

# Energy partition between internal waves and QG motions

in the moderately energetic area of the BIOSWOT-Med cruise

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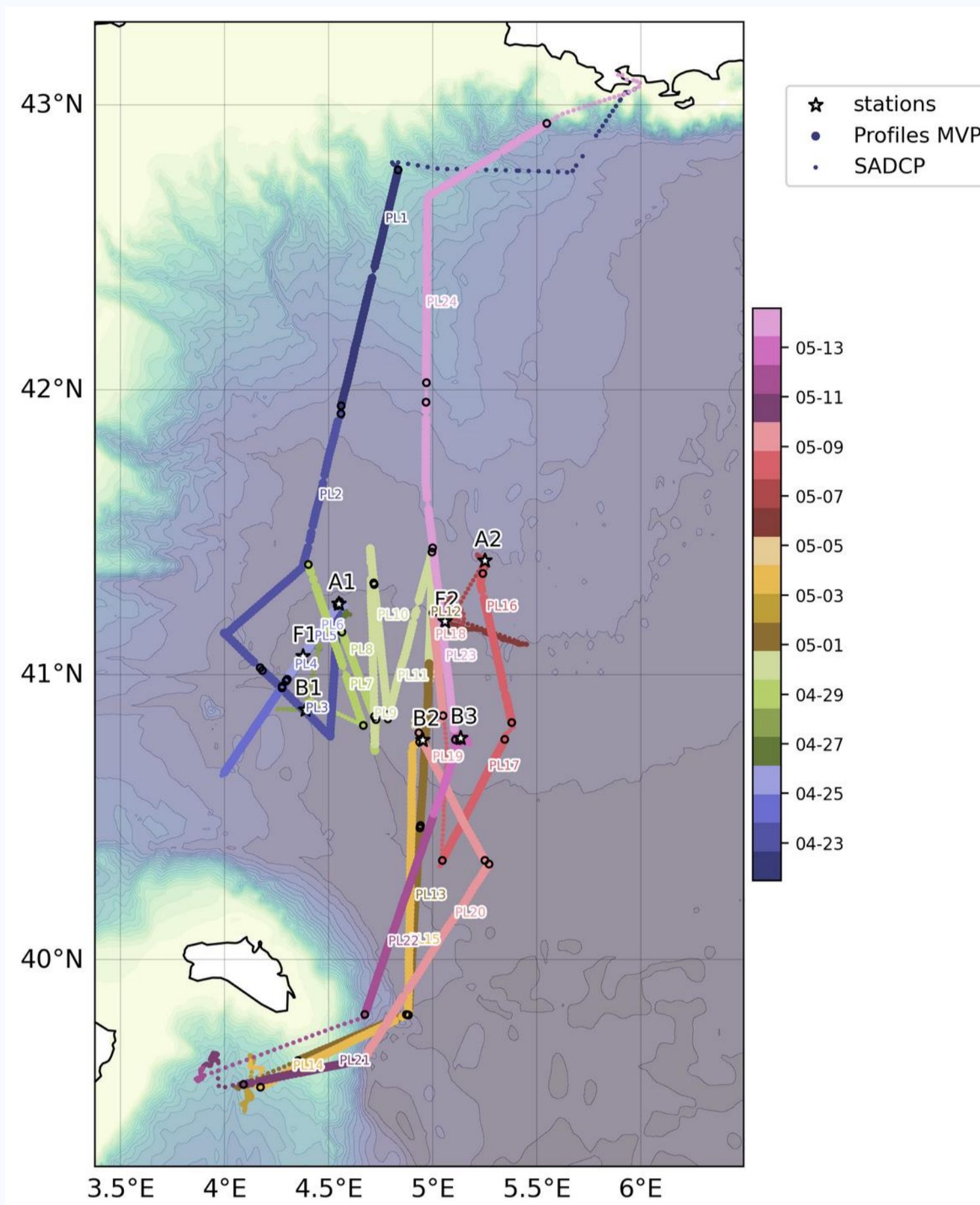
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The considerable refinement of SWOT measurements down to finescales has raised the question of the contribution of ageostrophic motions to the SSH signature. These finescales which include frontal structures, vortices and filaments are conducive of various instabilities feeding the direct energy cascade to small-scale turbulence, but also a reverse cascade to large-scale turbulence. The question of the transition scale between direct and reverse cascades is fundamental as a virtual boundary between "balanced" and "unbalanced" movements. This transition scale is highly dependent on fine-scale dynamics and the eddy kinetic energy level. In addition, the interaction of sub-mesoscale structures with internal waves acts as a catalyst for the energy cascade, whether internal tidal waves or wind-generated near-inertial frequency waves.

## BIOSWOT-MED : an ideal case study for characterizing NIW and QG interactions

Our study area is that of the BIOSWOT-MED cruise, near the North Balearic front. The dynamics, characterized by a moderate eddy kinetic energy level and an insignificant tidal signal. These features make it a specific case study for characterizing wind generated near inertial waves and vorticity structures interactions and how they impact the transition scale and reinforce the energy cascade. Thanks to the SWOT data finescale frontal structures were identified and guided the BIOSWOT-Med cruise investigations. The analysis is based upon vertical section of currents (acoustic Doppler current profiler « SADC ») and density measurements (Moving Vessel Profiler « MVP »).

BioSWOT-Med overview and Atalante cruise track. Bathymetry shown in the background; circles = MVP profiles, points = SADC measurements, stars = fixed stations (A = cyclonic vortices, B = anticyclonic vortices, F = fronts)

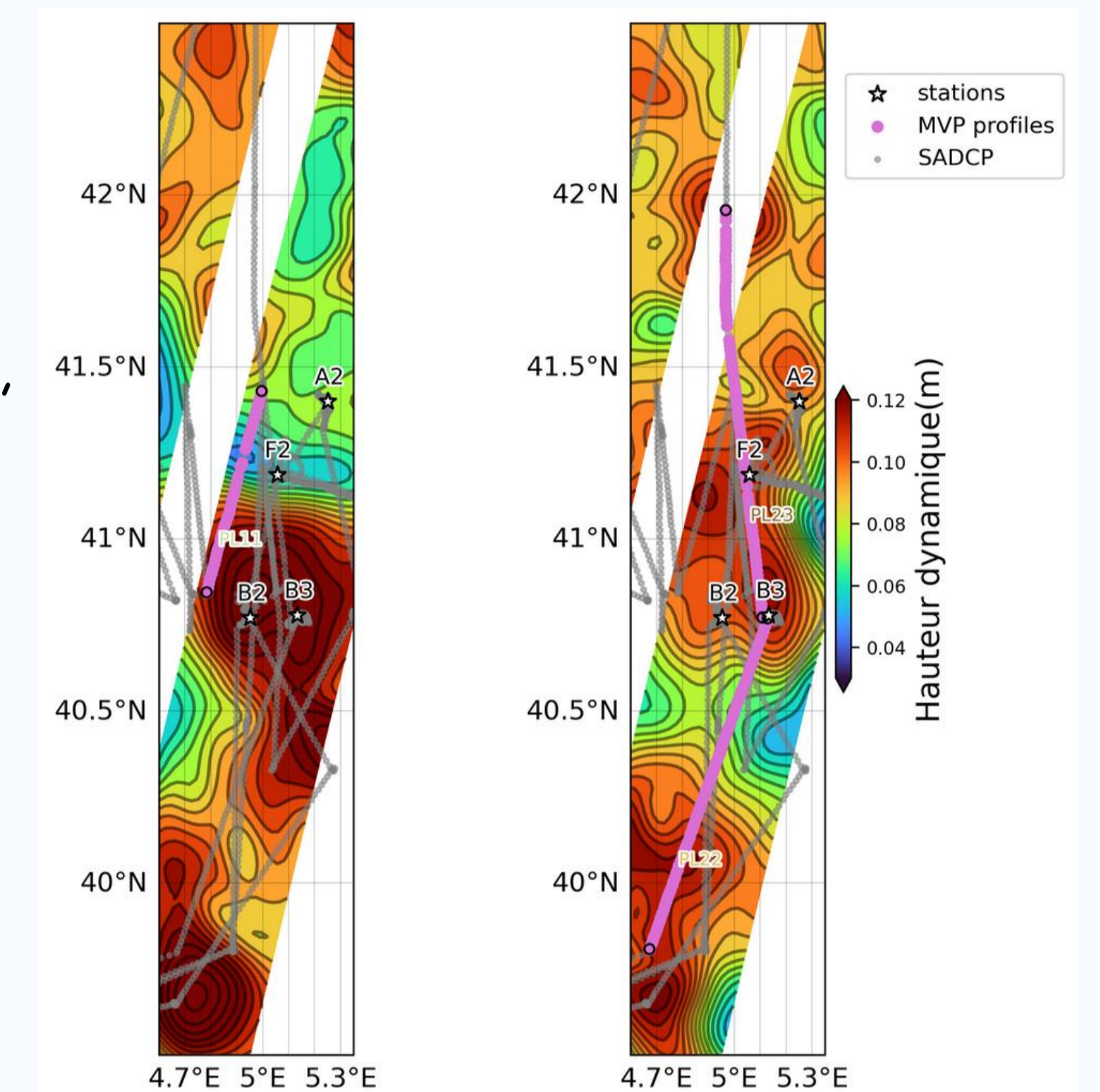


## Focus on two Contrasted Transects

Two sections were analyzed:

Section 11 (reference)  
Sections 22-23, which cross an anticyclonic eddy, B3

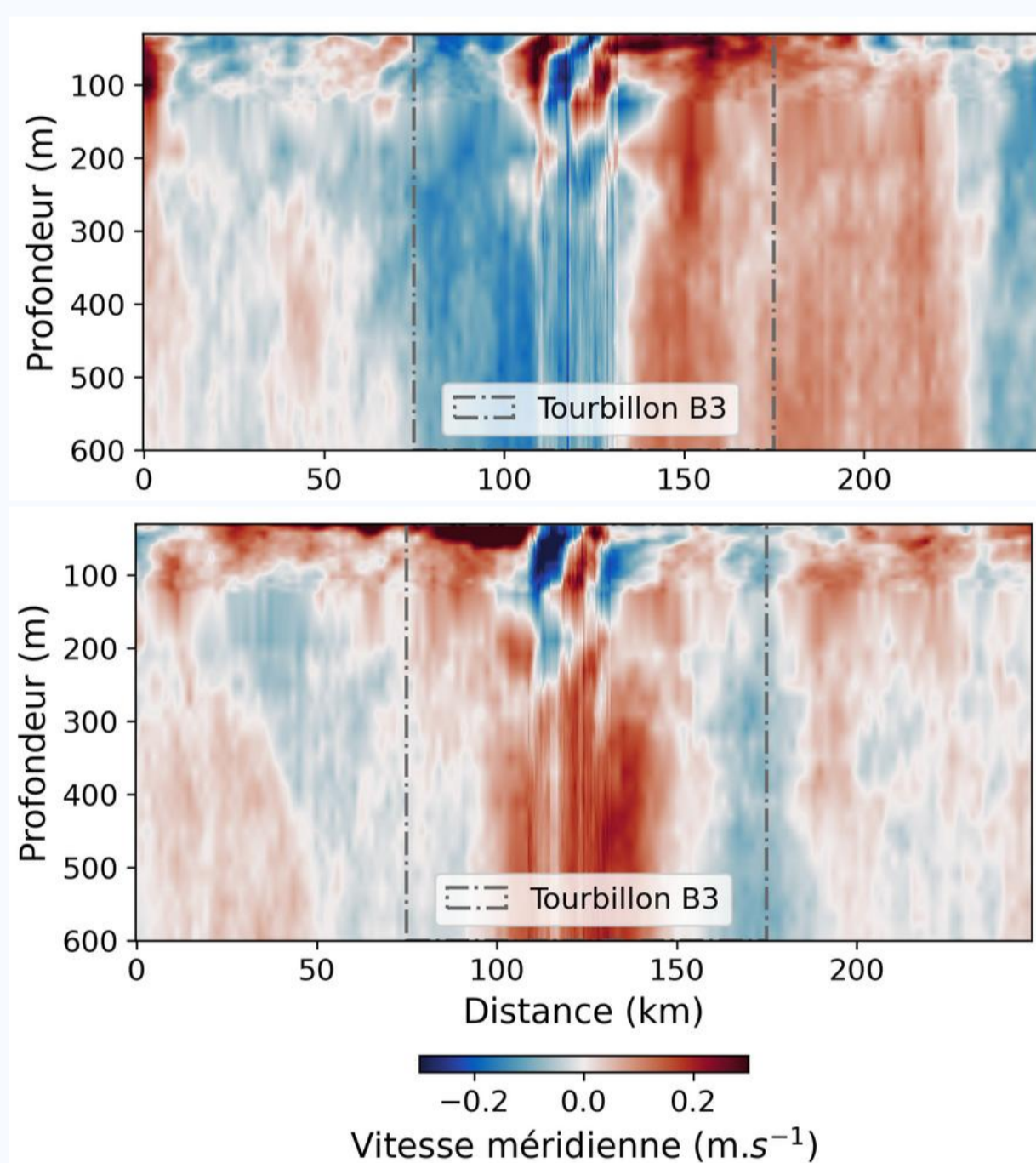
The figure shows a surface elevation characteristic of the B3 eddy (SSH  $\approx 0.12$  m) associated with negative vorticity, conditions favorable for the formation of an inertial chimney.



Sea Surface Height (SSH) along section 11 (left) and sections 22-23 crossing anticyclonic vortex B3 (right). SSH maxima indicate vortex cores.

## NIW trapped within anticyclone B3

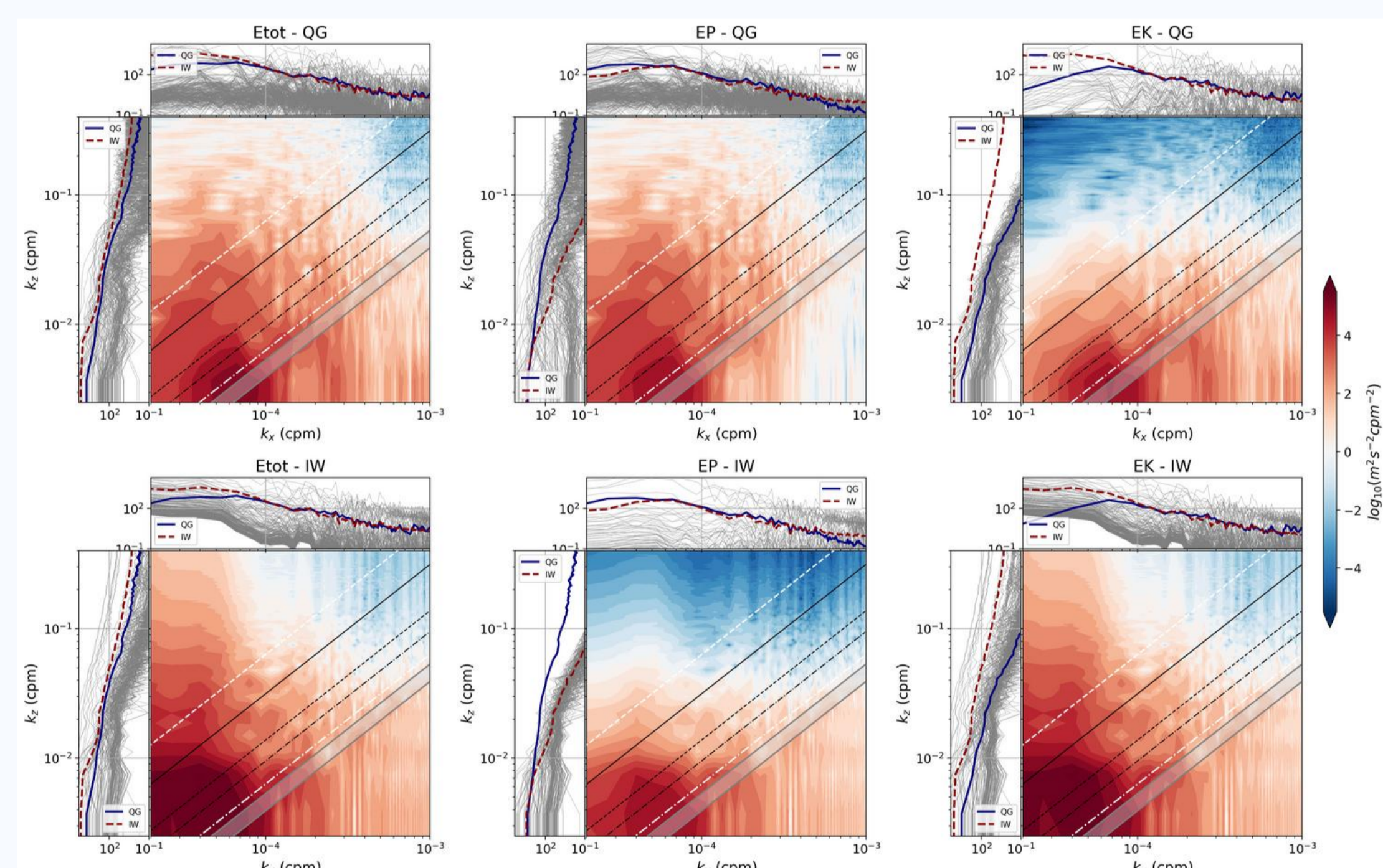
SADC data across B3 reveal the presence of alternating velocity bands, typical of trapped near-inertial waves within the vortex.



Raw zonal (U) and meridional (V) velocities along sections 22-23. Dashed lines mark vortex B3.

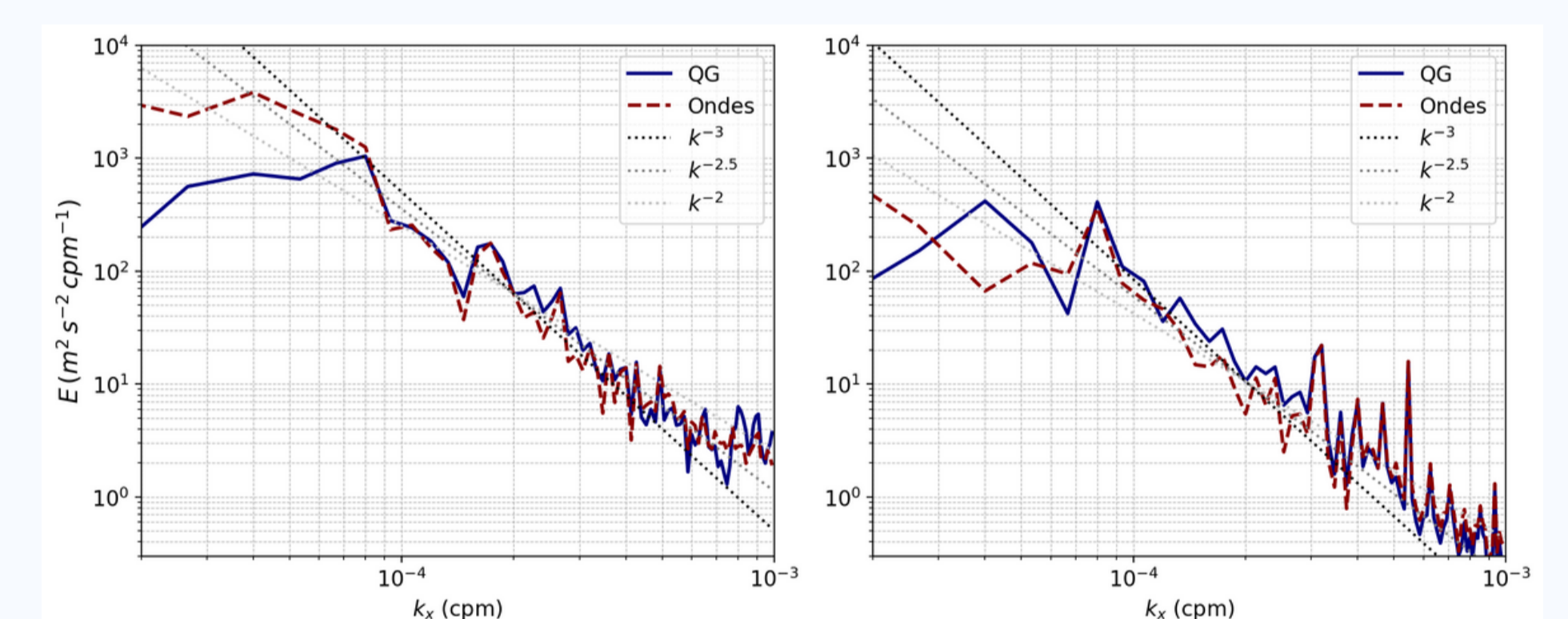
## Energy partition between QG and IW

2D spectral analysis shows that IW kinetic energy dominates at large horizontal wavelengths along sections passing through anticyclonic eddy B3 revealing the impact of inertial chimney.



2D spectral energy density: top row QG, bottom row IW. Left = total, center = available potential energy, right = kinetic energy. Red = IW, blue = QG. White lines = constant Burger number and frequency; shaded =  $Bu \approx 2$  domain.

The comparison between sections B3 and the reference section highlights an amplification of IW energy within the vortex, confirming an active wave-vortex interaction.

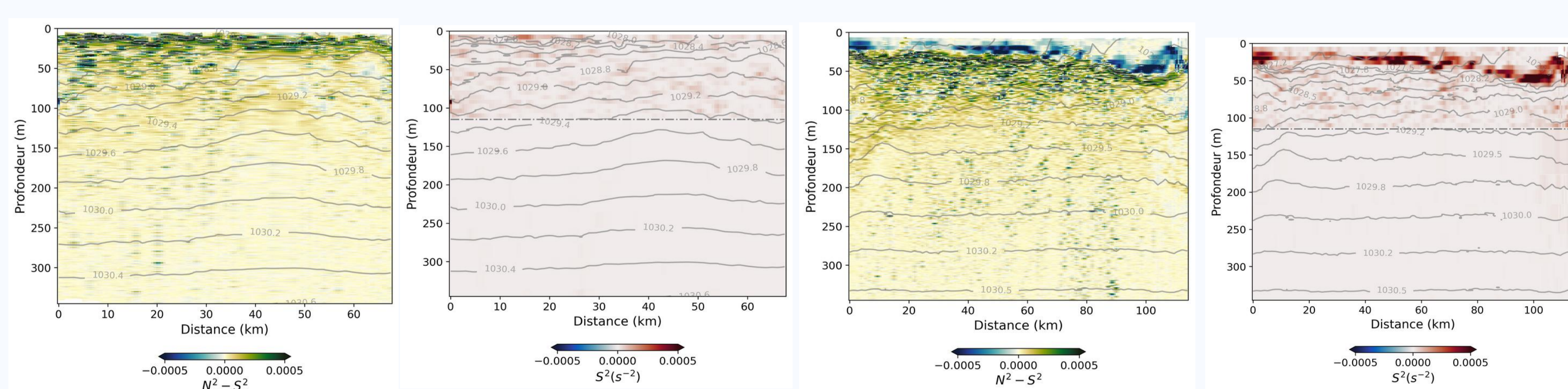


Mean energy vs horizontal wavenumber ( $k_x$ ) for QG (blue) and IW (red, dashed) components. Left = section B3 (wave-vortex interaction), right = section 11 (reference, no interaction).

The energy partition between QG motions and IW is contrasted and depends upon the wind forcing events and the sign of the background vorticity field. The largest IW total energy is observed along section crossing anticyclonic structures which is consistent with the inertial chimneys evidenced by Rolland et al (2025).

## Evidence for enhanced energy cascade within inertial chimneys

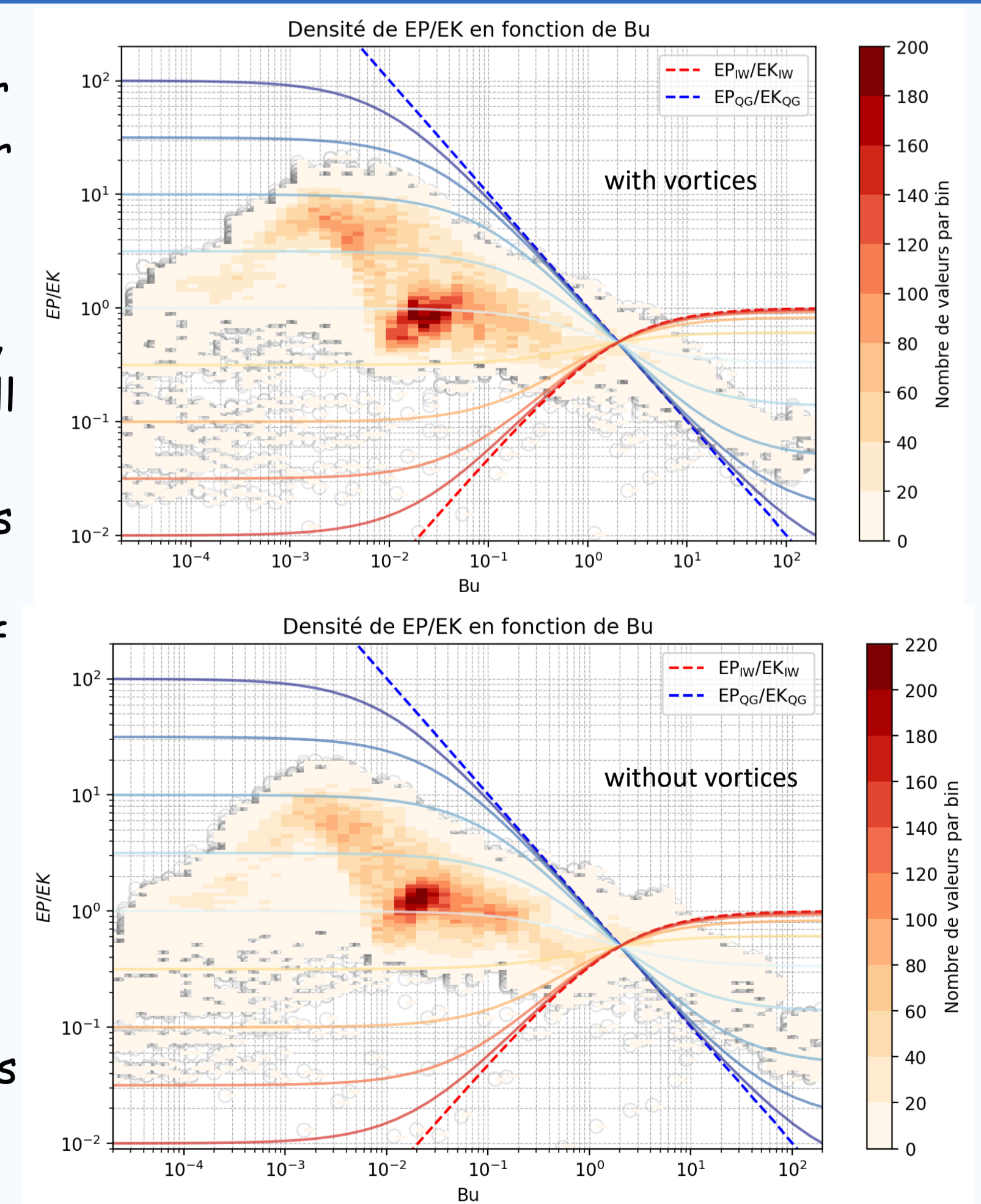
- The Richardson number ( $Ri = N^2/S^2$ ) identifies zones where shear-induced turbulence may occur
- Sections crossing anticyclonic vortices (e.g., B3) exhibit lower Ri values, in areas of strong vertical shear
- Reference sections without vortices (e.g., section 11) maintain higher Ri, consistent with more stable stratification
- This confirms that vortex-wave interactions increase vertical shear, favoring shear instability and energy transfer to smaller scales.



Richardson number estimation ( $N^2-S^2$ ), and shear square ( $S^2$ ) along section 11

Richardson number estimation ( $N^2-S^2$ ), and shear square ( $S^2$ ) along section 22 crossing B3

Histograms of APE/KE as a function of the Burger number  $Bu$ , with theoretical curves for APE/KE for different ratios  $E_{IW}/E_{QG}$  (from red to blue for increasing values: [-2, -1.5, -1, -0.5, 0, 0.5, 1, 1.5, 2]). Small APE/KE characterizing a dominance of the QG regime is observed for  $Bu \sim 10^{-3}$ , then a rapid growth toward a value of  $E_{IW} \approx E_{QG}$ . The trends are similar with and without vortices. However, most of points for  $Bu \approx [10^{-2} ; 10^{-1}]$  have an APE/KE ratio  $\sim$  twice smaller when sections with vortices/ without vortices. This is consistent with smaller IW KE in the absence of inertial chimneys.



## Conclusion and Perspectives

This study highlights the strong interaction between near-inertial waves and anticyclonic vortices in the North Balearic region at finescale scales. Internal wave kinetic energy dominates at large horizontal scales within inertial chimneys thus modifying the energy partition between IW and QG compared to the reference state. Richardson number analysis confirms enhanced shear-induced turbulence within inertial chimneys, demonstrating their role in the direct energy cascade. Implications regarding the interpretation of SWOT measurements are under present investigations.