and oxygen

The oxygen (O_2) response is generally weaker. Though relatively minor, the Western Gotland Basin has the strongest oxygen decline (3 to 4%) in E1 and E2. In contrast, shallower basins such as Arkona and Bornholm exhibit minor oxygen changes. Phytoplankton exhibit a positive response across all basins in E1 (2 to 4%) and E2 (4-7%), with only negligible sensitivity in E3 and E4.

3.2 Effect of enhanced biogeochemical process rates in the coastal zone

Following the basin wide assessment of enhanced temperature sensitivity on biogeochemical variables, the analysis now focuses on the coastal region. Figure 4 shows the sensitivity of key ecosystem variables to increased temperature dependence in process rates within the shallow coastal region (shaded region in Figure 2). All the targeted variables show weak responses to enhanced process rates except NH_4 (a positive sensitivity 3% in the western and northern Gotland basin, and the Gulf of Finland in C2.

It is crucial to note that the coastal region (depth less than 20m; $9.976 \times 10^4\ km^2$) constitutes a small fraction of the total area of the Baltic Sea ($3.459 \times 10^5\ km^2$). As a result, any enhancement in biogeochemical processes in coastal areas may not be strongly reflected in the biogeochemical cycles of the deep basins. The relatively weak sensitivity observed in Figure 4 does not necessarily mean that coastal processes are insignificant. Instead, their effects appear small when considering the deep basins due to the limited area of the coast. Since the coast occupies a smaller fraction of the Baltic Sea, any changes in the coastal process may appear to have minor effects on the deep basin's biogeochemistry. However, if we normalize the percentage sensitivity to accommodate the impact of the area, the actual impact relative to their spatial extent becomes more apparent.

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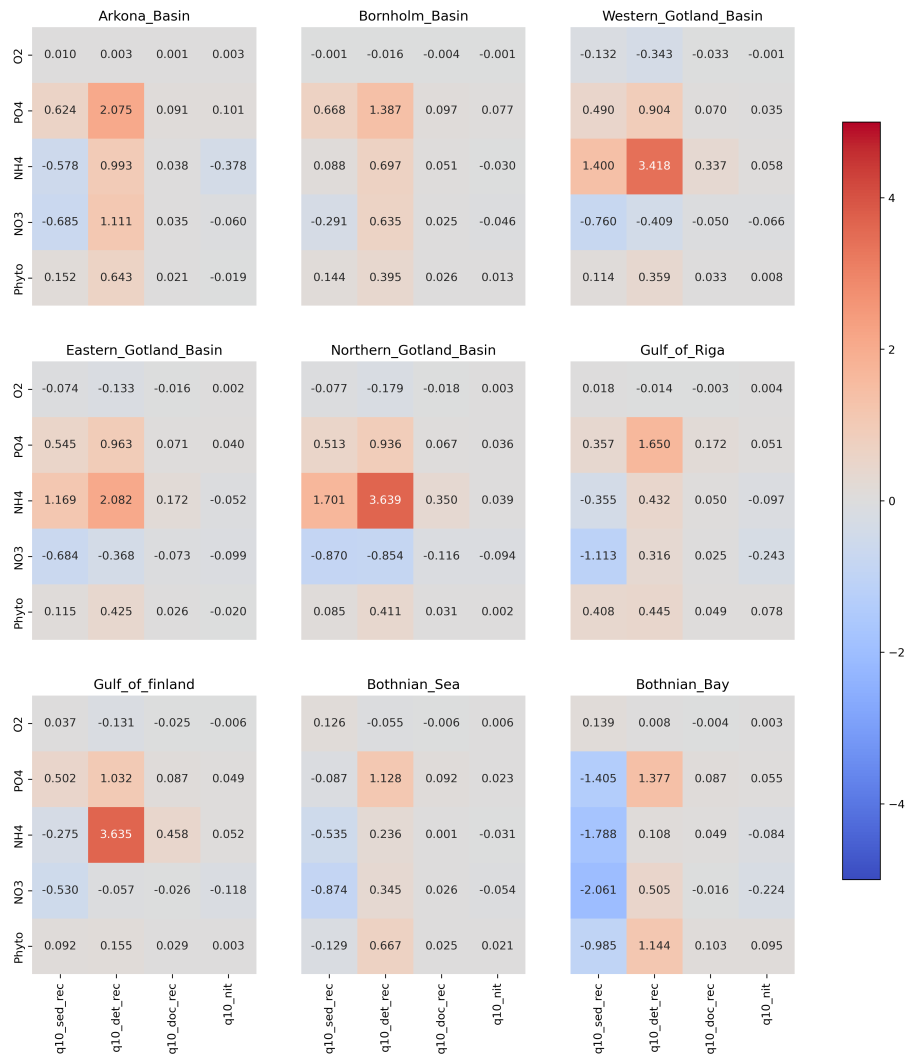

Figure 4. Percentage sensitivity on targeted ecosystem variables (Phytoplankton, NO_3, NH_4, PO_4, and O_2) to a 10% increase in biogeochemical parameters only in the coastal region (q_{10} sed rec, q_{10} det rec, q_{10} doc rec, and q_{10} nit) across nine basins of the Baltic Sea. The targeted variables are depth integrated from surface to deep layer, basin averaged, and year averaged. Red shades indicate positive sensitivity, suggesting increased target variable values, while blue shades indicate negative sensitivity. Units are in %

3.3 Relative coastal sensitivity (S_{cr})

The basin wide distribution of relative coastal sensitivity (S_{cr}; Figure 5) reveals clear influences of coastal biogeochemical parameterizations on nutrient and phytoplankton dynamics in various deep basins of the Baltic Sea. In the Arkona Basin, enhanced coastal sediment detritus recycling exerts a stronger influence on NO_3 concentrations than enhanced basin wide sediment recycling, as indicated by a S_{cr} value of -1.355. Interestingly, the NO_3 cycle in the Arkona basin exhibits con-

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trasting responses depending on the spatial extent of enhanced sediment recycling: NO_3 concentrations increase under a basin wide enhancement scenario (Figure 3 with S=2.26%), whereas a decrease is observed when enhancement is restricted to the coastal zone (Figure 4, with $S_c = -0.685\%$). This indicates an opposing response in the NO_3 cycle of the Arkona Basin to enhanced recycling in the sediment of coastal versus offshore regions, which warrants further investigation. For PO_4 and O_2, the changes fall well below the 1% threshold and are insignificant.

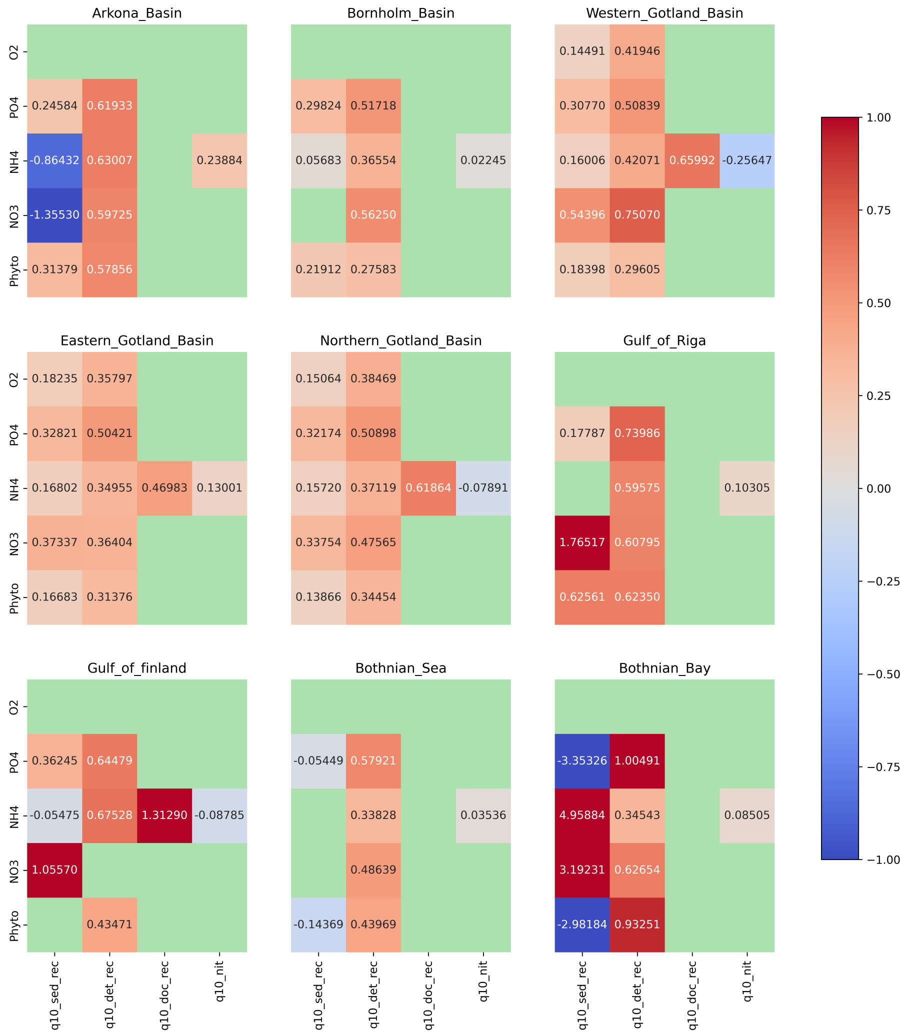

Figure 5. The relative coastal sensitivity S_{cr} is calculated in equation 5. The green boxes represent the masked S_{cr} where S is less than 1.

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In the Bornholm Basin, western Gotland Basins, eastern Gotland Basin, northern Gotland Basin, and the Bothnian Sea, the influence of enhanced process rates on the coast is negligible in the nutrient, phytoplankton, and oxygen cycle, with near-zero S_{cr} values. It implies that the temperature dependent process parameterizations in the coastal zone have limited impacts on the biogeochemical cycles in these basins. So ignoring the spatial differences in coastal v/s deep-sea process rates will not cause much bias in the model.

In contrast, the Gulf of Riga and Gulf of Finland show an elevated S_{cr} of 1.76 and 1.055 for NO_3, respectively, for the recycling in the sediment, highlighting a significant influence of coastal sediment recycling in the NO_3 dynamics in these basins. It emphasizes the need for a precise parameterization for the coastal sediment recycling to improve the nitrate cycling in these deep domains. In addition to nitrate, the NH_4 cycle is strongly affected by the coastal water column detritus recycling in the Gulf of Finland with an S_{cr} of 1.31. It indicates that the coastal zone plays a vital role in the nitrogen dynamics for the Gulf of Finland.

The Bothnian Bay exhibits the strongest influence of coastal processes of all other Baltic basins. The bay exhibits complex coastal sensitivities across multiple variables and processes. The detritus recycling in the sediment strongly influences the nutrient cycle and primary productivity of the basin. The phytoplankton and PO_4 show a strongly negative S_{cr} values of -2.98 and -3.35 respectively, indicating that the basin PO_4 cycle and primary production respond opposite to the enhanced sediment recycling in the coast from that of the entire Baltic Sea. In contrast, NO_3 and NH_4 have a strongly positive S_{cr} of 3.19 and 4.95, respectively, implying a disproportionately larger coastal influence on the nitrogen cycle of the basin. Here, any biases in coastal sediment recycling in the model can cause strong biases in the nutrient and primary production in the Bothnian Bay. For detritus recycling in the water column, S_{cr} values near unity for phytoplankton (0.93) and PO_4 (1.00) indicate that the coastal and basin wide enhanced water column recycling exerts comparable influences on these variables. The spatial complexity in the Bothnian Bay underscores the significance of process specific coastal parameterizations, especially for the detritus recycling both in the sediment and water column, to capture the biogeochemistry of the Bothnian Bay accurately.

3.4 Ecosystem response patterns to coastal and basin wide process enhancements

The sensitivity experiments reveal distinctive responses in water column nutrients, oxygen, and chlorophyll to increased temperature sensitivity of process rates. Notable differences emerge between the two sets of sensitivity experiments (E1 to E4 and C1 to C4; Figure 6 to Figure 10). In the Bothnian Bay, Gulf of Finland, Gulf of Riga, and parts of the Gotland Basin, water column nitrate concentrations respond similarly to both coastal and basin wide enhancement in sediment detritus recycling Figure 6a and 6e). However, a mechanistic difference is observed in other basins, namely the Bothnian Sea, Arkona Basin, and Bornholm Basin, where nitrate concentrations either decrease or increase depending on whether sediment recycling is enhanced in the coastal zone or in the entire basin (Figure 6a and 6e).

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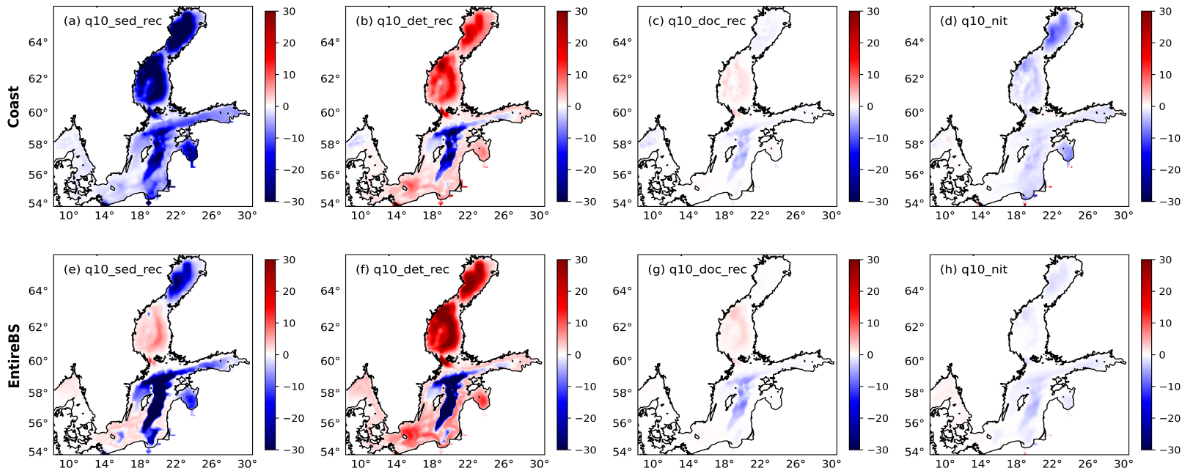

Figure 6. Entire depth integrated and annually averaged difference in water column nitrate concentration (NO_3, mol.m/kg) between the sensitivity and base simulations. Red and blue colors indicate an increase and decrease in NO_3 relative to the base simulation, respectively. The top row shows results from the coastal only sensitivity experiment (C1 to C4, area weighted), while the bottom panels represent the entire Baltic Sea experiment (E1 to E4).

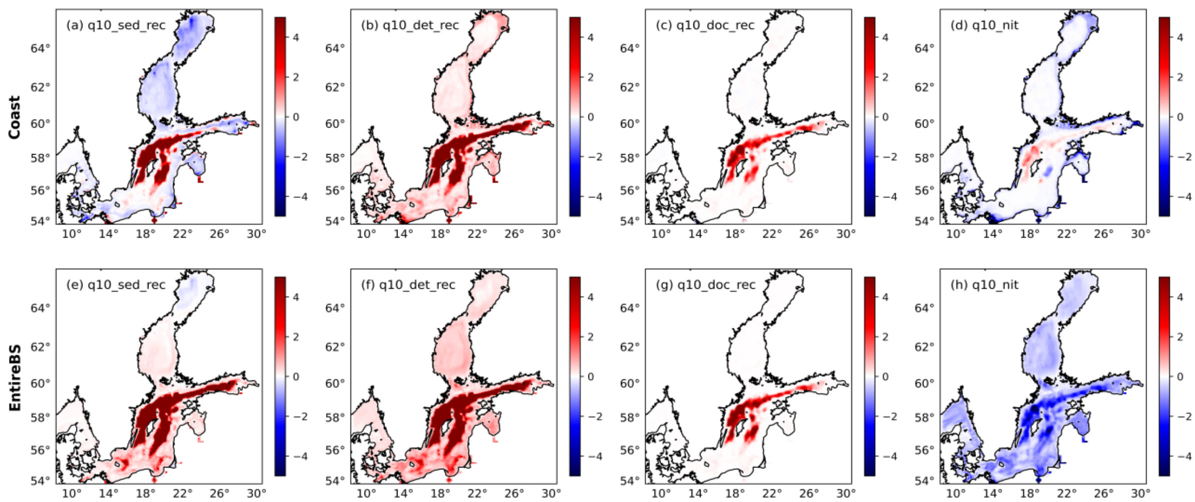

Figure 7. Entire depth integrated and annually averaged difference in water column ammonium concentration (NH_4, mol.m/kg) between the sensitivity and base simulations. Red and blue colors indicate an increase and decrease in NH_4 relative to the base simulation, respectively. The top row shows results from the coastal only sensitivity experiment (C1 to C4, area weighted), while the bottom panels represent the entire Baltic Sea experiment (E1 to E4).

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Basin wide enhanced sediment recycling leads to an increase in water column NH_4 throughout most of the Baltic Sea, except for a slight decline in the Bothnian Bay (Figure 7e). The accumulation of NH_4 (Figure 7e) coincides with a decline in NO_3 (Figure 6e) along the anoxic band of the Gotland Basin. In contrast, in oxic regions such as the Arkona Basin, Bornholm Basin, and the Bothnian Sea, NH_4 accumulation is less pronounced than in the anoxic zones of the Gotland Basin (Figure 7e).

The coastal experiment shows a decline in NO_3 throughout the Baltic Sea, with more pronounced decreases in the Bothnian Sea, Bothnian Bay, Gulf of Riga, and the Baltic proper (Figure 6a). Figure 10a indicates a decline in primary production in the northern basins (Bothnian Sea and Bothnian Bay), with only a slight increase in the other deeper basins. Additionally, in the coastal experiment, a decline in NH_4 is observed in the Bothnian Bay and Bothnian Sea (Figure 7a).

The water column NO_3 shows an increase (10 to 30 $molN \cdot m/kg$) in C2 (i.e., with enhanced coastal water column detritus recycling) in the northern Baltic basins (Bothnian Bay and Bothnian Sea; Figure 6b), with a slight increase also observed in the Gulf of Riga and the southern basins (Arkona and Bornholm basins). In the anoxic Gotland Basin, a strong reduction in NO_3 is accompanied by a significant accumulation of NH_4 (Figure 6b and Figure 7b).

The overall response of the Baltic Sea is similar in both the enhanced coastal and basin wide detritus recycling scenarios (C2 and E2). Water column NH_4 and PO_4 concentrations increase throughout the basin, with the strongest accumulation occurring in the anoxic region of the Gotland Basin (Figure 7b, 7f, 8b, and 8f). A slight decline in oxygen is observed throughout the Baltic Sea, except in the Bothnian Bay, in both cases of enhanced detritus recycling in the coast and the entire basin (Figure 9b and 9f).

In the case of enhanced DOC recycling, the Baltic basins respond similarly to process enhancements in both the shallow coastal areas (C3) and the entire basin (E3). Water column NO_3 shows a slight increase (less than five $molN \cdot m/kg$) in the southern and Gotland basins, as well as in the Bothnian Sea (Figure 6c and Figure 6g). Water column NH_4 accumulates along the anoxic zone in the Gotland Basin under both scenarios (Figure 7c and Figure 7g). No significant changes are observed in PO_4, O_2, or primary production in either scenario (Figure 8c, Figure 8g, Figure 10c, Figure 10g, Figure 9c, and Figure 9g). There is not much sensitivity observed for enhanced nitrification (C1 and E1, Figure 6-10 d and h).

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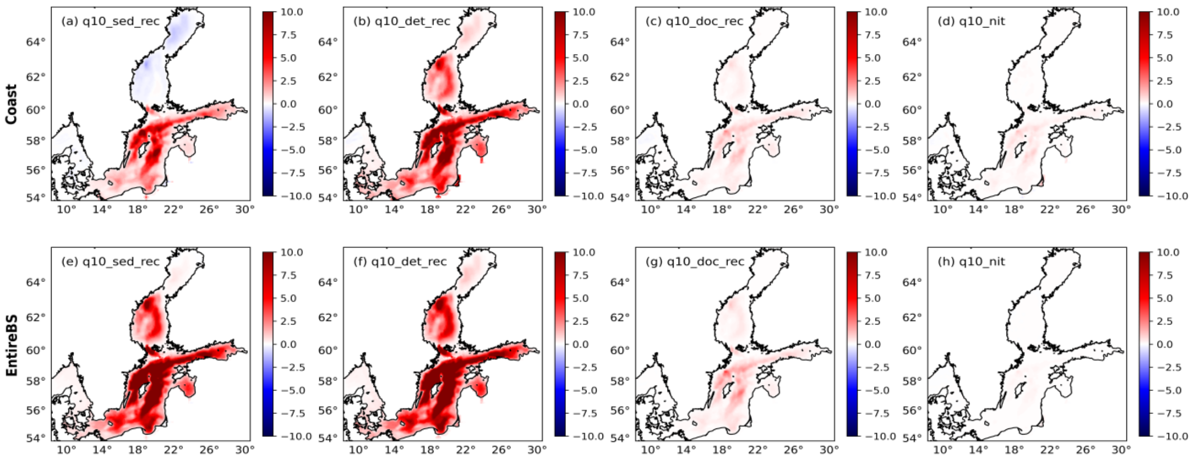

Figure 8. Entire depth integrated and annually averaged difference in water column phosphate concentration (PO_4, mol.m/kg) between the sensitivity and base simulations. Red and blue colors indicate an increase and decrease in PO_4 relative to the base simulation, respectively. The top row shows results from the coastal only sensitivity experiment (C1 to C4, area weighted), while the bottom panels represent the entire Baltic Sea experiment (E1 to E4).

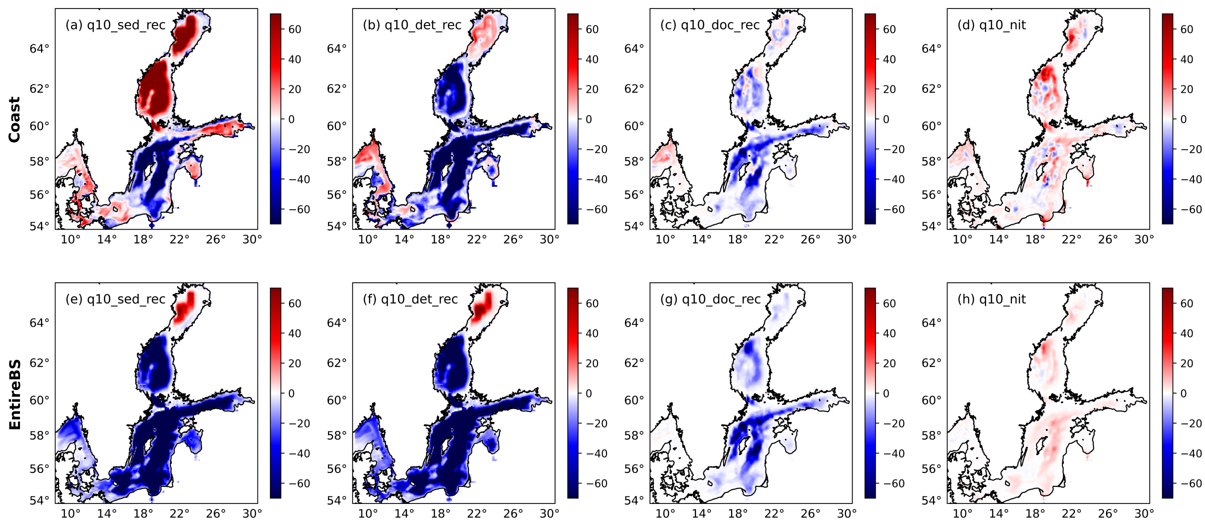

Figure 9. The entire depth integrated and annually averaged difference in water column nitrate concentration (O_2, mol.m/kg) between the sensitivity and base simulations. Red and blue colors indicate an increase and decrease in O_2 relative to the base simulation, respectively. The top row shows results from the coastal only sensitivity experiment (C1 to C4 area weighted), while the bottom panels represent the entire Baltic Sea experiment (E1 to E4).

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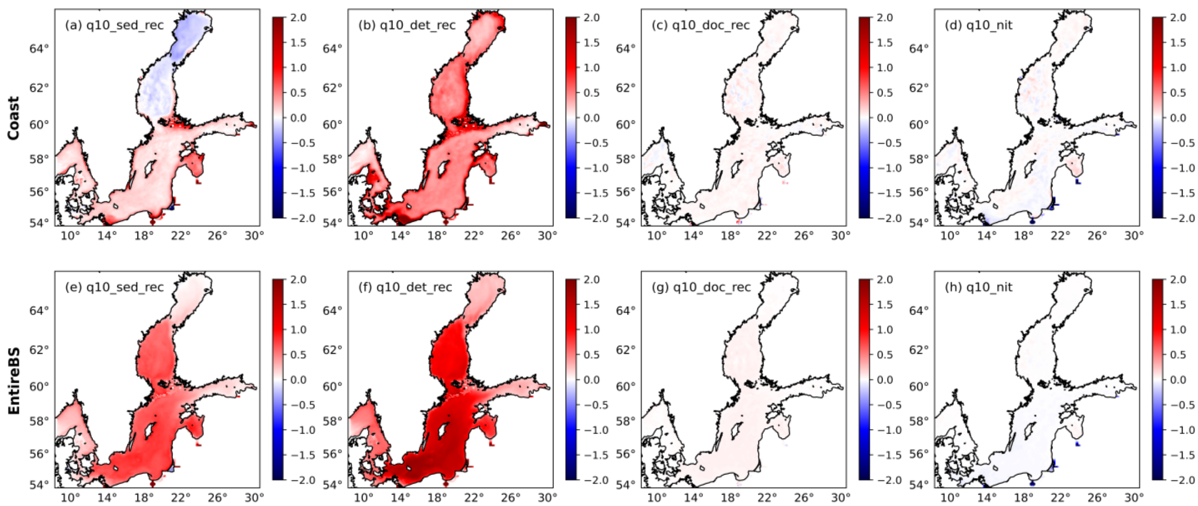

Figure 10. The entire depth integrated and annually averaged difference in water column phytoplankton concentration (Phytoplankton, mol N.m/kg) between the sensitivity and base simulations. Red and blue colors indicate an increase and decrease in Phytoplankton relative to the base simulation, respectively. The top row shows results from the coastal only sensitivity experiment (C1 to C4, area weighted), while the bottom panels represent the entire Baltic Sea experiment (E1 to E4)

4 Discussion

In this study, we investigated the role of q_{10} parameterization, and thus the temperature sensitivity of biogeochemical process rates, in shaping the biogeochemical dynamics of the deep basins of the Baltic Sea using a coupled physical and biogeochemical model, MOM5.1-ERGOM. The semi-enclosed Baltic Sea is particularly susceptible to climate-induced warming (Belkin, 2009), with surface warming driven by increasing air temperatures (Kniebusch et al., 2019; Dutheil et al., 2022) and deep-water warming driven by the lateral advection of heat (Meier et al., 2022; Barghorn et al., 2025b), and is naturally characterized by strong spatial temperature gradients (due to its large latitudinal extent), with warmer conditions in the southern regions and colder conditions in the northern basins (Rasool et al., 2015; Meier et al., 2022). This makes it a valuable natural laboratory for assessing temperature-dependent processes in marine ecosystems. By systematically increasing the q_{10} parameter, both uniformly across the entire Baltic Sea and selectively in the shallow coastal regions (depths less than 20 m), we evaluated how regional differences in temperature sensitivity propagate through the system and influence the biogeochemistry of the deep basins. The discussion below synthesizes our findings in terms of the extent and mechanisms by which coastal versus basin scale parameter perturbations affect deep water processes, the spatial heterogeneity in system responses, and the implications for model calibration and observational prioritization.

As expected, the basin wide enhancement of temperature sensitive process rates had a substantial influence on the biogeochemical cycles of the Baltic Sea and its deep basins (Neumann, 2010; Meier et al., 2011). The enhanced process rates led to

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both increases and decreases in water column NH_4 concentrations, depending on which q_{10} parameter and associated pathway were affected. NH_4 accumulation was primarily observed under intensified remineralization in both the water column and sediment (Maksymowska-Brossard and Piekarek-Jankowska, 2001). Increased remineralization enhances the decomposition of organic matter into inorganic nutrients, including NH_4. This accumulation was most pronounced in the anoxic basins of the Baltic Sea, particularly in the Gotland Basin (Kuliński et al., 2022). In contrast, NH_4 accumulation was weaker in the more oxic regions, such as the Gulf of Riga, Bothnian Bay, and Bothnian Sea. In these areas, coupled nitrification and denitrification are likely dominant processes. Nitrification, an oxygen dependent process that converts NH_4 to NO_3, is more efficient in oxic conditions, thereby limiting the buildup of NH_4 in the water column.

In contrast, in the deep Gotland Basins, a substantial buildup of NH_4 in the basin is due to enhanced sediment and water column recycling (Lengier et al., 2021). This can be explained as a combination of high temperature-driven remineralization rates and the anoxia in the basin, which inhibits nitrification (a process that is a sink for NH_4) and favors the anaerobic pathway, such as the denitrification process (a process that is a sink for NO_3). Under oxygen-limited conditions, the bacteria prefer NO_3 as an electron acceptor for the oxidation of organic matter, which reduces the water column NO_3 concentration while facilitating the production of NH_4. The simultaneous enhancement of NH_4 and the decline in NO_3 concentration in the anoxic basins of the Baltic Sea support this mechanism. Furthermore, the limited nitrification in the anoxic water column prevents the conversion of NH_4 back to NO_3, further contributing to the accumulation of NH_4 in the basin.

In the more oxygenated southern and northern basins of the Baltic Sea, enhanced detritus recycling led to only a modest increase in NH_4. Here, the oxygen-rich environment can support the coupled nitrification and denitrification, a process that inhibits the accumulation of NH_4 in the water column, maintaining a more balanced nutrient cycle.

The accumulation of NH_4 and removal of NO_3 as a response to enhanced remineralization in sediment and water column, particularly with the temperature increase, may have significant ecological implications. The high NH_4 levels in the euphotic zone can shift the primary production towards the regenerated production and favour plankton that adapted to nutrient recycling over those that rely on new nutrient input (Dugdale and Goering, 1967; Anju et al., 2020). This shift can then impact the entire food web and may reduce the carbon export and potentially reduce the ocean carbon pump. However, in the Baltic Sea, such ecosystem shifts may be more constrained due to its unique ecological characteristics.

In the Baltic Sea, the nitrogen dynamics show spatial heterogeneity in response to enhanced detritus recycling in E1 and E2. There is a significant decline of NO_3 in the Gotland Basin and a modest decline in the northern basins (Gulf of Riga, Gulf of Finland, and Bothnian Bay). The reduction in NO_3 can be due either to enhanced phytoplankton uptake or enhanced denitrification under anoxic/hypoxic conditions, especially in the stratified deep Gotland Basin. The insignificant sensitivity (increase) in phytoplankton and significant accumulation of NH_4 in these regions suggest that the observed decline in NO_3

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may be due to enhanced denitrification, especially in the stratified, anoxic deep Gotland Basin of the Baltic Sea.

In E2, where the basin wide detritus recycling is enhanced in the water column, the response of NO_3 cycling differs between the basins. The western basins (Arkona and Bornholm) show an increase in both NO_3 and NH_4, but the accumulation of NH_4 is not as strong as in the deep Gotland basins. It indicates that enhanced water column detritus recycling enhances the remineralization and forms NH_4. In the shallow and oxic northern basins, the coupled nitrification and denitrification convert NH_4 to NO_3 (source of NO_3) and remove NO_3 to N_2 through denitrification (sink for NO_3), and prevent significant accumulation of NH_4 (Hietanen et al., 2012). That is, in the northern basins, it likely boosted NO_3 availability without triggering immediate losses through denitrification. In contrast, the Gotland basins show a similar decline in NO_3 as in E1, with a significant accumulation of NH_4 and decline of NO_3, suggesting that in the central stratified anoxic basins, the biogeochemical cycling is characterised by stronger stratification and anoxic conditions, which amplify the NO_3 loss through denitrification.

An exciting finding is the contrasting response of NO_3 in the Gulf of Riga and the Bothnian Bay between E1 and E2. In E1, NO_3 declines, whereas in E2, an increase in water column NO_3 is observed. It suggests a mechanistic shift in the NO_3 cycling depending on whether the detritus remineralization occurs in the sediment or water column. These basin-specific dynamics indicate the importance of considering vertical and horizontal process coupling in the Baltic Sea to represent the biogeochemistry of the basin.

Phosphate responded positively across all the basins and all the cases (E1 to E4), with a substantial increase in E1 and E2 and the most pronounced effects in the western Baltic Basins (Arkona and Bornholm). This consistent increase in the water column PO_4 indicates that detritus remineralization is a robust source of bioavailable PO_4 in the system, potentially contributing to eutrophication risk in an already nutrient-rich Baltic Sea.

The contrasting sensitivities of NH_4 and NO_3 between the oxic and anoxic basins of the Baltic Sea suggest fundamentally different recycling pathways and nutrient dynamics under warming-induced enhanced recycling in the sediment and water column. Figure 11 provides a conceptual schematic summarizing the mechanistic differences in nutrient dynamics under oxic and anoxic conditions. Enhanced temperature-dependent sediment and water column remineralization releases NH_4 from sediments and the water column, which is largely nitrified to NO_3 under oxic conditions and subsequently lost through denitrification. In oxic basins, the accumulation of NH_4 in the water column is prevented by the coupled nitrification–denitrification process, which strongly depends on the redox conditions of the water and sediment. In contrast, in anoxic basins, enhanced detritus recycling in the sediment and water column promotes the accumulation of NH_4 in the water column, accompanied by a decline in NO_3 availability, thereby altering nitrogen cycle pathways. Enhanced remineralization promotes NH_4 production, and the anoxic and hypoxic conditions prevent nitrification while promoting denitrification. The dominance of denitrification over nitrification causes a decline in NO_3 along with an accumulation of NH_4 in these basins.

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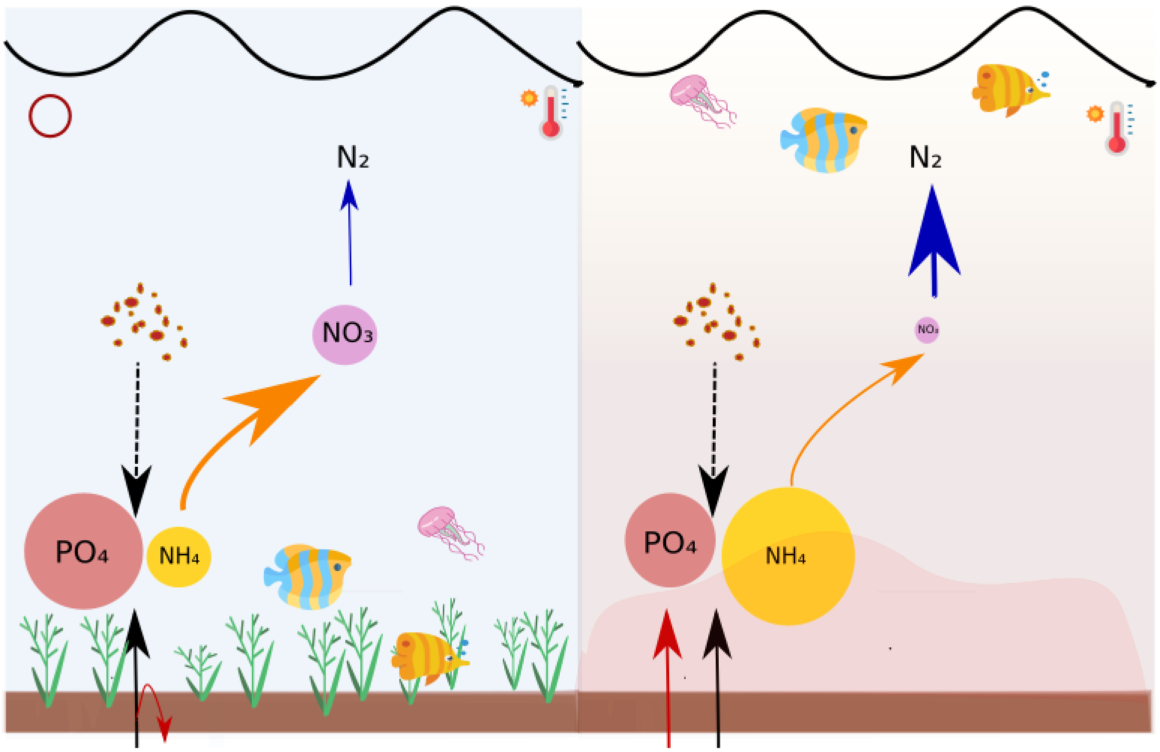

Figure 11. Conceptual schematic of how temperature induced enhanced recycling in the sediment and water column affects nutrient dynamics under oxic (left) and anoxic (right) conditions in the Baltic Sea. The black solid and dashed arrows show remineralization from the sediment and water column, respectively. The red curved arrow (left panel) and straight arrow (right panel) represent phosphate binding to iron and phosphate release from the sediment. The orange and blue arrows indicate nitrification and denitrification. The arrow sizes represent process intensity. The brick-red, yellow, and pink circles represent the pools of phosphate, ammonium, and nitrate, respectively, with circle size indicating changes in pool size relative to the base run (open red circle in the left panel). In the base run, the same pool size was assumed for all nutrients, making it easier to interpret changes in the enhanced remineralization runs. The light-red shaded region in the right panel represents anoxic bottom waters, with hypoxic and oxic layers above. The bottom brown layer represents the sediment.

The DOC recycling (E3) and nitrification (E4) show negligible influence on the nutrient cycling in all the Baltic Sea basins, apart from a decline in NH_4 in the oxic basins (north and south) in E4, due to the oxidation of NH_4 to NO_3 through nitrification in the oxic basins.

Overall, our findings highlight the central role of water column detritus remineralization in driving the regional differences in nutrient dynamics. They point to the fact that accurate representation of recycling processes is essential to understanding how nutrient dynamics change with climate change and anthropogenic pressures.

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Our analysis shows that the O_2 response to the enhanced temperature sensitivities in the process rates (E1 to E4) is weak and insignificant across the Baltic Sea basins, with a notable decline in water column O_2 in the western Gotland Basin under E1 and E2. This localized sensitivity can be attributed to the basin's high stratification and limited vertical mixing and ventilation, which reduces O_2 replenishment and makes it more susceptible to biological remineralization. In contrast, the shallower basins (Arkona and Bornholm) show insignificant sensitivity in O_2 in response to enhanced process rates, indicating that the strong vertical mixing and shorter residence time of water in these basins may buffer the decline of O_2 by the remineralization process. The phytoplankton, on the other hand, shows a basin-wide increase in all cases, indicating that the enhanced process rates in the entire Baltic Sea enhance the nutrient cycling and nutrient availability, which promotes phytoplankton growth. The negligible response in E3 and E4 implies that the processes altered in these scenarios are less critical for both O_2 and phytoplankton dynamics.

In order to examine the spatially varying temperature sensitivity on the biogeochemical cycles of the Baltic Sea, we have implemented enhanced temperature sensitivities on process rates only in the shallow coastal regions (depth less than 20 m). By this methodology, we implemented spatially varying process rates in the model. The sensitivity of coastal enhanced processes on biogeochemical variables shows minor impacts except for the modest increase in water column NH_4 in the western and northern Gotland Basins and the Gulf of Finland in C2. Here, the absolute changes on biogeochemical cycles appear minor due to the small area of the coastal zone compared to the entire Baltic Basin. As a result, the impact of coastal zones becomes negligible when assessed on a basin scale. However, the weak or coastal sensitivity in the deeper basins does not imply that the coastal processes are insignificant. In order to understand the real potential of coastal changes on the basin scale, we have normalized the coastal sensitivity with the area; then the coastal influence becomes more significant and comparable with that of the entire Baltic Sea experiments.

To examine the role of coastal processes on the biogeochemistry of the deeper Baltic Basins, we defined a non-dimensional metric called relative coastal sensitivity (S_{cr}), which can quantitatively answer the question, which processes are the most relevant ones to investigate and confine, when we are interested in an accurate representation of the function of coastal zones for the basin-wide biogeochemistry. The absolute (and dimensionless) value of S_{cr} now allows a direct interpretation. A value of zero or closer to zero means that the effect of changing the parameter in the coastal zone remains localized; it does not reach the deep location at which the targeted variables (nutrients, O_2, and phytoplankton) were observed. Here, it would not make much sense to assess this parameter in the coastal zone specifically. It rather means that confining this parameter in the open sea will reduce model uncertainty more substantially. A value of one means that the system reacts identically to local changes in the parameter P, independent of whether these occur at the coast or in the open basins. Applying the same relative change over the same number of square meters will have a similar effect on the biogeochemical cycles in the deeper basins. So, ignoring a deviation of this parameter in the coastal zone from the open sea will have a small effect if the coastal area is small. A value larger than one means that we have an enhanced coastal sensitivity: If the parameter differs in the coastal zone, this has an even larger impact on the open-sea conditions than a local change there. This means we should make an effort to

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specifically constrain the parameter in the coastal zone, since the system reacts with a higher sensitivity to errors we make in the parameterization here. A value below zero indicates a mechanistic difference between the coast and open sea: Changing the parameter in the coastal zone will affect our observed quantity in the opposite direction compared to a local change. This means that the system will react oppositely to errors that we make in the model parameters in the coastal zone and offshore. In this case, we should try to understand the mechanism why this happens, as this is a possible source of error: If we calibrate/tune the model, i.e., change the parameter such that the observations of targeted variables are matched better, this may lead to worse estimations of the model parameter P in the coastal zone and the process rates associated with it. Very large values of S_{cr} may occur if the sensitivity S is close to zero, but the coastal sensitivity S_c is not. These should not be interpreted quantitatively, but they indicate that the system may be much more sensitive to changes in the coastal zone than one might expect from the classical sensitivity analysis, where the parameter is changed everywhere in the model domain.

The relative coastal sensitivity (S_{cr}) reveals a spatially heterogeneous pattern of model sensitivity across the Baltic Sea. Basins such as Bornholm, the entire Gotland Basins (Western, Eastern, and Northern), and the Bothnian Sea exhibited uniformly low S_{cr} values ($\pm$ less than 0.5), indicating that the enhanced process rates have limited impact on the basin-scale biogeochemistry in these basins. This suggests that, for these regions, refining and calibrating model parameters in the open sea will be more effective in reducing model biases than concentrating calibration in the shallow coastal regions. These results highlight the variable role of coastal zones in different parts of the deep Baltic Sea basins in defining the biogeochemical dynamics and emphasize the need for region-specific monitoring and modeling approaches.

In contrast, the Arkona Basin shows a distinct mechanistic sensitivity, particularly with detritus recycling in the sediment. The observed negative S_{cr} for NO_3 suggests divergent responses between coastal only and basin-wide parameter perturbations, highlighting the need for cautious and targeted calibration of sediment nitrogen recycling processes in this basin.

The Bothnian Bay exhibits the most complex pattern of S_{cr}. Very high values of S_{cr} for nutrients (NH_4, NO_3, and PO_4) and phytoplankton for sediment detritus recycling indicate that coastal processes significantly impact the biogeochemical cycles of this basin. Here, confining the q_{10} parameter for detritus recycling in the sediment of the coastal region can help improve model biases in the nitrogen cycle, as the coastal processes show significantly higher sensitivity in the nitrogen cycling of the basin. However, at the same time, there is an evident mechanistic difference observed with PO_4 and phytoplankton in the Bothnian Bay, which suggests that any error in the parameterization of coastal recycling in the sediment can induce large errors in the PO_4 cycle in the basin. This pattern implies that the system's response in the Bothnian Bay may be governed by distinct feedbacks or transport processes, where coastal parameter changes lead to contrasting outcomes compared to changes applied basin-wide.

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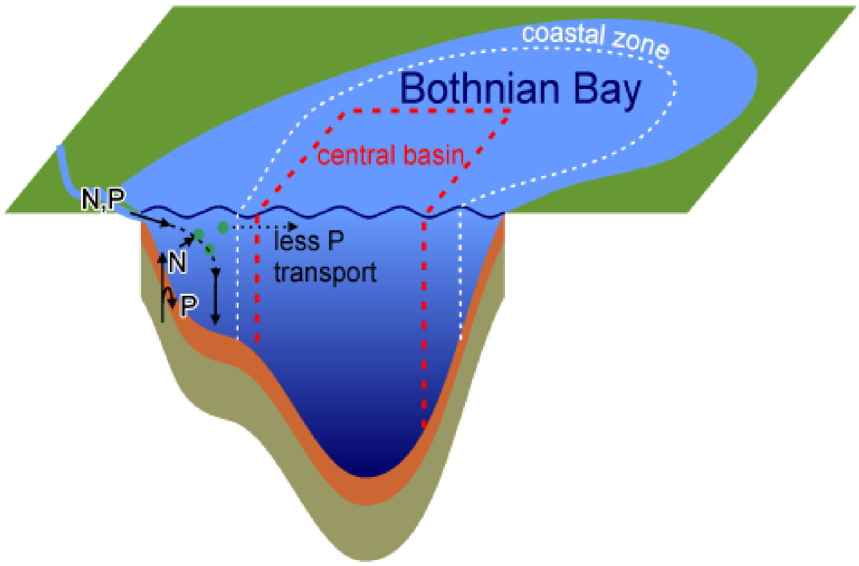

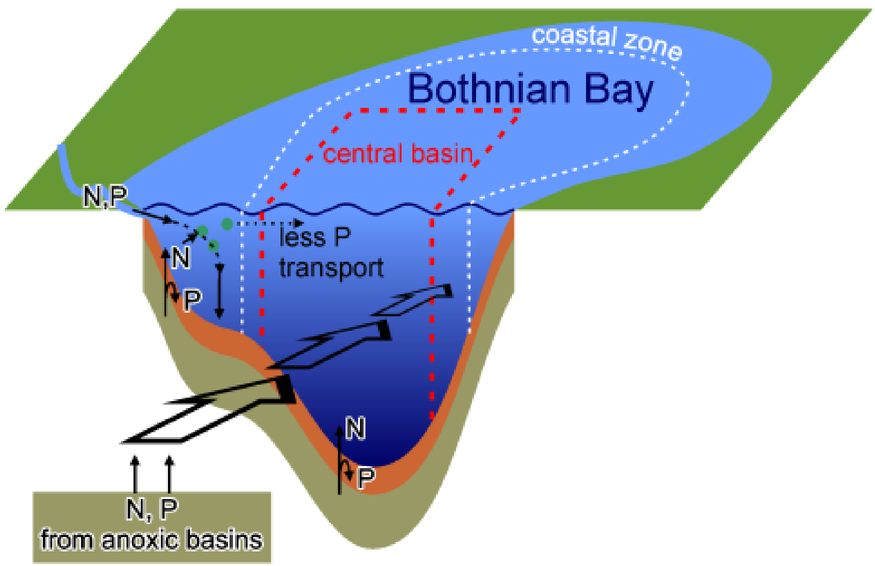

Figure 12. Schematic representation of the hypothesized mechanisms controlling PO_4 dynamics in the Bothnian Bay. Upper panel (Case-C1): White and red dashed contours represent the coastal zone and the central basin, respectively. The two-layer sediment is shown with an iron-rich surface layer (brick red) and a deeper layer. Black horizontal arrows indicate riverine nutrient input of N and P, small vertical arrows indicate remineralization-driven release of N and P from sediments, and curved arrows represent PO_4 retention as iron-bound phosphate. Green dots denote phytoplankton, and dotted black arrows indicate nutrient input from the coast to the deep basin. Lower panel (Case-E1): In addition to the processes described above, large black arrows illustrate the transport of PO_4 from adjacent anoxic basins (e.g., Gotland Basin) via anticlockwise circulation.

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These contrasting responses between the C1 and E1 experiments led us to formulate a mechanistic hypothesis for the PO_4 dynamics in the Bothnian Bay (Figure 12). When sediment recycling is enhanced only in the coastal zone (C1), remineralization produces additional NH_4 and PO_4, but under oxic conditions in the coastal sediments, much of the released PO_4 becomes bound as iron–phosphate and is retained in the sediment. At the same time, excess nitrogen species (NH_4 and NO_3) accumulate due to enhanced recycling and riverine inputs, while PO_4 remains largely trapped in the sediments. In this situation, phytoplankton growth in the coastal zone is fueled primarily by riverine phosphorus, and nutrients are temporarily retained in biomass, thereby strengthening the role of the coastal filter and ultimately reducing the PO_4 supply to the open Bothnian Bay. By contrast, when sediment recycling is uniformly enhanced across the entire Baltic Sea (E1), the local processes in the Bothnian Bay are supplemented by additional nutrient release from other basins. In the Bothnian Bay itself, the released PO_4 can still be sequestered in sediments due to oxic bottom waters, but in other anoxic basins such as the Gotland Basin, enhanced sediment recycling releases PO_4 that is not re-bound to the sediments. The PO_4 entering the Bothnian Bay is controlled by the flow through the channel connecting the Bothnian Sea and the Bothnian Bay. This excess PO_4 can then be transported northward via the prevailing anticlockwise circulation, ultimately increasing PO_4 concentrations in the Bothnian Bay. This mechanistic explanation is consistent with the strongly negative S_{cr} value for PO_4, suggesting that coastal processes can exert disproportionate and opposing effects on basin-scale phosphorus dynamics depending on whether parameter changes are confined to the coast or applied system-wide.

Our methodology helps to underscore the importance of targeted coastal parameterization in regions where S_{cr} is greater than one or less than one, as coastal processes in these zones have a disproportionately large or mechanistically unique impact on the deep basins, which must be captured correctly to reduce uncertainty in regional biogeochemical modeling.

5 Summary and Conclusions

In this study, we examine how temperature-driven changes in biogeochemical processes affect nutrient and primary production dynamics in the Baltic Sea using a 3D coupled physical biogeochemical (ERGOM) model that has nitrogen, phosphorus, oxygen, and partial sulfur cycles. Here we revisit the traditional way of representing the temperature-sensitive biogeochemical processes using the classical q_{10} parameterization with uniform values for both the coast and its deep. We tested the effects of enhanced q_{10} values applied either throughout the entire Baltic Sea or specifically in shallow coastal zones, analyzing the responses of nine major deep basins. We found that detritus recycling in both the sediment and water column is a crucial process that affects the basinwide biogeochemistry of the Baltic Sea. A 10% increase in the q_{10} parameter can result in up to 50% changes in the nitrogen species (nitrate and ammonium) indicating a strong nonlinear response. Increased remineralization due to warming raises the levels of phosphate, ammonium, and subsequently nitrate in oxic basins, where sufficient oxygen supports nitrification. The relatively low accumulation of ammonium and nitrate compared to the anoxic basins indicates an enhanced remineralization of detritus and organic matter in the sediment and water column. It suggests that nitrification plays a crucial

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and dominant role over denitrification in controlling the nitrogen turnover in the oxic basins of the Baltic Sea. In contrast, the anoxic basins of the Baltic Sea, such as the deep Gotland basins, exhibit strong ammonium and phosphate accumulation with a depletion of nitrate in the water column, reflecting oxygen-limited nitrification and enhanced denitrification in these basins. The rising nutrient levels due to the basinwide enhanced remineralization indicate a potential for higher primary productivity under a future warm climate. The oxic basins of the Baltic Sea may witness an increase in both new and regenerated production due to the greater availability of both nitrate and ammonium in the water column. At the same time, the anoxic basins may shift towards regenerated production due to the accumulation of ammonium in the water column. However, under climate change, increased stratification could limit the availability of these nutrients in the euphotic zone, potentially constraining productivity despite the higher concentrations of nutrients in the deeper depths. The Bothnian Bay displayed strong and complex coastal influences compared to all other basins. A significant accumulation of phosphate in this basin suggests that the bay may become less phosphate-limited with warming, which has implications for changes in productivity regimes. To comprehend the impact of coastal processes on the biogeochemistry of deeper basins, we conducted sensitivity analyses in which the enhancement of temperature-driven process rates was confined to the coastal zone. Although coastal zones are spatially limited, we aimed to determine whether local process changes could disproportionately influence the broader basin-scale biogeochemistry. Our experiments revealed that coast-only q_{10} perturbations did not always lead to substantial system-wide changes. To account for the coastal zone's smaller spatial extent, we developed a non-dimensional metric, called relative coastal sensitivity S_{cr}, which normalizes the difference in system response based on the area fraction of the coast. Using this metric, we observed that nitrate consistently showed greater sensitivity to coastal sediment recycling compared to basinwide enhancements, particularly in the Arkona Basin, Gulf of Riga, Gulf of Finland, and Bothnian Bay. The Bothnian Bay was especially sensitive to increased coastal sediment and water column recycling, with S_{cr} values ranging from 2 to 4 for nitrogen species. This suggests that coastal processes can have a 2–4 times greater relative influence on nutrient dynamics and phytoplankton than equivalent changes applied across the entire basin. These results emphasize the need to resolve coastal processes in ecosystem models spatially. While changes confined to coastal areas may seem limited in absolute magnitude, their normalized impact can be disproportionately significant, especially in sensitive basins like the Bothnian Bay. The differences in response between coast-only and full-basin perturbations also highlight the nonlinear and basin-specific nature of feedbacks, which must be taken into account in both model parameterization and management-oriented scenario studies. In summary, this study underscores the critical need to represent process-specific coastal parameterizations particularly for temperature-sensitive pathways such as remineralization and nutrient recycling in biogeochemical models in the context of climate change. Our study suggests that the influence of coastal processes on the biogeochemical cycles of the deep basins varies across the Baltic Sea. The Bothnian Bay is more sensitive to changes in coastal processes than other basins. Thus, high resolution representation of coastal processes is essential, although their influence on basin-scale biogeochemical cycles is limited to certain sub-basins. In particular, inaccurate representation of coastal processes in models can misrepresent the coastal filter in sensitive basins, leading to erroneous estimates of nutrient transport to the deeper open sea. This, in turn, can undermine efforts to mitigate the impacts of eutrophication and climate change.

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Author contributions. Anju Mallissery contributed to designing the study, designed the model experiments, conducted the model simulations, analyzed the results, and wrote the original manuscript. Hagen Radthke contributed to designing the study, setting up the model, and assisted with the interpretation of results and writing of the manuscript. Thomas Neumann contributed to setting up the model and provided critical feedback on the manuscript. Markus Meier provided the initial idea for the research and assisted with the interpretation of results. All authors discussed the results and contributed to the final manuscript through review and corrections.

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