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Title:	Interior Pathways to Dissipation of Mesoscale Energy
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Interior Pathways to Dissipation of Mesoscale Energy

(JFM 2014)

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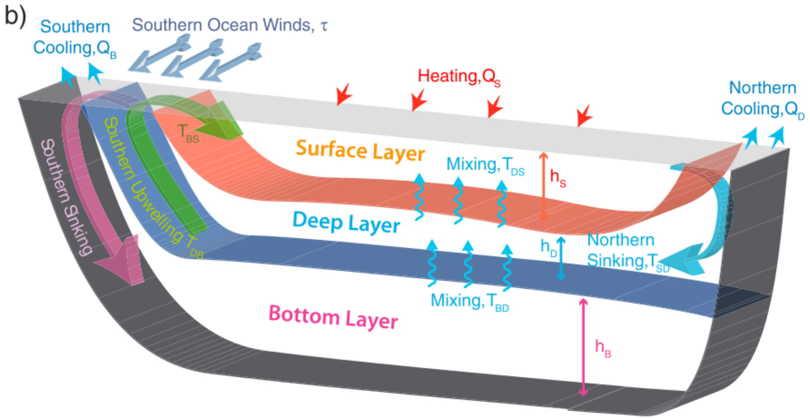
Outline

Small Scale Turbulence and Global Circulation

Significant Amounts of Dense Deep Waters Have to be Transformed to Lighter Water



Boer and Hogg, 2014

Small Scale Turbulence and Global Circulation

Significant Amounts of Dense Deep Waters Have to be Transformed to Lighter Water

- How is deep mixing energized?
- Where does the energy come from?
  - Tides, Winds
  - Interaction of barotropic mode with rough bottom topography
    - Local dissipation by Lee waves
    - Remote dissipation of radiated IWs
  - Submesoscales in the surface layer (ML instabilities)
  - Interior instabilities?
  - Radiation of NIWs from surface layer?
- What is the mixing efficency?

THIS STUDY: There is a HUGE reservoir of energy sitting in the interior ocean. Can fluid dynamic instabilities contribute to the mixing required to drive global overturning circulation? Study designed to eliminate distinguished horizontal surfaces such as bottom BL and surface layer

How does the ocean equilibrate when continually forced at large scales? This is a Conundrum of Ocean Turbulence

Large scale circulation comprises of (i) Wind Driven Circulation

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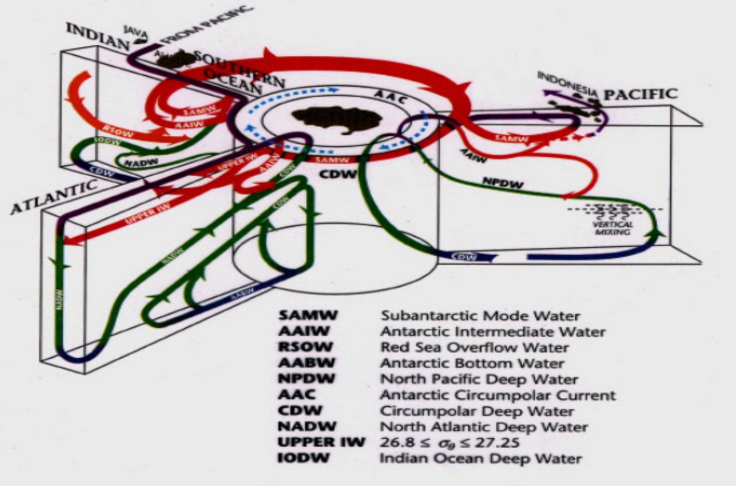
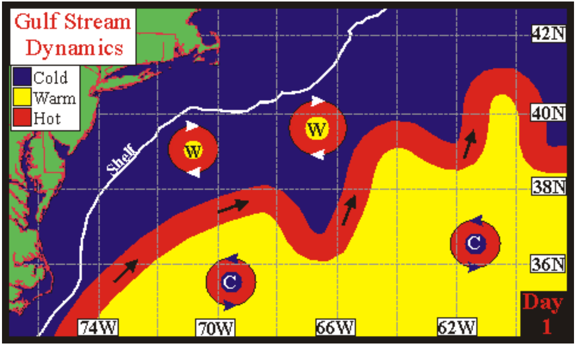


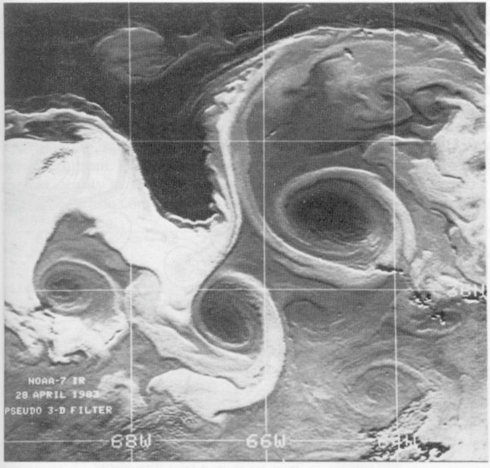
Large scale circulation comprises of (ii) Overturning Circulation

How does the ocean equilibrate when continually forced at large scales? This is a Conundrum of Ocean Turbulence



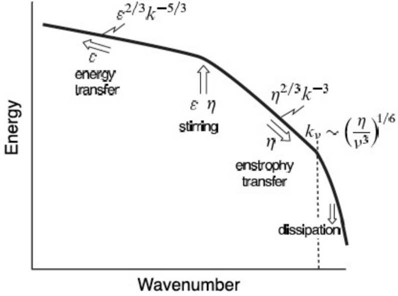
Instability of large-scale mean ocean circulation produces mesoscales and they contain a dominant fraction of the oceanic kinetic energy

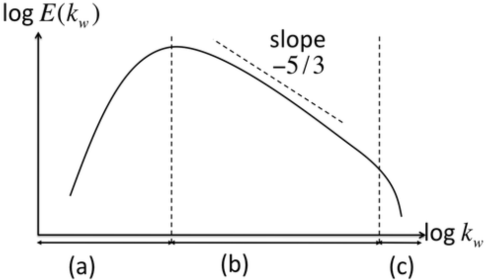
How does the ocean equilibrate when continually forced at large scales? This is a Conundrum of Ocean Turbulence



Instability of large-scale mean ocean circulation produces mesoscales and they contain a dominant fraction of the oceanic kinetic energy

Mechanisms of dissipation of balanced mesoscale energy depends crucially on direction of cascade





Governing Eqs.: Non-Hydrostatic Boussinesq Eqs.

Non-Dimensional #s: (1) Rossby (Rotation) (2) Froude (Stratification) (3) Aspect Ratio

$$
\begin{aligned}
\frac{\partial \mathbf{u}_h}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}_h + \frac{\mathbf{k} \times \mathbf{u}_h}{Ro} &= -\frac{\nabla_h \phi}{Ro} + D_{\mathbf{u}_h} \\
\lambda^2 \left(\frac{\partial w}{\partial t} + \mathbf{u} \cdot \nabla w \right) &= -\frac{1}{Ro}\frac{\partial \phi}{\partial z} + \frac{b}{Fr} + D_w \\
\frac{\partial b}{\partial t} + \mathbf{u} \cdot \nabla b + \frac{w}{Fr} &= +D_b \\
\nabla \cdot \mathbf{u} &= 0.
\end{aligned}
\tag{2.1}
$$

Encompasses a wide range of dynamical regimes

Interaction between vortical modes and internal wave modes *weak*

This Study Spans Across Asymptotic Regimes

Theoretical Analysis Confined to Individual Asymptotic Regimes

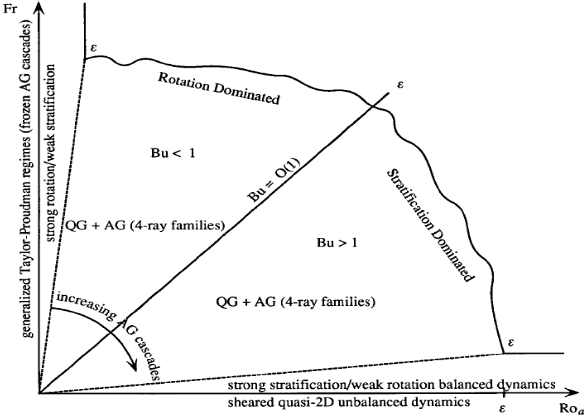


Figure 1. Geophysical dynamics: the global picture for small Froude or small Rossby regimes.

(Babin et al., 1997)

Interested in the direction of increasing Ageostrophic Cascades

Note that AG cascades can still be balanced

Highlights

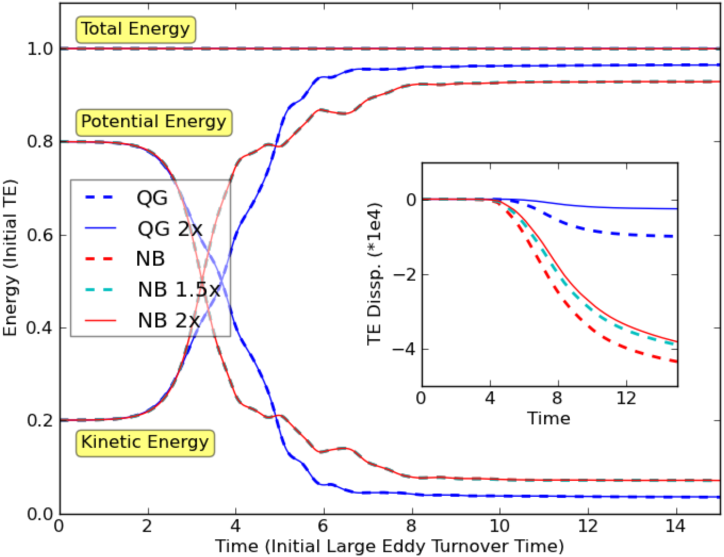
See J. Fluid Mech. (2014), vol. 756, pp. 965-1006 for details

- Small Ro, Fr, λ—Regime of Relevance to Ocean
- No Boundaries to Support SQG or any Other Surface-Related Imbalanced Instabilities
  - Boundary-Related Processes *are* Important Sinks but do not contribute to Interior Mixing Required for Meridional Overturning Circulation
- Compare Balanced (QG) and Imbalanced (Non-hydrostatic Boussinesq) Evolution of unstable baroclinic wave
- Phenomenology of Pathway Between Balanced and Imbalanced Turbulence in the *Interior*
- Imbalanced dissipation scales exponentially with Rossby number of the base flow

Resolution and Other Numerical Considerations

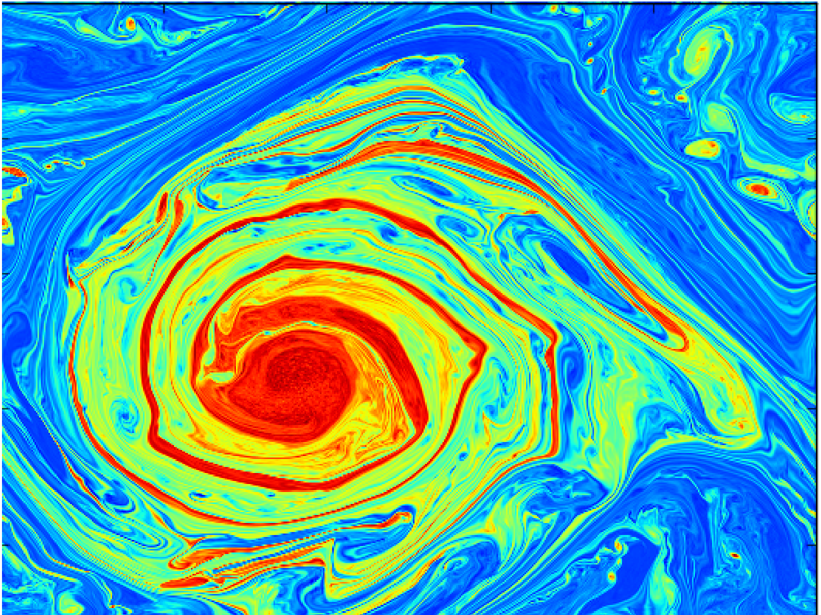
- When $Ro \ll 1$ wave-vortex interactions weak
- Easy to *over-estimate* imbalanced processes
  $\Rightarrow$ Essential to have good (balanced) control simulations
- Stringent Resolution Requirement
  -
    $$\text{QG}: \quad \frac{\Delta L}{\Delta z} = \frac{N_0}{f}, \quad \text{e.g., Lindzen and Fox-Rabinowitz, 1989}$$
  - Aspect Ratio of fronts in non-hydrostatic Boussinesq Equations $\sim f/N_0$ (e.g., Snyder et al., 1993) and leads to
    $$\Delta z = \frac{f}{N_0} \Delta x.$$
  - Not satisfying requirement leads to spurious solutions
- All simulations in present study satisfy these requriements

Baroclinic Instability Pulls the Trigger

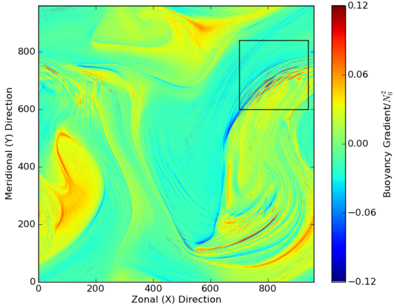


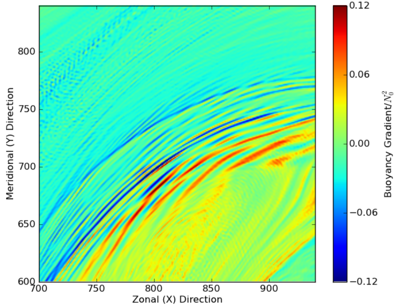
Wide Variety of Flow Features at Submesoscales

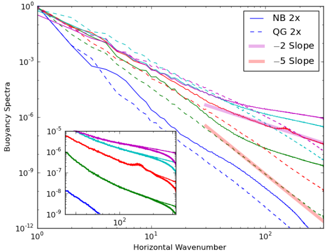
e.g., Cyclonic Spiral Eddies (Seen in Sat. Images at $\sim$ 10 km scale)



Density Fronts in the Interior in the Boussinesq System

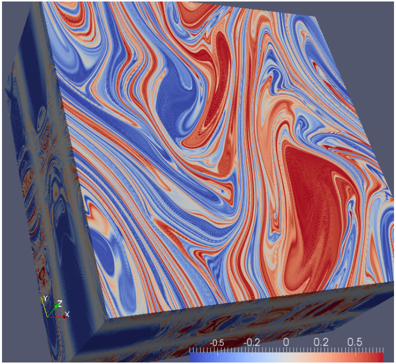


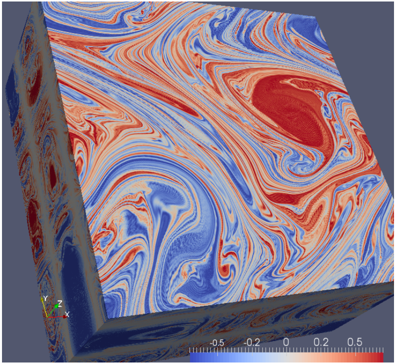




- Shallow Bouy. Spectra at Small Scales in Bous. System vs. Steep Spectra in Control QG System

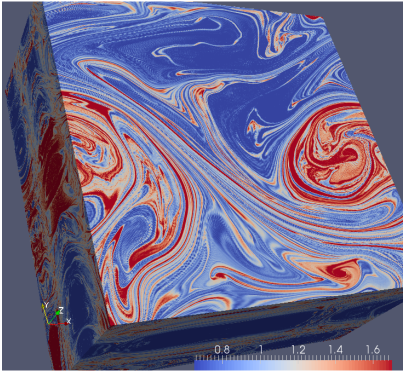
(Control) QG PV Evolution

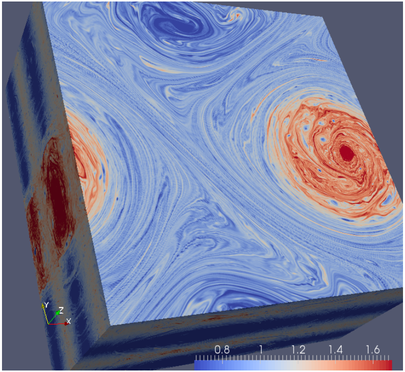




No Shortage of Small Scale Instabilities. But they are all
Balanced and Energy Cascades Back-up to Large Scales

Boussinesq PV Evolution

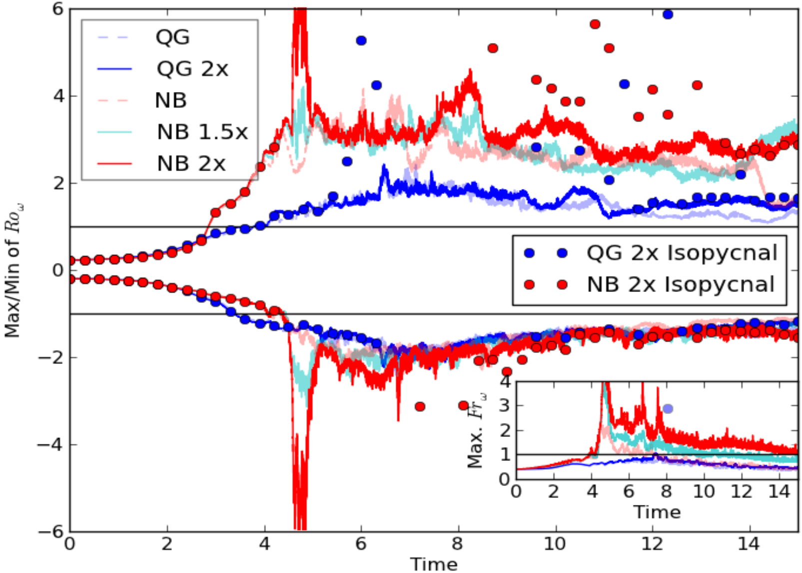




Small Scale Behavior in the Boussinesq System is
Qualitatively Different From that in the QG System
Left: Mesoscale Shear & Strain Driving Frontogenesis
Right: Reduced Frontogenesis at a Later Time

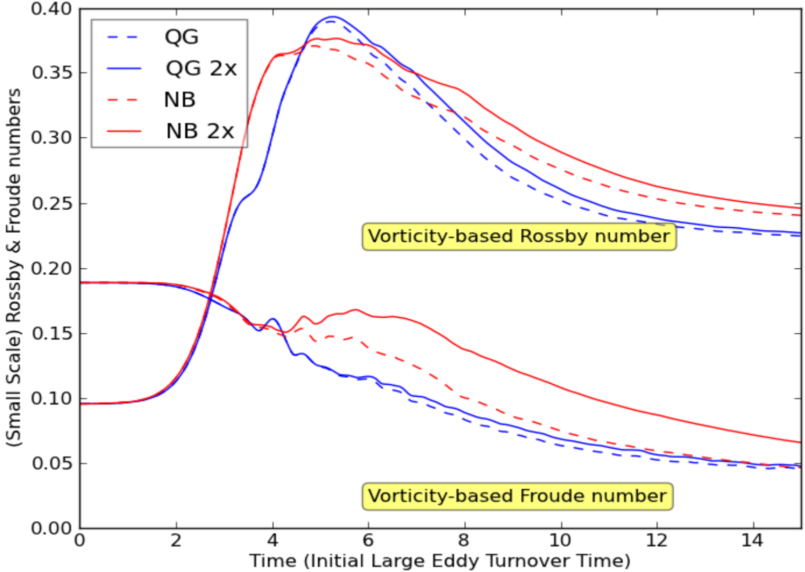
Strong Intermittency & Cyclone-Anticyclone Asymmetry in Imbalanced Boussinesq System Only

Peak of vorticity-Based Rossby ζ/f & Froude ω_h/N_0 Numbers



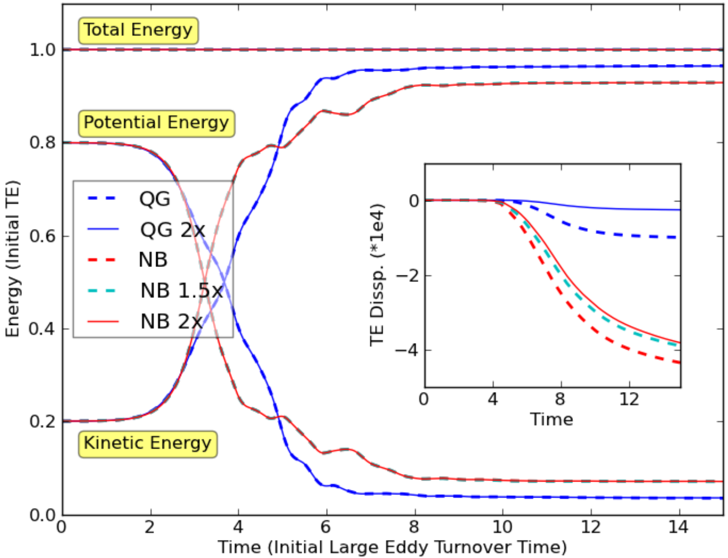
The Overall Flow Remains Fairly Well-Balanced

Evolution of RMS of vorticity-Based Rossby ζ/f and Froude ω_h/N_0 numbers

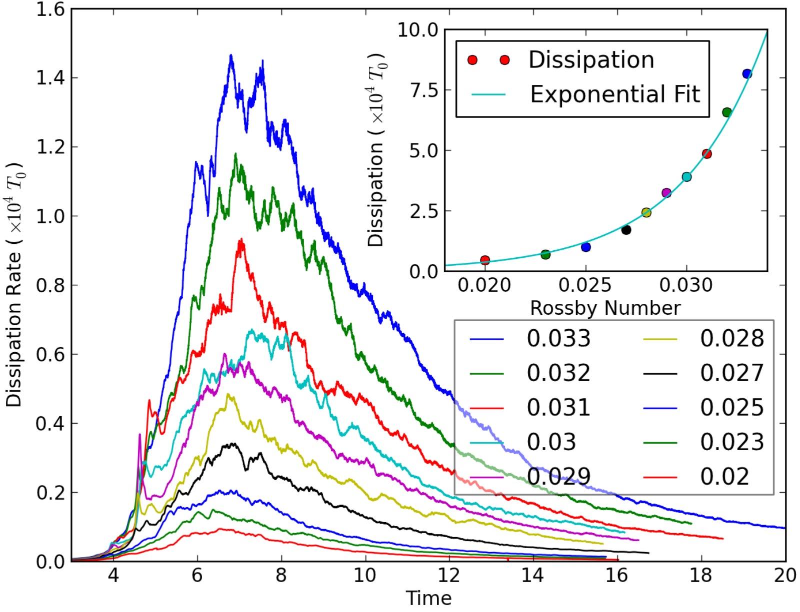


Flow is Largely Adiabatic (TE almost constant) Fwd. Cascade Due to Imbalanced Processes is small (Inset)

Evolution of KE, PE, and TE: QG and Boussinesq



Scaling of Dissipation with Rossby number



Distinct Balanced and Imbalanced Vertical Velocity Peaks

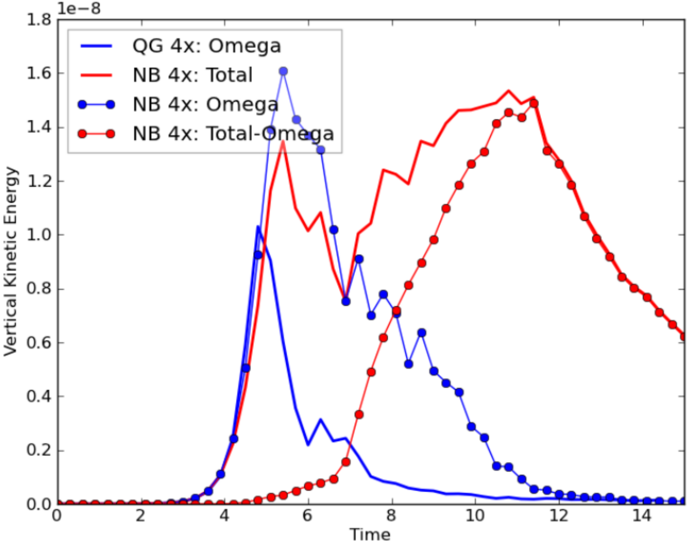
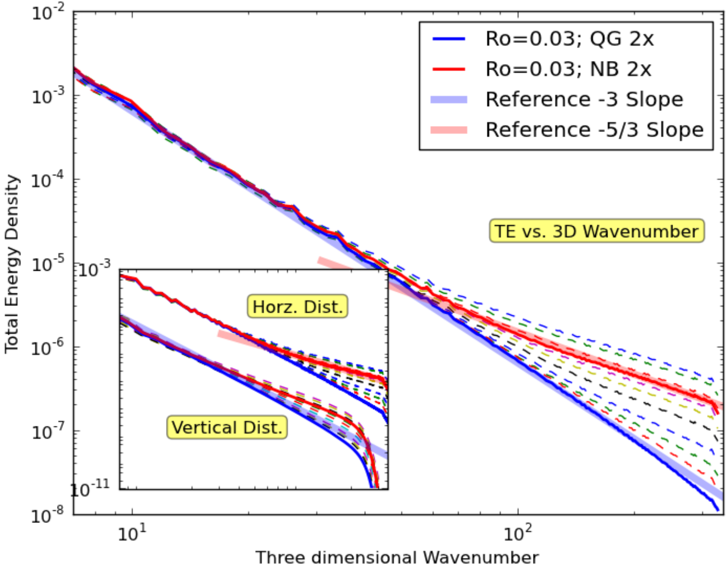


FIGURE 9. Vertical kinetic energy (VKE) diagnostics related to the omega equation. The blue line without symbols shows VKE evolution as diagnosed using the omega equation. The other three lines are for the Boussinesq simulation. The red line without symbols corresponds to the total VKE in the Boussinesq simulation. The blue line with circles shows the VKE diagnosed

Break in Energy Spectra in Boussinesq System

-3 slope at large scales transitions to $-5/3$ slope at small scales *a la* Nastrom-Gage

No matter how small Ro, Fr are



Spectral Flux Confirms Small Forward Cascade Due to Secondary Instabilities

Large Inverse Cascade at Large Scales

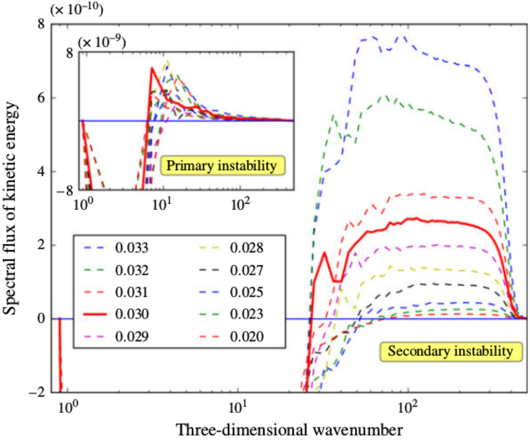


FIGURE 22. Spectral flux of energy in the Boussinesq system with 2× resolution. The $Ro = 0.03$ case considered in detail in previous diagnostics is shown in heavy (red online) line; other cases with Ro ranging from 0.02 to 0.033 are shown as thinner lines. In the main panel, spectral flux of KE is plotted against the three-dimensional wavenumber averaged over 13 equispaced snapshots between times 6 and 10, a period when dissipation is high. In the inset the average of spectral flux of KE over six snapshots between times

Minimum in Vertical Shear Spectrum suggests that some of the simulations span the regimes of Stratified Turbulence

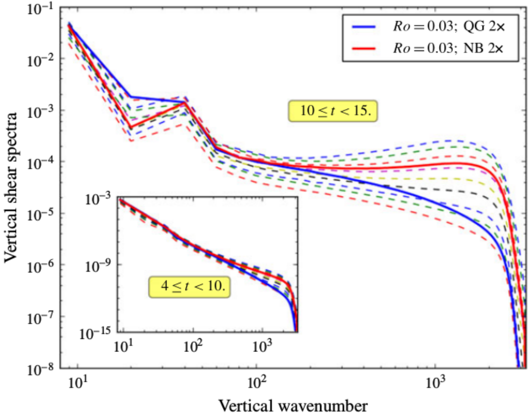


FIGURE 20. Spectrum of vertical shear of horizontal velocity as a function of vertical wavenumber for the main sequence of 2× cases considered. Main panel shows the average over late times whereas the inset shows the average over intermediate times. A minimum in this spectrum, seen here at late times for the larger of the Rossby numbers considered, is indicative of a transition from anisotropic stratified turbulence to more isotropic turbulence. A similarity of this figure to figure 1 of Gargett *et al.* (1981) which is a composite based on *in situ* measurements is noted.

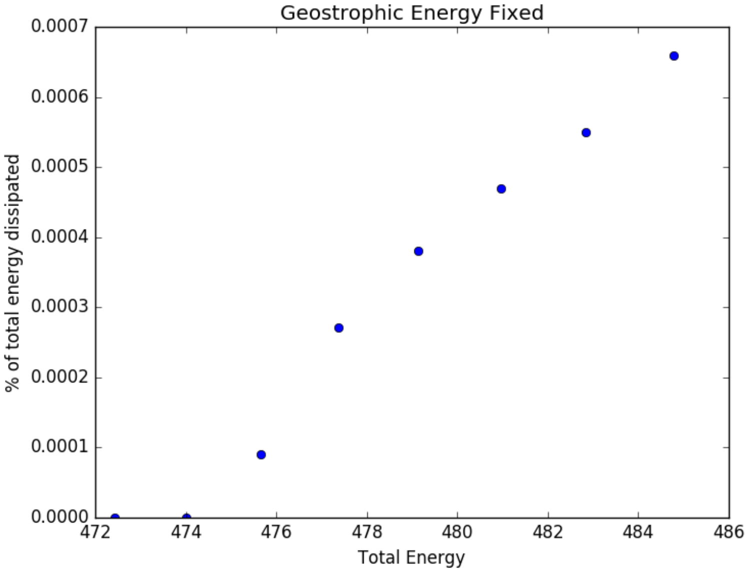
Imbalanced Instabilities

- Gravitational/Static Instability
- Inertial/Centrifugal Instability
  - Disturbance KE grows at the expense of rotational KE
  - Centrifugal force on the displaced parcels $>$ Centrifugal force acting on the environment
  - Occurs if absolute angular momentum decreases outward from rotation axis
  - Occurs in anti-cyclonic regions
- Symmetric and Instability
  - Caused by imbalance between pressure gradient and inertial forces for disturbances that displace fluid along isopycnals
  - Similar to inertial Instability
  - Negative Potential Vorticity
  - Occurs in regions of low static stability and large vertical shear

Summary & Conclusions
Balanced-Imbalanced Interactions: Interior Pathway

- Primary Instability of Mean Ocean Circ. Produces Mesoscales that Contain a Dominant Fraction of the Kinetic Energy, but are BALANCED
- However, Mesoscale Shear & Strain of Primary Geostrophic Hydrostatic Baroclinic Instability Drive Frontogenesis
- Ageostrophic Secondary Circ. and Imbalanced Instabilities Ensue
- Primary Instability Leads to an (Reversible) Inverse Cascade of the Bulk of the Energy
- Imbalanced Secondary Instabilities Cascade a Small Fraction of Energy Irreversibly Forward to Dissipation
- Imbalanced Dissipation Scales Exponentially with Rossby Number
- Balanced and Imbalanced Motions Eventually Decouple

A Shallow Water Experiment



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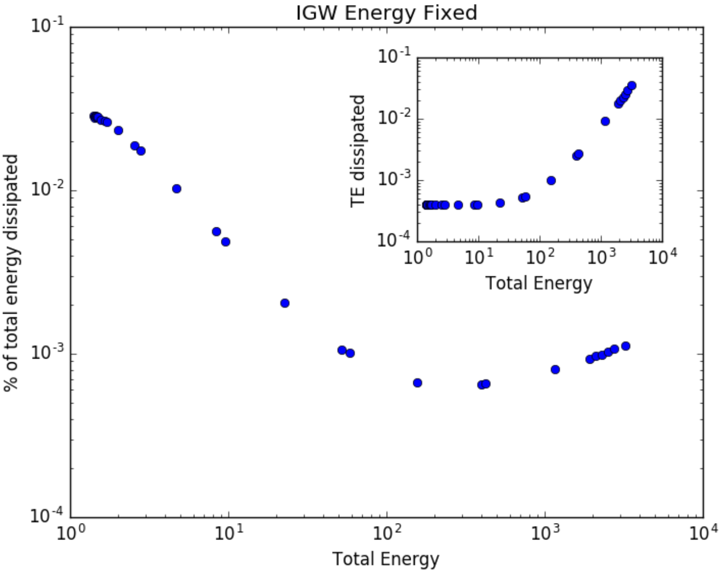
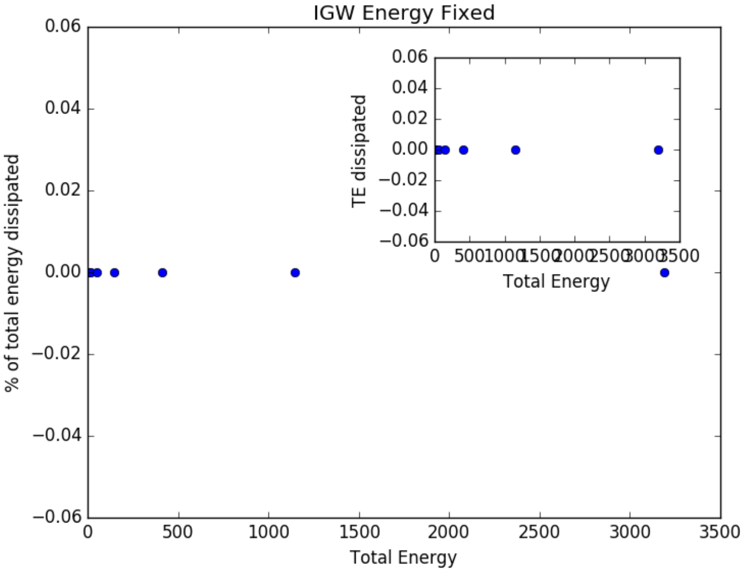


A Shallow Water Experiment



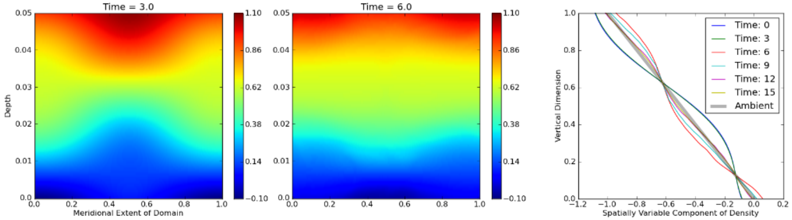


FIGURE 1. Left & center: snapshots of depth-meridional distribution of buoyancy (at a particular zonal location) reveal the slumping of buoyancy surfaces in the process of baroclinic instability. Right: Density profile (x-axis: spatially variable component of density; y-axis: depth) at $y = 0.5$ at indicated times.