Vertical Wavenumber Spectra of Western North Atlantic Eddies: Energy and Enstrophy Cascades in Geostrophic Turbulence

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Conventional Paradigm:

"Ocean mesoscale eddies are dominated by the barotropic & 1st baroclinic modes" (Corollary: nothing much else matters)

Not so very true for submesoscale eddies…..

Geostrophic Turbulence Theory: Energy & Enstrophy Cascades

Models of geostrophic turbulence describe oppositely directed cascades of energy and enstrophy (vorticity variance) through the wavenumber spectrum *E(k)*. (Charney, J. G., 1971. JAS, *28*, 1087-1095)

Energy ➔ larger scale: $E(k)$ varies as $k^{-5/3}$
Enstrophy ➔ smaller scale: $E(k)$ varies as k^{-3}

Has such a spectrum been observed in the ocean??

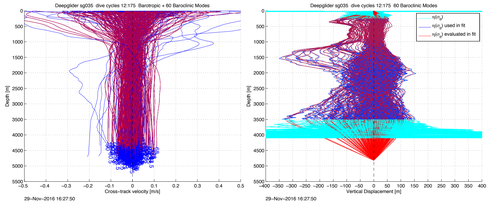
Vallis, G.K., 2006. Atmospheric and oceanic fluid dynamics, Cambridge Univ. Press.

What really IS the vertical wavenumber spectrum of geostrophic eddies?

Observations: Fortnightly Deepglider™ repeat surveys surrounding the Bermuda Atlantic Time Series (BATS) site collected full depth temperature and salinity profiles roughly daily and roughly 15 km apart for 9 months.

Analysis:

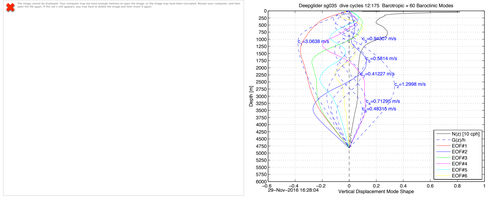
- Absolute geostrophic current normal to the glider track estimated using pairs of successive dive/climb cycles to find geostrophic shear which was vertically integrated and referenced to full-depth averaged (barotropic) current.
- Density anomalies from record mean profile converted to vertical displacements
- Current and displacement independently fit by 60 dynamical modes (excluded near surface and near bottom regions to avoid contamination by thermodynamic effects and measurement noise)



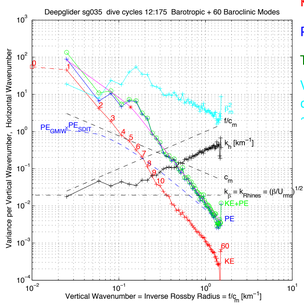
Cross-track absolute geostrophic current σ_θ-based vertical displacement

Results of Empirical Orthogonal Function (EOF) expansion:

- The first 3 EOFs of *geostrophic current* are composed mainly of:
  - EOF#1: barotropic + 1st baroclinic mode
  - EOF#2: barotropic - 1st baroclinic mode
  - EOF#3: 2nd baroclinic mode
- The first 3 EOFs of *vertical displacement* are composed mainly of:
  - EOF#1: 1st baroclinic mode
  - EOF#2: 3rd - 4th + 5th - 6th baroclinic mode !!!!
  - EOF#3: 2nd baroclinic mode



Spectra of Kinetic & Potential Energy



Kinetic Energy KE~k^{-3} for $m>1$

Potential Energy PE~k^{-3} for $m>6$

Total Energy TE~k^{-3} for $m>6$

Variance in vertical displacement mode coefficient ~ k^{+1} for $m<6$, ~ k^{-1} for $m>6$

PE >> KE for $m>2$ so
$k_h \sim f/c_m$ for $m=1$ & $m=2$
$k_h \sim \frac{1}{4} f/c_m$ for $m \geq 6$
$k_h >> k_{Rhines}$ for $m>1$

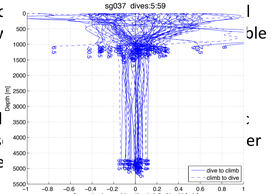
PE >> $PE_{GM\ internal\ wave}$ for $m<50$
PE >> $PE_{semidiurnal\ tide}$ for $m=1$

piecewise fit TE ~ $k^{-5/3}$ for $m \leq 5$
piecewise fit TE ~ k^{-3} for $m \geq 6$

c_m = vertical mode m Kelvin wave speed

Conclusions

- While most geostrophic current variance is associated with the barotropic and 1st baroclinic mode, vertical displacement variance is spread over the first several baroclinic modes.
- Predictions of geostrophic … slopes, roughly $k^{-5/3}$ at low … from k^{-3} over a decade at … with those observed.
- Existence of both spectral … energy and enstrophy cas… in nature for the first time.

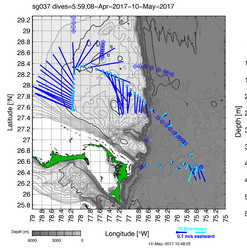


- Kinetic and potential energy spectra are nearly identical for the first two baroclinic modes, implying horizontal scales close to the respective Rossby radii of deformation and comparable contributions of vortex stretching and relative vorticity to potential vorticity conservation for these modes.
- Potential energy dominates kinetic energy for modes 3 and higher, typically by ~16, implying horizontal scales ~4 times longer than the respective Rossby radius and dominance of vortex stretching at modestly high vertical mode number.
- Geostrophic turbulence dominates internal wave variance by 2 orders of magnitude for the first baroclinic mode, and drops to equal it by about mode 50 (an average vertical scale of ~30 m).

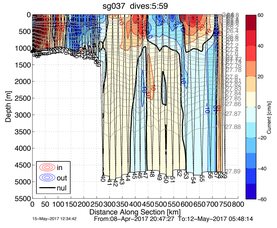
Absolute Western Boundary Current Repeat Sections on the RAPID-MOCHA Line

Observations

- Two Deepgliders are currently surveying the westernmost 125 km deep water portion of the RAPID-MOCHA Line. Sampling has been modified (beyond what is shown below) for the vehicles to each survey contiguous 125 km sections, together covering 250 km.
- Each dive cycle takes under two days to complete.
- All measurements are telemetered in near real time via Iridium satellite altimetry.
- One-way sections require 6-7 days to obtain full-depth sections of temperature, salinity, and dissolved oxygen.
- Absolute geostrophic current is obtained by vertically integrating geostrophic shear estimated over pairs of dive cycles and referencing it to estimates of full-depth averaged (barotropic) current found from the difference between dive cycle GPS and dead-reckoned displacement.



Surface to bottom depth-averaged (barotropic) current (blue) and volume transport across section (cyan) along Deepglider track from launch over Blake Plateau offshore to RAPID-MOCHA Line (26.5°N)



Absolute geostrophic current to the left of vehicle track shown in figure to the left. Poleward (equatorward) flow is depicted by reddish (bluish) hues for offshore directed portions of the section (e.g. from 275-450 and 600-725 km). Antilles Current is evident in the top 1 km with DWBC oppositely directed in the bottom 4 km.