

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

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

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

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

18 **Short Summary.** Over the past 30 years, the Baltic Sea’s surface mixed layer has changed unevenly: it is shoaling in the
19 southwest due to warming and increased stratification, while deepening in the northeast as ice loss allows more winter
20 mixing. These shifts may affect ecosystems by reducing deep-water ventilation and worsening hypoxia in the south, while
21 enhancing nutrient redistribution and spring bloom potential in the north. The Baltic Sea’s climate response is strongly
22 regional.

23 1 Introduction

24 The oceanic upper Mixed Layer Depth (MLD) is a fundamental physical parameter governing the exchange of heat,
25 momentum, and gases between the ocean and atmosphere. It plays a central role in modulating climate variability, regulating
26 marine biogeochemical processes, and influencing the structure and productivity of marine ecosystems (Lorbacher et al.,
27 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; Bulczak 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.

58 **2 Data and methods**

59 **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

60

61 The Baltic Sea physics reanalysis multi-year product (BAL-MYP; product ref. no. 1) is derived from the ocean model
62 NEMO v4.0 (Gurvan et al., 2019). It assimilates satellite observations of sea surface temperature (SST) (EU Copernicus
63 Marine Service Product, 2022) and in-situ temperature and salinity profiles from the ICES database (ICES Bottle and
64 low-resolution CTD dataset, 2022). The model data is provided on a grid with a horizontal resolution of 1 nautical mile,
65 including 56 vertical layers, covering the entire Baltic Sea and the transition zone to the North Sea. The dataset covers the
66 period from 1993 to 2023, with the model setup detailed in the Product User Manual (Ringgaard et al., 2024).

67 The BAL-MYP has been extensively validated, as documented in the Quality Information Document (QuID; Panteleit et al.,
68 2025), focusing on the period from 1st January 1993 to 31st December 2018. Additionally, the BAL-MYP data were
69 evaluated using a clustering method with the K-means algorithm (Raudsepp and Maljutenko, 2022), which provided insights
70 into the reanalysis accuracy by categorising errors (Lindenthal et al., 2024). Fifty-seven percent of the data are clustered with
71 a bias of $dS=-0.40$ g/kg and $dT=-0.02$ °C, encompassing 57% of all data points with RMSE $S=0.92$ g/kg and $T=0.54$ °C
72 (Lindenthal et al., 2024). These points are distributed throughout the Baltic Sea. Clusters with high positive and negative
73 temperature biases account for 11% and 8% of total points, respectively, with marginal salinity biases and relatively even
74 spatial distributions across the Baltic Sea. Twenty-six percent of the points have low temperature but high salinity errors,
75 both negative and positive, predominantly located in the southwestern Baltic Sea, indicating occasional underestimation or
76 overestimation of the inflow/outflow salinity (Lindenthal et al., 2024).

77 The MLD, also referred to as the Upper Mixed Layer (UML), was included in the analysis using data from a multi-year
78 reanalysis product (product ref. no. 1). The MLD was calculated based on density stratification following the method of de
79 Boyer Montégut et al. (2004), which defines MLD as the depth at which seawater density deviates from the reference density
80 at 10 m depth by a specified threshold. For the Baltic Sea, this threshold was adjusted to 0.03 kg/m³ to better represent the
81 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 profiles 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.

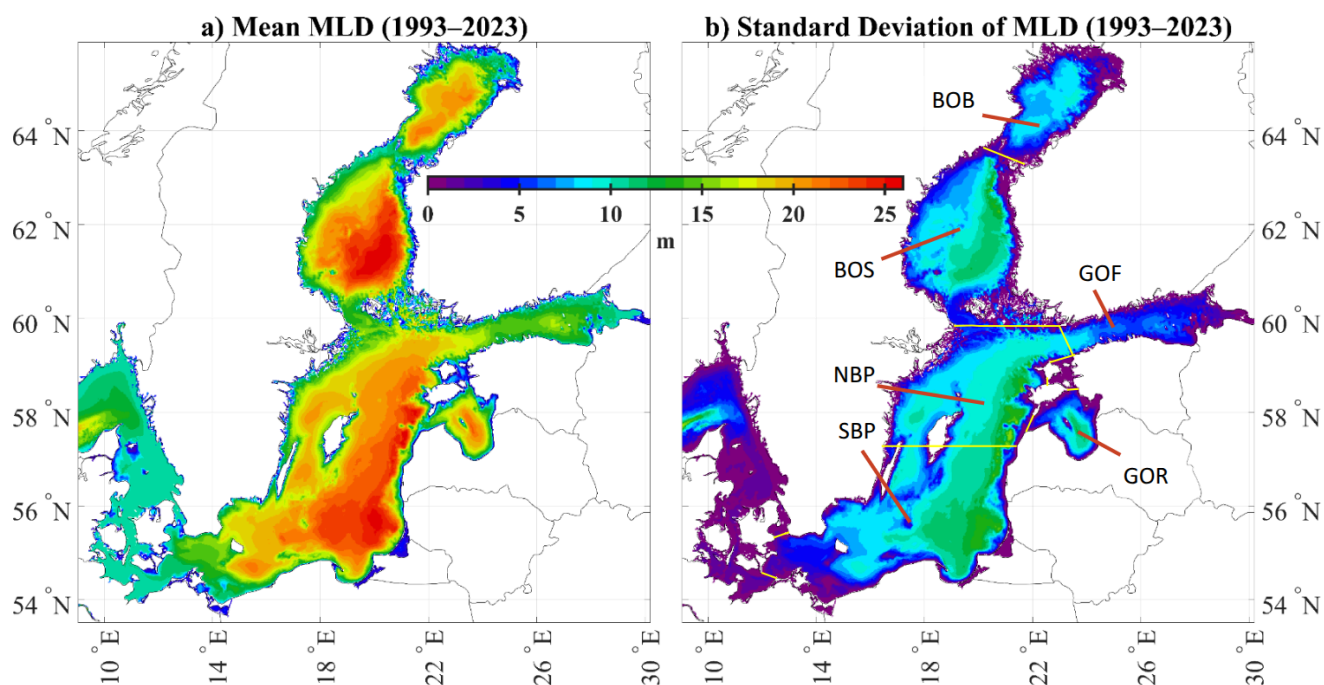
The annual cycle of the MLD of the products follows the MLD calculated from observations for the whole reanalysis period (Panteleit et al., 2025). It is possible to observe the seasonal variability of the MLD product in summer and winter. During the summer, the MLD is lower, and during the winter, the 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 01.01.1993-30.12.2019. 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-meter air temperature, total precipitation, and the wind speed, estimated from the daily averaged zonal (u) and meridional (v) components of 10-meter 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:

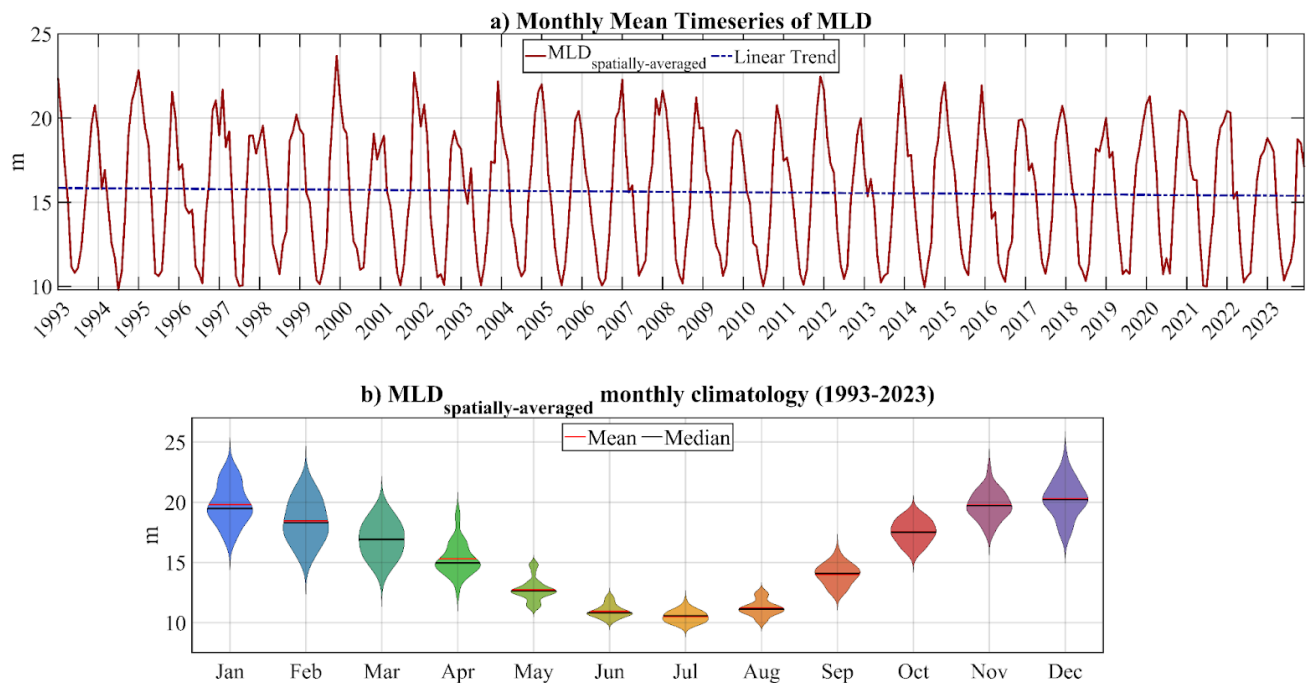
$$PEA = \frac{1}{H-h} \int_h^H g(\rho(z) - \bar{\rho})(z - h) dz \quad (1)$$

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.



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Figure 1. Spatial distribution of the long-term mean (left panel) and standard deviation (right panel) 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).



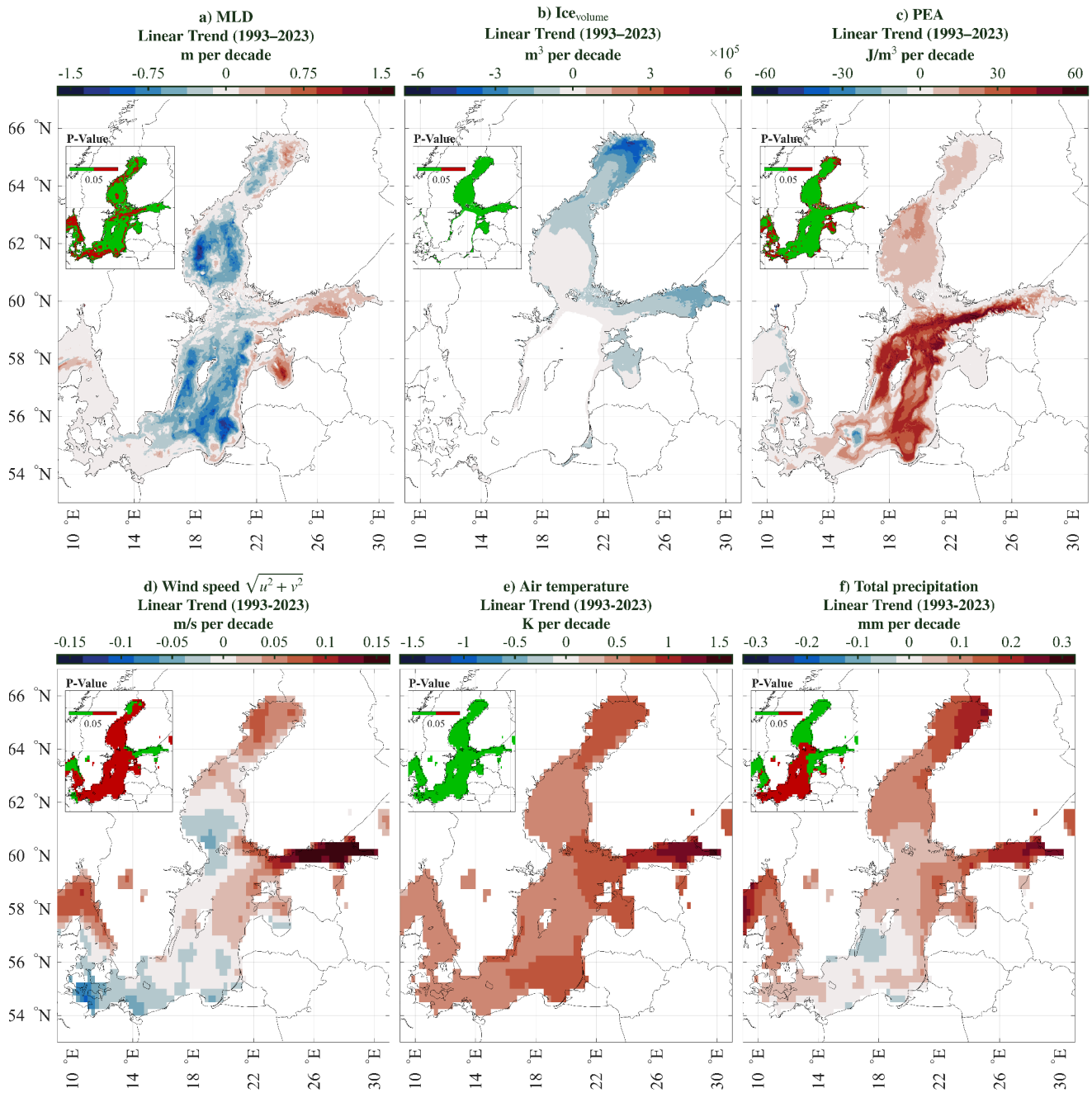
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Figure 2. Monthly mean MLD variability in the Baltic Sea over the 29-year period from 1993 to 2023 (Table 1, product ref. no. 1). a) monthly mean MLD time series alongside a linear trend (red dashed line), highlighting pronounced seasonal variability 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.

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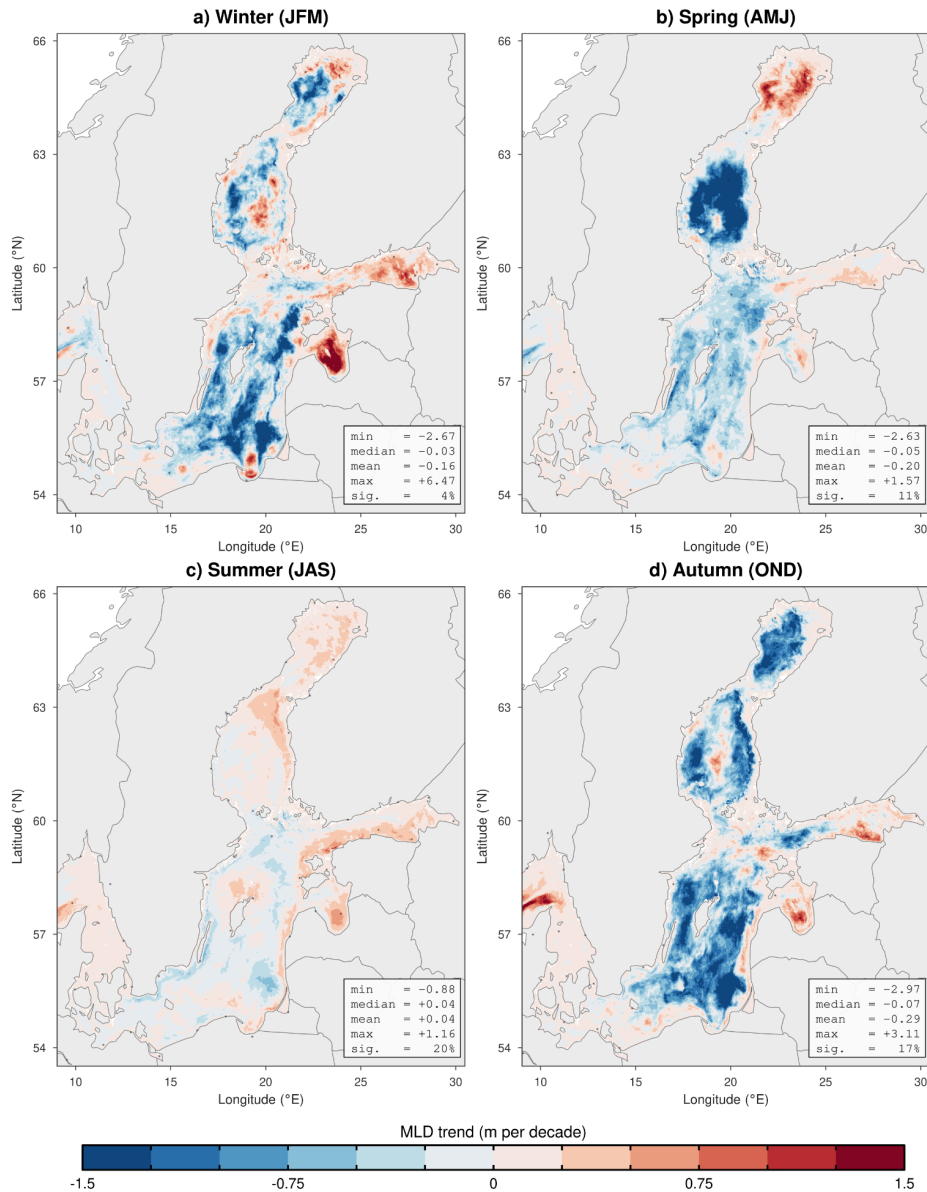
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130 **Figure 3.** Linear trends (1993–2023) of oceanic and atmospheric parameters in the Baltic Sea region. (a) mixed layer depth
 131 (MLD) Eq. (1), (b) Sea ice volume trend during the ice season (November–May), (c) potential energy anomaly (PEA),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



145 The climatological mean MLD exhibits pronounced regional differences across the Baltic Sea (Figure 1a). The presented
146 fields (Figure 1) were computed from monthly averaged data derived from the high-resolution oceanographic reanalysis.
147 Deeper mixed layers occur in the central and southern Baltic basins (e.g., Gotland Basin), while shallower layers dominate in
148 coastal areas and the northern basins, such as the Gulf of Finland and Bothnian Bay. These differences reflect the influence
149 of bathymetry, wind exposure, and surface buoyancy forcing (Lass & Matthäus, 1996, Liblik & Lips, 2012, Liblik et al.,
150 2020).

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

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

164 The MLD follows a clear seasonal cycle, as illustrated by the monthly climatology (Figure 2b). Maximum depths are
165 typically observed during winter (October–March), driven by convective mixing under cold air temperatures. Minimum
166 MLDs occur in summer (June–August), when surface heating leads to strong stratification and shallow mixing layers. The
167 transitional periods in spring and autumn are characterized by rapid changes in MLD, reflecting the formation and erosion of
168 seasonal thermoclines. These patterns are consistent with prior studies (e.g., Fu et al., 2012; Bulczak et al., 2024)
169 documenting deep winter mixing and shallow summer layers across the Baltic.

170 The spatial pattern of MLD linear trends (Figure 3a) reveals a striking west–east dipole: MLD has shoaled in the western
171 Baltic (e.g., western Baltic Proper, Bothnian Sea), while deepening trends are observed in the eastern basins (e.g., eastern
172 coasts of the Baltic Sea, Gulf of Finland, Gulf of Riga, and Eastern Bothnian Bay). This feature is repeated on seasonal
173 trends except for summer (Figure 4). The spatial contrast suggests region-specific responses to environmental changes. Sea
174 ice volume trends (Figure 3b), computed for the ice season (November–May), show significant declines. Reduced ice cover
175 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. (2024), who found significant reductions in ice thickness and extent throughout the Baltic.

The PEA trends shown in Figure 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 (Figure 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 modeling studies that suggest wind speeds in the region have not changed significantly over recent decades (Meier et al., 2022). In contrast, air temperature trends (Figure 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 (Figure 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 & Myrberg, 2009), while greater wind exposure over the open central basins promotes deeper mixing compared to the more sheltered coastal and archipelago regions (Kõuts & Omstedt, 1993; Miettunen 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 (Figure 1b) reflects their greater responsiveness to synoptic-scale

208 wind events and seasonal buoyancy changes compared to the persistently stratified and shallow regions (Umlauf et al.,
209 2018).

210 In the western subbasins, the overall shoaling is mechanistically linked to increasing thermal stratification driven by rising
211 air temperatures (Lehmann et al., 2022; Meier et al., 2022) and enhanced precipitation (Rutgersson et al., 2002), both
212 contributing to increased PEA, which stabilizes the water column and impedes vertical mixing.

213 For the eastern subbasins, the observed deepening trends in the Gulf of Finland, Eastern Gotland Basin, and Eastern
214 Bothnian Bay appear counterintuitive in a warming climate. However, the dramatic decline in sea ice volume (Singh et al.,
215 2024) offers a key mechanistic explanation. Reduced ice cover extends the open-water season—especially during autumn to
216 spring when wind energy is highest—allowing significantly more wind-driven mixing (Vihma & Haapala, 2009; Uotila et
217 al., 2023). This region also exhibits weaker positive or slightly negative PEA trends (Figure 3c), indicating reduced
218 stratification. The retreat of ice likely counteracts expected thermal stratification from warming by enhancing wind mixing
219 and reducing the freshwater lens effect from melting ice (Hordoir et al., 2019).

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

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

231 The observed changes in MLD have significant implications for the Baltic Sea’s physical and ecological state. A deeper
232 winter mixed layer in previously ice-covered regions (e.g. northern gulfs) can lead to greater ventilation of the water column
233 (Meier et al., 2019; Droste et al, 2025). This may be a positive outcome in terms of oxygen distribution: deeper mixing in
234 winter helps transport oxygen from the surface to intermediate depths, which can alleviate oxygen depletion that often
235 develops below the halocline (Kõuts et al., 2021a). However, the flip side is that shallower mixing in the central and southern
236 Baltic can exacerbate oxygen stress in those areas. These processes, combined with episodic inflows of warm saline water
237 that strengthen stratification, have been shown to exacerbate oxygen depletion in the western Baltic (Barghorn et al., 2025;).
238 When the mixed layer no longer reaches as deep into the halocline, less oxygen is injected into the deep layer each winter.
239 Over time, this contributes to more severe or persistent hypoxia in the deeper basins (Krapf et al., 2022). The Baltic Sea is

240 already well known for its extensive oxygen-depleted bottom areas, often referred to as "dead zones" (Carstensen et al.,
241 2014; Kõuts et al., 2021a), and stronger stratification only worsens this issue by further isolating the deep water. Recent
242 studies have indeed reported an increasing frequency of hypoxic events in the Baltic Proper, correlating with intensifying
243 stratification and warming (Rolff et al., 2022; Hepach et al., 2024; Liblik et al., 2025; Stockmayer and Lehmann, 2023). Our
244 findings of MLD shoaling in the main basins are thus a warning sign of potentially deteriorating deep-water oxygen
245 conditions if these trends persist.

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

259 Additionally, as shallow summer mixed layer (driven by increased stratification) prolongs periods of nutrient depletion in
260 surface waters, organisms that can utilize alternate nutrient sources or fix nitrogen (e.g. cyanobacteria in summer) have an
261 advantage (Munkes et al., 2021). Cyanobacteria can fix N_2 and thus dominate when nitrate is low and the water is stably
262 stratified (Munkes et al., 2021; Spilling et al., 2025). A trend toward stronger stratification (Fig. 3c) could facilitate
263 cyanobacteria blooms in the long term, since vertical mixing is less available to disrupt their suitable living conditions or to
264 bring up nitrate. This is relevant because the Baltic Sea already experiences extensive cyanobacterial blooms in summer
265 when stratification is strong (Kahru and Elmgren, 2014). We emphasize that MLD represents only one of several interacting
266 factors influencing phytoplankton and cyanobacterial bloom dynamics in the Baltic Sea, alongside variables such as
267 irradiance, and interspecific competition (Olofsson et al., 2020; Degerholm et al., 2006; Mohlin et al., 2012; Kahru et al.,
268 2025). Consequently, the relationship between MLD and bloom development is unlikely to be linear, but can play an
269 important role within the broader set of environmental drivers, especially in a longer time scale.

270 The physical changes we document are likely to have complex ecosystem effects, from altering the timing and composition
271 of phytoplankton blooms to influencing higher-trophic-level processes that depend on the distribution of nutrients and
272 oxygen. Our results also align with the emerging consensus from Baltic Sea climate assessments, which state that air and

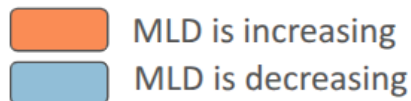
273 water temperatures are rising, and ice extent is decreasing (Meier et al., 2022). These changes in turn modify physical
274 oceanographic processes such as stratification and vertical mixing. The Baltic Sea is often cited as an amplified case of
275 climate-driven change, reacting faster or more intensely than the global ocean due to its shallowness and restricted exchange
276 (Hepach et al., 2024). The mixed layer trends we observe can thus be seen as part of this larger picture of a system in
277 transition. In particular, the long-term shoaling of the winter mixed layer in the central Baltic is a strong indicator of how
278 increased heat content and salt stratification are altering the fundamental vertical structure of the sea.

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

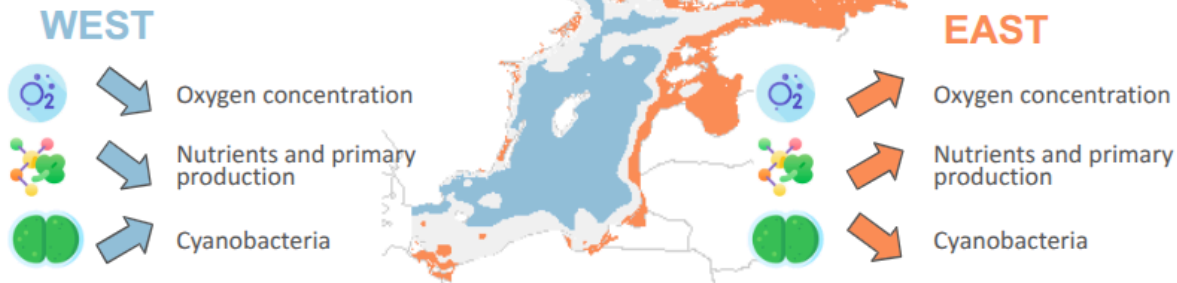
287 Overall, the contrasting MLD trends suggest that different parts of the Baltic Sea will face distinct ecological challenges and
288 feedback under continued climate change. Looking ahead, sustained observations and high-resolution modeling will be
289 critical to track and predict how the Baltic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

293

Long term trends of the mixed layer depth (MLD) in the Baltic Sea



Potential impacts



294

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

297 Conclusions

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

307

308 Data Availability

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

310 Author contribution

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

315 **Competing Interests**

316 The authors declare that they have no conflict of interest.

317 **Disclaimer**

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324 **Special issue statement**

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