

Review

Submesoscale dynamics in the Baltic Sea – a review

Urmas Lips^{a,*}, Kai Salm^a, Germo Väli^a, Taavi Liblik^a, Lars Arneborg^b, Louise C. Biddle^c, Anna I. Bulczak^d, Evridiki Chrysagi^{e,f}, Małgorzata Falarz^g, Peter Holtermann^f, Jaromir Jakacki^d, H. E. Markus Meier^f, Martin Mohrmann^c, Kai Myrberg^h, Per Pemberton^b, Lars Umlauf^f

^a Department of Marine Systems, Tallinn University of Technology, Akadeemia Rd. 15a, 12618 Tallinn, Estonia

^b Department of Research and Development, Swedish Meteorological and Hydrological Institute, Göteborgskaderns Plats 3, 426 71 Västra Frölunda, Sweden

^c Voice of the Ocean Foundation, Skeppet Årans Väg 19, 426 71 Västra Frölunda, Sweden

^d Physical Oceanography Department, Institute of Oceanology Polish Academy of Sciences, Sopot, Poland

^e Institute of Oceanography, University of Hamburg, Bundesstr. 53, 20146 Hamburg, Germany

^f Department of Physical Oceanography, Leibniz Institute for Baltic Sea Research Warnemünde, Seestrasse 15, 18119 Rostock, Germany

^g Faculty of Natural Sciences, University of Silesia in Katowice, ul. Bedzinska 60, 41-200 Sosnowiec, Poland

^h Finnish Environment Institute, Latokartanonkaari 11, 00790 Helsinki, Finland

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ABSTRACT

The main aim of this work is to provide a comprehensive literature review of the current state of knowledge on submesoscale (SMS) dynamics in the Baltic Sea, with potential implications for other similar coastal and marginal seas. Relevant spatial and temporal scales in the Baltic Sea, as well as idealized quantitative descriptions of SMS instabilities, are presented. The methods for studying SMS processes are described, and the availability of the required research infrastructure and relevant data is discussed. The knowledge on SMS processes and their role in coastal-offshore exchanges, vertical and horizontal mixing, and the development of stratification in the Baltic Sea is reviewed and compared with studies in other regions. Processes at adjacent scales and their links to SMS dynamics, including mesoscale features such as upwelling events, fronts, and baroclinic currents in geostrophic balance, as well as small-scale turbulence, are described. This analysis demonstrates that SMS processes may substantially influence large-scale dynamics of the Baltic Sea, challenging the classical understanding of energy transfer across spatial scales that omits instabilities and feedback loops in the SMS range. The review suggests that SMS processes play a role in the biogeochemical functioning of the Baltic Sea by providing vertical fluxes of substances and redistributing plankton biomass. We emphasize that extensive model validation with high-resolution in-situ data remains an urgent task, and a more accurate description of SMS processes in sub-grid parameterizations within large-scale models is necessary. Gaps in knowledge of SMS dynamics and potential further steps to address them are highlighted.

1. Introduction

Submesoscale (SMS) processes in the ocean occupy spatial scales between geostrophically balanced mesoscale processes and small-scale turbulence, while their temporal scales range from hours to days (Taylor and Thompson, 2023). SMS processes are dynamically characterized by $O(1)$ Rossby (Ro) and balanced Richardson (Ri_b) numbers (Thomas et al., 2008). The former implies that SMS are still influenced but not firmly constrained by the Earth's rotation, indicating that they are associated with large vertical vorticity and thus can enhance fluxes

between the surface layer and the ocean interior (Callies et al., 2015). The latter implies that in the presence of horizontal buoyancy gradients, the SMS flows can emerge and restratify the water column (Yu et al., 2019). Submesoscales are therefore particularly prominent in the surface and bottom boundary layers, where horizontal buoyancy gradients are abundant and vertical stratification is weak, contributing significantly to ocean dynamics (Dong et al., 2024) and biogeochemistry (Lévy et al., 2012; Gray et al., 2024). SMS processes provide a pathway for the energy transfer from the mesoscale to smaller scales, ultimately leading to microscale dissipation and diapycnal mixing (McWilliams, 2016;

* Corresponding author.

E-mail address: urmas.lips@taltech.ee (U. Lips).

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Naveira Garabato et al., 2022). SMS processes may play a role in the global heat budget (Su et al., 2018), and it has been argued that their inaccurate parametrization in coarse-scale ocean (climate) models can cause biases in long-term forecasts (Taylor and Thompson, 2023).

Based on idealized analyses of instabilities, various mechanisms have been suggested that create variability at the submesoscale (Gula et al., 2022; Taylor and Thompson, 2023). SMS baroclinic instability (BI) follows a similar logic to mesoscale instability of large-scale flows (Eady, 1949). Since vertical stratification in the surface mixed layer (SML) is weak, eddies that develop due to BI have smaller spatial scales in the SML than in the ocean pycnocline. Such instability leads to a restratifying buoyancy flux (Boccaletti et al., 2007; Fox-Kemper et al., 2008; Chrysagi et al., 2021), significantly affecting the depth of the mixed layer. Another type of instability – symmetric instability (SI) – develops in stably stratified flows when potential vorticity takes the opposite sign of the Coriolis parameter due to baroclinic effects (Taylor and Ferrari, 2009; Arobone and Sarkar, 2015). SI (Thomas et al., 2013) can be forced, for instance, by surface cooling or downfront winds (directed along the frontal jet). SI and ageostrophic secondary circulation at SMS fronts (McWilliams, 2021) can induce substantial vertical fluxes and subduction of surface waters (Pham et al., 2024).

The main physical forcing components for the Baltic Sea system are atmospheric forcing, including the exchange of heat and freshwater through the sea surface, and the input of freshwater from rivers and saltier water through the Danish Straits (Omstedt et al., 2004). In response to the external forcing, internal dynamics of the system at multiple temporal and spatial scales shape the observed layered structure of the water column, typical lateral gradients of tracers (e.g., salinity), and general circulation of the Baltic Sea (Elken and Matthäus, 2008; Leppäranta and Myrberg, 2009). While the role of mesoscale processes (eddies, fronts, upwelling/downwelling) in the Baltic Sea dynamics is well recognized (Aitsam et al., 1984; Kononen et al., 1996; Vortmeyer-Kley et al., 2016, 2019), the contribution of SMS processes is poorly understood.

An overview of mixing processes in the Baltic Sea by Reissmann et al. (2009) did not explicitly mention SMS processes. However, more recent reviews of physical oceanography (Omstedt et al., 2014), salinity dynamics (Lehmann et al., 2022), and water exchange (Elken and Omstedt, 2025) stress the need for better understanding of small-scale (including SMS) processes and their impact on general, overturning circulation (Döös et al., 2004; Placke et al., 2021). Nevertheless, the variability at the submesoscale and SMS processes in the Baltic Sea have been receiving more attention in recent years, driven by advances in in-situ

observations, remote sensing, and numerical modeling (e.g., Lips et al., 2011, 2016a; Liblik and Lips, 2012; Gurova and Chubarenko, 2012; Liblik et al., 2017; Väli et al., 2017, 2024, 2025; Carpenter et al., 2020; Chrysagi et al., 2021, 2022; Salm et al., 2023, 2025; Hariri et al., 2024, 2025; Lilover et al., 2025). A typical example of small-scale inhomogeneities in a cyanobacterial bloom in the Baltic Sea, which can be attributed to the action of SMS processes, is presented in Fig. 1 (ESA Copernicus, Sentinel-2, 8 August 2022; Lilover et al., 2025). We suggest that the synthesis of mixing processes in the Baltic Sea by Reissmann et al. (2009) could be complemented by considering also processes at scales between mesoscale and microscale, their effects, and links to processes and variability at other scales.

SMS processes, with spatial scales from 200 m to 20 km in the ocean (Capet et al., 2008; Taylor and Thompson, 2023), have slightly smaller sizes in the Baltic Sea (Väli et al., 2017) due to its location at relatively high latitudes and shallowness (Fig. 2a), as well as the layered structure of the water column. They are more abundant in the presence of intense mesoscale processes, including mesoscale straining and frontogenesis (Gula et al., 2022; Adams et al., 2017), suggesting their significant role in Baltic Sea dynamics (Lips et al., 2016a). Due to its configuration and stratified water column, local wind forcing generates coastal upwelling and downwelling events characterized by mesoscale baroclinic fronts and currents (Myrberg and Andrejev, 2003; Suursaar and Aps, 2007; Lips et al., 2009; Lehmann et al., 2012). Furthermore, faster warming in shallow areas (Lips et al., 2014), wind-driven cross-shore inclination of pycnoclines (Liblik and Lips, 2017), and riverine water spreading (Stipa et al., 1999; Beszczyńska-Möller, 1999; Lips et al., 2017; Liblik et al., 2020) create horizontal buoyancy gradients that are conducive to SMS development. Thus, the Baltic Sea serves as a natural laboratory for investigating SMS processes due to the ubiquitous lateral density gradients generated by salinity differences and wind-driven upwelling events and fronts. We can test existing SMS concepts here and generate new knowledge that may be relevant elsewhere, especially regarding complex and heterogeneous coastal ocean submesoscales that are difficult to parameterize.

On the other hand, since Baltic Sea conditions are favorable for the development and action of SMS processes, their inclusion is crucial for understanding the dynamics of the Baltic Sea. SMS processes are inherently 3D and contribute to both horizontal and vertical transport and mixing. Acting alongside other processes at a multitude of scales, they alter vertical stratification (Carpenter et al., 2020; Chrysagi et al., 2021), drive exchanges between coastal and offshore regions (Väli et al., 2024) and surface and subsurface layers (Salm et al., 2025), as well as

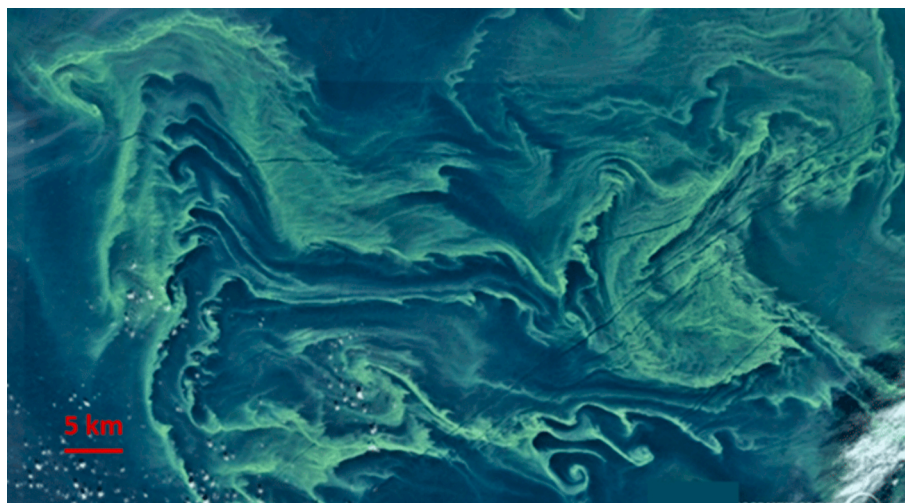


Fig. 1. Satellite image depicts small-scale inhomogeneities in a cyanobacterial bloom in the Baltic Sea (entrance area of the Gulf of Finland, 8 August 2022, European Union, Copernicus Sentinel-2 imagery processed by @DEFIS_Eu). The size of the image is about 90×50 km, and its location is shown in Fig. 2b. (from Lilover et al., 2025).

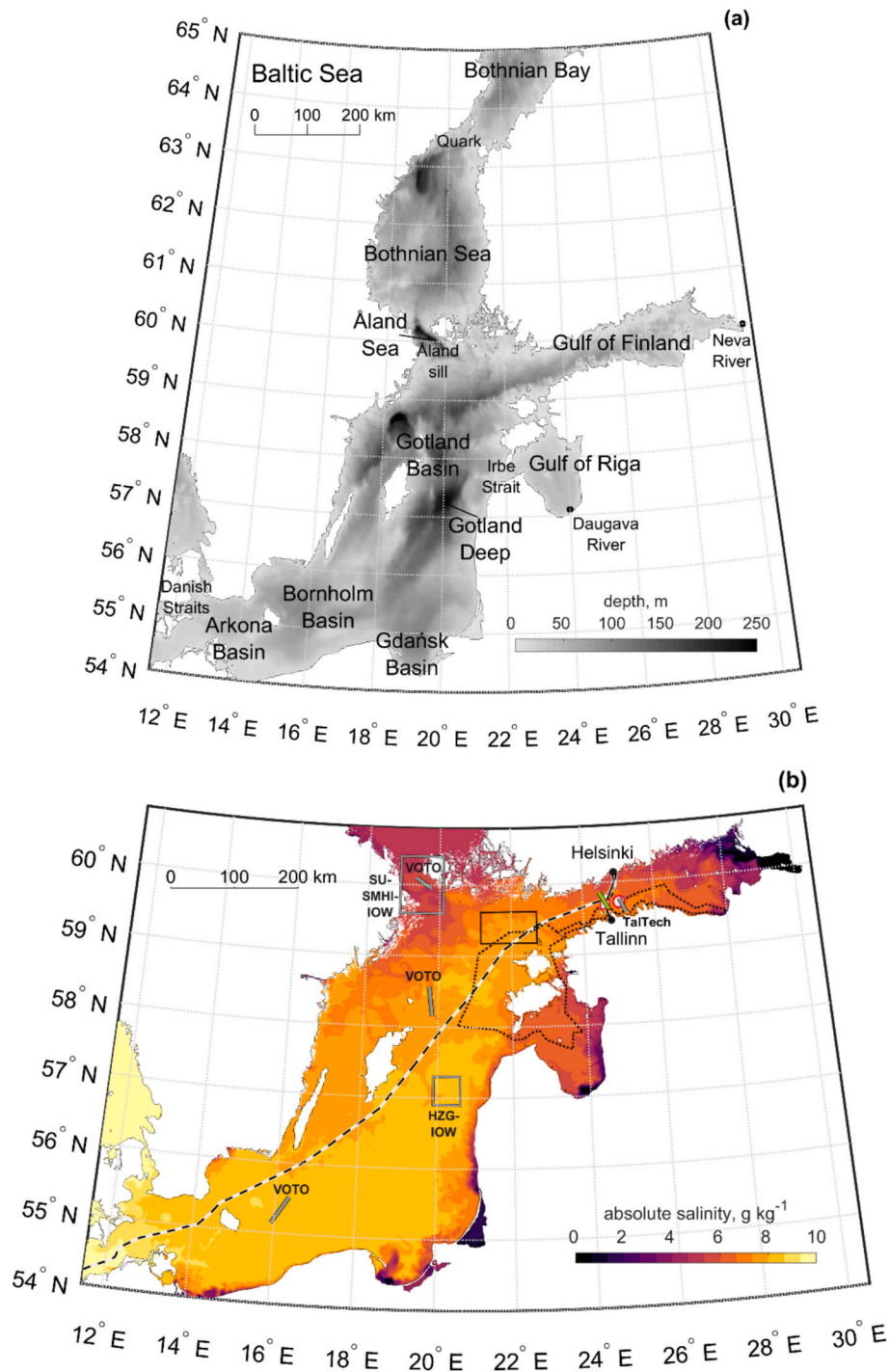


Fig. 2. (a) Baltic Sea bathymetry with sub-basin names and referred sites. (b) Surface salinity distribution in the Baltic Sea (example from a high-resolution, grid step 250 m, simulation by Väli et al. (2024) on 4 April 2017). Black rectangle shows the location of the photo in Fig. 1. Referred study locations and transects are indicated as follows: solid black line – Tallinn-Helsinki, black-white line – Helsinki-Travemünde, dotted line – r/v Salme ferrybox; red circle and square – profilers in the Gulf of Finland; green line – scanfish section; gray lines – glider sections; and gray rectangles – study sites in the Gotland Deep (HZG-IOW) and Aland Sea (SU-SMHI-IOW).

influence larger-scale dynamics (Väli et al., 2025). Intermittent occurrence of SMS processes indicates the conditions under which the coastal-offshore exchange is most intense (Väli et al., 2024) and where the hotspots of estuarine mixing emerge (Henell et al., 2023). Since SMS processes significantly influence the development of seasonal stratification and mixing, they in turn influence productivity (Cahill et al., 2024; Vortmeyer-Kley et al., 2025) and distribution of plankton (Lips et al., 2011; Lips and Lips, 2017), as well as carbon fluxes, as shown in other sea areas (e.g., Omand et al., 2015).

Although SMS phenomena are particularly prominent in SML, they can also emerge in the ocean interior, primarily originating near sloping topography through flow-topography interactions (e.g., Molemaker et al., 2015; Gula et al., 2015; Naveira Garabato et al., 2019). These interior structures can be instrumental for the turbulent boundary mixing and the forward cascade of energy towards the dissipation scales. Near-bottom propagation of dense water and associated entrainment and mixing (Umlauf and Arneborg, 2009a, b) is an important process for the Baltic Sea dynamics. Flows over rough topography can create small-

scale features and turbulence, as shown in the Baltic Sea (Muchowski et al., 2023a, b) and other sea areas (e.g., de Marez et al., 2024). The latter study assigned these small-scale structures to SMS processes. It can be suggested that great similarities exist between the mixing and SMS instabilities in SML, leading to subduction and SMS variability in the sub-thermocline layer (Salm et al., 2025), and the mixing and instabilities in the bottom boundary layer (BBL), leading to interleaving and SMS variability in the sub-halocline layer of the Baltic Sea. Thus, SMS processes may play a significant role in shaping oxygen conditions of deep basins of the Baltic Sea, and advancing related knowledge is crucial for a better understanding of the biogeochemistry of the Baltic Sea and similar stratified coastal sea areas.

Due to their limited spatial and temporal extent, capturing SMS processes requires high-resolution observations and models that can resolve the associated variability. Conventional ship-borne measurements must be complemented by autonomous observational platforms, such as gliders, drifters, and profilers, as well as towed vehicles and flow-through systems (e.g., ferryboxes), which are increasingly employed to resolve the variability associated with SMS dynamics in the ocean (e.g., Rudnick and Cole, 2011; Swart et al., 2023) and the Baltic Sea (Lips et al., 2016a; Carpenter et al., 2020; Salm et al., 2023). Numerical models with SMS-permitting resolutions have revealed high variability and richness of features in the respective wavenumber range (Capet et al., 2008; Väli et al., 2017). Furthermore, finer-resolution models may suggest large-scale circulation patterns that differ from those derived from the coarser-scale simulations (Andrejev et al., 2004; Maljutenko and Raudsepp, 2019; Westerlund et al., 2019). However, the lack of observational data with the required resolution and coverage hinders proper validation of these high-resolution model runs. This observational gap introduces uncertainty into the interpretation of simulation outcomes and complicates the development of accurate sub-grid parameterizations for large-scale ocean (climate) models.

While general knowledge of SMS currents and their role in multiscale ocean dynamics has been reviewed by, e.g., McWilliams (2016, 2019) and Taylor and Thompson (2023), comparable syntheses remain lacking for the Baltic Sea. The scope of this review is therefore to summarize the current understanding of SMS processes and their linkages with the dynamics at other scales in the Baltic Sea. Internal waves occupying similar spatial and temporal scales as well as stratified turbulence are not directly within the scope of this review, but the relationship between them and SMS processes is mentioned where relevant.

The paper is organized as follows: SMS domain in space and time and theoretical considerations of SMS development are described in Section 2. Section 3 presents a review of applied methods to study the SMS processes in the Baltic Sea. State-of-the-art knowledge on SMS dynamics and knowledge gaps are presented in Section 4, focusing on horizontal exchanges, development of stratification, subduction, near-bottom flows and mixing, multiscale interactions, and large-scale impacts. A summary and an outlook are compiled in Section 5.

2. SMS domain and processes

2.1. Scales in space and time

The Rossby number (Ro), defined as the ratio of inertial and Coriolis forces, can be estimated using relative vertical vorticity (ζ) as

$$Ro = \frac{\zeta}{f}; \zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \quad (1)$$

where f is the Coriolis parameter and u and v are the zonal (along x -axis) and the meridional (along y -axis) velocities, respectively. According to this formula, Ro can take negative or positive values corresponding respectively to anticyclonic or cyclonic rotation in the Northern Hemisphere.

Assuming a characteristic velocity scale of 0.1 m s^{-1} and Coriolis

parameter of 10^{-4} s^{-1} at $50\text{--}60^\circ\text{N}$ gives $Ro \approx 1$ at a length scale of 1 km . For $Ro \ll 1$ ($L \geq 10 \text{ km}$), Earth's rotation dominates, and the flow is close to geostrophic balance, while for $Ro \gg 1$ ($L \leq 100 \text{ m}$), the Coriolis effect is negligible. The advection timescale (L/U) for SMS flows ranges from less than an hour to a few days. Dominating periods of current oscillations in the Baltic Sea, inertial oscillations (14 h) and low-frequency seiches ($26\text{--}31 \text{ h}$) (e.g., Suhhova et al., 2018; Lilover et al., 2025), fall within the same range.

Vertical stratification in the Baltic Sea is relatively strong compared to the open ocean. A permanent (or quasi-permanent) halocline exists at depths of $40\text{--}80 \text{ m}$ in deeper basins, and a seasonal thermocline develops at $5\text{--}20 \text{ m}$ in almost the entire sea area from spring to autumn (Leppäranta and Myrberg, 2009). Vertical stratification is quantified using the Brunt-Väisälä frequency (N):

$$N \equiv \sqrt{\frac{g}{\rho} \frac{\partial \rho}{\partial z}}, \quad (2)$$

where g is gravitational acceleration, ρ is density, and the vertical axis z is directed up. Typical values of N in the seasonal thermocline and halocline are a few times 10^{-2} s^{-1} corresponding to a minimum period of internal waves of a few minutes (e.g. Lass et al., 2003; Alenius et al., 2003; van der Lee and Umlauf, 2011).

The Froude number, defined as the ratio of inertial and gravitational forces, indicates the relative importance of vertical stratification. For $Fr \ll 1$, buoyancy forces dominate, while for $Fr \gg 1$, they are weak. The Froude number separates the domains of stratified turbulence and 3D isotropic turbulence. In the stratified Baltic Sea, conditions relevant to 3D turbulence ($Fr \gg 1$) occur at spatial scales of $\leq 0.1 \text{ m}$.

A widely used parameter indicating a characteristic spatial scale of geostrophically balanced flows (eddies) is the baroclinic Rossby radius (R_d) derived as the horizontal scale of the fastest-growing perturbations in conditions of $Ro \ll 1$ (Eady, 1949). It can be roughly estimated as

$$R_d \equiv \frac{c_1}{f} \approx \frac{NH}{f} \quad (3)$$

where c_1 is the phase speed of the first baroclinic mode internal waves, H is the sea depth or the water layer thickness, and N is the average buoyancy frequency in the water layer under consideration. In the Baltic Sea, R_d varies between 1.3 km in the shallow Belt Sea and 7 km in the central deep basins (Fennel et al., 1991; Lass et al., 2003; Osinski et al., 2010), is about 4 km in the Gulf of Finland (Alenius et al., 2003) and $<3 \text{ km}$ in the Gulf of Riga (Lips et al., 2016c). Since the typical baroclinic Rossby radius is 5 km ($1\text{--}7 \text{ km}$) and strong vertical stratification is a characteristic feature of the Baltic Sea water column, SMS processes and stratified turbulence occupy a broad range of spatial scales between balanced flows and 3D isotropic turbulence (from $5\text{--}10 \text{ km}$ to 0.1 m).

2.2. SMS instabilities and processes

SMS processes extract energy from the lateral buoyancy gradients (fronts) and larger-scale balanced flows via several proposed instability mechanisms (Thomas et al., 2008; Gula et al., 2022). The horizontal buoyancy gradient is expressed as

$$b_s = -\frac{\partial b}{\partial s}; b = -g \frac{\rho}{\rho_0} \quad (4)$$

where ρ_0 is a reference density and the s -axis is directed along the maximum horizontal buoyancy gradient (across the front). Under the assumption that background currents are quasi-geostrophic (i.e., there is a balance between the vertically sheared horizontal currents and horizontal buoyancy gradients, the so-called thermal wind balance), the bulk (balanced) Richardson number can be estimated as

$$Ri_b \equiv \frac{N^2 H^2}{U^2} = \frac{N^2 f}{b_s} \quad (5)$$

The sheared flow is stable to perturbations when $Ri_b \gg 1$, while SMS instabilities can occur at Ri_b of O(1) or less (except inertial instability, see below), i.e., under conditions of strong horizontal buoyancy gradients and/or weak vertical stratification (Thomas et al., 2008).

Considering $f \approx 10^{-4} \text{ s}^{-1}$ for the Baltic Sea latitudes, one can derive the relationship between vertical and horizontal buoyancy gradients for O(1) Ri_b . A characteristic pycnocline with $N \approx 10^{-2} \text{ s}^{-1}$ in the Baltic Sea and a characteristic horizontal density gradient across a mesoscale front (e.g., density difference of 0.5 kg m^{-3} across a front with a width of 5 km at the entrance to the Gulf of Finland observed by Pavelson et al., 1997) with $b_s = 10^{-6} \text{ s}^{-1}$ result in $Ri_b \sim 1$. For weaker stratification, as in the SML and BBL, the required horizontal buoyancy gradients to achieve O(1) Ri_b can be smaller. For instance, Chrysagis et al. (2021) showed that $Ri_b \sim 1$ and $b_s = 10^{-6} \div 10^{-7} \text{ s}^{-2}$ are typical in SMS filaments in the surface layer of the central Baltic Sea.

Similar to the baroclinic instability (BI) at the mesoscale with $Ro \ll 1$ (Eady, 1949), BI can develop at smaller scales. For instance, in the SML, where stratification is weak, smaller-scale (SMS) ageostrophic ($Ro \approx 1$) eddies can develop due to BI (Molemaker et al., 2010). This mechanism, also called mixed layer instability (MLI), can restratify the SML by carrying light water up and dense water down (Fox-Kemper et al., 2008; Taylor and Thompson, 2023). Furthermore, it has been shown that the resulting SMS buoyancy fronts can trigger 3D turbulence, providing a route for energy dissipation from the balanced flows via SMS processes (Molemaker et al., 2010).

While MLI draws energy from the horizontal buoyancy gradient (i.e., potential energy), ageostrophic SMS flows can also occur due to gravitational, inertial or shear-induced instabilities. A general condition for such instabilities is formulated by Hoskins (1974), stating that they can develop when potential vorticity (PV) takes the opposite sign of the Coriolis parameter. It can be written as:

$$f\mathbf{q} = f(f\hat{\mathbf{k}} + \nabla \times \mathbf{u}) \cdot \nabla \mathbf{b} < 0 \quad (6)$$

where $\mathbf{q}$ is the Ertel potential vorticity, $\hat{\mathbf{k}}$ is the unit vector in vertical direction, $\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right)$ is the Del operator, and $\mathbf{u}$ is the velocity vector. Following Thomas et al. (2013) and Gula et al. (2022), the developed instabilities can be divided into different types depending on the energy source. For gravitational instability, energy is provided by the buoyancy flux, e.g., by surface cooling or downfront winds that could lead to unstable vertical stratification ($N^2 < 0$). Inertial instability (II; also called centrifugal instability) develops when $N^2 > 0$ but relative vertical vorticity is negative (in the Northern Hemisphere) with its absolute value exceeding planetary vorticity, i.e., $\zeta_{abs} = f - \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} < 0$ (Thomas et al., 2013). For II, the energy is extracted from the lateral shear of the flow field, which can be barotropic.

In strongly baroclinic conditions, the flow can become unstable even if $N^2 > 0$ and $\zeta_{abs} > 0$. It is called symmetric instability (SI), which extracts energy from the vertical shear, leading to inertially unstable but gravitationally stable flows (Taylor and Ferrari, 2009; Arobone and Sarkar, 2015). It can be shown that SI occurs when horizontal buoyancy gradient is sufficiently strong to produce a baroclinic (vertically sheared) current. If assumed, as above, that the current is quasi-geostrophic, PV becomes negative when $\left| -\frac{1}{f} b_s^2 \right| > f \zeta_{abs} N^2$ (Thomas et al., 2013).

Thomas et al. (2013) showed that the emerging instability type can be related to the value of the balanced Richardson number or so-called Thomas angle (Th ; the name introduced by Gula et al., 2022) calculated as

$$Th \equiv \tan^{-1} \left(-\frac{1}{Ri_b} \right) \quad (7)$$

When $-180^\circ < Th < -135^\circ$, gravitational instability develops, while for $-135^\circ < Th < -90^\circ$, energy is extracted from both the buoyancy flux and geostrophic shear production, and the instability can be regarded as a hybrid of gravitational and symmetric instabilities. SI develops when $-90^\circ < Th < -45^\circ$ in the case of anticyclonic relative vorticity and when $-90^\circ < Th < Th_c$ in the case of cyclonic relative vorticity, where $Th_c \equiv \tan^{-1} \left(-\frac{\zeta_g}{f} \right)$ and ζ_g is the vertical component of the absolute vorticity of the geostrophic flow. Inertial instability (introduced above) can develop in the case of anticyclonic relative vorticity when $-45^\circ < Th < Th_c$.

SI produces symmetric SMS flows predominantly along inclined isopycnals, which do not modify the buoyancy distribution. However, these sheared flows can lead to secondary instabilities that intensify diapycnal turbulent mixing (Taylor and Ferrari, 2010). Furthermore, Wenegrat et al. (2020) demonstrated that a combination of SI-driven along-isopycnal mixing and episodic vertical mixing events (e.g., due to strong winds deepening the SML) can lead to lateral, cross-front, and diapycnal mixing of water properties.

Frontogenesis due to a mesoscale straining flow involves the sharpening of lateral density gradients that can disrupt geostrophic balance in the frontal current and generate an ageostrophic secondary circulation (ASC; McWilliams, 2021). Beyond strain-induced frontogenesis (Hoskins, 1982; Hoskins and Bretherton, 1972), frontogenesis can also occur in SMS fronts and filaments due to a secondary circulation associated with a modified Ekman balance, sometimes referred to as the Turbulent Thermal Wind (TTW) balance (McWilliams et al., 2015; Gula et al., 2014). The TTW balance – which includes not only the Coriolis force and the baroclinic pressure gradient, but also the vertical mixing of momentum due to surface-layer turbulence, provides a good approximation of SML dynamics in the presence of SMS flows, as demonstrated in both open-ocean (e.g., Gula et al., 2014) and Baltic Sea studies (Chrysagis et al., 2021).

Recent studies, focusing mainly on major current systems (e.g., Molemaker et al., 2015; Gula et al., 2015; Naveira Garabato et al., 2019), suggest that SMS processes and instabilities can also emerge near sloping topography through flow-topography interactions. Initial modeling results from the Eastern Gotland Basin suggest that such phenomena can also develop in the Baltic Sea, where pronounced SMS activity was found below the pycnocline, particularly close to sloping topography (for details see Section 4.2). Flow instabilities due to topographic irregularities generate internal waves and SMS eddies, which play a role in the BBL (e.g., Wenegrat et al., 2018). Both these mechanisms can be highly relevant in the Baltic Sea for understanding the pathways, mixing, and transformation of dense saline inflow waters from the North Sea (Meier et al., 2004; Mohrholz et al., 2015; Liblik et al., 2018; Schmidt et al., 2021), especially within the sub-halocline layer (Holtermann et al., 2014; Holtermann et al., 2017). These processes have critical implications for the ventilation of deep basins, the maintenance of oxygen-depleted zones, and the overall biogeochemical cycling in the region.

The above analysis of scales and balances for SMS instabilities under idealized assumptions shows that these instabilities and associated SMS processes are linked to both larger-scale (geostrophic) dynamics and smaller-scale processes (small-scale turbulence). In the Baltic Sea, atmospheric forcing along with basin configuration and topography, can create a variety of background hydrographic conditions favorable for the development of SMS instabilities. From larger to smaller scales, the typical ranges relevant to the SMS in the Baltic Sea are: mesoscales of order 10 km and larger, ageostrophic secondary circulation at fronts and SMS (mixed layer) eddies with scales of order 1 km (the latter depending on the mixed-layer Rossby radius), symmetric and inertial instabilities

with scales from order 1 km to <100 m, stratified turbulence of order 10 to 1 m and small-scale (3D isotropic) turbulence with scales of 0.1 m and less. Understanding these scales guides the selection of observational approaches and determines the resolution of model grids required to permit or resolve SMS processes in the Baltic Sea. If the model grids do not resolve SMS processes, the parametrization of sub-grid processes must account for their impact.

An indication of the role of SMS processes in energy transfer and tracer mixing can be provided by analyzing wavenumber spectra of kinetic and potential energy or tracer variance. Many studies (e.g., Capet et al., 2008) have shown that spectral slopes of kinetic energy tend to converge toward -2 (corresponding to a -2 power law) in the SMS range (see a schematic diagram of typical horizontal wavenumber spectra of kinetic energy in the upper ocean in Fig. 1 of Jing et al., 2021). This is inconsistent with the internal quasi-geostrophic (QG) theory, which predicts a -3 slope (Charney, 1971; Callies and Ferrari, 2013). The surface quasi-geostrophic (SQG) theory (Blumen, 1978) predicts a $-5/3$ spectral slope in the ocean with constant stratification. Since SQG turbulence is expected to decay rapidly with depth, internal QG should dominate at small scales in the subsurface layers (Callies and Ferrari, 2013), implying that wavenumber spectra would converge toward a -3 slope in the SMS range below the surface.

Another method to reveal the role of SMS processes is to calculate spatial tracer variance spectra along isopycnal surfaces, i.e., along-isopycnal variance of temperature and/or salinity (Ferrari and Rudnick, 2000). A steep spectrum of kinetic energy (i.e., with a slope of -3) could result in a tracer variance spectrum with a slope of -1 (Balwada et al., 2024). However, most of the results indicate slopes close to -2 in both the surface and subsurface layers (Callies and Ferrari, 2013; Cole and Rudnick, 2012; Balwada et al., 2024). It can be interpreted as a result of tracer stirring by local SMS processes (Balwada et al., 2024). Only a few analyses of observational data have been conducted in the Baltic Sea, where shapes of wavenumber spectra are presented to reveal the role of SMS processes in energy transfer and mixing (Lips et al., 2016a; Salm et al., 2023). This topic is discussed further in Section 4.3.

3. Methods

3.1. In-situ observations

Early ship-borne surveys using CTD probes revealed mesoscale eddies in the ocean (MODE Group, 1978) and the Baltic Sea (Aitsam et al., 1984), as well as small-scale structures on vertical profiles that could be assigned to SMS features (Hayes et al., 1975). However, due to relatively long distances between CTD casts, information on the horizontal extent of those small-scale structures was unavailable (except for staircase layering below Mediterranean lenses in the Atlantic, e.g., Lips and Laanemets, 1991). CTD profiling with station spacing shorter than the internal Rossby radius (Sellschopp et al., 2006; Lips et al., 2009; Lips et al., 2010) and from a slow-moving vessel (Köuts et al., 1990; Piechura et al., 1997; Zhurbas and Paka, 1999; Rak and Wiczorek, 2012) enabled the mapping of, e.g., intra-halocline lenses and subsurface patches of phytoplankton. Although the resolution of these measurements was adequate for studying SMS phenomena, the primary focus of these earlier studies was on mesoscale variability and vertical fine-structure.

Towed undulating vehicles have been used in the Baltic Sea to map mesoscale background and smaller-scale variability in connection with studies of vertical turbulent mixing (Lass et al., 2003), subsurface North Sea water propagation in the Bornholm Basin (Mohrholz et al., 2006), and phytoplankton dynamics (Pavelson et al., 1999; Kononen et al., 2003). Scanfish data provide sufficiently fine horizontal resolution, ranging from 300 m (Lips et al., 2016a) to 1300 m (Meyer et al., 2018), depending on the vessel speed and scanned layer thickness, allowing for the study of variability in the mesoscale-submesoscale domain. Targeted surveys in the Gulf of Finland (see location in Fig. 2b) revealed SMS intrusions, upwelling filaments, and patches of high chlorophyll-*a* in the

water column, along with wavenumber spectra of temperature close to the -2 slope in the seasonal thermocline between the lateral scales from 10 to 1 km (Lips et al., 2016a).

Fixed profilers collect data of very high temporal (~ 1 – 6 h, depending on technology and water depth) and vertical resolutions, enabling studies of small-scale variability (Lips et al., 2011; Liblik and Lips, 2012; Prien and Schulz-Bull, 2016; Liblik et al., 2017; Stoicescu et al., 2019). Similar profilers have been used to study SMS variability in other coastal environments. For instance, the Aqualog profiler deployed in 2010 in the Japan Sea was able to register the passage of SMS eddies through the mooring site (Fayman et al., 2019), analogous to SMS patches in central Baltic waters that penetrate into the subsurface layers of the Gulf of Riga (Liblik et al., 2017). Using a set of profilers that measure multiple parameters in a coordinated manner could further improve insight into SMS dynamics (Lilover et al., 2025).

Argo floats were first tested in the Baltic Sea in 2011 (Purokoski et al., 2013). Being part of an international program, they offer high-resolution CTD and biogeochemical data for various applications (Haavisto et al., 2018; Roiha et al., 2018; Siirä et al., 2018; Walczowski et al., 2020), although the time step between profiles from a single float is usually relatively long (2–7 days) for investigating SMS variability. More recently, Argo floats have been successfully applied in the Baltic Sea in a virtual mooring mode (Merchel et al., 2024) and as anchored systems (Merchel et al., 2025). In principle, these approaches could be suitable for registering SMS variability if the profiling frequency is increased.

Ocean gliders can effectively resolve SMS processes (Rudnick and Cole, 2011; Balwada et al., 2024). This also applies to the relatively shallow Baltic Sea (Alenius et al., 2014), with the horizontal resolution of collected data ranging between 150 and 700 m, depending on the mission design (Meyer et al., 2018; Carpenter et al., 2020; Salm et al., 2023; see locations in Fig. 2b). Regular glider transects have been proven to be an effective approach for studying multi-scale ocean dynamics, offering sufficient coverage and resolution (Rudnick et al., 2017). Similar regular glider observations have been initiated in the Baltic Sea by The Voice of the Ocean Foundation (VOTO; locations are shown in Fig. 2b). These data sets have been used for various applications (Liblik et al., 2022; Mohrmann et al., 2025) and have great potential for advancing knowledge of SMS dynamics.

A combination of long-term and high-resolution measurements enables detection of SMS processes while providing opportunities to analyze seasonal and annual variations across multiple variables, including temperature, salinity, oxygen and bio-optical parameters (chlorophyll-*a*, phycocyanin, backscatter, turbidity, CDOM, etc.). Furthermore, gliders can be equipped with microstructure shear sensors and an acoustic current profiler, as demonstrated by the glider deployed in the Eastern Gotland Basin in 2016 (Carpenter et al., 2020). The constant presence of gliders helps to catch hardly predictable extreme events, such as storms (Carpenter et al., 2020), subsurface blooms, upwelling events (Karstensen et al., 2014; Salm et al., 2025), Baltic inflows, or industrial accidents (Mohrmann et al., 2025). Glider data collected regularly by the Finnish Meteorological Institute since 2016 (see locations on their dedicated website http://nnodc.fmi.fi/glider/mission_m4.html) have been used to analyze oxygen conditions in the Bothnian Sea (Polyakov et al., 2022), but not yet for studies of SMS variability and processes.

In principle, marine animals can serve as platforms for collecting vertical CTD profiles (McMahon et al., 2021), as demonstrated by Siegelman et al. (2020) in the Antarctic Circumpolar Current. They analyzed data from elephant seals (up to 80 dives per day) to estimate upward heat flux associated with deep SMS fronts. Marine mammals can also be used to collect observations of SMS processes from less accessible environments, such as underneath sea ice (Biddle and Swart, 2020). In the Baltic Sea, ringed seals are tracked using GPS devices (Oksanen et al., 2015); however, wider use of additional sensors has not yet been adopted.

Ferrybox measurements have been proven to be an effective approach for regularly collecting spatially well-resolved data from the surface layer (Rantajärvi, 2003; Lips et al., 2014; Groetsch et al., 2014). Depending on the sampling frequency and vessel speed, the spatial resolution of data is about 150–500 m (Kikas and Lips, 2016). These data sets have been analyzed for various purposes, including cyanobacterial bloom dynamics (Lips and Lips, 2008; Karlson et al., 2022), carbon fluxes (Schneider et al., 2014) and upwellings and their effects on biogeochemistry (Kikas and Lips, 2016; Jacobs et al., 2021).

Baltic Sea ferrybox data are less exploited for studies of SMS variability, although their spatial resolution and regularity make them highly suitable for this purpose (Lips et al., 2016a). They have been used, for example, in SMS studies to validate high-resolution numerical models (Chrysagi et al., 2022), and can be particularly valuable when satellite observations are unavailable. Applying proper statistical methods to data collected along the ship track in the SML could reveal linkages within the multi-scale variability and their regional and seasonal patterns (Ferrari and Rudnick, 2000; Kolodziejczyk et al., 2015). Research vessels are also often equipped with flow-through systems similar to ferryboxes, providing data from the SML with high spatial resolution, e.g., 250 m on board research vessel *Salme* (Lainela et al., 2024). These data sets have been utilized for various applications (Liblik et al., 2017; Lainela et al., 2024), although not yet extensively in studies focusing on SMS dynamics.

Lagrangian drifters are not systematically used in the Baltic Sea. However, their applications in other regions have shown valuable results regarding SMS dynamics in the surface layer (e.g., d'Asaro et al., 2018; Dräger-Dietel et al., 2018). Delpeche-Ellmann et al. (2021) and Pärt et al. (2023) described surface drift influenced by wind and surface waves in the Gulf of Finland. Kjellsson and Döös (2012) showed that the dispersion of drifters in the sea is much larger than predicted by a coarse-resolution circulation model (with a grid spacing of 2 nm, close to the baroclinic Rossby radius). This data set is not used for comparisons with the results of high-resolution numerical models. In general, Lagrangian drifters can provide in-situ data for validating SMS-permitting and SMS-resolving models.

Standard broadband echo sounders on board research vessels show potential for bridging the gap from SMS to microstructure scales (Muchowski et al., 2022), providing direct evidence of microscale thermal and haline structures in the water column with high (meter-scale) vertical and horizontal resolution. These surveys can be performed at transect speeds large enough to avoid coupling of temporal and spatial variability. Comparison between dissipation rate of turbulent kinetic energy estimates based on microstructure profiles and broadband echo sounder data showed good results for a region with strong turbulence over the southern Quark sill in the northern Åland sill, especially when combined with complementary underway CTD profiles, though the method is sensitive to fish in the water column (Muchowski et al., 2022).

In conclusion, research groups around the Baltic Sea are well-equipped with the necessary infrastructure to study SMS dynamics. It is essential to continue regular observations in the surface layer along the ferry routes and in the water column at fixed stations, as well as to conduct regular glider missions in selected areas and sections. More data with sufficient resolution and coverage are needed to serve emerging data analysis methods (Yao et al., 2025) and validate high-resolution numerical models (Salm et al., 2025). The way forward would be to combine different platforms (Lips et al., 2016a) and organize international measurement campaigns (Liblik et al., 2022) dedicated to SMS processes. Similar efforts were made when mesoscale variability became a major research focus, for example, by arranging the Patchiness Experiment in 1986 in the central Baltic Sea (Kahru et al., 1990). We stress that most of the observational campaigns cited above were not explicitly designed to study SMS processes. Thus, while the research infrastructure with the necessary capabilities is available, focused studies on SMS processes and their impact remain rare and need to be

prioritized in the near future.

3.2. Remote sensing

Available satellite techniques for observing mesoscale and SMS structures at the sea surface include synthetic aperture radar (SAR) imagery, true color and infrared (IR) spectroradiometry, and satellite altimetry, specifically the newly available wide-swath altimetry (SWOT). Sea surface height (SSH) from radar altimeters can be used to observe mesoscale eddies but not SMS features in the Baltic Sea (except for SWOT) due to their limited spatio-temporal resolution and long revisit times (10–30 days) between tracks. Sea surface salinity (SSS) can also be retrieved; however, cloud contamination and low data resolution make this method not yet relevant for studying SMS dynamics in the Baltic. Note also that while remote sensing images provide snapshots of large areas simultaneously, the time step between images is relatively long (about a day), and they allow for detecting structures only at the sea surface.

An early study of sea surface temperature (SST) gradients revealed a ubiquity of thermal fronts in the Baltic Sea (Kahru et al., 1995). SST is also used to distinguish cyclones and anticyclones and to detect upwelling events. Upwelling statistics in the Gulf of Finland, as well as the characteristics of filaments stretching towards the open sea from the upwelling areas, were presented by Uiboupin and Laanemets (2009). They detected that the filaments covered the largest offshore area during the strongest upwelling events.

Karimova et al. (2012) used multiple remote sensing datasets to identify SMS eddies in the southern Baltic Sea, whereas Gurova and Chubarenko (2012) employed coastal radar measurements and satellite remote sensing to investigate the development of SMS eddies. Karimova and Gade (2016) detected that the occurrence of SMS eddies on the sea surface depends on wind conditions, and cyclonic eddies are generally smaller than anticyclonic eddies (ASAR images from 2009 to 2011 were used). In a recent study, SMS eddies with spiral structures were detected in the Baltic Sea in 167 of 270 analyzed SAR images with a 20 m spatial resolution (Zi et al., 2024).

Ocean color can be used as a tracer to illustrate the complicated surface structures at the submesoscale. Zhurbas et al. (2019b) compared true color images from Landsat-8 with model results to study coastal SMS dynamics. Marmorino and Chen (2019) demonstrated that using very high-resolution satellite imagery enabled the tracking of the development of a single SMS feature. Cahill et al. (2024) used ocean color observations from Sentinel-3, a coupled bio-optical model and particle tracking techniques to investigate co-occurring marine heat-wave and phytoplankton bloom events in the Arkona Basin. They found that these events were primarily associated with eddy-like coherent structures and SMS features.

The launch of the SWOT satellite in December 2022 has enabled direct space-based observations of SMS ocean surface topography (Fu et al., 2024). SWOT offers more than a ten-fold improvement in spatial resolution compared to products derived from all merged altimeters. Validation campaigns have been started in the Baltic Sea (covering the Gotland Basin and Danish Straits), which should be expanded to leverage this data source and enhance our understanding of Baltic Sea dynamics.

3.3. Numerical modeling

Numerical modeling is a widely used tool to study SMS processes and their role in ocean dynamics. Experiments are conducted in idealized conditions (Brannigan et al., 2015) and under realistic forcing (Capet et al., 2008). Realistic simulations in the Baltic Sea have aimed to demonstrate the impact of grid spacing (Gröger et al., 2022), reproduce an observed process or situation (Väli et al., 2017; Chrysagi et al., 2021), extrapolate observational findings over large sea areas (Salm et al., 2025), or characterize temporal and spatial variability in the intensity of

SMS processes (Väli et al., 2024).

To resolve the SMS processes in the Baltic Sea, much finer horizontal (and vertical) grids and a higher temporal resolution are required compared to open-ocean models due to the much smaller Rossby radius of 1–7 km (Fennel et al., 1991). Several recent studies have employed horizontal grid spacings ranging from 250 to 600 m. These simulations were based on either the General Estuarine Transport Model (GETM; Burchard and Bolding, 2002), e.g., Chrysagi et al. (2021) and Väli et al. (2024) or the Princeton Ocean Model (POM; Blumberg and Mellor, 1987), e.g., Väli et al. (2017). Other studies have implemented the Nucleus for European Modelling of Ocean (NEMO; Madec, 2015), e.g., Vankevich et al. (2016) and Westerlund et al. (2019) or the Regional Ocean Modelling System (ROMS; Haidvogel et al., 2000), e.g., Onken et al. (2020).

All these models utilize spherical coordinates on rectangular grids, and sub-grid lateral mixing in most setups is based on the Smagorinsky parameterization (Smagorinsky, 1963). Vertical mixing in numerical experiments is implemented by additional equation(s) for turbulent kinetic energy (and dissipation rate) either from GOTM (General Ocean Turbulence Model; Burchard et al., 1999), directly from K-profile (Large et al., 1994) or Mellor-Yamada turbulence model (Mellor and Yamada, 1982).

The framework for quantifying the numerical mixing of tracers in ocean models was introduced by Burchard and Rennau (2008), revisited for GETM by Klingbeil et al. (2014), and applied to evaluate the physical and numerical mixing in the presence of strong SMS features in the Eastern Gotland Basin (Chrysagi, 2020). Similar or other approaches are used in other numerical models (e.g., Ralston et al., 2017; Broatch and MacCready, 2022; Schlichting et al., 2023). In general, reducing the grid spacing in numerical simulations can reduce numerical diffusion. However, Henell et al. (2023) estimated, by focusing on the Baltic Sea, that numerical mixing could be responsible for about 50% of the total mixing, leading to too deep SML in models (Bulczak et al., 2024). On the other hand, in coarse-resolution circulation model simulations, the SML depth was often underestimated, which over time led to the development of more complex mixing schemes (Meier, 2001). A recent idealized study by Schlichting et al. (2024) suggests that numerical mixing can exceed physical mixing in high-resolution numerical models, especially at fronts due to sharp lateral buoyancy gradients.

Thus, future modeling studies using SMS-resolving grids in the Baltic Sea could also address changes in numerical and physical diffusion through cross-comparison experiments with different resolutions. Diapycnal, numerical mixing due to discrete grids is associated with vertical advection across the model vertical coordinate and with lateral advection in the case of inclined isopycnal surfaces (Fox-Kemper et al., 2019; Gibson et al., 2017). Uncertainties remain regarding the physically most appropriate aspect ratio of vertical and horizontal grid steps, and whether this should differ between coarse-resolution (where sub-grid horizontal mixing can be approximated by QG turbulence) and high-resolution (where sub-grid processes are highly ageostrophic) numerical models. Furthermore, it is unclear whether an uncoupled parameterization of horizontal and vertical mixing can be applied in numerical experiments with SMS-permitting and –resolving grid spacing. We suggest that, in addition to further numerical experiments, extensive validation of model runs with realistic settings is necessary, leveraging the growing data sets of high-resolution observations. Due to the pronounced internal variability, high-resolution data sets need to be available to enable a statistical model-data comparison (Placke et al., 2018).

Using high temporal and spatial grid resolutions in numerical models is computationally expensive. Therefore, most numerical studies in the Baltic Sea, especially those focusing on climate change, typically use coarser-resolution setups in which SMS processes cannot be resolved (Gröger et al., 2022; Meier et al., 2022). Considering that SMS features can significantly alter the depth of the mixed layer (Thompson et al., 2016), parameterizations are needed to reduce biases in the SML,

particularly in climate models (Huang et al., 2014; Calvert et al., 2020). For instance, Fox-Kemper et al. (2011) have suggested and implemented a parameterization scheme for restratification by mixed-layer SMS eddies to approximate eddy fluxes of density and other tracers in global ocean models. This parameterization was recently revised by Bodner et al. (2023) to account for frontogenesis arrested by boundary-layer turbulence. Another relevant parametrization that appears to improve stratification and vertical mixing within the SML is that proposed by Bachman et al. (2017) for parameterizing SI. These parameterizations have not yet been tested in Baltic Sea models. One problem is that usually fluxes of turbulent kinetic energy from the atmosphere are insufficiently known (e.g., Meier et al., 2011).

We have different model codes with Baltic Sea settings available to simulate SMS variability, as well as large-scale patterns and long-term changes. The former models (SMS-permitting or SMS-resolving) need to be more extensively validated. Coarser numerical models could benefit from testing sub-grid parameterizations that account for the effects of SMS processes. Furthermore, long-term SMS-resolving model simulations are computationally demanding, and their analysis is partly constrained by data storage limitations. Developing on-the-fly analysis methods will be essential to make full use of future high-resolution simulations.

3.4. Combined approaches

Since all the described approaches have strengths and weaknesses, a combination of multiple methods would be the most beneficial strategy for studying SMS processes and their impacts. For instance, observed SMS features and variability (Carpenter et al., 2020; Salm et al., 2023) can be simulated by numerical models to allow the identification of the mechanisms of their development (Chrysagi et al., 2021) and to extrapolate the observational results over larger areas and longer time periods (Salm et al., 2025).

SMS-resolving simulations used to study the statistical characteristics of SMS processes over large sea areas and time spans (e.g., Väli et al., 2024) need to be accompanied by appropriate in-situ measurements to provide data for validating the results (i.e., the derived statistical characteristics). A large pool of information is available, for instance, from ferrybox measurements in different parts of the Baltic Sea, which have been used to validate the spatial variability in high-resolution simulations, along with direct validations of surface gradients or tracers, such as temperature and salinity (Chrysagi et al., 2022). The value of systematic glider missions, as initiated by VOTO in some Baltic Sea regions, will grow over time, as they can be used for validating SMS-permitting (and SMS-resolving) models, among other applications.

Additionally, remote sensing products can be utilized in conjunction with realistic modeling experiments. A series of images from different dates was qualitatively compared with the model results in the southern Baltic Sea by Zhurbas et al. (2019b). Besides vertical profiles at monitoring stations, Chrysagi et al. (2021) used satellite images from the central Baltic Sea to evaluate how their model reproduces SST variability and spatial structures. Furthermore, remote sensing provides snapshots with good coverage of the sea surface, while in-situ observations and numerical simulations can reveal the dynamics in the sub-surface layers, highlighting the need for their simultaneous application. The integration of models, EO observations and in-situ measurements can be used to reconstruct 4D fields of physical and biochemical parameters. This is, for instance, the main objective of the recently started “Baltic Sea Dynamics through 4D Modelling and Integrated Earth Observation” (<https://4dbaltdyn.albavalor.es/>).

Similar to multi-sensor (e.g., using gliders with a variety of sensors as Carpenter et al., 2020) and multi-platform observational programs (employing research vessel, ferrybox, scanfish and other platforms by Lips et al., 2016a), as well as utilizing an ensemble of models for operational and climate-related applications, combined modeling, in-situ and remote sensing experiments must be arranged for studying SMS

processes in the Baltic Sea. This requires the involvement of several research groups from different Baltic Sea countries, each bringing their expertise and resources to jointly achieve comprehensive coverage of SMS dynamics.

4. State-of-the-art and knowledge gaps

4.1. SMS processes in the surface layer and thermocline

4.1.1. Baltic Sea settings and examples of SMS dynamics

Strong lateral buoyancy gradients – instrumental for the development of submesoscales – are characteristic features of the Baltic Sea due to its estuarine nature, with large freshwater discharge and a general horizontal salinity gradient (Fig. 2b). Because of the relatively narrow basins, frequent upwelling events are generated by variable local wind forcing (e.g. Lehmann et al., 2012; Kikas and Lips, 2016). Strong upwelling events are characterized by strong buoyancy gradients (Lips et al., 2009) and along-coast baroclinic currents (Suursaar and Aps, 2007; Salm et al., 2025). The inclination of pycnoclines (thermocline and halocline) that depends on wind forcing is a common feature across the Gulf of Finland (Liblik and Lips, 2017), even when temperature and salinity gradients at the sea surface are weak. Furthermore, differential warming and cooling of shallow coastal and offshore areas result in horizontal temperature and density gradients in the surface layer (e.g. Lips et al., 2014; Lips et al., 2016a). Thus, large-scale and mesoscale buoyancy gradients in the Baltic Sea create favorable conditions for the generation of SMS processes, which could alter vertical stratification, drive exchanges between coastal and offshore regions and between surface and subsurface layers, as well as influence larger-scale dynamics (Carpenter et al., 2020; Chrysagi et al., 2021; Salm et al., 2023, 2025).

These hydrographic conditions naturally support the SMS activity to emerge across the Baltic Sea. Early indications of SMS features, with distinct patterns at scales below mesoscale, were first illustrated by remote sensing observations (e.g., Karimova, 2012; Karimova and Gade, 2016; McWilliams, 2016; see also Fig. 1). Ferrybox observations in the Gulf of Finland, conducted between Tallinn and Helsinki since 1997 (see location in Fig. 2), have also provided examples of small-scale variability in the surface layer. Kikas and Lips (2016) suggested that, besides events with a single sharp density front, upwelling events, where variability at scales <5 km dominates in the spatial distribution of temperature in the surface layer, often occur. It can be explained by the development of upwelling filaments (Uiboupin and Laanemets, 2009) or SMS instabilities of the upwelling front, especially when the wind forcing that created the upwelling vanishes or varies (Kikas and Lips, 2016). High-resolution numerical simulations in the Eastern Gotland Basin during summer conditions reveal weak SMS activity prior to an upwelling event, followed by the emergence of strong SMS motions after the upwelling episode (Chrysagi et al., 2022).

Beyond surface expressions, early observations also revealed small-scale subsurface variability in the Baltic Sea, although these features were not initially interpreted within an SMS framework. Vertical fine-structure and intrusions/interleaving (Zhurbas and Paka, 1999; Holtermann et al., 2012) were recognized as important for redistributing water mass properties and mixing, but not yet linked to SMS dynamics. Subsurface and deep chlorophyll-a maxima have long been recognized as features of the summer phytoplankton community (Kahru et al., 1982; Pavelson et al., 1999). Lips et al. (2011) suggested that these subsurface patches of high chlorophyll-a could be related to SMS processes. Using vertical profilers, applied since 2009 in the Gulf of Finland, and targeted ship-borne measurements, they revealed subsurface chlorophyll-a maxima, which could contain up to $2.5 \text{ million cells l}^{-1}$, as well as SMS patches of higher temperature in and below the seasonal thermocline. A detailed analysis of data from autonomous profilers by Liblik and Lips (2012) revealed that along-isopycnal SMS intrusions of waters with different temperatures and salinities were the principal thermohaline features in periods of reversed estuarine circulation and its

transformation back to the ordinary pattern in the Gulf of Finland.

Lips et al. (2016a) provided a series of examples of SMS occurrences in the surface and subsurface layers of the Gulf of Finland based on data from autonomous and towed instruments. They noted an enhanced presence of SMS salinity intrusions in the seasonal thermocline during upwelling events and their relaxation; however, the generation mechanisms and the role of SMS features in a quantitative form were not analyzed. Scanfish surveys have demonstrated that intrusions of water with different temperatures and salinities (Fig. 3) often occur along inclined pycnoclines (Lips et al., 2016a). Motivated by such observational data collected in the Eastern Gotland Basin (for details see Burchard et al., 2017), Chrysagi et al. (2022) simulated the appearance of salinity inversions (minima) in the thermocline during summer conditions. The inversions were primarily attributed to the interaction between lateral surface salinity gradients and wind-induced differential advection. However, it was suggested that during wind-induced upwelling events, when strong SMS filaments form in the upwelling area, inversions can also be triggered by frontal subduction within these filaments. Such lateral dispersal of waters with different temperatures and salinities near the pycnocline can also be explained by active SMS processes there, as discussed below (section 4.1.4).

To assess whether such mechanisms and SMS structures are robust beyond individual case studies, high-resolution regional modelling has been used to generalize and extend observational evidence. Numerical simulations (grid step 250 m) by Väli et al. (2017) revealed numerous SMS features in the surface layer of the Gulf of Finland. The SMS structures with high Rossby numbers ($Ro > 1$) had the following spatial scales: threads had a characteristic width of 2–3 km and a length of 10–50 km, cyclonic vortices had a characteristic diameter of 3–6 km, and spiral eddies had a characteristic diameter of 10–15 km. Väli et al. (2017) suggested that the high-potential vorticity threads presumably formed during the development phase, while the cyclonic vortices and spiral cyclonic eddies formed during the relaxation phase of upwelling. High Rossby number threads in the surface layer extended to depths of 10 m, while cyclonic vortices with high Rossby number extended to the depths of 20 m.

These model-identified features require validation with high-resolution in-situ observations, particularly those resolving the vertical thermohaline structure such as glider measurements. Glider observations and analyses of SMS dynamics (including relevant instabilities and role) in the surface layer and thermocline have been conducted in the Gotland Basin (Carpenter et al., 2020) and the Gulf of Finland (Salm et al., 2023). When analyzing the intensity of SMS processes, it can be estimated as along-isopycnal spice, i.e., the sum of temperature (ΔT) and salinity (ΔS) fluctuations compensating each other regarding their contribution to density (Salm et al., 2025):

$$\text{spice} = \rho(\alpha\Delta T + \beta\Delta S) \quad (8)$$

where α is the thermal expansion coefficient and β is the haline contraction coefficient. An example of SMS features at a baroclinic front in the Gulf of Finland, mapped by a glider mission in May 2018, is presented in Fig. 3 (see location in Fig. 2b). Temperature and salinity fluctuations used to calculate spice were defined in relation to average along-isopycnal temperature and salinity values estimated at a base of 4 km along the glider track. Spice highlights SMS variability as patches of positive (negative) anomalies, indicating regions with higher (lower) salinities and temperatures relative to the average values at the isopycnal surfaces. Thus, spice is best visible if large-scale along-isopycnal gradients of temperature and salinity exist and SMS flows act on them.

The baroclinic front presented in Fig. 3 developed in response to prevailing easterly (upwelling-favorable) winds (Salm et al., 2023). However, before this section was mapped, the wind changed (weakened and turned). The appearance of a secondary front (with an opposite inclination of isopycnals) and SMS features indicating upward movement of colder subsurface waters and downward movement of warmer

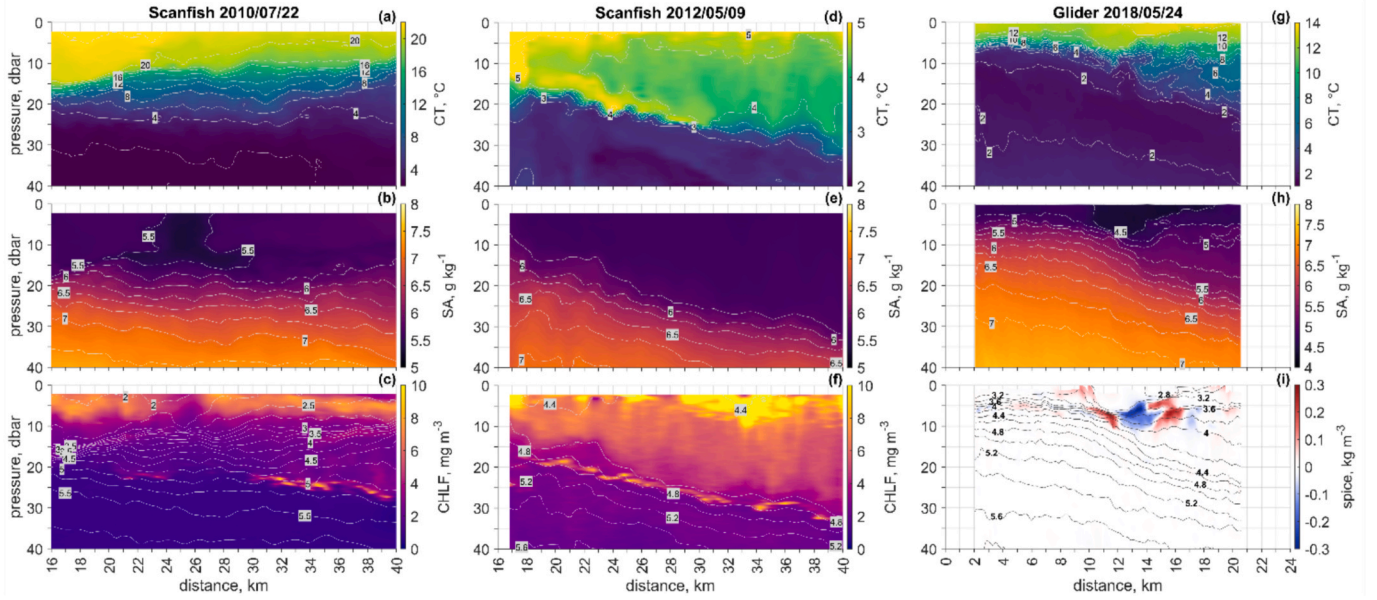


Fig. 3. Vertical sections of temperature, salinity and chlorophyll-a across the Gulf of Finland based on scanfish surveys on 22 July 2010 (a–c) and 9 May 2012 (d–f, see location in Fig. 2; Lips et al., 2016a) and an example of SMS features at a baroclinic front based on a glider mission on 24–25 May 2018 (g–i, see location in Fig. 2). The latter example presents isolines of potential density anomaly with temperature, salinity, and spice distributions (from Salm et al., 2025).

surface waters can be interpreted as a result of instabilities of the baroclinic front under changing wind conditions. SMS features, as noticed in temperature and salinity distributions, are clearly highlighted in the vertical section of spice.

Parts of the Baltic Sea are seasonally ice-covered, but the influence of sea-ice cover on mesoscale and SMS dynamics remains poorly understood in this region. A study in the Arctic Ocean has shown that seasonal sea ice strongly suppresses the propagation of mesoscale eddy activity in the SML, while eddy activity at deeper layers can persist throughout the year (Meneghello et al., 2020). However, the sea-ice edge can also act as a source of eddy formation, as observed by satellite altimetry in the Arctic (Bulczak et al., 2015). Observations using tagged Southern Elephant seal data from the Antarctic seasonal ice zone showed the opposite trend, with increased values for SMS parameters in mid-winter, potentially linked to the presence of leads in sea ice (Biddle and Swart, 2020). In both the Arctic and the Antarctic, the energizing effect of meltwater fronts at the sea-ice edge is important for SMS flows and ocean heat exchange with the atmosphere and sea ice (e.g., Manucharyan and Thompson, 2017; Prend et al., 2025). Due to lower SML salinity in the Baltic Sea, such meltwater-induced buoyancy gradients are presumably weaker, and whether such sea ice meltwater and SMS couplings exist in the Baltic Sea is presently unknown.

4.1.2. Impact of SMS processes on coastal-offshore exchanges

River plumes, which transport tracers and nutrients offshore, are affected by variable forcing and may change shape and position drastically over time (Fofonova et al., 2021; Chegini et al., 2020; Hetland and Hsu, 2013). The development of eddies due to the baroclinic instability of the buoyant coastal plume has been shown by Cushman-Roisin et al. (2007) and Kobashi and Hetland (2020). In the Baltic Sea, similar mesoscale eddies have been simulated for the baroclinic coastal current from the Daugava River plume by Lips et al. (2016c). However, SMS eddies associated with river plumes have not yet been captured by observations or simulated by models, probably due to their very small scales in the Baltic Sea. Freshwater discharge from rivers may occupy a relatively thin surface layer under weak winds, e.g., only a few meters as suggested by Soosaar et al. (2016). Thus, the instability scales of such a plume front could be smaller than for the SML elsewhere. Since these scales are small (horizontal scale of ~100 m), strong coupling between

SMS dynamics and turbulent mixing can be expected to drive lateral dispersion and vertical fluxes associated with river plumes.

To reveal when and where in the Baltic Sea intense coastal-offshore exchanges can occur, a long-term high-resolution simulation was conducted by Väli et al. (2024). The simulation covered 9 years and had a horizontal grid resolution of ~250 m. In addition to the probability maps of occurrences of high vertical relative vorticity (Fig. 4), indicating active SMS dynamics, we also estimated joint probability density functions (JPDFs) of relative vorticity and strain rate, whereas the latter was calculated as

$$\text{Strain} = \sqrt{\left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2} \quad (9)$$

following an approach by Shcherbina et al. (2013). On the JPDF graphs, presented as 99.9% probability areas (Fig. 5), active SMS regions were identified by $\text{Strain} > |\zeta|$ and $|\text{Ro}| > 0.5$, according to Picard et al. (2024).

A relatively inhomogeneous distribution of vorticity (Fig. 4) indicates that SMS processes occur more frequently in narrow straits and several coastal areas of the Baltic Sea (Väli et al., 2024). When comparing five sub-regions of the Baltic Sea using the Strain-Ro graphs (Fig. 5), more frequent occurrences of SMS processes were identified for the Gulf of Finland and the Northern Baltic Proper, while less frequent in the central and southern parts of the Baltic Proper and the Gulf of Riga. Fig. 5 also indicates that intense SMS processes occur more frequently in winter than in summer, consistent with findings elsewhere (Callies et al., 2015; Schubert et al., 2020). Furthermore, $\text{Ro} > 1$ had clearly higher probabilities than $\text{Ro} < -1$ (Fig. 4) and <99.9% probability areas of JPDFs with $\text{Strain} > |\zeta|$ and $|\text{Ro}| > 0.5$ were larger on the positive Ro side of Fig. 5, indicating that intense cyclonic vortices are more common than anticyclonic ones. It is in accordance with earlier results (e.g., Shcherbina et al., 2013; Väli et al., 2017) and can be explained by the stable character of strong cyclonic eddies and unstable character of strong anticyclonic eddies with $\zeta < -f$ (Hoskins and Bretherton, 1972).

High probabilities of $|\text{Ro}| > 0.5$ in the Gulf of Finland (Figs. 4 and 5) suggest that SMS processes could actively contribute to spreading of coastal waters (including Neva River waters) over this relatively narrow basin. In the Northern Baltic Proper, brackish water is fed into this sea

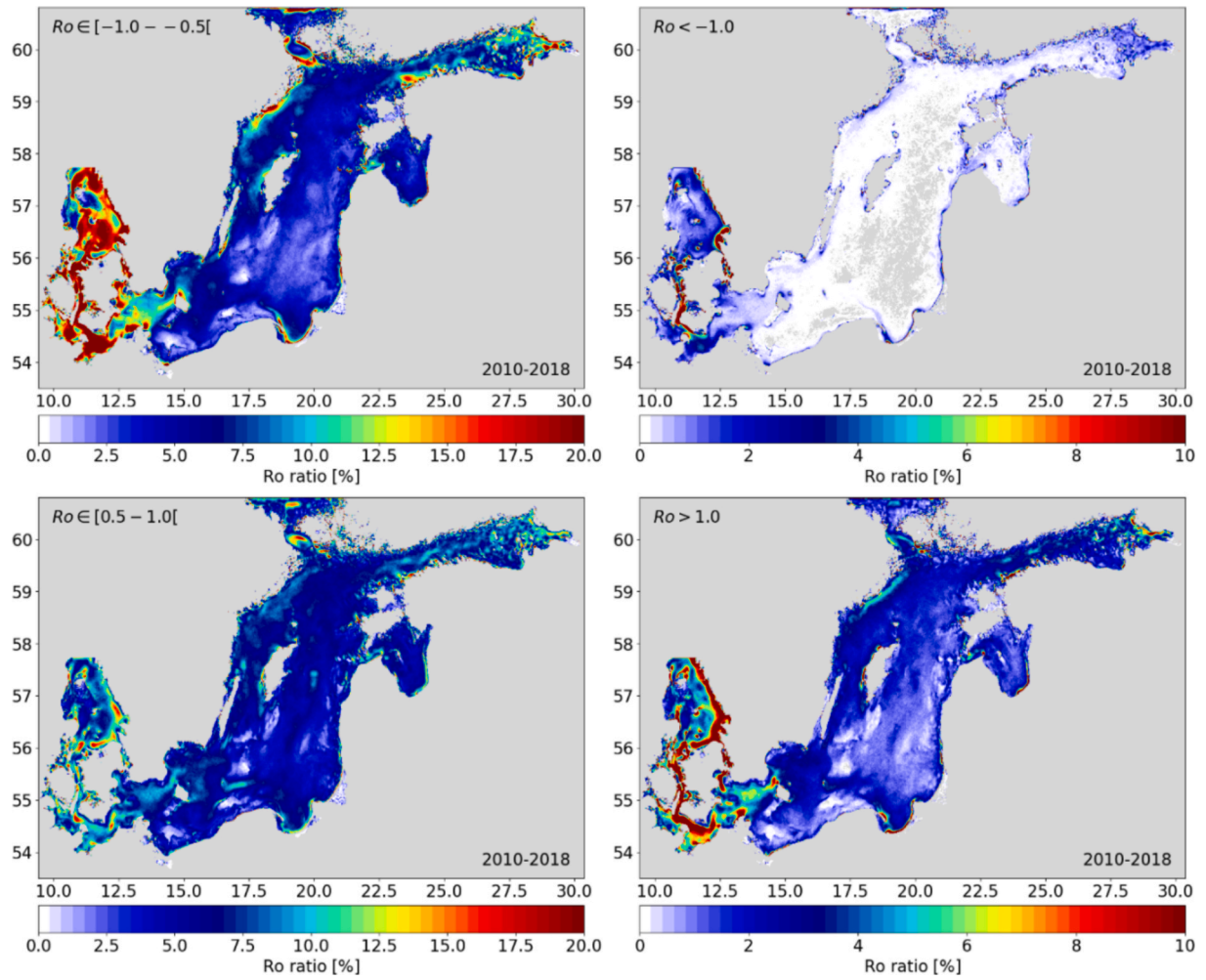


Fig. 4. Spatial distributions of occurrence probabilities of different ranges in Rossby number in the surface layer for the annual mean in 2010–2018 (from Väli et al., 2024).

area from both the Bothnian Sea and the Gulf of Finland, leading to intensive eddy formation due to baroclinic instability, and thus to intense SMS variability (Fig. 4; Väli et al., 2024). Offshore areas of the Central and Southern Baltic Proper generally experience low SMS activity (Fig. 4), while intense SMS features have been suggested to appear in coastal regions (Zhurbas et al., 2019a,b, 2022; Chrysagi et al., 2022). Zhurbas et al. (2019a) demonstrated that cyclonic SMS eddies redistributing the coastal-offshore gradients tend to have higher angular velocities than anticyclonic SMS eddies (implying that cyclonic eddies contribute more actively to vertical exchanges), while anticyclonic vortices could lead to faster lateral transport of particles in the surface layer. Furthermore, Zhurbas et al. (2022) suggested that SMS processes contribute to coastal-offshore exchanges not only in the SML but also in the subsurface layer, influencing exchanges between the slope regions and the basin interior.

The results of the described high-resolution simulation (Väli et al., 2024) were compared with those from the low-resolution simulations, which had horizontal grid resolutions of 926 m (Hariri et al., 2024, 2025) and 1,852 m (Väli et al., 2025), allowing for the analysis of the statistical properties of flow and tracer fields with and without consideration of SMS. These analyses showed that the inclusion of SMS processes hindered rapid transport of coastal waters and tracers toward the basin centers in the SML, but enhanced tracer transport toward the subsurface layer in offshore areas. The results of these studies are reviewed in more detail in subsection 4.4, where large-scale impacts of SMS processes are discussed.

We state that the knowledge and characteristics of coastal-offshore exchanges involving SMS processes need to be advanced. This requires extensive validation of model results using in-situ observations, including focused, regular surveys in selected areas. Additionally, an essential knowledge gap concerns SMS processes associated with river water spreading and their role in coastal-offshore exchange.

4.1.3. SMS processes in the surface layer

Based on data from an ocean glider equipped with a turbulence microstructure package and a high-resolution ADCP, Carpenter et al. (2020) conducted one of the few detailed investigations of SMS fronts during storm conditions that are usually not accessible by ship observations (Fig. 6). Their data from the central Baltic Sea showed that small-scale fronts may impact the SML in contrasting ways: geostrophic adjustment after storm-induced mixing is associated with SML restratification (frontal tilting), which effectively suppresses turbulence by sheltering the deeper parts of the SML from surface forcing. However, they also showed that near-inertial oscillations induced during the adjustment processes may be associated with ageostrophic shear that is sufficient to trigger shear instability. This process was shown to provide an important sink of SMS energy.

Motivated by these glider observations, Chrysagi et al. (2021) used a realistic high-resolution simulation to further investigate the impact of storms on SMS dynamics. Their results revealed pronounced SMS activity in the Eastern Gotland Basin associated with a mesoscale frontal structure. SMS fronts and filaments characterized by sharp lateral

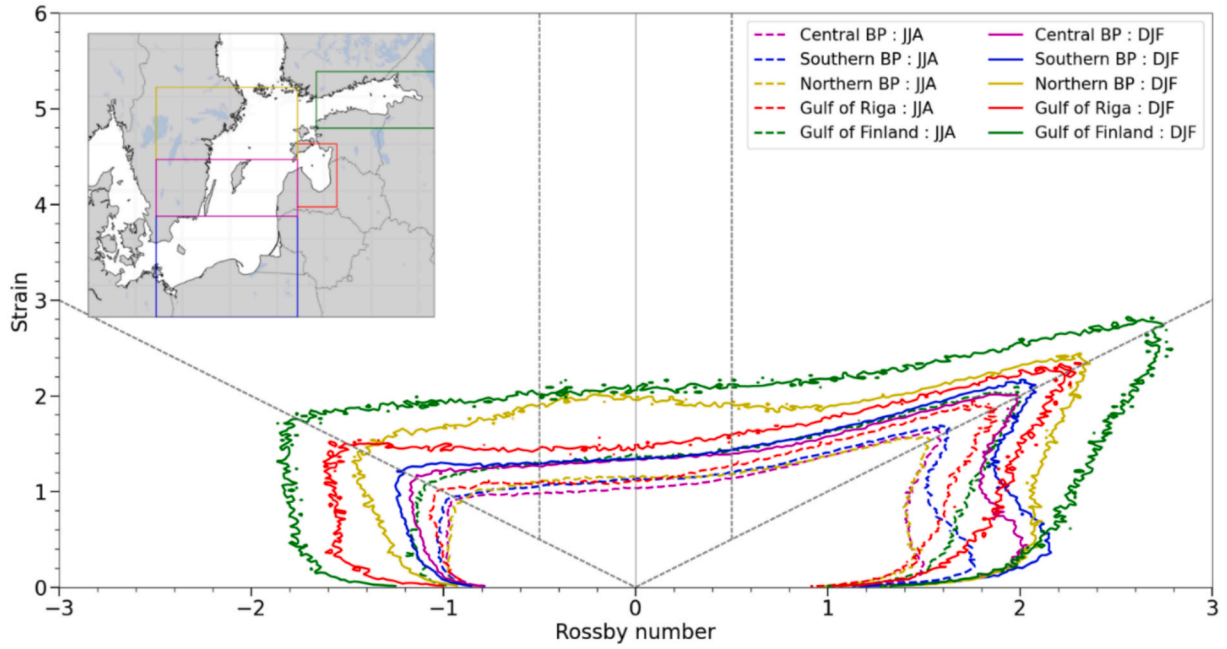


Fig. 5. Joint probability density functions (JPDFs) of relative vorticity and strain rate, showing the areas corresponding to the probability of 99.9% in the five sub-regions of the Baltic Sea in summer (JJA) and winter (DJF). Dashed lines indicate the boundaries of SMS domains identified by $\text{Strain} > |\zeta|$ and $|\text{Ro}| > 0.5$ (Picard et al., 2024).

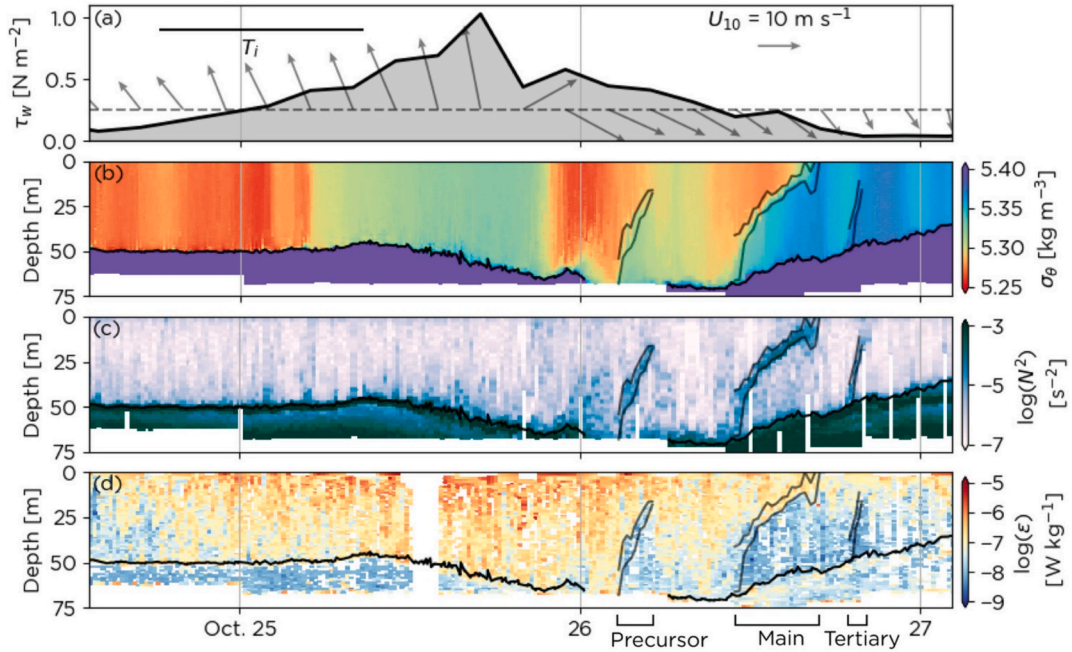


Fig. 6. SML structure during the storm and restratification periods: (a) wind speed and surface stress, (b) potential density (σ_θ) with a color scale chosen to highlight the SML variability, (c) squared buoyancy frequency, and (d) turbulent dissipation rate. Frontal boundaries are indicated by the dark lines. Sampling times of the three fronts are labeled at the bottom of (d). The base of the SML is indicated by the black line in (b–d). (from Carpenter et al., 2020).

buoyancy gradients, strong surface convergence, and high vertical velocities were widespread in the SML. Inside these features, the mixed layer depth was significantly shallower than in the ambient waters.

The study found that SMS can maintain shallow mixed layers even during storm events and rapidly restratify the SML after each storm episode. This suggests that SMS restratification can counteract the destratifying effects of atmospheric forcing, leading to highly efficient mixing within SMS fronts. On the other hand, both the glider (Carpenter et al., 2020) and the model data (Chrysagis et al., 2021) also revealed an

elevated level of microscale turbulent mixing associated with the emerged SMS fronts. While Carpenter et al. (2020) demonstrated that SMS can act both as a source and a sink of turbulence in the SML, Chrysagis et al. (2021) showed, by focusing on a single SMS filament, that the conditions for SI (see section 2.2) were satisfied with the modeled dissipation rates, presenting good agreement with the theoretical estimates.

Note that most of the SMS features in this study were temperature-controlled regarding buoyancy as they emerged from a larger-scale

(upwelling-related) temperature front (Chrysagi et al., 2021). On the other hand, salinity is the main contributor to density variability in the Baltic Sea from late autumn to spring, with temperature contributing at a similar level or exceeding it in summer. There are examples of studies of SMS dynamics in both temperature-stratified and salinity-stratified regions. In the open ocean (temperature-dominated stratification), submesoscales generally induce an upward heat flux (Su et al., 2018), while a downward heat flux similar in magnitude to the net air-sea flux was found in the northern Gulf of Mexico (salinity-dominated stratification; Hilditch et al., 2025). Thus, the Baltic Sea provides suitable conditions to analyze SMS variability regimes and their impacts in seasons (or areas) with temperature- and salinity-dominated stratification.

4.1.4. Role of SMS for the development of seasonal stratification

Numerous examples demonstrate that coarse-scale models are unable to accurately predict mixed layer depths in the ocean (Damerell et al., 2020) and the Baltic Sea (e.g., Tuomi et al., 2012; Bulczak et al., 2024). A general framework for buoyancy fluxes and the development of stratification encompasses air-sea heat flux, evaporation-precipitation, vertical mixing due to winds and currents (such as tides and seiches), and horizontal buoyancy flux resulting from a layered flow structure in the upper ocean. However, simulating the development of seasonal stratification in the surface layer is challenging without an appropriate parameterization of SMS processes and mixing due to the breaking of surface waves and Langmuir circulation. SMS processes can enhance mixing and vertical fluxes under certain conditions and lead to rapid restratification under other conditions (du Plessis et al., 2017), whose impacts are challenging to account for in models (Calvert et al., 2020).

The long-term, high-resolution simulation by Väli et al. (2024) demonstrated that eddy activity exhibits a pronounced seasonal cycle in the Baltic Sea, with higher eddy activity in winter and lower in summer. Thus, SMS processes could influence the development of vertical stratification more in winter, when vertical mixing is at its maximum, than in summer. However, Väli et al. (2024) detected the seasonal minimum in eddy activity in the SML in June, while the seasonal minimum in wind forcing and in kinetic energy was in April (two months earlier). They suggested that this time lag can be explained by the decomposition of larger and stronger eddies into smaller and weaker eddies, which takes longer than the lifetime of individual eddies. It also indicates that lateral buoyancy gradients, resulting from strong vertical mixing in winter and further enhanced by mesoscale eddies, could, in turn, lead to SMS instabilities in the SML during the development phase of seasonal stratification under decreasing wind forcing.

Salm et al. (2025) analyzed SMS variability in the Gulf of Finland surface and subsurface layers (including thermocline) by calculating along-isopycnal spice. They reported that both glider surveys and high-resolution modeling revealed a vertical maximum in SMS variability at the base of the SML under conditions of positive buoyancy flux. The authors suggested that this spice maximum reflects the presence of SMS processes acting to restratify the deeper portion of the SML (Salm et al., 2025). It indicates that SMS processes are active in a lower part of the SML, which is not under direct influence of atmospheric forcing (convection or wind-induced mixing). This agrees with the suggestion that SI can develop under these conditions, particularly in the presence of horizontal buoyancy gradients, such as those caused by slanted isopycnals (Buckingham et al., 2019).

This finding offers an alternative explanation for the development of salinity and temperature inversions near the pycnoclines (as presented in Fig. 3). Besides wind-driven differential advection suggested by Chrysagi et al. (2022) and offshore Ekman transport under significant surface warming (Burchard et al., 2017), along-isopycnal mixing by SMS flows could create such distributions of temperature (in cases when mostly salinity defines the vertical buoyancy gradient) and salinity (in cases when mostly temperature defines the vertical buoyancy gradient). SMS flows are probably generated by SI near locally enhanced

horizontal buoyancy gradients, on the background of a large-scale inclination of the pycnocline. This suggestion aligns with the presentation by Johnston and Rudnick (2009) of the transition layer with the highest SMS spice variance between the SML and the thermocline. Note that, when wind forcing (mixing) reaches the thermocline, the highest SMS variability was found close to or just below the strongest vertical buoyancy gradient (Salm et al., 2025).

These results, together with the example from the previous subsection, highlight the significance of SMS processes in restratifying the SML when negative buoyancy flux vanishes (following a storm), positive buoyancy flux is present and/or wind mixing does not completely arrest the entire SML. In the presence of large horizontal buoyancy gradients in the SML, MLI can occur to restratify the SML. High spice at the base of the SML indicates active SMS flows there, likely due to SI. However, it remains an open question whether such SMS flows are responsible for creating the observed inversions in the vertical distribution of temperature and/or salinity, or whether differential advection is a more dominant driving process.

Further knowledge gaps regarding mixing in the SML and the development of stratification in the Baltic Sea concern the interactions between SMS processes and Langmuir circulation, as well as SMS processes and surface waves. For instance, Hamlington et al. (2014) suggested that Langmuir turbulence counters the restratifying effects of SMS eddies in the SML, indicating a potentially important interplay between these mechanisms that remains poorly understood.

4.1.5. Subduction and vertical fluxes

The most significant vertical mixing of the Baltic Sea water column and vertical fluxes of various substances occur during the autumn–winter convective and wind-induced mixing period (Reissmann et al., 2009). This is also the period when submesoscales are most abundant, according to a high-resolution simulation in the Baltic Sea by Väli et al. (2024) and several studies focusing on other marine basins (e.g., Branigan et al., 2015; Mensa et al., 2013). When seasonal thermal stratification has developed, coastal upwelling events are a major process that causes surfacing of sub-thermocline waters, mixing between surface and subsurface waters, and the formation of mesoscale baroclinic fronts and jet currents (Lehmann and Myrberg, 2008), which might be susceptible to SMS instabilities. It has been estimated that the new surface water in the upwelling area contained 85% subsurface water and 15% surface water during the peak of an upwelling event in the Gulf of Finland in August 2006 (Lips et al., 2009). However, except for very simple approximations (Reissmann et al., 2009) and some case studies (Laanemets et al., 2011; Lass et al., 2010), more general estimates of the upwelling contributions to vertical mixing and fluxes are not available for the Baltic Sea or its basins.

Offshore areas of the Baltic Sea are also rich in fronts, which can be detected by SST (Kahru et al., 1995) or salinity differences (e.g., Pavelson et al., 1999; see an overview by Suursaar et al., 2021). Such fronts provide favorable conditions for the development of SMS instabilities and related processes, including SMS subduction and associated vertical fluxes. Enhanced upward heat transport due to existing deep SMS fronts has been proposed by Siegelman et al. (2020). Recently, a further instability mechanism – mixed transitional layer instability (MTI) – which can explain SMS variability below the thermocline in the subtropical ocean, was introduced by Zhang et al. (2025).

Several studies in the Baltic Sea have also indicated that SMS features emerge not only in the SML but also in the thermocline and below (Lips et al., 2016a; Salm et al., 2023). Based on a high-resolution simulation, Zhurbas et al. (2022) found that SMS inhomogeneities or stripes (10–20 km in length and 1 km in width) are common in summer in both the SML and the interior, whereas the interior is not directly exposed to atmospheric forcing. They suggested that SI and strain-induced frontogenesis are probably responsible for the formation of the SMS striped texture. Since conditions for SI were satisfied only in the SML and the near-bottom layer, most probably, SMS stripes in the interior were most

likely generated by strain-induced frontogenesis (Zhurbas et al., 2022). In the presence of large-scale temperature and salinity gradients along isopycnal surfaces, SMS features observed in the temperature and salinity distributions can also form due to the stirring of large-scale gradients by the eddy field.

Further evidence of SMS-driven vertical exchange has been provided by Salm et al. (2025). They compared the occurrence of elevated spice (as a sign of intense SMS variability) with lateral buoyancy gradients and relative vertical vorticity using results of high-resolution, realistic simulations in the Gulf of Finland. They found that high spice can be linked to high vorticity; however, it was not always the case. The highest spice in the thermocline layer (corresponding to a density range selected to represent the thermocline) occurred during a period when Ro was not elevated in the surface layer of the same sea area. Instead, this situation with high spice in the offshore subsurface layer was characterized by $O(1)$ Ro near the topographic features and outcropping isopycnals closer to the coast (Fig. 7). Salm et al. (2025) suggested that the spatial decoupling between spice and Ro patterns likely reflects the downstream advection and transformation of SMS features beyond their generation sites. These results support a mechanism of subduction driven by persistent frontal tilting and vertical shear (see the current fields at the surface and at 20 m depth in Fig. 7), as well as by enhanced vertical velocities. Similar SMS activities at fronts have been described in other regions (e.g., Hosegood et al., 2013).

While downwelling fronts and associated currents could also create favorable conditions for SMS appearance, Salm et al. (2025) did not register a similar enhancement of subsurface SMS variability linked to an analyzed downwelling situation. SMS patterns may have been outside the analyzed area or absent because inclined isopycnals reached the near-bottom layer closer to the coast, where intense microscale mixing could occur. A major difference between upwelling and downwelling situations is the outcropping of isopycnals, which occurs during upwelling but not during downwelling. Thus, a direct impact of wind forcing (turbulent mixing or down-front wind) could lead to SMS

instabilities at the front in an upwelling situation and to subduction of surface waters along slanted isopycnals. Furthermore, Salm et al. (2025) suggested that SMS instabilities of the baroclinic current could be induced by the interaction of the current with topographic features. Similar to this result, Capó et al. (2023) suggested that flow-topography interactions generate vertical vorticity, which is advected offshore into the subsurface layers. The effects of topography on SMS variability and processes influencing the dynamics of the SML and the interior have also been demonstrated in several studies in the Southern Ocean (see a review by Swart et al., 2023).

Mixing in the surface water and its subduction along outcropping frontal isopycnal surfaces together with the upwelled water from the pycnocline (that probably occurs over spatially larger regions; Verma et al., 2019), can be a significant mechanism of vertical exchanges in the stratified environment (Thomas et al., 2008; Hosegood et al., 2013; Brannigan et al., 2017; Taylor, 2018). The process of SMS subduction could also explain a fraction of subsurface mixing in estuarine basins, such as the Baltic Sea sub-basins, e.g., the Gulf of Finland. However, no quantitative estimates of the impact of SMS-driven subduction in the Baltic Sea are available.

Furthermore, the dominant sources of instability – whether the interaction of the baroclinic current with topography, SI or other SMS instabilities at fronts (potentially enhanced by variable local forcing), or strain-induced frontogenesis as suggested by Zhurbas et al. (2022) – are not fully understood. These questions may serve as a basis for future studies of SMS dynamics in the Baltic Sea.

4.2. Flow-topography interaction

Although surface SMS have been extensively studied, their counterparts in the oceanic interior are still largely unexplored. However, recent studies focusing mainly on energetic current systems – such as the Gulf Stream (Gula et al., 2015, 2019), the California Undercurrent (Molemaker et al., 2015; Dewar et al., 2015), and the Antarctic

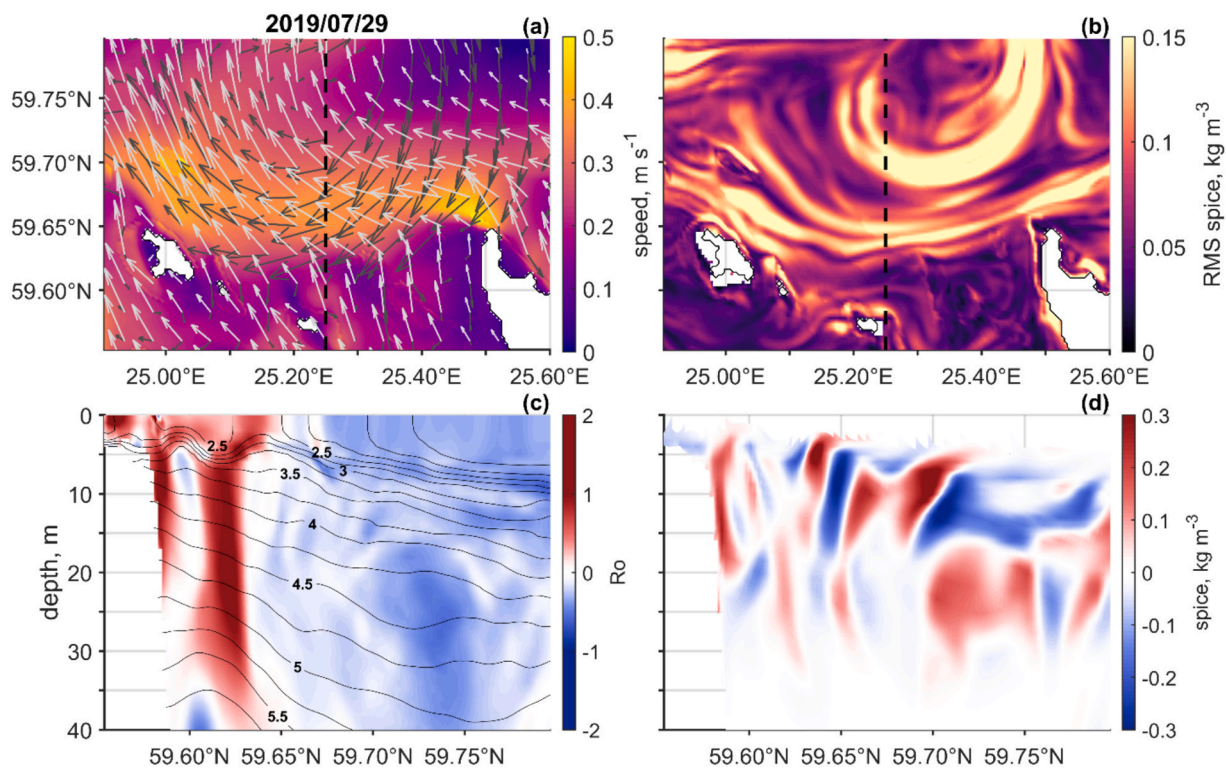


Fig. 7. (a) Current fields at 0 m (light-grey arrows and speed in color) and 20 m (dark-grey arrows) depth, and (b) root mean square of along-isopycnal spice in the density range from the surface until the depth of minimum temperature on 29 July 2019. Vertical sections of Ro and density anomaly (d) and spice (e) along the meridional transect at 25.25° E on 29 July 2019. (from Salm et al., 2025).

Circumpolar Current (Naveira Garabato et al., 2019; Siegelman et al., 2020) – suggest that SMS are widespread in the oceanic interior. These processes primarily arise from flow-topography interactions along sloping bottoms. Strong along-slope currents and steep bathymetric slopes, therefore, appear to promote the development of SMS in the deeper layers of the ocean (Dewar et al., 2015; Wenegrat and Thomas, 2020). Many of the instabilities in the SML described above have their counterparts in the BBL, where bottom friction and mixing generate the lateral buoyancy gradients needed for their development (Gula et al., 2015). An additional process in sloping BBL is the frictional creation of vertical vorticity, which may be exported outside the boundary layer in the case of boundary layer separation, producing cyclonic or anticyclonic eddies depending on the flow direction relative to the bottom (Gula et al., 2015). There are some indications that the latter process may be important for the Baltic Sea deepwater, despite its absence of strong permanent currents or energetic tidal flows.

4.2.1. Topographic SMS generation

Preliminary results from a high-resolution, realistic simulation show that filaments, fronts, and spiral-like eddies are widespread in the interior of the Baltic Proper, just below the main pycnocline (located at ~ 80 m depth, Chrysaghi et al., 2021), as can be seen in Fig. 8 for the Eastern Gotland Basin during autumn conditions. These interior structures are characterized by $O(1)$ Ro dynamics, indicating that they belong to the SMS regime. They largely originate from the lateral boundaries

where enhanced Ro results from the vertical vorticity generated by bottom friction of the along-slope current at the sloping bottom shown in Fig. 8b. This is consistent with earlier studies showing that when an interior current moves along sloping topography, bottom friction generates horizontal shear and therefore vertical relative vorticity (enhanced Ro values). Such regions with enhanced Ro and small potential vorticity (not shown) may be exported out of the BBL in case of BBL separation. A typical example can be clearly seen in Fig. 8a around 20.4°E and 57.2°N , where the sheared current rolls up and forms an anticyclonic vortex.

To further highlight this process, a passive tracer was released at 80 m depth, exclusively within the BBL (Fig. 8b). The tracer shows distinct structures closely aligned with the Ro anomalies (Fig. 8a), suggesting that ageostrophic features govern lateral dispersion by initially trapping the tracer and then transporting it away from the boundary and into the stratified interior. SMS, therefore, seem to facilitate boundary-interior exchanges, consistent with earlier studies (Naveira Garabato et al., 2019). Such interior-BBL exchange processes mediated by SMS dynamics likely are of special relevance in the Baltic Sea and similar marine and limnic systems, where biogeochemical deep-water properties are largely controlled by benthic fluxes.

A recent observational study Muchowski et al., 2023b) highlights the importance of small-scale topographic corrugations for both isopycnal and diapycnal mixing based on data from the western part of the Åland Sea. This area is characterized by extremely rugged topography at

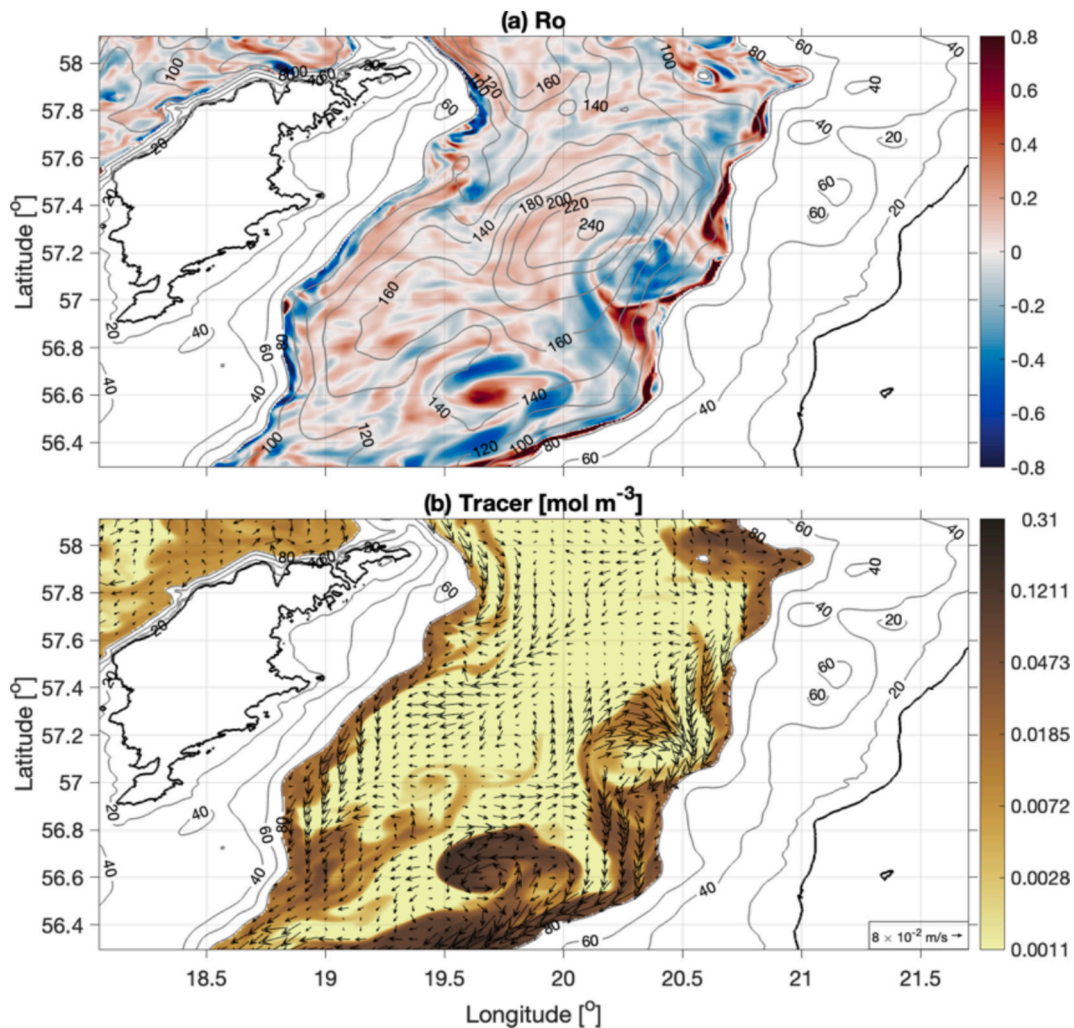


Fig. 8. Spatial distribution of (a) Rossby number and (b) passive tracer concentration with circulation patterns shown as arrows. Gray lines indicate isobaths. Both patterns represent instantaneous fields below the main pycnocline, at 80 m depth, on 23 October 2019 at 09:00 UTC.

horizontal scales of about 100–200 m and vertical topographic variations of about 20 m at depths close to the halocline depth of the Baltic Proper. Such an area with small-scale bathymetric features penetrating the halocline was studied with microstructure and broadband echo sounder transects (Muchowski et al., 2023b), showing highly enhanced dissipation rates of turbulent kinetic energy and diapycnal mixing in the halocline. One of the main hypotheses explaining this strong mixing was the generation of topographic wake eddies by the flow around bathymetric features and boundary layer separation behind them. Another hypothesis was breaking internal lee waves. Both processes transfer energy directly from the large-scale mean flow into the SMS wave-number regime imposed by the lateral topographic length scales. The rugged bathymetry in large parts of the northern Baltic Sea (e.g., Jakobsson et al., 2019) suggests that similar processes may be broadly important.

Stratified flow over steep topography provides a direct pathway from large-scale barotropic and baroclinic currents into SMS and small-scale features and turbulence, although not all processes strictly qualify as being SMS. Baroclinic flows over the southern Quark sill, a steep sill with vertical and horizontal scales of about 70 m and 500 m in the northern Åland Sea, were studied using microstructure observations, moored ADCPs, and a broadband echo sounder (Muchowski et al., 2022, 2023a; see location in Fig. 2b). The non-tidal flows showed characteristics similar to tidal flows over fjord sills (e.g., Arneborg et al., 2017) with partial blocking of the deepest waters and at times, supercritical overflows with downstream hydraulic jumps, large overturning eddies with vertical length scales of order 100 m, lee waves with lateral length scale similar to the sill (~500 m) breaking in the halocline, and clear Kelvin-Helmholtz billows with much smaller horizontal length scale (~50 m) in the halocline. These small-scale dynamics, probably not well represented in any existing models of the Baltic Sea, are important for the exchange of water between the Baltic Proper and the Gulf of Bothnia as well as for modification of the water masses due to mixing (Muchowski et al., 2023b). The 2D interpretation in terms of lee waves and vertically overturning eddies is probably also highly simplified (e.g., Klymak and Gregg, 2001), meaning that there is a 3D continuum of internal waves, jets and eddies, including large vertical vorticity eddies at SMS scales.

4.2.2. Bottom gravity currents and intrusions

Saltwater inflows from the North Sea, including Major Baltic Inflows (MBIs), strongly influence the hydrographic conditions of the deep basins and the overall environmental conditions of the Baltic Sea (e.g., Väli et al., 2013; Eilola et al., 2014; Carstensen et al., 2014; Meier et al., 2018; Mohrholz, 2018; Naumov et al., 2023a, b; Barghorn et al., 2023, 2025). Many studies have focused on the inflows themselves, their occurrence and entrainment of surrounding waters as saltier water is transported towards the central Baltic deep basins (e.g., Meier et al., 2004, 2006; Arneborg et al., 2007; Burchard et al., 2009; Rak, 2016; Bulczak et al., 2016). Building on these earlier studies, recent high-resolution modeling has provided a more quantitative perspective. Based on ensemble simulations with a high-resolution numerical model and a new analysis framework, Henell et al. (2025) quantified water mass transformation during an MBI and estimated the predictability of the MBI pathway and timing during its eastward propagation towards the central Baltic Sea. Complementary observational advances have also emerged. While most observations of MBIs were based on indirect evidence (e.g., changes in water mass properties), recent progress in the development of autonomous sampling systems (Prien and Schulz-Bull, 2016) allowed, for the first time, direct observations of the intruding water masses and mixing parameters during an MBI (Holtermann et al., 2017).

Dense inflows may cause swift bottom gravity currents and set up circulating pools of dense inflow water in downstream basins, both of which may be susceptible to SMS instabilities. However, one of the most detailed studies of dense gravity currents in the Baltic Sea, north of the Kriegers Flak, did not show clear signs of such instabilities (Umlauf

et al., 2007; Umlauf and Arneborg, 2009a, b). The study analyzed a dense, narrow (~10 km wide) gravity current with Ro close to 1, flowing into the Arkona Basin, using both observations (Umlauf et al., 2007; Umlauf and Arneborg, 2009a, b) and an idealized model (Umlauf et al., 2010). The study revealed relatively strong transverse density gradients within the gravity current maintained by a transverse circulation moving interfacial fluid towards the shallow side of the geostrophically and frictionally balanced gravity current. It was speculated that the pinching of the interface on the deep side of the current, due to divergent interfacial flow, facilitated the generation of interfacial water and thereby entrainment by decreasing the interfacial gradient Richardson number. Interestingly, no signs of symmetric instabilities were observed despite lateral density gradients of order 10^{-5} s^{-2} , i.e. one to two orders of magnitude larger than the typical cross-front buoyancy gradients found in surface-layer SMS fronts (see above). We attribute this lack of SMS instabilities to the relatively short (compared to the inertial period) passage times of the gravity currents through the topographic constructions, not leaving sufficient time for the growth of SI.

New types of autonomous profiling platforms enabled a detailed investigation of the temporal evolution of deep-water properties in the central Baltic Sea during an MBI (Holtermann et al., 2017) and highlighted the crucial role of frequently occurring small-scale intrusions that import oxic waters at and below the halocline. Later, Holtermann et al. (2020) showed that such intrusions constitute an integrative component of the deep-water dynamics of the Baltic Sea throughout the year, independent of MBI activity. They influence (or even determine) the depth of the redoxcline during stagnation periods, and, contrary to the widespread belief that MBIs provide the most important deep-water oxygen source, were shown to exceed the contribution of MBIs to the deep-water oxygen budget by a factor of 10.

By inducing small-scale temperature inversions in the salinity-stratified deep layers of the Baltic Sea, small-scale lateral intrusions may also create conditions favorable for double diffusion. Based on linear stability analysis, Kuzmina et al. (2005) presented indirect (based on stability parameters) evidence for double diffusion in the central Baltic Sea and suggested that it is a key factor in driving thermohaline interleaving. The first direct observational evidence of double-diffusive staircases in the Baltic Sea was provided by Umlauf et al. (2018) from the Bornholm Basin. Their microstructure data from a glider and an autonomous profiling system revealed rapid formation of sharp (cm-scale) temperature steps of order 1 K at the edges of meter-scale intrusions. Based on their high-resolution temperature data, they computed double-diffusive heat fluxes of order $10\text{--}100 \text{ W m}^{-2}$, which are among the largest values ever observed in the ocean. Comparable investigations in other parts of the Baltic Sea are still lacking.

Saline inflows impact Baltic Sea oxygen conditions below the halocline: they improve oxygen conditions in the short term through direct oxygen import, but also strengthen vertical stratification and reduce vertical oxygen fluxes, leading to long-term oxygen deficiency. In the Gulf of Finland, MBIs can initially worsen near-bottom oxygen conditions (Laine et al., 1997; Lessin et al., 2014). The impact of the December 2014 inflow reached the Gulf of Finland nine months later than the Gotland Deep (Liblik et al., 2018). It has been shown that the dense water overflows over the sills separating the Gotland Deep and the north-easterly basins are influenced by prevailing atmospheric forcing (Liblik et al., 2022). Oxygen and nutrient dynamics in the Gulf of Finland have been linked to the conditions in the northern Baltic Proper and wind forcing (Lehtoranta et al., 2017). However, a simple division of the impact of the physical processes on subsurface oxygen dynamics into horizontal advection and vertical mixing (the latter parameterized via local vertical stratification), without considering (SMS) mixing along the inclined isopycnal surfaces, may cause a bias in the estimates of this impact (Stoicescu et al., 2019, 2024).

Similar overflows to those from the Gotland Deep towards the Gulf of Finland and the Åland Sea occur through the Irbe Strait, where, in stratified seasons, waters between the seasonal thermocline and

halocline of the Gotland Deep make their way to the Gulf of Riga (Lilover et al., 1998). The water masses of these inflows are further transported by the basin-wide circulation, which is anti-cyclonic in summer months (Lips et al., 2016b). They experience baroclinic instabilities (Lips et al., 2016c) and can form SMS patches in the subsurface layer (Liblik et al., 2017). These inflows influence the near-bottom oxygen conditions in the Gulf of Riga by bringing more oxygen but strengthening stratification in the deep layer (Stoicescu et al., 2022). The observed short-term variability suggests strong multi-scale control of the dynamics (Liblik et al., 2023), and due to high local consumption, inflow-related improvements are difficult to quantify (Liblik et al., 2023; Stoicescu et al., 2022). High-resolution observations and model runs are therefore needed to disentangle the impacts of riverine inputs, local sedimentation and consumption, and physical processes on near-bottom oxygen dynamics in the Gulf of Riga.

Processes driving vertical mixing in and below the halocline remain poorly quantified (Reissmann et al., 2009), yet evidence suggests that SMS and SMS-scale processes may play a significant role. A tracer release experiment in the Gotland Deep (the BATRE experiment) combined with microstructure measurements showed clearly that diapycnal mixing was primarily happening when the tracer approached the sloping BBL (Holtermann et al., 2012, 2022), as has been shown in other geophysical settings, e.g. the deep ocean, lakes and fjords. The enhanced mixing near the bottom was mainly explained in terms of basin-scale topographic waves, a deep rim current, and near-inertial waves (Holtermann and Umlauf, 2012), but the potential contribution of SMS processes was not investigated.

To advance understanding, combined observational and high-resolution model studies are needed. As emphasized in Sections 3.3 and 3.4, these efforts should (1) verify that SMS processes and other processes of similar length scale over smoothly sloping bottoms as well as rougher topography are correctly represented in high-resolution models, especially regarding water-mass transformation, diapycnal mixing, and water exchange between the benthic boundary layer and the interior; (2) develop parameterizations to include these processes correctly also in coarser models, in order to improve the representation of vertical and lateral mixing in these models as well as the coupling of benthic and interior biogeochemical processes in coupled physical-biogeochemical models.

4.3. Multiscale interactions, energy transfer

Based on ferrybox observations in summers 2009–2012,

wavenumber spectra of temperature at 5 m depth had slopes of -2 or flatter for spatial scales ranging from 10 to 0.5 km during periods when relatively high horizontal buoyancy variations at larger scales existed in the area (Fig. 9; Lips et al., 2016a). This suggests the variance is broadly consistent with SQG expectations (spectral slope of $-5/3$), with eddy generation dominated by baroclinic instabilities in the SML (MLI; Balwada et al., 2024). Based on scanfish observations, wavenumber spectra of temperature at fixed depth also exhibited slopes of about -2 for spatial scales from 10 to 1 km in the surface layer and in the thermocline (Fig. 9; Lips et al., 2016a). Such a slope in the subsurface layers, not only in the SML, is not in accordance with the theory (which would require $-5/3$ near the surface and -3 in the interior), suggesting that ageostrophic flows play a role at these scales (Callies and Ferrari, 2013). These observations indicate that SMS dynamics are active in the Baltic Sea surface layer and thermocline, modifying the classical energy cascade.

Analysis of wavenumber spectra of temperature and salinity at isopycnal surfaces helps separate SMS-driven stirring from internal-wave signals, as internal waves have a minimal influence on along-isopycnal deviations of temperature and salinity (Ferrari and Rudnick, 2000). Salm et al. (2023) analyzed glider measurements and showed that, in the presence of a mesoscale baroclinic front, wavenumber spectra of isopycnal temperature had slopes close to -2 in the surface layer and the thermocline and were flatter in the layer below the minimum temperature depth (Fig. 9). For interpretation, it is important to recall that a -2 (-1) slope of wavenumber spectra of isopycnal temperature (passive tracer) corresponds to the -2 (-3) slope of wavenumber spectra of kinetic (potential) energy, respectively. This relatively steep slope (k^{-2}) of wavenumber spectra is inconsistent with the SQG theory, which predicts flatter tracer variance spectra at these spatial scales in the subsurface layers, e.g., due to the domination of interior QG turbulence or non-local stirring by larger-scale flows (Callies and Ferrari, 2013). Similar -2 slopes of isopycnal temperature variations at the mesoscale-submesoscale transition have been reported by Balwada et al. (2024) based on glider measurements near the Antarctic Circumpolar Current. They concluded that such a spectral shape indicates that SMS variability is primarily driven by local, ageostrophic stirring induced by SMS flows. However, wavenumber spectra of temperature at isopycnal surfaces between 5.7 and 6.0 kg m^{-3} (below the depth of minimum temperature) presented by Salm et al. (2023) exhibited flatter slopes (Fig. 9c), suggesting a reduced influence of SMS and a shift toward interior-dominated dynamics at these depths.

Lilover et al. (2025) analyzed simultaneously measured vertical

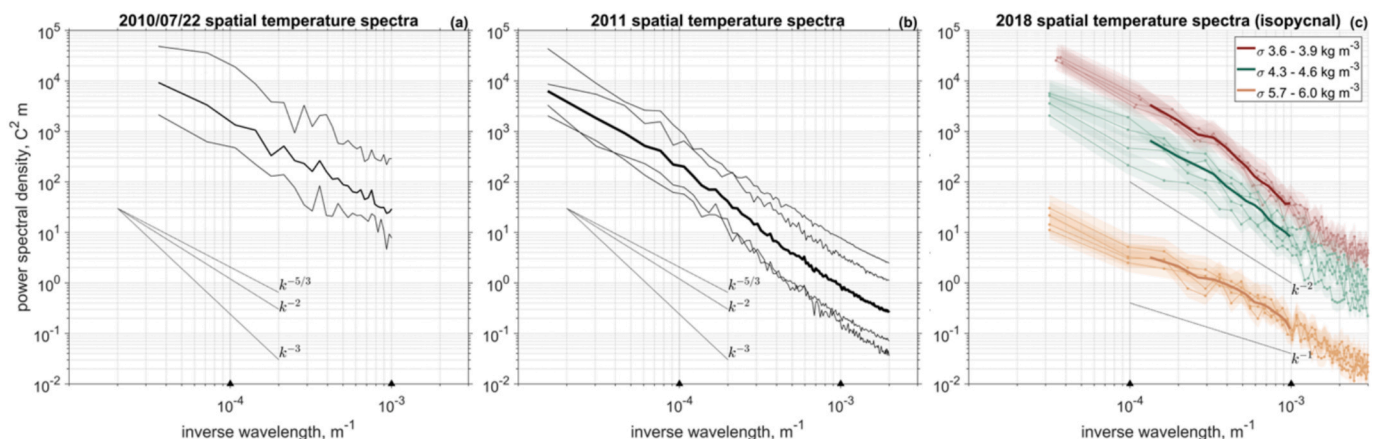


Fig. 9. Examples of wavenumber spectra of temperature variance: (a) in the thermocline based on scanfish data from the Gulf of Finland on 22 July 2010 (thin curves show averages over 10 m layers centered at 15 and 25 dbar, and the thick curve shows the overall average for the 3.5–32 m layer), and (b) in the surface layer based on the Tallinn-Helsinki ferrybox data (thin curves show averages for different periods and the thick line shows the average for the entire analyzed period from 29 June to 31 August 2011) along constant pressure surfaces (from Lips et al., 2016a), as well as (c) in the thermocline and deep layer based on glider data from May–June 2018 along selected isopycnal surfaces (thick curves correspond to the averages over the presented density ranges; from Salm et al., 2023).

profiles of temperature, salinity and currents in the Gulf of Finland (location is marked by red circle in Fig. 2b). They revealed that the temperature spectrum at isopycnal surfaces exhibited a slope of -2 , a characteristic sign of active SMS processes. Note that they analyzed the spectra in the frequency domain, which can be compared to spectra in the wavenumber domain if a frozen flow-field approximation is assumed (Balwada et al., 2024). In the thermocline, periods of intensified high-frequency temperature fluctuations coincided with marked changes in the velocity field, suggesting a dynamical link between temperature and flow variability.

They suggested that about 50% of the observed high-frequency temperature variability (in case of intense fluctuations with periods <36 h) could be explained by SMS processes and the remaining 50% by vertical excursions of isopycnals (internal waves). This estimate was obtained by comparing the high-frequency temperature variability at a constant depth with that at the isopycnal surfaces occupying an adjacent depth range during periods of elevated temperature fluctuations. The assumption that temporal variability at isopycnal surfaces can be attributed to SMS processes was tested by calculating the spectral density of isopycnal temperature variations, which did not exhibit peaks at any frequency, including the frequency of inertial oscillations (Lilover et al., 2025). The absence of spectral peaks supports the interpretation that these variations were generated by broadband SMS stirring rather than coherent wave motions.

Their results show that SMS processes, along with the internal waves, could provide a pathway for energy transfer from larger scales to the microscale. However, it is important to note that if the along-isopycnal tracer gradients are weak, SMS signatures may not be detectable via spice or tracer variability at isopycnal surfaces. Thus, it remained unclear whether SMS processes were active when temperature variations at a depth (pressure) level were primarily attributed to internal waves.

In the above analysis, we mostly focused on SMS processes as a pathway of energy transfer from large-scale processes to microscale dissipation. However, they could also transfer energy from small-scale to large-scale motions, thereby influencing the general circulation and the distribution of density (temperature and salinity). For instance, SMS baroclinic instabilities obtain energy from the potential energy associated with horizontal buoyancy gradients in the SML, and this kinetic energy at the submesoscale could cascade upscale and feed larger-scale flows (Taylor and Thompson, 2023). Such multiscale linkages are increasingly recognized as bidirectional rather than purely downscale.

Baltic Sea examples suggest similar connections between processes at different scales. After the relaxation of strong wind forcing, MLI could emerge and convert potential energy (stored in horizontal buoyancy gradients) into kinetic energy (Carpenter et al., 2020; Chrysagi et al., 2021). In addition, generation of SMS flows at the base of the SML, when atmospheric forcing does not reach these depths, could be a reason for high spice (along-isopycnal SMS variability) there (Salm et al., 2025) and for enhanced lateral spreading and dispersion of tracers over large distances (see examples in Fig. 3). Furthermore, SMS subduction has been suggested to provide a direct link between small-scale boundary-layer turbulence and gyre-scale circulation (Wenegrat et al., 2018). By analogy, a similar role of shaping general density (temperature and salinity) distribution and circulation in the Baltic Sea could be assigned to subduction and interleaving originating from the SMS instabilities and mixing in the SML and BBL.

Sketches of interlinkages between processes at different spatial scales, presented in Fig. 10 (with scales shown for the Baltic Sea settings), highlight the differences in concepts with and without SMS processes. If internal gravity waves are assumed to be the primary pathway for energy transfer from the mesoscale to the microscale (Fig. 10a), then turbulent mixing resulting from wave breaking or

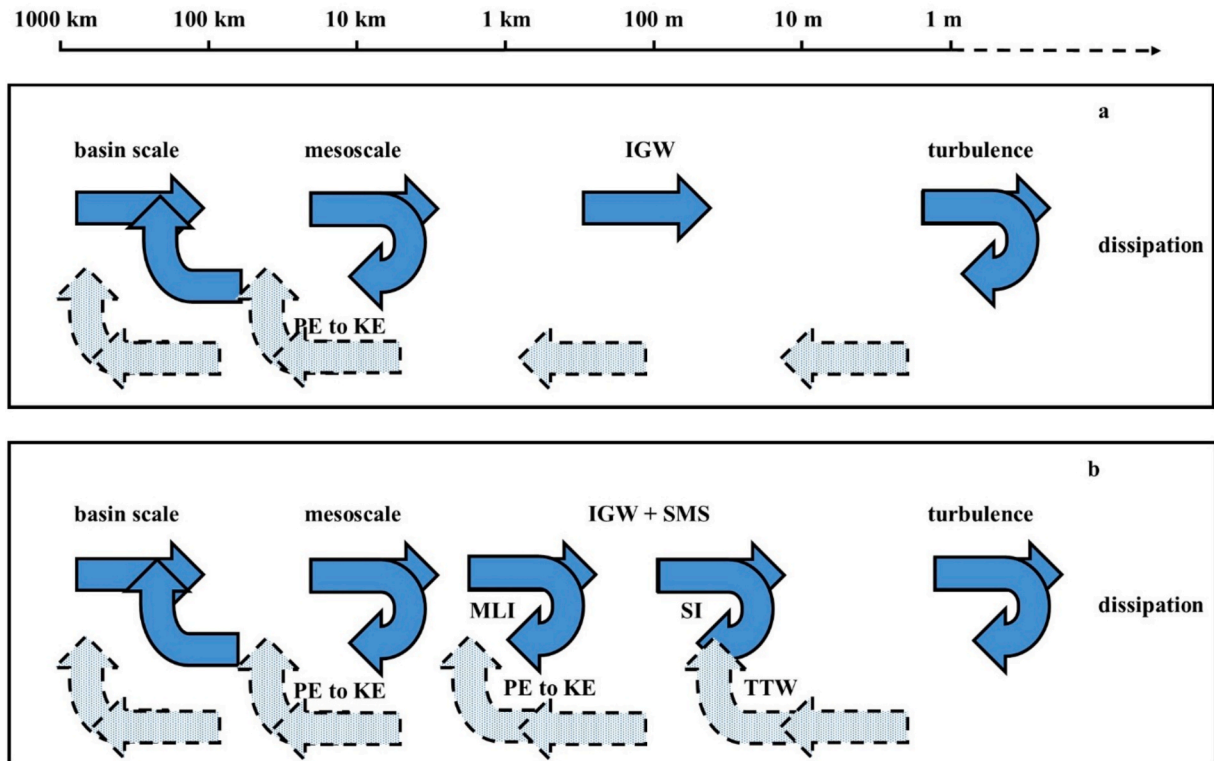


Fig. 10. Simplified sketches of interlinkages between the processes from the basin scale to the microscale, where (a) internal gravity waves (IGW) act as the primary pathway for energy transfer, and (b) SMS processes introduce additional pathways. Energy transfer is shown by filled solid arrows, while dashed arrows indicate the impact of mixing on the distribution of potential energy (PE) and its potential conversion to kinetic energy (KE). In both cases, large-scale energy input is ultimately balanced by microscale mixing and dissipation. However, (a) includes potential feedback at the mesoscale, whereas (b) features additional feedback loops in the SMS range due to MLI and SI/TTW.

boundary-layer processes, along with consequent dissipation, is balanced by the input of energy at larger scales. In contrast, if SMS processes play a role, additional loops for energy transfer between scales exist (Fig. 10b). This introduces a more complex and bidirectional multiscale cascade, where energy transferred from large-scale processes to microscale dissipation is partly utilized along that pathway to create SMS flows through respective instabilities.

For instance, MLI uses potential energy stored in the lateral buoyancy gradient to generate SMS flows and restratify the water column. Similarly, localized mixing (along with down-front wind in the SML) generates SI and subduction along slanted isopycnal surfaces. Thus, part of the available energy is first used to reshape the density structure and redistribute tracers along isopycnal surfaces (which can contribute to interior mixing) before continuing downscale toward dissipation. All these flows may cause secondary mixing. Furthermore, fronts in TTW balance create additional routes to arrive at SI, providing yet another pathway for SMS-driven vertical and lateral exchange.

These additional loops of energy transfer between the scales are in accordance with the flatter slopes of wavenumber spectra of potential energy than expected without SMS processes, since a larger fraction of energy is retained and transformed within the SMS domain. Additionally, this is in accordance with the faster decay of tracer variability in the SMS domain (i.e., steeper slopes of wavenumber spectra of tracers), as active SMS processes redistribute tracers along isopycnal surfaces. Taken together, these arguments and examples above suggest that the balance between energy inputs and dissipation can result in different basin-scale distributions of temperature, salinity, density, and other tracers, depending on the assumed pathways of energy transfer and whether SMS processes are accounted for.

4.4. Large-scale and long-term impacts

A general cyclonic circulation pattern has been suggested for the Baltic Sea (Elken and Matthäus, 2008) and its sub-basins, such as the Gulf of Finland and the Gulf of Riga, based on early measurements (Palmén, 1930) and numerical simulations (Lehmann and Hinrichsen, 2000; Andrejev et al., 2004; Meier, 2007). However, for the Gulf of Finland, this view has been questioned by results from higher-resolution models, especially when different periods and seasons are considered (Westerlund et al., 2019; Maljutenko and Raudsepp, 2019). A discrepancy between modeled and observed surface-layer circulation and salinity distribution has been attributed to stronger vertical mixing near the southern coast than near the northern coast (Maljutenko and Raudsepp, 2019). It remains an open question whether SMS processes play a role (high-resolution simulations should account for their contribution), whether sub-grid parameterization is crucial in defining the residual circulation (since finer grids require adjustments of parameterization), or whether numerical mixing influences the results (as it is still unclear which models simulate the dynamics and circulation more accurately).

The Baltic Sea is a strongly stratified, fjord-like basin, as classified based on the freshwater Froude number and mixing number (Geyer and MacCready, 2014). Lips et al. (2017) suggested that the Gulf of Finland belongs to the stratified estuaries, as expected, except when energetic self-oscillations (seiches) are generated by atmospheric forcing. Burchard (2020) introduced a universal law of estuarine mixing, combining the approaches of salinity coordinates (Walín, 1977), Knudsen relations (Knudsen, 1900), total exchange flow (MacCready, 2011), mixing definition as salinity variance loss (Burchard et al., 2009; Burchard and Rennau, 2008), and the mixing-exchange flow relation (MacCready et al., 2018). This approach to estimating mixing in estuaries is promising, as the classical division into vertical (3D isotropic) and horizontal (QG) mixing is not straightforward at scales and conditions where Ro is $O(1)$.

To fully understand the formation of the general thermohaline structure and circulation of the Baltic Sea, joint modeling and

observational studies focusing on small-scale variability are needed (Lehmann et al., 2022). As shown by Henell et al. (2023), the application of the estuarine mixing framework introduced by Burchard (2020) and formulated by Klingbeil and Henell (2023) can identify the mixing hotspots in the Baltic Sea that are essential for the formation of the overturning circulation. The debate continues over the pathways of upward mixing in the ocean meridional overturning circulation (Ferrari et al., 2016) and the Baltic overturning circulation (Henell et al., 2023; Lehmann et al., 2022; Döös et al., 2004; Placke et al., 2021). Using observed temperature and salinity data together with assumed vertical buoyancy fluxes and diffusivity profiles, Hieronymus et al. (2025) showed that the Baltic Sea also supports an overturning circulation characterized by upwelling in the BBL and downwelling in the stratified interior. Additionally, seasonal variability in mixing and SMS intensity must be considered (Väli et al., 2024).

Recent model intercomparisons show that resolution and the representation of SMS processes strongly affect tracer transport and circulation. A comparison of high-resolution and low-resolution simulations revealed that surface-layer transports in the low-resolution models (without SMS processes) are generally larger, moving tracers more rapidly away from the river mouths and the coastal zone than in the high-resolution model, due to higher persistency of surface currents in the low-resolution setup (Väli et al., 2025). This results, for instance, in higher tracer concentrations along the northern coast of the Gulf of Finland and the Gulf of Riga (Väli et al., 2025). However, the calculated patterns are more complex. A higher spatial resolution means, on the one hand, higher horizontal velocities in coastal currents, but, on the other hand, higher vertical velocities, which result in higher diffusivity of tracers and smaller horizontal transports in the surface layer.

Although the methods applied differed (Lagrangian particles vs. Eulerian tracers), Hariri et al. (2024, 2025) found similar results, demonstrating asymmetric particle spread in the Gotland Basin in high- and low-resolution simulations. Hariri et al. (2024) estimated that particle transit times between the coastal zone and the basin center differed by 15–43%, depending on whether SMS processes were included (depending on the applied horizontal resolutions). The range describes transit time differences due to the varying source locations. Hence, large-scale particle spread and connectivity between various coastal areas and between the coastal zone and the offshore area may not be accurately described by state-of-the-art circulation models used for multi-year simulations.

For example, the north-western Gotland Basin is characterized by increased eddy formation due to baroclinic instabilities and associated SMS processes, which contribute to the horizontal and vertical diffusion of particles, especially visible in areas without strong coastal currents (Hariri et al., 2025). This SMS activity is underestimated in coarse-resolution models. Interestingly, greater salinity variability is simulated when SMS processes are taken into account, whereas temperature variability remains largely unchanged, suggesting relatively short time scales for vertical SMS structures (Väli et al., 2025). However, in the sub-basin centers, the differences between simulations with and without SMS processes are small, indicating an overall quasi-steady-state balance in the coastal-offshore exchange.

We do not know whether the investigated high-resolution model accurately describes SMS processes, as systematic validation remains limited due to the lack of high-resolution observational data. Beyond validation, reliable parameterizations of SMS dynamics are also lacking.

4.5. Impact on water column biogeochemistry and fluxes

Without understanding the internal dynamics (i.e., the processes responsible for physical mixing), it is challenging to quantify the role of physical processes in changes in nutrient and oxygen concentrations (Fennel and Testa, 2019; Stoicescu et al., 2019, 2022; Naumov et al., 2023a, b). Since horizontal buoyancy gradients are common in the Baltic Sea, lateral and vertical fluxes associated with SMS processes also shape

the nutriclines, redoxcline, and occurrence of subsurface chlorophyll-*a* (phytoplankton) maxima (Lips et al., 2016a). In other sea areas, it has been demonstrated that eddy-driven subduction at scales of order 1 to 10 km can lead to episodic injections of water from the SML and a net transport of particulate organic carbon (POC) to depth (Omand et al., 2015). On the other hand, SMS-induced transport and variability are critical in the second half of the summer to maintain the secondary maximum in primary productivity when background nutrient concentrations in the surface layer are negligible (Zeng et al., 2022).

Subsurface maxima of chlorophyll-*a* and phytoplankton (Fig. 4) are a common feature of summer phytoplankton distribution in the Baltic Sea (Kononen et al., 1998; Lips et al., 2010). Lips et al. (2011) estimated that the dinoflagellate species *Heterocapsa triquetra* (Ehrenberg) Stein, which forms subsurface biomass maxima in the Gulf of Finland, is capable of vertical migration at speeds up to 1.6 m h^{-1} . The potential role of downward nighttime migration, asynchronous upward motions (taking more time), and layered SMS flows in the formation of a bimodal distribution of *H. triquetra* and its biomass growth near the surface has been discussed by Lips and Lips (2014). However, it remains an open question how much this pattern is related to the vertical migration of organisms (Lips et al., 2011; Lips and Lips, 2017) or to physical mesoscale and SMS processes (Berdalet et al., 2014; Lips and Lips, 2014).

Thus, SMS processes likely impact productivity, but the response may vary depending on the organisms (Hernández-Hernández et al., 2020). Furthermore, as demonstrated by a simplified simulation of biogeochemical processes within an eddy-like coherent structure in the southern Baltic Sea, SMS dynamics can promote the growth of specific phytoplankton groups (Vortmeyer-Kley et al., 2025). In general, productivity is believed to increase due to active SMS processes (Lévy et al., 2012). On the other hand, subduction of organic matter-rich upwelled waters at the sharp lateral density gradients of upwelling fronts and filaments has been shown (Nagai et al., 2015). Kessouri et al. (2020) suggested that SMS currents reduce productivity in the productive coastal region while enhancing the upward transport of nutrients and fueling new production in the offshore areas. Data from repeated glider sections, suggesting SMS subduction due to instabilities of the baroclinic current (Salm et al., 2023, 2025), can be used to reveal the development and influence of subsurface chlorophyll-*a* maxima on phytoplankton dynamics in the Gulf of Finland.

The impact of physical processes on the air-sea exchange of CO_2 (and CH_4) in the Baltic Sea has been studied by Norman et al. (2013), Jacobs et al. (2021) and Lainela et al. (2024). Norman et al. (2013) investigated four upwelling events (two in July, two in October) of the east coast of Gotland in the Baltic Sea, while Jacobs et al. (2021) analyzed ship-of-opportunity (SOOP) data from eight years along the ferry line from Lübeck-Travemünde to Helsinki. Both studies revealed a relationship between $p\text{CO}_2$ (and $c\text{CH}_4$) and SST in the upwelling area. Upwelling events cause the surface water to reverse from a carbon sink to a source, thereby intensifying CH_4 outgassing (Jacobs et al., 2021). There were different regimes with respect to $p\text{CO}_2$ -SST correlation in October and July, which are likely due to seasonal differences in thermal stratification and total inorganic carbon in the water column (Norman et al., 2013).

Lainela et al. (2024) associated local maxima of surface layer $p\text{CO}_2$ and $c\text{CH}_4$ in the Gulf of Finland and the Gulf of Riga with river bulges, coastal upwelling events, fronts, and episodes of vertical mixing reaching the seabed in shallow areas. It can be suggested that upwelling events seem to have a major impact on the total Baltic Sea carbon budget. However, the lack of high-resolution observations in the surface layer and simultaneous measurements in the water column, together with high CO_2 variability in the coastal areas, complicates accurate flux estimates. For instance, Lainela et al. (2024) concluded that although seasonal averaging over the CO_2 flux suggests a weak sink for atmospheric CO_2 in the Baltic Sea basins, more data is needed to confirm this. Furthermore, the impact of SMS processes on air-sea fluxes has not yet been studied in the Baltic Sea. At the same time, Resplandy et al. (2009)

showed that air-sea flux derived from observed $p\text{CO}_2$ could have an error of 15 to 30% due to undersampling. High variability of CO_2 at sub-mesoscale in the Peruvian upwelling area has been observed by Köhn et al. (2017).

Sea-air fluxes also have an impact on microbiological life in the Baltic Sea (Ploug, 2008). In cyanobacterial layers accumulating in calm weather at the air-sea interface, photosynthesis occurs to a significant extent. Net fluxes of oxygen at the air–water interface are, on average, 2.7 times higher than those at the aggregate–water interface beneath the layers. Photosynthesis ceases in darkness, causing the concentration of oxygen to decline due to its consumption and diffusion away. The pH showed a similar response to light: the microenvironment pH varied between 7.4 and 9.0, depending on the transition from darkness to saturating light.

In summary, studies explicitly addressing the impact of SMS processes on air-sea fluxes are almost absent for the Baltic Sea. However, high-resolution glider and scanfish data sets already exist that allow analyzing statistical properties of along-isopycnal variability of temperature and salinity as passive tracers and chlorophyll-*a*, which can be influenced by both physical processes and biological behavior of organisms. Such an analysis could enable us to test the assumption that phytoplankton (and ciliates) can take advantage of physical processes at the mesoscale and submesoscale to enhance their growth and distribution.

5. Summary and next steps to advance knowledge

This paper provides an overview of the study results from the last few decades, demonstrating the presence of SMS processes and their interlinkages with processes at adjacent scales in the stratified Baltic Sea. In the surface layer, spatial buoyancy gradients resulting from background freshwater and saltier water inputs, as well as mesoscale stirring and straining, create favorable conditions for SMS instabilities. When atmospheric forcing deepens the SML, large spatial buoyancy gradients may emerge, leading to baroclinic instability and the subsequent re-establishment of vertical stratification. Furthermore, if convective and wind-induced mixing do not occupy the entire depth of the SML, spatial buoyancy gradients in the lower portion of the SML generate SMS flows. Thus, SMS processes play a significant role in the development and maintenance of stratification in the sea surface layer. The development of vertical stratification cannot be approximated as a simple 1D process; instead, SMS processes counteract convective and wind-induced vertical mixing, maintaining stratification strength, which depends not only on atmospheric forcing but also on spatial buoyancy gradients.

Favorable conditions for SMS instabilities to develop in the lower portion of the SML, above the thermocline (or the salinity-maintained pycnocline in winter and early spring), could lead to SMS flows redistributing water mass properties. Such effects are especially evident when either temperature or salinity dominates in their contribution to vertical stratification (salinity in early spring and temperature in summer). It can be assumed that this mechanism also acts even when temperature or salinity inversions are not apparent. The detected spice maximum, located close to the strongest vertical buoyancy gradient at the base of the SML in conditions of positive buoyancy flux from the atmosphere, provides evidence for this process.

Baroclinic fronts and currents in the Baltic Sea, driven by background salinity and temperature gradients, their mesoscale stirring, and coastal upwelling and downwelling events, are conducive to the development of SMS flows and subduction. SMS subduction appears to be a significant contributor to vertical mixing in elongated basins, including their offshore areas. Due to frontal dynamics and upwelling events, subsurface waters are exposed to direct atmospheric forcing and mix with the surface waters. The development of SMS instabilities at fronts leads to the subduction of these mixed waters below the thermocline, particularly when steep isopycnals reach the sea surface or the base of the SML.

This mechanism provides a distinct way for mixing in the subsurface layers, separate from mixing caused by the breaking of internal waves. However, the specific mechanisms leading to SMS instabilities may differ, including instabilities of baroclinic (geostrophic) currents interacting with topography, as well as various types of instabilities, such as SI. SMS flows can emerge due to gravitational (energy provided by buoyancy flux or down-front wind forcing), inertial, or shear-induced instabilities. A similar mechanism of interior mixing could be suggested for near-bottom flows, where mixing occurs near the sloping seabed and over rough topography. The impact is then dispersed by SMS flows across the basin, especially in conditions of slanted isopycnal surfaces.

Thus, SMS processes play a significant role in shaping the spatial distribution of salinity and other substances in estuaries. They hinder the rapid transport of freshwater in the surface layer towards basin centers, but conduct it more effectively towards the subsurface layer in the offshore areas. Such an impact of SMS processes on coastal-offshore exchange has been demonstrated by comparing the outcomes of low-resolution and SMS-resolving (or SMS-permitting) models. However, these high-resolution models still require more extensive validation. Nevertheless, the results indicate that when the SMS processes are explicitly resolved, model outcomes differ markedly from those obtained with low-resolution models that implement QG parametrization of sub-grid horizontal mixing.

The effects of SMS processes on the biogeochemistry of the Baltic Sea remain poorly understood, particularly their impact on the carbon system and associated fluxes. Subsurface SMS patches of phytoplankton are common in summer. Since plankton is not a passive tracer (dinoflagellates and ciliates are capable of vertical migration), the role of SMS flows in generating such patches remains unclear. However, it can be assumed that, similar to zooplankton taking advantage of estuarine circulation, phytoplankton may employ SMS flows for their vertical excursions needed to acquire nutrients at depths and photosynthesize in the euphotic layer. A comparison of statistics regarding passive tracers and along-isopycnal chlorophyll-a variability could shed light on this question.

Thus, the Baltic Sea serves as a unique natural laboratory for SMS studies due to background lateral buoyancy gradients and active mesoscale processes. We conclude that the required expertise and research infrastructure are available in the Baltic Sea basin for SMS analysis. However, high-resolution datasets suitable for it and potential synergies for combining efforts are not yet being used to their full extent. The following list of topics and activities could form a basis for projects and experiments to be implemented in the coming years, collaboratively or by individual research groups or by the whole community targeting SMS processes:

- SMS subduction. Glider missions along coastal-offshore transects and realistic high-resolution simulations shall be conducted to demonstrate and quantify the effects of SMS subduction. The aim is to characterize the subduction process and its relation to background mesoscale dynamics and changes in atmospheric forcing. Microstructure measurements will be conducted to characterize turbulent mixing associated with SMS features.
- Multiscale analysis of spatial variability in the SML. Data collected by ferryboxes, including flow-through systems on board research vessels, will be analyzed to reveal connections between processes at different scales in the SML. Wavenumber spectra of potential energy and spatially binned statistics of tracer variability will be produced and interpreted. Data from SML will be combined with data from the water column (simultaneous glider sections, scanfish tows, and CTD casts) to investigate a potential link between horizontal gradients and vertical stratification. Besides other results, this analysis will characterize thermohaline (SMS) variability regimes in the seasons (or areas) with temperature-dominated stratification (Su et al., 2018)

and salinity-dominated stratification (Hilditch et al., 2025). Model experiments should complement this analysis.

- High-resolution mapping and modeling of river plumes to improve the knowledge of mixing and fate of riverine waters in the Baltic Sea system. Immediate mixing near the sources of freshwater can potentially make a significant contribution to the total budget of mixing between marine and terrestrial waters. The recently emerging micro AUVs are promising platforms for conducting in-situ experiments in river mouths, which, when combined with numerical models using unstructured grids, can advance knowledge in these systems with strong gradients. This knowledge is crucial for understanding the Baltic Sea system and estuarine systems in general.
- Near-bottom layer and interior mixing – the role of SMS processes. There is a growing amount of glider data from repeated glider transects at various locations in the Baltic Sea (e.g., VOTO observatories, Fig. 2b). These can be examined for SMS structures in the interior water mass, as well as near sloping topography and near rough topography. At positions of high SMS activity, combined microstructure observations and high-resolution model studies should be performed to quantify the role of SMS processes in diapycnal and isopycnal mixing, as well as in connecting benthic fluxes to the interior water masses.
- Model experiments. Only one multi-year, high-resolution model simulation with a horizontal grid step of 250 m is available for the Baltic Sea. This run was not calibrated. Using available observations, an evaluation and recalibration are needed. Tracer experiments with different horizontal resolutions can illustrate the impact of SMS on particle dispersion, connectivity, and residence times, among other factors.
- SMS processes and subsurface chlorophyll-a patches. Analysis of variability of passive tracers and chlorophyll-a along isopycnal surfaces from repeated glider sections. Differences in spatial variability could reveal how much of the subsurface patchy distribution of chlorophyll-a can be attributed to physical processes, including SMS subduction.
- SMS processes and sea ice. Initiate high-resolution observations in the surface layer throughout the ice season to detect potential effects of ice edge on SMS dynamics in the SML and formation of meltwater-induced buoyancy gradients, as well as estimate whether resulting SMS flows play a role in the Baltic Sea by altering the heat exchange with the atmosphere.

CRediT authorship contribution statement

Urmaz Lips: Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Kai Salm:** Writing – review & editing, Writing – original draft, Visualization. **Germo Väli:** Writing – review & editing, Writing – original draft, Visualization. **Taavi Liblik:** Writing – review & editing. **Lars Arneborg:** Writing – review & editing, Writing – original draft. **Louise C. Biddle:** Writing – review & editing. **Anna I. Bulczak:** Writing – review & editing, Writing – original draft. **Evridiki Chrysagi:** Writing – review & editing, Writing – original draft, Visualization. **Małgorzata Falarz:** Writing – review & editing. **Peter Holtermann:** Writing – review & editing. **Jaromir Jakacki:** Writing – review & editing. **H. E. Markus Meier:** Writing – review & editing, Writing – original draft. **Martin Mohrmann:** Writing – review & editing. **Kai Myrberg:** Writing – review & editing, Writing – original draft. **Per Pemberton:** Writing – review & editing. **Lars Umlauf:** Writing – review & editing, Writing – original draft.

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Declaration of competing interest

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Data availability

It is a review paper. Data availability depends on the authors of original papers.

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