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
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
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 $\varepsilon$ at 1 m resolution
Turbulence: direct measurements and estimates

**Vertical cross-section of density**

- **Focus on wavebreaking**

- **20m**

**Vertical scale**

- **5m**

**SCAMP: 0-100m**
- Self-Contained Autonomous Microstructure profiler
- Temperature (dt ~10ms)
- Vertical resolution ~1mm

**CTD/LADCP**

- **Internal waves**
- **Stratified turbulence**
- **Inertial range**
- **Dissipative zone**

**Fine scale measurements**

- 1km
- 100m
- 10m
- 1m
- 1cm
- 1mm

**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 \( (f_{\text{eff}} = f + 1/2\zeta) \) 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 \( (0.8f \approx f + 1/2\zeta) \) at station A, suggests near inertial waves trapping
• M2 internal tides at Station C, (M4 at Station B?)
• Spectral level slightly 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

- Cyprus eddy over Therastostene sea mount
- Geostrophic vorticity of the order of 0.2f in the eddy core
Potential temperature & salinity

Eddy C:

Temperature ~17.4
Salinity 39.4

oscillations above, below and within the eddy
Eddy: Ageostrophic current

SADCP current perpendicular to the XBT section

- Geostrophic current
- Ageostrophic current

✓ horizontal structure ~40km length scale in the left half of the eddy
Eddy C: dynamics inferred from a 3 day station

✓ 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

Eastward velocity- upward phase

Eastward velocity- downward phase

⇒ Downward energy propagation dominates: atmospheric forcing & geostrophic adjustment play a role
Near-inertial waves: characteristics of the waves and energy fluxes

- Infer vertical wavelength $\lambda_z \sim 100m$
- Horizontal wavelength $\lambda_h \sim 11km$ (from dispersion relation)
- Vertical group velocity, $c_{g_z} \sim 0.8mm/s$
- Vertical energy flux $\sim 6mW/m^2$
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 forcing (numerical simulations)
- Spatial structure of the waves and energy fluxes
Dissipation rate from microstructure measurements

Station C

Log10(\(\varepsilon\) (W/kg))

• Strong variability of dissipation: \(10^{-11} < \varepsilon < 5 \times 10^{-6}\) W/kg,
  - High values in the seasonal pycnocline (10-20 m): \(\varepsilon_{\text{mean}} = 2 \times 10^{-7}\) W/kg
  - Moderate values below the seasonal pycnocline (z > 20 m): \(\varepsilon_{\text{mean}} = 7 \times 10^{-9}\) W/kg

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

• Background in gray scale = strain \( \frac{\partial \xi}{\partial z} \) with \( \xi \) isopycnal displacement

Mixed Layer

\(T_{\text{inertial}}\)
• 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

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

• 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 $R_\omega$ is the ratio of shear variance to strain variance.

$$\varepsilon_{param} = h(R_\omega) \varepsilon_{IW}$$
Parameterized $\varepsilon$ vs measured $\varepsilon$

- 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).
Kz is estimated from (Shih et al. 2005)
- for $\varepsilon / (\nu N^2) < 100$
$$Kz = \Gamma \varepsilon N^{-2} \quad \text{(Osborn 1980)}$$
- for $\varepsilon / (\nu N^2) > 100$
$$Kz = \nu \left( \frac{\varepsilon}{\nu N^2} \right)^{1/2}$$

- 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 al. 2005) but with stronger wind forcing.
Increasing trend of $\varepsilon$ at the base of eddy C and A where maximum near inertial shear is observed.
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 $\varepsilon$ 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 $\varepsilon$ values in the seasonal pycnocline and relatively high $K_z$, suggest that the seasonal pycnocline may be permeable to exchange between mixed layer and deeper stratified water.
- $\varepsilon$ and $K_z$ estimates are comparable to GM below the seasonal pycnocline for ($z<100m$)

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

$K_z$ and $\varepsilon$ transect:
- Strong shear, dissipation rate and eddy diffusivity 1000 m above the bottom
- Strong $K_z$ above the bottom bounds the WMDW and EMDW
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 mediterranean 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)

- Smaller $K_z$ above 500m and above the bottom in the simulation
- Larger $K_z$ within [500-1500] m in the simulation 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 parameterization 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
- Fluorescence sensor $dt$: 10 ms
- Fall velocity $U_{\text{fall}} = 0.1 \text{m/s}$
  - Vertical resolution: $U_{\text{fall}} \ dt \approx 1 \text{mm}$
How are dissipation rate and eddy diffusivity inferred from temperature SCAMP measurements?

(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