Are we underestimating eddy–wave interaction in the Mediterranean Sea?

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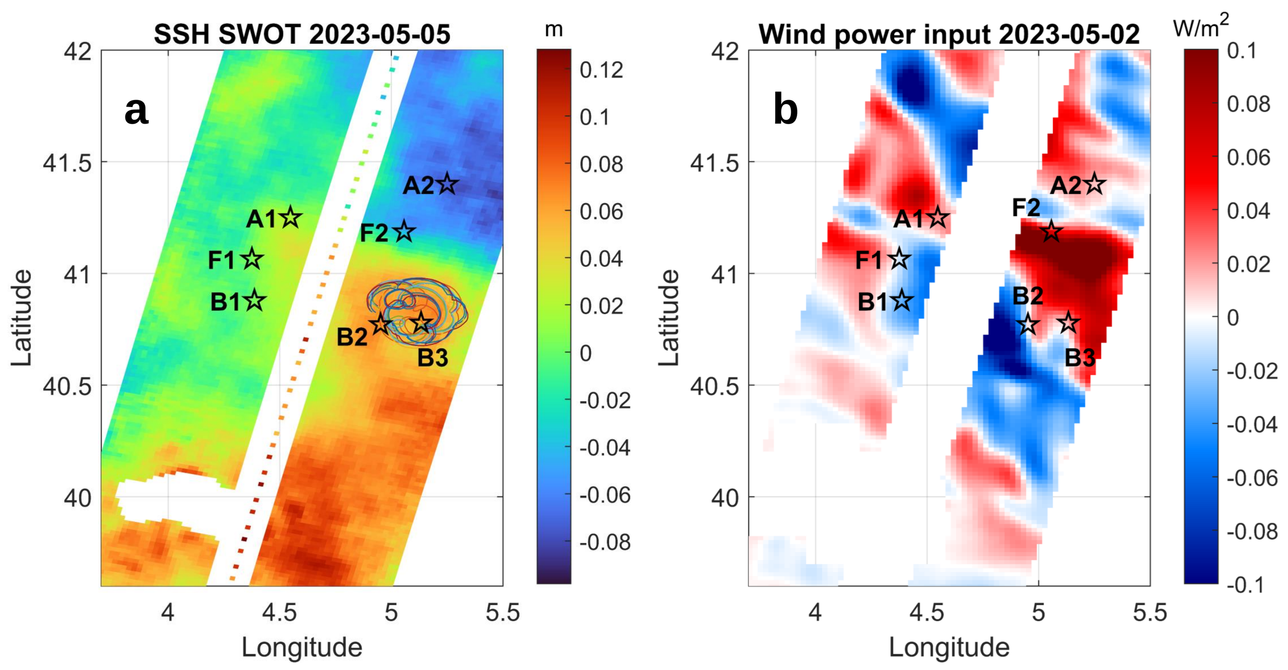
Context and highlights

- The Mediterranean Sea is an oligotrophic region with very low turbulence levels except in a few dynamically energetic areas such as straits or boundaries (Ferron et al., 2017).
- Turbulence mainly comes from internal gravity wave breaking.
- In the Mediterranean Sea, IGWs are principally generated by the atmospheric forcing at the base of the mixed-layer.
- Eddy–wave interactions are an important source of energy injection at depth through wind-induced near-inertial wave (NIW) trapping by anticyclonic eddies.
- However, in the Mediterranean Sea there are few evidences of this process and in large mesoscale permanent structures such as Cyprus eddy (Cuypers et al., 2012; Lelong et al., 2020).

- During the BioSWOT–Med cruise (https://doi.org/10.17600/18002392), 2 consecutive storms generated strong NIWs trapped within an intense (Ro ∼ 1) mesoscale anticyclonic eddy (D ∼ 30 km), typical of the Mediterranean Sea.
- NIWs propagation at depth generated intense turbulence levels until 250 m, that contrast with very low turbulence levels in the frontal and cyclonic areas.
- NIW generation, characteristics and vertical energy propagation are estimated from in-situ data (SADCP, drifters, CTD) and reanalyzes data.

An ideal case study: intense (Ro ∼ 1) mesoscale anticyclonic eddy revealed by SWOT and drifters, undergoing 2 strong wind events



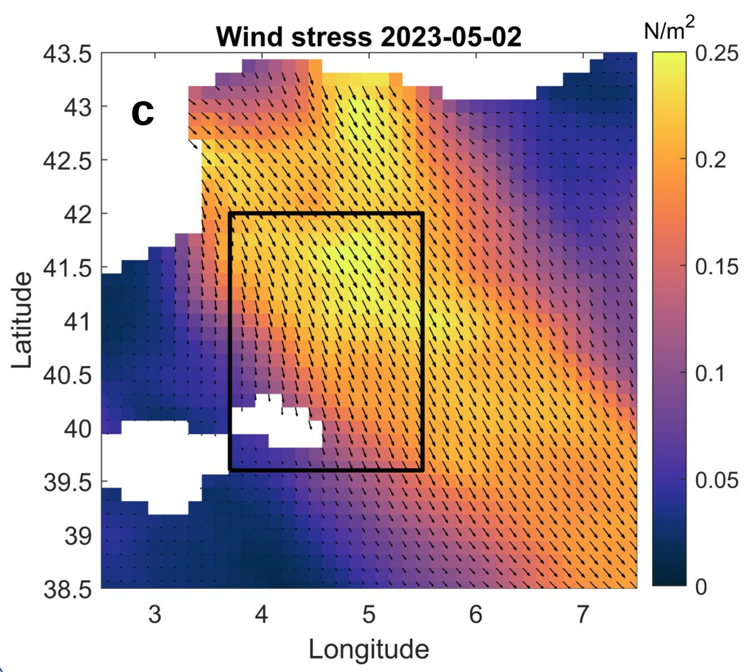


Figure 1. (a) Sea Surface Height (SSH) from SWOT the May 5th 2023 when the drifters were deployed during station B2.
(b) Wind power input to oceanic motions averaged on the 2nd May 2023 computed from wind reanalysis (ECMWF) and SWOT cyclogeostrophic currents.
(c) Wind stress averaged on the 2nd May 2023 from wind reanalysis (ECMWF).

The concomitant presence of an intense anticyclonic eddy well observed by SWOT and of strong wind events before stations B2 and B3 makes the BioSWOT–Med cruise an ideal case study for near-inertial wave–anticyclonic eddy interactions in the Mediterranean Sea.

PRE-VALIDATED SWOT DATA

All SWOT data are pre-validated L3 product version 0.3

Major impact of the wind event with an inertial chimney evidenced in the anticyclonic part of the front only

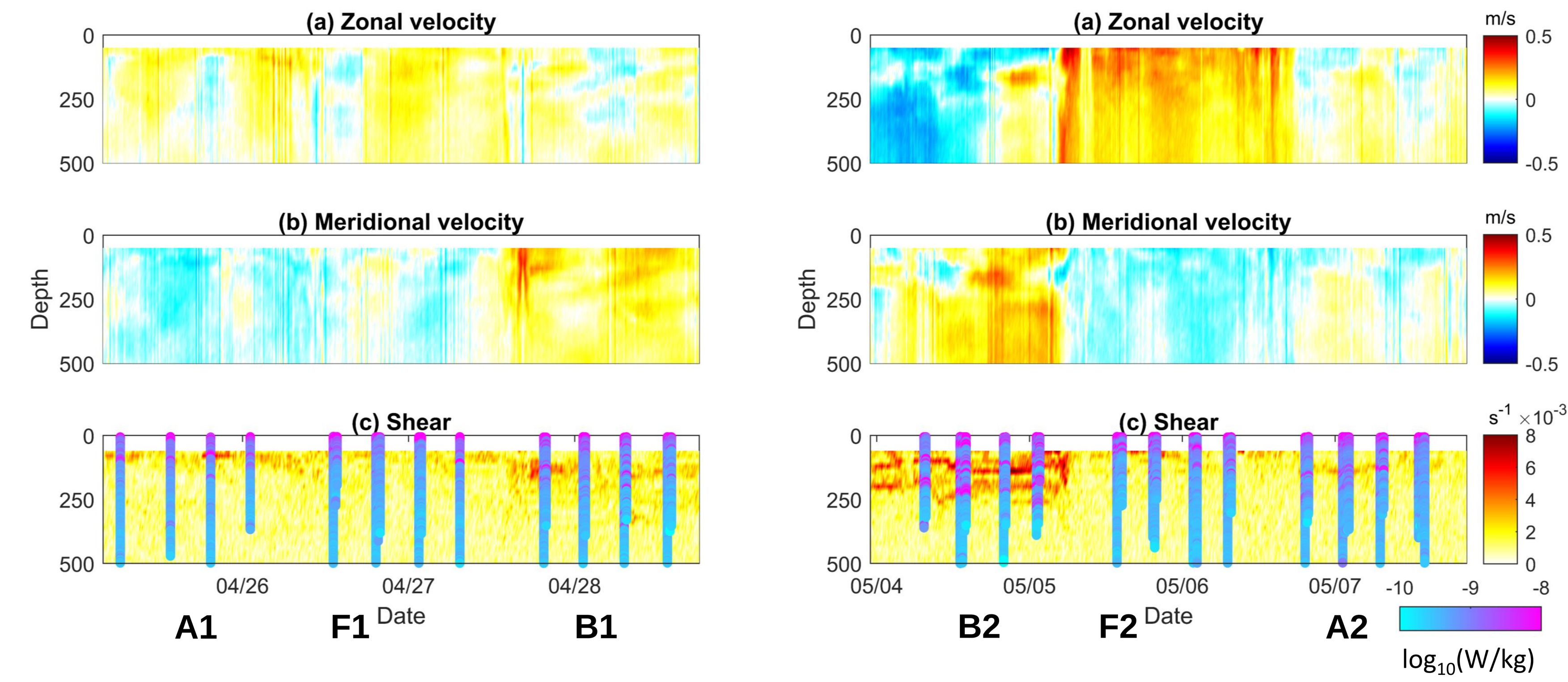


Figure 2. Ship ADCP measurements during stations A1, F1 and B1 (left) and during B2, F2 and A2 (right). Scatter plots indicate dissipation of turbulent kinetic energy ε measured with a Vertical Microstructure Profiler. B and A stations are respectively located in the anticyclonic and cyclonic side of the front. F stations are located on the front.

A weak near-inertial signal is observed in B1 with near-inertial shear correlated with a few peaks in dissipation. Vertical propagation of strong NIWs is evidenced in B2. The trapping of NIWs in B2 is highlighted by the abrupt change in shear between B2 and F2. One can note the co-localization of strong shear with strong turbulence activity ε.

Near-inertial waves strongly increase turbulence at depth

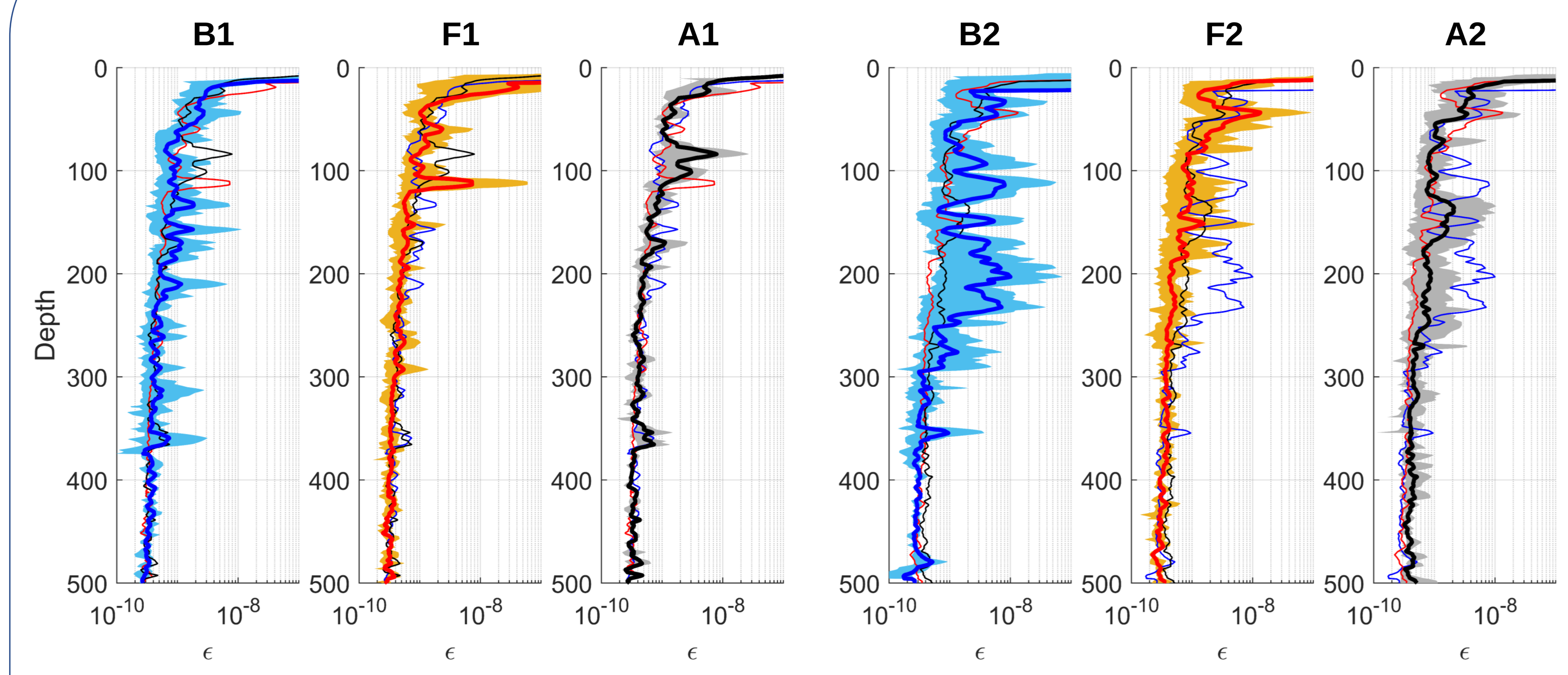
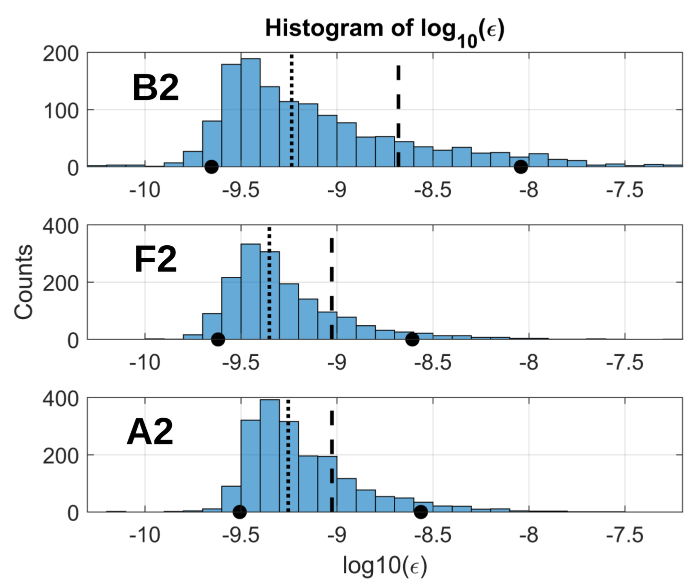


Figure 3. Average (solid line) and min–max range (shaded area) dissipation of turbulent kinetic energy ε profiles measured with a Vertical Microstructure Profiler for the 1st (top left) and 2nd (top right) series of stations. (Bottom right) Histogram of $\log_{10}(\varepsilon)$ below 20 m for the 2nd series of stations. The dashed and dotted lines indicated the mean and median values. The thick dots indicate the 5 and 95 % percentiles.



The 1st series of stations show very low turbulence levels below 100 m ($\varepsilon \sim 10^{-10}$–$10^{-9}$) and no clear contrast between stations. In the 2nd series, the strong turbulence levels in B2 until 250 m ($\varepsilon \sim 10^{-9}$–$5\ 10^{-8}$), resulting from the near-inertial wave propagation, contrast with low turbulence in F2 and A2 ($\varepsilon \sim 5\ 10^{-10}$–$5\ 10^{-9}$) where near-inertial waves are absent.

References

- Ferron, B., P. Bouruet Aubertot, Y. Cuypers, K. Schroeder, and M. Borghini (2017). How important are diapycnal mixing and geothermal heating for the deep circulation of the Western Mediterranean?, Geophys. Res. Lett., 44, 7845–7854, doi:10.1002/2017GL074169.
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- Lelong, M., Y. Cuypers, and P. Bouruet-Aubertot (2020). Near-Inertial Energy Propagation inside a Mediterranean Anticyclonic Eddy. J. Phys. Oceanogr., 50, 2271–2288, https://doi.org/10.1175/JPO-D-19-0211.1.

Near-inertial wave characterization and vertical energy flux at station B3

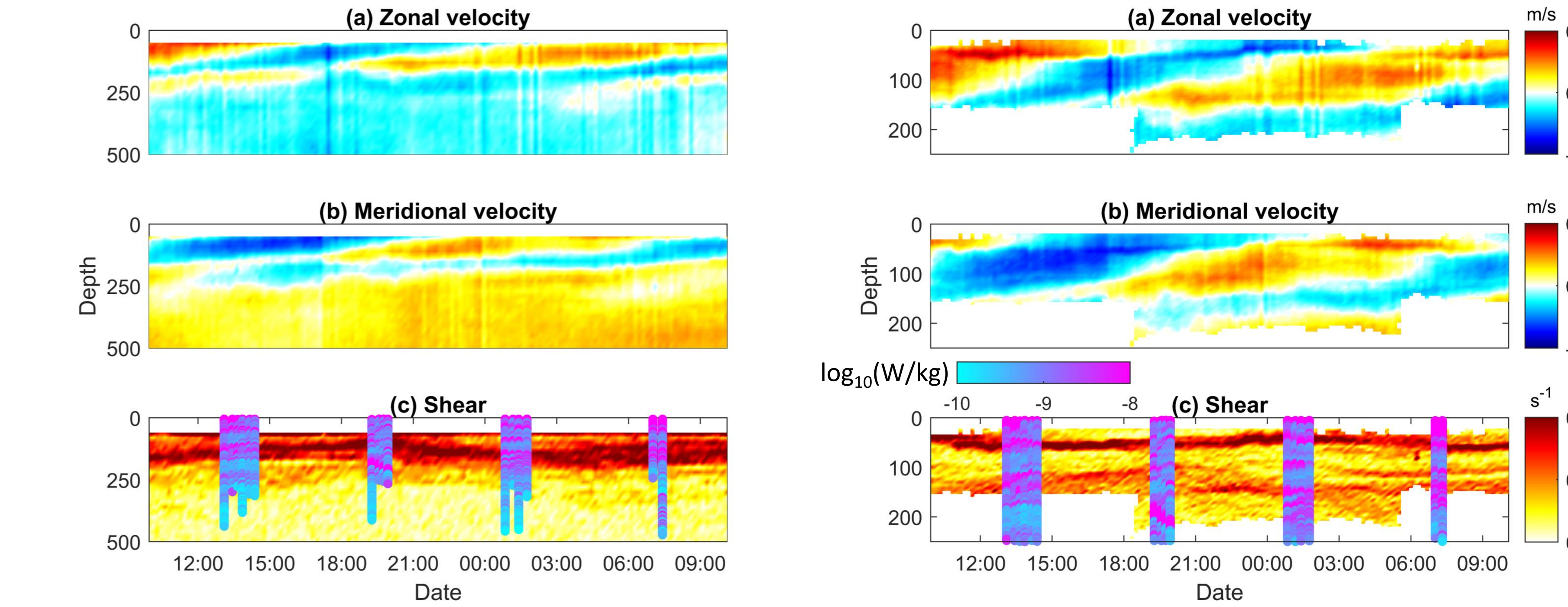
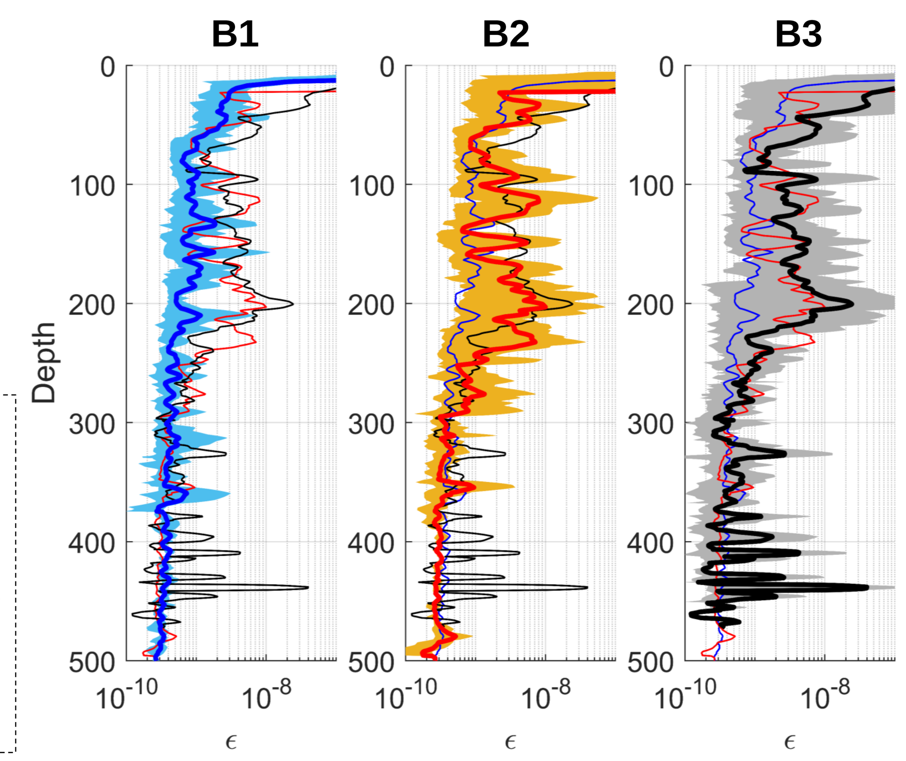


Figure 4. Ship ADCP measurements with the 38 kHz (top left) and 150 kHz (top right) during the B3 station. Scatter plots as in figure 2. (bottom right) Average (solid line) and min–max range (shaded area) dissipation of turbulent kinetic energy ε profiles measured with a Vertical Microstructure Profiler.



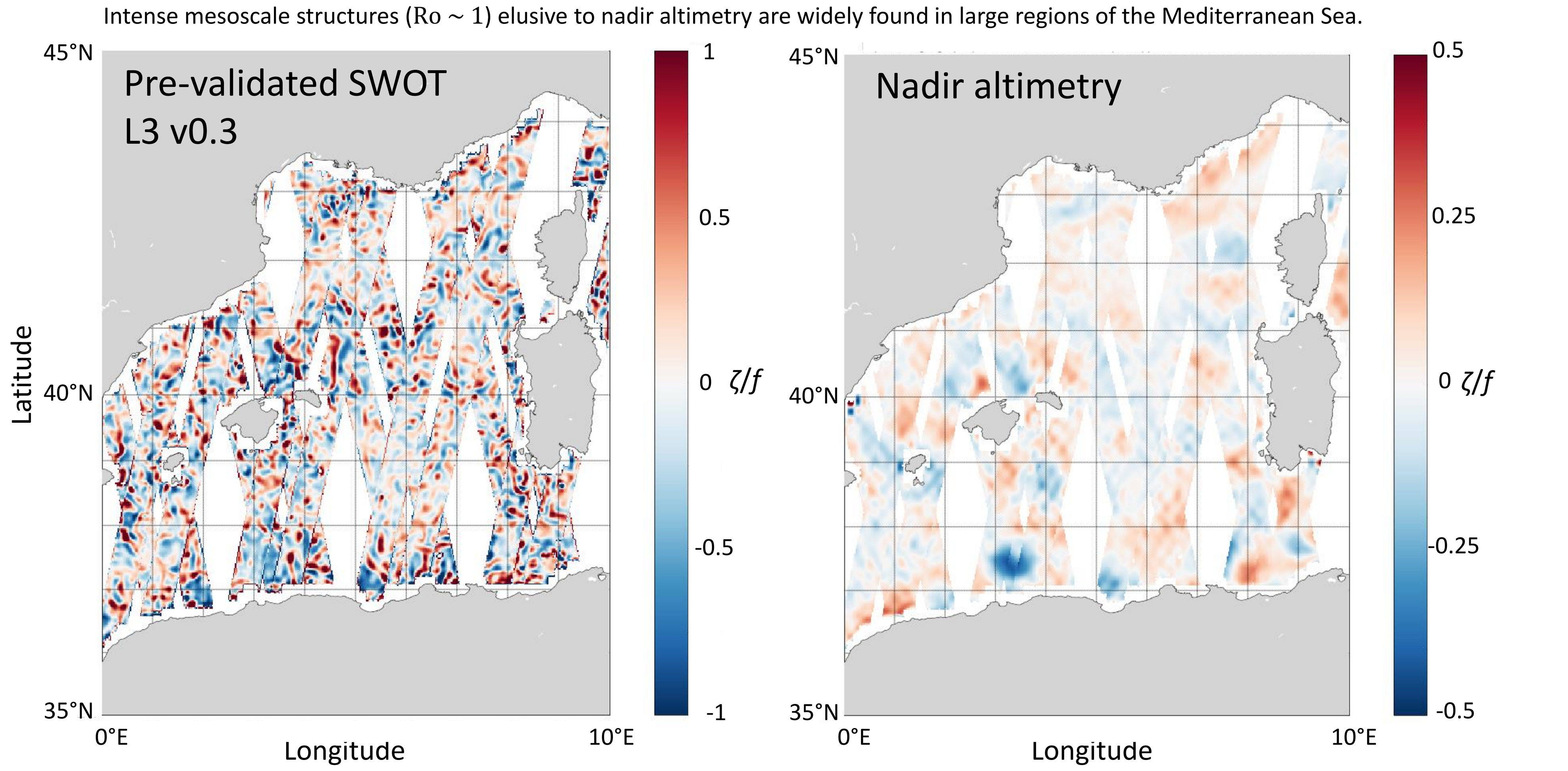
Near-inertial waves dominate the signal until ∼ 300 m. Very strong shear (compared to others stations) results from their propagation at depth, inducing strong turbulence until ∼ 250 m.

Near-inertial wave characterization from in-situ data

- Vertical wavenumber $k_z = 2\pi/150$ rad m^{-1}
- Vertical phase velocity $c_{\phi_z} \approx 1.92 \times 10^{-3}$ m s^{-1} (∼ 165 m day^{-1})
- Effective inertial frequency $f_{eff} \approx 7.46 \times 10^{-5}$ rad s^{-1} → $0.783 f$ (40.8°N)
- Observed frequency $\omega_o = c_{\phi_z} k_z \approx 7.98 \times 10^{-5}$ rad s^{-1} → $0.837 f$ & $1.069 f_{eff}$
- Horizontal wavenumber $k_h \approx 2\pi/35$ rad km^{-1} (close to the eddy diameter)
- Vertical group velocity $c_{g_z} \approx 2.34 \times 10^{-4}$ m s^{-1} (∼ − 20.2 m day^{-1})
- Vertical energy fluxes $\Pi_{KE} = c_{g_z} KE_{NIW} \approx 6.5$ mW m^{-2} (∼ 1–10 % WPI)

SWOT reveals intense mesoscale structures in large regions of the Mediterranean Sea

Figure 5. Geostrophic normalized vorticity seen by SWOT (left) and actual nadir altimetry (right) between November 11th and 15th 2023. Note the **different colorbars**. Courtesy: Chloé Goret.
Intense mesoscale structures (Ro ∼ 1) elusive to nadir altimetry are widely found in large regions of the Mediterranean Sea.



Conclusions and perspectives

- The small Rossby deformation radius (∼ 10–15 km) make typical mesoscale eddies elusive to nadir altimetry.
- SWOT images reveal small & intense mesoscale structures in large regions of the Mediterranean Sea.
- Our preliminary results suggest that NIW–anticyclonic eddy interactions may be much more frequent in space and time than expected, and their role in energy injection at depth may have been largely underestimated in the Mediterranean Sea.