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New insights on mesoscale activity in the western Mediterranean Sea

Laura Gómez-Navarro[1], Maxime Ballarotta[2], Diego Cortés-Morales[1], Marie-Isabelle Pujol[2], Laura Fortunato[3], Baptiste Mourre[1], Ananda Pascual[1]

[1] IMEDEA (UIB-CSIC), Esporles, 07190, Spain
[3] CLS, Ramonville-Saint-Agne, 31520, France
[3] Università degli studi di Napoli Parthenope, Dipartimento di Scienze e tecnologie, 80143, Naples, Italy

Correspondence to: Laura Gómez-Navarro (laura.gomez@uib.es)

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Abstract. Mesoscale ocean variability plays a crucial role in regional circulation, heat transport, and the distribution of tracers such as nutrients, biological material, and pollutants. Mesoscale eddies are key drivers of this variability, and their observation (particularly of small-scale and coastal structures) has been limited by the resolution of conventional altimetry products. The Surface Water and Ocean Topography (SWOT) mission provides unprecedented high-resolution sea surface height data, offering new opportunities to refine mesoscale observations and improve our understanding of their impact on surface ocean dynamics. In this study, we assess the potential of a new product that incorporates SWOT wide-swath data and its improvements with respect to the current Copernicus Marine Environment Monitoring Service (CMEMS) satellite sea-level-derived velocity product. We analyze the eddy field in the western Mediterranean region, important for many different socio-economic activities like tourism, maritime transport, and fisheries and aquaculture. We identify differences not only in the number of eddies, but on their characteristics: size, intensity and associated kinetic energy. This is relevant for defining optimum marine traffic routes, but also for operational activities such as marine pollution management. To evaluate this impact, we analyse the retention capacity of Algerian Eddies, which in the past have been found relevant in the transport of marine debris between the North African coast and the Balearic Islands. Our findings evaluate how well SWOT-enhanced data affects the representation of mesoscale eddies and their velocity structures, showing important implications for ocean monitoring, climate studies, and marine ecosystem management.

Table 1: Product table.

Product ref. no.	Product ID & type	Data access	Documentation
1	SEALEVEL_EUR_PHY_L4_NRT_008_060; satellite observations	EU Copernicus Marine Service Product (2025a)	Quality Information Document (QUID): Ballarotta et al. (2025a) Product User Manual (PUM): Pujol (2025a)
2	SEALEVEL_EUR_PHY_L4_MY_008_068; satellite observations	EU Copernicus Marine Service Product (2025b)	QUID: Ballarotta et al. (2025b) PUM: Pujol (2025b)
3	Gridded Sea Level Height and geostrophic velocities computed with Multiscale Interpolation; MIOST-K v2.0.1; satellite observations	AVISO (2025)	PUM: Ballarotta (2025c)

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1 Introduction

As the ocean continues to undergo rapid physical and ecological change, the ability to monitor and understand its dynamics at finer scales is increasingly critical. This study presents emerging approaches and technologies that are advancing our capacity to observe ocean processes. Among these, the enhanced detection and characterization of mesoscale features (such as eddies), represents an unprecedented leap forward, particularly in regions like the western Mediterranean Sea, where such structures strongly influence circulation, ecosystem connectivity, and pollutant dispersion (e.g. Suaria and Aliani, 2014; Cotroneo et al., 2021).

Conventional mesoscale monitoring has relied primarily on satellite altimetry products such as the Copernicus Marine Environment Monitoring Service (CMEMS), Sea Level - Thematic Assembly Centre (SL-TAC) dataset (e.g. Le Traon et al., 1998; Sánchez-Román et al., 2023). However, the launch of the Surface Water and Ocean Topography (SWOT) mission, and its Ka-band Radar Interferometer (KaRIn) instrument, has opened new observational pathways (Morrow et al., 2019; Fu et al., 2024). This study evaluates the added value of a new pre-operational Level-4 (L4) surface product (MIOST with KaRIn; Ballarotta et al., 2025c), which integrates SWOT KaRIn data during the science phase (September 2023–December 2024), by comparing it with existing CMEMS products based solely on nadir altimetry.

Using an eddy detection method, based on Mason et al., 2014, we assess differences in the eddy field across both products. We focus on key properties of eddies detected in both datasets, particularly Eddy Kinetic Energy (EKE). Centering our comparison in a case study focused on the Algerian eddies and their potential to transport floating marine debris towards high environmental interest areas such as the marine protected Cabrera National Park or areas nearby (Compa et al., 2020). In this region, mesoscale dynamics (particularly eddy transport and retention) have been identified as key facilitators of plastic pollution arriving from the southern Mediterranean coast (Compa et al., 2020). Multiple media reports have documented the arrival of remarkable quantities of marine debris to Cabrera National Park, underscoring the vulnerability of this protected area to pollution transported by regional ocean dynamics (e.g. 20minutos, 2015; Última Hora, 2015; Diario de Mallorca, 2022). As bio-physical hotspots, eddies with longer retention times may enhance exposure risks for sensitive ecosystems. This makes Algerian eddies a compelling target for evaluating the added value of high-resolution SWOT-based surface current products in tracking and forecasting marine debris transport. Therefore, we evaluate the retention rate of particles inside Algerian eddies and thus the risk of marine debris reaching the park's vicinity. Algerian eddies have been found to also be a very important dynamic structure for heat, water masses and matter transport in the basin (e.g. Taupier-Letage et al., 2003; Escudier et al., 2016). In contrast to cyclonic eddies, anticyclonic Algerian eddies last longer and are known to travel farther from their origin and play a stronger role in regional connectivity (Pessini et al., 2018; Cotroneo et al., 2021). Their ability to trap and retain floating material has important implications for both ecological impact and the dispersion of pollutants (Suaria and Aliani, 2014).

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Beyond advancing scientific knowledge, this work offers practical value for marine operational applications such as maritime transport optimization and marine spatial planning. For instance, more accurate surface current information can aid in route planning to reduce ship emissions (e.g. Wang et al., 2023), while enhanced mesoscale monitoring can support risk assessments for marine pollution in protected areas. The case of Cabrera highlights how new altimetry-driven products can directly inform conservation strategies by more accurately identifying exposure pathways to drifting pollutants.

This study aims to assess the extent to which the integration of SWOT KaRIn data into gridded altimetric products improves the characterization of surface mesoscale activity in the western Mediterranean. By comparing eddy fields derived from both legacy and SWOT-enhanced datasets, we evaluate how these differences impact the monitoring of surface circulation, with a focus on the impact on EKE and the retention capacity of eddies. The overarching objective is to determine the added value of high-resolution altimetry for support applications ranging from marine pollution mitigation to improved maritime operations.

2 Data

2.1 DUACS optimal interpolation (DUACS-OI)

The *European Seas Gridded L4 Sea Surface Height* dataset (Table 1, product reference 1 and 2) from the Copernicus Marine Service, provides daily Sea Level Anomaly (SLA) fields at 1/8° resolution over European regional seas. The product is generated by the Data Unification and Altimeter Combination System (DUACS) system (CNES/CLS) using optimal interpolation of along-track altimeter measurements from multiple satellites (Le Traon et al., 1998). It includes SLA, Absolute Dynamic Topography (ADT), and derived surface geostrophic currents. ADT is obtained by adding the Mean Dynamic Topography (MDT) to SLA. The MDT used is the Mediterranean 2020 product (MDT_CMEMS_2020_MED, Jousset et al., 2022). The dataset, is available in Near-Real-Time (NRT, product reference 1) and delayed-time (DT, product reference 2), and supports studies of mesoscale and large-scale sea level variability (e.g. Pascual et al., 2007; 2009; Marcos et al., 2015; Taburet et al., 2018; Ballarotta et al., 2019; Sánchez-Román et al., 2023). The NRT data is updated daily, and at the moment of the study had a temporal coverage from 04/10/2022 to 25/11/2024 to November 2024, while the delayed-time data from 01/01/1992 to 31/12/2023. Therefore, the DT product is only used for the analysis of the mean circulation (fig. 1), and the NRT product is used for the rest of analyses as it covers 2024.

2.2 MIOST with SWOT KaRIn (MIOST-K)

The Multiscale Inversion of Ocean Surface Topography (MIOST) product (Table 1, product reference 3) is a new-generation gridded altimetry dataset that incorporates SWOT KaRIn data, i.e., two-dimensional swath (SSHA) observations. This global product is available at a spatial resolution of 1/8° and at daily temporal frequency. We utilized the experimental L4 multimission sea level product distributed by AVISO v2.0.1, which combines SWOT swath altimetry with conventional

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nadir altimeter measurements. The dataset relies on the MIOST method (Ubelmann et al., 2021, 2022), a statistical technique that reconstructs sea surface height fields by decomposing variability across multiple spatial and temporal scales. The MDT product used is also the MDT_CMEMS_2020_MED (Jousset et al., 2022). More details can be found in Ballarotta et al., (2025c). These products were processed by SSALTO/DUACS and distributed by AVISO (https://www.aviso.altimetry.fr) supported by CNES.

The inclusion of SWOT's Ka-band Radar Interferometer (KaRIn) observations improves the resolution of SSH fields, allowing finer-scale ocean dynamics (such as mesoscale and submesoscale structures) to be resolved. This experimental product (from hereinafter MIOST-K) provides daily gridded maps of SSH and derived geostrophic velocities, offering new opportunities to study ocean surface variability at unprecedented detail. (Ballarotta et al., 2025c)

3 Methods

3.1 Py-eddy tracker

The py-eddy-tracker is an eddy tracking algorithm based on geometric and physical techniques. This eddy tracking algorithm was firstly developed by Mason et al. (2014). This was later updated by Delepoulle et al. (2022) and has been widely used to study eddies and to release updated eddy field datasets (e.g. Pegliasco et al. 2022). We identify eddies in daily snapshots of ADT fields (using version 3.6.1. (Delepoulle et al., 2022)). Two types of contours are provided: effective (outer) and speed contour (inner), and further details can be found in Mason et al. (2014). Compared to SLA, ADT provides more reliable eddy identification, especially in the Mediterranean Sea (Pegliasco et al., 2021, 2022). A pre-processing and set of parameterizations are necessary to implement the py-eddy tracker (see Mason et al., 2014; Pegliasco et al., 2022 for further details):

1) The ADT fields are filtered with a Bessel high-pass filter of 500 km to remove the background large-scale signal and isolate the eddies (Pegliasco et al., 2022).
2) A 0.002 m step between two isolines of detection. This refers to the height between two layers, used to identify the eddy contours in which starting from the eddy center (minimum value for cyclonic and maximum for anticyclonic eddies), the closed isolines (of ADT in our case) are identified outward in steps of 0.002 m till the eddy edge is reached (Cui et al., 2025).
3) A maximum shape error of 55%, which is defined as the ratio between the circle fit and identified outermost contour. This shape error (Kurian et al., 2011) is to limit the identification to eddies, and remove other elongated closed-contour structures like filament (Mason et al., 2019).

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3.2 Particle simulations and eddy retention calculation

We calculate the eddy particle retention to quantify the impact of the different eddy characteristics. For this analysis, Lagrangian simulations are performed using the OceanParcels Lagrangian framework v2.4.2 (Delandmeter and van Sebille, 2019) to simulate 2D trajectories of virtual particles at the sea surface. Particles are advected using the velocity fields of the two datasets (DUACS-OI and MIOST-K). A fourth order Runge-Kutta particle advection scheme is used with a run-time time-step (dt) of 25 minutes. We consider infinitesimal, passive and buoyant particles influenced only by advection. Simulations are performed with particles released within a 2 by 2˚ box around identified Algerian eddies' contours separated by 1/30˚ (~3.5 km) with an advection time (T) of 20 days. This timescale represents a trade-off between the minimum lifetime of the Algerian eddies (~60 days) and the requirement that enough particles remain within the eddy core during the simulation. Particles which leave the domain are removed from the analysis. Here we showcase the impact on the retention capacity by selecting 3 Algerian eddies as representative examples. Further details are shown in Table B1.

Next, the eddy retention is calculated as the relative difference in the number of particles enclosed by the eddy contour between the release day and 20 days later. The Eddy Retention Percentage (ERP) is then calculated as:

$$ERP = \frac{N_T - N_0}{N_0} x\, 100 \,, \quad (1)$$

where N_T and N_0 are the number of particles at the final and the release days, respectively.

3 Results

The general circulation of the western Mediterranean has been thoroughly studied in the past. The new SWOT data is unveiling smaller oceanic scales and partially or even unobserved dynamics, but the impact of this on the general circulation patterns will be better understood when we have more years of SWOT data. Currently, with the nearly 1.5 years of SWOT data during the science phase, we can already infer a first estimate how and if these general circulation patterns are affected by this new dataset, and thus the consequences this could have for different monitoring efforts (Fig. 1). The main circulation features shown in Fig. 1A are also observed in the other 2 panels, showing that these are represented in both datasets. We can observe that between Figs. 1B and C, differences arise on the smaller scale features, and in the characteristics of the mesoscale structures, already giving us a first insight that at the mesoscale the circulation will be impacted by the inclusion of the new SWOT observations.

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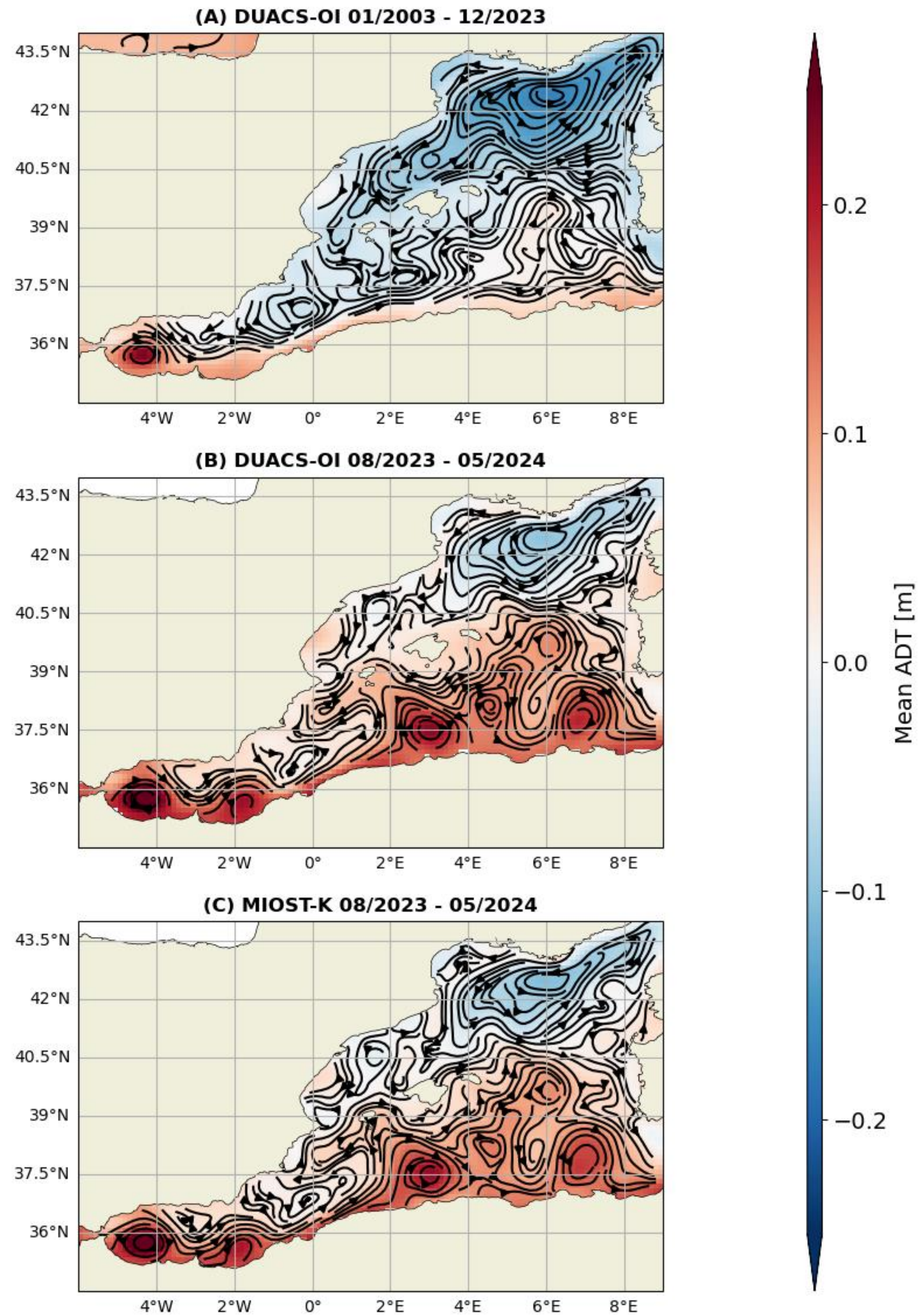

Figure 1: General circulation represented by the mean Absolute Dynamic Topography (ADT) and the mean velocity field (streamlines) calculated from the different altimetric products: (A) 20 years mean from DUACS-MY (product reference 2), (B) 17 months mean of DUACS-NRT (product reference 1), and (C) 17 months mean of MIOST-K (product reference 3).

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We obtain the daily fields of eddy identifications for both datasets from August 2023 to June 2024, and we calculate the total number of cyclonic (blue) and anticyclonic (red) eddies. An example of all the eddies identified daily during April 2024 is shown in panels (A) and (B) in Fig. 2. The daily variability of the eddy number for anticyclones and cyclones is shown in panels C and D in Fig. 2. Although there is high temporal variability in the eddy number, in general we observe a greater number of eddies with the MIOST-K than the DUACS-OI product. This is particularly noticeable in coastal areas, such as off the western coast of Corsica (Fig. 2A and B). Complementary observations such as satellite chlorophyll data, show the presence of coastal eddies in this region (Fig. A1, Fortunato et al., 2025). Moreover, the DUACS-OI product seems to merge multiple cyclonic eddies into one, affecting notably the mesoscale field in areas such as the Gulf of Lions. Therefore, throughout most of the analysis period we can observe an increase in the number of daily identified eddies with MIOST-K.

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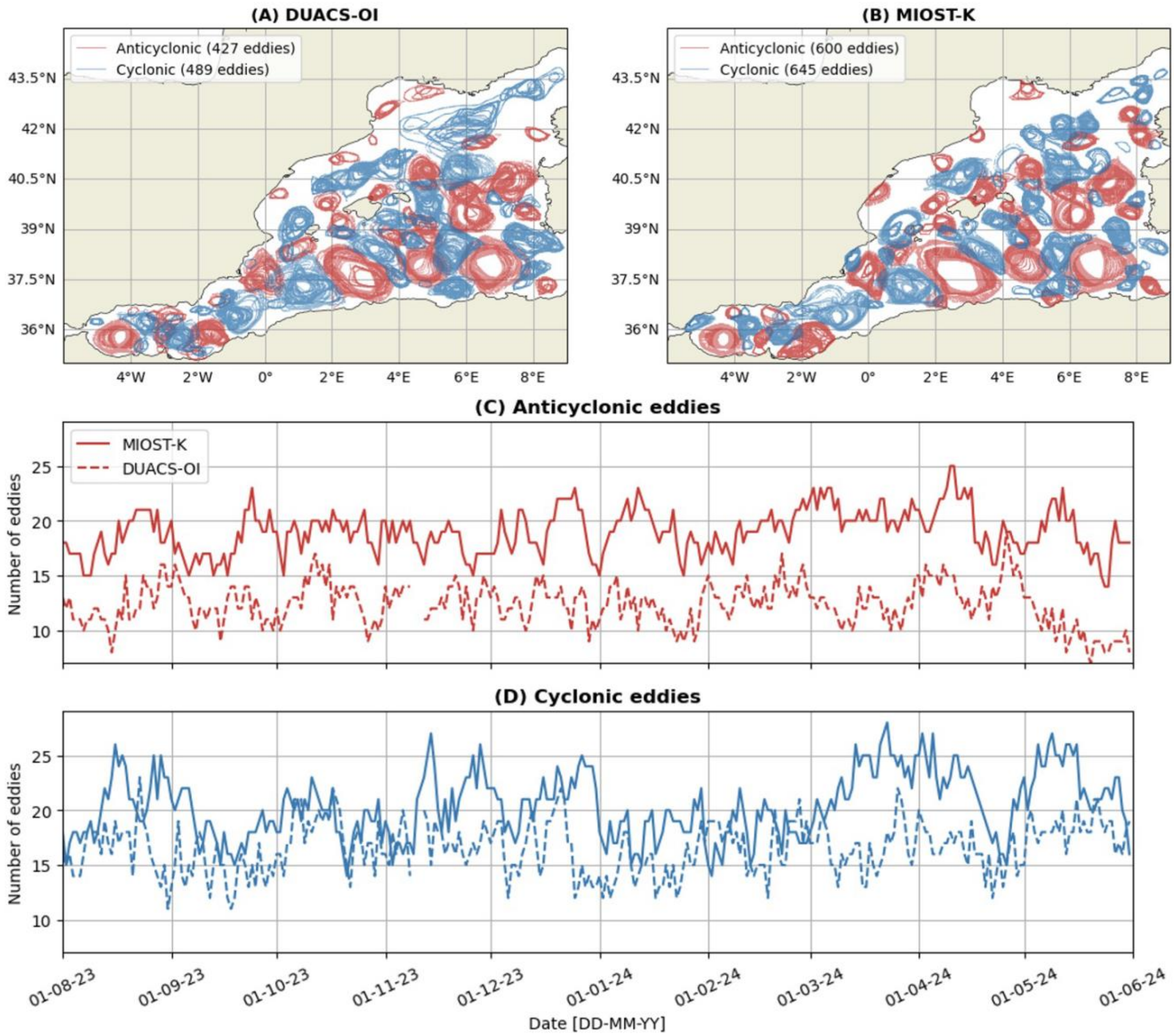

Figure 2: Number of daily eddy identifications. Panels (A) and (B) show all the daily eddies (outer contours) identified during April 2024 for DUACS-OI (product reference 1) and MIOST-K (product reference 3), respectively. Panels (C) and (D) show the temporal variability of the anticyclones and cyclones, respectively, identified throughout the study period.

With the inclusion of the SWOT data, we also observe changes in the already observed big mesoscale eddies of the DUACS-OI product. An important change is in the EKE associated with these eddies. Firstly, the EKE field is retrieved (Delepoulle et al., 2022) for each daily field (Figs. 3a and 3c). Then we find the eddies that match for both datasets and calculate the mean EKE associated to these eddies (Figs. 3b and 3d). Fig 3e shows the temporal variability of the daily mean EKE of all the matching eddies identified. MIOST-K shows a higher mean EKE throughout the majority of the study's time period. On

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93% of the days, the daily mean EKE in MIOST-K is higher than in DUACS-OI (we also checked the differences in the maximum daily EKE, and these are higher 95% of the time). This may be due to enhanced signal capture by the altimetric constellation, made possible by SWOT's wide-swath. This has important implications for KE trend studies (e.g. Martínez-Moreno et al., 2019; Barcelo-Llull et al., 2025), which in turn also can mean a challenge for current climate model projections (Barcelo-Llull et al., 2025). For example, Hogg et al. (2015) mention the significant impact EKE trend variations have on the ocean's carbon and heat sinks in regions like the Southern Ocean, and the consequent global climatic implications.

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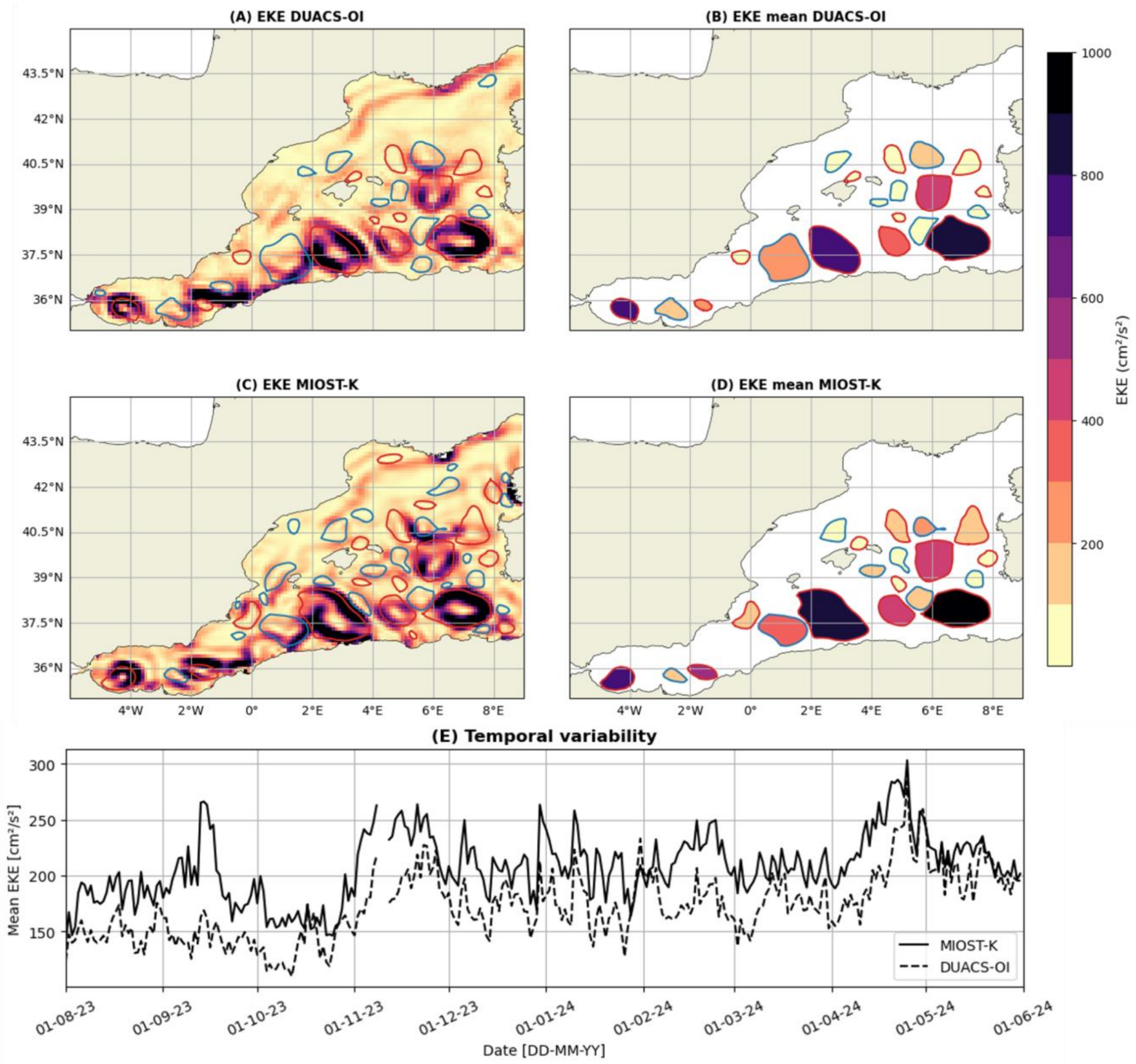

Figure 3: Temporal variability of the mean Eddy Kinetic Energy (EKE) associated with the detected eddies. Panels (A) and (C) show the EKE field on 20/04/2024 and all the identified (outer eddy contours) anticyclones (red) and cyclones (blue) for DUACS-OI (product reference 1) and MIOST-K (product reference 3), respectively. Panels (B) and (D) show the associated mean EKE of only the eddies identified on both datasets. (E) shows the mean EKE temporal variability for DUACS-OI (dashed) and MIOST-K (solid).

Figure 4 illustrates three examples of Algerian Eddies, and their retention capacity. We observe that after 20 days, they have retained different percentages of particles. In Eddy 1, the DUACS-OI eddy shows leakage, while the MIOST-K eddy retains

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and even increases the number of particles inside. In Eddy 2, both retain more particles, with slightly higher retention in MIOST-K. In Eddy 3, DUACS-OI retains more particles, while MIOST-K shows high leakage. This demonstrates an important impact of the differences in eddy properties observed so far with operational datasets such as DUACS-OI and the new dataset, MIOST-K. Despite only subtle qualitative differences in eddy contours (Fig. 2), the particle retention over just 20 days shows a high variability.

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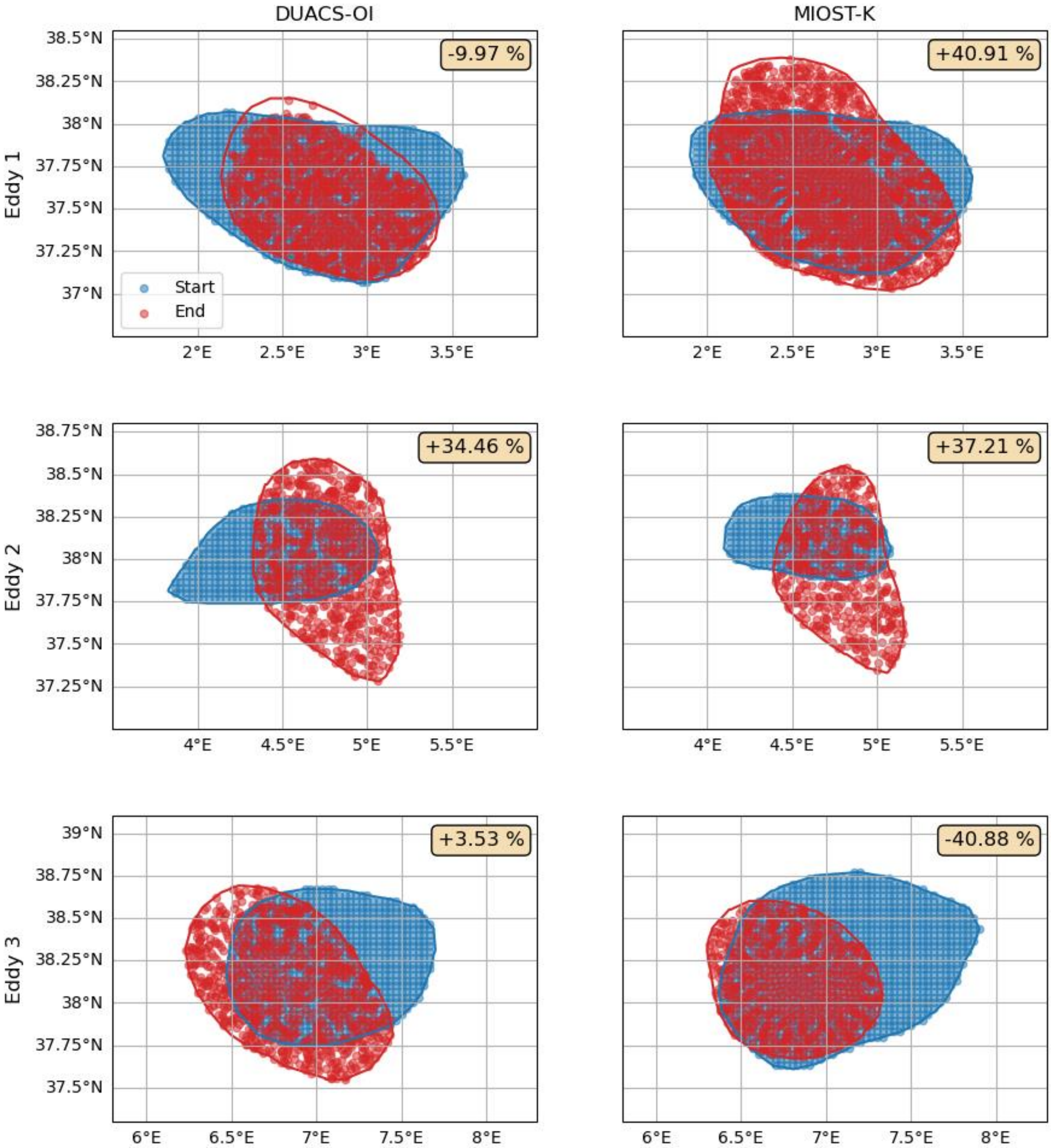

210 **Figure 4: Eddy retention capacity of three Algerian Eddies examples for DUACS-OI (left panels, product reference 1) and MIOST-K (right panels, product reference 3). Blue (red) particles and contours (inner eddy contours) correspond to the initial (final) dates (see Table B1). Only particles inside the eddy contours are shown. The top right box indicates the eddy retention percentage, with positive (negative) values indicating retention (leakage).**

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4 Discussion

In this study, we highlight the value of incorporating wide-swath altimetric observations for advancing the representation of mesoscale ocean dynamics. A key dynamic property of mesoscale eddies is their associated EKE. Results indicate a notable increase in signal strength, with MIOST-K capturing regional means of daily EKE up to 1.8 times greater than DUACS-OI. This result is important due to its link with the understanding of atmosphere-ocean interactions, especially in the current climate change scenario. Better monitoring these structures, not only their occurrence, but their characteristics, is key for related monitoring studies of for example sea surface temperature, and marine operational activities such as forecasts of extreme events and marine fisheries management.

We also observe clear changes in the retention capacity of Algerian eddies with MIOST-K over a 20-day period. This result has important consequences for marine pollution management strategies, namely those that can affect marine protected areas like the Cabrera National Park. This also influences the transport properties of these eddies related to the redistribution of temperature, salinity and nutrients, which influence the circulation of the area, and the nutrient inputs in other regions of the western Mediterranean Sea.

The eddy identification algorithm used to identify eddies is quite sensitive to pre-processing choices and parameterizations (e.g. Pegliasco et al., 2021), and could be refined in follow-up studies. Here it is used to compare 2 datasets, so the impact on the conclusions obtained should be minimal. The Eulerian method used here is commonly implemented in the community, namely in altimetry. Many other eddy identification and tracking techniques exist which use an Eulerian framework (e.g. Ioannou et al., 2024), but also Lagrangian ones, which could help to better capture retention capabilities, as Lagrangian structures could assess material coherence in space and time simultaneously (Cortes-Morales et al., in prep.). To further validate the robustness of our retention findings, future work could extend the Lagrangian analysis to a larger ensemble of eddies. Statistical comparison across datasets would help quantify whether observed differences are consistent and significant, and whether eddy properties such as size or eccentricity correlate with retention efficiency. This would also support the operational use of eddy-based transport estimates in pollution risk forecasting and coastal marine management. Lastly, we take advantage of a very novel dataset (MIOST-K), but it is under continuous improvement due to the young age of SWOT. It will be interesting to continue this study with a longer series of data to further evaluate these mesoscale eddies in the Mediterranean region and look further into the improvement of the coastal eddy field in the region (Fortunato et al., 2025).

It is worth mentioning that, by design, conventional interpolation methods tend to filter out small-scale features detected by SWOT, leading to an underrepresentation of fine-scale eddies (typically around 50 km in diameter, or <100 km in wavelength) in Level-4 products such as DUACS and MIOST. Moreover, SWOT captures a broader range of high-resolution

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ocean dynamics, including nonlinear eddies and internal waves, that are beyond the reach of nadir altimeters and not resolved by current mapping techniques. A key limitation lies in the coarse temporal sampling imposed by the 21-day repeat cycle of the science phase, which hinders the analysis of rapidly evolving fine-scale dynamics (Archer et al., 2025). To fully exploit SWOT's potential, especially at submesoscales, new frameworks are needed. Promising advances in this direction are emerging from data- and model-driven mapping approaches (e.g., Fablet et al., 2021; Le Guillou et al., 2023, 2024) and in the development of robust validation strategies tailored to SWOT observations (Coadou-Chaventon et al, 2025; Verger-Miralles et al, 2025).

5 Conclusions

This study provides new insights on how the monitoring capabilities of surface circulation, namely mesoscale activity will improve with the new SWOT wide-swath satellite, and its relevance for improving operational oceanography services, for example in managing and forecasting marine pollution events. The objective is to assess changes in the mesoscale eddy field by quantifying eddy count, variability, and associated kinetic energy. We then examine how the detected eddy properties affect their retention capacity. While this study does not aim to compare the datasets, it does show how the surface currents monitoring scenario might change in the near future, opening the door to a better representation of the different processes involved and its implications.

The results show the promising potential of new wide-swath products to better understand the eddy field, achieving specific capacities, particularly for observing small mesoscale eddies and resolving features in coastal areas. We also find that the already observed mesoscale eddy field by conventional products (DUACS-OI) has notable differences when compared to new products including SWOT (MIOST-K). An increase in Eddy Kinetic Energy (EKE) is found, which plays a vital role in the Mediterranean Sea by driving the variability of ocean circulation, redistributing heat, salt, and nutrients, and supporting marine productivity in this climatically sensitive region. Mesoscale eddies, which contribute to EKE, influence biological hotspots, the dispersion of pollutants, and local weather patterns such as marine heatwaves and Mediterranean cyclones. Monitoring EKE is therefore essential for improving ocean forecasting, managing fisheries, and understanding the impacts of climate change. This requires high-resolution observations from satellites, autonomous platforms, and regional cooperation to effectively track these dynamic processes and inform environmental management and policy. With this new dataset, the gap of high-resolution satellite data is further filled. The retention capacity of the eddies is strongly affected with this new data, meaning that once this data is incorporated into the operational products, a better estimation of marine pollution impacts will be possible. This will be of importance for different marine management strategies, especially those related to marine pollution and fisheries management.

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Our findings demonstrate that incorporating SWOT wide-swath observations affects the representation of surface mesoscale features in the western Mediterranean, including in regions where conventional altimetry has limitations. By comparing eddy characteristics such as associated EKE and retention capacity, we show how these improvements can directly support marine applications such as pollution risk assessment for the protection of marine reserves. Looking ahead, the integration of next-generation satellite technologies and data-processing methodologies will be essential to further refine surface current products. This work contributes to a framework for ongoing monitoring and evaluation of regional circulation patterns, and underscores the importance of sustained innovation in ocean observing systems.

Appendices

Appendix A

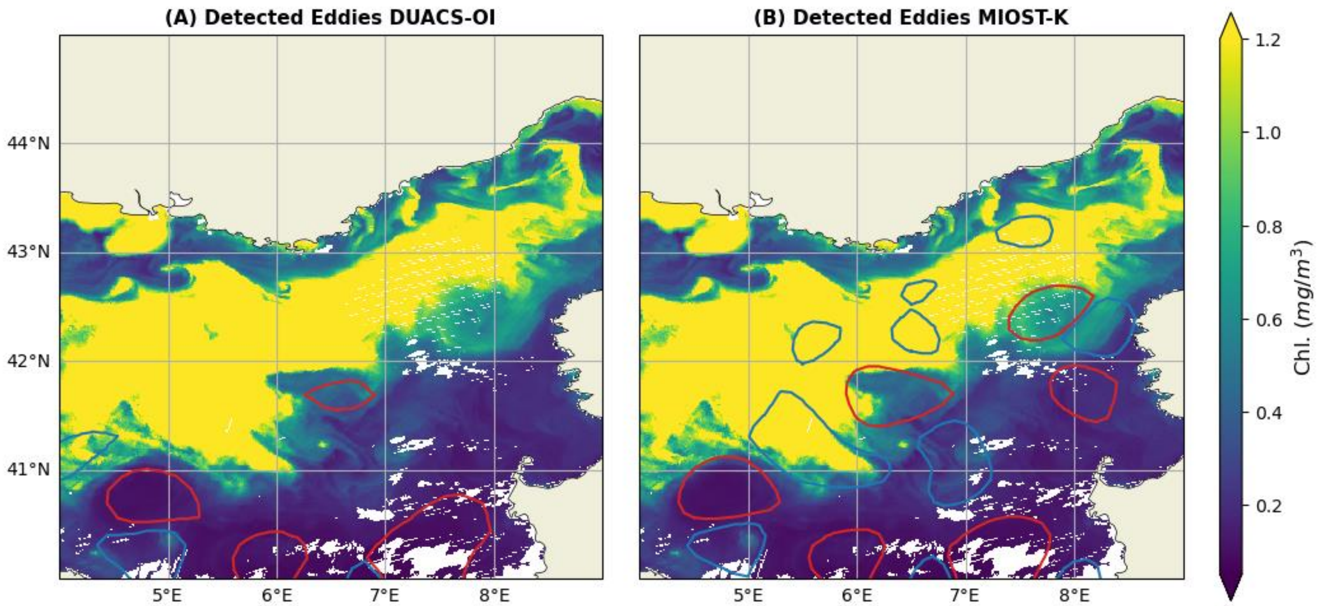

Figure A1: Chlorophyll fields (Chl.) on 02/04/24 with the corresponding eddy effective contours (anticyclonic red, cyclonic blue) for DUACS-OI (left) and MIOST-K (right).

Appendix B

Table B1. Eddy retention information.

	Date		Number of particles (DUACS-OI; **MIOST-K**)	
	Initial	End	Initial	End
Eddy 1	01/04/2024	21/04/2024	1123; **1078**	1011; **1519**

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Eddy 2	01/02/2024	21/02/2024	502; **344**	675; **472**
Eddy 3	01/02/2024	21/02/2024	821; **1140**	850; **674**

Code availability

The codes used in this study are available on GitHub: https://github.com/LauraGomezNavarro/paper-OSR10_Gomez-Navarro_etal_2026, and the version used for the manuscript is published on Zenodo: https://doi.org/10.5281/zenodo.16940147 (Gomez-Navarro_2025).

Data availability

The data used in this study can be downloaded directly from the Copernicus Marine Service and the AVISO websites. The exact product names are given in Table 1, and the associated DOIs are indicated in the references.

Author contribution

LGN, AP, MIP, MB, DCM, and LF contributed to the conceptualization of the study. LGN carried out the formal analysis, investigation, and prepared the original draft of the manuscript. DCM, AP, and LGN developed the methodology. MIP and MB curated the data. All authors contributed to the review and editing of the manuscript.

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