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Seasonality of surface turbulence in the Mediterranean Sea observed from space

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Abstract

The Mediterranean Sea is a climate change hotspot, experiencing warming rates faster than the global average. However, its surface fine-scale dynamics remain largely unexplored, despite robust evidence that oceanic fine scales play a key role in regulating the oceanic energy cycle, material transport, and air–sea exchanges, with direct implications for climate. Here, we use the Surface Water and Ocean Topography (SWOT) mission resolving sea surface height at kilometer scales, enabling the observation of surface submesoscale dynamics previously inaccessible to conventional altimetry. Using two years (from August 2023 to November 2025) of SWOT L3 swath sea surface height data, we show for the first time that surface dynamics in the Mediterranean Sea exhibit a clear seasonal cycle. SWOT reveals eddy kinetic energy levels 1.8 times higher than those previously obtained by conventional gridded altimetry products. The basin-mean eddy kinetic energy increases by 50% from summer minima to winter maxima while standard altimetry product do not exhibit this seasonal variability. Strain and relative vorticity distributions likewise display a clear seasonal cycle, in agreement with the seasonal variability of eddy kinetic energy. These results demonstrate that submesoscales fundamentally revise the observed energy and seasonality of Mediterranean surface dynamics with an impact on climate.

Keywords: Submesoscale, SWOT, Seasonal, Skewness

1 Introduction

Since the launch of TOPEX Poseidon mission in 1992, satellite altimetry has revolutionized our understanding of meso to large-scale ocean surface dynamics. Global gridded sea surface height maps from the Data Unification and Altimeter Combination System (DUACS), which combine observations from multiple nadir-looking altimeters, have been instrumental in monitoring and quantifying ocean circulation, as well as in studying the behavior and interactions of mesoscale eddies at the global scale (Pascual et al. (2006); Chaigneau et al. (2009); Chelton et al. (2011); Ioannou et al. (2024)). However, the spacing between the ground tracks provides a spatial resolution in current two-dimensional sea surface height maps only on the order of 150-200 km (Chelton et al. (2011); Ballarotta et al. (2019)). This resolution is insufficient to accurately capture mesoscale features, which account for most of the eddy kinetic energy, and submesoscale features with wavelengths ranging from a few kilometers to the baroclinic Rossby radius of deformation (Ferrari and Wunsch (2009)). Thus, the currently available along-track satellite altimetry data are considered to have reached their limits (e.g Lawrence and Callies (2022)).

The launch of the Surface Water and Ocean Topography (SWOT) satellite on 16 December 2022 by the National Aeronautics and Space Administration (NASA) and the Centre National D'Etudes Spatiales (CNES) marked a major advance in remote sensing capabilities by providing a two-dimensional view of sea surface height across a 120-km wide swath at a resolution of 2 km (Morrow et al. (2019)). SWOT is designed to resolve features at spatial scales 10 times smaller and with an accuracy an order of magnitude greater than conventional Jason-class altimeters (Chelton et al. (2019)). Since becoming operational, SWOT has enabled the detection of submesoscale eddies that could not previously be observed from space (Zhang et al. (2024); Verger-Miralles et al. (2025)). It can resolve sharper fronts than conventional altimetry products (Coadou-Chaventon et al. (2025)) and detect oceanic processes at scales below 100 km (Zhang and Callies (2025); Wang et al. (2025); Fortunato et al. (2025); Kachelein et al. (2025)). New estimates of vertical velocities at the ocean surface have been proposed (Carli et al. (2024, 2025)), and submesoscale ocean–atmosphere interactions have been analyzed, confirming the influence of the ocean on the atmosphere down to a few kilometers (Kaouah et al. (2025)). We now have sufficient data available to analyze seasonal variations in submesoscale dynamics locally (e.g. Qiu and Chen (2025)).

Here, we focus on the Mediterranean Sea, a hot spot for climate change (Giorgi (2006); Giorgi and Lionello (2008); Tuel and Eltahir (2020); Cos et al. (2022)). Indeed, the Mediterranean region is experiencing atmospheric warming that exceeds the global average (Tuel and Eltahir (2020); Lazoglou et al. (2024); Cusack and Cox (2025)), along with increasing temperature extremes and marine heatwaves (Marullo et al. (2023); Pastor et al. (2024); Napolitano et al. (2025)). Its mesoscale dynamics is well-known with an eddy kinetic energy mean level between 30 cm^2s^{-2} and 80 cm^2s^{-2} on average over the entire Basin, determined either by conventional altimetric products (Pujol and Larnicol (2005); Jordi and Wang (2009); Pascual et al. (2007)) or numerical models (Jordi and Wang (2009); Sorgente et al. (2011)), with regions where that mean can exceed 200 cm^2s^{-2} such as in the Strait of Gibraltar, the Algerian basin or in the Levantine basin (Pujol and Larnicol (2005); Menna et al. (2012)). However,

these studies are restricted to mesoscale temporal variability, as they rely primarily on conventional altimetry. The use of high-resolution numerical simulations is limited to local studies (e.g. Sorgente et al. (2011); Mourre et al. (2018)), which does not allow for a comprehensive picture of the entire basin. Thus, the seasonal variability of surface dynamics in the Mediterranean Sea remains poorly (if ever) studied, as does the effect of the submesoscale on this variability.

The objective of this study is to investigate the submesoscale variability associated with the Mediterranean Sea using nearly available sea surface height data from the SWOT Ka-band Radar Interferometer (KaRIn) measurements, covering the period from August 2023 to November 2025 (called the Science phase). Specifically, we examine (1) the spatial distribution of eddy kinetic energy in the Mediterranean Sea and its seasonal modulation, (2) the strain and relative vorticity distribution and their seasonal evolution, (3) the seasonal evolution of the sea surface height spectra. Despite the seasonality in submesoscale turbulence is well-known in the Atlantic Ocean or in the Pacific ocean (Mensa et al. (2013); Callies et al. (2015); Rocha et al. (2016); Sasaki et al. (2017); Dong et al. (2020)), we still lack some quantification in the Mediterranean Sea although ocean submesoscales are a key component of basin heat budget impacting climate Su et al. (2018).

Here, we show that the seasonality of the submesoscale turbulence does exist in the Mediterranean Sea and can be observed from space using the newly released SWOT L3 expert products (version 3, hereafter SWOT L3 v3). We show that resolving submesoscales considerably increase the level of eddy kinetic energy compared to previous studies and that its seasonal cycle is much more pronounced than previously demonstrated. Submesoscales also enhance the seasonality of traditional surface dynamics metrics such as strain and relative vorticity. The seasonality of those metrics was previously difficult to observe on the sea surface in this region. In particular, the asymmetry between anticyclonic and cyclonic dynamics presents a seasonal variation, which is in agreement with previous studies. SWOT satellite refines our understanding of surface submesoscale dynamics and seasonality in the Mediterranean Sea with a certain impact on numerical model calibration and sea forecast.

2 Results

2.1 Basin-scale variability of eddy kinetic energy

We first analyse the basin-scale variability of mean geostrophic eddy kinetic energy over a 2-year period from August 2023 and August 2025. We used the same sampling strategies for each product (see section 4 for more details). The idea was to reproduce the way SWOT is sampling the ocean in DUACS L4 product to avoid biases in the data processing methodology.

Eddy kinetic energy exhibits a pronounced spatial heterogeneity across the Mediterranean Sea, with values higher than 1200 cm^2s^{-2} in the Alboran Sea and relatively weak levels in the central and eastern interiors (see Fig. 1, 2), consistent with previous studies (Pujol and Larnicol (2005); Sorgente et al. (2011); Escudier et al. (2016)). The submesoscale eddy kinetic energy maxima are consistent with the

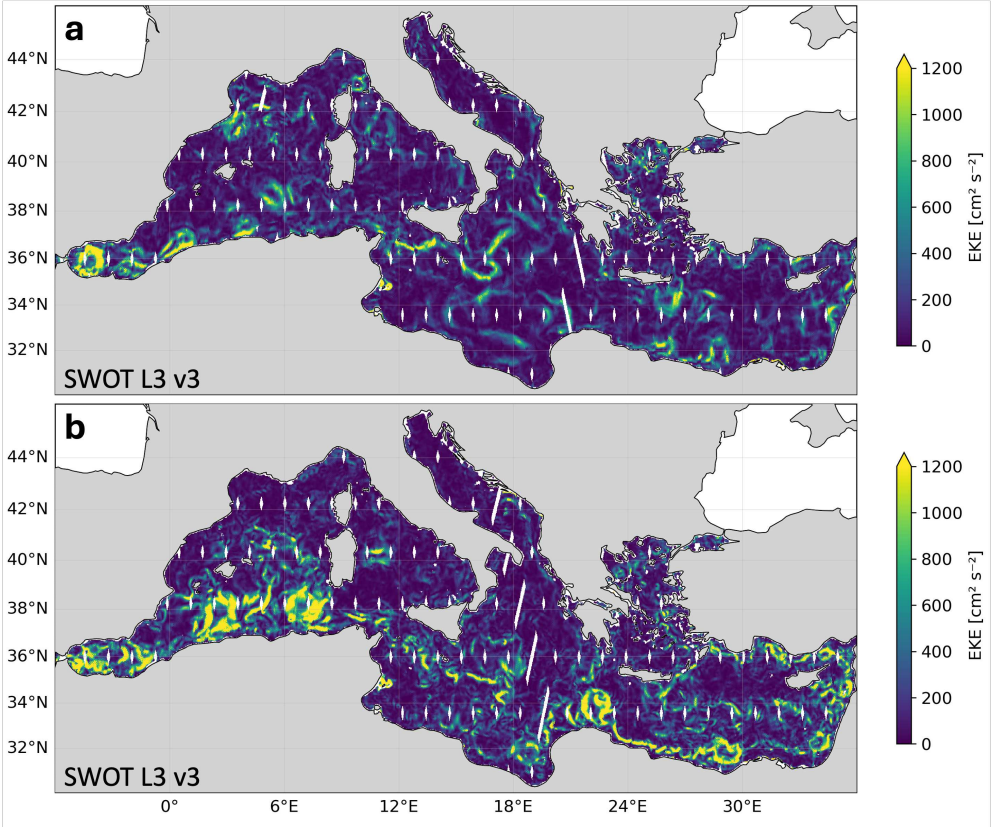


Fig. 1 Eddy kinetic energy snapshots from SWOT L3 v3 (a) summer minimum in August 2023 and (b) winter maximum in February 2023.

mesoscale ones whether in the Algerian basins, the strait of Gibraltar or even the Eastern basin. Mesoscale recirculations, clearly observable by regions of high eddy kinetic energy within DUACS L4, resemble more a set of filaments in submesoscale resolving products (see Fig. 1). At the basin scale, SWOT L3 v3 provides much more energetic structures than the DUACS L4 product, with local eddy kinetic energy levels sometimes higher than 1200 cm^2s^{-2}. For comparison, structures in DUACS L4 are limited to maximums of 730 cm^2s^{-2}. Submesoscales thus increase the local level of eddy kinetic energy. The Mediterranean Sea is thus much more energetic than previously observed.

Consequently, despite broadly consistent large-scale patterns, the two products differ in their mean eddy kinetic energy amplitude and seasonality (see Fig. 3. a.). SWOT L3 v3 shows a mean eddy kinetic energy level 1.8 times higher than DUACS L4 product on average over the 2-year period. Thus, the resolved submesoscales in SWOT L3 v3 accounts for 44% of the mean eddy kinetic energy level from August 2023 to August 2025 in the Mediterranean Sea.

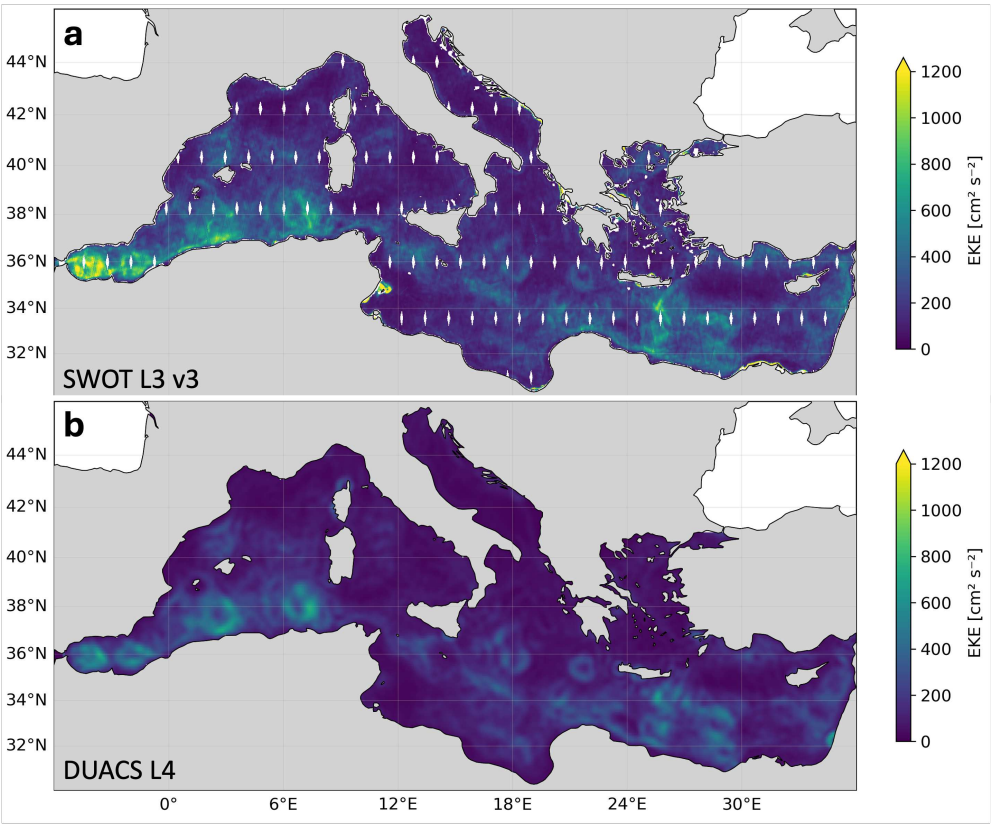


Fig. 2 Mean eddy kinetic energy in the Mediterranean Sea. Maps of mean eddy kinetic energy (EKE) over a 2-years period from August 2023 to August 2025 derived from (a) SWOT L3 v3, (b) DUACS L4 for comparison. The color scale is identical in all panels.

Submesoscales also amplify the seasonal variation of eddy kinetic energy (see Fig. 3.a.) with an increase of 83 cm^2s^{-2} from the summer minimum in August 2023 to the winter maximum in February 2023 from SWOT L3 v3. This represents a 50% increase from the summer minimum. In contrast, the seasonality of mesoscale eddy kinetic energy is not clearly visible in DUACS L4 products with mean eddy kinetic energy levels consistent with previous publications (Pujol and Larnicol (2005); Sorgente et al. (2011); Escudier et al. (2016)). The seasonal cycle of eddy kinetic energy is not symmetric with respect to eddy kinetic energy maxima but this asymmetry seems to vary according to years (see Fig. 3.a.).

2.2 Seasonal modulation of surface submesoscale dynamics

Submesoscales enhance the seasonal modulation of surface dynamics in the Mediterranean Sea. The joint distributions of normalized strain S/f and normalized relative vorticity ζ/f, with f the Coriolis parameter, present a clear seasonal cycle (see Fig.

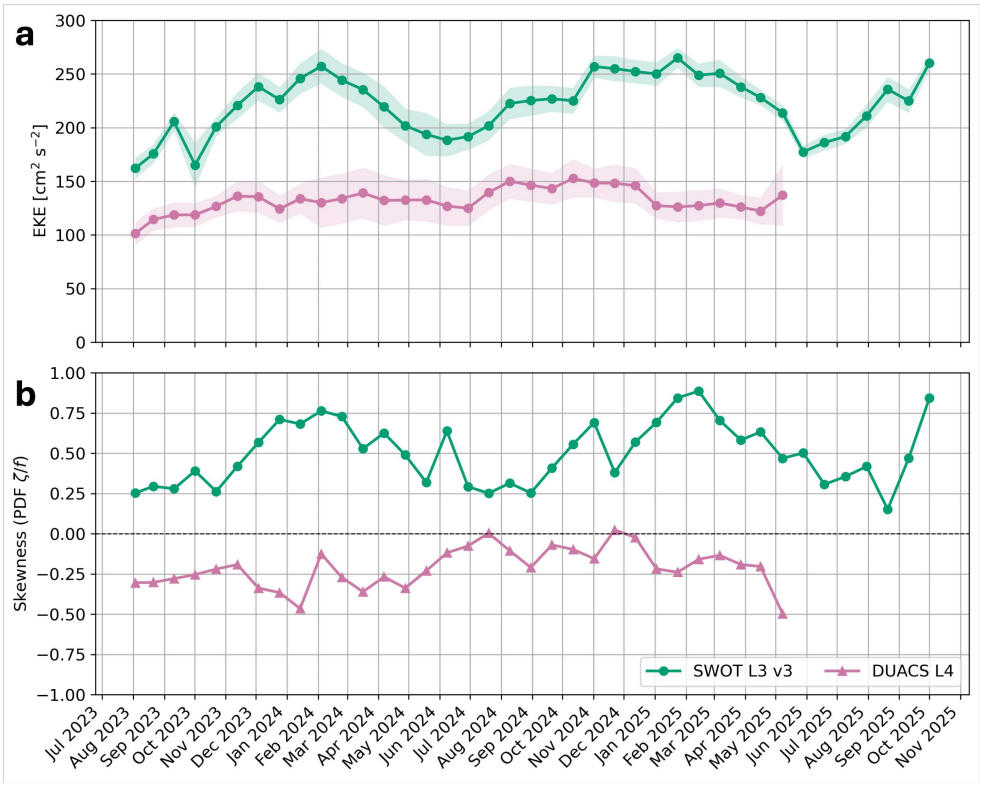


Fig. 3 Temporal variability of basin-integrated surface dynamics (a) Time series of eddy kinetic energy (EKE) averaged over the Mediterranean basin, using "SWOT-like" 21-day sampling windows centered on each SWOT L3 cycle. Each dot corresponds to one cycle average, and envelopes indicate the standard error of the mean. (b) Time series of relative vorticity skewness. See section 4 for the sampling strategy.

5) with maximum values in winter, which is consistent with the peak in eddy kinetic energy. Fig. 4 shows the two maps of normalized relative vorticity from SWOT L3 v3 for the eddy kinetic energy minimum and maximum in August and February 2023, respectively. Positive ζ/f rarely reaches 0.6 at the eddy kinetic energy summer minimum whereas it exceeds 1 at the eddy kinetic energy winter maximum.

Submesoscales also amplify the asymmetry between cyclonic and anticyclonic dynamics. The monthly skewness of normalized relative vorticity exhibits a clear and systematic separation between SWOT L3 v3 and DUACS L4 products (Fig. 3.b.). SWOT L3 v3 show predominantly positive skewness, with values typically between 0.1 and 0.8, indicating an excess of intense cyclonic events at smaller scales. This behavior is consistent with *in situ* and modeling studies that identify positive vorticity skewness as a hallmark of energetic, high-Rossby-number surface flows (Rudnick (2001); Roullet and Klein (2010); Shcherbina et al. (2013); Buckingham et al. (2016)). Those previous studies reported a skewness between 0.36 up to 1 in winter in other regions,

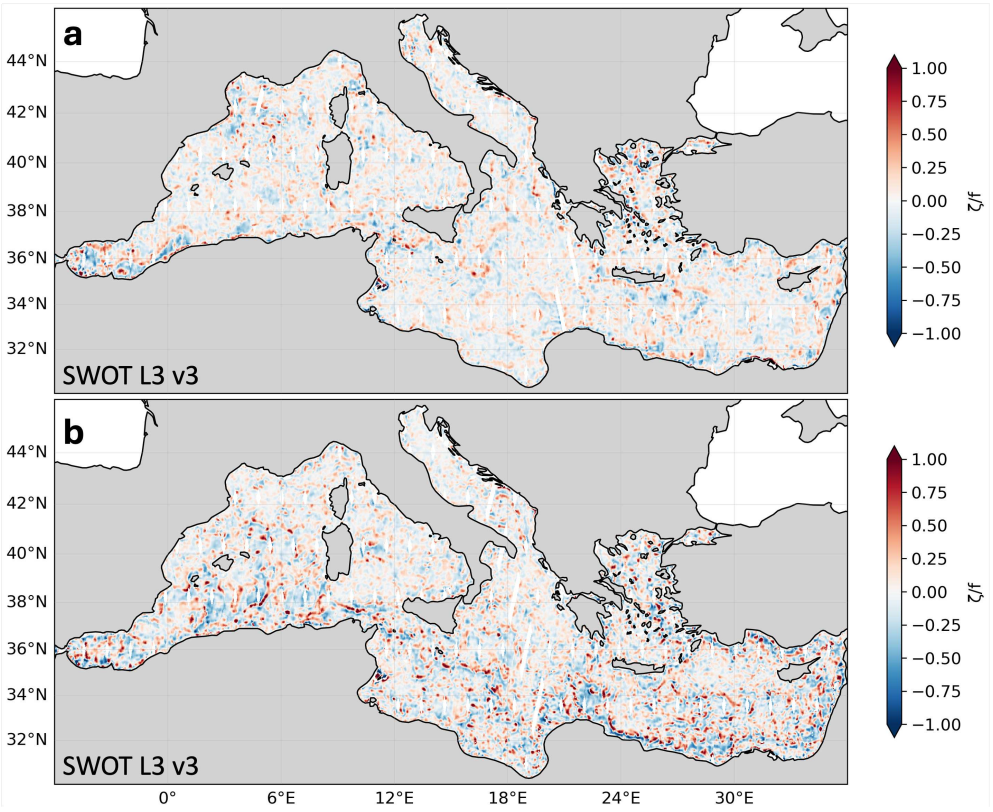


Fig. 4 Snapshots of surface dynamics observed from SWOT L3 v3. Normalized relative vorticity ζ/f maps from SWOT L3 v3 in (a) eddy kinetic energy summer minimum in August 2023 and (b) eddy kinetic energy winter maximum in February 2023.

which is consistent with what we observe from space in the Mediterranean Sea. In the Eastern Mediterranean Sea, this positive skewness has already been observed in numerical simulation (Solodoch et al. (2023)).

In contrast, DUACS L4 remains weakly negative with values between -0.3 and 0, implying that in the gridded altimetric fields intense anticyclones are relatively more prominent than cyclones at mesoscale wavelengths (Backeberg et al. (2009)). This anticyclonic dominance is consistent with basin-scale eddy statistics in the Mediterranean Sea, which show that long-lived large anticyclonic eddies are dynamically favored and more reliably detected in DUACS L4 products than cyclonic eddies (Isern-Fontanet et al. (2006); Escudier et al. (2016); Pegliasco et al. (2021); Bonaduce et al. (2021); Stegner et al. (2021)).

The seasonal modulation of ζ/f skewness, with enhanced positive values during late winter, shows the known strengthening of submesoscale activity in the mixed layer during periods of strong buoyancy forcing (Buckingham et al. (2016)). In contrast, the much flatter DUACS L4 curve highlights the inability of conventional L4

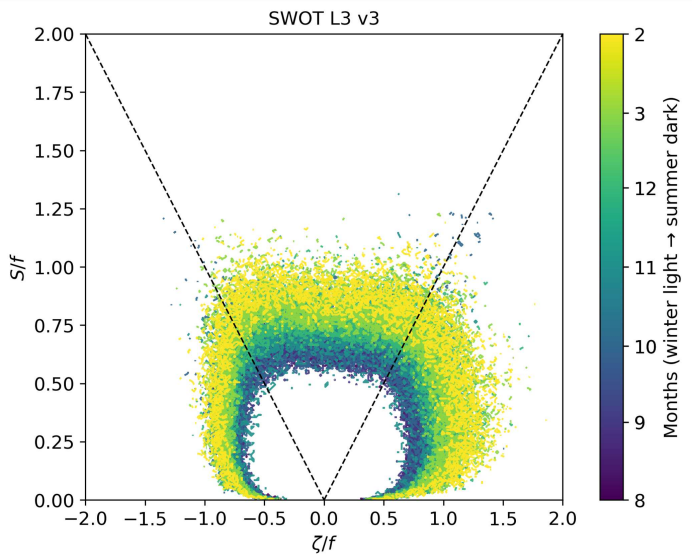


Fig. 5 Seasonal variation of joint probability distribution contours. Colored contours contain 99% of values. One color is associated to one month. Winter colors are lighter than summer colors.

mapping procedures to capture this seasonal cycle in ζ/f asymmetry. Overall, in the Mediterranean Sea, SWOT L3 v3 uniquely resolves the cyclonic submesoscale regime anticipated from theory and observations, while conventional gridded altimeter L4 products mainly reflect a mesoscale field dominated by comparatively larger and more persistent anticyclonic eddies, consistent with previous studies.

2.3 Seasonal modulation of sea surface height spectra

At large spatial scales ($k < 10^{-2}$ cycles km^{-1}), the two products display comparable spectral levels and slopes throughout the year, indicating that the basin-scale and mesoscale circulation of the Mediterranean Sea is robustly captured and exhibits limited seasonal modulation at these wavelengths (see Fig. 6). At smaller scales ($10^{-2} < k < 10^{-1}$ cycles km^{-1}), a clear seasonal signal emerges, particularly in the SWOT L3 v3 product. During winter and early spring, the variance in sea surface height increases markedly, leading to elevated energy levels compared to summer and early autumn. This seasonal enhancement is consistent with intensified submesoscale activity during periods of deep mixed layers, strong buoyancy loss and enhanced frontogenesis, which promote the generation of sharp sea surface height gradients and energetic filaments at the sea surface. This seasonal cycle cannot be captured with DUACS L4 products. At these scales, the surface dynamics observed by SWOT seems to be governed by surface quasi-geostrophic dynamic regardless of the season, as spectra present slopes of value -11/3 (Blumen (1978); Held et al. (1995); Klein et al. (2008)) . In contrast, the surface dynamics observed by DUACS L4 seems to be closer to quasi-geostrophy with slopes of value -5 (Vallis (2017)). This indicates that conventional

nadir altimetry largely misses the seasonal amplification of submesoscale variability, even though it captures the mesoscale background circulation. The presence or absence of submesoscales in observational products thus changes our interpretation on the nature of the surface turbulence dynamics.

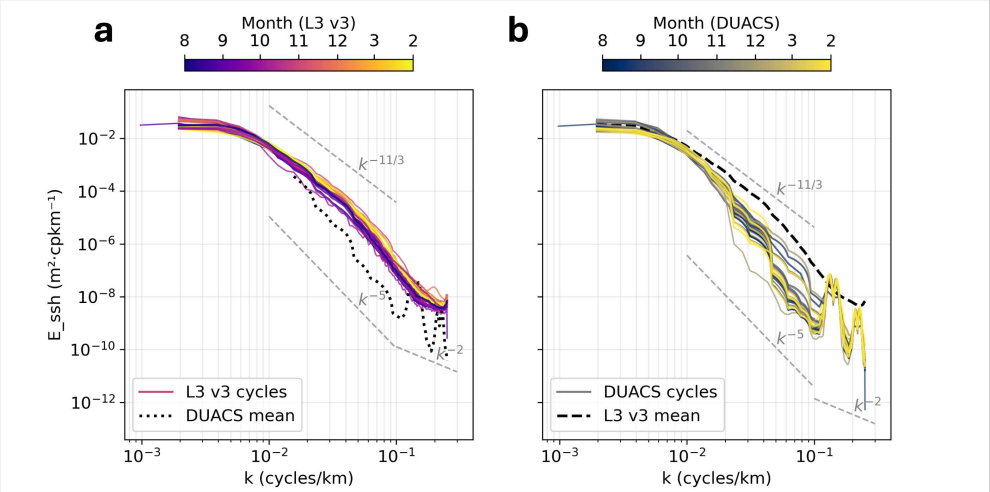


Fig. 6 Seasonal variation of sea surface height spectra. (a) SWOT L3 v3, (b) DUACS L4 for comparison.

3 Discussion

To robustly characterize the seasonality of the surface dynamics in the Mediterranean Sea, we exploited two altimetric products. We used the version 3 of SWOT L3 swath data and DUACS L4 product to compare. In the supplementary material, we perform the same analysis using the version 2.0.1 of SWOT L3 swath data. This version 2.0.1, which has been extensively used in recent validation studies (Coadou-Chaventon et al. (2025); Verger-Miralles et al. (2025)), preserves sharp sea surface height gradients and has proven effective in detecting energetic submesoscale features, but has a tendency to overestimate velocities and thus geostrophic eddy kinetic energy in regions dominated by strong, partly ageostrophic fronts. In contrast, version 3 applies a dedicated filtering strategy to suppress some of the non-geostrophic high-wavenumber signals and to retrieve surface velocities more consistent with *in situ* and drifter-derived geostrophic currents (Tranchant et al. (2025)). This filtering thus better reproduces geostrophic dynamics, which is crucial to study balanced motions as was the case in previous studies based on conventional altimetry products.

To emphasize SWOT's high-resolution capability, we also analyzed the classical DUACS product, which remains the reference for large-scale and mesoscale circulation studies. This product also underpins the majority of Mediterranean Sea eddy analyses

over the past two decades. Including DUACS L4 product in this study is essential to demonstrate that the absence or presence of seasonal cycles arises from the intrinsic capacity of an altimetric product to resolve or not the submesoscale motions.

As a result, submesoscales account for 44% of the mean level of eddy kinetic energy from August 2023 to August 2025 in the Mediterranean Sea. The eddy kinetic energy level thus presents a clear seasonal cycle with an increase of 50% in winter compared to summer time. This eddy kinetic energy peaking in late February is also associated with higher strain and relative vorticity often exceeding the value of the local Coriolis parameter. The meso to submesoscale range of turbulence is in agreement with the surface quasi-geostrophy, regardless of the season.

This study also filled the gap between what was known in the global ocean about seasonal submesoscales dynamics and the current state of the art in the Mediterranean Sea. The asymmetry between cyclonic and anticyclonic structures is also present in the Mediterranean Sea and shows a clear seasonal cycle with skewness values consistent with what can be found in the global ocean.

This study updates our vision of surface dynamics in the Mediterranean Sea and shows a much more energetic and complex region than previously expected, with intense strain and relative vorticity. This study impacts numerical model calibration, climate predictions and sea forecast.

4 Methods

4.1 Satellite observations

The primary dataset used in this study is the SWOT Level-3 KaRIn Expert SSH product (version 3), obtained from the AVISO repository (https://doi.org/10.24400/527896/A01-2023.018). Launched on 16 December 2022, the SWOT mission entered its global science mapping phase on 21 July 2023 (Fu et al. (2024)). During this phase, SWOT provides near-global ocean coverage between $\pm 78^{\circ}$ latitude on a 21-day repeat cycle. For this study, we analyzed all available data from science mission cycles 1 through 39, encompassing a of 27 months from August 2023 to November 2025. Two variables were utilized, *ugosa_filtered* and *vgosa_filtered* the geostrophic velocity anomalies.

We evaluate SWOT altimetry against the level-4 delayed-time SSH product from the Copernicus Marine Environment Monitoring Service (CMEMS, European Seas Gridded L4 Sea Surface Heights And Derived Variables Reprocessed 1993 Ongoing ref). This dataset, referred to as DUACS L4, is generated using the Data Unification and Altimeter Combination System, which applies a multiscale and multivariate mapping approach to merge along-track altimetric data from multiple satellite missions. DUACS SSH provides daily, gridded maps of SSH at a spatial resolution of 0.125° ($\approx$12 km). (https://doi.org/10.48670/moi-00141). Two variables were utilized, *ugosa* and *vgosa*, the geostrophic velocity anomaly. At the time of writing, DUACS data was only available up to June 2025.

The along-swath SWOT and the multi-mission merged DUACS L4 velocity anomaly data described above are referenced to the 20-year mean SSH field, also

known as the Mean Dynamic Topography field, for the period 1993-2012, enabling direct comparison of SSH and derived velocity fields.

Our approach to comparing products consists of constructing a "swot-like" version of DUACS L4. For each cycle, each swath of SWOT L3 product is used to build a mask that is applied to the daily map of DUACS L4 coinciding with the date of the swath. Then, each constructed swath of DUACS L4 corresponding to the date of the SWOT L3 cycle is gathered to construct a unique map for each SWOT L3 cycle.

Sea surface height spectra were computed using the methodology of Qiu and Chen (2025)

4.2 Dynamic properties

Noting (u', v') the two-dimensional geostrophic velocity anomaly, the eddy kinetic energy was obtained using

$$\mathrm{EKE} = \frac{1}{2}(u'^2 + v'^2). \tag{1}$$

The strain rate was calculated using

$$S = \sqrt{\left(\frac{\partial u'}{\partial x} - \frac{\partial v'}{\partial y}\right)^2 + \left(\frac{\partial v'}{\partial x} + \frac{\partial u'}{\partial y}\right)^2}. \tag{2}$$

The relative vorticity was calculated using

$$\zeta = \frac{\partial v'}{\partial x} - \frac{\partial u'}{\partial y}. \tag{3}$$

Data availability. The SWOT L3_LR_SSH product, derived from the L2 SWOT KaRIn low rate ocean data products (NASA/JPL and CNES), is produced and made freely available at https://doi.org/10.24400/527896/A01-2023.018 by AVISO and DUACS teams as part of the DESMOS Science Team project (AVISO/DUACS (2024)).

The DUACS L4 products were processed by the DUACS multimission altimeter data processing system and freely available at https://data.marine.copernicus.eu/product/SEALEVEL_EUR_PHY_L4_MY_008_068/description (DUACS (2025)).

Code availability.

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represents a revolution in our understanding and quantification of ocean dynamics and impacts on climate.

Authors contributions. AP, BM and YB conceived the study. YB conducted the analyses, prepared the figures and wrote the initial manuscript with contributions from GL. BM and AP discussed the results and implications, and commented on the manuscript at all stages. AP and BM obtained the funding.

Competing interests. The authors declare no competing interests.

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