Eddy PV Fluxes in the Kuroshio Extension at 144°-148°E

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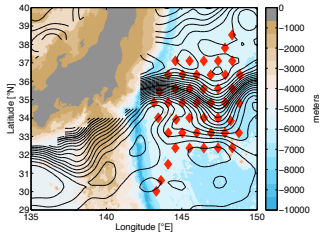
Overview Eddy PV fluxes are quantified from observations made during the Kuroshio Extension System Study from 2004-2006. The eddy PV fluxes were found to play two different roles: 1) eddies draw energy from the background flow. 2) cross-stream eddy PV fluxes account for observed changes in the thickness PV within the southern recirculation gyre (RG). Cross-stream eddy PV fluxes to the south offer an additional mechanism in modification of Subtropical Mode Water (STMW) in the RG from that offered by Qiu et al. (2006)[4].

A. Introduction

Kuroshio Extension System Study (KESS)



◆ Current and Pressure Equipped Inverted Echo Sounders (CPIES)

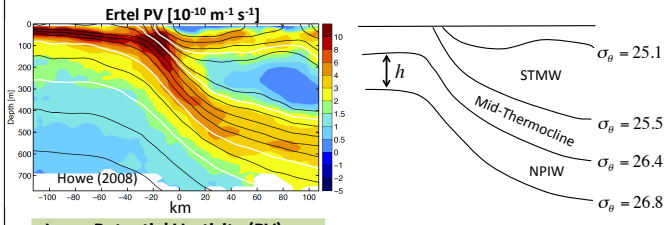
KESS

- Mesoscale-resolving array of 46 current and pressure equipped inverted echo sounders (CPIES).
- Located east of Japan in region of highest EKE.
- Provides 3-D maps of geostrophic velocity and temperature for 16 months (Donohue et al. 2010)[1].

Motivation

1. Eddies release mean potential energy of baroclinic jet.
2. Eddy fluxes have the potential to modify water masses such as Subtropical Mode Water (STMW).

B. Isopycnal Layers & Layer PV



Layer Potential Vorticity (PV)

$$q = \frac{f + \zeta}{h}$$

f Coriolis parameter
ζ Relative vorticity
h Layer thickness

The Kuroshio Extension is separated into layers that encompass water masses:
1) STMW
2) Mid-Thermocline
3) North Pacific Intermediate Water (NPIW)

C. Time-Mean PV Equation & Eddy PV Flux

Time-Mean PV Equation

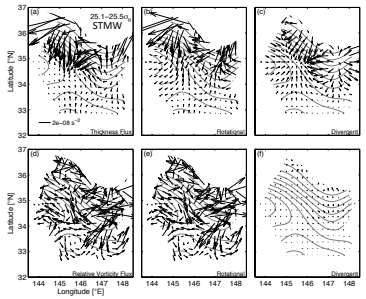
$$\bar{\mathbf{u}} \cdot \nabla \bar{q} = -\nabla \cdot \overline{\mathbf{u}'q'}$$

Eddy PV Flux

$$\overline{\mathbf{u}'q'}^{div} = \overline{\mathbf{u}'\zeta'}^{div} - f_0 \frac{\overline{\mathbf{u}'h'}^{div}}{\bar{h}^2}$$

In the absence of external torques and sources or sinks, PV is conserved following a water parcel. The time-mean PV equation relates the mean advection of PV to the divergence of eddy PV flux ($\overline{\mathbf{u}'q'}$). Eddy PV flux is the combination of relative vorticity flux ($\overline{\mathbf{u}'\zeta'}$) and thickness flux ($-f_0 \frac{\overline{\mathbf{u}'h'}}{\bar{h}^2}$). The **divergent component** of PV flux is the dynamically important quantity.

D. Divergent Vs. Rotational Eddy PV Fluxes



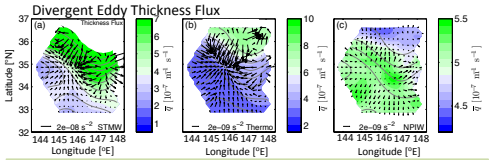
Helmholtz Theorem

$$\overline{\mathbf{u}'q'} = \overline{\mathbf{u}'q'}^{rot} + \overline{\mathbf{u}'q'}^{div}$$

- Divergent fluxes were obtained by removing the rotational component determined by Objective Analysis (OA).
- Divergent fluxes of thickness are much larger than of relative vorticity.

$$\overline{\mathbf{u}'q'}^{div} \approx -f_0 \frac{\overline{\mathbf{u}'h'}^{div}}{\bar{h}^2}$$

E. Eddy Growth



Eddy Enstrophy Equation

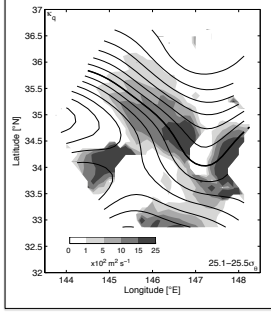
$$\frac{\partial}{\partial t}\frac{1}{2}\overline{q'^2} = -\overline{\mathbf{u}'q'}^{div} \cdot \nabla \bar{q} + \overline{D'q'}$$

Time-rate of change of eddy enstrophy is balanced by cross mean PV divergent thickness fluxes and dissipation. Triple correlations have been neglected and mean advection of eddy enstrophy is taken to balance cross mean PV rotational thickness fluxes[2].

Divergent PV Flux

- Thickness fluxes are down-gradient.
- Thickness fluxes are 10x larger in STMW layer.
- Path displacement variance is observed to more than double between 144°-146°E[3].
- Down-gradient divergent PV fluxes are indicative of eddy growth ($\frac{\partial}{\partial t}\overline{q'^2} > 0$).

F. PV Eddy Diffusivity

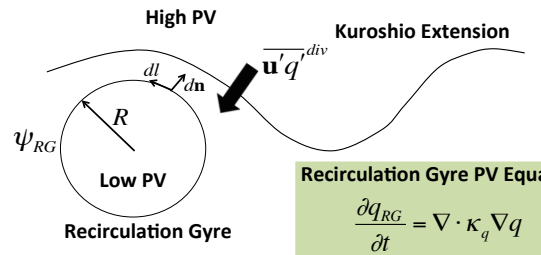


PV Flux Parameterization

$$\overline{\mathbf{u}'q'}^{div} = -\kappa_q \nabla \bar{q}$$

- Eddy PV fluxes are parameterized as a flux-gradient Fickian relation.
- Eddy diffusivity (κ_q) ranges from 100-2500 $m^2\ s^{-1}$ in the STMW layer.

G. STMW Modification: Schematic

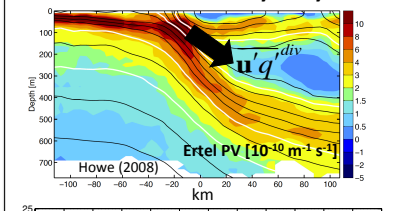


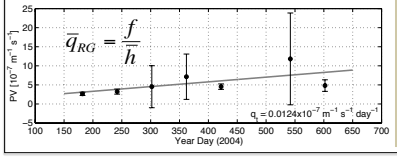
Recirculation Gyre PV Equation

$$\frac{\partial q_{RG}}{\partial t} = \nabla \cdot \kappa_q \nabla q$$

$$\frac{\partial}{\partial t}\iint q_{RG}\,dA = \oint \kappa_q \nabla q \cdot \mathbf{n}\,dl$$

H. STMW Modification by Eddy PV Fluxes





- The area-integrated PV equation for the recirculation gyre (RG) demonstrates that eddy PV fluxes into the RG are large enough to explain the observed increase in thickness PV for the RG over 16 months during KESS.

$$\frac{\partial}{\partial t}\iint q_{RG}\,dA = \frac{\Delta q_{RG}}{\Delta t} A = 5.82 \times 10^{-4}\ \mathrm{m\ s^{-2}}$$

$$\oint \kappa_q \nabla q \cdot \mathbf{n}\,dl = \kappa_q \frac{\Delta q}{L} \frac{l}{4} = 6.3 \times 10^{-4}\ \mathrm{m\ s^{-2}}$$

- The following were used to make these calculations:
  R = 100 km
  κ_q = 1000 $m^2\ s^{-1}$
  PV gradient = 4×10^{-12} $m^{-2}\ s^{-1}$
  Estimating that the eddy PV fluxes only act over ¼ of the RG boundary.

Summary

- Divergent eddy PV fluxes in the Kuroshio Extension are dominated by thickness fluxes over relative vorticity fluxes which were insignificant.
- Divergent eddy thickness fluxes were mostly down-gradient and strongest in the topmost layer encompassing STMW.
- Eddy thickness fluxes were parameterized as a flux-gradient relation with eddy diffusivities ranging from 100-2500 $m^2\ s^{-1}$.
- Cross-stream eddy PV fluxes to the south account for the increase in thickness PV within the southern RG and are a mechanism by which STMW is modified.

References and Acknowledgements

1. Donohue, K. A., D. R. Watts, K. Tracey, A. D. Greene, and M. Kennelly, 2010. Mapping circulation in the Kurohsio Extension with an array of Current and Pressure recording Inverted Echo Sounders. *J. Atmos. Oceanic Technol.*, 27:507-527.
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4. Qiu, B., S. Chen, and P. Hacker, 2007. Effect of mesoscale eddies on Subtropical Mode Water variability from the Kuroshio Extension System Study (KESS). *J. Phys. Oceanogr.*, 37, 982-1000.

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