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Impact of coastal currents and eddies on particle dispersion in the Baltic Sea: a Lagrangian approach to marine ecosystems

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This study analyzes the dynamics of coastal currents and eddies in the Baltic Sea, focusing on their role in particle dispersion and ecosystem connectivity. Combining the General Estuarine Transport Model (GETM) and Lagrangian methods, it examines both single and paired particle dynamics, initially deployed in coastal areas of the Baltic Sea, for 2D and 3D simulations. Results show significant variability in transit times as it takes for 3D particles from the eastern coastal zone over 700 days to reach the central Gotland Basin, while those from the western coastal zone arrive 90 days faster. Longer transit times in the eastern coastal areas can influence the distribution of nutrients and pollutants, potentially exacerbating eutrophication, harmful algal blooms, and hypoxic conditions. In contrast, shorter transit times in the western Baltic accelerate dispersal, reducing localized impacts while increasing the spread of contaminants. In addition, (sub-)mesoscale eddies and vertical advection play a key role in particle transport, particularly in the northern Gotland Basin, where complex circulation slows movement and prolongs exposure to nutrients and pollutants. Moreover, relative dispersion analysis shows an initial nonlocal growth regime lasting up to 25 days in 3D but only 4-10 days in 2D, affecting connectivity between marine habitats. The subsequent ballistic regime, lasting 350 days in 2D but only 75 days in 3D, suggests enhanced mixing in 3D, influencing species recruitment and the dispersion of pollutants. 3D simulation results show that, depending on the region, absolute dispersion exhibits ballistic growth for the first 7 days, followed by a transition to a super-diffusion regime before normal diffusion sets in after 70-85 days. Furthermore, particle exit times vary also significantly, with those from the Gulf of Finland taking over 1,300 days to exit the Baltic Sea, compared to less than 700 days for particles from western regions. These findings highlight the role of physical processes such as eddies, coastal currents and mesoscale structures in shaping species dispersal, nutrient cycling, and pollution transport. Understanding these mechanisms is crucial for marine conservation, sustainable fisheries, and climate adaptation strategies in coastal marine protected areas (MPAs) of the Baltic Sea, particularly as circulation patterns evolve due to climate change.

KEYWORDS

Baltic Sea, Lagrangian analysis, coastal currents, transit time, relative dispersion, eddies (oceanic), vertical advection

1 Introduction

The Baltic Sea, with its unique geographical and environmental characteristics, serves as an essential case study for understanding coastal current dynamics and their ecological impacts. As a semienclosed, brackish body of water, it exhibits pronounced salinity gradients and limited water exchange with the North Sea, creating conditions that amplify the influence of localized currents and eddies (Snoeijs-Leijonmalm and Andrén, 2017; Weckström et al., 2017; Viitasalo, 2019; Blenckner et al., 2021; Kuliński et al., 2021; Meier et al., 2022). These coastal currents, primarily driven by the interplay of freshwater input, wind forcing, and density gradients arising from stratified layers of salinity and temperature, generate complex eddy systems. The interaction between these drivers leads to spatially and temporally varying circulation patterns, where freshwater plumes modify stratification, wind stress redistributes surface waters, and internal mixing processes influence vertical exchange (Andersson, 2002; Meier, 2007; Bierstedt et al., 2015; Placke et al., 2018; Jędrasik and Kowalewski, 2019; Bednorz et al., 2021; Lehmann et al., 2022). These dynamics are critical for understanding how energy and matter are transported across different regions of the Baltic Sea.

Given its relatively low salinity and restricted exchange with adjacent seas, the Baltic Sea is highly sensitive to climate-driven changes, including accelerated warming, sea-level rise, and variations in freshwater inflow from rivers and precipitation. These changes can significantly alter the characteristics of coastal currents and eddies, modifying their frequency, strength, and spatial extent. For example, increased stratification due to warming has been shown to enhance eddy lifetimes by reducing vertical mixing. Observations from Liblik and Lips (2019) indicate that stratification in the Baltic Sea has strengthened over recent decades, with the seasonal thermocline and the halocline increasing by rates of 0.33-0.39 and 0.70-0.88 kg m-3, respectively, from 1982 to 2016. This enhanced stratification reduces vertical mixing. Studies by Hordoir and Meier (2012) suggest that future climate warming will exacerbate stratification in the Baltic Sea, particularly in the northern regions. This increase in vertical stratification is expected to be driven by higher mean temperatures, leading to thermally induced stratification without the need for prior thermal convection, as is currently observed. These changes in stratification will likely reduce the role of freshwater-controlled re-stratification and may influence vertical nutrient fluxes and the onset of the spring bloom. Zhurbas and Väli (2021) found that submesoscale coherent vortices in the northern Baltic Sea persist for several months, with mergers between similar vortices increasing their longevity. These shifts in eddy behavior, influenced by changing stratification, can significantly impact the distribution and availability of marine resources, with direct implications for both the ecology and economy of the region. Eddies trap and redistribute nutrients, forming localized "hotspots" of productivity that support phytoplankton growth-the foundation of the Baltic food web. Variability in upwelling and downwelling, induced by shifts in atmospheric forcing and current dynamics, further affects nutrient cycling, influencing phytoplankton abundance and species composition (Meier et al., 2012; Liu et al., 2017; Zandersen et al., 2019; Saraiva et al., 2019). These cascading effects ultimately shape fish stocks, impacting commercial fisheries and biodiversity.

Beyond nutrient dynamics, eddies also influence biological connectivity by affecting the dispersal of marine larvae and planktonic organisms, thereby shaping population structures and genetic diversity. The connectivity between fish and invertebrate populations depends on eddy-induced transport pathways, which determine larval retention or dispersion across different habitats. This can impact recruitment success and the resilience of marine species to environmental perturbations (Corell et al., 2012; Teacher et al., 2013; Sjöqvist et al., 2015; Jönsson and Watson, 2016; Hariri, 2020; Drouet et al., 2021; Cristiani et al., 2021; Bharti et al., 2022; Hariri et al., 2022, 2023, 2024). Furthermore, climate-driven changes in current and eddy dynamics may disrupt natural dispersal routes, potentially leading to shifts in species distributions and ecosystem stability.

Understanding these oceanographic processes is crucial for effective management and conservation of Baltic Sea resources. Coastal current changes influence not only nutrient cycling and biological productivity but also the transport of pollutants and harmful algal blooms, affecting water quality, fisheries, and public health (Karlsson et al., 2005; Almroth-Rosell et al., 2011; Andersson et al., 2015; Kahru et al., 2020; Munkes et al., 2021; Riedinger et al., 2024). These challenges necessitate comprehensive monitoring and adaptive management strategies that integrate physical oceanography with ecological and socio-economic considerations. As such, improved knowledge of Baltic Sea hydrodynamics is vital for enhancing the resilience of its coastal ecosystems and the communities that depend on them.

While previous Lagrangian studies in the Baltic Sea have provided critical insights into regional connectivity (Corell et al., 2012; Teacher et al., 2013; Sjöqvist et al., 2015; Jonsson et al., 2020), pollutant transport (Soomere et al., 2014), and general circulation patterns (Döös et al., 2004; Kjellsson and Döös, 2012), they have largely relied on relatively coarse-resolution flow fields that are insufficient to resolve mesoscale and sub-mesoscale processes. This limitation constrains our understanding of the fine-scale structures -such as coastal eddies, and fronts, -that are key drivers of dispersion and connectivity. In contrast, our study employs higher-resolution, sub-mesoscale-permitting velocity fields, allowing us to investigate detailed particle trajectories and the role of small-scale dynamics in shaping transport pathways. Furthermore, whereas previous efforts often focused predominantly on the surface layer (Drouet et al., 2021; Cristiani et al., 2021; Bharti et al., 2022; Hariri et al., 2022), we expand the analysis into the vertical dimension using fully three-dimensional Lagrangian particle tracking. This approach captures vertical advection and depth-dependent retention mechanisms, which are especially important in stratified and ecologically sensitive regions such as the Gotland Basin. By doing so, we bridge a major gap in existing Lagrangian research in the Baltic Sea and offer a more comprehensive view of multiscale ocean dynamics.

Moreover, our study introduces a quantitative framework for analyzing dispersion based on metrics such as transit times, absolute and relative dispersion, and the temporal evolution of transport regimes, which have not been systematically examined in the Baltic Sea. These indicators allow us to examine the role of (sub-)mesoscale structures and vertical dynamics in controlling connectivity and retention, with implications for the potential exposure of particles to different environmental conditions. While the broader motivation includes ecological considerations, this study offers a foundational framework for future interdisciplinary or management-oriented applications grounded in physical transport analysis. In this sense, we aim to address key questions related to marine ecosystem connectivity and resource management:

- i. How do coastal currents and eddies affect particle dispersion in the Baltic Sea?
- ii. How do the transit times (movement patterns) of particles initially deployed from various coastal areas of the Baltic Sea differ?
- iii. How do relative and absolute particle dispersions differ in 2D and 3D simulations in the Baltic Sea?

2 Data and methods

The velocity fields used in our analysis are generated with the high-resolution General Estuarine Transport Model (GETM; Burchard and Bolding Kristensen, 2002). To perform the Lagrangian analysis, we are conducting offline Lagrangian transport experiments by releasing numerical particles in the coastal areas of the Baltic Sea.

2.1 Data: velocity fields

High-resolution GETM simulations were used to obtain the current fields for the Baltic Sea. GETM is a primitive equation, 3D hydrostatic model that utilizes vertically adaptive coordinates (Hofmeister et al., 2010; Klingbeil et al., 2018), which combined with a TVD advection scheme and Superbee limiter minimizes numerical mixing (Gräwe et al., 2015). Vertical mixing of tracers and momentum is calculated with coupling to GOTM (General Ocean Turbulence Model; Burchard and Bolding, 2001) and more precisely, a k- ε scheme with algebraic closure (Canuto et al., 2001) has been used. Horizontal mixing is done with Smagorinsky (1963) parameterization.

A model run with a horizontal grid spacing of 250 m and 60 adaptive layers was performed to obtain high-resolution current fields at the surface (HR2D) and in three dimensions (HR3D). The model region covered the key basins of the Baltic Sea including Kattegat in the western and remote gulfs in the eastern part – Gulf of Riga and Gulf of Finland. A one-way nesting approach with data from a 1 nautical mile Baltic Sea model at the lateral boundaries was used to simulate a nine-year period (2010-2018). The heat and momentum flux at the sea surface was calculated from the UERRA-HARMONIE dataset (Gröger et al., 2022) and freshwater input from combined hydrological hindcast and forecast products (Väli et al., 2019).

The high-resolution model run started from zero sea surface height and current velocities. Temperature and salinity fields were interpolated from the coarse-resolution model. It has been shown that the current field in the Baltic Sea adjusts with the wind forcing within less than 5 days (e.g. Krauss and Brügge, 1991; Lips et al., 2016). More information about the model configurations were presented in Hariri et al. (2024) and Väli et al. (2024).

The model simulations were validated against onshore tide gauge observations and offshore temperature and salinity measurements by Väli et al. (2024). The highest correlations, with values close to 0.976, and the lowest absolute biases, less than 0.027 m, were found in the eastern and central parts of the model domain. The largest errors in sea surface height (SSH) occurred in the Danish Straits, where correlations dropped below 0.2 and root mean square differences (RMSD) exceeded 0.26 m, with absolute biases reaching 0.13 m. The salinity comparison indicated an overestimation at the sea surface but showed good agreement in the bottom layers. Temperature was overestimated in the southern areas, while better agreement with observations was achieved in the central and northern regions. For more details on model validation, the reader is referred to Väli et al. (2024).

2.2 Lagrangian method

2.2.1 Simulation of trajectories

Lagrangian numerical particles were released on different coastal areas in the Baltic Sea (Figure 1). The particle positions at each time step (every 10 minutes) are calculated using OceanParcels (Lange and van Sebille, 2017), a three-dimensional Lagrangian particle tracking model that is compatible with many Ocean General Circulation Models (OGCM) outputs. The model utilizes the Runge–Kutta method to interpolate velocity values and to move the particle over a user-defined time step, which was set to 10 minutes (for further details about OceanParcels, refer to Lange and van Sebille, 2017; Delandmeter and van Sebille, 2019).

For each simulation, a total of 250,000 particles were released along the coastal areas of the Baltic Sea to ensure statistically robust estimates, while accounting for the model resolution. This number, chosen based on Hariri et al. (2024) and computational feasibility, provides a balance between statistical significance and efficiency. To maintain statistical independence, particles were released at random initial times and coastal locations, reducing clustering effects, while the temporal resolution of the velocity fields further ensured independent trajectories.

To verify that results were independent of particle count, multiple simulations were conducted with varying initial particle numbers. The distribution of particles in each grid cell was systematically monitored to ensure statistical robustness, following previous studies (Hariri et al., 2024, 2023; Hariri, 2020, 2022; Poulain and Hariri, 2013). Additionally, a sensitivity analysis was performed by comparing results with a previous study (Hariri et al., 2024) where particles were released from river mouths instead of coastal areas, confirming consistency for specific locations.



(A) A map of the Baltic Sea (source: www.d-maps.com); (B) A schematic representation of the large-scale internal water cycle in the Baltic Sea. The deep layer beneath the halocline is illustrated in the lower section of the figure. Surface and bottom layer circulations are indicated by green and red arrows, respectively. Entrainment is depicted by light green and beige arrows, while diffusion is shown with a grey arrow (adapted from Elken and Matthäus, 2008); (C) Bathymetry of the study area. Boxes indicate the specified coastal areas for studying the dispersion of particle pairs. Yellow dots indicate the sample locations of particle deployments in the coastal areas of the Baltic Sea (abbreviations for different basins: AB, Arkona Basin; BB, Bornholm Basin; EGB, Eastern Gotland Basin; NGB, Northern Gotland Basin; WGB, Western Gotland Basin; GoR, Gulf of Riga; GoF, Gulf of Finland).

Two different simulations of particles have been performed. The first simulation, HR3D, involved trajectory simulations using high-resolution 3D velocity fields with a horizontal resolution of 250 m. The second simulation, HR2D, involved the same velocity fields but only at the surface in two dimensions.

In the 3D simulations, particles were released at initial depths randomly ranging from the surface to 20 m, ensuring coverage of vertical variability. Trajectories were tracked for a minimum of four years, with a maximum integration period of eight years (2011– 2018) for both 2D and 3D simulations.

2.2.2 Identification of particle pairs

A particle pair is defined as any two drifters (particles) that come within a predefined distance of each other at a given time. This approach allows us to examine how drifter pairs evolve over time within the flow field. The initial separations (δ_0) used to identify these pairs were $0 < \delta_0 < 1$ km. For each identified pair, we calculated the values of relative dispersion and other related parameters across the initial separations.

2.2.3 Relative and absolute dispersion

Relative dispersion, an important concept in turbulence theory, is related to the fluctuations of scalar quantities within the flow field. It quantifies the mean squared separation of drifter (particle) pairs as a function of time, and is given by the following equations (Provenzale, 1999; Batchelor, 1952):

$$R(t) = \frac{1}{N_p} \sum_{i \neq j} \left\| \boldsymbol{r}_i(t) - \boldsymbol{r}_j(t) \right\|^2 \tag{1}$$

Where: R(t) is the relative dispersion at time t, N_p is the number of particle pairs and the sum is over all pairs of particles. $r_i(t) = (x_i(t), y_i(t), z_i(t))$ is the position vector of particle i in a pair at time *t*, and $r_j(t) = (x_j(t), y_j(t), z_j(t))$ is the position of particle *j* in a pair at time *t* in the 3D case.

Absolute dispersion measures the mean squared displacement of individual drifters from their initial positions and provides insight into the overall spreading of drifters in the flow field. This is computed as (Provenzale, 1999):

$$D(t) = \frac{1}{N} \sum_{i=1}^{N} \left\| \mathbf{r}_{i}(t) - \mathbf{r}_{0,i} \right\|^{2}$$
(2)

Adding that $r_i(t) = (x_i(t), y_i(t), z_i(t))$ is the position vector of particle *i*, $r_{0i} = (x_{0i}, y_{0i}, z_{0i})$ is the initial position vector of particle *i*, and *N* is the number of particles.

2.2.4 Separation angle

In addition to dispersion metrics, we also analyze the angles between the velocities of particle pairs. The angle between their velocity vectors provides information on the correlation of their motions and the underlying flow structures (Koszalka et al., 2009). This angle is calculated as:

$$\theta_{ij} = \cos^{-1}\left(\frac{\boldsymbol{u}_i \cdot \boldsymbol{u}_j}{\|\boldsymbol{u}_i\| \|\boldsymbol{u}_j\|}\right)$$
(3)

 u_i and u_j are the velocity vectors of the two particles in a pair. This comprehensive approach allows us to explore the dynamics of particle pairs and the characteristics of the flow field, contributing to a better understanding of turbulent dispersion processes.

3 Results

3.1 Transit time across the coastal areas

Figure 2A presents the mean transit time values for particles initially deployed across various coastal regions in the Baltic Sea (for a detailed definition of transit time, see Hariri et al., 2023, 2024). The results indicate that particles take significantly longer to reach the eastern central Gotland Basin compared to the western Gotland Basin. Notably, the northern part of the basin, especially around northern Gotland, shows increased transit times due to the influence of eddies and filaments. Sample FTLE and FSLE fields (Finite-Time and Finite-Size Lyapunov Exponents; for more information about the method, see Hariri et al., 2015 and Hariri, 2022), along with Rossby number fields (Figure 2), reveal the presence of numerous cyclonic and anticyclonic eddies, primarily around the Gotland Basin, that can trap and recirculate particles, prolonging their transit times. These mesoscale structures enhance lateral mixing and induce local retention, which explains the observed delays in particle transport. Additionally, filamentary structures contribute to complex transport pathways, further increasing transit times by promoting intricate and intermittent exchanges between different water masses.

Particles require over 700 days to travel from the coastal areas to the eastern Gotland Basin, whereas transit times to the western Gotland Basin are approximately 90 days shorter. Particles originating from the southern basin take over 750 days to reach the center of the basin. Overall, particle movement from coastal areas to the eastern Gotland Basin is markedly slower than movement to other regions within the basin. Flow current maps (Figures 1B, 2D, E) indicate that particles originating from the eastern side of the basin tend to drift northward before aligning with the strong southward-flowing currents along the eastern coast of the Gotland. Conversely, particles on the western side generally follow the currents along the western flank of the Gotland Basin, consistent with the broader cyclonic circulation pattern of the Baltic Sea.

A comparison of particle trajectories using 3D and 2D (surface) simulations reveals significant differences in movement patterns (Figure 2B). In the northwestern Gotland Basin, 2D particles exhibit higher transit times, while in the southern Baltic Sea, 3D particles experience longer transit times due to vertical movement. This pattern extends to the northern basin, where vertical advection plays a substantial role in prolonging transit times. These findings suggest that the western coastal areas are predominantly influenced by surface dispersion driven by eddies and small-scale processes (see FTLE, FSLE, and Rossby number fields in Figure 2), whereas the eastern coastal areas are more significantly affected by vertical advection dynamics, which contribute to the retention and prolonged transit of particles.

Figure 2C illustrates the mean transit time (in days) for particles to exit the Baltic Sea after being initially deployed from various coastal regions. The findings reveal significant variability in transit times, influenced by the complex hydrography and circulation patterns within the Baltic Sea. The longest transit times are observed for particles deployed near the Gulf of Finland, requiring over 1,300 days to exit the basin. This extended duration is primarily attributed to the Gulf's unique hydrographic characteristics, including its restricted exchange with the central Baltic Sea, weaker currents, and the presence of a large number of eddies and sub-mesoscale structures, as confirmed by FTLE and FSLE maps (Figure 2), which together contribute to slower particle transport. In contrast, particles released from the western coastal areas of the basin require less than 700 days to exit the Baltic Sea. Particles originating from the eastern side of the basin take nearly 1000 days to reach the southern parts of the Baltic Sea before exiting.

The movement of particles within the Gotland Basin also exhibits significant variability. Particles in the eastern and northern regions of this basin require approximately 300 days longer to exit than those in the western regions. This disparity is due to the basin's large-scale cyclonic circulation (Figure 2).

3.2 Relative and absolute dispersion

To analyze relative dispersion, we applied Equation 1 to all particle pairs on the eastern and western sides of the Baltic Sea, as shown in Figure 3. Generally, relative dispersion is considered local if $R(t) \sim t^3$, corresponding to Richardson's law (LaCasce, 2008). In the local regime, dispersion is dominated by eddies of a size comparable to the pair separation. When the relative dispersion exhibits exponential growth over time, $R(t) \sim e^t$, it is classified as



FIGURE 2

(A) Mean transit time values (days) for particles deployed from the coastal areas; (B) the difference in mean transit time values (days) between HR3D and HR2D; (C) mean transit time values (days) for particles exiting the basin; (D, E) mean flow fields. (F, G) FSLE and FTLE fields on October 10, 2014; (H–K) Rossby number fields.



non-local (LaCasce, 2008). Initially, dispersion is expected to follow this exponential (nonlocal) growth regime. Figure 3a presents the relative dispersion of particle pairs released from the eastern and western coastal zones of the Baltic Sea for both 2D (surface) and 3D trajectories with initial separations of less than 1 km. During the early time steps, pair separations grow exponentially with time. Following this phase, relative dispersion transitions to a growth rate that scales approximately as $R(t) \sim t^3$ or $R(t) \sim t^2$. Ultimately, over longer periods, relative dispersion decelerates significantly, transitioning to a diffusive regime $R(t) \sim t$ (Ollitrault et al., 2005).

The results demonstrate that relative dispersion exhibits nonlinear initial growth, followed by nearly linear growth after 70 to 400 days, depending on the specific test case. The exponential regime (nonlocal regime) persists for up to 25 days for particle pairs on both the eastern and western sides of the Baltic Sea in the 3D simulation, whereas, in the 2D simulation, this regime is much shorter, lasting about 4 days on the eastern side and 10 days on the western side.

For particle pairs deployed on the eastern side of the Baltic Sea in the surface layer, the dispersion follows Richardson's law $R(t) \sim t^3$ for approximately 30 days from the initial deployment. However, for 3D trajectories, the Richardson regime is absent. On the western side, 2D simulations reveal that the Richardson regime begins

around 4 days after deployment and continues for up to 30 days, while, similar to the eastern side, the Richardson regime is not observed in 3D trajectories. This suggests that the presence of submesoscale structures in the surface layer is a key factor in generating the Richardson regime in the Baltic Sea, whereas vertical advection tends to dominate in the 3D simulations, thereby suppressing the Richardson regime. Following the Richardson regime, the ballistic (shear) region emerges, where relative dispersion evolves with a slope of $R(t) \sim t^2$. The longest ballistic region is observed in 2D simulations for particle pairs deployed on both the eastern and western sides of the Baltic Sea, lasting over 350 days. In contrast, in the 3D simulations, the ballistic regime in both coastal areas lasts approximately 75 days. Subsequently, relative dispersion transitions directly to the diffusive regime, where the pair separations exceed the scale of the energy-containing eddies, leading to uncorrelated velocities. In this regime, relative dispersion becomes proportional to absolute dispersion, increasing linearly with time. The flow is considered diffusive since the diffusivity (the derivative of the dispersion) remains constant, as described by Taylor (1935).

Our study also evaluates absolute (single particle) dispersion (using Equation 2) for particles deployed in the coastal areas of the Baltic Sea using 3D trajectories (Figure 3). Absolute dispersion begins

to grow linearly with time after approximately 70 days in the eastern Baltic Sea and 85 days in the western Baltic Sea. It is noteworthy that the maximum relative dispersion exceeds its absolute counterpart. During the initial phase (approximately the first 7 days), absolute dispersion exhibits ballistic transport, characterized by $R(t) \sim t^2$. It then transitions to a super-diffusive regime, scaling with a slope R(t)) $\sim t^{1.5}$ until about 70 and 85 days in the eastern and western Baltic Sea, respectively. Beyond this period, dispersion follows a normal diffusive regime, where $R(t) \sim t$. It should be noted that in normal diffusion, the mean squared displacement increases linearly with time, typical of particles undergoing random Brownian motion with a constant diffusion coefficient. Conversely, in super-diffusion, the mean squared displacement increases faster than linearly with time, indicating that particle motion is influenced by persistent directional currents or long-range correlations. Moreover, in ballistic transport, the mean squared displacement is quadratically related to time, reflecting particles moving in a straight line at a constant velocity without significant scattering or diffusion. This regime is generally observed over very short timescales, approximately 7 days in the Baltic Sea.

3.3 Separation angle

Initially, paired particles exhibit nearly parallel velocity vectors, but as they separate, their velocity vectors begin to diverge. Figure 4 illustrates the mean angle between velocity vectors (using Equation 3) for all 3D particle pairs on the western and eastern sides of the Baltic Sea.

In both cases, particularly along the eastern coast, particle pairs move together and separate slowly during the first few days after deployment. However, after 10 to 15 days, the mean angle between the velocity vectors increases, indicating that the particles begin to move more independently. On the western side of the basin, the mean angle increases more rapidly after 10 days, reaching approximately 85° by day 50, after which the rate of increase slows, eventually stabilizing around 90° by day 100. As shown in Figure 4, particle pairs on the western side exhibit more unstable behavior due to the influence of (sub-)mesoscale structures compared to those on the eastern side. These particles reach the eastern side of the Gotland Basin after approximately 1000 days, during which the mean separation angle becomes increasingly unstable. In contrast, for particles originating from the eastern side of the basin, variations in the mean separation angle are much smaller after around 100 days. These results highlight that the separation angle of particle pairs is a clear indicator of the dynamic nature of the region. Areas with high numbers of eddies and smallscale structures, such as the western Baltic Sea, exhibit more vibrant and unstable particle behavior compared to other parts of the basin.

4 Discussions and conclusion

Our analysis provides insights into particle transport dynamics in the Baltic Sea, offering valuable information for ecosystem

management, pollution control, and biological connectivity. By quantifying transit times, dispersion properties, and the influence of (sub-)mesoscale structures, we improve our understanding of how physical oceanographic processes shape ecological interactions and pollutant transport. These parameters directly inform marine protected area (MPA) planning, pollution mitigation, and predicting the movement of organisms like plankton and larvae.

Understanding how larvae and adults with limited swimming abilities disperse from MPAs is crucial for conservation. Many coastal species rely on retention mechanisms or behaviors that reduce dispersal, possibly shaped by natural selection to match local oceanographic conditions. These adaptive traits can promote localized population structures and reduce gene flow, underscoring the importance of aligning MPA design with regional hydrodynamics.

Consequently, we highlight our results and their relevance to the ecological issues in the Baltic Sea:

- i. Transit Times: Particles originating in the eastern Baltic take over 700 days to reach the central Gotland Basin, about 90 days longer than those from the western Baltic. This difference impacts nutrient and pollutant distribution. In the east, nutrients and contaminants experience prolonged transport, leading to sustained exposure in regions like the Gulf of Finland and Gulf of Riga—contributing to eutrophication and hypoxia. However, these nutrients do not necessarily accumulate in specific coastal regions but are transported northward with the coastal current before reaching the central Gotland Basin. In contrast, faster transport in the west enhances dispersion, which may lower localized impacts but increase pollutant spread to broader areas.
- ii. Influence of Eddies and Vertical Advection: Slower particle movement in the northern Gotland Basin results from prevalent (sub-)mesoscale structures and vertical advection. These mechanisms retain particles longer, especially in 3D simulations, prolonging exposure to pollutants and nutrients, potentially worsening coastal eutrophication. They also influence larval dispersal from MPAs, affecting recruitment and inter-population connectivity.
- iii. Relative Dispersion: In both 2D and 3D simulations, particle pairs initially separate exponentially (nonlocal regime), with this phase lasting up to 25 days in 3D simulations but much shorter in 2D simulations. Afterward, relative dispersion transitions to nearly linear growth, followed by slower growth in a diffusive regime. In 2D models, the ballistic (shear) region extends over 350 days, while in 3D simulations, this phase lasts about 75 days before transitioning to the diffusive regime. In the eastern Baltic Sea, the Richardson regime is observed for about 30 days in 2D simulations but is absent in 3D simulations. On the western side, the Richardson regime lasts 4 to 30 days in 2D simulations, but similar to the eastern side, it is not present in the 3D model, which is dominated by vertical advection.



The mean separation angle between the individual velocities for pair particles deployed initially from (A) the western, and (B) eastern sides of Baltic Sea for 3D simulations (red line is a gaussian filter applied to the data).

- iv. Absolute Dispersion: Absolute dispersion begins growing linearly after about 70 days in the eastern Baltic Sea and 85 days in the western Baltic. In the early phase (first 7 days), particles undergo ballistic transport, where the mean squared displacement scales quadratically with time. Following this, they enter a super-diffusive regime, eventually transitioning into a normal diffusive regime where dispersion increases linearly with time, typical of random Brownian motion. These findings reinforce the need to investigate how transport and dispersal processes influence larval connectivity between coastal MPAs, which could ultimately affect species persistence and genetic exchange among populations.
- v. Model Limitations: While higher resolution models provide more detailed insights, they also come with increased computational demands. The trade-off between computational feasibility and model resolution limits our ability to fully capture sub-mesoscale structures and eddies, which could affect the accuracy of the connectivity estimates.
- vi. Applications to Baltic Sea Ecological Issues:
 - a. Eutrophication and Nutrient Cycling: Prolonged particle transit times in the eastern Baltic promote greater nutrient retention, intensifying eutrophication and associated ecological stress. Persistent

Cyanobacteria blooms and hypoxic events (Wasmund et al., 2012)—particularly in deep basins like Bornholm—are sustained by limited oxygen renewal, adversely affecting benthic communities such as *Zostera marina* (Röhr et al., 2016; Schätzle et al., 2024). In contrast, the western Baltic Sea has shorter particle transit times (about 90 days shorter) and faster dispersion of nutrients. This means that nutrients, while still contributing to localized eutrophication, may be more rapidly transported and diluted across larger areas, potentially reducing the intensity of hypoxic conditions in areas like the Kattegat (Gibson et al., 2002) but increasing the spread of pollutants and affecting larger regions.

b. Pollutant Distribution and Contaminant Dynamics: Persistent organic pollutants (POPs), heavy metals, and microplastics are influenced by slow circulation and vertical advection. In the northern Gotland Basin, pollutants may accumulate in deep layers and sediments, threatening benthic fauna and fish like cod and herring (HELCOM, 2010). Meanwhile, vertical advection in the southern Baltic can retain contaminants such as pesticides and pharmaceutical residues at intermediate depths, facilitating their bioaccumulation through the food web (HELCOM, 2010). This process poses ecological risks for marine top predators, such as seals and porpoises, and may ultimately impact human health via seafood consumption.

- c. Larval Dispersal and Connectivity of Marine Populations: The Baltic Sea hosts unique species like the Baltic cod (Gadus morhua) and Baltic herring (Clupea harengus), which have limited dispersal abilities during their early life stages (Olson and Walther, 2007; Scotti et al., 2022). Our findings show that in regions such as Gulf of Finland, slow particle movement and retention could promote the local retention of larvae, which is critical for maintaining these populations. However, slower dispersal in these areas may also prevent genetic exchange between distant populations, which could affect genetic diversity in species like the Baltic cod, which is already struggling due to overfishing and environmental changes especially on the western side of the Baltic Sea (Steinkopf et al., 2024).
- d. Impacts on Primary Productivity and Food Webs: The Baltic Sea is home to important primary producers like phytoplankton and macrophytes, which form the basis of the food web (Korpinen et al., 2022). Our study's findings on the relative and absolute dispersion of particles have direct implications for nutrient distribution, which in turn affects primary production in the Central Baltic and coastal areas. The Eastern Gotland Basin is particularly sensitive to changes in nutrient dynamics, where longer retention times may support prolonged phytoplankton growth and nutrient cycling, potentially leading to overproduction of organic matter (Kuliński et al., 2022). These dynamics affect higher trophic levels, including key species like sprat and herring, and highlight the importance of region-specific nutrient management.
- e. Climate Change and Future Outlook: Rising temperatures and changing wind/salinity patterns will alter circulation and stratification, intensifying eutrophication and hypoxia risks. Climate-driven changes will particularly affect species dependent on specific temperature-oxygen niches, such as Baltic cod. Our findings establish a baseline and fundamental approach for predicting future changes in larval transport, pollutant dispersion, and ecosystem responses.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

SH: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. GV: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – review & editing. HEMM: Formal analysis, Funding acquisition, Investigation, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

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