Response to Reviewer 2 Comments

Börgel, Ruvalcaba Baroni et al.

General Response

We sincerely thank the reviewer for the thorough, constructive, and highly valuable evaluation of our manuscript. We appreciate the recognition of the effort invested in this work and the detailed suggestions that have significantly improved the clarity, structure, and scientific precision of the paper.

In our answer, reviewer's comments are in red, our responses in blue and our suggested modified text in italics.

1 Summary

Reviewer: The study highlights potential teleconnections of the North Atlantic Region to the Baltic Sea and collects evidence from the available literature. Potentially impacted variables range from sea ice cover and oceanographic variables (such as temperatures or sea level elevations) to biogeochemistry. The manuscript considers various time scales (from synoptic to multi-decadal). Future research is encouraged and priority research needs are outlined.

Major Comments

Reviewer: I appreciate all the effort that went into this manuscript. Overall, it is well written - however, at times the presentation would benefit from greater precision and clarity. For example, the phrase "Teleconnections between the North Atlantic and the Baltic Sea region" (Ln 1, 55) may be misleading, as it could be interpreted as implying a mutual or two-way interaction with the North Atlantic Ocean. Also, it would be helpful to clarify early on that variability in the Baltic Sea is predominantly governed by local atmospheric dynamics. These local synoptic systems are embedded within the large-scale circulation, which allows atmospheric patterns in the North Atlantic region to exert an indirect impact on regional atmospheric dynamics and, consequently, on the Baltic Sea. The mechanisms underlying these potential remote influences from the North Atlantic should be explained more explicitly, and known effects should be quantified whenever possible, including contemporary estimates of uncertainty. In its present form, the manuscript appears somewhat vague and lacks a clearly articulated objective. Previous findings are often described using rather unspecific terminology (e.g., "robust connections" (Ln

320), “fundamentally connected” (Ln 37), “closely connected” (Ln 65), which makes it difficult to assess their precise meaning. Moreover, the discussion appears somewhat one-sided, with many processes being primarily attributed to the North Atlantic Oscillation (NAO) (e.g., Sect. 2.3).

Response:

We will rephrase misleading terminology throughout the manuscript (e.g., “teleconnections between the North Atlantic and the Baltic Sea”) to avoid implying mutual or two-way oceanic coupling. We will also clarify that Baltic Sea variability is predominantly governed by local atmospheric dynamics, embedded within large-scale Northern Hemisphere circulation and improve our explanation of underlying processes.

Greater care will be taken to address previously vague terminology. However, it should be noted that most processes have not been systematically quantified or statistically evaluated in the literature. As our aim is not limited to well-established and quantified processes, we will also include and describe plausible or potential mechanisms where relevant. Care will be taken to add estimations where possible.

Furthermore, if the discussion places particular emphasis on the North Atlantic Oscillation (NAO), this reflects the fact that the majority of existing studies focus on this phenomenon. Consequently, there is substantially more available evidence on the NAO than on other processes. Nevertheless, we will make efforts to balance the discussion and explicitly acknowledge that much of the current literature is centered on the NAO.

Changes in the text will be made according to specific comments and thus detailed below.

Specific Comments

Reviewer: Ln 1: This sounds like a mutual or two-way relationship. If so, this statement needs evidence.

Response:

We agree that the wording in the title suggests a two-way relationship. Hence, we will change the title to suggest an impact of the North Atlantic on the Baltic Sea region.

Changes to the text: Title: “Large-scale atmospheric circulation and its impact on the Baltic Sea Region: Controls, Predictability and Consequences”

Reviewer: Ln 2: It remains unclear what “in the region” refers to.

Response:

We agree that in the abstract “Baltic Sea region” has not been yet defined and thus, we will remove ”region” from the sentence.

Reviewer: Ln 5: Shouldn't this be "regional ocean model data" instead of "climate models data"? I don't expect classical climate models can resolve the Baltic Sea in the level of detail needed for this study.

Response:

We agree that for the Baltic Sea, a regional model is necessary as global ocean models do not capture relevant dynamics. However, in this manuscript we do look at global models results in the literature to understand mechanisms that can potentially affect the Baltic Sea. We believe the sentence is thus correct as it is. Nevertheless, we have rephrased the sentence for clarity.

Changes to the text: "By integrating evidence from the published literature, observational datasets, and both global and regional climate model simulations, we assess established as well as potential linkages to key climatic variables, including temperature, precipitation, and storm activity, across temporal scales ranging from synoptic events to multidecadal variability."

Reviewer: Ln 6: "other key indicators from synoptic to multidecadal time scales" is rather vague.

Response:

We agree with the reviewer and will rephrase the sentence as pointed out in the revised text above.

Reviewer: Ln 17: what does "their" refer to?

Response:

We will change two sentences to clarify this point.

Changes to the text: "Many resident species already live close to species-specific salinity tolerance limits and are simultaneously exposed to multiple human stressors, making them highly sensitive to environmental change (e.g., HELCOM, 2023). Even small shifts in physical or biogeochemical conditions can substantially influence species abundance and growth. "

Reviewer: Ln 18: I think "modulating" should rather be "modulate". Could you provide a reference?

Response:

We agree with the reviewer and will also rephrased the entire sentence to improve clarity.

Changes to the text: "Superimposed onto these pressures, atmospheric variability in the Euro-Atlantic region further modulates the Baltic Sea's ecosystem across synoptic to multidecadal time scales (e.g., Kahru et al., 2020)."

Reviewer: Ln 27f: The flowing sentence is unclear and might be misinterpreted "The Baltic Sea represents a unique interface where Atlantic, Arctic and continental climate influences create a dynamic system that is governed by remote teleconnections.". The Baltic Sea is mostly impacted by local atmospheric dynamics, which is certainly embedded in the large-scale atmospheric circulation of the Northern Hemisphere.

Response:

We agree and will rephrase the whole paragraph.

Changes to the text: "The Baltic Sea is shallow, with a mean depth of 53 m and a maximum depth of 459 m (e.g., Jakobsson et al., 2019). It is shaped by a unique topography comprising several sub-basins and is connected to the North Sea only via the narrow and shallow Danish straits, which severely restrict water exchange between the two seas (e.g., Meier et al., 2022). The result is an estuarine-like circulation with a fresher upper layer - sustained mainly by river runoff and, to a lesser extent, excess precipitation - that overlies more saline bottom waters which are renewed by intermittent saline inflows from the North Sea. This stratification suppresses vertical mixing and ventilation, increasing the vulnerability to hypoxic and eutrophic conditions."

Reviewer: Ln 28: I find these paragraphs somewhat confusing. It does not become clear from the text which processes act on which time scales and how local and larger scale dynamics are related.

Response:

We agree with the reviewer and will rephrase the whole paragraph.

Changes to the text: "Given this strongly stratified, weakly ventilated system, local atmospheric forcing dominates the Baltic Sea's hydrodynamic variability on short time scales. On longer time scales, however, large-scale Euro-Atlantic circulation variability shapes the statistics of that forcing, most clearly in winter, by modulating the prevalence and persistence of westerlies, cold-air outbreaks, and storm-track activity (Stigebrandt and Gustafsson, 2003). The regional climate reflects a sensitive balance between moist, relatively mild marine air from the North Atlantic and the Eurasian continental influence, resulting in transitions between maritime and subarctic conditions. Accordingly, the southern and western parts ..."

Reviewer: Ln 35: Please explain why these are considered key modes and add some explanation on their definition. I would expect specific local atmospheric pattern to be of interest (e.g. Lehmann et al. (2002)) and it would be interesting how these relate to the considered larger-scale modes.

Response:

The reviewer has a good point and we will clarify why NAO, blocking, and AMV are treated as key modes and now also address the role of local patterns, citing Lehmann et al 2002 as an example of how the NAO projects onto a Baltic Sea pressure - gradient/wind pattern that directly governs Baltic Sea storage and exchange through the Danish Straits. The paragraph will thus be rephrased.

Changes to the text: "Key large-scale modes influencing the Baltic Sea include the North Atlantic Oscillation (NAO; Hurrell et al., 2003), atmospheric blocking (Woollings et al., 2010a) and, on longer timescales, their interplay with the Atlantic Multidecadal Variability (AMV; Börgel et al., 2018). These modes are widely used because they can be linked to variability in the North Atlantic atmosphere (i.e., pressure and wind field) and are associated with jet shifts. Together they explain a substantial fraction of observed variability over the Baltic Sea region (e.g., Meier and Kauker, 2003; Stockmayer and Lehmann, 2023; Kniebusch et al., 2019a; Börgel et al., 2020). Changes in the jet's position and strength shape storm-track activity and thereby influence regional atmospheric forcing over the Baltic Sea including the frequency and persistence of local circulation states. For example, Lehmann et al. (2002) relate the large-scale NAO to a Baltic Sea pressure-gradient pattern (their Baltic Sea Index) that co-varies with Baltic Sea filling level and exchange through the Danish Straits, illustrating how remote modes project onto the local forcing that directly drives Baltic Sea dynamics."

Reviewer: Ln 40: It does not become clear what is meant by "these climate drivers". I would expect that local air temperature, local winds and precipitation are the key physical drivers for the Baltic Sea ocean dynamics. There might well be a relation to the major atmospheric modes in the North Atlantic – but it does not become clear how and how much these could explain all the local atmospheric phenomena.

Response:

The paragraph will be modified and "these climate drivers" have been clarified in the new formulation. Please see the revised text above.

Reviewer: Ln 43: "Permanent anoxic bottom waters have developed in the deep basins of the central Baltic Sea during the 20th century". Is this right? cf. Moros et al (2024).

Response:

We will clarify what we mean and refer to Moros et al., 2024.

Changes to the text: "While episodic large saltwater inflows from the North Sea (so-called "Major Baltic Inflows; MBIs) can temporarily oxygenate bottom waters (e.g., Moros et al., 2024), anoxia intensified in the deep basins of the central Baltic Sea during the 20th century, driven by increased anthropogenic nutrient loads and subsequent eutrophication. Since the 1980s, when nutrient levels were at their peak, anoxia has become largely permanent (e.g., Gustafsson et al., 2012; Carstensen et al., 2014; Meier et al., 2012, 2019; Papadomanolaki et al., 2018; Carstensen and Conley, 2019). Despite substantial efforts to reduce nutrient inputs since the 1980s, the Baltic Sea has shown little improvement in its eutrophication status, and deep-water oxygen conditions have continued to deteriorate (Gustafsson et al., 2012; Almroth-Rosell et al., 2021; Hansson et al., 2020; Krapf et al., 2022). "

Reviewer: Ln 46: "Atmospheric . . . ." This sentence is completely unrelated to the foregoing sentence but gives somehow the impression that atmospheric Euro-Atlantic teleconnections are responsible that there has been only a limited success in improving eutrophication.

Response:

We will split this into a new paragraph and rephrase to avoid confusion also addressing the reviewer's comment on line 48f.

Changes to the text: "Large-scale Euro-Atlantic circulation variability has been shown to impact the Baltic Sea ecosystem by modulating the statistics of local forcing (e.g., Hänninen et al., 2000; Dippner et al., 2019; Gröger et al., 2024). However, the effects vary regionally as coastal and sub-basin dynamics respond differently to changes in local forcing (e.g., winds, heat fluxes, freshwater input, or vertical mixing) (Eremina et al., 2012; Lehtoranta et al., 2017; Dietze and Löptien, 2021; Gröger et al., 2021; Stoicescu et al., 2022; Löptien and Dietze, 2022; Polyakov et al., 2023; Dabulevičienė and Servaitė, 2024). In the Baltic Sea, such differences can emerge as changes in coastal upwelling and cross-shore transport, shifts in riverine freshwater and nutrient supply, or altered stratification, deep-water ventilation, and oxygen depletion in the central basins. Disentangling these sources of internal variability from anthropogenic trends,"

Reviewer: Ln 48ff: This paragraph is rather vague. Could you explain "the multiple interacting drivers" and the statement "coastal and sub-basin dynamics respond differently to various physical forcing" a bit more?

Response:

We agree with the reviewer and will modify the text according to the revised text above.

Reviewer: Ln 54: I don't understand the special focus on biogeochemistry as it depends on local ocean dynamics and local nutrient dynamics. Please delete or clarify.

Response:

This will be clarified according to the revised text above, more specifically by adding the following:

Changes to the text: "... by modulating the statistics of local forcing ..."

Reviewer: Ln 56: This last sentence implies that the aim is to understand climate variability while the following text is about weather pattern. It should be clarified throughout the manuscript which processes act on which timescales and which might be important. Also, I lack a clear relation to the title of the manuscript.

Response:

This will be clarified and the text modified. Note that we will also specify what is meant by Baltic Sea region and refer to the figure here instead of earlier in the text. We will rephrase also according to the main point 2b of reviewer #1:

Changes to the text: "This review synthesizes current understanding of how large-scale atmospheric Euro-Atlantic circulation variability relates to local forcing over the Baltic Sea region (here defined as the Baltic Sea and its surrounding catchment area; Figure 1) across timescales ranging from synoptic to multidecadal. It also examines how the resulting hydrodynamic variability is linked to oxygen dynamics, primary productivity and ocean acidification. We focus specifically on the recent evolution of the Baltic Sea, during which anthropogenic climate change has become the dominant long-term external driver. Against this background, we examine how variability in Euro-Atlantic circulation patterns governs local forcing over the region and critically assess how these large-scale atmospheric influences interact with ongoing climate change."

Reviewer: Ln 68: What is meant by "climate modes"? (e.g. the NAO is relevant mainly for winters and acts on various time scales; I would tend to call it something like atmospheric mode of variability).

Response:

Climate modes is used to prescribe persistent or recurrent pattern in the climate system. To be more precise we will replaced this by the IPCC wording (`https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_AnnexIV.pdf`):

Changes to the text: "modes of climate variability"

Reviewer: Ln 70ff: The description of the jet dynamics on the various time scales and it's relation to the major large scale atmospheric modes could be more precise and systematic. How predictable is the jet dynamics?

Response:

We agree that the introduction of the North Atlantic jet can be framed more systematically by time scale and by its projection onto canonical modes. We therefore will rephrase this paragraph and an additional paragraph that organizes jet variability from synoptic to multidecadal scales and link jet latitude/strength/tilt to two examples (NAO, EA) and Scandinavian/blocking patterns and the regime framework.

Changes to the text: "The North Atlantic jet influences regional weather across Europe and the Baltic Sea region by modulating pressure systems, temperature advection, cloud cover, radiative processes and precipitation patterns (Woollings et al., 2010a, 2014; Hallam et al., 2022). More specifically, jet variability in the North Atlantic can be organized by time scale. On synoptic time scales, it primarily reflects baroclinic wave growth and downstream development that is tightly coupled with the storm track. On longer intraseasonal time scales, the dominant variability is captured by persistent flow patterns (weather regimes) (Vautard, 1990; Cassou et al., 2004; Cassou, 2008; Grams et al., 2017; Falkena et al., 2020). On seasonal to interannual scales, anomalies in the jet latitude and strength project onto canonical modes of climate variability *such as the NAO or the East Atlantic pattern (Hurrell, 1995; Barnston and Livezey, 1987a; Woollings et al., 2010b; Woollings and Blackburn, 2012; Woollings et al., 2015; Perez et al., 2024). On decadal and longer time scales, coupled ocean-atmosphere variability in the North Atlantic can modulate the jet and storm track, providing a pathway for low-frequency variability to influence Northern Europe and the Baltic Sea region (O'Reilly et al., 2017; Simpson et al., 2019; Athanasiadis et al., 2020; Ruggieri et al., 2021; Börgel et al., 2020)."*

"It should be noted that several localized processes further modulate this large-scale circulation and form the basis for typical synoptic-scale weather phenomena and dominant modes of climate variability affecting Baltic Sea region. Factors such as orography, seasonal snow, ice cover, radiative processes, ocean heat transport and differences between land and ocean surfaces all contribute to a distinct thermal structure that drives a seasonal cycle. As a consequence, the jet stream follows a seasonally varying pattern with locally modified characteristics (Hallam et al., 2022; Woollings et al., 2010a). ".

Reviewer: Ln 84: Again, this sentence is very vague and it does not become clear which processes and dynamics it refers to: "Given the complexity of mid-latitude dynamics, it is difficult to disentangle the individual impacts of these processes" . Please delete or be more specific.

Response:

We agree and will remove the sentence. For clarity, we will slightly change the sentence that follows right after as follows:

Changes to the text: "Pattern-based dimensionality reduction approaches are commonly used to assess this complexity, including canonical large-scale circulation patterns such as the NAO (Hurrell, 1995) or the Euro-Atlantic weather regimes (Vautard, 1990), which collapse jet and storm-track variability, Rossby-wave dynamics, and related regional modulation into a small number of reference states and display a systematic connection to jet characteristics (Madonna et al., 2017)."

Reviewer: Ln 84ff: It does not become clear which time scales are to be considered and why these where chosen. E.g. major Baltic inflows play a major role and depend on very specific weather pattern - not the NAO (e.g. Schimanke et al (2014); Schinke & Matthäus (1998), Matthäus & Franck (1992) and many more to follow).

Response:

We will state explicitly which time scales are considered and why due to changes earlier in the text. We will also add a remark and references noting that MBIs are driven by specific synoptic pressure/wind sequences and are therefore not well summarized by a single index at the end of the paragraph.

Changes to the text: "They are less suited to describe phenomena that are controlled by spe-

cific synoptic sequences rather than low-dimensional modes, such as MBIs, which depend on particular wind and pressure patterns (e.g., Matthäus and Franck, 1992)."

Reviewer: Ln 91ff: It does not become clear to me how local blocking might be impacted by teleconnections and how or if it relates to 2.1.1. and what is the current state of knowledge.

Response:

We agree with the reviewer that the previous text mainly defined blocking and listed impacts, but did not explicitly connect blocking to the jet/Rossby-wave framework introduced earlier. To address this, we will rephrase the paragraph to connect blocking to amplified planetary-wave/Rossby-wave dynamics and jet deformation and also mention the potential that modes of climate variability modulate frequency, persistence, and preferred location of blocking by shifting the jet and storm track.

Changes to the text: An atmospheric block is a long-lasting (days to a few weeks) weather pattern that occurs when persistent and quasi-stationary highs hinder the climatological westerly winds in the midlatitudes (Liu, 1994). Dynamically, blocking is closely tied to the jet-stream and Rossby wave variability discussed in the previous section, as it reflects amplified planetary-wave patterns and is often accompanied by wave breaking and a deformation or splitting of the jet. This commonly leads to a deflected and strong zonal flow north and south of the blocking system (Michel et al., 2023) and prevents the usual progression of synoptic weather systems across large areas (Rex, 1950; Steinfeld et al., 2022). Blocking systems typically extend vertically across the whole troposphere and are associated with large high pressure systems at the surface. As a consequence of their tight coupling to the background flow, changes in the large-scale circulation states (and modes of climate variability) can modulate blocking statistics by shifting the jet and storm track and therefore also the region of dominant wave amplification and breaking.

Reviewer: Ln 113ff: The authors might consider to rename this section as it does not become clear what is meant by "Natural variability" in this context. In any case I would appreciate a clear distinction which time scales are considered.

Response:

We acknowledge the reviewer's comment and after reflection, we think that adding the definition of "natural variability" following the IPCC glossary in the beginning of the section will clarify this point. The motivation for the time scales will be given earlier in the document as follows:

Changes to the text: "Natural variability refers to climatic fluctuations that occur without any human influence, that is, internal variability (i.e., noise generated within the system) combined with the response to external natural factors such as volcanic eruptions or changes in solar activity (Arias et al., 2021). The natural variability of the North Atlantic climate system affects the Baltic Sea region across multiple temporal and spatial scales, "

Reviewer: Ln 122: I find it confusing to start the subsection "Synoptic, intraseasonal and seasonal time scales" with the sentence "The climate of the Baltic Sea region is driven by ...." as according to the common definition climate refers to averages of 30 years or more.

Response:

We agree and will rephrase as follow:

Changes to the text: "Atmospheric circulation variability over the Baltic Sea region spans a broad range of time scales, from synoptic to multidecadal, and reflects the interplay of atmospheric, oceanic, and terrestrial factors. At shorter time scales, departures from the climatological reference state often take the form of large-scale geopotential height anomalies that persist from several days to about two weeks (Kautz et al., 2022)."

Reviewer: Ln 130: I would not count the NAO as a classical "weather regime" – rather as a leading atmospheric mode in an EOF analysis of sea level pressure anomalies on at least monthly time scales for a certain region and it is dominant during winter. All modes should be clearly introduced somewhere. Also, it should be mentioned that in most EOF-based NAO definitions, the Baltic Sea region is included in the analysis domain. So it's not a teleconnection in a classical sense. Still, while the Baltic contributes variance it does not control the structure or phase of the NAO.

Response:

We will clarify the wording of section 2.2.1 and also add a short paragraph at the start of section 2.2. We also agree and will avoid the framing as teleconnection.

in section 2.2.1, 2d paragraph, we add the following:

Changes to the text: "Traditionally, the canonical Euro-Atlantic weather-regime classification refers to the four recurrent large-scale circulation regimes most robustly identified in boreal winter (Vautard, 1990; Cassou, 2008; Barrier et al., 2014; Falkena et al., 2020). In this manuscript, weather regimes refer to statistically identified, recurrent large-scale circulation states, rather than to individual synoptic weather patterns. The Zonal and Greenland-Blocking regimes are often described as NAO-like, in the sense that they project strongly onto the positive and negative phases of the NAO, respectively."

Response:

And, as a second paragraph at the start of 2.2:

Changes to the text: "In this review we distinguish between different statistical methods to describe large-scale circulation patterns, such as the NAO derived from EOF-based analyses of sea-level pressure or geopotential-height anomalies, or weather regimes, which describe recurrent, quasi-stationary circulation patterns diagnosed from clustering methods on daily to sub-seasonal time scales. While these frameworks are related, weather regimes often project onto leading modes, and are not interchangeable."

Reviewer: Ln 138ff: Please specify how exactly these regimes were identified. Also, it does not become clear how these regimes relate to the local atmospheric dynamics in the Baltic Sea region.

Response:

We thank the reviewer for this comment. The weather regimes used here are not subjectively defined in our study; they follow the objective regime classification described in Grams et al. 2017. In brief, the regimes are obtained by applying an unsupervised clustering (k-means) to daily large-scale circulation anomalies over the Euro-Atlantic sector (based on standardized geopotential-height/sea-level-pressure anomaly fields after removing the seasonal cycle and reducing dimensionality using leading EOFs / principal components). Each day is assigned to the regime whose centroid it is closest to in phase space, yielding discrete regime labels (e.g., NAO+, NAO-, Scandinavian blocking, Atlantic Ridge naming as in Grams et al., 2017).

We will add a short methodological description and clarify the physical interpretation for the Baltic Sea region: the regimes represent recurrent large-scale pressure and flow configurations that systematically modulate the near-surface wind direction and strength, storm-track positioning, and the balance between maritime vs. continental air-mass advection over Northern Europe. Consequently, they provide a physically meaningful bridge between Euro-Atlantic synoptic variability and regional atmospheric dynamics over the Baltic Sea (e.g., shifts in westerly flow vs. blocking, changes in meridional advection, and associated temperature/precipitation and wind field responses).

Changes to the text: "The regimes are identified objectively from daily large-scale circulation anomalies over the Euro-Atlantic sector: the seasonal cycle is removed and anomaly fields are normalized by their standard deviation, dimensionality is reduced using the leading EOFs (principal components), and k-means clustering is applied in this reduced phase space. This yields a daily sequence of regime occurrence, with some days assigned to one of the recurrent regimes and others classified as transition or "no regime" days (Grams et al., 2017). The regimes affect the Baltic Sea region by shaping the synoptic-scale pressure gradient over Northern Europe. They are closely linked to jet-stream variability and the associated characteristic flow patterns (Madonna et al., 2017). As a result, they modulate the prevalence and intensity of westerly flow into the Baltic Sea catchment versus blocking situations, as well as the position and strength of the storm tracks affecting the region."

Reviewer: Ln 166: I would rather say something like this "the NAO reflects observed interannual variability in winter" - it's not really a driver. Then it should be clarified what kind of variability.

Response:

We will rephrase our wording to be more precise as follows:

Changes to the text: "The NAO reflects a leading mode of observed interannual wintertime *variability in North Atlantic–European atmospheric circulation and is tightly coupled to the zonal jet."*

Reviewer: Ln 174ff: This is interesting. Could you provide some more details? As I understood this also refers to the North Atlantic while the links to the Baltic Sea region remain unclear. Please correct me if I am mistaken.

Response:

Thanks for spotting this. We will clarify the link between weather regimes and climate patterns but also end subsection 2.2.2 with the role for the Baltic Sea.

Changes to the text: "To link this interannual view with the synoptic–intraseasonal weather-regime diagnostics of the previous section, we map the interannual teleconnection indices to their weather-regime analogues by comparing the composite circulation."

Response:

and at the start of the last paragraph of this subsection:

Changes to the text: "In summary, these interannual modes systematically alter the direction and strength of the flow over Northern Europe/Scandinavia, modulating winter advection, storminess, temperature, and sea-ice. Multiple other interannual circulation patterns in the Euro-Atlantic sector have been identified, for example the East Atlantic / West Russia pattern (Barnston and Livezey, 1987b; Kauker and Meier, 2003; Craig and Allan, 2022) or the Barents Sea Oscillation (Skeie, 2000; Tremblay, 2001). They all represent a statistical description of characteristic jet features. However, there is little literature specifically addressing their role in modulating the climate of the Baltic Sea region on interannual timescales."

Reviewer: Ln 183: What is meant by "multidecadal tendencies".

Response:

We agree that "tendencies" is a vague term and will thus replace it as follows:

Changes to the text: "multidecadal variability"

Reviewer: Ln 200ff: It should be quantified how strong all the mentioned teleconnections are (within contemporary uncertainty bounds) and mention that the expected impact on the Baltic Sea region is presumably even weaker.

Response:

We agree and we will quantify - when possible (e.g. SST) - the impact of the respective mode of variability on the Baltic Sea under section 2.3. However, we will also follow wording of changing statistics of local weather as specified on reviewer's comment of line 138ff.

Changes to the text: "On decadal time scales, atmospheric variability in Northern Europe is modulated by an interplay of the aforementioned atmospheric modes with the North Atlantic ocean, shaping the statistics of local climate in the Baltic Sea region."

Reviewer: Ln 202: Better replace "On decadal time scales, climate variability ..." by "On decadal time scales, atmospheric variability ..."

Response:

We will rephrase following the reviewer's suggestion (see above).

Reviewer: Ln 224: Better add "decadal atmospheric variability in winter time over the North Atlantic"

Response:

We will modify as follows:

Changes to the text: "Similar to the interannual timescale, in Northern Europe, decadal atmospheric variability in wintertime over the North Atlantic is dominated by the NAO (e.g., Paolini et al., 2022; Patrizio et al., 2023)."

Reviewer: Ln 233: I expect that most teleconnections were identified based on model results rather than "observed". Please be more precise or correct me. The NAO reflects the atmospheric variability over the North Atlantic during winters and I doubt that teleconnections could be established for individual synoptic systems (as the text might imply).

Response:

We agree with the reviewer and will rephrase the sentence as follows:

Changes to the text: "On decadal to multidecadal time scales, the relevance of modes of climate variability such as the NAO arises from changes in the frequency and persistence of large-scale circulation states and from their coupling to slowly varying boundary conditions, especially North Atlantic SSTs and ocean circulation, rather than from direct analogies with individual synoptic systems (Müller et al., 2020).

Reviewer: Ln 246: Why is that? "This highlights important room for improvement through model development". Aren't these feedbacks included in the models already? Most Baltic Sea models are forced by prescribed atmospheric boundary conditions which implicitly should include all the mentioned feedbacks. Please clarify.

Response:

The reviewer is correct and we will rephrase this paragraph accordingly. We will also distinguish between global and regional modeling approaches.

Changes to the text: 'In this context, the representation of coupled North Atlantic ocean–atmosphere variability in global climate models has recently been questioned. In particular, Carvalho-Oliveira et al. (2024) showed that the observed link between spring North Atlantic SST variability and summer Euro-Atlantic circulation is temporally non-stationary and is generally not reproduced, or is too weakly reproduced, in the evaluated global model. More broadly, persistent deficiencies in the simulation of Euro-Atlantic jet and regime dynamics, including blocking, further limit the realism of atmosphere–ocean coupling pathways in models. This is also relevant for the Baltic Sea region, because many regional Baltic Sea models are still forced by prescribed atmospheric boundary conditions and therefore inherit biases in the large-scale circulation from their driving models."

Reviewer: Ln 247: Where do "North Atlantic freshwater anomalies" originate from and which specific region do the authors have in mind?

Response:

We will clarify this in the paragraph as follows:

Changes to the text: "Freshwater anomalies in the subpolar North Atlantic (SPG) may also influence European, and potentially Baltic Sea, climate through downstream circulation anomalies. Oltmanns et al. (2024) linked such anomalies - likely related to anomalous Arctic/sub-Arctic runoff and meltwater input - to a sharper winter SST front between the subpolar and subtropical North Atlantic and to associated large-scale atmospheric circulation anomalies. "

Reviewer: Ln 266 Consider to rename "Key regional climatic effects of natural variability". It's not clear which Atlantic pattern are "natural" or if these undergo shifts due to global warming. Also, this has so far not been subject of the manuscript.

Response:

We agree with the reviewer that the title of section 2.3 is confusing and thus we will change the title. We will also clarify this in the first paragraph of the section.

Changes to the text: New section title: "Large-scale atmosphere–ocean controls on regional climate variability"

New sentence: "In this section, we describe the impacts of the large-scale atmosphere-ocean patterns on the natural variability of regional processes in the Baltic Sea, without assessing the effect of anthropogenic climate change."

Reviewer: Ln 267 I find it very confusing to talk about climate here after considering various time scales but not climate change in the Section above.

Response:

As also mentioned in comment for ln 266, we will clarify that in this section the focus is on large ocean-atmospheric patterns and not climate change (see our suggestion to revised text above).

Reviewer: Ln 271: Again, I would suggest to be a bit more careful when it comes to cause and effect in this paragraph. There is information lacking how strongly the NAO relates to precipitation in the Baltic Sea region.

Response:

We agree that our original wording was too strong in implying a direct cause–effect relationship between the NAO and precipitation in the Baltic Sea region. We will rephrase the paragraph to clarify that the NAO is used to describe large-scale circulation states associated with precipitation anomalies, rather than as a deterministic driver. The new text is below, under reviewer's comment for line 279ff.

Reviewer: Ln 279ff: Doesn't this rather belong to Section 3.2.2? Here I would rather expect some quantification how strong all these effects might impact the Baltic Sea region.

Response:

We will remove the part about sea ice. In addition, we will revise the whole subsection to focus more on the strength, seasonality, and spatial heterogeneity of the precipitation response in the Baltic Sea region. The new text will be rephrase as follows:

Changes to the text: "Precipitation in the Baltic Sea region varies across time scales, with different mechanisms dominating at each scale. The best-established link is for wintertime variability, when large-scale North Atlantic circulation exerts a strong control on moisture transport and cyclone pathways into Northern Europe. On synoptic and intraseasonal time scales, precipitation anomalies are primarily associated with variations in the latitude and strength of the North Atlantic jet and the resulting shifts in storm-track activity, rather than with any specific weather regime. When the jet is stronger and displaced northward, cyclones and moisture transport more frequently reach Northern Europe and parts of the Baltic Sea catchment, favoring wetter conditions. In contrast, a more southerly jet or blocked circulation over Scandinavia tends to suppress precipitation over large parts of the region, while enhancing it along the flanks and poleward side of the block, where moisture transport and warm conveyor belts are concentrated (Kautz et al., 2022; Lenggenhager and Martius, 2020). On interannual time scales, the NAO is the most widely used index for precipitation variability in the Baltic Sea region, especially in winter, but its influence is not spatially uniform across the region (Hurrell, 1995; Hurrell et al., 2003; Wrzesiński and Paluszkiewicz, 2011). Positive NAO conditions are generally associated with strong westerly flow and wetter-than-average conditions over the northern and western parts of the Baltic Sea region, whereas negative NAO conditions tend to favor reduced precipitation there. However, the strength and even the sign of the precipitation response can vary within the Baltic catchment depending on the longitudinal position of the NAO centers of action and on the state of other circulation patterns (Börgel et al., 2020). In particular, the East Atlantic and Scandinavian patterns modulate both the spatial structure and the magnitude of precipitation anomalies over the Baltic Sea region (Cassou, 2008; Craig and Allan, 2022; Lehmann et al., 2011). On multidecadal time scales, the influence is more indirect. North Atlantic sea-surface *temperature variability can alter the mean position of the jet and the associated sea-level pressure patterns, thereby changing the background likelihood of wet and dry conditions in the Baltic Sea region. Available evidence suggests relatively drier conditions during positive AMV phases and wetter conditions during negative AMV phases, although these relationships are less robust and more weakly constrained than the wintertime interannual links associated with the NAO (Ruggieri et al., 2021; Börgel et al., 2022). Potential influences from Arctic or Pacific sea-ice variability on Baltic precipitation remain uncertain, and their net effect on the region has not yet been robustly established (Screen et al., 2014; McKenna et al., 2018).*

Reviewer: Ln 287ff: Could you be more explicit how strong the described effects were suggested to be (opposed to locally driven dynamics)?

Response:

We agree that the previous wording was too unspecific and did not distinguish between the role of large-scale circulation for the statistics of storminess and the role of local dynamics in shaping the realized winds and impacts of individual events. We will rephrase the whole paragraph as follows:

Changes to the text: "Variability in storminess in the Baltic Sea region is closely connected to the location and strength of the North Atlantic storm track, but the relative importance of associated large-scale circulation and locally driven dynamics depends on the timescale. On synoptic to intraseasonal timescales, the NAO and jet-stream configuration provide a useful framework for describing the regional likelihood, pathways, and clustering of storms reaching the Baltic Sea region (Lehmann et al., 2011; Börgel et al., 2020; Rutgersson et al., 2022). In this sense, large-scale circulation exerts a strong control on the statistics of storminess, especially in winter, whereas the realized near-surface winds and local impacts of individual events remain strongly shaped by local factors such as coastline orientation, basin geometry, bathymetry, and land–sea contrasts. Generally, a stronger and northward-shifted jet – such as during NAO+ or a positive East Atlantic pattern – favors enhanced storm-track activity and increased storminess over the Baltic Sea region. In contrast, blocked regimes (Atlantic Ridge and European/Scandinavian Blocking) tend to suppress storms locally beneath the ridge, while enhancing activity along the flanks. A positive NAO also increases extreme wind return levels along the southern Baltic Sea and downstream, indicating an elevated risk of storm surges (Priestley et al., 2023).

On interannual timescales, the influence of large-scale atmospheric variability is spatially heterogeneous across the Baltic region. The Scandinavian Pattern appears to be the strongest modulator of winter storm activity in the Baltic region, followed by the NAO and the Polar/Eurasian pattern – a pattern projecting onto a zonal/NAO+ regime during its positive phase, while the negative phase projects onto blocked regimes, mainly Greenland Blocking (NAO-) and sometimes Scandinavian Blocking. The East Atlantic pattern also plays an important role, especially for the forecasting skill of storm tracks into the Baltic Sea region (Degenhardt et al., 2023; Walz et al., 2018). Moreover, the positioning of the jet stream and the strength of the meridional pressure gradient in the North Atlantic can explain a large part of the decadal changes in 10 m *wind speeds in northern Europe, with low windiness in winters of the 1980s and 2010s and high windiness in the 1990s (Laurila et al., 2021). On multidecadal timescales, the warm phase of the AMV corresponds to an equatorward-shifted jet and a storm track that is less extended poleward compared to the AMV cold phase (Ruggieri et al., 2021), favoring reduced storminess in the Baltic region."*

Reviewer: Ln 311: How strong is this correlation?

Response:

We will add the strength of the correlation as follows:

Changes to the text: "Against this seasonal background, interannual sea-level variability has been found to correlate with the NAO, especially in winter, although the strength of the relationship varies in time and across the Baltic Sea region. For example, Andersson (2002) reported a correlation of $r = 0.63$ *between the winter (JFM) NAO index and the winter mean Baltic Sea level over 1825–1997, increasing to* $r = 0.74$ *for 1902–1997. "*

Reviewer: Ln 316: For which purpose has this index been defined and how does it relate to the major North Atlantic climate modes (e.g. correlation strengths)?

Response:

We will add this information to the text.

Changes to the text: "An index based on the sea level pressure difference between the Bay of Biscay and Tromsø has also been suggested as an alternative to the NAO (Karabil et al., 2018). This Baltic Sea and North Sea Oscillation (BANOS) index was introduced because the NAO–Baltic sea-level relationship is non-stationary in time and spatially heterogeneous, whereas BANOS is more stably linked to Baltic and North Sea sea-level variability. Karabil et al. (2018) showed that it explained locally up to 90 % of interannual sea-level variance in winter and up to 79 % in summer during 1993–2013..."

Reviewer: Ln 320: Please quantify "robust connections".

Response:

This will be added in the text as follows:

Changes to the text: In contrast, they found no robust connection to the AMV, as the strongest correlation reported for any season was only 0.2.

Reviewer: Ln 325: How strong were these correlations. Why were these not mentioned in the respective subsections?

Response:

We will add the strength of the correlation. These studies were cited here because they are directly relevant for compound flooding, where sea level, waves and runoff act together. However, we added Wrzesiński and Paluszkiewicz (2011) to precipitation. The text will be rephrased as follows:

Changes to the text: "Moreover, NAO variability extends to other flooding-relevant drivers. For example, along the southern coast of Sweden, total annual wave energy is positively correlated with the winter NAO (r=0.51) offshore, and this relationship is even stronger closer to the coast (Adell et al., 2023). Runoff has likewise been reported to show seasonally significant NAO correlations in parts of the Baltic catchment, although these relationships are more regionally heterogeneous than for mean sea level (Wrzesiński and Paluszkiewicz, 2011). Together, these links suggest that the risk of compound flooding may also be modulated by the NAO (e.g., Hieronymus et al., 2024)."

Reviewer: Ln 326: Doesn't this also depend on region? E.g. the storm surge event in October 2023 brought exceptionally high water levels to the German Baltic Sea coast due to strong easterly winds across the Baltic Sea (i.e. apparently not NAO-driven). This section could be more objective and precise on the estimated impact of the NAO compared to other factors.

Response:

The reviewer has a good point. We will add a passage to clarify this:

Changes to the text: "However, this relationship is regionally heterogeneous and generally weaker than for mean sea level. In part, the relationship can be explained as a preconditioning, where storm surges occur from a higher baseline during positive NAO phases owing to its effect on the mean sea level, but there is likely an effect also on the surges themselves (Weisse et al., 2021). Yet, the magnitude of individual storm-surge events depends strongly on regional and event-specific wind forcing, coastline orientation, fetch, and basin geometry."

Reviewer: Ln 333: Please quantify "Low winter SST" and "high SST". Where?

Response:

We will rephrase to clarify this point.

Changes to the text: "Anomalously low winter SSTs in the Baltic Sea are associated with negative NAO phases and severe winters, whereas anomalously high SSTs are linked to positive NAO phases and mild winters (Schmidt et al., 2007; Kniebusch et al., 2019b) closely following the winter NAO-SAT relationship (Tinz, 1996)."

Reviewer: Ln 335: I find it somewhat confusing to introduce suddenly a new pattern that was never mentioned before.

Response:

We agree and will delete the reference to the Barents Sea Oscillation.

Reviewer: Ln 340: Please quantify "SST is likely to increase during positive AMV state". How likely? How much?

Response:

We will add this information and rephrase the text.

Changes to the text: "On decadal and longer time scales, positive AMV phases are associated with higher Baltic Sea SSTs, but this response is strongly seasonal and spatially heterogeneous rather than uniform throughout the year. Previous work estimated that about 58% of the decadal Baltic SST variability can be linked to the AMV after removing the global warming signal (Kniebusch et al., 2019b). More recent work further showed that the linear annual-mean SST response to the AMV is relatively weak, on the order of 0.2°C, whereas the influence is strongest in winter, when up to 40% of regional SST variability can be associated with multi-decadal variability closely linked to the AMV, corresponding locally to about 1.2°C per standard deviation AMV(Börgel et al., 2023). "

Reviewer: Ln 353: Is there evidence or is this speculation? "Consequently, atmospheric conditions resembling the positive phase of the NAO elevate the risk for MHWs in the Baltic Sea." I am especially puzzled because the NAO is dominant mainly in winter.

Response:

Yes, there is evidence for this. In this sentence, we refer to the work of Gröger, M., Dutheil, C., Börgel, F. et al. Drivers of marine heatwaves in a stratified marginal sea. Clim Dyn 62, 3231–3243 (2024). https://doi.org/10.1007/s00382-023-07062-5

Reviewer: Ln 361: Please quantify "strongly influenced".

Response:

We agree that strongly is too vague. Later in the paragraph, concrete numbers are given, hence the word "strongly" will be deleted.

Reviewer: Ln 362: Please quantify how much zonal and meridional flows contribute. Can you specify the meridional flow and the relation to the leading atmospheric modes?

Response:

We rephrased and now refer to the correlation as documented in the (Omstedt and Chen, 2001)

Changes to the text: "Statistical modelling shows that zonal flow is the dominant circulation control on Baltic Sea ice extent, with the winter NAO accounting for about 29 % of the year-to-year variance in annual maximum ice extent, while meridional flow also contributes, particularly *in November and January (Omstedt and Chen, 2001)"*

Reviewer: Ln 398ff: Please quantify the magnitude of all the mentioned effects.

Response:

We added the estimated magnitude to the text.

Changes to the text: The river runoff lowers the salinity in the surface layer of the Baltic Sea via direct dilution accounting for 27 % of the salinity variations (Radtke et al., 2020)

Changes to the text: On a multidecadal scale, the salinity of the Baltic Sea is correlated with the AMV. During the course of the last millennium, the dominant time scales were above 120 years and 60-90 years during the Little Ice Age (Börgel et al., 2018, their Figure 2) and were linked to salinity changes of about 0.7 g/kg

Changes to the text: For the 20th century, common power was also found between 20 and 30 years (Radtke et al., 2020), resulting in changes of about 0.2 g/kg

Reviewer: Ln 425: Please quantify how strong this effect is (relative to the mean seasonal signal).

Response:

That was a great hint and made us revisit the cited paper. We rephrased and have now a more accurate statement.

Changes to the text: A recent modeling study suggested that the PDO accounts for about 20–40% of the unforced year-to-year shortwave-flux variability in Northern Hemisphere continental averages, mainly through cloud redistribution. For Europe, the modeled response is weaker, with anomalies of about $\pm 2\ Wm^{-2}$*, and negative PDO phases are associated with reduced atmospheric shortwave reflectivity. However, the signal is strongest in spatially aggregated averages and is difficult to distinguish from atmospheric noise over most of Europe, so its relevance for the Baltic Sea region remains uncertain (Chtirkova et al., 2024).*

Reviewer: Ln 426ff: "3 Biogeochemistry" It might be good to mention right at the beginning that this sections starts with general facts and while respective teleconnections will be explored later in Section 3.2.

Response:

We agree with the reviewer that this clarification will aid the reader. We will add a sentence at the end of the paragraph as follows:

Changes to the text: "Here, however, we focus on the potential links between large-scale circulation variability and local biogeochemical functioning on different time scales. We start by briefly introducing the three key biogeochemical processes."

Reviewer: Ln 441: Are there indications that the very specific local atmospheric pattern leading to Major Baltic Inflows are impacted by teleconnections? What about local mixing - e.g. Reissmann et al (2009).

Response:

As far as we know, no direct evidence exists linking Major Baltic Inflows to teleconnections. However, a year-to-year variability is observed at subhalocline layer (100 m) likely connected to the minor inflows, as described in lines 595-600. As mentioned in the comment above, we will specify that in this section we do not yet mention teleconnections.

As for the local mixing, we do mention this as a key factor controlling oxygen in the Basin: "In the central and western Baltic proper, ..., oxygenation is controlled by the Major Baltic Inflows (MBIs), the smaller inflows ..., vertical mixing and oxygen consumption due to organic matter degradation". We will add the relevant references brought up by the reviewer to address this point.

Changes to the text: "... is controlled by MBIs, the smaller inflows ..., vertical mixing (e.g. Reissmann et al., 2009a) and oxygen consumption ..."

Reviewer: Ln 460ff: A classical impacting factor would also be upwelling (e.g. Lehmann & Myrberg (2008), Janssen et al (2004)).

Response:

The reviewer is correct and it is included in our sentence as "vertical mixing". We will add the reference Lehmann and Myrberg (2008) as it is directly linked to upwelling.

Changes to the text: "The high nutrient concentrations result from human-induced nutrient enrichment, long water residence times due to limited exchange with the North Sea, vertical mixing and efficient benthic nutrient recycling (e.g., Lehmann and Myrberg, 2008; Reissmann et al., 2009b; Carstensen et al., 2014; Carstensen and Conley, 2019)."

Reviewer: Ln 487ff: I do not generally agree with the statement on cyanobacteria having a low salinity tolerance. Or do you mean that they can tolerate low salinities? Please double check (e.g. Munkes et al. (2021))

Response:

In this sentence, we mean that cyanobacteria do not grow at high salinities as also stated in the study pointed out by the reviewer (Munkes et al., 2021): " ... high salinities seem to restrict the growth of Baltic Sea cyanobacteria and estimate a threshold around 10 PSU. ". For clarity, we will rephrase this sentence as follows:

Changes to the text: "Cyanobacteria in the Baltic Sea, which grow in low salinity (< 10 PSU; Munkes et al. 2021) and are capable of fixing atmospheric nitrogen, form blooms in summer ..."

Reviewer: Ln 512: "is increasing with time" which time scale is considered here?

Response:

Here we refer to the long-term increase mentioned in (Müller et al., 2016), which is about 20 years. We will rephrase the sentence to address the reviewer's comment:

Changes to the text: "However, total alkalinity in the Baltic Sea has shown an increase over the past two decades (Müller et al., 2016)."

Reviewer: Ln 526: How strong are these correlations?

Response:

According to (Kahru et al., 2020), which use Partial Least Squares to detect significant correlations for 35 different environmental variables, R^2 values that are significant at $p < 0.01$ range between 0.17-0.6. The assessed temperature variables (e.g., in situ annual mean temperature, mean temperature for June-Sept or that for Jul-Aug) showed R^2 higher than 0.2. We will rephrase the sentence to address the reviewer's comment as follows:

Changes to the text: "One example assessing the relative roles of physical parameters on modulating a biogeochemical parameter across different times scales is that of Kahru et al. (2020). Using Partial Least Squares analysis, they show that, in addition to biogeochemical properties (such as nutrient inputs), the temperature is a key driver for surface cyanobacteria accumulation (FCA) on decadal timescales (with $R^2 > 0.2$). ..."

Response:

We will also rephrase the sentence after to improve readability.

Changes to the text: "The occurrence and development of cyanobacterial blooms are thus among the few examples in the field of biogeochemistry where attempts have been made to explain natural variability on different timescales through physical drivers. "

Reviewer: Ln 529: There are many more studies (e.g. Karlson et al. 2008; Lips (2008), Löptien & Dietze (2023), Rakko & Seppäälä (2014), Wasmund (1997) and many more to follow)

Response:

We are fully aware that there are many more studies on potential trigger mechanisms for cyanobacterial blooms. This paragraph aims to point out that statistical analysis linking biogeochemistry, time scales and teleconnections are greatly lacking. We agree that this particular sentence is confusing and will thus remove it from the text. The revised text will be as presented above.

Reviewer: Ln 601ff: These studies refer to the western Baltic where hypoxia are seasonal. I would expect a strong relation to late summer mixing as well as late summer temperatures.

How can this we related to the (winter?) NAO.

Response:

Contrary to what the reviewer writes, these studies mainly focus on the Gulf of Finland and in this section, we describe the interannual variability (1-9 years) and thus not seasonal features. We are unsure what does the reviewer mean with this comment and believe it does not fit this section.

Reviewer: Ln 728ff: Please provide examples including a quantification of the respective impacts.

Response:

We agree that this would improve the conclusion and therefore, we will rephrase the paragraph.

Changes to the text: The Baltic Sea is located at the confluence of Atlantic, Arctic and continental influences, with variability controlled primarily by large-scale atmospheric circulation over the North Atlantic-European sector, especially the North Atlantic jet and associated circulation patterns such as the NAO, East Atlantic, and Scandinavian patterns (e.g., Chafik et al., 2017; Comas-Bru and McDermott, 2014b). Their impacts on the Baltic Sea region are substantial (e.g., Rutgersson et al., 2022). For example, in winter the NAO explains about 87% of the surface air temperature variability at Stockholm (Meier and Kauker, 2003), accounts for about 29% of the year-to-year variance in annual maximum Baltic Sea ice extent (Omstedt and Chen, 2001), and correlates strongly with winter mean Baltic Sea level ($r = 0.63$ for 1825–1997 and $r = 0.74$ for 1902–1997; (Andersson, 2002)). On longer time scales, coupled ocean–atmosphere interactions linked to the AMOC, the SPG, and the AMV exert additional control (Årthun et al., 2017; Börgel et al., 2023; Yan et al., 2018): for instance, about 58% of decadal Baltic Sea SST variability has been linked to the AMV after removing the long-term warming trend (Kniebusch et al., 2019b), and local winter SST responses can reach about 1.2 °C per standard deviation of AMV-related multidecadal variability (Börgel et al., 2023). However, quantifying the effect of the NAO on the past and future climate of the Baltic Sea region remains a challenge (Hurrell et al., 2003).

Reviewer: Ln 733: Please quantify "strong".

Response:

See our previous answer. We removed this paragraph and merged it into the starting paragraph.

Reviewer: Ln 735: Please explain and quantify the "reshaping".

Response:

We removed this paragraph and merged it into the starting paragraph.

Reviewer: Ln 736: I find this statement is rather vague: "Across time scales, the available literature defines different teleconnection patterns which may also be viewed through the lens of the Weather Regime framework". It would be good to provide concrete examples to back it.

Response:

We agree that this paragraph was too short and made it more explicit.

Changes to the text: "Across time scales, the literature uses different frameworks to describe large-scale circulation patterns and their variability, but many of these can be related to the weather-regime framework. For example, the Zonal and Greenland Blocking regimes are commonly interpreted as NAO-like states (Cassou, 2008; Vautard, 1990; Barrier et al., 2014; Fabiano et al., 2021). Similarly, the East Atlantic pattern has been linked to Atlantic Ridge and Atlantic Trough-like circulation anomalies (Barnston and Livezey, 1987a; Carvalho-Oliveira et al., 2024), while the Scandinavian pattern resembles Scandinavian Blocking in its positive phase and Scandinavian Trough in its negative phase (Kauker and Meier, 2003; Comas-Bru and McDermott, 2014a). Thus, apparent differences across studies often arise from the framework and time scale used, rather than from entirely distinct circulation dynamics (Vautard, 1990; Grams et al., 2017)."

Reviewer: Ln 738/739 Which "Apparent differences described in the literature" appear?

Response:

See the answer above

Reviewer: Ln 720ff: I must admit that I am confused about the natural variability aspect in this paragraph. To me both local and remote atmospheric variability could well be impacted by climate change.

Response:

We will add the definition of natural variability in the text according to the reviewer's comment of Ln 113ff, which will help to clarify this point.

In essence, natural variability is the variability that would occur with or without recent climate change. Once anthropogenic climate change is underway, the background state of the climate system shifts, altering mean conditions such as temperature, stratification, and circulation patterns. Natural variability continues to operate, but it does so on top of this modified baseline, meaning that fluctuations are superimposed on a changing mean state rather than occurring around a stable equilibrium. Moreover, climate change can influence the characteristics of natural modes of variability by modifying their amplitude, frequency, or spatial expression, for example through the intensification or alteration of teleconnections. As a result, distinguishing between internally generated variability and externally forced change become complex.

In this section (section 3.3), we place all relevant information found in the literature (from section 3.2) into context to highlight and synthesize the relative roles impacting biogeochemistry of teleconnections and physical drivers. We also pin point the missing links or knowledge gaps. We will add information and rephrase the following at the beginning of the section to clarify this point:

Changes to the text: "Disentangling climate change from natural variability is essential for correctly attributing observed changes in the Earth system. Without separating internally generated fluctuations from externally forced trends, long-term shifts may be misinterpreted as short-term variability, or vice versa. Clear attribution improves projections, strengthens confidence in model simulations, and supports effective policy and management decisions by distinguishing persistent climate-driven changes from temporary natural fluctuations. This is particularly valid for biogeochemical processes as in the Baltic Sea achieving good environmental status is crucial and a priority in EU conventions. This requires up-to-date environmental information and improved predictability of key processes for sustainable policy-making.

We have revised and gathered evidence from the literature linking the potential effects of teleconnections and physical controls on three key biogeochemical processes. In this section, we synthesize relevant evidence from Section **??***, placing it in the context of climate change and remaining knowledge gaps. We also identify, where possible, the relative roles and importance of teleconnections and physical controls for these biogeochemical processes. Our analysis, consistent with Neumann and Schernewski (2008), shows that ecosystem dynamics are influenced not only by temperature and salinity, but also by a broader range of atmospheric and oceanic drivers."*

Reviewer: Ln 740ff: This omits all other aspects such as nutrient controls, species composition etc.: "Biogeochemical responses mirror the physical controls but ..."

Response:

We agree with the reviewer and will rephrase this sentence as follows:

Changes to the text: "Our literature review highlights that, although still greatly underexplored, all three key biogeochemical parameters in the Baltic Sea are influenced by large-scale circulation patterns across all previously discussed timescales. These patterns affect biogeochemistry primarily by shaping the statistics of local physical processes such as stratification, water exchange, temperature, and advection, which then regulate nutrient availability, oxygen concentrations, species distributions, and phytoplankton abundance. However, quantitative and basin-wide evidence directly linking large-scale circulation variability to oxygenation, primary production, and ocean acidification in the Baltic Sea remains scarce. Important knowledge gaps persist, particularly regarding the spatial and temporal dynamics of total alkalinity (Kuliński et al., 2017). Likewise, although the physical controls on primary-production variability, especially for the summer cyanobacterial bloom, are partly linked to large-scale variability (Kahru et al., 2020, 2025), a substantial fraction of the annual variability remains unexplained (Kahru et al., 2025).

Similar to the physical controls, the NAO, the East Atlantic, and the Scandinavian pattern were identified as relevant. For example, a positive NAO can reverse the advection of oxygen-

depleted water and remove hypoxia on inter-annual timescales in the Gulf of Finland, whereas strong heat fluxes during European Blocking can enhance stratification and exacerbate deep-water deoxygenation in the Gulf of Riga. Wind speed, light, and cloud coverage have also been identified as potential triggers for initiating or ending phytoplankton blooms on synoptic scales. Importantly, the relative influence of these physical drivers varies with timescale. These findings underscore that understanding and predicting regional biogeochemical states requires explicit consideration of both large-scale atmospheric forcing and its timescale-dependent effects on the local physics.

This results in a system where large-scale circulation shapes the statistics of local processes. Yet, the attribution of their quantitative contributions, especially for biogeochemistry, remains challenging and understudied. "

Reviewer: Ln 740: Not sure what is meant here "filtered by strong stratification" and where the strong stratification occurs.

Response:

This will be rephrased according to comment above.

Reviewer: Ln 741: How is this sentence supported? "This results in a system where teleconnections clearly matter," I would like some evidence.

Response:

First, we will rephrase this sentence as follows:

Changes to the text: 'This results in a system where large-scale circulation shapes the statistics of local processes. Yet, the attribution of their quantitative contributions, especially for biogeochemistry, remains challenging and understudied."

Response:

Moreover, direct evidence is greatly lacking, as mentioned in the introduction (lines 52-56):

"direct empirical evidence from field studies that link large-scale atmospheric and oceanic patterns to Baltic Sea variability are rare and many implications remain theoretical, especially for biogeochemistry" and in the beginning of section 2.3:

"While dedicated studies quantifying the teleconnection effects on biogeochemical processes in the Baltic Sea are rare (see Neumann and Schernewski (2008) and references therein)...".

However, potential links can be found in the literature, as mentioned in section 2.3: "links - often local - between biogeochemical and physical processes have been suggested in the literature". While section 3.2 analyze and synthesizes the evidence for potential drivers by classifying their impacts across three different timescales, section 3.3 together with figure 10 summarize the relevant teleconnection and physical controls affecting the biogeochemistry, placing them into the context of climate change and multiple remaining knowledge gaps. All studies, even if they are only a few, assessing such links do find a connection and/or potential impacts on all 3 analyzed biogeochemical processes. This suggests that it is not because teleconnections effects on biogeochemistry remain largely unexplored, that it is not existing.

To better highlight this important point, we will rephrase the end of section 3.2 as follows:

Changes to the text: "In this section, we present a synthesis and analysis from relevant information found in the literature on how remote and local physical processes drive natural variability in deoxygenation, primary productivity, and ocean acidification, classifying their potential impacts across the timescales defined in section **??***."*

Response:

We will also rename the section 3.2 to:

Changes to the text: "Linkages between large-scale circulation patterns, physical drivers, and biogeochemical processes across timescales"

Response:

We will also rename the title of section 3.3 as follows:

Changes to the text: "Large-scale circulation patterns and physical controls in key biogeochemical processes: Roles and knowledge gaps"

Response:

In addition, we will add a description in the beginning of section 3.3 to highlight the purpose of the section as written in reviewer's comment of line 720ff.

We will also rework the conclusion section. For changes in the conclusion text please see the answer to the reviewer's comment of ln 740ff.

Reviewer: Ln 742: This is the first time global warming is mentioned. While I generally agree it comes a bit "out of the blue".

Response:

We agree and will add a sentence that gives a better context.

Changes to the text: "Large-scale circulation patterns are nonstationary: their spatial structure and strength evolve with changes in the background climate, including, for example, Arctic amplification (Zappa and Shepherd, 2017), likely altering their relative importance for the Baltic Sea in the future. Thus, anthropogenic climate change as well as legacy nutrient loads set the stage for the biogeochemistry in the Baltic Sea upon which large-scale circulation patterns superimpose variability."

Reviewer: Ln 750ff: If the physical controls of the biogeochemistry are so uncertain already, how can an analysis of teleconnections help?

Response:

As mentioned in the introduction (second to last paragraph), the Baltic Sea has not shown significant singes of improvements in the environmental conditions, despite great effort from countries to reduce nutrient loads into the basin:

"Despite great efforts to reduce the nutrient loads into the basin since the 1980s, the Baltic Sea shows little improvement in eutrophication and even a worsening in oxygen conditions in its deep waters".

This implies that despite all our understanding of how biogeochemical mechanistic work, we are not yet capable of accurately predicting the response of all drivers and processes involved on both short- and long-term scales. This is not surprising, as the system is very complex with many interconnecting links. Atmospheric Euro-Atlantic teleconnections inevitably impact the marine ecosystem but the topic is a largely understudied. Given the urgency to improve our knowledge in such interactions, we here provide a first attempt to identify relevant and potential interactions and knowledge gaps to better study missing links. To clarify this later point, we will add the following to the sentence in the introduction (after the the revised paragraph of reviewer's comment of line 40.:

Changes to the text: "Large-scale Euro-Atlantic circulation variability has been shown to impact the marine ecosystem by modulating the statistics of local forcing... However, ... and how local biogeochemistry relates to large-scale processes.

The challenging yet urgent need to better understand the relationships between natural variability, climate change, and regional effects motivates this study. This study represents a first attempt to identify potential interactions, relevant knowledge gaps and may provide key missing links for improving our ability to predict both physical drivers and biogeochemical responses."

Response:

For clarity and to improve the text readability, we will replace "study" by "first identify" in the sentence starting with "Given the multiple interacting drivers...".

Reviewer: Ln 755: Is the "Possible predictability in the North Atlantic" the major reason for writing this manuscript? This would be a nice motivation, consistent with the title, and the authors might consider to mention this early on. However, especially for the biogeochemistry it would be good to then add some background information on the state-of-the-art of predictability, including some discussion on the major sources for uncertainties.

Response:

We thank the reviewer for this helpful comment. We agree that predictability is an important perspective arising from this review, but it is not the primary motivation of the manuscript.

Our main aim is to synthesize and clarify the current understanding of how large-scale circulation variability influences the Baltic Sea region, with particular emphasis on physical and biogeochemical processes, and to identify key knowledge gaps. We have revised the text to make this point clearer. At the same time, we now state more explicitly that improved process understanding may also support future advances in predictability, especially for local processes. For biogeochemical processes, however, the current basis for predictability remains limited because observational evidence is sparse, process-based links are still poorly constrained, and uncertainties in coupled physical–biogeochemical models remain substantial.

Changes to the text: "This review represents a first attempt to synthesize these links for the Baltic Sea region, identify key knowledge gaps, and clarify how large-scale circulation patterns and their variability influences both physical processes in the Baltic Sea and biogeochemical responses. Improved understanding of these links may also support future advances in predictability, although this prospect is currently much more developed for physical variables than for biogeochemical processes."

Response:

Regarding the general background on predictability, if the reviewer means the predictability of biogeochemical processes and their potential response to physical drivers, we have in fact mainly identified the lack of robust constrains on physical drivers in both section 3.2 and 3.3. This hinders the possibility of reducing uncertainties in the predictability of biogoechemical processes. We believe that both section describe well the background information which leads to this conclusion. We will however, add a sentence in the end of section 3.3 highlighting the lack of constraint information to reduce uncertainties in the predictability.

Changes to the text: " All regional physical effects on natural variability mentioned in section 2.3 affect in some way these three main biogeochemical processes. However, most of the impacts remain poorly constrained or quantified and are therefore difficult to accurately implement in models, hindering the possibility of reducing uncertainties."

Reviewer: Ln 760: Which design do you suggest for a multi-model ensemble such that it is able to detect teleconnections? What is meant here with "external variability"?.

Response:

We agree with the reviewer that the wording was too vague. What we mean here is not an arbitrary multi-model ensemble, but ensemble designs that allow separating internally generated variability from the externally forced response. This is important because the large-scale circulation patterns discussed in this manuscript are nonstationary and their regional expression may change both due to internal variability and due to anthropogenic forcing.

More specifically, coordinated multi-model ensembles and, where available, initial-condition large ensembles can be used to test whether the identified links between large-scale circulation patterns and Baltic Sea processes are robust across models and realizations. Such ensembles also help to assess whether an apparent change in the statistics of these patterns or their regional impacts reflects internal variability or an externally forced response.

We agree that the term "external variability" was misleading and imprecise. We will therefore replace it by "externally forced response" and rephrase the sentence accordingly.

Changes to the text: "Regime-based diagnostics paired with in-depth process analysis to move beyond correlation. In addition, the nonstationarity of large-scale circulation patterns must be addressed, because their spatial structure and regional impacts may evolve over time. This can be investigated with coordinated multi-model ensembles, ideally complemented by initial-condition large ensembles which make it possible to separate internally generated variability from the externally forced response and to test the robustness of circulation–impact relationships across models and realizations."

Reviewer: Ln 764: I cannot follow this argumentation from the above text. Please help me out. A regional coupled model instead of using a forced model with prescribed atmospheric boundary conditions would introduce feedbacks from the Baltic Sea to the atmosphere. This seems unrelated to the teleconnections, considered in this manuscript.

Response:

We agree that the original wording mixed two separate points and therefore made the argument difficult to follow. First, fully coupled regional Earth-system models are needed to better represent regional feedbacks within the Baltic Sea system, including interactions among atmosphere, ocean, sea ice, and biogeochemistry. Second, because the influence of large-scale circulation enters the regional model through the global parent model and lateral/boundary forcing, the realism of jets, storm tracks, the subpolar gyre, and the Atlantic Meridional Overturning must be evaluated carefully in that parent model. We have revised the text accordingly and separated these two arguments more clearly.

Changes to the text: "Fully coupled regional Earth-system models that resolve the complex topography of the Baltic Sea can represent regional feedbacks among atmosphere, ocean, sea ice, and biogeochemistry more consistently.

Targeted evaluation of the large-scale circulation and ocean state in the global parent model – including jets, storm tracks, the subpolar gyre, and the AMOC – because biases in these features can propagate into the regional model through the imposed boundary conditions and thereby affect the simulated Baltic Sea variability."

Reviewer: Ln 768: While I appreciate event-based modelling, I struggle to see the benefit for teleconnections.

Response:

In this case, the benefit is not on teleconnections but on biogeochemical processes.

Reviewer: Ln 769: Again – while I certainly appreciate high-frequency measurements I need some help to understand the benefit for advancing teleconnections.

Response:

Similar than above, here, the benefits are not to improve teleconnection knowledge, but on their effects on regional/local processes. For clarity, we will specify this at the beginning of the bullet points:

Changes to the text: "To advance our understanding on links between large-scale circulation patterns and local processes, we highlight the need for:"

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