Near-inertial waves observed within an anticyclonic eddy and turbulence measurements in the Mediterranean Sea during BOUM experiment

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Outline

- BOUM project overview
- Physical measurements during the cruise
- Near-inertial waves within anticyclonic eddies: focus on Cyprus eddy
- Turbulence and Fine-scale parameterization of dissipation rate of turbulent kinetic energy
- Conclusions & Perspectives

BOUM Objectives

Biogeochimie de l'Oligotrophie a l'Ultra-oligotrophie Mediterraneenne

▪A main goal: The representation of the interactions between planktonic organisms and the cycle of biogenic elements, considering scales ranging from single isolated processes to the entire Mediterranean Basin (Moutin et al 2012).

▪Vertical transport by turbulent mixing has a transverse impact on biogeochemical processes studied in BOUM

➢brings nutrient to the depleted euphotic zone of the oligotrophic Mediterranean sea waters, fuels primary production and impacts carbon export

▪But turbulent mixing is poorly documented in the central Mediterranean sea

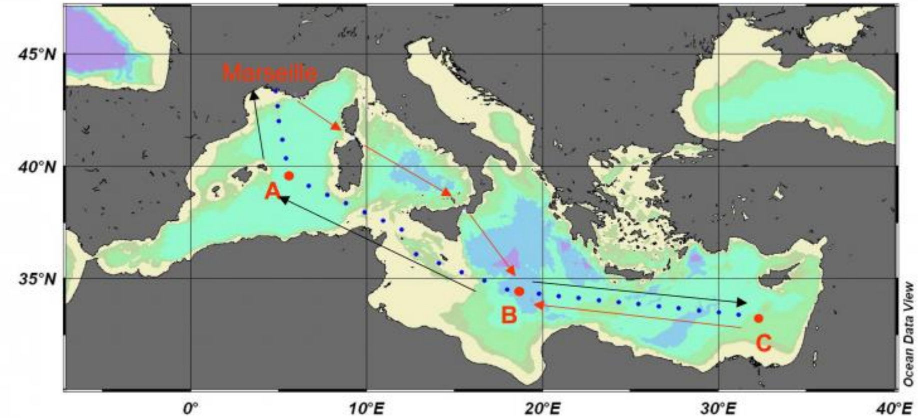
To our knowledge, there is only one dataset of microstructure measurements (Woods & Wiley 1972)

More recent measurements in the Gulf of Lion, Petrenko et al. 2000 (LATEX) and over the Cycladic Plateau in the Aegean Sea, Gregg et al. 2012

➢Effort made during BOUM to characterize vertical mixing

➢focus on 3 anticyclonic eddies => Isolated environments => importance of vertical transport, intrinsic physical processes such as upwelling, internal wave trapping (Ledwell 2008, Kunze 1995)

Objectives



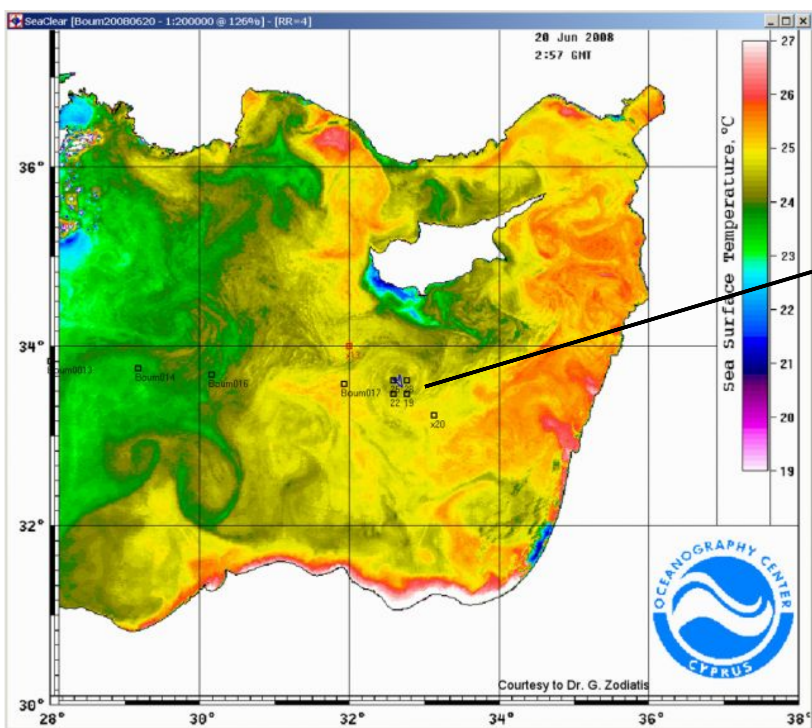
Impact of small-scale dynamics on the distribution of nutrients and ecosystem functioning

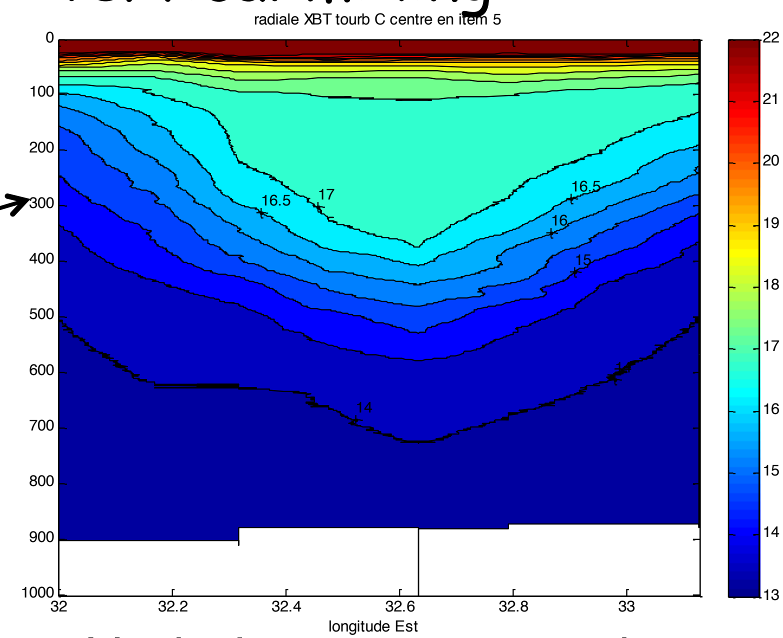
Focus on anticyclonic eddies

=> Characterize inertia-gravity waves

=> isolate the impact of vertical mixing

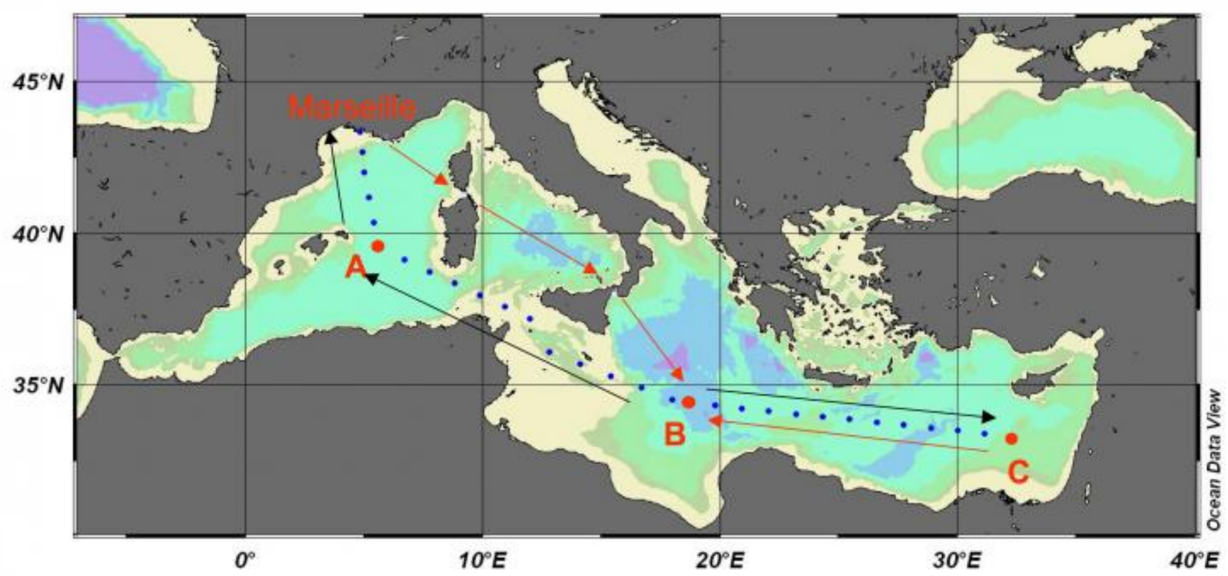
A case study: Cyprus eddy





Vertical temperature section

BOUM Measurements



- Classical fine-scale measurements:

Repeated CTD/LADCP profiles ~ every 3 h for 3 days at station A, B and C (within eddies)

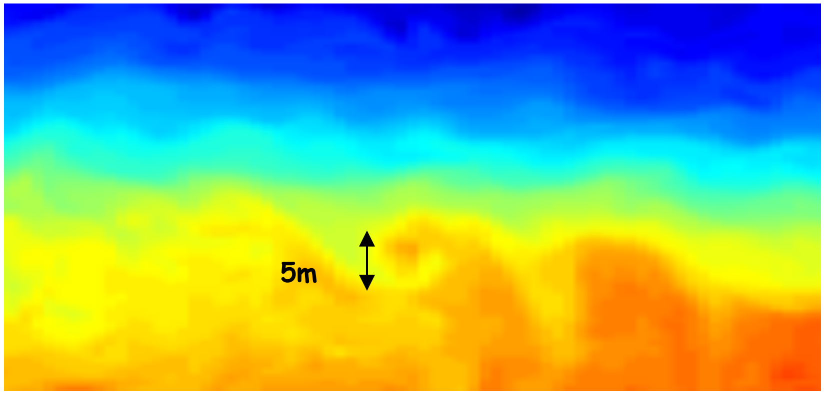
➢Salinity and Temperature at 1 m resolution

➢Horizontal currents at 8 m resolution

- Temperature microstructure measurements at station A, B and C

=>dissipation rate ε at 1 m resolution

Turbulence: direct measurements and estimates



20m

Focus on wavebreaking

Vertical cross-section of density

CTD/LADCP

SCAMP: 0-100m
Self-Contained
Autonomous
Microstructure profiler

Temperature (dt~10ms)
Vertical resolution
~1mm

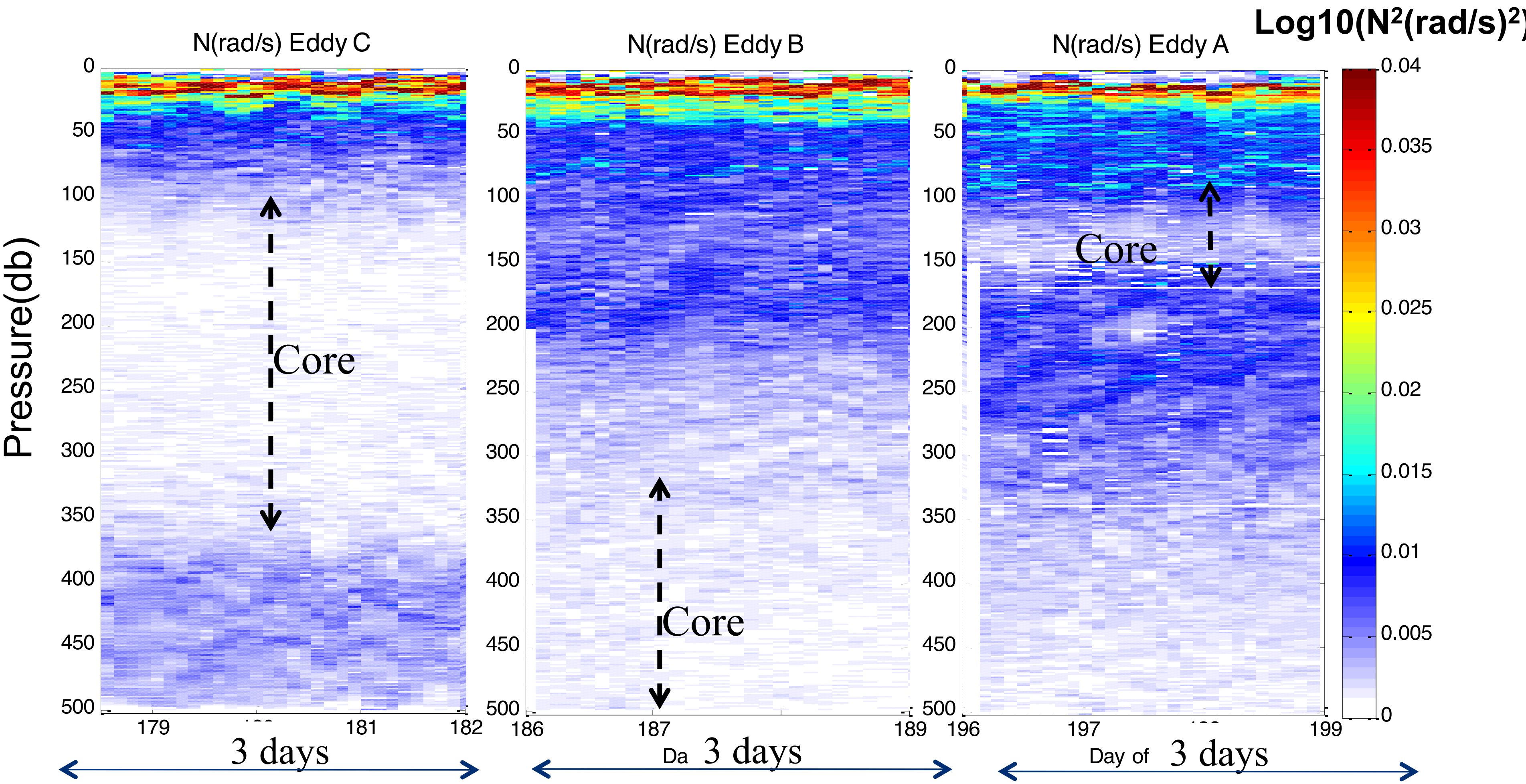
Internal waves | Stratified turbulence | Inertial range | Dissipative zone

Vertical scale: 1km, 100m, 10m, 1m, 1cm, 1mm

Fine scale measurements

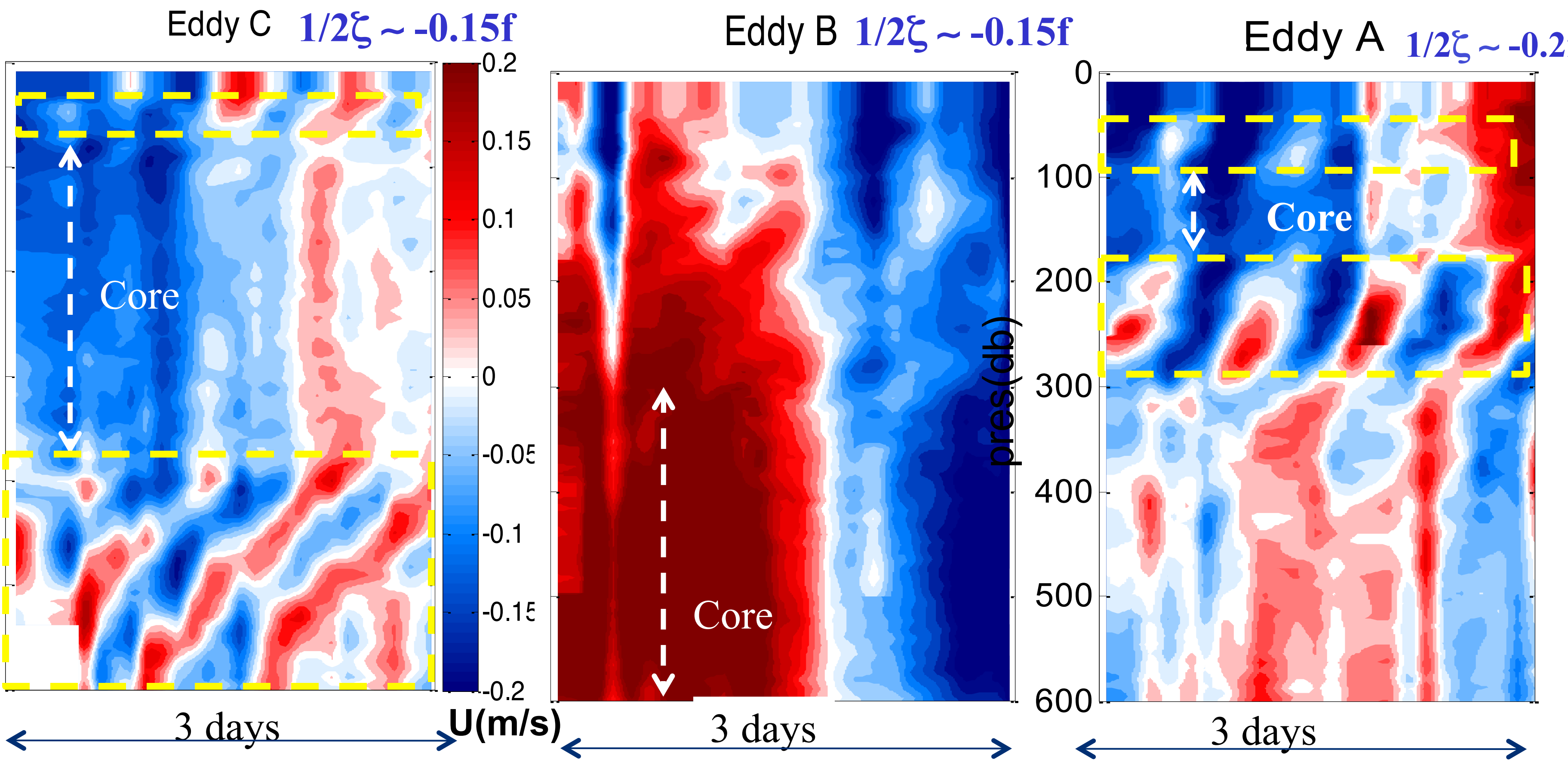
Microstructure measurements

Stratification within eddies A, B and C



- Shallow seasonal pycnocline ~15 m
- Low stratification within homogeneous eddy cores

Zonal velocity for eddies A, B and C

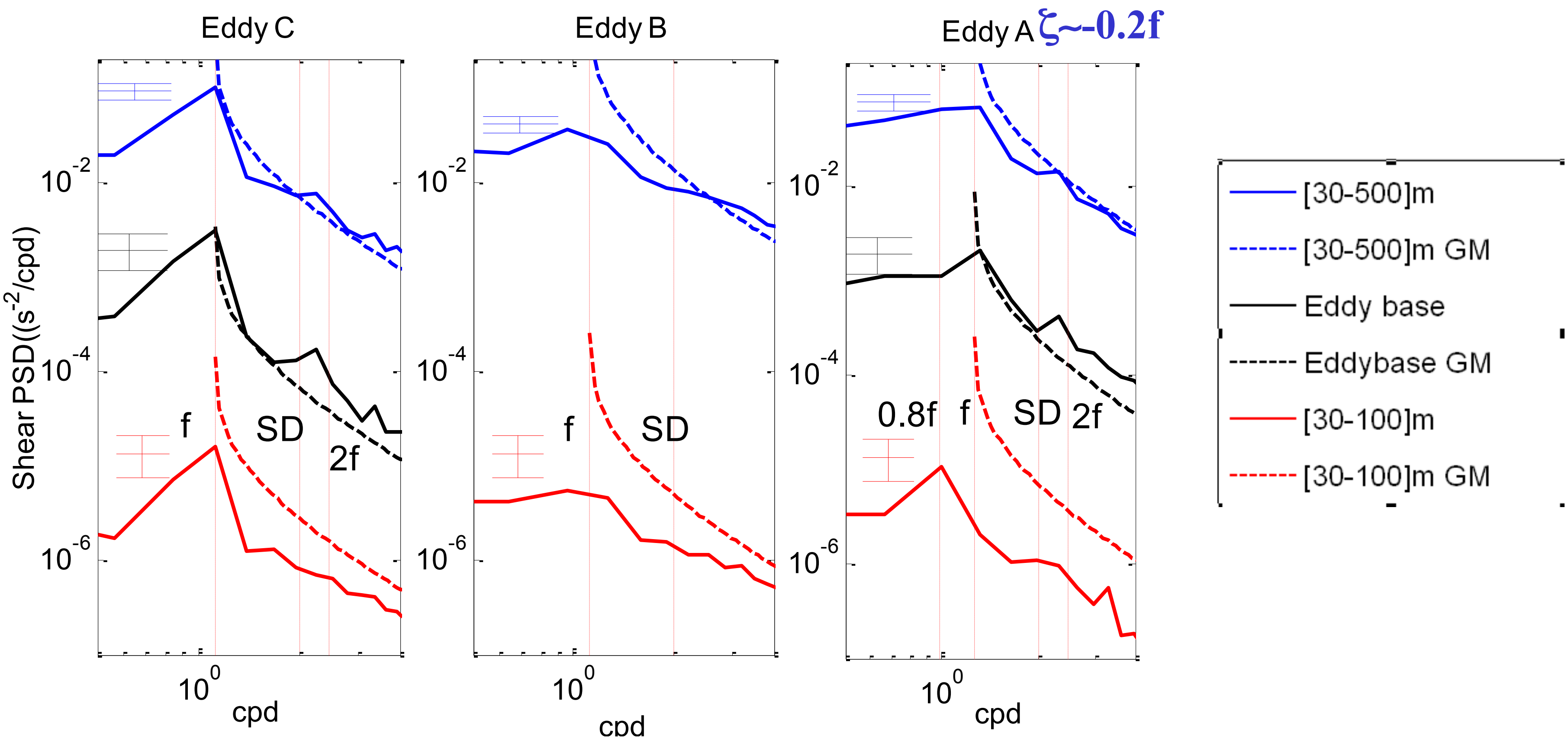


- Strong near inertial shear at the top and base of Eddy A and C
- What is the mechanism generating strong near inertial shear at depth?

✓Trapping of subinertial waves ($f_{eff}=f+1/2\zeta$) and energy increase at a critical layer at the eddy base (Kunze 1985)?

✓Baroclinic adjustment of the eddy ?

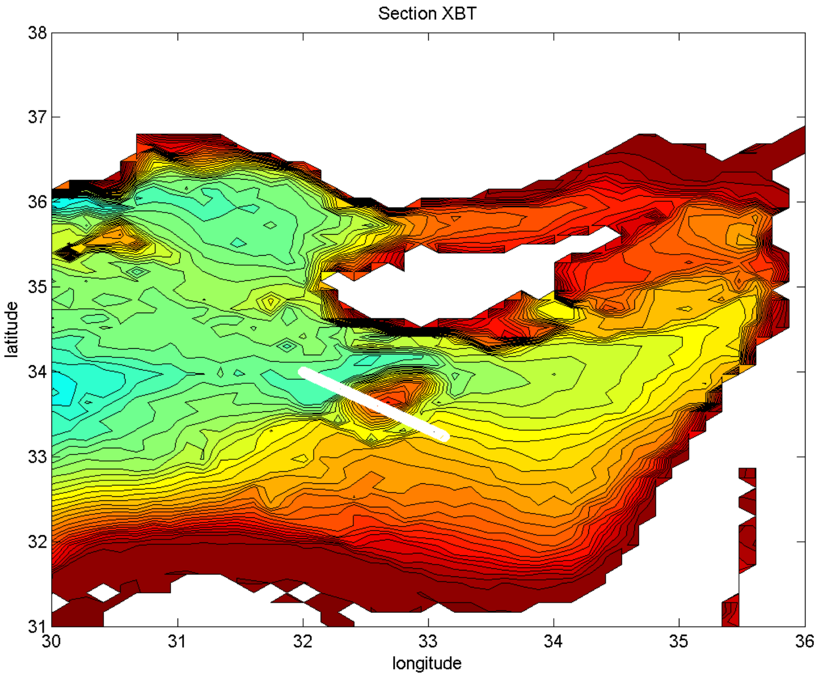
Frequency shear spectra



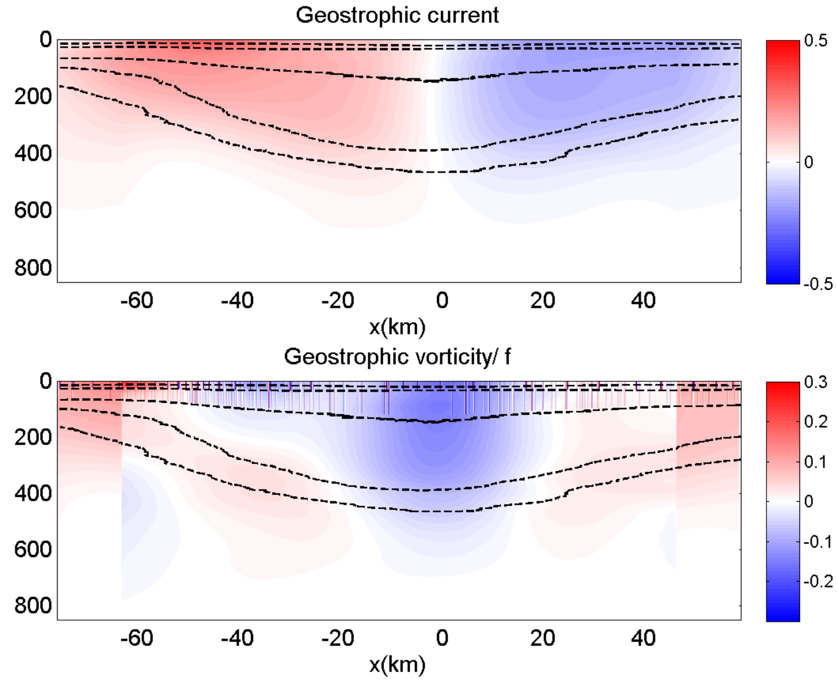
- Dominant near inertial peak at Stations C and A
- Subinertial peak (0.8f~f+1/2ζ) at station A, suggests near inertial waves trapping
- M2 internal tides at Station C, (M4 at Station B?)
- Spectral level sligthly below canonical Garrett-Munk (1976) level for station A and C slightly above Garrett-Munk level for station B

Eddy C (Cyprus Eddy): Geostrophic current & vorticity

XBT section & bathymetry



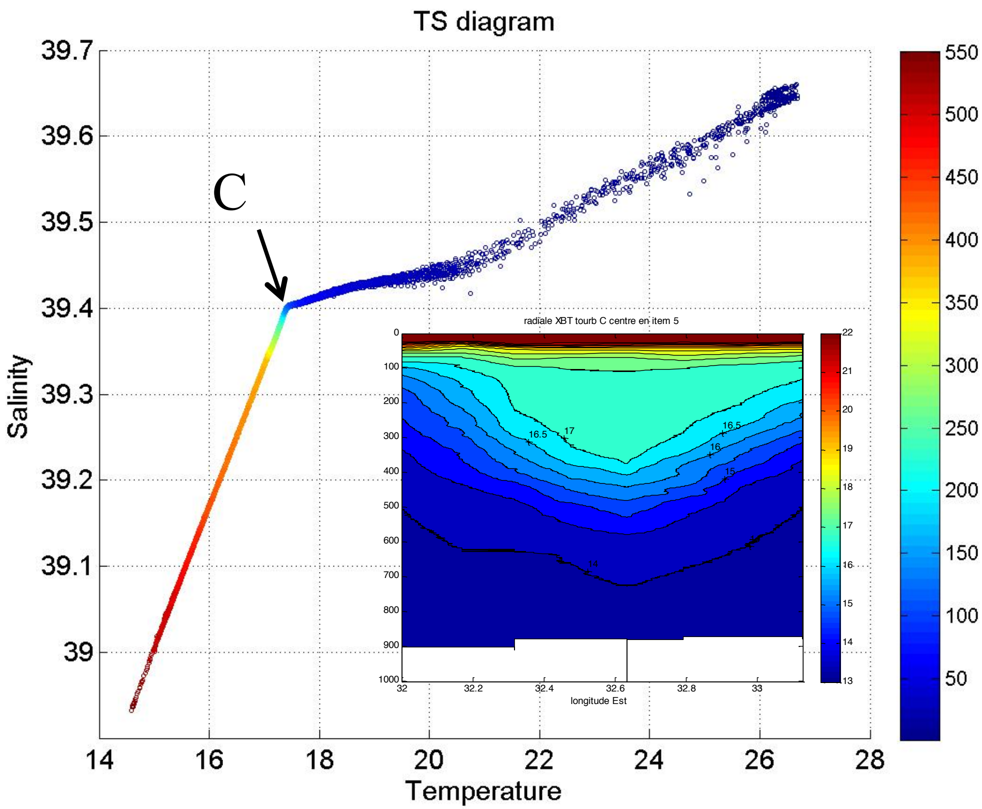
Geostrophic current & vorticity

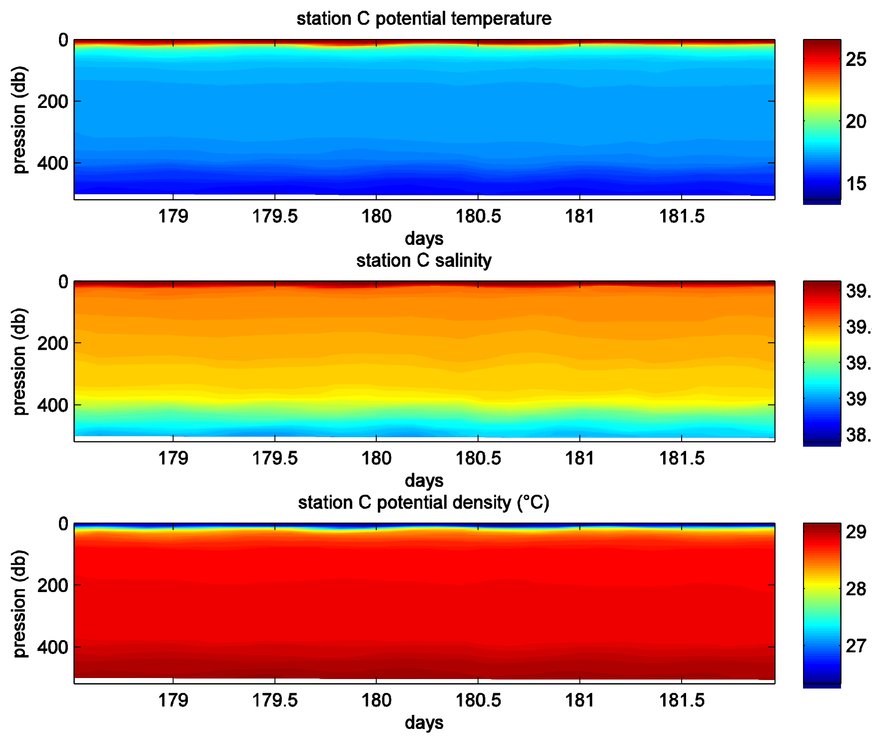


- ✓ Cyprus eddy over Therastostene sea mount
- ✓ geostrophic vorticity of the order of 0.2f in the eddy core

Eddy C:

Potential temperature & salinity

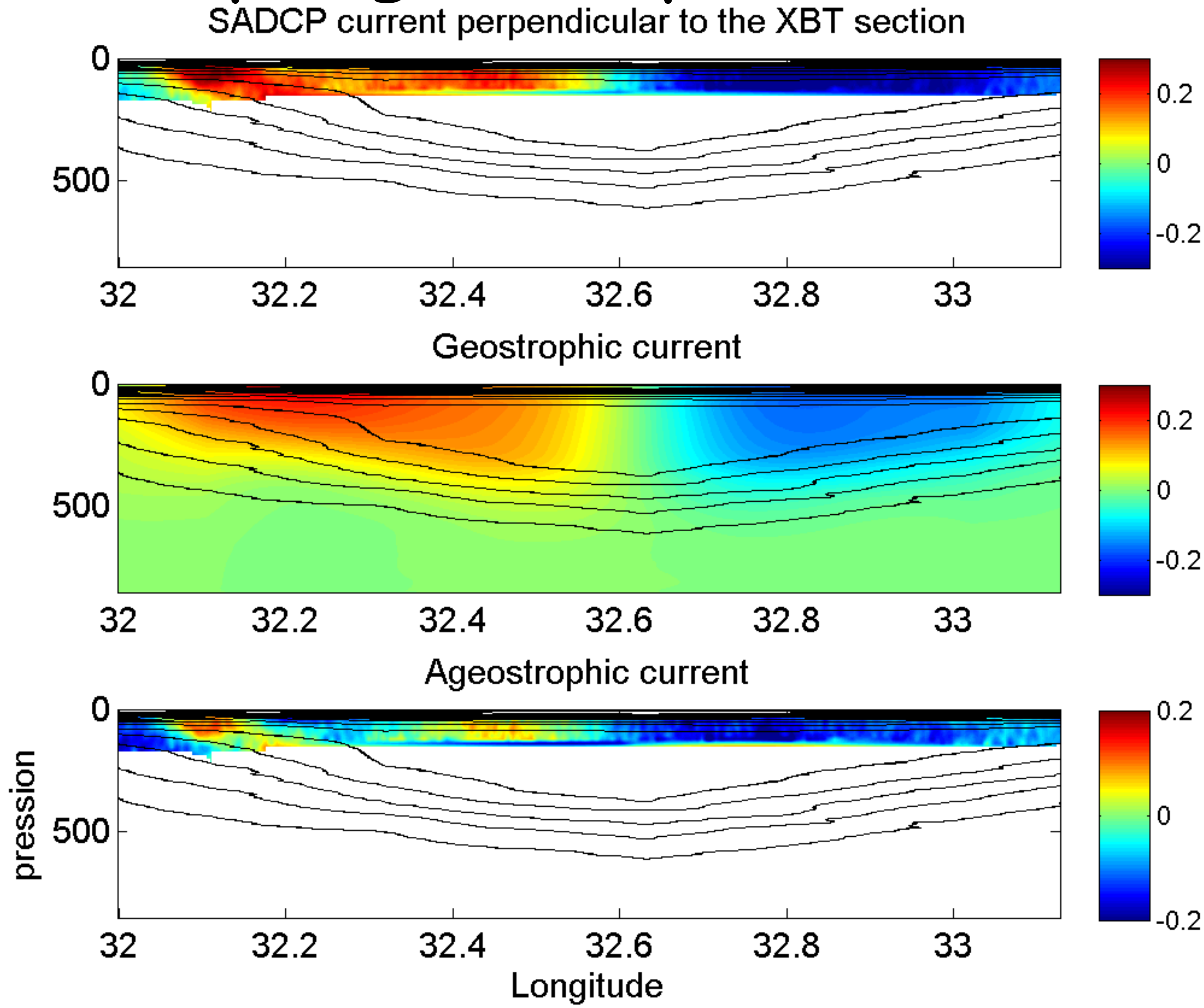




Temperature ~17.4
Salinity 39.4

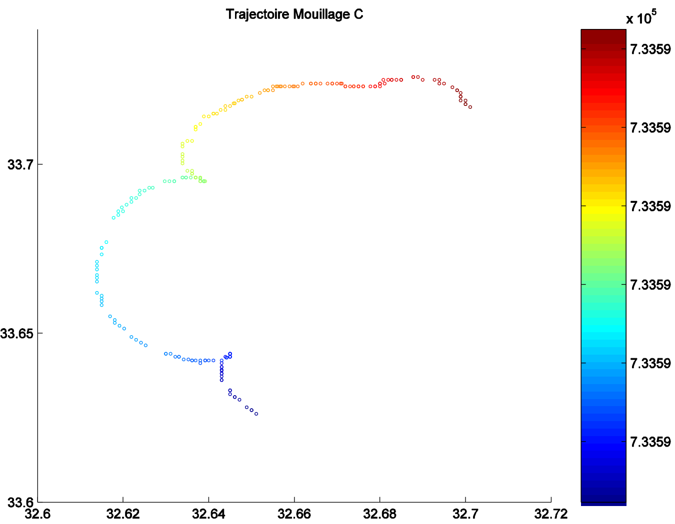
oscillations above, below and within the eddy

Eddy: Ageostrophic current

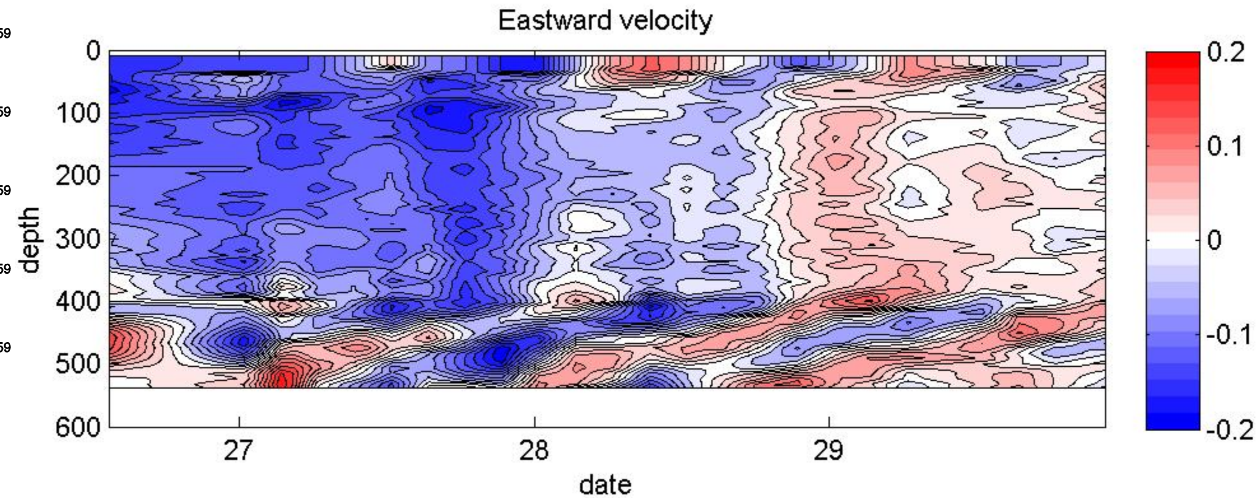


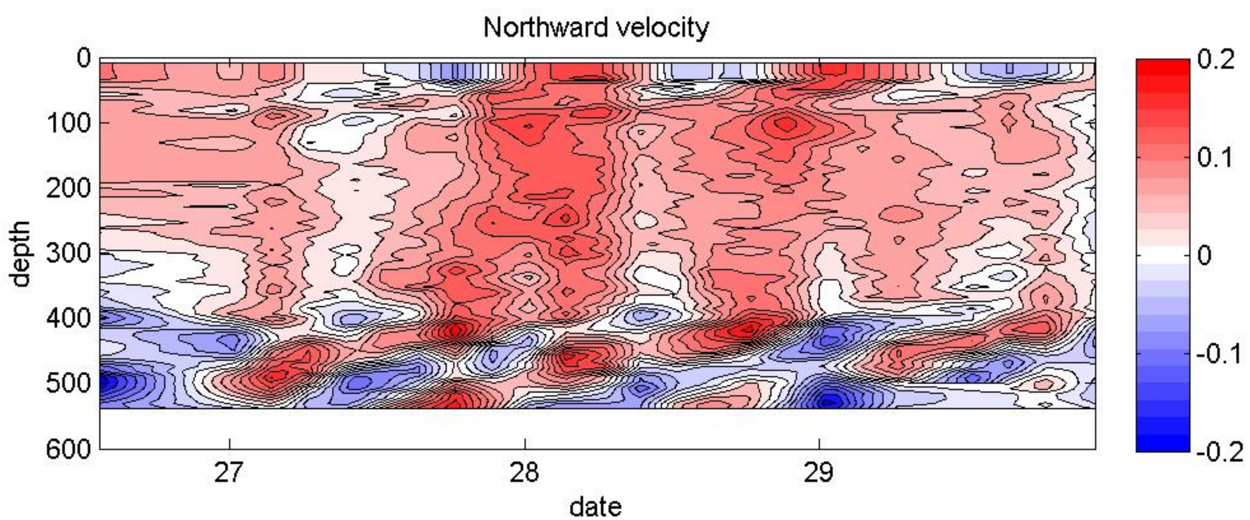
✓ horizontal structure ~40km length scale in the left half of the eddy

Eddy C: dynamics inferred from a 3 day station



Currents from LADCP data





- ✓Trajectory of the drifting mooring consistent with the currents measured from the ship: anticyclonic eddy
- ✓oscillations ~ 22h ~ 0.98f ~ 1.22 f_eff

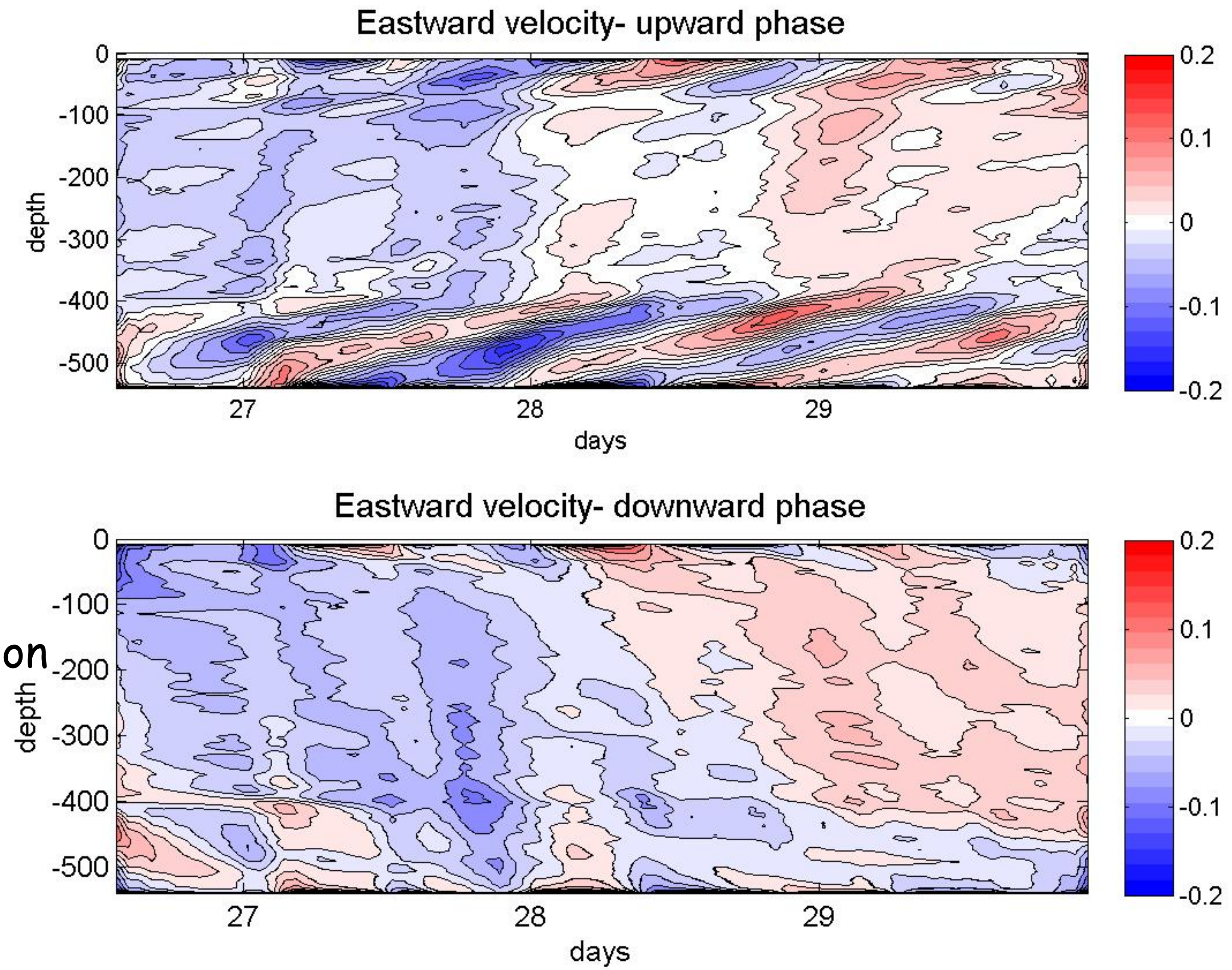
=> sub-inertial oscillations and possible wave trapping.

Near-inertial waves

Decomposition into upward/ downward phase propagation

Upward phase propagation & Downward Energy prop.

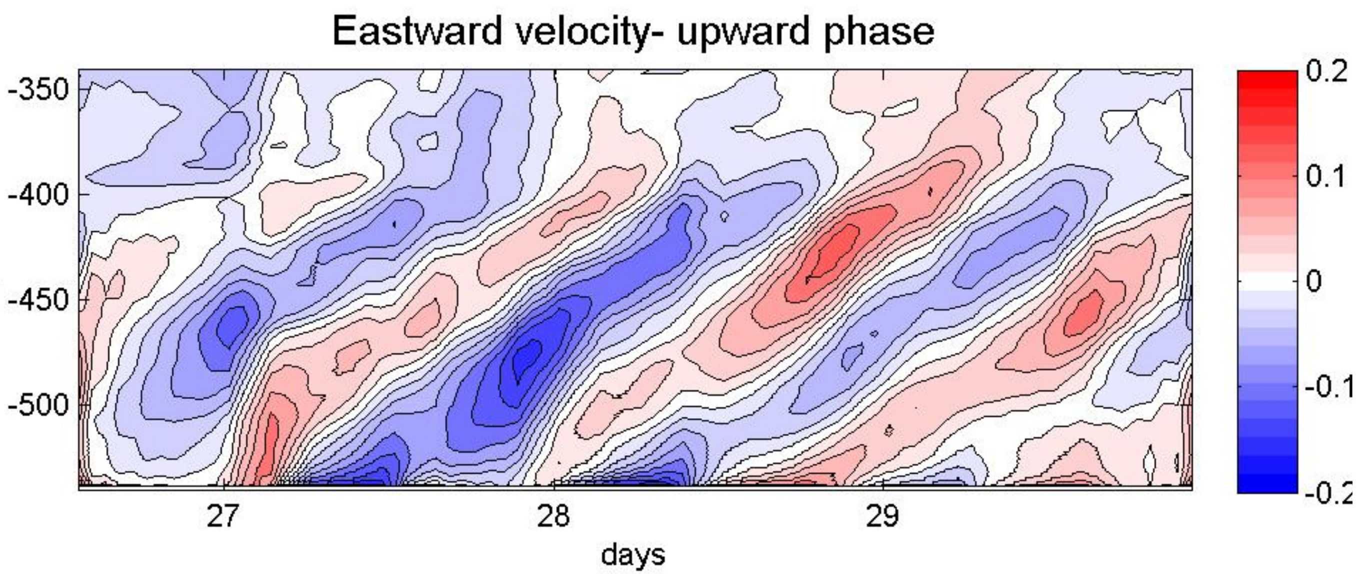
Downward phase propagation & Upward Energy prop.



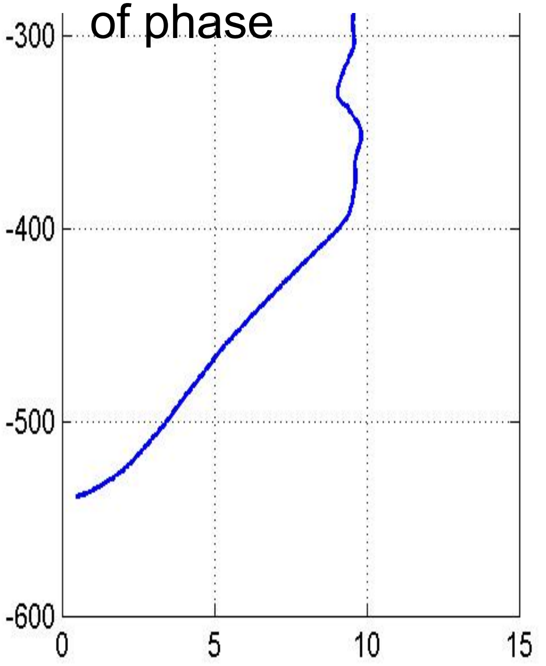
⇒Downward energy propagation dominates: atmospheric forcing & geostrophic adjustment play a role

Near-inertial waves:

characteristics of the waves and energy fluxes



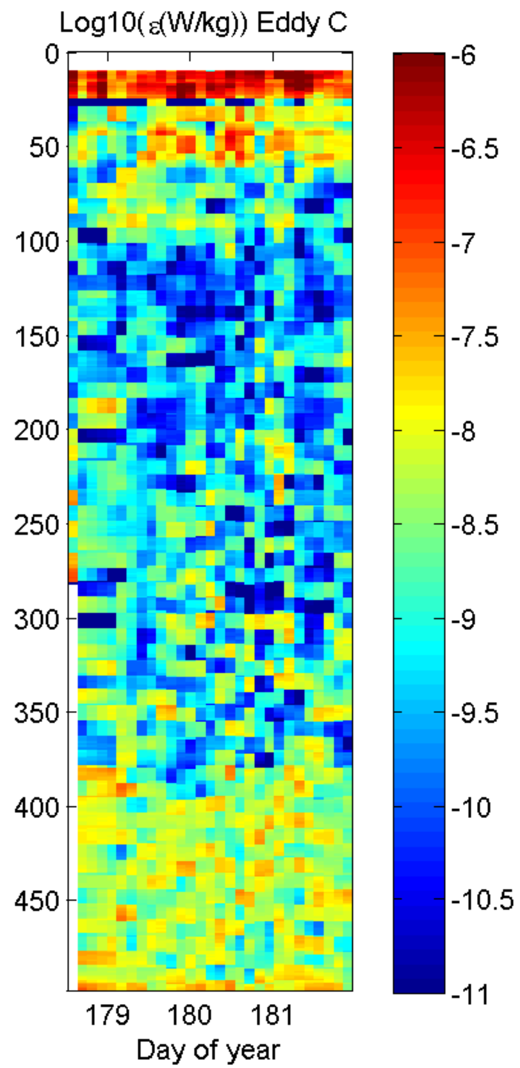
Vertical profile of phase

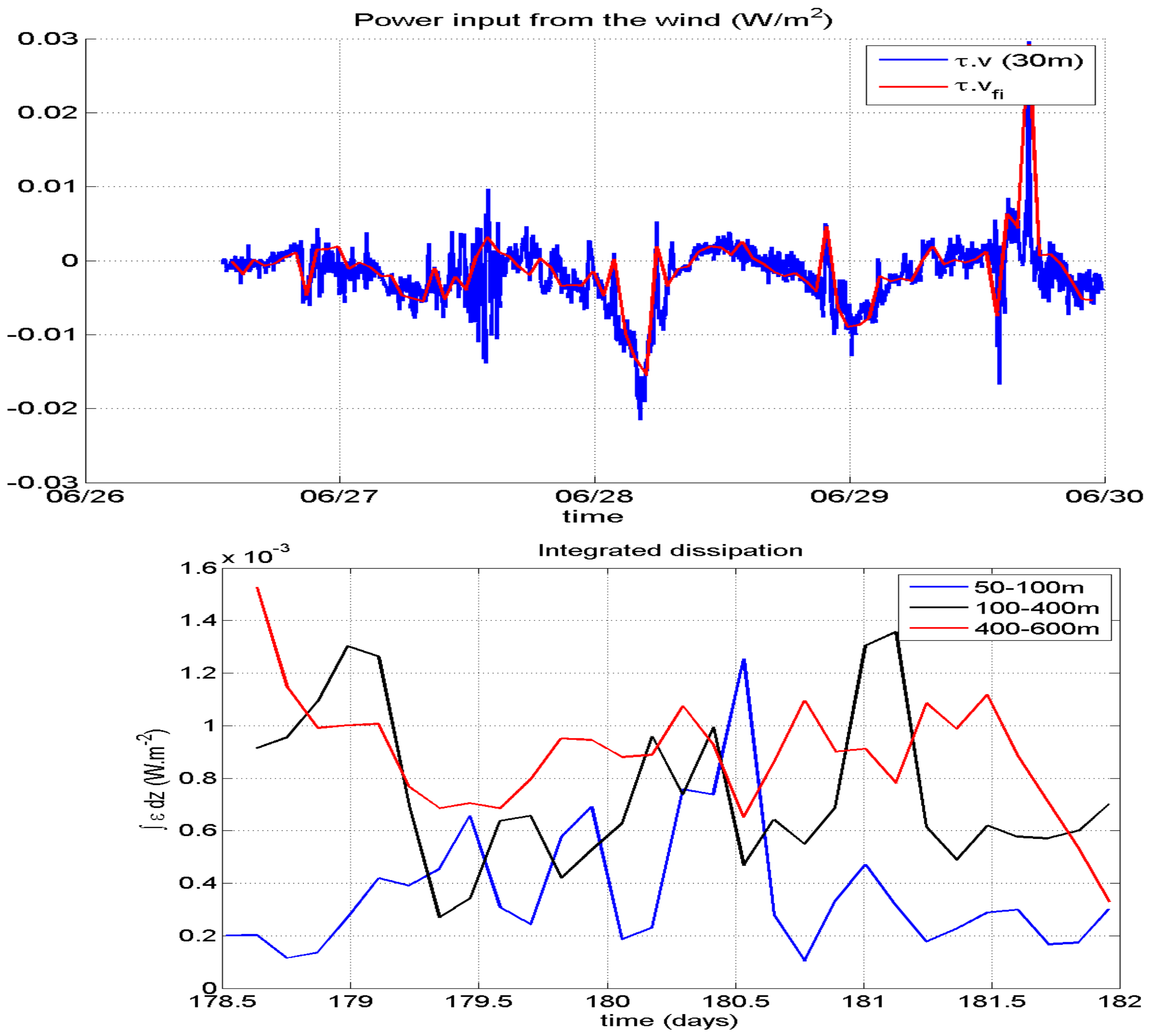


Complex demodulation:

- Infer vertical wavelength λ_z~ 100m
- Horizontal wavelength λ_h~11km (from dispersion relation)
- Vertical group velocity, cg_z~0.8mm/s
- Vertical energy flux ~6mW/m2

Power input from the wind into total currents and inertial currents/ Vertically integrated dissipation within the eddy





Summary

- Cyprus eddy

evidence of baroclinic near-inertial waves in the first 550m, especially at the top and base of the eddy

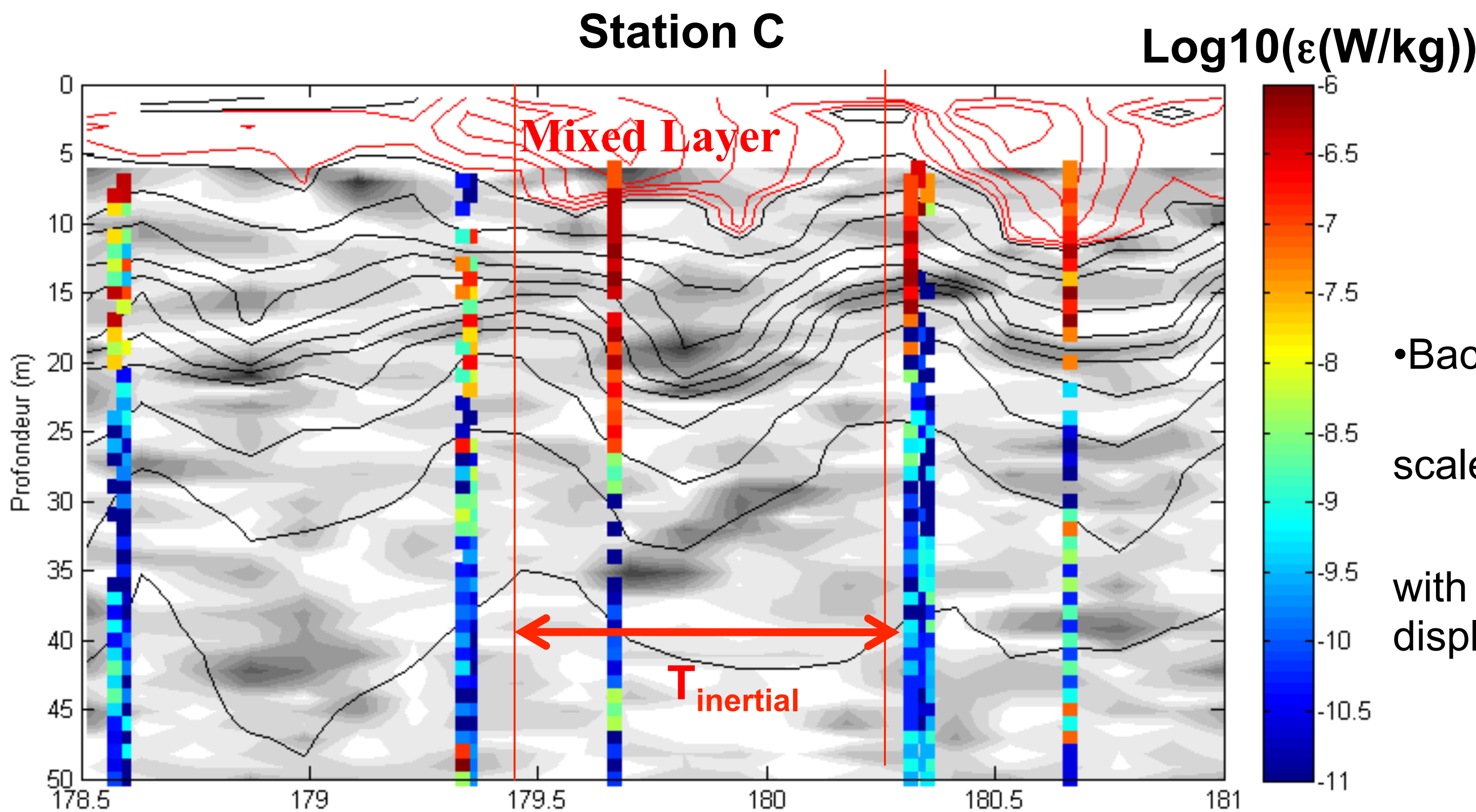
- Scenario of generation through inertial pumping consistent with the observations and with estimates of energy fluxes

- a case study for the impact of vertical mixing induced by near-inertial baroclinic waves

Perspectives

- Investigate further geostrophic adjustment and impact of wind forci (numerical simulations)
- Spatial structure of the waves and energy fluxes

Dissipation rate from microstructure measurements



•Background in gray

scale=strain $\left|\frac{\partial \xi}{\partial z}\right|$

with ξ isopycnal displacement

•Strong variability of dissipation : $10^{-11} < \varepsilon < 5.10^{-6}$ W/kg,

➢High values in the seasonal pycnocline (10-20)m: $\varepsilon_{mean}=2.10^{-7}$W/kg

➢Moderate values below the seasonal pycnoncline (z>20m) $\varepsilon_{mean}=7.10^{-9}$W/kg

▪Influence of internal waves strain (Alford 2010, Alford Pinkel 2000) (important to take into account in a parameterization)

Fine scale parameterization of dissipation

•Assuming a Garrett and Munk spectrum , nonlinear wave wave interaction models predict a scaling $\varepsilon \sim E_{GM}{}^2 N^2$ (D'Asaro and Lien 1999, Henyey et al 1985)

•Gregg (1989) proposed a popular incarnation of this scaling expressed with shear and taking into account deviation from GM level

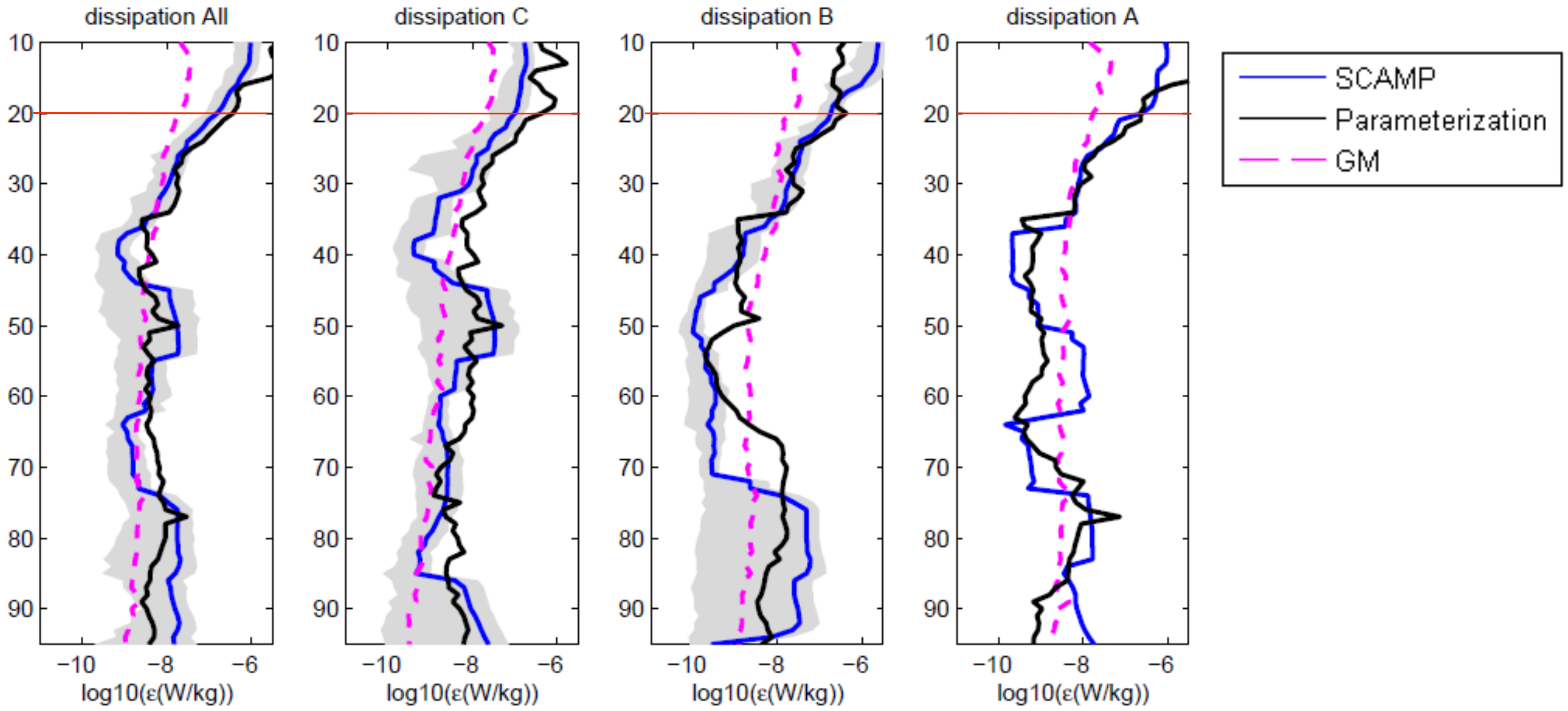
$$\epsilon_{IW} = 1.8 \times 10^{-6} \left[f cosh^{-1} \left(\frac{N_0}{f} \right) \right] \left(\frac{N^2}{N_0^2} \right) \left(\frac{S_{10}^4}{S_{GM}^4} \right)$$

•Several studies (Alford 2010, Alford and Gregg 2001) and models (Kunze 2006, Gregg 2003, Polzin 2005) suggest taking into account the influence of strain.

•We consider strain through the function $h(R_\omega)$ (Kunze 2006), where R_ω is the ratio of shear variance to strain variance.

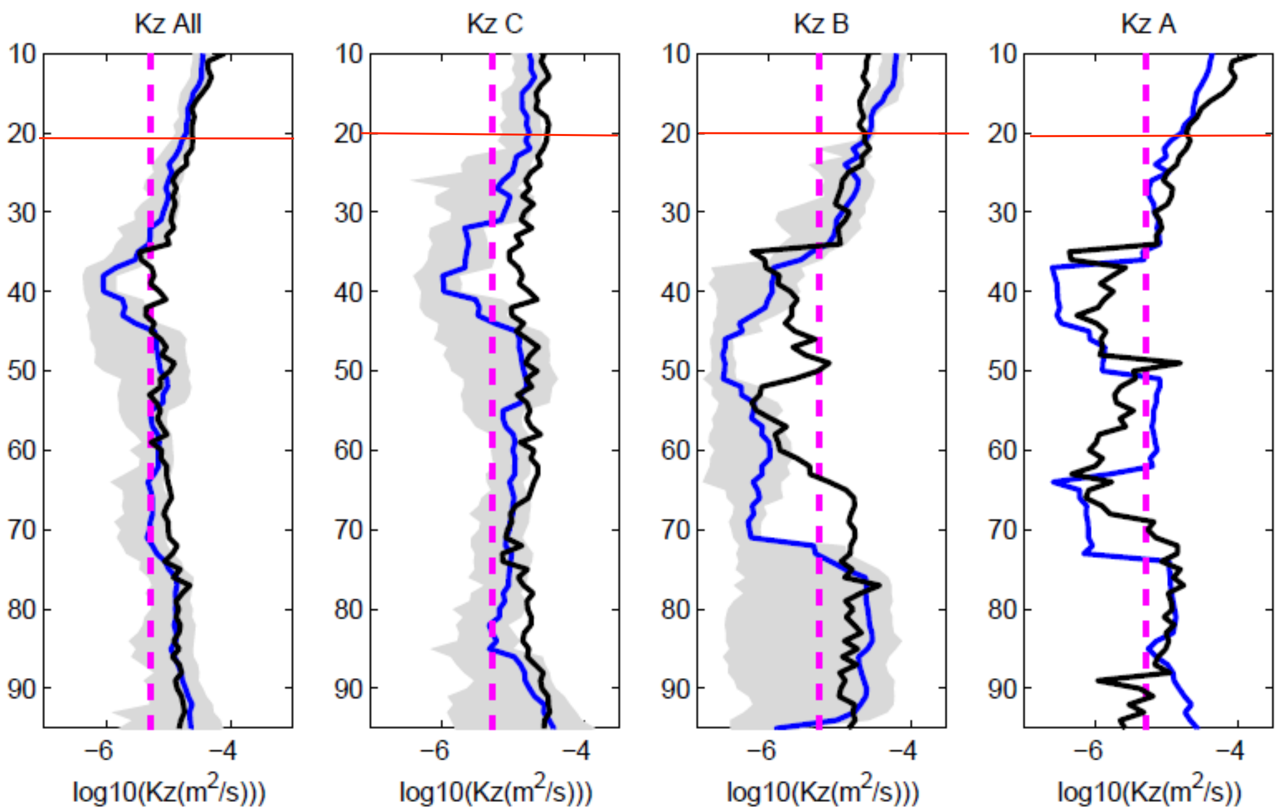
$$\epsilon_{param} = h(R_\omega)\epsilon_{IW}$$

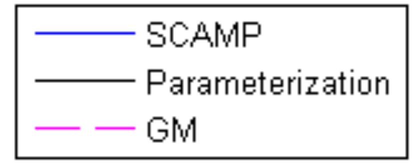
Parameterized ε vs measured ε



- Good agreement between measurements and parameterization that falls within the 95% CI over 80% of the profile length
- The dissipation level is comparable to GM below the seasonal pycnocline (20m depth) but nearly two order of magnitude higher above
- Parameterization should be considered with much caution above 20 m depth because comparison with GM may not be valid there (proximity of surface boundary)

Parameterized Kz vs experimental Kz





Kz is estimated from

(Shih et al 2005)

- for $\varepsilon/(\upsilon N^2) < 100$

$$Kz = \Gamma \varepsilon N^{-2} \quad \text{(Osborn 1980)}$$

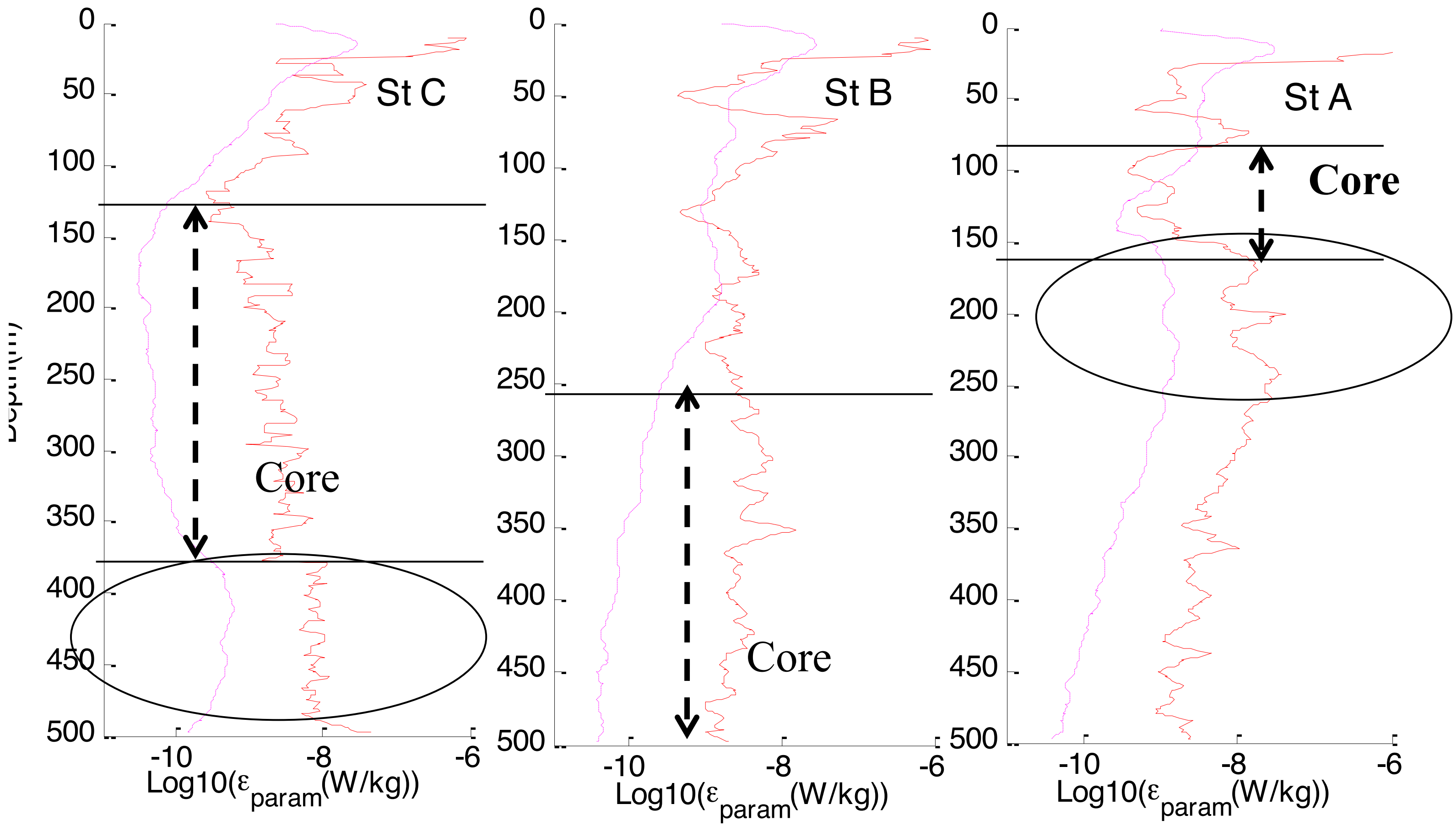
- for $\varepsilon/(\upsilon N^2) > 100$

$$Kz = \upsilon \left(\frac{\varepsilon}{\upsilon N^2} \right)^{1/2}$$

- Kz is comparable to GM below the seasonal pycnocline (20m depth) but one order of magnitude higher in the pycnocline, suggesting important exchange with the mixed layer

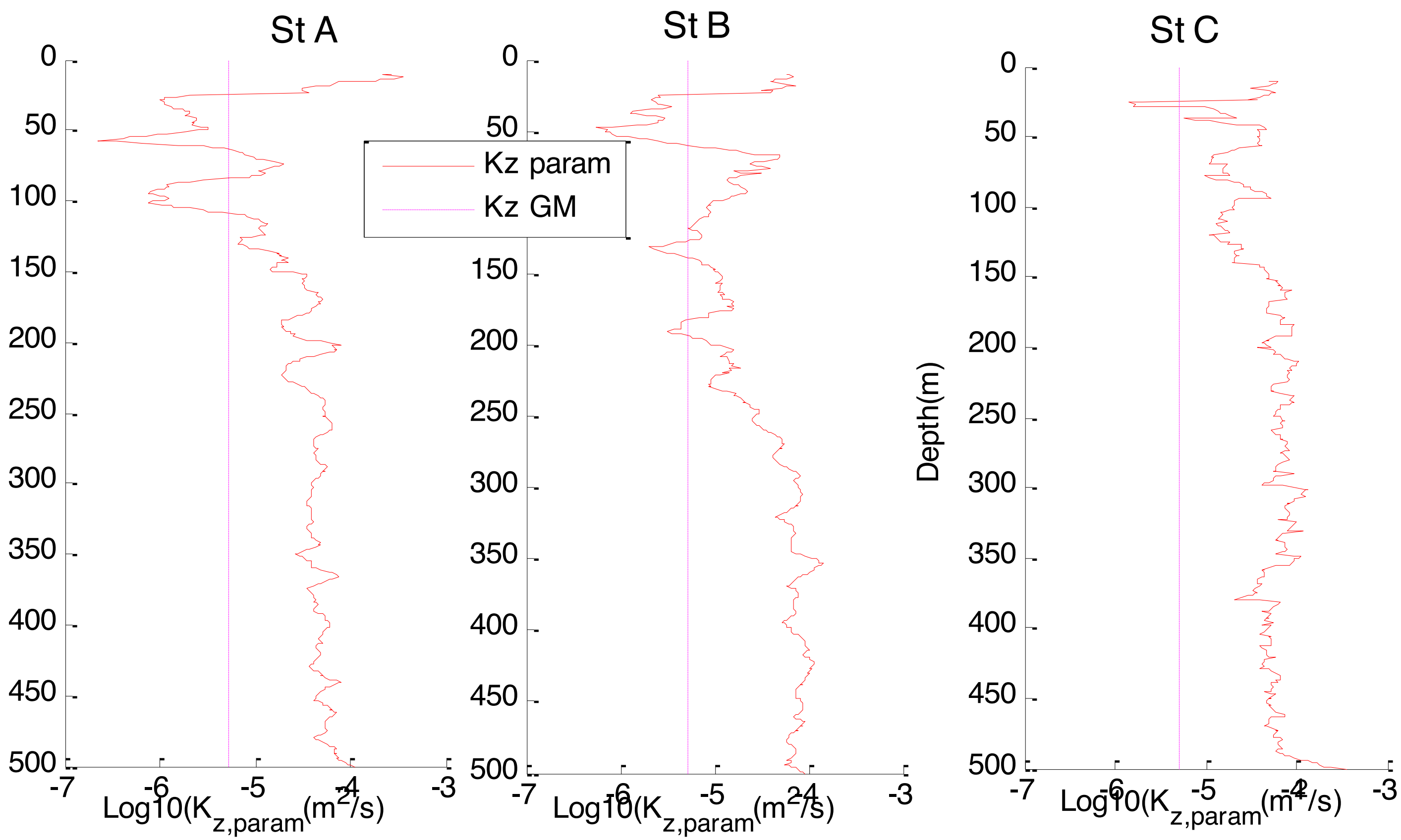
- Values slightly smaller than found within upper 100 m in other anticyclonic eddies with similar shallow seasonal pycnocline in Sargasso sea (Ledwell 2008) or in North Atlantic (Dae Oak et et al 2005) but with stronger wind forcing

ε estimates over full depth range of eddies



- Increasing trend of ε at the base of eddy C and A where maximum near inertial shear is observed

Kz estimates over eddies full depth range

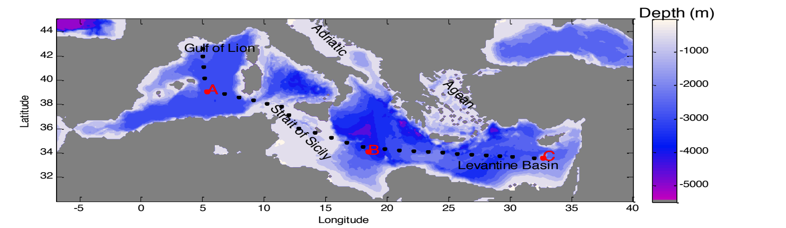


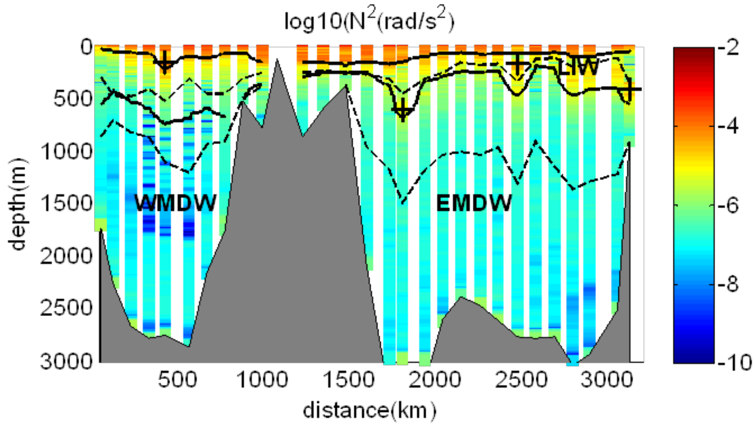
- Dissipation rate trends partly balanced for Kz by the lower stratification within the eddies
- Kz is generally higher by a factor 2 to 3 to GM values below 150m despite low internal wave energy sources (weak winds in summer and weak tides) =>Trapped near inertial waves?

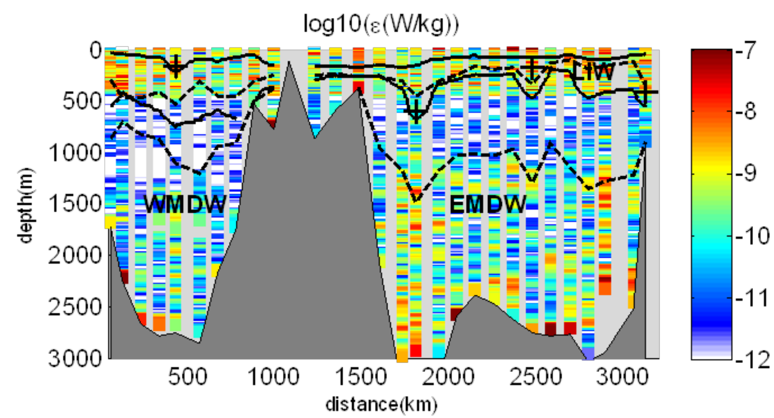
W-E transect of ε and Kz estimates from isolated full depth stations

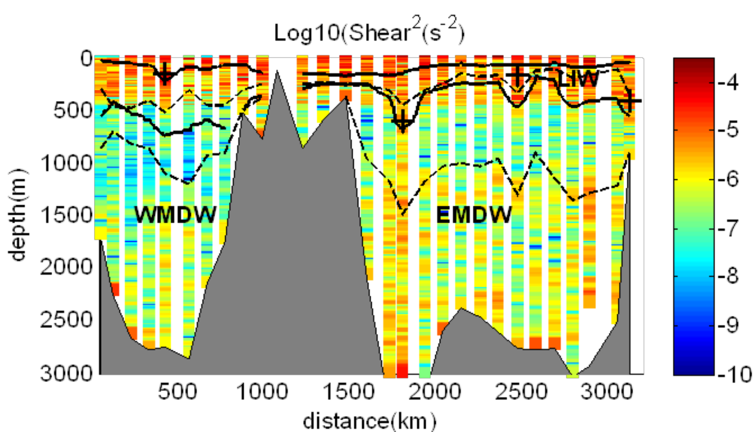
- Strong shear, dissipation rate and eddy diffusivity 1000 m above the bottom

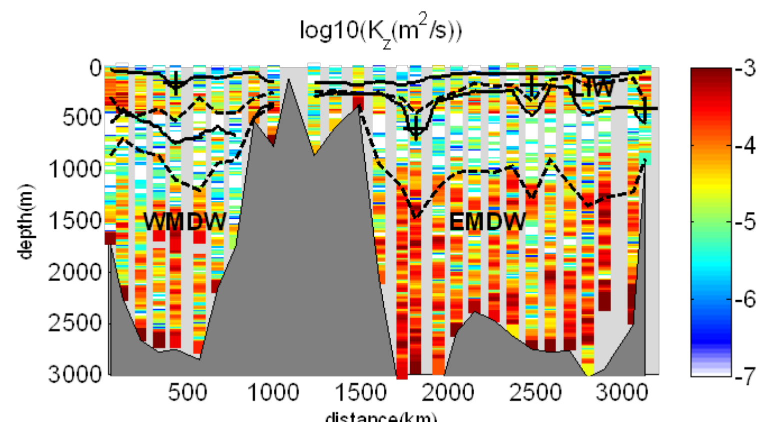
- Strong Kz above the bottom bounds the WMDW and EMDW











Conclusions

- Microstructure measurements:
  - High ε values in the seasonal pycnocline and relatively high Kz, suggest that the seasonal pycnocline may be permeable to exchange between mixed layer and deeper stratified water.
  - ε and Kz estimates are comparable to GM below the seasonal pycnocline for ($z<100$m)

- Fine scale parameterization is in good agreement with direct measurements ($0<z<100$m)
  - high ε_{param} values at the base of eddies associated with inertial shear
  - Kz values higher than GM level at depth ($z>100$m) resulting from strong shear at the eddy base or weak stratification within eddies

- Kz and ε transect:
  - Strong shear, dissipation rate and eddy diffusivity 1000 m above the bottom
  - Strong Kz above the bottom bounds the WMDW and EMDW

Perspectives

- Determine the mechanism of strong near inertial waves generated at the base of eddies A and C. Geostrophic adjustment ? wave trapping at the eddy base decrease of group velocity and increase of energy (Kunze 1985, Lee and Niler 1998)?

  - High resolution idealized simulations (P. Lelong)

- Venus campaign (K. Schoeder) with full depth microstructure profiles (VMP) in the Western mediteranean sea (June 2013), coll (B. Ferron)

- Implement the parameterization in numerical model after defining a formulation relevant to numerical models (Nemo in the Med sea at different resolutions)

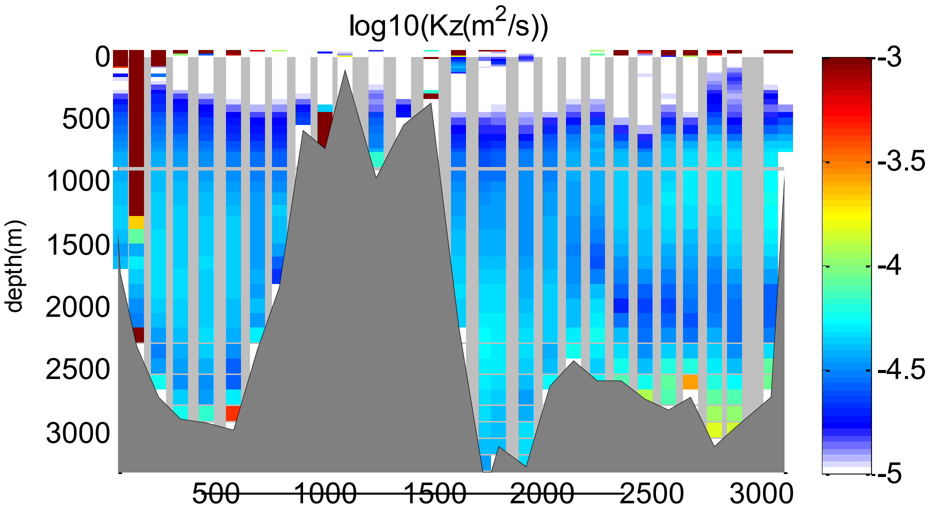
- Long-term mooring measurements coupled with autonomous turbulence measurements (if funded)

- fin

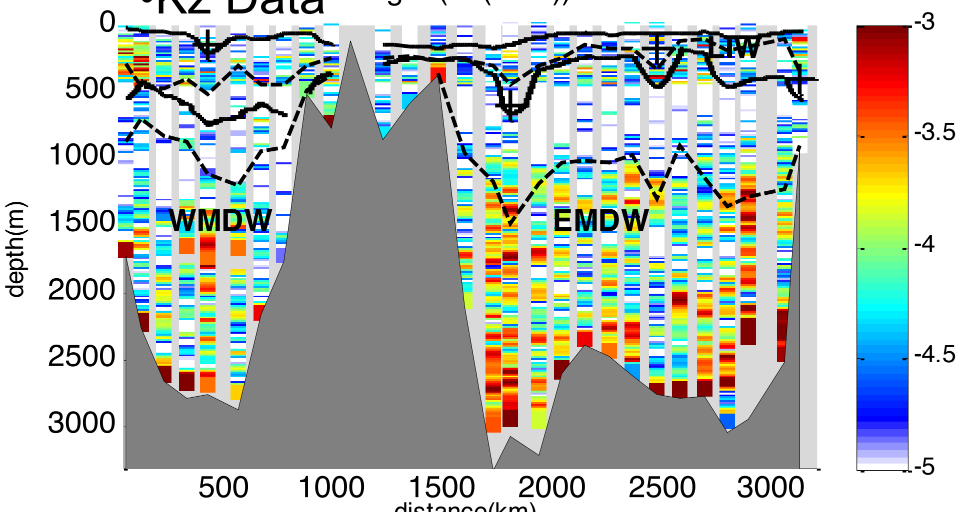
Comparison with high resolution numerical simulation Nemo Orca 36 (1/36°) 75 levels

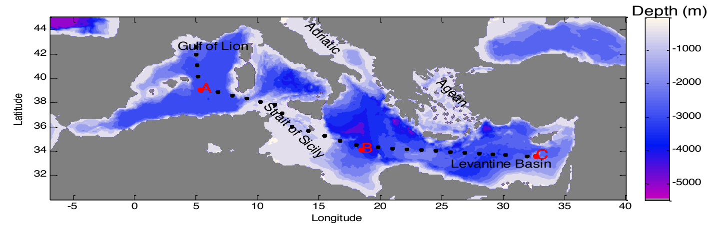
(T. Arsouze and K. Beranger)

•Kz Simu



•Kz Data





- Smaller Kz above 500m and above the bottom in the simulation
- larger Kz within [500-1500] m in teh simulation
- ➢ New data from Venus campaign will allow more comparisons with direct estimates

Perspective

- ➢ Applying fine scale parameterization to model outputs
- ➢ Implementation of fine scale parmetrization in the model

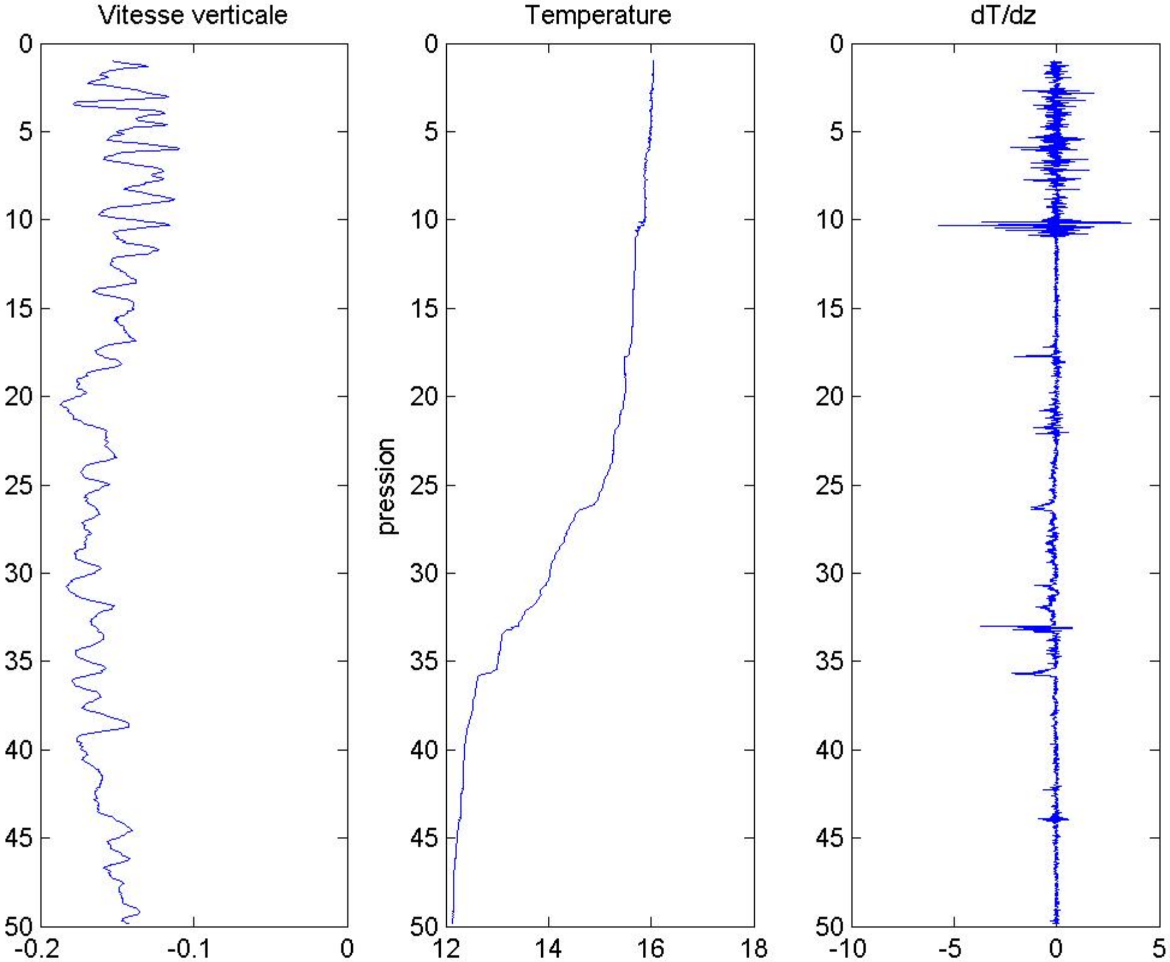
Scamp microstructure profiler

Small free fall microstructure profiler (max depth 100m)

- Temperature microstructure measurements, time response dt: 10 ms
- Conductivity measurements time response: 1s
- Flurorescence sensor dt: 10 ms
- Fall velocity U_{fall}=0.1m/s
- ➢Vertical resolution: U_{fall} dt≈1mm

How are dissipation rate and eddy diffusivity inferred from temperature SCAMP measurements?

(a) (b) (c)



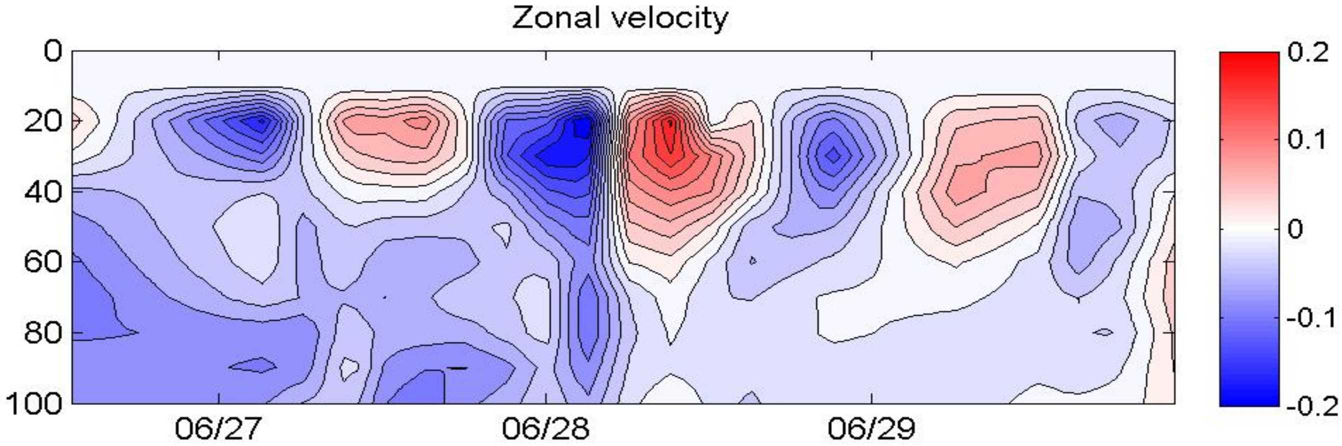
(a) Vertical speed (m/s)

(b) Temperature

(c) Vertical temperature gradient

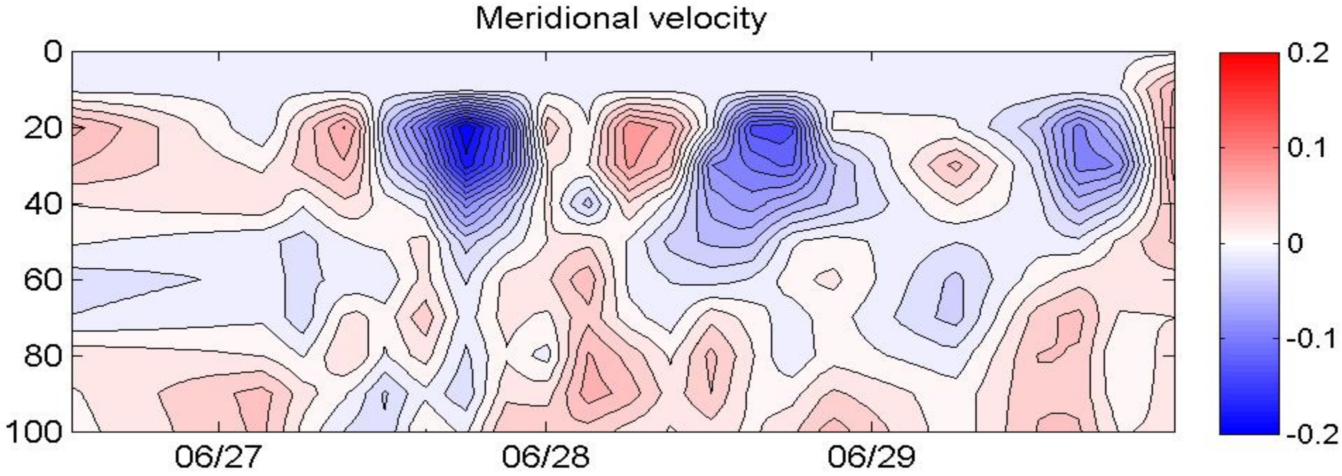
Near-inertial waves

Zoom over [0-100m]



~inertial currents

Propagation at depth starts ~ 28/06



Measurements

Classical fine-scale measurements

- Repeated CTD/LADCP profiles
 ~ every 3 h for 3 days

- Drifting mooring

- Microstructure measurements with SCAMP

SCAMP: 0-100m
Self-Contained Autonomous Microstructure profiler