Eddy-Mean Flow Interactions in Western Boundary Current Jets

An observation driven theoretical study

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Weekly snapshots of the 2.1 m SSH contour (proxy for the Kuroshio Extension jet axis) during the KESS observational period: May 2004 – June 2006.
Western Boundary Current (WBC) Jets

Western boundary currents and their jet extensions of the subtropical gyres are dominant features of the general circulation; understanding their dynamics is fundamental.
Western Boundary Current (WBC) Jets

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Eddy Variability in WBC Jet Systems
orders of magnitude larger in these regions; effects of eddy variability likely important in the description of system dynamics

root mean square of variations in dynamic sea surface height from combined satellite measurements 1992-1998

source: CNES
Impacts of Eddy-Mean Flow Interactions in WBC Jets

eddies can dissipate mean flows, drive mean flows and flux dynamically active tracers
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eddies can dissipate mean flows, drive mean flows and flux dynamically active tracers

- altering mean jet strength, structure and stability
- driving recirculations
- coupling strong upper ocean motions to deep abyssal motions
- modulating low-frequency variability

References:
- Schmitz (1980)
- Hogg et al. (1986)
- Thompson (1977, 1978)
- Hogg (1992)
- Watts et al. (1995)

source: AVISO
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Scheme for recirculation in the Gulf Stream system consistent with transport observations

source: Shermet 2002; adapted from Hogg 1992

References:
Rhines and Holland (1979)
Thompson (1978); Spall (1994); Jayne and Hogg (1999)
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Gulf Stream meander trough steepening and spin-up of a deep cyclone beneath

thermocline depth (contour interval 200 m) (indicates upper ocean jet position)
perturbation pressure field at 3500 m (indicates deep ocean circulation)
velocity vectors at 3500 m (indicates deep ocean motion)

References:
Cronin (1996)
Hogg (1983; 1985; 1993)
Impacts of Eddy-Mean Flow Interactions in WBC Jets

Eddies can dissipate mean flows, drive mean flows and flux dynamically active tracers

- altering mean jet strength, structure and stability
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Superimposed snapshots of the Kuroshio Extension jet axis (from satellite altimetry)

“Unstable” State
(strongly meandering jet; weak recirculations)

“Stable” State
(weakly meandering jet; strong recirculations)

References:
Spall (1996)
Qui et al. (2000)
The Kuroshio Extension System Study (KESS) 

an observational program to investigate the processes that govern the jet's variability and the role of eddy fluxes in forcing the jet's recirculation gyres
The Kuroshio Extension System Study (KESS) is an observational program to investigate the processes that govern the jet's variability and the role of eddy fluxes in forcing the jet's recirculation gyres. Deployment of the KESS mooring array: June 2004.
Guiding Questions
motivated by the KESS observations, we examine the nature and importance of eddy-mean flow interactions in WBC jet systems from both theoretical and observational perspectives

1. **What is the role of eddies** in the downstream development of an idealized model of a western boundary current jet in a configuration and parameter regime appropriate to the observed Kuroshio Extension system?

2. What is the **relevance** of the theoretical findings **to the actual oceanic system**?
Today...

1. Theoretical Study
   i. idealized model set-up
   ii. model justification from observations
   iii. theoretical results
      • effect of eddies on the mean circulation
      • dependence on system parameters

2. Observational Analysis
   i. sources of observational data
   ii. analysis methods
   iii. observational results in the form of model-observation comparisons
Model Set-Up

A baroclinic, unstable, boundary-forced jet in an open domain

- QG
- Fully non-linear
- 1 or 2-layer
- Unstable jet inflow
-Insensitive to outflow condition
- Sponge layers on all boundaries to model “open ocean”
- Posed in terms of time-mean and deviation from time-mean state
Model Justification
simplifications we employ and the physics we retain are appropriate to the Kuroshio Extension system
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- weakly depth-dependent below the thermocline
- subject to mixed instability
- strongly nonlinear
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\[
\left. \frac{\partial^2 U}{\partial y^2} \right|_{\text{mean}} \sim 2 \times 10^{-11} \frac{1}{m s} \\
\left. \frac{\partial^2 U}{\partial y^2} \right|_{\text{extreme}} \sim 7 \times 10^{-11} \frac{1}{m s} \\
\left( \text{vs. } \beta \sim 2 \times 10^{-11} \frac{1}{m s} \right)
\]

\[
\left. \Delta U \right|_{\text{mean}} \sim 0.8 \frac{m}{s} \\
\left. \Delta U \right|_{\text{extreme}} \sim 1.0 \frac{m}{s} \\
\left( \text{vs. } \Delta U \right|_{\text{critical}} \sim 0.1 \frac{m}{s} \right)
\]
Model Justification
simplifications we employ and the physics we retain are appropriate to the Kuroshio Extension system

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power density spectra
zonal velocity at 250 m at KESS 3 and 4

- 42 days
- 23 days
- 16 days
Model Justification

simplifications we employ and the physics we retain are appropriate to the Kuroshio Extension system

- weakly depth-dependent below the thermocline
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Hovmoller plot of zonal velocity at 1500 m at KESS 3
mean = 0.008 m/s
std = 0.08 m$^2$/s$^2$

c $\sim$ 0.15 m/s
$u \sim$ 0.2 m/s

Hovmoller plot of zonal velocity at 5000 m
Model Results I: Effect of Eddies on the Mean Circulation

eddies play a critical role in the downstream evolution of the jet through:
1. stabilizing the jet and 2. driving the time-mean recirculations
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1. The Effective “Eddy Force” \( \left( \frac{\partial}{\partial x} (u'u') + \frac{\partial}{\partial y} (u'v') = v'q'_{TEM} \right) \)

![Diagram showing the effect of eddies on the mean circulation](image-url)
Model Results I: Effect of Eddies on the Mean Circulation

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1. The Effective “Eddy Force”

![Diagram showing the downstream evolution of U (top) and Qy (bottom). The recirculation strength maximizes at x=30. The jet profile stabilizes at x=30.](image-url)
Model Results I: Effect of Eddies on the Mean Circulation

Eddies play a critical role in the downstream evolution of the jet through:
1. **stabilizing** the jet and 2. **driving** the time-mean recirculations.

2. **Eddy Vorticity Forcing** \( J(\psi', \nabla^2 \psi') \)

- Recirculation strength maximizes.
- Jet profile stabilizes.

![Graph showing the dominant contribution of eddy vorticity forcing](image-url)
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### 2. Eddy Vorticity Forcing

- **Recirculation strength maximizes**
- **Jet profile stabilizes**

The diagram shows:
- A wave field from a localized forcing
- A time-mean circulation from the rectification of the above wave field
- Eddy vorticity forcing
- Eddies drive recirculations by eddy vorticity forcing

**Regimes:**
- **“Unstable jet” regime**
- **“Wave radiator” regime**
Model Results I: Effect of Eddies on the Mean Circulation

Eddies play a critical role in the downstream evolution of the jet through:
1. stabilizing the jet and 2. driving the time-mean recirculations

3. Eddy Enstrophy

\[
\langle u'q' \rangle \cdot \nabla \bar{q} = -\nabla \cdot u_{\|2} - \nabla \cdot u_{\|2}^{q'2}
\]

deathuction dissipation advection

(= sense of eddy PV flux relative to the mean PV gradient)
Model Results I: Effect of Eddies on the Mean Circulation

Eddies play a critical role in the downstream evolution of the jet through:
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3. Eddy Enstrophy

**Destruction** $\left( \overline{u'q'} \cdot \nabla \overline{q} \right)$

- Recirculation strength maximizes
- Jet profile stabilizes

**Advection** $\left( \nabla \cdot \overline{u'^2} \right)$

- Recirculation strength maximizes
- Jet profile stabilizes

Eddies drive recirculations via an up-gradient PV flux

Advection counteracts dissipation permitting an up-gradient eddy PV flux
Model Results II: Adding Baroclinicity

the mechanism is unchanged by the addition of baroclinicity and/or baroclinic instability

- regardless of unstable configuration – eddies drive recirculations

- baroclinic instability postpones (in x) the barotropic mechanism: it creates (or adds to) the barotropically unstable jet

- new thickness fluxes reduce recirculation strength in the upper layer but drive lower layer recirculations
Model Results III: Dependence on System Parameters

eddy-driven time-mean circulation can be predicted empirically given the stability properties of the up-stream jet.

Summary of Parameter Studies
Mixed Instability Jet

Fr_1 = 2
Fr_2 = 0.2
Fr_1 = 0.25
Fr_2 = 0.6
Model Results III: Dependence on System Parameters

eddy-driven time-mean circulation can be predicted empirically given the stability properties of the up-stream jet.
Model Results Summary

in an idealized model of a WBC jet appropriate to the Kuroshio Extension:

- eddies play two distinct and critical roles in the downstream development of the time-mean jet by:
  - **stabilizing** the jet
  - **driving** time-mean recirculations

- zonal variation is important: the role of eddies changes upstream vs. downstream of jet stabilization and zonal advection is key

- the addition of baroclinicity does not affect the barotropic mechanism responsible for the driving of the recirculations

- jet criticality determines mean recirculation properties
Sources of Observational Data

KESS + sources up and downstream and extended back in time
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- **KESS**
- past mooring deployments upstream and downstream
- satellite altimetry record

**location of KESS array relative to mean jet and EKE**

**jet meandering during KESS:** June 2004 - May 2006

**time-mean EKE (m²/s²)**

**weekly snapshot of 2.1 m SSH contour**

**7 Deep Moorings**

- ADCP
- Profiler
- Current Meters
  - 250 m
  - 1500 m
  - 2000 m
  - 3500 m
  - 5000 m

**thermocline**

**“upper ocean”**

**“deep ocean”**

**Shipboard Surveys**

**Satellite SSH and SST**

**40 Profiling Floats**

**50 CPIES**

credit: Paul Oberlander

www.uskess.org
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goals were to characterize the mean state, the variability and eddy-mean flow interactions using observations and test relevance of theoretical results
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- **look (i) cross-stream (ii) in the vertical AND (iii) downstream at mean and eddy properties**

- define a stream coordinate system to evaluate synoptic mean and characterize jet meandering

- identify and remove rings to quantify their effect

- consider the time-mean, the synoptic mean AND the instantaneous snapshot
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Superposition of all temperature measurements at 250 m

before ring removal

after ring removal

Distribution of ring events

in time

in space
Analysis Methods

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vertical zonal velocity profiles
at +/- 25 km from the jet axis: KESS mooring array

- geographical mean
- synoptic mean
- extreme snapshot
Observational Results
model-observation consistencies suggest model has relevance to the oceanic system
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- **existence of time-mean recirculations**

- downstream development of mean jet-gyre structure

- downstream development of eddy properties
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**KESS CPIES array at 1500 m depth**

**Argo floats during KESS at 1500-2000 m depth**

**Altimetry 1992-2006**

**Geographic mean**

**Synoptic mean**

**POP GCM**

**138°E 144°E 150°E 156°E**

**28°N 32°N 36°N 40°N**

**Time-mean geostrophic pressure (cm)**

**Longitude**

**Latitude**

**Depth (m)**

**Time-mean zonal velocity (m/s)**
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model-observation consistencies suggest model has relevance to the oceanic system

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**Observational Results**

Model-observation consistencies suggest model has relevance to the oceanic system.

- **existence of time-mean recirculations**

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- **downstream development of eddy properties**

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**Figure: Upper layer of model run with KE-like parameters**

**Figure: Time-mean EKE observed from altimetry (1992-2006)**

**Figure: Distance from jet axis**

**Figure: Time-mean zonal velocity**
Observational Results
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- existence of time-mean recirculations
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Observational Results
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barotropic **model run** with KE-like parameters

downstream development of mean jet-gyre structure

downstream development of eddy properties

- time-mean jet axis
- time-mean EKE

**covariance ellipses**
- tilt > 0 (uv > 0)
- tilt < 0 (uv < 0)

**EKE maximum**
Observational Results

Model-observation consistencies suggest model has relevance to the oceanic system.

- Existence of time-mean recirculations
- Downstream development of mean jet-gyre structure
- Downstream development of eddy properties

**Observed Altimetry**

Maximum recirculation strength

**Eddy Flux Divergence of Zonal Momentum ("Effective Eddy Force")**

Upper layer of model run with KE-like parameters

Eddy flux divergence of zonal momentum ("effective eddy force")
In Summary...

model teaches us the importance of eddy-mean flow interactions in the Kuroshio Extension system

- consistencies between model and observations --> **model has relevance to the actual oceanic system**

- results therefore

  - support the hypothesis that the recirculations in the Kuroshio Extension and Gulf Stream are, at least partially, **eddy driven**

  - link properties of this eddy-driven circulation to the stability properties of the upstream jet

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