Mean Stream-Coordinate Structure of the Kuroshio Extension
First Meander Trough

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The Kuroshio Extension (KE) alternates on decadal timescales between “stable” and “unstable” meander states.

Goal here is to examine cross-stream fluxes in the stable state by investigating:

- Down- and cross-stream velocity structure
- Cross-current PV structure
- Differences in structure between crest and trough

After Qiu and Chen, 2005
**Kuroshio Extension System Study**

**KESS:**

- 46 Current and Pressure sensor-equipped Inverted Echo Sounders (CPIES)
- June 2004 - June 2006
- First meander crest and trough
- Stable for first 6 months
- Unstable thereafter

*After Qiu and Chen, 2005*
Feature Surveys

• 2004, CPIES deployment, stable state
• Conducted fine-scale ADCP/CTD surveys to obtain a synoptic picture of the current structure

- Transects 1-4 over mean SSH contours for time of surveys (5/2-5/6)
- Sample transect
  - ~15 km CTD resolution
  - ADCP data ~70-650m
  - CTD data 0-1200m
Why Use Stream Coordinates?

- **Meanders** cause shifts in direction of main jet flow
- Necessary for estimating **cross-frontal flow**
- Increases accuracy of **PV calculations**

Stream-coordinate system reveals greater magnitude of core maximum and velocity gradients.

Averaging east-west velocities by latitude...

...or as a function of distance from core...

...smears out structure.
Defining the Stream-Coordinate System

- ADCP data averaged over 100-300 m depth range
- **Core** = location of maximum velocity

Sample transect

5 km gridded, 100-300 m averaged ADCP
Defining the Stream-Coordinate System

• ADCP data averaged over 100-300 m depth range

• **Core** = location of maximum velocity

• **Down-stream direction** = vector average of three central ADCP vectors

• Project data to cross-stream line

• Rotate to down- and cross-stream components

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Sample transect

5 km gridded, 100-300 m averaged ADCP
Mean Down- and Cross-stream Velocity

- Maximum core down-stream velocity > 1.8 m/s
- Cross-stream velocities ~0.1 m/s
- Horizontal gradients stronger on cyclonic (north) side of core
Potential Vorticity

• Combining hydrographic and velocity data allows calculation of PV

• Looking for locations of **PV gradients along isopycnals**

• Is thickness PV the only significant component?

• Use **Ertel’s PV** in stream coordinates *(Bower, 1989)*:

\[
\frac{D}{Dt} \left( \mathbf{\zeta_a} \cdot \nabla \rho \right) = 0 \quad \Rightarrow \quad Q = -\frac{1}{\rho} \frac{\partial \rho}{\partial z} \frac{\partial v}{\partial x} + \frac{1}{\rho} \frac{\partial \rho}{\partial x} \left( f + \frac{\partial v}{\partial x} + \kappa v \right)
\]

- “twisting”
- “thickness”
- “curvature”
- “cross-stream shear”
Mean Potential Vorticity Structure

**Total PV**
\( q = -1/\rho \, dp/dx \, dv/dz + (f + dv/dx + \kappa v) * N^2 / g \)
\([10^{-10} \, m^{-1} \, s^{-1}]\)

- CTD data: surface-1200m
- ADCP data extrapolated to surface
- Strong band of high-PV water follows isopycnals down from north to south of core
- Low-PV **mode water** evident
- \((Ro) \sim 0.8\) just north of core, weakly negative south of core

Colors are PV, contour lines are \(\sigma_\theta\)
Does Shear Vorticity Matter?

- **Cross-stream shear** ~40% of total PV (~80% of $f$) at shallow depths north of core
- **Twisting vorticity** ~15-20% of total PV (~30% of $f$) north of core
PV as a Function of Density

Where are PV gradients?

• $\sim \sigma_\theta = 25.1-25.5$, **Mode water region**: strong gradients, “barrier”
• $\sim \sigma_\theta = 25.5-26.4$, **Main thermocline**: weaker gradients
• $\sim \sigma_\theta > 26.4$, **NPIW**: no gradients, “blender”
How Representative is the Survey Mean?

- **CPIES** provide a longer time series of geopotential height…

- Frontal waves may cause **variability** in flow speed and structure
CPIES

- **Tau** (round-trip acoustic travel time) is a proxy for **geopotential height**
- Use **geostrophy** to obtain baroclinic velocity shears
- Add **bottom CM velocities** to get absolute (barotropic + baroclinic) velocity profiles
To generate 6-month stream-coordinate mean at a longitude:

- **Mean core location** = latitudinal average of cores at set longitude
- **Mean down-stream** = vector-average direction of core velocities
- **Mean velocities** = East-north vector-average as function of distance from core after co-locating cores and cross-stream axes

Mean SSH contours in gray provide context
Clockwise rotation of velocity with depth at and south of core

- Implies **southward cross-frontal flux** and subpolar-to-subtropics **downwelling**
Core Down-stream Velocity Variability

- Maximum **surface** down-stream velocities vary between 1-2 m/s
- **Bottom** down-stream velocities at the core reach as high as 0.15 m/s but are also negative at times
  - Deep flow direction reversal may be due to deep eddy activity

Down–stream Bottom and Surface Velocities
Core at 146.00°E

- Velocity [m/s]
- Days in 2004
- Surface
- Bottom
Core Cross-stream Flow Variability

Cross-stream Bottom Velocities
Core at 146.00°E

- Cross-stream bottom velocities show significant variability; southward cross-stream flow dominates at this location.
- Suggestive of an event-driven process; mixture of remote and local forcing?

Regime change to unstable
Structural Changes: Crest-Trough-Crest

Mean Absolute Velocities In Increments of 15 km from the Core
2004/06/01 to 2004/12/01

- Repeat stream-coordinate averaging procedure at other longitudes…
Structural Changes: Crest-Trough-Crest

Mean Absolute Velocities In Increments of 15 km from the Core
2004/06/01 to 2004/12/01

Counter-clockwise rotation with depth at first meander crest

- Implies **northward cross-frontal flux** and subtropics-to-subpolar upwelling
Structural Changes: Crest-Trough-Crest

Mean Absolute Velocities In Increments of 15 km from the Core 2004/06/01 to 2004/12/01

Surface and deep currents aligned leaving meander trough

- Implies little cross-stream flux
Structural Changes: Crest-Trough-Crest

Mean Absolute Velocities In Increments of 15 km from the Core
2004/06/01 to 2004/12/01

- Southern recirculation gyre
  - Surface and deep currents not quite aligned implies interaction of gyre with KE jet
Structural Changes: Crest-Trough-Crest

Mean Absolute Velocities In Increments of 15 km from the Core
2004/06/01 to 2004/12/01

Northern recirculation gyre
In Summary…

- Down-stream velocities vary significantly in magnitude (1-2 m/s); cross-stream velocities also vary, shifting between northward and southward cross-frontal flow.

- Relative vorticity plays a large role in strengthening PV gradients across the jet along shallow isopycnals; cross-stream shear and twisting vorticity both contribute significantly (~40% and 15-20% of total PV respectively).

- Tendency for northward cross-stream flux and upwelling is seen in the first meander crest, southward flux and downwelling into the first meander trough; southern recirculation gyre interacts with jet.
### Comparison with Gulf Stream

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<tr>
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<th>Gulf Stream</th>
<th>Kuroshio</th>
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<tbody>
<tr>
<td><strong>Down-stream Velocity</strong></td>
<td>Maximum averages around 2 m/s, varying between 1.5-2.5 m/s(^1,2,3,4)</td>
<td>Maximum averages around 1.5 m/s, varying between 1-2 m/s</td>
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<td><strong>Stream Width</strong></td>
<td>214 km between lines of 0 transport over 0-2000 m(^3), narrower in troughs than crests(^1)</td>
<td>~150-200 km between lines of 0 down-stream velocity estimated from surveys and CPIES</td>
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<td><strong>Total PV</strong></td>
<td>(O(10^{-10}))(^1)</td>
<td>(O(10^{-10}))</td>
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<td><strong>Contribution of Lateral Shear Vorticity</strong></td>
<td>In steepening crest, up to 120% of (f) on cyclonic side, ~-40% of (f) on anticyclonic side(^1)</td>
<td>Entering trough, &gt;80% of (f) on cyclonic side, ~-30% of (f) on anticyclonic side</td>
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\(^1\) Liu and Rossby, 1993; \(^2\) Rossby and Gottlieb, 1998; \(^3\) Halkin and Rossby, 1985; \(^4\) Rossby and Zhang, 2001