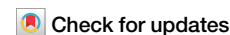




Reduced trapping efficiency of mesoscale eddies under eddy-eddy interactions



Tongya Liu¹✉, Xiaoming Zhai², Weijie Sun¹ & Dake Chen^{1,3}

Oceanic mesoscale eddies are commonly assumed to act as coherent structures that trap and transport water masses over long distances. However, recent Lagrangian studies suggest that long-lived coherent structures in the ocean are much more limited than implied by Eulerian eddy boundaries. In this study, surface drifters are used to examine the material transport capabilities of mesoscale eddies, and it is found that drifters initially enclosed by eddies tend to rapidly leak out after only a few days on average, indicating that these drifters are not effectively trapped and coherently transported by mesoscale eddies. Furthermore, a series of numerical experiments suggests that while an isolated eddy can effectively transport initially enclosed water parcels, significant water leakage occurs in the presence of multiple eddies, which may be associated with eddy–eddy interactions. And the degree of this leakage is found to be positively correlated with the intensity of the background strain field. Our results suggest that, in realistic multi-eddy environments, eddy stirring may contribute more significantly to material transport than eddy trapping, with broad implications for heat and biogeochemical tracer redistribution and for the representation of eddy transport in climate models.

Oceanic mesoscale eddies, ranging from tens to hundreds of kilometers in size and lasting from several weeks to months, are pervasive throughout the global ocean and are considered the most prominent feature of the upper ocean circulation system¹. These eddies dominate the ocean's kinetic energy and can transport oceanic tracers such as heat, salt, potential vorticity, and biochemical components^{2–6}, thereby significantly impacting the ocean's heat budget^{7,8}, large-scale circulation patterns⁹, and climate variability¹⁰. Therefore, understanding the physical processes and magnitude of eddy transport is crucial for accurately parameterizing the effect of mesoscale eddies in coarse-resolution climate models that cannot explicitly resolve these turbulent features.

As rotating structures, mesoscale eddies influence the distribution of oceanic tracers in two ways: eddy trapping and eddy stirring^{4,11}. Eddy trapping refers to the ability of mesoscale eddies to trap and transport the internal water mass during their lifespan due to strong nonlinearity, a process also known as coherent transport. Eddy stirring refers to the advection process around mesoscale eddies induced by their rotation and propagation. Due to the different physical meanings of eddy stirring and eddy trapping, their corresponding parameterization methods also differ¹². Although numerous studies have sought to examine eddy transport^{8,13,14}, the extent and relative contributions of eddy trapping and eddy stirring remain unclear, posing a challenge for eddy transport parameterization.

Previous studies have generally assumed that oceanic mesoscale eddies can maintain a coherent structure throughout their lifecycle and transport the water mass within them^{1,13}. This has been widely regarded as a key characteristic of mesoscale eddies over the past decades, especially for sea surface height (SSH) eddies defined based on the Eulerian framework. Under this paradigm, the outermost closed SSH contour is commonly used as a practical eddy boundary for identifying eddies and estimating transport. However, such an instantaneous Eulerian boundary does not necessarily act as a material barrier that isolates the eddy core from the surrounding flow. Recent studies based on the Lagrangian framework indicate that long-lived coherent structures in the ocean are quite rare and that Eulerian boundaries frequently fail to conserve water mass over time. For example, while the Southern Ocean contains rich SSH eddies with large amplitudes, very few of these eddies maintain a coherent structure^{15,16} (ref. 16 referred to as LA23). In addition, particle simulations based on numerical models and altimeter-inferred geostrophic flows suggest that the initial water parcels enclosed by SSH eddies can leak significantly into the surrounding background flow^{17–19}. This leaky nature suggests that the mere presence of a closed SSH contour does not guarantee the existence of a Lagrangian coherent core.

Two different theoretical frameworks reveal significant disparities in coherent transport induced by mesoscale eddies. Based on the Eulerian method, westward zonal eddy mass transport in the subtropical gyre has been estimated at 30–40 Sv¹³, surprisingly comparable to wind-driven gyre

¹State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, Ministry of Natural Resources, Hangzhou, China. ²School of Environmental Sciences, University of East Anglia, Norwich, UK. ³Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, China.

✉e-mail: liutongya@sio.org.cn

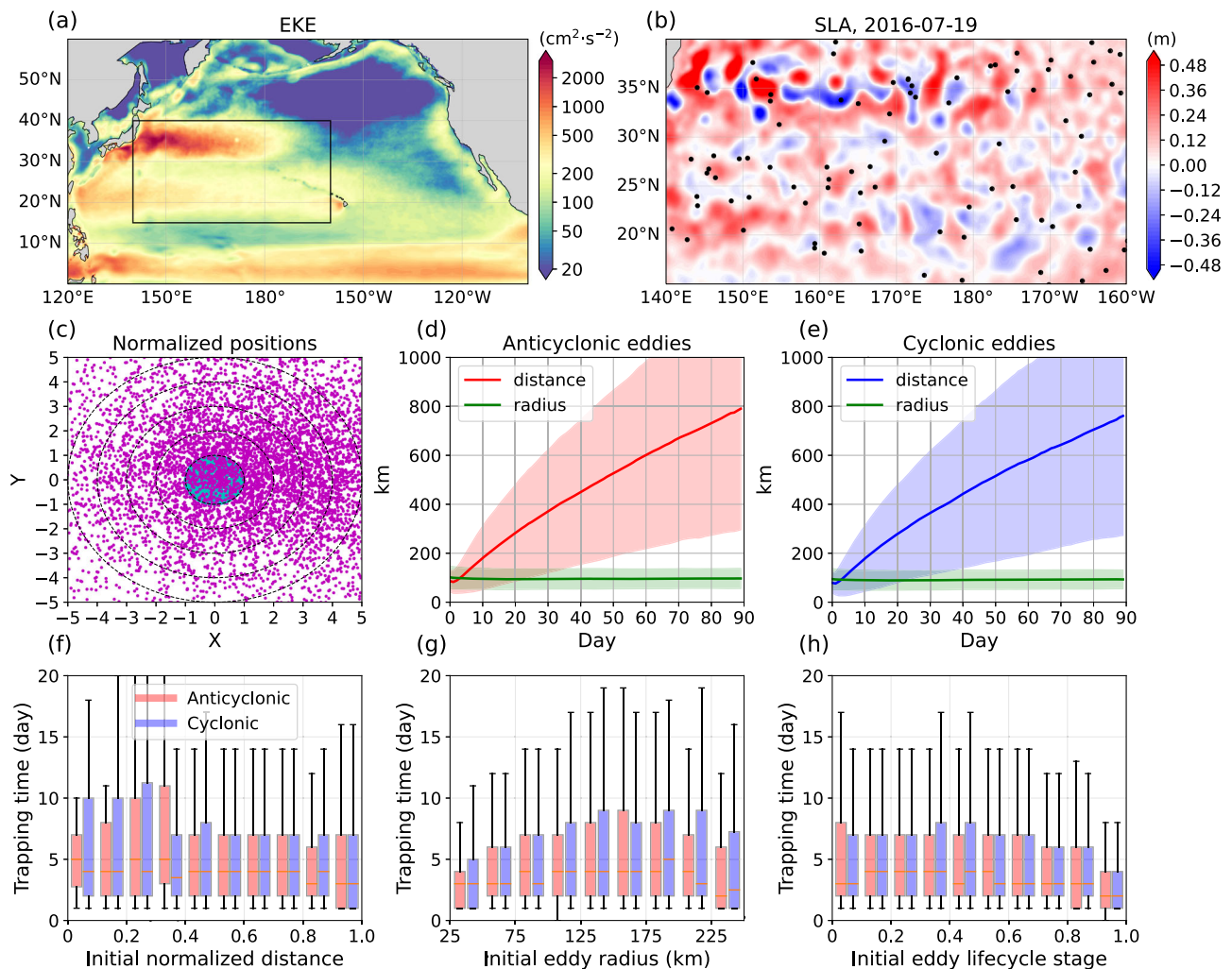


Fig. 1 | Eddy activity and drifter leakage from sea surface height (SSH) eddies. **a** Climatological eddy kinetic energy in the North Pacific from 1993 to 2020 (colors; $\text{cm}^2 \cdot \text{s}^{-2}$). **(b)** Instantaneous sea level anomaly (SLA; colors; m) and surface drifter locations (black dots) in the black box shown in **(a)**. **c** Locations of surface drifters at the initial time (blue dots) and final time (purple dots) in eddy-centered coordinates normalized by the eddy radius. **d** Mean distance between surface drifters and the centers of anticyclonic eddies (red; km) and mean eddy radius (green; km) over

90 days. Shading represents one standard deviation over all samples. **e** Same as **(d)**, but for cyclonic eddies. **f–h** Trapping time as a function of **f** initial distance from the eddy center normalized by eddy radius, **g** initial eddy radius, and **h** initial eddy lifecycle stage. Red and blue boxplots represent anticyclonic and cyclonic eddies, respectively. Boxes indicate the interquartile range, central lines denote the median, and whiskers extend to 1.5 times the interquartile range. This figure was generated using Python 3.10.

transport. In contrast, the Lagrangian diagnostic reveals that coherent transport across each longitude amounts to only 1 Sv^{20} . This discrepancy lies in how the boundaries of coherent eddies are defined. The Eulerian method, based on instantaneous flow fields (e.g., the widely used SSH contour method), cannot ensure water mass retention due to active water exchange^{21,22}. In contrast, the Lagrangian method tracks particle trajectories to determine whether a water mass is truly trapped and transported²³. Moreover, recent numerical and observational studies have revealed the three-dimensional nature of mesoscale eddy boundaries, suggesting that coherent structures may be primarily concentrated below the ocean surface^{24–28}. These discrepancies and uncertainties highlight the need for a deeper understanding of the features and mechanisms governing eddy transport.

In light of the aforementioned uncertainties among existing studies regarding material transport by mesoscale eddies, this study has two main objectives. First, we evaluate whether Eulerian SSH eddies can trap and transport water parcels using observational drifter data. Second, we seek to elucidate the physical mechanisms responsible for the limited number of coherent eddies in the ocean. Our main finding is that surface drifters are not effectively trapped and coherently transported by mesoscale eddies, and the

coherent structure of an eddy is significantly reduced when multiple eddies are present and interact with each other. These results have important implications for improving the representation of mesoscale eddy transport in climate models, particularly for the redistribution of heat, carbon, and biogeochemical tracers in the ocean.

Results

Observational evidence

We first conduct the statistical analysis using observations to examine whether surface drifters could be trapped by mesoscale eddies in the North Pacific (140°E–160°W, 15°–40°N). The climatological EKE (Fig. 1a) shows two high-value bands: one located in the Kuroshio Extension (KE) region and the other in the subtropical countercurrent (STCC) region. These two regions correspond to the two main eddy-active bands in the North Pacific and represent contrasting background-flow conditions. The KE region is strongly influenced by the energetic western boundary current and its extension, whereas the STCC region is characterized by westward-propagating eddies embedded in a weaker background current. Surface drifters and mesoscale eddies are matched based on date and location. Mesoscale eddies are obtained from the global mesoscale eddy trajectory

atlas²⁹, in which eddies are identified using an SSH contour-based method. If a drifter is located within an eddy on the same day, it is recorded as a sample. We identify a total of 5403 anticyclonic eddy samples and 5853 cyclonic eddy samples from 1993 to 2020. The positions of the eddy centers and drifters are then recorded during the remaining lifespan of the eddies, and the distances between them are calculated.

Figure 1c–e presents the statistical results for the KE and STCC regions (black box in Fig. 1a). At the initial time, all drifters are located within one eddy radius, in accordance with our criteria. At the final time, corresponding to either eddy disappearance or the end of the 90-day tracking window, only about 6% of the drifters remain enclosed by SSH eddies. The vast majority have moved outside the eddy boundary, and over 50% are located at distances beyond five times the eddy radius. This result aligns with previous research in the South China Sea, where the leakage of initial water for SSH eddies exceeds 80%³⁰. For both cyclonic and anticyclonic eddies, the average remaining lifespan is about 90 days, and the average radius is approximately 100 km. Interestingly, the surface drifters can be enclosed by the eddies for only a few days, after which they rapidly leak out from the eddies. The distance between the drifter and the eddy center linearly increases with time. It should be emphasized that the trapping time reported here is a statistical measure rather than a precise residence time for every individual eddy, as the actual SSH contours may be irregular. Nevertheless, the ensemble statistics consistently indicate that long-term trapping of surface drifters by SSH eddies is limited. The overall trends are similar for drogued and undrogued drifters, although undrogued drifters generally moved farther away from the eddy center (not shown). This is expected because undriven drifters are more strongly affected by wind and wave-driven motions and therefore tend to have larger velocities. Moreover, trapping time varies little with the initial normalized drifter–eddy distance, initial eddy radius, or eddy lifecycle stage (Fig. 1f–h), indicating that rapid leakage is robust across different eddy properties.

Separate analyses of the KE (27.5°–40°N) and STCC (15°–27.5°N) regions show qualitatively consistent leakage patterns, with substantially more rapid drifter dispersion in the KE region (Supplementary Fig. 1). Under the influence of the intense Kuroshio jet, drifters are not only ejected from the eddy boundaries but are also advected significantly farther from their originating structures. By the end of the 90-day tracking period, the average distance between the drifters and the eddy centers exceeds 800 km in the KE region, compared with approximately 650 km in the STCC region. Leaked drifters in the KE region are also preferentially displaced to the east of the eddy centers, consistent with eastward advection by the Kuroshio jet. These results suggest that conventionally defined Eulerian eddies are largely leaky and ineffective at long-term material trapping, particularly in regions with strong background flows.

Impact of eddy–eddy interactions

Mesoscale eddies are generally considered rotating structures that are nearly in geostrophic balance, and they are thought to trap the interior water parcels within their lifespans¹³. However, observations show that mesoscale eddies are significantly leaky. This discrepancy between theory and observations can be further examined through the numerical experiments reported below.

Figure 2 shows instantaneous surface temperature anomalies and SSH fields on the initial, 90th, and 180th days for four experiments. In EX1, the anticyclonic eddy moves westward and equatorward relative to its initial position (due to the beta effect), covering a distance of approximately 300 km westward within 180 days. This propagation feature is consistent with observations and simulations^{1,31}. In EX2, after eddy–eddy interaction, the anticyclonic eddy still can live for 180 days, while the cyclonic eddy dissipates after around 90 days. The anticyclonic eddy exhibits a westward motion greater than that in EX1, covering approximately 500 km. This is attributed to the formation of a westward jet between the anticyclonic and cyclonic eddies. In addition, the anticyclonic eddy appears noticeably elongated on the 180th day, with detaching filamentary structures indicating a structural change influenced by the cyclonic eddy. In EX3, under the

influence of the stronger cyclonic eddy, the filamentary structures detaching from the anticyclonic eddy become more pronounced. In EX4, the intensity of the anticyclonic eddy significantly weakens after 180 days under the influence of surrounding eddies, and its direction of motion is completely different from that in the other experiments. These results suggest that, beyond its intrinsic westward propagation, the eddy's movement is significantly influenced by the background flow field, as noted by previous studies^{32–34}.

The evolution of particles and tracers can effectively represent changes in coherent transport across different experiments. Previous studies have indicated that the outermost SSH contour cannot be considered as the material boundary for mesoscale eddies (e.g., refs. 17,30). EX1 also vividly illustrates this process, where particles initially enclosed by the SSH contour (green dots) are not consistently trapped (Fig. 3a, e, i). The actual coherent structure (blue dots in EX1) is identified using the Lagrangian-averaged vorticity deviation method²³. In EX2 and EX3, the presence of a background cyclonic eddy disrupts the coherent structure identified in EX1, with EX3 exhibiting a higher degree of particle dispersion. In a random eddy field (EX4), only a small number of particles initially inside the anticyclonic eddy are consistently trapped and carried by the eddy, while a large number of blue particles move out of the eddy and into the background flow field. In the region of interest, the tracer is initially set with cool colors on the west side and warm colors on the east side. If mesoscale eddies can effectively transport interior water parcels, as suggested in previous studies (e.g., refs. 8,13), we would expect this region to exhibit a predominantly warm-colored tracer distribution after some time, given that eddies primarily move westward. However, our results reveal intense water exchange from both sides, indicating that filamentary structures (eddy stirring) play a primary role in material transport, rather than eddy trapping.

Response of eddy trapping to enhanced strain fields

To quantify the degree of material coherency of an eddy, the coherency index (CI) is used here³⁵, measuring the degree of particle aggregation and dispersion (Eqs. 1 and 2).

$$\sigma^2(t) = \langle |X(t) - \langle X(t) \rangle|^2 \rangle \quad (1)$$

$$CI = \frac{\sigma^2(0) - \sigma^2(t)}{\sigma^2(0)} \quad (2)$$

Here X is particle position, $||$ denotes the standard Euclidean distance, and $\langle \rangle$ represents the ensemble mean. In an ideal scenario, where an eddy remains perfectly coherent without any expansion or contraction, the CI should be equal to 0. A more negative CI indicates a greater degree of particle dispersion. In the following analysis, the CI is calculated using particles that remain coherent in EX1, in order to examine how the same initially coherent particle group evolves under different experimental conditions.

As shown in Fig. 4, the anticyclonic eddy well maintains a coherent structure in EX1, evidenced by a CI value close to zero. However, in the other experiments, CI consistently falls below -10 at the final time, especially in the ten random experiments, indicating that particles undergo significant dispersion under the influence of the background flow field. The reduced eddy coherency from EX1 to EX4 is associated with the increase in straining and deformation as a result of eddy–eddy interactions, which can be quantified by the strain rate averaged within the eddy area (also see Supplementary Fig. 3). It is evident that, throughout almost the entire lifecycle, the strain rate within the anticyclonic eddy in EX2–EX13 is much higher than in EX1. The time-averaged strain rates in EX3 and the ensemble of EX4–EX13 are approximately twice as high as those in EX1 (not shown). This feature is evident at both the surface and subsurface (200 m), suggesting that the degradation of eddy coherence may extend vertically and be associated with eddy–eddy interactions.

To examine the influence of background flow intensity on eddy coherent transport, we compare the results of EX14 and EX15 against the control case (Supplementary Fig. 4). In the weak background field of EX14,

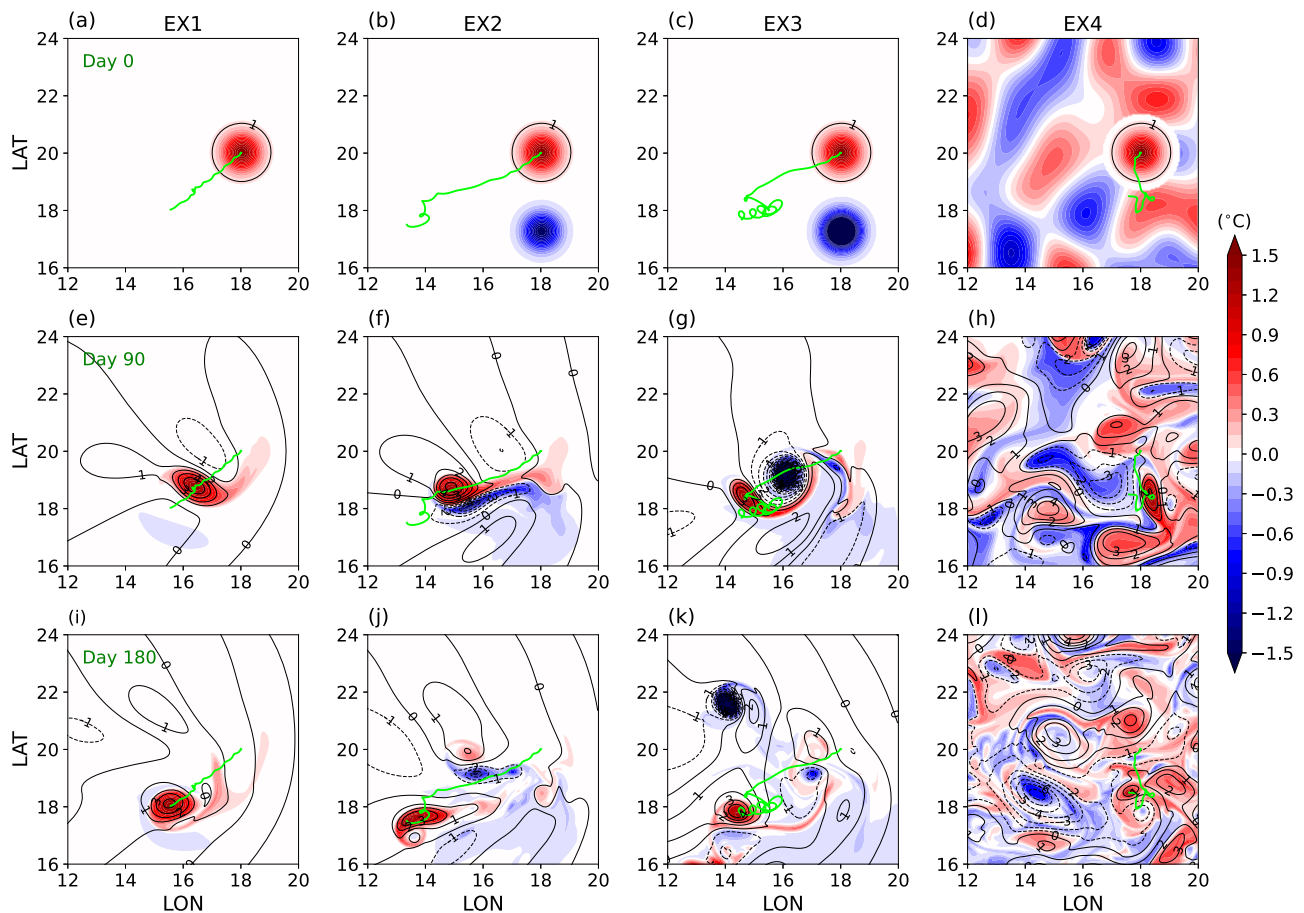


Fig. 2 | Evolution of idealized eddy experiments. Instantaneous surface temperature anomalies (colors; in °C) and sea surface height (SSH) fields (black contours; in cm) on the initial, 90th, and 180th day for four experiments. The initial SSH

field indicates only the boundary of the anticyclonic eddy. The SSH contour interval is 1 cm. The green line represents the trajectory of the eddy center over 180 days. This figure was generated using Python 3.10.

the anticyclonic eddy maintains high coherency throughout the 180-day period, exhibiting CI values similar to the isolated case of EX1. However, under the intensified background conditions of EX15, the particles undergo severe dispersion, with CI values plummeting below -50 and the strain rate remaining significantly higher than those in both EX1 and EX14 during the initial 50 days. And the eddy structure becomes virtually indiscernible after approximately 100 days. These findings demonstrate that the eddy's capacity for coherent transport is closely related to the ambient flow strength. Specifically, when intense eddy–eddy interactions are accompanied by severe eddy deformation, the trapped water mass tends to leak out rapidly and is assimilated into the surrounding background flow.

The intense deformation within high-strain environments typically signifies regions where water masses are subjected to significant stretching, shearing, and filamentation, often giving rise to potent ageostrophic motions, particularly along eddy peripheries^{36–38}. In such dynamics, initially proximal particles diverge exponentially, leading to a rapid collapse of material coherency. This physical intuition motivates a global investigation into the relationship between background strain rates and the spatial distribution of coherent eddies.

By analyzing the population of eddies with lifetimes exceeding 30 days from the LA23 dataset within $2^\circ \times 2^\circ$ grids, we identify a significant negative spatial correlation between the climatological geostrophic strain rate and the density of coherent structures, with a spatial Pearson correlation coefficient of -0.45 (Fig. 5). In high-strain regions, such as the Western Boundary Currents (e.g., Kuroshio Extension, Gulf Stream) and the Antarctic Circumpolar Current, the number of coherent eddies per grid cell is markedly low, often falling below 100. In contrast, eddy populations are more abundant in the eastern basins, where the background flow is relatively

quiescent. The bin-averaged statistics in Fig. 5c reveal a clear monotonic decrease in the number of coherent eddies as the background strain rate increases. A similar decreasing relationship remains evident when the number of coherent eddies is normalized by the number of SSH eddies within each grid cell. Although this global statistical analysis is qualitative, its consistency with the preceding numerical experiments supports the interpretation that high-strain environments might be less favorable for eddies to maintain coherent structures, potentially limiting eddy trapping as a mechanism of material transport in these regions.

It is crucial to emphasize that a lower count of coherent eddies does not imply a lack of mesoscale energy. Instead, it suggests that eddies may play a different role in energetic regions, where strong strain is associated with reduced eddy coherence and less effective long-term material trapping, while lateral stirring may become more important. These results suggest that the strain rate serves as a critical indicator of coherent transport by mesoscale eddies, providing a more nuanced understanding of eddy material transport in the global ocean.

Discussion

In this study, we investigate the ability of mesoscale eddies to maintain a coherent structure and the underlying physical mechanisms through observational analysis and numerical experiments. We find that surface drifters initially inside SSH eddies could only be trapped for the first few days, after which they rapidly leak out, with only about 10% of the drifters remaining enclosed by eddies throughout their lifecycle. Observational data demonstrate the strong leakage of mesoscale eddies and the rarity of coherent structures in the ocean. Moreover, numerical experiments show that an isolated eddy can effectively trap and transport water parcels during

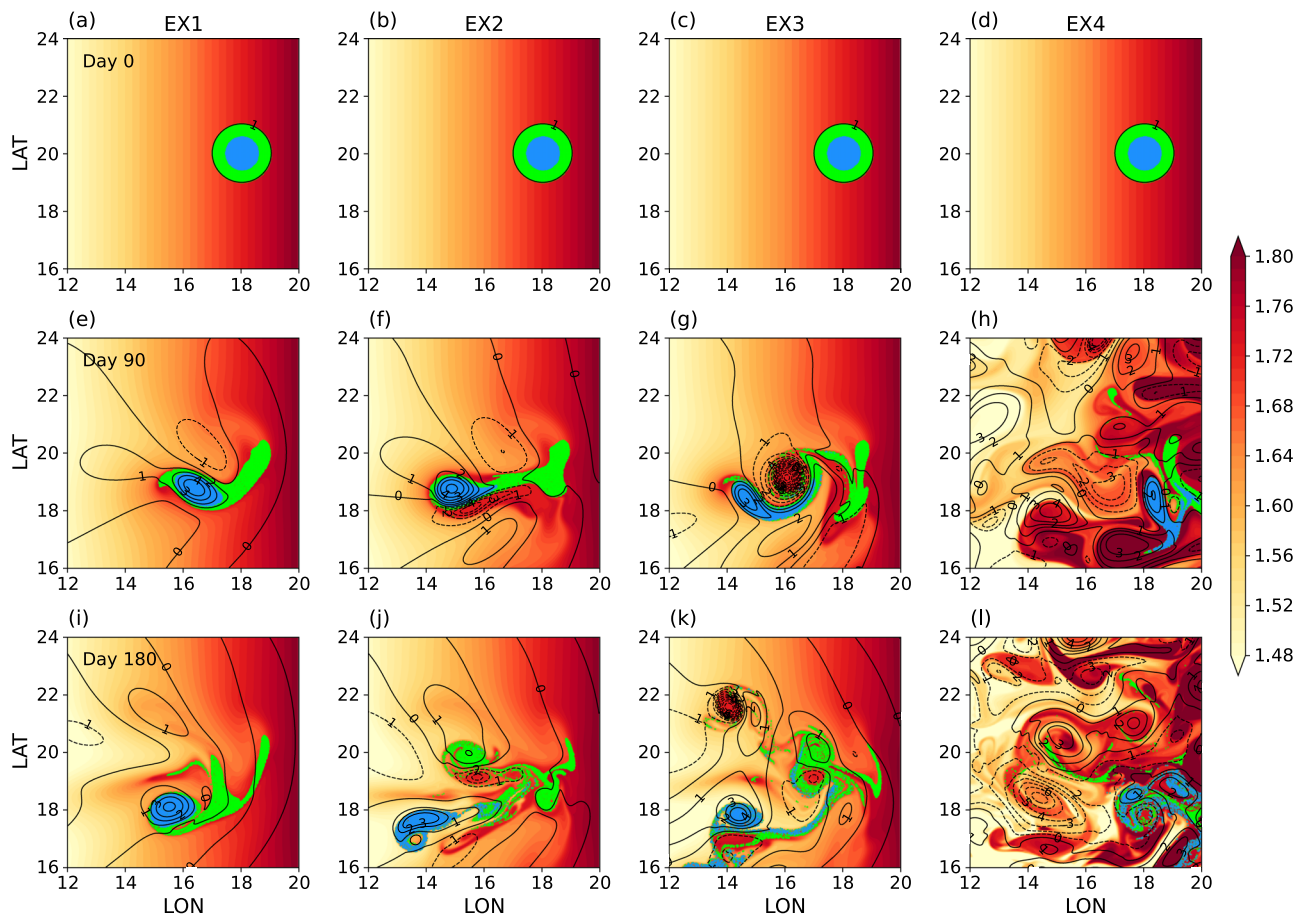


Fig. 3 | Passive tracer evolution in idealized experiments. Instantaneous surface passive tracer (colors; dimensionless), sea surface height (SSH) fields (black contours; in cm), and Lagrangian particle locations (green and blue dots) on the initial, 90th, and 180th day for four experiments. The initial SSH field indicates only the

boundary of the anticyclonic eddy. The SSH contour interval is 1 cm. The green dots represent water particles enclosed by the SSH eddy boundary at the initial time. The blue dots represent water particles that can maintain a coherent structure in EX1. This figure was generated using Python 3.10.

its lifetime. However, in the presence of a crowded eddy field, eddy–eddy interactions are associated with increased strain and deformation around the eddies, accompanied by the detachment of the originally trapped water from the eddy. And the degree of this leakage is found to be positively correlated with the intensity of the background strain field. Furthermore, the distribution of the geostrophic strain rate is negatively correlated with the number of coherent eddies on the global scale, implying that strain rate may be a useful indicator for measuring coherent eddy transport.

Previous studies considering SSH or potential vorticity contours as material boundaries for internal water parcels are primarily based on the perspective of isolated eddies^{8,13}. However, isolated eddies are uncommon in the ocean, whereas observations show that a more realistic scenario involves crowded eddies^{1,4}. Although our experiments are idealized and results may slightly vary depending on specific parameter choices (e.g., eddy radius, polarity, or intensity), we have provided a clear physical understanding by comparing the differences among a series of numerical experiments. This comparative analysis suggests that eddy–eddy interactions may represent a potential mechanism influencing material transport, consistent with the observational statistics.

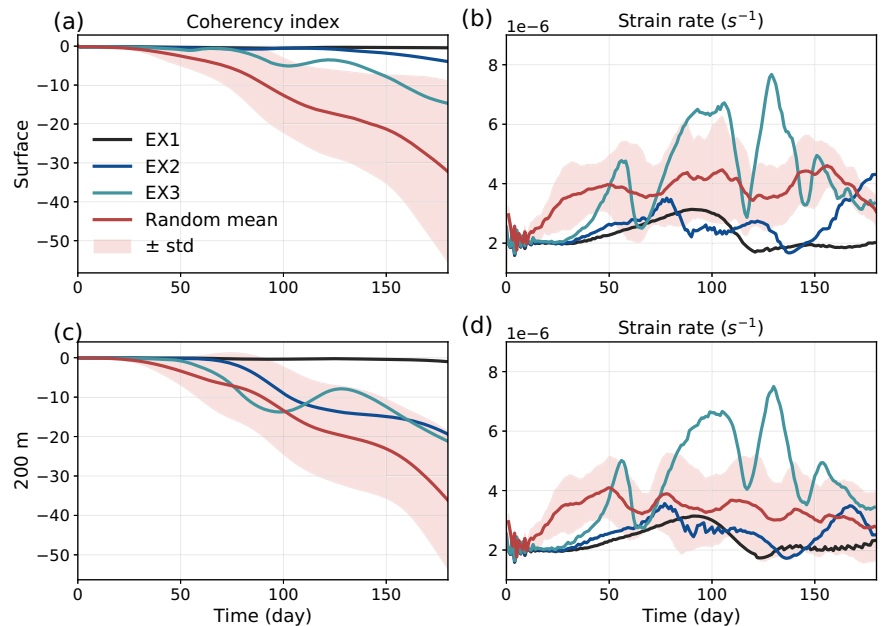
We should acknowledge that while the model resolution (~5 km) is sufficient for resolving mesoscale processes, it is inadequate for resolving submesoscale motions, which also play a role in modulating lateral transport^{39,40}. Apart from eddy–eddy interactions, future studies should also consider the effects of near-inertial waves, submesoscale instabilities, and Ekman flows induced by winds in the realistic ocean^{34,38,39,41–43}. These small-scale processes and wind-driven dynamics are expected to further energize the deformation field, potentially leading to even higher rates of material

leakage than those estimated in the eddy-only framework. We also acknowledge that strain is not varied independently, as the experiments differ in background kinetic energy, flow geometry, eddy number, and other dynamical properties. Moreover, because the present experiments are highly idealized, the effects of realistic ocean conditions, including bathymetry, stratification, and background flows, require further investigation. These environmental factors may produce substantial regional variations in eddy trapping and leakage. For example, strong Agulhas rings can maintain efficient material transport even in crowded eddy environments^{24,44}.

It is important to note that our experiments only examine the movement of particles at the surface and subsurface (200 m). Considering the strong baroclinicity of ocean eddies⁴⁵, the extent to which the relative contributions of eddy trapping and eddy stirring change at greater depths requires further investigation. As the intensity of background flow changes with depth, the trapping efficiency might differ in the deeper layers. Indeed, previous studies have identified pronounced coherent structures below the ocean surface^{24,26,28,46}. Exploring the three-dimensional structure of these leaky eddies using high-resolution multi-layer simulations and observations will be essential for a comprehensive understanding of how the ocean redistributes tracers throughout the water column.

Our results suggest that Eulerian eddy boundaries should be interpreted with caution when estimating coherent transport, especially in the upper ocean. Although alternative criteria, such as Okubo–Weiss or relative vorticity, may identify more compact eddy cores and yield different quantitative estimates, Eulerian boundaries are not necessarily material barriers⁹. We further evaluate the material coherence of the eddies identified in LA23 using surface drifter observations. Although these eddies retain drifters

Fig. 4 | Evolution of eddy coherence and strain. Time series of **a, c** the coherency index of particles initially enclosed by the coherent structure identified in EX1 and **b, d** the mean strain rate within the anticyclonic eddy at the surface (**a, b**) and 200 m depth (**c, d**). The black, blue, and teal lines represent EX1, EX2, and EX3, respectively. The red line shows the ensemble mean of the ten random experiments (EX4–EX13), and the shaded region denotes ± 1 standard deviation.



slightly more effectively than SSH eddies (Supplementary Fig. 5), substantial leakage still occurs. The coherent eddies in LA23 are identified from geostrophic flow and therefore do not include the ageostrophic motions that influence surface drifter trajectories. These results indicate that truly coherent eddies may be even more limited in the real upper ocean than suggested by geostrophic flow-based diagnostics.

It is also important to emphasize that a smaller number of coherent eddies does not imply that mesoscale eddies are unimportant in material transport. Rather, it suggests that the relative contribution of eddy trapping is limited^{17,47}, and more attention should be paid to the contribution of eddy stirring in future research. These findings suggest that future climate model parameterizations should better account for eddy interactions and associated deformation. Incorporating dynamic indicators such as strain rate may help represent the relative contributions of eddy trapping and stirring more realistically, thereby improving projections of heat, carbon, nutrient, and tracer redistribution under climate change.

Methods

Observational data

The observational data used in this study include surface drifters, satellite altimetry, and derived eddy datasets. Surface drifter data from the Global Drifter Program (GDP) of the National Oceanic and Atmospheric Administration (NOAA) provide drifter locations and velocities estimated at hourly intervals⁴⁸. The drifter locations from dataset Version 1.04c spanning from 1993 to 2020 are used here to verify whether mesoscale eddies are indeed capable of trapping and transporting water parcels. GDP drifters are designed with a subsurface drogue centered at approximately 15 m depth, which reduces direct wind slip and allows the drifter to better follow near-surface currents. Drifters whose drogues remain attached are referred to as drogued drifters, whereas those that have lost their drogues are referred to as undrogued drifters and may be more strongly affected by wind and wave-driven motions.

Satellite altimetry data (ID: SEALEVEL_GLO_PHY_CLIMATE_L4_MY_008_057) distributed by the Copernicus Marine Environment Monitoring Service provide daily sea level anomaly (SLA), surface geostrophic velocity (u_g, v_g), and geostrophic velocity anomalies (u'_g, v'_g). The

surface geostrophic strain rate S_g is calculated as

$$S_g = \sqrt{\left(\frac{\partial u_g}{\partial x} - \frac{\partial v_g}{\partial y}\right)^2 + \left(\frac{\partial v_g}{\partial x} + \frac{\partial u_g}{\partial y}\right)^2}, \quad (3)$$

where x and y are zonal and meridional coordinates. The surface eddy kinetic energy (EKE) in the North Pacific is calculated as

$$\text{EKE} = \frac{1}{2} \left(u_g'^2 + v_g'^2 \right) \text{ (Fig. 1a)}.$$

The global mesoscale eddy trajectory atlas²⁹ (META3.1exp) derived from satellite data is employed to provide eddy-related information (spanning from 1993 to 2020), including eddy center, radius, and location. The eddies in this atlas are identified based on the conventional SSH closed-contour method. The eddy radius used here is the time-varying equivalent radius provided by the atlas. In this study, we combine surface drifter trajectories with the SSH eddy dataset to evaluate the trapping capacity of Eulerian eddies. In our analysis, drifters and eddies are first matched according to their positions on the same day. A sample is defined when a drifter enters the area within one equivalent radius of an eddy center. To avoid repeated sampling, only the first encounter between each drifter and each eddy is retained. The distance between the drifter and the initially matched eddy is then calculated over the following 90 days when complete records for both are available. Therefore, if a drifter leaves one eddy and subsequently enters another eddy, this process is included in our statistics as two separate samples.

Furthermore, the global Lagrangian eddy dataset (LA23) is used to show the general features of coherent eddies. Unlike the conventional SSH method, the LA23 dataset is constructed using the Lagrangian-averaged vorticity deviation²³ (LAVD) method. By advecting millions of virtual particles with satellite-derived geostrophic velocities, this Lagrangian approach captures the coherent cores of eddies that are capable of trapping and transporting water masses over their entire lifetimes.

Numerical experiments

The MITgcm (checkpoint 67c) is employed to conduct a series of idealized numerical experiments. The model domain is a rectangular basin spanning 25° in longitude (from 0°E) and 30° in latitude (from 5°N). The horizontal grid resolution is 1/20°, sufficiently fine to resolve mesoscale eddies. The

basin bottom is set to a constant depth of 3000 m. There are 64 unevenly spaced vertical layers, with the upper 1000 m divided into 50 layers. In addition, sponge layers have been applied to all four open boundaries to eliminate the impact of reflected gravity waves on the model interior circulation. Other specific configurations not detailed here are adopted from the eddy-resolving simulation framework described in refs. 9,17. The

detailed numerical parameters are provided in Supplementary Table 1 to ensure reproducibility.

Although some studies have examined vertical characteristics of mesoscale eddies using numerical simulations and observations^{28,46,49,50}, a unified understanding of eddy vertical structure remains limited, with substantial regional variations. To simplify the problem, the horizontal and vertical structures of the initial eddies are described by Eqs. (4) and (5), similar to those used in refs. 51,52. Supplementary Figure 6 depicts the horizontal and vertical temperature anomalies of an anticyclonic eddy. This is a surface-intensified eddy ($T_m = 1.5^\circ\text{C}$) with a radius of approximately 100 km and a maximum vertical depth of 1000 m. We consider the evolution of eddies in the subtropical region, and thus set the initial latitude to 20°N .

$$T_a(x, y, z) = T_m e^{\frac{-(x-x_0)^2 + (y-y_0)^2}{R^2}} I(z) \quad (4)$$

$$I(z) = \begin{cases} 1, & z \leq 100 \text{ m} \\ \sin\left(\frac{z-100}{1800}\pi + \frac{\pi}{2}\right), & 100 \text{ m} < z < 1000 \text{ m} \end{cases} \quad (5)$$

Here, we aim to examine how the capability of an anticyclonic eddy to trap water parcels changes with increasing complexity of the flow field (Table 1). In EX1, only an isolated anticyclonic eddy serves as the control case (Fig. 2a). In EX2, a cyclonic eddy with the same intensity and size is placed to the south of the anticyclonic eddy (Fig. 2b) to investigate changes in the coherent structure under the influence of the cyclonic eddy. In EX3, the temperature anomaly of the cyclonic eddy is doubled compared to EX2 (Fig. 2c) to examine material transport under the influence of a stronger cyclonic eddy. In EX4, the background field is set to a random eddy field (Fig. 2d), resembling the multi-eddy field observed in the real ocean. To reduce randomness, we repeat EX4 experiments nine times (EX5–EX13). It should be noted that EX2 and EX3 represent only one idealized eddy-pair configuration, while other possible eddy combinations are included in the random eddy-field experiments.

The temperature anomaly for the random eddy field is synthesized by a superposition of two-dimensional sinusoidal waves:

$$T_{\text{random}}(x, y, z) = A \sum_{i,j} G_{i,j} \sin\left(\frac{2\pi k_i x}{L_x} + \phi_i\right) \sin\left(\frac{2\pi k_j y}{L_y} + \phi_j\right) I(z), \quad (6)$$

where A is a scaling factor that modulates the maximum amplitude of the temperature anomalies; L_x and L_y denote the zonal and meridional spans of the model domain, respectively; ϕ_i and ϕ_j are random phases. The spectral weighting function is defined as: $G_{i,j} = e^{\frac{\phi_j(k_i - k_j)}{2 \times 3.5^2}}$, where $k = \sqrt{k_i^2 + k_j^2}$ is the radial wavenumber and the peak wavenumber is set to $k_c = L_x/320$.

For the experiments from EX4 to EX13, A is set to 1.5°C , which is consistent with the temperature anomaly of the anticyclonic eddy to simulate a balanced interaction environment. In EX14, A is reduced to 0.5°C to represent a scenario where a relatively strong eddy is embedded in a

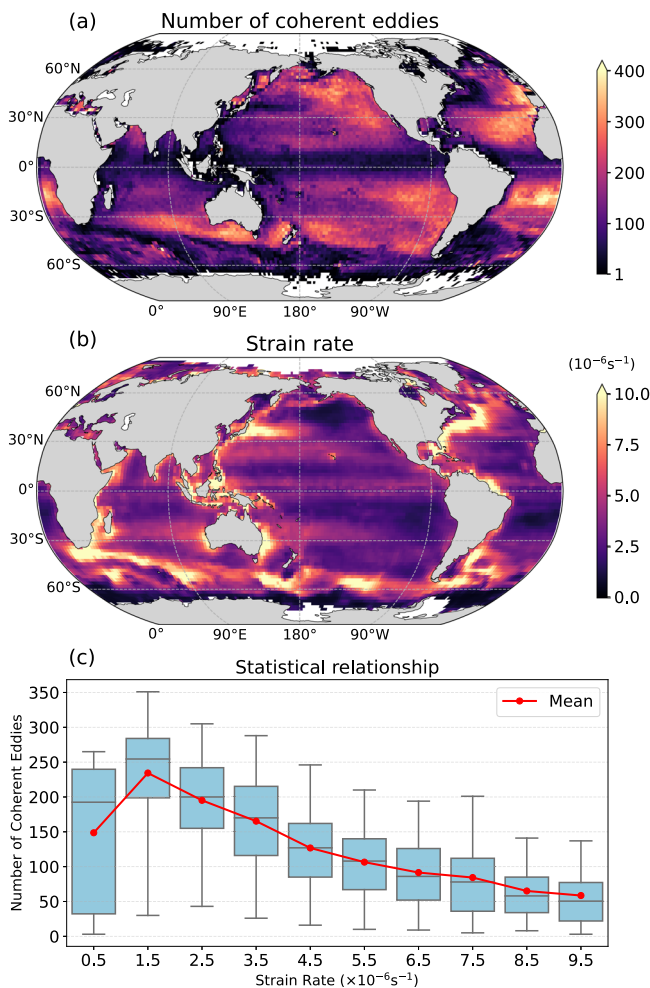


Fig. 5 | Global relationship between strain and coherent eddy occurrence. **a** Number of coherent eddies in $2^\circ \times 2^\circ$ grids based on global Lagrangian eddy dataset; **b** climatological geostrophic strain rate (in s^{-1}); **c** statistical relationship between strain rate and eddy counts. Within each strain rate bin, the box represents the interquartile range between the 25th and 75th percentiles, while the horizontal black line indicates the median. Whiskers extend to the 5th and 95th percentiles. The red line denotes the bin-averaged mean. This figure was generated using Python 3.10.

Table 1 | Experiment designation

ID	Description	Objective
EX1	An anticyclonic eddy	Control run
EX2	An anticyclonic eddy and a cyclonic eddy	Increase the complexity of the background flow field
EX3	An anticyclonic eddy and a stronger cyclonic eddy	
EX4	An anticyclonic eddy in a random eddying field	
EX5-EX13	Repeat EX4 nine times	
EX14	An anticyclonic eddy in a weak random eddying field	Modify the relative intensity of eddies and the background flow field
EX15	An anticyclonic eddy in a strong random eddying field	

weak background field. Conversely, in EX15, A is increased to 2.5°C to simulate a weak eddy under the influence of a strong background field. All numerical experiments are integrated for a total duration of 180 days, and the model attains steady conditions after roughly 30 days (Supplementary Fig. 2).

Both Lagrangian particles and a passive tracer are employed in the model. The Lagrangian particles with a resolution of $1/20^{\circ} \times 1/20^{\circ}$ are released at the sea surface and at a depth of 200 m, and integrated online with the MITgcm velocity field using a fourth-order Runge–Kutta scheme. These particles can move horizontally and vertically. The passive tracer is initialized with normalized values (ranging from 1 to 2) derived from the initial longitude. The 200 m level is chosen as a representative subsurface layer of the modeled eddy, allowing us to compare the trapping efficiency near the surface and in the subsurface eddy interior.

Data availability

The altimeter data is available at <https://data.marine.copernicus.eu/products>. The surface drifter data is available at <https://www.aoml.noaa.gov/phod/gdp/>. The global mesoscale eddy trajectory atlas (META3.1exp) is available at <https://www.aviso.altimetry.fr/en/data/data-access.html>. The global Lagrangian eddy dataset is available at <https://zenodo.org/records/7349753>.

Code availability

The code used in this study is available on Zenodo at <https://doi.org/10.5281/zenodo.22249459>.

Received: 1 June 2026; Accepted: 7 September 2026;

Published online: 19 September 2026

References

- Chelton, D. B., Schlax, M. G. & Samelson, R. M. Global observations of nonlinear mesoscale eddies. *Prog. Oceanogr.* **91**, 167–216 (2011).
- Jayne, S. R. & Marotzke, J. The oceanic eddy heat transport. *J. Phys. Oceanogr.* **32**, 3328–3345 (2002).
- Wunsch, C. & Ferrari, R. Vertical mixing, energy, and the general circulation of the oceans. *Annu. Rev. Fluid Mech.* **36**, 281–314 (2004).
- Frenger, I., Münnich, M., Gruber, N. & Knutti, R. Southern Ocean eddy phenomenology. *J. Geophys. Res.* **120**, 7413–7449 (2015).
- He, Q. et al. A new assessment of mesoscale eddies in the South China Sea: surface features, three-dimensional structures, and thermohaline transports. *J. Geophys. Res.* **123**, 4906–4929 (2018).
- Zhang, Z. W. et al. Submesoscale inverse energy cascade enhances Southern Ocean eddy heat transport. *Nat. Commun.* **14**, 1335 (2023).
- Volkov, D. L., Lee, T. & Fu, L. L. Eddy-induced meridional heat transport in the ocean. *Geophys. Res. Lett.* **35**, L20601 (2008).
- Dong, C., McWilliams, J. C., Liu, Y. & Chen, D. Global heat and salt transports by eddy movement. *Nat. Commun.* **5**, 3294 (2014).
- Liu, T., Ou, H. W., Liu, X. & Chen, D. On the role of eddy mixing in the subtropical ocean circulation. *Front. Mar. Sci.* **9**, 832992 (2022).
- Busecke, J. J. & Abernathey, R. P. Ocean mesoscale mixing linked to climate variability. *Sci. Adv.* **5**, eaav5014 (2019).
- Hausmann, U. & Czaja, A. The observed signature of mesoscale eddies in sea surface temperature and the associated heat transport. *Deep Sea Res. Part I* **70**, 60–72 (2012).
- Kamenkovich, I., Berloff, P., Haigh, M., Sun, L. & Lu, Y. Complexity of mesoscale eddy diffusivity in the ocean. *Geophys. Res. Lett.* **48**, e2020GL091719 (2021).
- Zhang, Z. G., Wang, W. & Qiu, B. Oceanic mass transport by mesoscale eddies. *Science* **345**, 322–324 (2014).
- Abernathey, R. & Haller, G. Transport by Lagrangian vortices in the eastern Pacific. *J. Phys. Oceanogr.* **48**, 667–685 (2018).
- Haller, G. Lagrangian coherent structures. *Annu. Rev. Fluid Mech.* **47**, 137–162 (2015).
- Liu, T. & Abernathey, R. A global Lagrangian eddy dataset based on satellite altimetry. *Earth Syst. Sci. Data* **15**, 1765–1778 (2023).
- Liu, T., Abernathey, R., Sinha, A. & Chen, D. Quantifying Eulerian eddy leakiness in an idealized model. *J. Geophys. Res.* **124**, 8869–8886 (2019).
- Denes, M. C., Froyland, G. & Keating, S. R. Persistence and material coherence of a mesoscale ocean eddy. *Phys. Rev. Fluids* **7**, 034501 (2022).
- Lin, Y. & Wang, G. Divergent leakage features of anticyclonic and cyclonic mesoscale eddies. *Geophys. Res. Lett.* **52**, e2024GL113486 (2025).
- Xia, Q., Li, G. & Dong, C. Global oceanic mass transport by coherent eddies. *J. Phys. Oceanogr.* **52**, 1111–1132 (2022).
- Beron-Vera, F. J., Wang, Y., Olascoaga, M. J., Goni, G. J. & Haller, G. Objective detection of oceanic eddies and the Agulhas leakage. *J. Phys. Oceanogr.* **43**, 1426–1438 (2013).
- Cetina-Heredia, P., Roughan, M., van Sebille, E., Keating, S. & Brassington, G. B. Retention and leakage of water by mesoscale eddies in the East Australian Current system. *J. Geophys. Res.* **124**, 2485–2500 (2019).
- Haller, G., Hadjighasem, A., Farazmand, M. & Huhn, F. Defining coherent vortices objectively from the vorticity. *J. Fluid Mech.* **795**, 136–173 (2016).
- Laxenaire, R., Speich, S. & Stegner, A. Evolution of the thermohaline structure of one Agulhas ring reconstructed from satellite altimetry and Argo floats. *J. Geophys. Res.* **124**, 8969–9003 (2019).
- De Marez, C., Meunier, T., Morvan, M., L'hégaret, P. & Carton, X. Study of the stability of a large realistic cyclonic eddy. *Ocean Model.* **146**, 101540 (2020).
- McCoy, D., Bianchi, D. & Stewart, A. L. Global observations of submesoscale coherent vortices in the ocean. *Prog. Oceanogr.* **189**, 102452 (2020).
- Barabinot, Y., Speich, S. & Carton, X. Defining mesoscale eddies boundaries from in-situ data and a theoretical framework. *J. Geophys. Res.* **129**, e2023JC020422 (2024).
- Barabinot, Y., Speich, S. & Carton, X. Assessing the thermohaline coherence of mesoscale eddies as described from in situ data. *Ocean Sci.* **21**, 151–179 (2025).
- Pegliasco, C. et al. META3.1exp: A new global mesoscale eddy trajectory atlas derived from altimetry. *Earth Syst. Sci. Data* **14**, 1087–1107 (2022).
- Liu, T., He, Y., Zhai, X. & Liu, X. Diagnostics of coherent eddy transport in the South China Sea based on satellite observations. *Remote Sens.* **14**, 1690 (2022).
- Early, J. J., Samelson, R. M. & Chelton, D. B. The evolution and propagation of quasigeostrophic ocean eddies. *J. Phys. Oceanogr.* **41**, 1535–1555 (2011).
- Légaras, B. & Dritschel, D. G. Vortex stripping and the generation of high vorticity gradients in two-dimensional flows. *Appl. Sci. Res.* **51**, 445–455 (1993).
- Mariotti, A., Légaras, B. & Dritschel, D. G. Vortex stripping and the erosion of coherent structures in two-dimensional flows. *Phys. Fluids* **6**, 3954–3962 (1994).
- Ni, Q., Zhai, X., Wang, G. & Marshall, D. P. Random movement of mesoscale eddies in the global ocean. *J. Phys. Oceanogr.* **50**, 2341–2357 (2020).
- Tarshish, N. et al. Identifying Lagrangian coherent vortices in a mesoscale ocean model. *Ocean Model.* **130**, 15–28 (2018).
- Molemaker, M. J., McWilliams, J. C. & Yavneh, I. Baroclinic instability and loss of balance. *J. Phys. Oceanogr.* **35**, 1505–1517 (2005).
- Zhang, Z. G. & Qiu, B. Evolution of submesoscale ageostrophic motions through the life cycle of oceanic mesoscale eddies. *Geophys. Res. Lett.* **45**, 11–847 (2018).

38. Qiu, C., Yang, Z., Wang, D., Feng, M. & Su, J. The enhancement of submesoscale ageostrophic motion on the mesoscale eddies in the South China Sea. *J. Geophys. Res.* **127**, e2022JC018736 (2022).
39. Sinha, A., Balwada, D., Tarshish, N. & Abernathy, R. Modulation of lateral transport by submesoscale flows and inertia-gravity waves. *J. Adv. Model. Earth Syst.* **11**, 1039–1065 (2019).
40. Liu, R., Wang, G. & Balwada, D. The multi-scale response of the eddy kinetic energy and transport to strengthened westerlies in an idealized Antarctic circumpolar current. *Geophys. Res. Lett.* **51**, e2023GL106747 (2024).
41. Gaube, P., Chelton, D. B., Samelson, R. M., Schlax, M. G. & O'Neill, L. W. Satellite observations of mesoscale eddy-induced Ekman pumping. *J. Phys. Oceanogr.* **45**, 104–132 (2015).
42. McWilliams, J. C. Submesoscale currents in the ocean. *Proc. R. Soc. A* **472**, 20160117 (2016).
43. Beron-Vera, F. J., Hadjighasem, A., Xia, Q., Olascoaga, M. J. & Haller, G. Coherent Lagrangian swirls among submesoscale motions. *Proc. Natl. Acad. Sci. USA* **116**, 18251–18256 (2019).
44. Laxenaire, R., Speich, S. & Stegner, A. Agulhas ring heat content and transport in the South Atlantic estimated by combining satellite altimetry and Argo profiling floats data. *J. Geophys. Res.* **125**, e2019JC015511 (2020).
45. Zhang, Z., Zhang, Y., Wang, W. & Huang, R. X. Universal structure of mesoscale eddies in the ocean. *Geophys. Res. Lett.* **40**, 3677–3681 (2013).
46. Barabinot, Y., Speich, S. & Carton, X. Insights into mesoscale eddy dynamics: a three-dimensional perspective on potential density anomalies. *Ocean Sci.* **21**, 2527–2553 (2025).
47. Yuan, Q., Zhang, Z., Liu, T., Zhao, W. & Tian, J. Stirring by mesoscale eddies dominates meridional eddy heat transport in global ocean. *Sci. China Earth Sci.* **68**, 2904–2912 (2025).
48. Elipot, S. et al. A global surface drifter data set at hourly resolution. *J. Geophys. Res.* **121**, 2937–2966 (2016).
49. Dilmahamod, A. F. et al. SIDDIES corridor: a major east-west pathway of long-lived surface and subsurface eddies crossing the subtropical South Indian Ocean. *J. Geophys. Res.* **123**, 5406–5425 (2018).
50. Li, H., Xu, F. & Wang, G. Global mapping of mesoscale eddy vertical tilt. *J. Geophys. Res.: Oceans* **127**, e2022JC019131 (2022).
51. Yang, S. et al. The impact of the planetary β -effect on the vertical structure of a coherent vortex in the South China Sea. *Ocean Dyn.* **70**, 879–896 (2020).
52. Liu, R., Wang, G., Chapman, C. & Chen, C. The attenuation effect of jet filament on the eastward mesoscale eddy lifetime in the southern ocean. *J. Phys. Oceanogr.* **52**, 805–822 (2022).

Author contributions

T.L. and X.Z. contributed to the study's design, data processing and analysis, interpretation of the results, and writing of the paper. W.S. contributed to data processing, visualization, and revision of the paper. D.C. contributed to discussing the results and editing the paper.

Funding

This study was supported by the National Key R&D Program of China (2023YFF0805300), the Scientific Research Fund of the Second Institute of Oceanography, Ministry of Natural Resources (QNYC2401, SZ2649, XRJH2305), Zhejiang Provincial Natural Science Foundation of China (LY24D060003), the Key R&D Program of Zhejiang Province (2024C03257), the National Natural Science Foundation of China (42176009, 42106008), and the Project of State Key Laboratory of Satellite Ocean Environment Dynamics (SOEDZZ2520). The funders had no role in the study design, data collection and analysis, interpretation of the results, preparation of the paper, or the decision to submit the manuscript for publication.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41612-026-01551-0>.

Correspondence and requests for materials should be addressed to Tongya Liu.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2026

This Article in Press is shared early to give you faster access to new research. It is citable and carries a permanent DOI. The final edited version will replace it automatically.