



Long term trends and variability of the mixed layer depth in the Baltic Sea

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Abstract. The depth of the upper mixed layer (MLD) in the Baltic Sea is a critical physical parameter that influences heat exchange, nutrient cycling, and oxygenation in this semi-enclosed basin. Variations in MLD have significant ecological consequences: a shallower mixed layer restricts the supply of oxygen and nutrients to deeper waters, potentially exacerbating hypoxia, whereas deeper mixing in previously ice-covered areas can enhance ventilation and nutrient entrainment.

To investigate long-term MLD variability, we analyzed a 30-year (1993–2023) high-resolution ocean reanalysis data set across the Baltic Sea. The results reveal pronounced spatial heterogeneity in MLD trends. In the western and southern Baltic, the MLD has become shallower, driven by surface warming and intensified stratification that stabilizes the upper layer. Conversely, in the eastern and northern Baltic, MLD has deepened, coinciding with reduced winter sea-ice cover and increasing wind speeds that promote wind-driven mixing – despite concurrent warming, increased precipitation, and enhanced stratification.

These region-specific trends highlight the complex interplay among warming, ice loss, and stratification in shaping upper-ocean dynamics. Our findings provide a baseline for understanding mixed-layer variability in the Baltic Sea under climate change and emphasize the need to consider regional differences in future projections.

1 Introduction

The oceanic upper Mixed Layer Depth (MLD) is a fundamental physical parameter governing the exchange of heat, momentum, and gases between the ocean and atmosphere. It plays a central role in modulating climate variability, regulating marine biogeochemical processes, and influencing the structure and productivity of marine ecosystems (Lorbacher et al., 2006; Wang et al., 2022). Variability in MLD is driven by atmospheric forcing (wind stress, air temperature, radiation, and precipitation), surface buoyancy fluxes, and oceanic dynamics, such as eddies and currents, with pronounced seasonal and regional differences (de Boyer Montégut et al., 2004; Treguier et al., 2023).

Globally, the MLD responds to climatic shifts by altering the vertical structure and stratification of the upper ocean (Li et al., 2020; Sallée et al., 2021). In equatorial regions, persistent heating and weak wind stress maintain a shallow MLD,

whereas in mid- and high latitudes, stronger winds and surface cooling during winter promote deepening through enhanced vertical mixing and convective processes (Somavilla et al., 2017; Gao et al., 2023; Sallée et al., 2021). The response of the MLD to climate change is not uniform: increasing stratification from surface warming tends to shoal the MLD (Li et al., 2020), whereas intensified wind stress or buoyancy loss can promote deeper mixing (Sallée et al., 2021; Gao et al., 2023; Amaya et al., 2021). These changes have far-reaching implications for heat storage, ocean carbon uptake, and nutrient fluxes, particularly under scenarios of continued global warming (Li et al., 2020; Sallée et al., 2021; Shi et al., 2022).

In semi-enclosed marginal seas like the Baltic Sea, MLD variability reflects a complex interplay of atmospheric forcing (Liblik et al., 2020; Liblik and Lips, 2019; Bulczak et al., 2024), bathymetric constraints (Liblik et al., 2020; Bul-

Table 1. Product table.

Product ref. no.	Product ID & type	Data access	Documentation
1	BALTICSEA_MULTIYEAR_PHY_003_011; Numerical models	EU Copernicus Marine Service Product (2025)	Quality Information Document (QUID): Panteleit et al. (2025); Product User Manual (PUM): Ringgaard et al. (2024)
2	ERA5; Numerical models	Copernicus Climate Change Service (2023)	Product reference: Hersbach et al. (2023) Journal article: Hersbach et al. (2020)

czak et al., 2024), freshwater inflows (Hordoir and Meier, 2012; Väli et al., 2013), and permanent haline stratification (Väli et al., 2013; Liblik and Lips, 2019). The Baltic Sea, with its strong horizontal salinity gradients and seasonal ice cover in the northern basins, presents a unique environment for studying MLD dynamics in a high-latitude coastal setting. Seasonal patterns dominate, with deep wintertime MLDs driven by wind mixing and surface cooling, and shallow summertime MLDs resulting from thermal stratification (Bulczak et al., 2024). Spatial heterogeneity is also prominent: the Baltic Proper often exhibit deeper mixed layers due to enhanced wind exposure and reduced freshwater influence, whereas coastal and ice-covered regions display shallower MLDs (Panteleit et al., 2025).

Recent studies using high-resolution reanalysis datasets and model simulations have begun to reveal long-term trends in MLD across the Baltic Sea (Meier et al., 2022a; Dutheil et al., 2023). These analyses suggest spatially variable responses to climate forcing, with evidence of deepening MLDs in the northern and eastern sub-basins – potentially linked to reduced winter ice cover – and shoaling trends in southern and central areas, possibly related to increased stratification and changes in halocline dynamics.

Given the MLD’s pivotal role in modulating biological productivity, carbon cycling, and hypoxia development, understanding its long-term variability is essential for predicting future changes in the Baltic Sea ecosystem. This study aims to assess the spatial and temporal variability of MLD across the Baltic Sea from 1993 to 2023, utilizing state-of-the-art reanalysis products (Table 1, product ref. no. 1). Specifically, we investigate the trends, regional differences, and potential climate forcings of the trends in MLD, with the goal of providing a robust basis for evaluating the ecological and biogeochemical consequences of mixed-layer variability in a warming world.

2 Data and methods

The Baltic Sea physics reanalysis multi-year product (BAL-MYP; product ref. no. 1) is derived from the ocean model NEMO v4.0 (Madec et al., 2019). It assimilates satellite observations of sea surface temperature (SST) (EU Copernicus

Marine Service Product, 2025) and in-situ temperature and salinity profiles from the ICES database (ICES Bottle and low-resolution CTD dataset, 2022). The model data is provided on a grid with a horizontal resolution of 1 nmi, including 56 vertical layers, covering the entire Baltic Sea and the transition zone to the North Sea. The dataset covers the period from 1993 to 2023, with the model setup detailed in the Product User Manual (Ringgaard et al., 2024).

The BAL-MYP has been extensively validated, as documented in the Quality Information Document (QUID; Panteleit et al., 2025), focusing on the period from 1 January 1993 to 31 December 2018. Additionally, the BAL-MYP data were evaluated using a clustering method with the *K*-means algorithm (Raudsepp and Maljutenko, 2022), which provided insights into the reanalysis accuracy by categorising errors (Lindenthal et al., 2024). 57 % of the data are clustered with a bias of $dS = -0.40 \text{ g kg}^{-1}$ and $dT = -0.02 \text{ }^{\circ}\text{C}$, encompassing 57 % of all data points with $\text{RMSE } S = 0.92 \text{ g kg}^{-1}$ and $T = 0.54 \text{ }^{\circ}\text{C}$ (Lindenthal et al., 2024). These points are distributed throughout the Baltic Sea. Clusters with high positive and negative temperature biases account for 11 % and 8 % of total points, respectively, with marginal salinity biases and relatively even spatial distributions across the Baltic Sea. 26 % of the points have low temperature but high salinity errors, both negative and positive, predominantly located in the southwestern Baltic Sea, indicating occasional underestimation or overestimation of the inflow/outflow salinity (Lindenthal et al., 2024).

The MLD, also referred to as the Upper Mixed Layer (UML), was included in the analysis using data from a multi-year reanalysis product (product ref. no. 1). The MLD was calculated based on density stratification following the method of de Boyer Montégut et al. (2004), which defines MLD as the depth at which seawater density deviates from the reference density at 10 m depth by a specified threshold. For the Baltic Sea, this threshold was adjusted to 0.03 kg m^{-3} to better represent the characteristics of the regional UML (Panteleit et al., 2025).

Panteleit et al. (2025) has performed validation of the reanalysis product of the MLD (product ref. no. 1) with comparison to the observations at eight stations. From observations, the MLD is derived from salinity and temperature pro-

files of ICES-HELCOM observations that are located over the open parts of the Baltic Sea. The cRMSD of MLD for the reanalysis product (product ref. no. 1) is 11.34 m and correlation coefficient is 0.69 for the whole reanalysis period 1993–2019 in the bulk comparison of MLD product with observations. On average the reanalysis product underestimates MLD by 7 m.

The annual cycle of the MLD of the products follows the MLD calculated from observations for the whole reanalysis period (Panteleit et al., 2025). It is possible to observe the seasonal variability of the MLD product in summer and winter. During the summer, the MLD is lower, and during the winter, the MLD is deeper. In the Baltic Proper the MLD is small from late spring until end of summer reaching values of 10–20 m during the period 1 January 1993–30 December 2019. In autumn and winter, MLD increases considerably with a maximum MLD of 70 m. In the Gulf of Bothnia, the MLD varies from 10 to 80 m deep during the reanalysis period. The MLD is small from late spring until the end of summer reaching values of 10–15 m, and in autumn and winter, MLD increases considerably with a maximum MLD of 80 m.

Atmospheric data were sourced from the ERA5 hourly dataset on single levels, available from 1940 to the present (product ref. no. 2), and accessed via the Copernicus Climate Data Store. For this study, based on the availability of MLD data, the analysis focuses on the period 1993–2023. Daily means were calculated for the following parameters: 2 m air temperature, total precipitation, and the wind speed, estimated from the daily averaged zonal (u) and meridional (v) components of 10 m wind.

Higher potential energy anomaly (PEA) corresponds to a more stratified water column, i.e. more energy is required to mix the water column uniformly. The PEA below the MLD was computed to quantify stratification in the Baltic Sea. Daily temperature and salinity profiles obtained from the CMEMS dataset were initially subsetting within a defined geographic region and vertical extent (0.5–250 m). Absolute Salinity and Conservative Temperature were calculated from Practical Salinity and potential temperature using the Gibbs SeaWater (GSW) Oceanographic Toolbox. These derived quantities were subsequently used to compute seawater density (ρ) across pressure levels determined from depth and latitude. To isolate stratification effects, density profiles were masked above the daily MLD, with layers below this depth considered for PEA calculation. The calculation of PEA follows the formula:

$$\text{PEA} = \frac{1}{H-h} \int_h^H g(\rho(z) - \bar{\rho})(z-h)dz \quad (1)$$

where g is gravitational acceleration, $\rho(z)$ is the density at depth z , $\bar{\rho}$ is the mean density below the MLD (from depth h to bottom depth H) and z is the depth. The integral of density deviations from the layer-wise mean density, weighted

by gravitational acceleration and depth increments, was performed to yield daily PEA fields. These fields were normalized by local bathymetric depth, thus enabling robust spatial comparison. Subsequently, a linear trend analysis was executed on normalized daily PEA over the 1993–2023 period.

3 Results and Discussion

The climatological mean MLD exhibits pronounced regional differences across the Baltic Sea (Fig. 1a). The presented fields (Fig. 1) were computed from monthly averaged data derived from the high-resolution oceanographic reanalysis. Deeper mixed layers occur in the central and southern Baltic basins (e.g., Gotland Basin), while shallower layers dominate in coastal areas and the northern basins, such as the Gulf of Finland and Bothnian Bay. These differences reflect the influence of bathymetry, wind exposure, and surface buoyancy forcing (Lass and Matthäus, 1996; Liblik and Lips, 2012; Liblik et al., 2020).

Figure 1b shows the spatial distribution of the standard deviation of MLD across the Baltic Sea, based on daily-averaged data over the period 1993–2023. This metric represents the statistical dispersion of MLD values at each location – that is, how far individual daily MLD values deviate from the long-term average at that point. Since the standard deviation is derived from daily MLD values over multiple years, it represents how strongly MLD values tend to deviate from their long-term average on a daily basis. The resulting spatial pattern shows clearly defined gradients in standard deviation across the basin. Higher values, ranging from approximately 5 to 15 m, are observed in deeper areas such as eastern parts of BOS, NBP, and SBP. In contrast, much lower standard deviations – typically below 5 m – are found in shallower and more enclosed regions such as the BOB, GOF.

The spatially averaged time series of MLD from 1993 to 2023 (Fig. 2a) shows strong seasonal fluctuations superimposed on a non-significant long-term trend. While individual years exhibit pronounced peaks and troughs, there is an overall shoaling tendency, particularly in winter months, which is consistent with previous studies in the southern Baltic Sea (Bulczak et al., 2024). Such reductions are attributed to increasing thermal stratification and warmer surface waters, both of which inhibit vertical mixing (Bulczak et al., 2024).

The MLD follows a clear seasonal cycle, as illustrated by the monthly climatology (Fig. 2b). Maximum depths are typically observed during winter (October–March), driven by convective mixing under cold air temperatures. Minimum MLDs occur in summer (June–August), when surface heating leads to strong stratification and shallow mixing layers. The transitional periods in spring and autumn are characterized by rapid changes in MLD, reflecting the formation and erosion of seasonal thermoclines. These patterns are consistent with prior studies (e.g., Fu et al., 2012; Bulczak et al.,

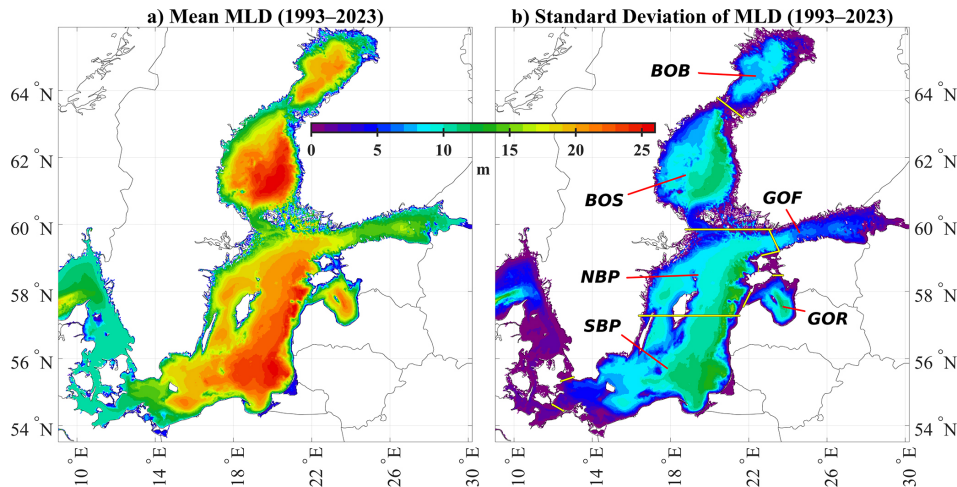


Figure 1. Spatial distribution of the long-term mean (a) and standard deviation (b) of MLD in the Baltic Sea over the period 1993–2023 (Table 1, product ref. no. 1). Boundaries of major Baltic Sea sub-basins are shown with yellow lines (IHO 2012): the Bothnian Bay (BOB), Bothnian Sea (BOS), Gulf of Finland (GOF), Northern Baltic Proper (NBP), Gulf of Riga (GOR), and Southern Baltic Proper (SBP).

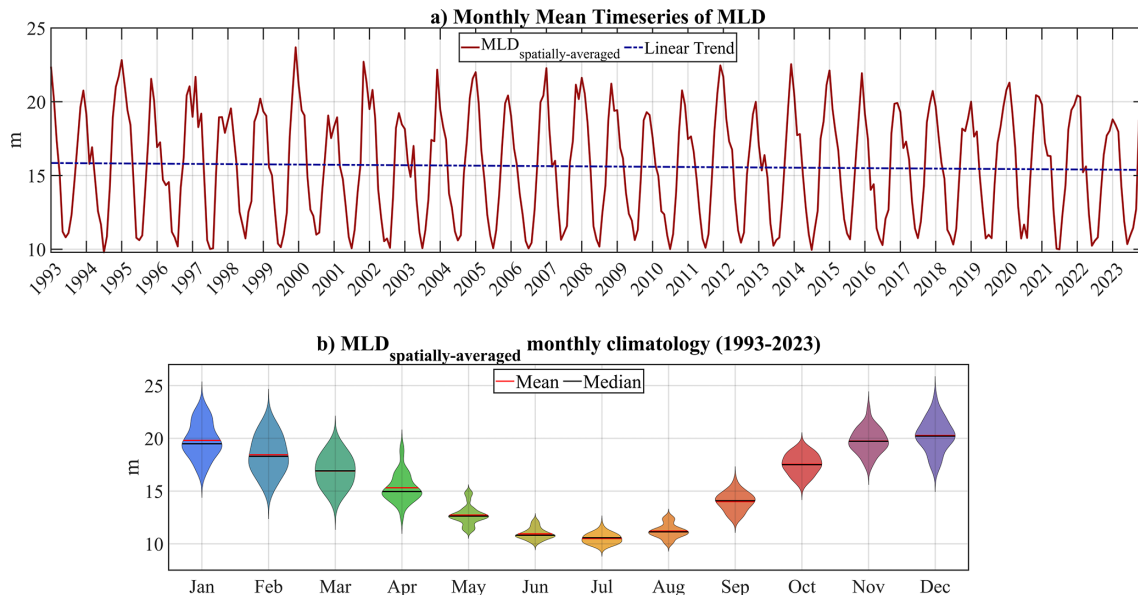


Figure 2. Monthly mean MLD variability in the Baltic Sea over the 29-year period from 1993 to 2023 (Table 1, product ref. no. 1). (a) Monthly mean MLD time series alongside a linear trend (red dashed line), highlighting pronounced seasonal variability but minimal overall long-term trend. (b) Violin plots illustrating statistical distributions of monthly MLD values, clearly distinguishing deeper, more variable winter mixed layers (December–February), caused by enhanced vertical mixing and cooling events, from shallower, stable summer conditions (June–August) associated with surface warming and increased stratification.

2024) documenting deep winter mixing and shallow summer layers across the Baltic.

The spatial pattern of MLD linear trends (Fig. 3a) reveals a striking west–east dipole: MLD has shoaled in the western Baltic (e.g., western Baltic Proper, Bothnian Sea), while deepening trends are observed in the eastern basins (e.g., eastern coasts of the Baltic Sea, Gulf of Finland, Gulf of Riga, and Eastern Bothnian Bay). This feature is repeated on seasonal trends except for summer (Fig. 4). The spatial

contrast suggests region-specific responses to environmental changes. Sea ice volume trends (Fig. 3b), computed for the ice season (November–May), show significant declines. Reduced ice cover extends the open-water period and permits more wind-driven mixing, which likely contributes to the observed deepening of MLD in the eastern/northern regions (Raudsepp et al., 2020). This interpretation is consistent with Singh et al. (2025), who found significant reductions in ice thickness and extent throughout the Baltic.

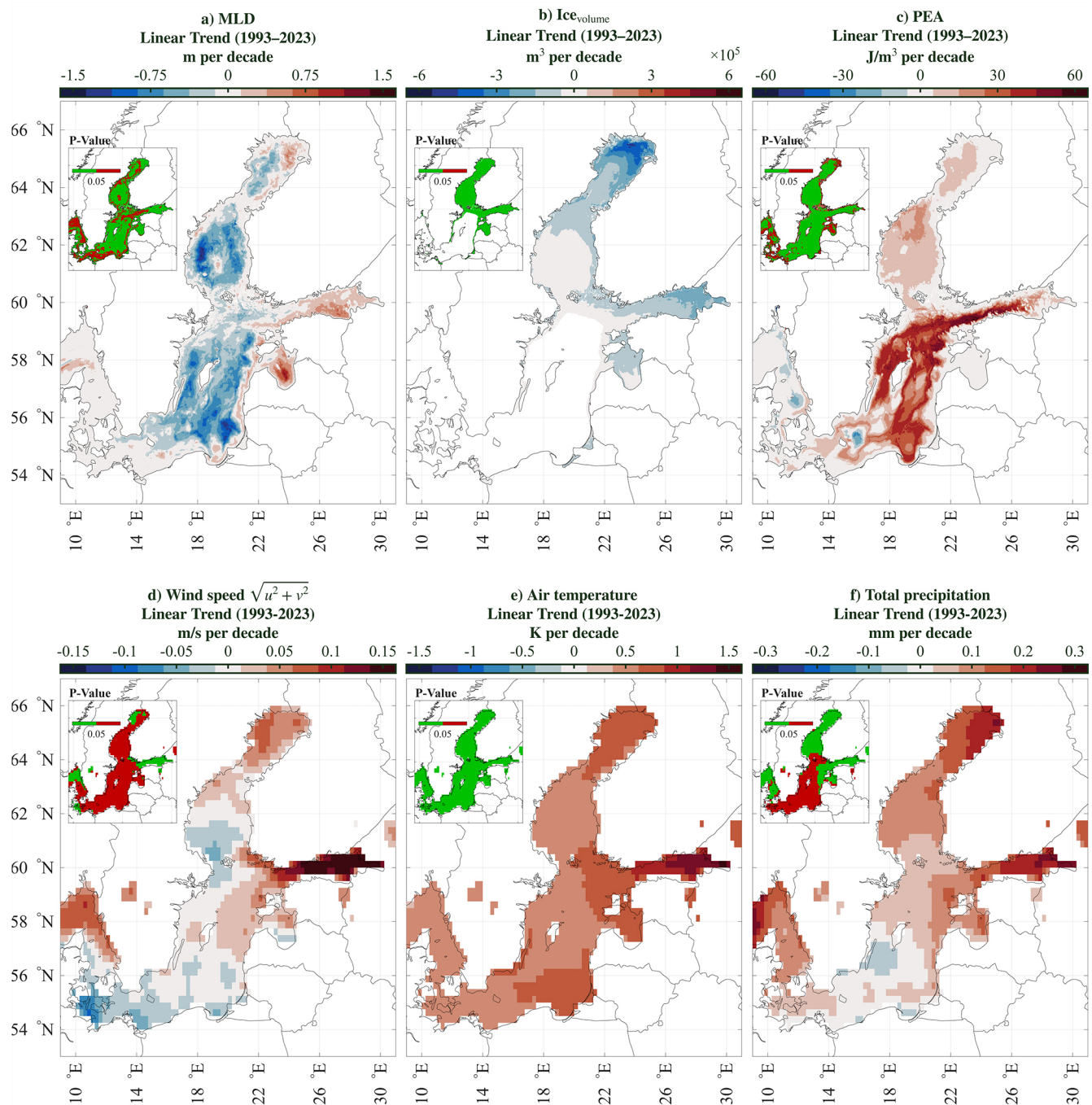


Figure 3. Linear trends (1993–2023) of oceanic and atmospheric parameters in the Baltic Sea region. **(a)** Mixed layer depth (MLD) Eq. (1), **(b)** sea ice volume trend during the ice season (November–May), **(c)** potential energy anomaly (PEA), **(d)** wind speed, **(e)** air temperature, and **(f)** total precipitation (panels **a–c** from product ref. no. 1; panels **d–f** from product ref. no. 2). Inset maps in each panel display p-values associated with the linear trends at each grid point. Areas with $p < 0.05$ (shaded in green) indicate statistically significant trends at the 95 % confidence level, while red areas denote non-significant trends. These p -value maps provide an *uncertainty* metric for the estimated trends and help to distinguish robust regional changes from areas of high variability or low confidence.

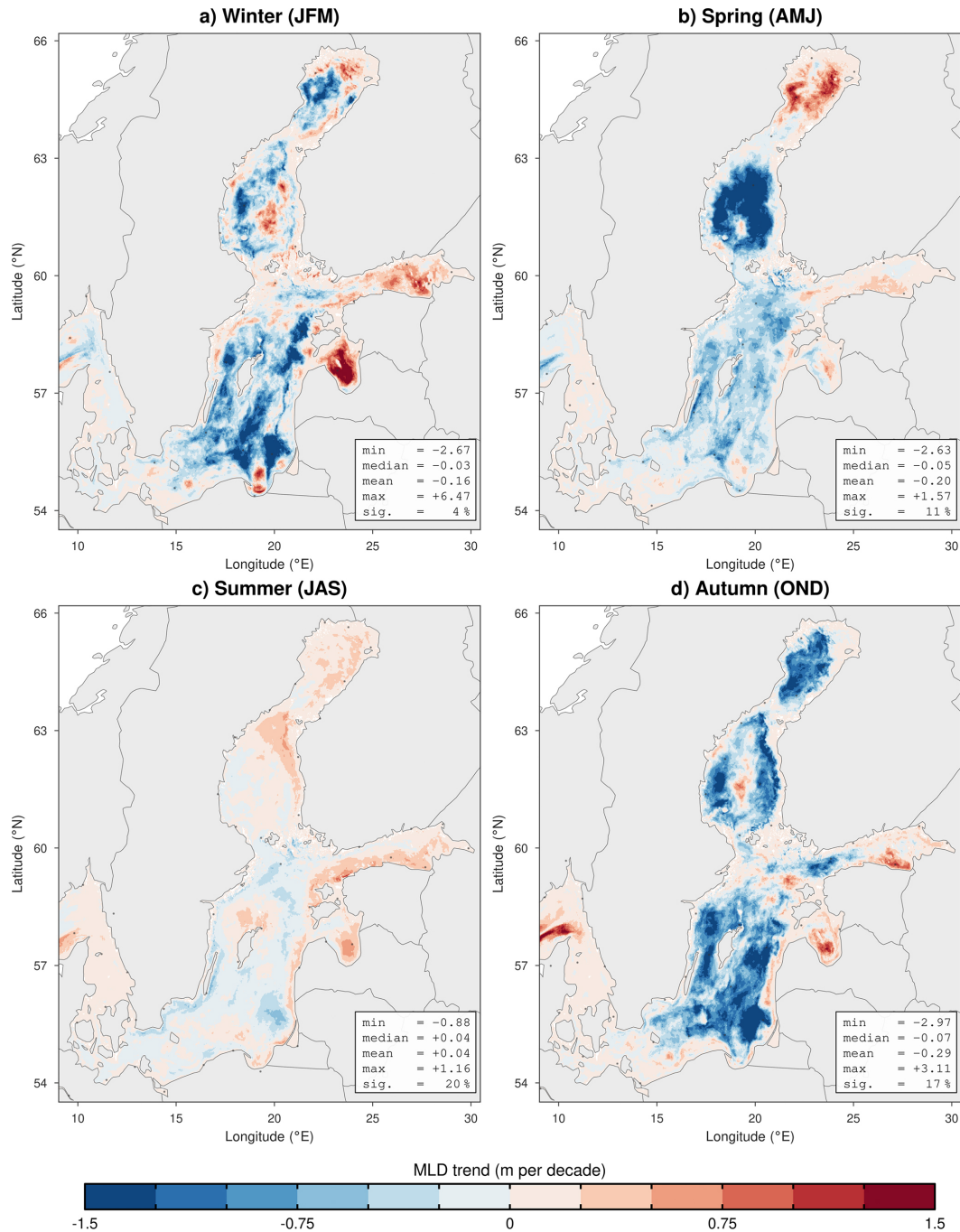


Figure 4. Seasonal linear trends (1993–2023) of mixed layer depth (MLD) in the Baltic Sea region. **(a)** Winter (JFM), **(b)** Spring (AMJ), **(c)** Summer (JAS), and **(d)** Autumn (OND) trends derived from product ref. no. 1. The summary box in the lower-right of each panel reports basin-wide statistics of the underlying slope field – minimum, median, mean, and maximum values (m per decade) – together with the fraction of grid cells (sig.) where the trend is statistically significant. The colorbar is saturated at ± 1.5 m per decade; reported minimum and maximum values may therefore exceed the displayed range.

The PEA trends shown in Fig. 3c provide a diagnostic of the stratification barrier relevant to mixed-layer evolution. Positive trends indicate that the water column has become more resistant to further vertical mixing, which favors shallower MLDs where atmospheric forcing is not sufficient to

overcome this barrier. Areas with positive PEA trends correspond broadly to regions of MLD shoaling. Conversely, weaker or negative PEA trends indicate a reduced stratification barrier and are consistent with deeper mixing in parts of the eastern and northern Baltic, where reduced sea ice cover

increases the exposure of the water column to wind-driven mixing. As defined in the Methods, the PEA diagnostic used here is evaluated beneath the diagnosed MLD. This formulation is used because the mixed layer itself is already approximately homogeneous, while the density structure below the MLD controls the resistance to further deepening. The diagnostic therefore does not represent the external energy available for mixing, but rather the internal oceanic stratification barrier that must be overcome by mixing processes such as wind-driven turbulence and convective cooling. The MLD trend should therefore be interpreted as the outcome of a balance between stabilizing stratification and mixing supplied by other drivers.

Wind speed trends (Fig. 3d) are spatially heterogeneous and generally weak. Although some localized increases are evident, there is no basin-wide pattern suggesting wind changes as the primary driver of MLD trends. This aligns with previous assessments indicating no clear overall trend in regional wind speed over recent decades (Meier et al., 2022b). In contrast, air temperature trends (Fig. 3e) are uniformly positive, with strongest warming observed in the western Baltic. Warmer air temperatures reduce wintertime surface heat loss, weakening convective mixing and enhancing stratification. This likely contributes to the observed shoaling of MLD in the southwestern basins. Meanwhile, in the eastern Baltic, the concurrent retreat of ice cover may counteract some warming effects, allowing for deeper winter mixing. Precipitation trends (Fig. 3f) are also positive across most of the basin, particularly in the northeastern catchments. Increased rainfall enhances surface freshwater input, which strengthens stratification and supports MLD shoaling. The alignment of increasing precipitation and positive PEA trends in the western Baltic reinforces the role of freshwater in inhibiting mixing.

The pronounced spatial heterogeneity in mean MLD, with deeper layers in the central/southern basins (e.g., Gotland Basin) and shallower layers in coastal zones and northern basins (e.g., Gulf of Finland, Bothnian Bay), aligns well with established knowledge. Bathymetry sets fundamental limits (Omstedt et al., 2004; Leppäranta and Myrberg, 2009), while greater wind exposure over the open central basins promotes deeper mixing compared to the more sheltered coastal and archipelago regions (Kõuts and Omstedt, 1993; Miettinen et al., 2024). Surface buoyancy forcing, particularly the strong haline stratification prevalent in the Baltic (Reissmann et al., 2009; Liblik et al., 2017), is a dominant factor suppressing MLD, especially in areas with significant freshwater inflow like the northern gulfs and nearshore zones. The higher temporal variability (standard deviation) observed in deeper basins (Fig. 1b) reflects their greater responsiveness to synoptic-scale wind events and seasonal buoyancy changes compared to the persistently stratified and shallow regions (Umlauf et al., 2018).

In the western subbasins, the overall shoaling is mechanistically linked to increasing thermal stratification driven

by rising air temperatures (Lehmann et al., 2022; Meier et al., 2022a, b) and enhanced precipitation (Rutgersson et al., 2002), both contributing to increased PEA, which stabilizes the water column and impedes vertical mixing.

For the eastern subbasins, the observed deepening trends in the Gulf of Finland, Eastern Gotland Basin, and Eastern Bothnian Bay appear counterintuitive in a warming climate. However, the dramatic decline in sea ice volume (Singh et al., 2025) offers a key mechanistic explanation. Reduced ice cover extends the open-water season – especially during autumn to spring when wind energy is highest – allowing significantly more wind-driven mixing (Vihma and Haapala, 2009; Uotila et al., 2015). This region also exhibits weaker positive or slightly negative PEA trends (Fig. 3c), indicating reduced stratification. The retreat of ice likely counteracts expected thermal stratification from warming by enhancing wind mixing and reducing the freshwater lens effect from melting ice (Hordoir et al., 2019).

Enhanced ageostrophic currents (Barzandeh et al., 2024), driven by increased wind stress over newly ice-free areas (Fig. 3b), may further contribute to deeper mixing due to the loss of the ice damping effect. Our observed MLD deepening (Fig. 3a) aligns with these dynamics (Fig. 3d) and is supported by reduced ice cover (Fig. 3b), which increases wind stress impact and vertical shear at density interfaces. This weakens stratification via Ekman pumping, submeso/mesoscale instabilities, and inertial oscillations (Umlauf et al., 2018; Chrysagi et al., 2021), contributing to deeper mixed layers.

The accompanying weak or negative PEA trends (Fig. 3c) further reflect this stratification reduction. Additionally, Bashiri et al. (2024) report intensified marine heatwaves (MHWs) in the eastern Baltic: atmospheric blocking in summer leads to surface-intensified warming and temporary MLD shoaling, while wintertime advection promotes subsurface warming and suppressed convection. Although both western and eastern Baltic regions exhibit air temperature increases, the influence of atmospheric warming on MLD deepening appears less significant in the east, where oceanic and dynamic atmospheric processes likely dominate stratification and MLD variability.

The observed changes in MLD have significant implications for the Baltic Sea's physical and ecological state. A deeper winter mixed layer in previously ice-covered regions (e.g. northern gulfs) can lead to greater ventilation of the water column (Meier et al., 2019; Droste et al., 2025). This may be a positive outcome in terms of oxygen distribution: deeper mixing in winter helps transport oxygen from the surface to intermediate depths, which can alleviate oxygen depletion that often develops below the halocline (Kõuts et al., 2021a). However, the flip side is that shallower mixing in the central and southern Baltic can exacerbate oxygen stress in those areas. These processes, combined with episodic inflows of warm saline water that strengthen stratification, have been shown to exacerbate oxygen depletion in the western

Baltic (Barghorn et al., 2025). When the mixed layer no longer reaches as deep into the halocline, less oxygen is injected into the deep layer each winter. Over time, this contributes to more severe or persistent hypoxia in the deeper basins (Krapf et al., 2022). The Baltic Sea is already well known for its extensive oxygen-depleted bottom areas, often referred to as “dead zones” (Carstensen et al., 2014; Kõuts et al., 2021a), and stronger stratification only worsens this issue by further isolating the deep water. Recent studies have indeed reported an increasing frequency of hypoxic events in the Baltic Proper, correlating with intensifying stratification and warming (Rolff et al., 2022; Hepach et al., 2024; Liblik et al., 2025; Stockmayer and Lehmann, 2023). Our findings of MLD shoaling in the main basins are thus a warning sign of potentially deteriorating deep-water oxygen conditions if these trends persist.

Another important consideration is the impact on nutrient cycling and biological productivity. The MLD forms the interface between the deep layer and the euphotic zone, thereby controlling growing conditions and nutrient availability for phytoplankton (Wasmund et al., 1998; Hieronymus et al., 2018). A shallower winter mixed layer in the central Baltic means that come spring, a smaller reservoir of deep nutrient-rich water has been entrained to the surface layer (Kõuts et al., 2021b). This could limit the amount of nutrients (like nitrate and phosphate) available for the spring phytoplankton bloom, possibly reducing the magnitude and duration of the bloom (Reissmann et al., 2009). Areas with deepening MLD (e.g. the northern and eastern Baltic) might see enhanced nutrient entrainment, potentially hampering the effect of nutrient input reductions in coastal areas. It should be noted, however, that oxygen conditions strongly influence nutrient fluxes from sediments. Improved bottom-water oxygenation in coastal areas promotes nutrient retention within sediments, whereas increasing oxygen deficiency enhances the release of nutrients, particularly phosphorus, into the water column (Viktorsson et al., 2013; Bonaglia et al., 2014). Consequently, these opposing processes may partially offset the effects of changing stratification and could help explain why corresponding long-term ecosystem trends have not been consistently reported in recent Baltic Sea observations (Olofsson et al., 2020; Stoń-Egiert and Ostrowska, 2022).

Additionally, as shallow summer mixed layer (driven by increased stratification) prolongs periods of nutrient depletion in surface waters, organisms that can utilize alternate nutrient sources or fix nitrogen (e.g. cyanobacteria in summer) have an advantage (Munkes et al., 2021). Cyanobacteria can fix N_2 and thus dominate when nitrate is low and the water is stably stratified (Munkes et al., 2021; Spilling et al., 2025). A trend toward stronger stratification (Fig. 3c) could facilitate cyanobacteria blooms in the long term, since vertical mixing is less available to disrupt their suitable living conditions or to bring up nitrate. This is relevant because the Baltic Sea already experiences extensive cyanobacterial

blooms in summer when stratification is strong (Kahru and Elmgren, 2014). We emphasize that MLD represents only one of several interacting factors influencing phytoplankton and cyanobacterial bloom dynamics in the Baltic Sea, alongside variables such as irradiance, and interspecific competition (Olofsson et al., 2020; Degerholm et al., 2006; Mohlin et al., 2012; Kahru et al., 2025). Consequently, the relationship between MLD and bloom development is unlikely to be linear, but can play an important role within the broader set of environmental drivers, especially in a longer time scale.

The physical changes we document are likely to have complex ecosystem effects, from altering the timing and composition of phytoplankton blooms to influencing higher-trophic-level processes that depend on the distribution of nutrients and oxygen. Our results also align with the emerging consensus from Baltic Sea climate assessments, which state that air and water temperatures are rising, and ice extent is decreasing (Meier et al., 2022b). These changes in turn modify physical oceanographic processes such as stratification and vertical mixing. The Baltic Sea is often cited as an amplified case of climate-driven change, reacting faster or more intensely than the global ocean due to its shallowness and restricted exchange (Hepach et al., 2024). The mixed layer trends we observe can thus be seen as part of this larger picture of a system in transition. In particular, the long-term shoaling of the winter mixed layer in the central Baltic is a strong indicator of how increased heat content and salt stratification are altering the fundamental vertical structure of the sea.

The changes in MLD carry important implications for the Baltic Sea ecosystem and biogeochemistry (Fig. 5). In areas where the winter mixed layer has shoaled, likely less oxygen is being delivered to the deep waters each year, which could exacerbate hypoxia and alter nutrient availability. Conversely, deeper winter mixing in the northern and eastern Baltic could improve water column ventilation, nutrient retention in the sediments and nutrient redistribution in those regions. Additionally, a trend toward stronger stratification and shallower summer mixed layers could benefit, in favourable combination with other factors, cyanobacterial blooms by prolonging surface nutrient depletion and stable conditions. These potential changes are obscured by the counteracting influence of oxygen conditions on nutrient dynamics and the complex set of additional factors influencing phytoplankton and cyanobacteria blooms in general.

Overall, the contrasting MLD trends suggest that different parts of the Baltic Sea will face distinct ecological challenges and feedback under continued climate change. Looking ahead, sustained observations and high-resolution modeling will be critical to track and predict how the Baltic Sea's mixed layer evolves under future warming scenarios – especially as winters with little or no ice and more intense summer stratification become increasingly common. By recognizing the region-specific nature of MLD responses, future

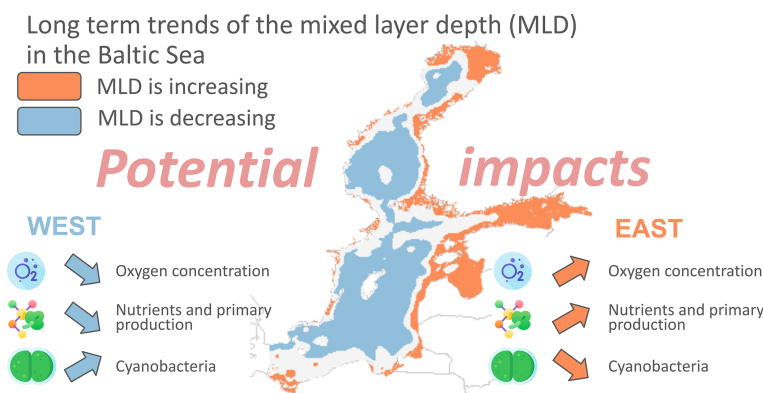


Figure 5. Infographic illustrating the potential relationship between mixed layer depth (MLD) trends and changes in the ecological state of the Baltic Sea, including various eutrophication indicators.

efforts can better anticipate the impacts of climate change on Baltic Sea conditions and ecosystem services.

4 Conclusions

Our study demonstrates that climate-driven changes in the Baltic Sea have led to divergent trends in MLD across different regions. Climate warming emerges as a fundamental driver: higher air and water temperatures, together with feedbacks like reduced ice cover and altered freshwater input, have created conditions for the mixed layer to shoal in some areas and deepen in others. The Baltic Sea's response to this global forcing is highly nuanced – regional differences (such as whether an area is seasonally ice-covered or influenced by strong haline stratification) modulate how the mixed layer responds. We found that from 1993 to 2023, Baltic Sea MLDs exhibit significant spatial and temporal variability, with clear trends linked to atmospheric warming, declining ice extent, and changing stratification patterns. The southern parts of the Baltic are shifting toward a more stratified state with generally shallower winter mixed layers, while the northern sub-basins are experiencing enhanced winter mixing due to the loss of ice cover.

Data availability. The model products used in this study from both the Copernicus Marine Service and other sources are listed in Table 1.

Author contributions. UR designed the concept of this study, interpreted the results, and wrote the initial manuscript. UA performed the calculations and prepared the figures. AB and IM contributed to the manuscript development. MK contributed to the study of the variations of MLD on the biogeochemistry and ecology of the Baltic Sea. PL was responsible for the funding. All authors contributed to writing and revising the manuscript.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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