

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

6 March, 2008

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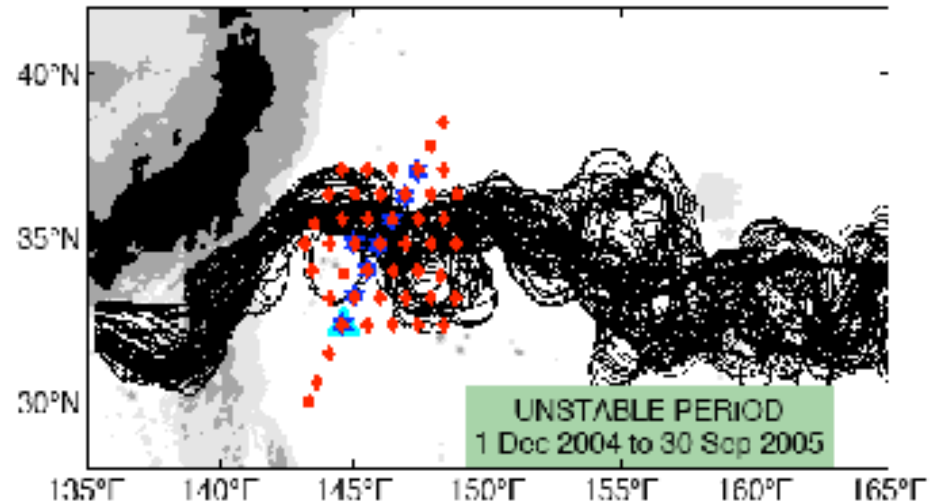
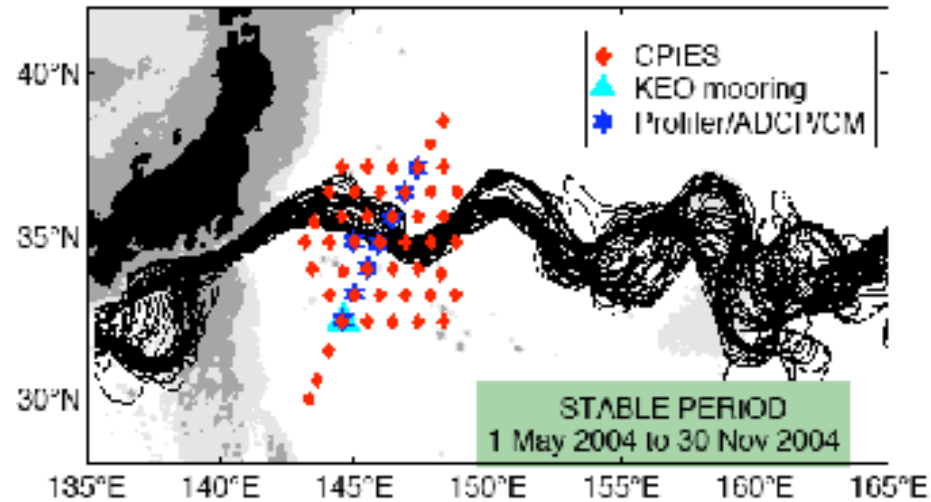
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Kuroshio Extension System

- 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**

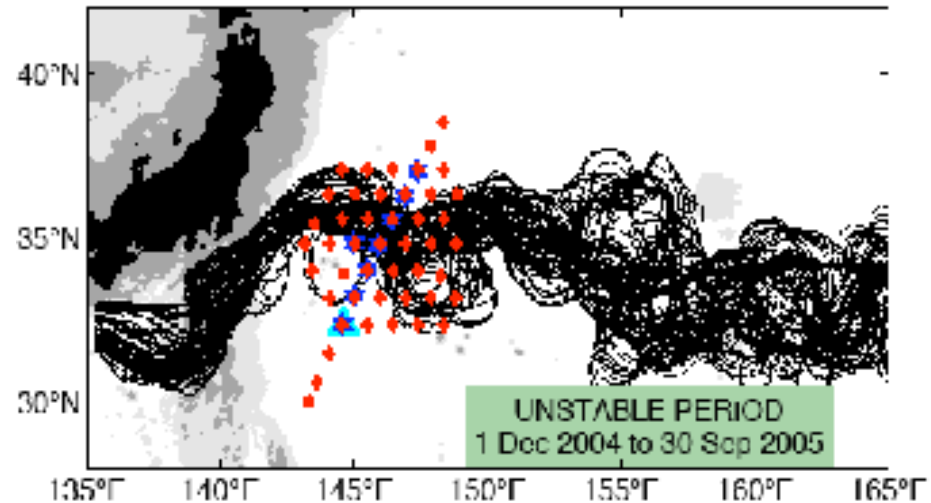
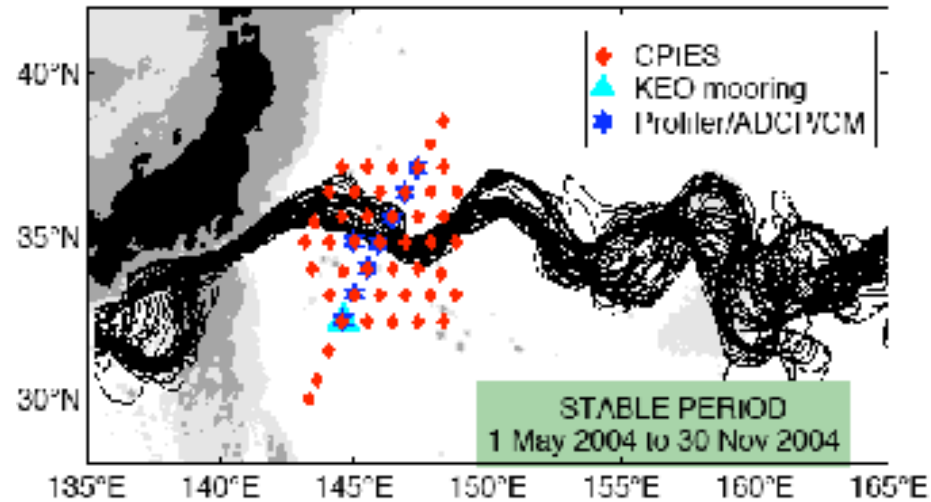


After Qiu and Chen, 2005

Kuroshio Extension System Study

KESS:

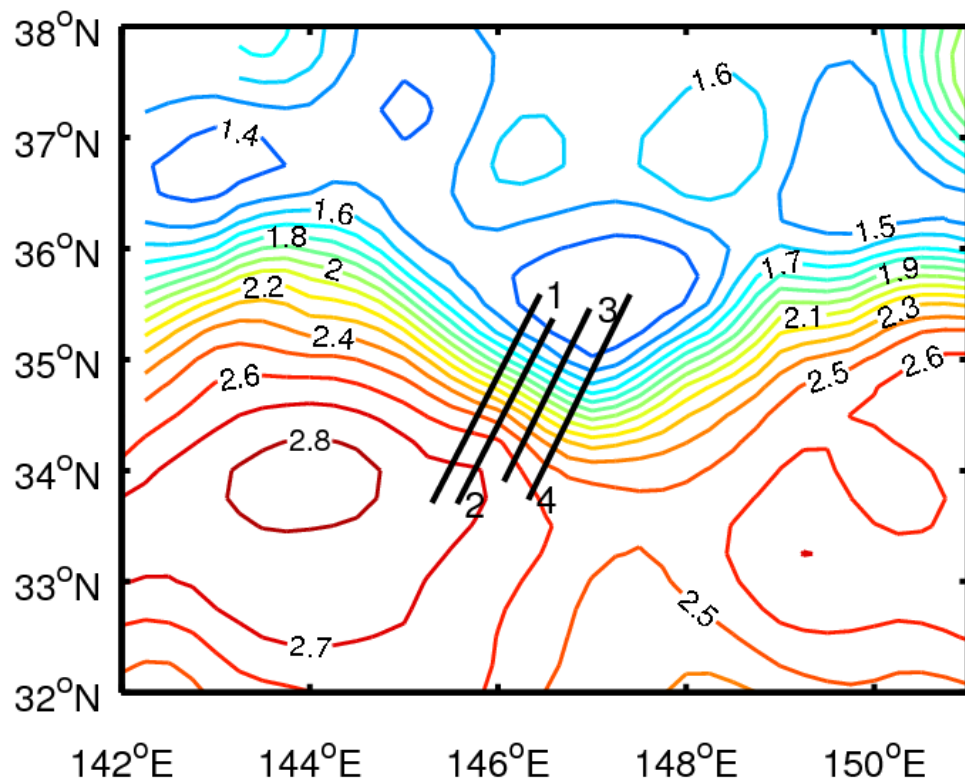
- 46 **C**urrent and **P**ressure sensor-equipped **I**nverted **E**cho **S**ounders (**CPIES**)
- June 2004 - June 2006
- First meander crest and trough
- Stable for first 6 months
- Unstable thereafter



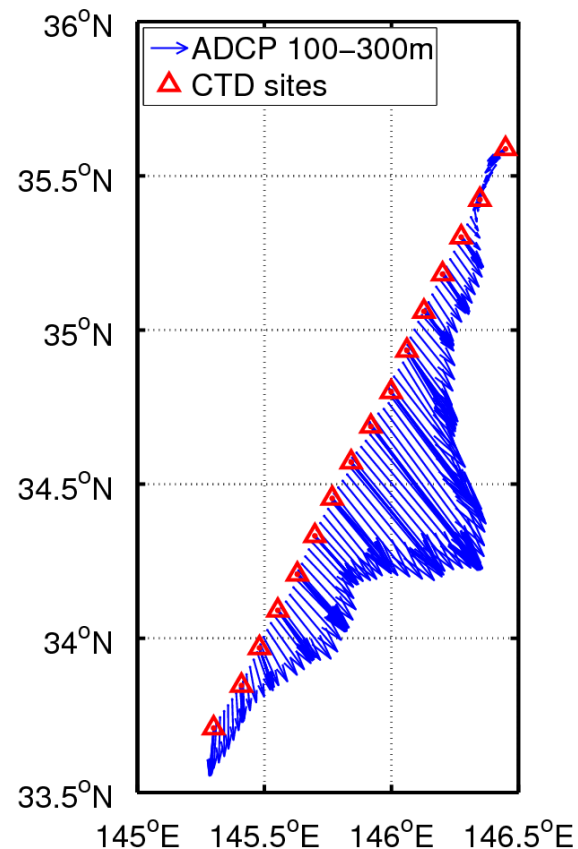
After Qiu and Chen, 2005

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)

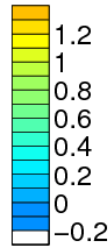
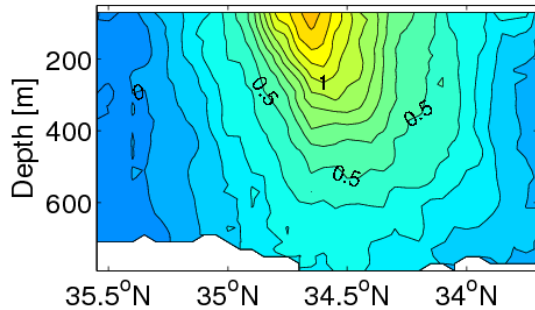


Sample transect

- ~15 km CTD resolution
- ADCP data ~70-650m
- CTD data 0-1200m

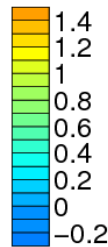
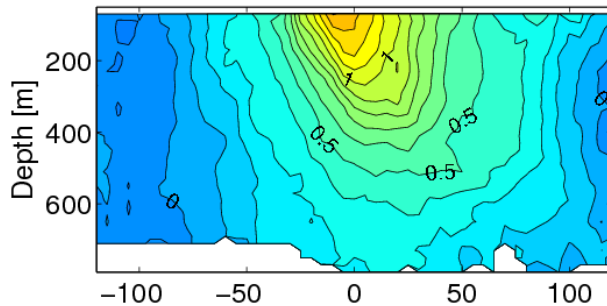
Why Use Stream Coordinates?

a) Latitudinally Averaged East–West Velocity [m/s]



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

b) East–West Velocity as Function of Distance from Core [m/s]

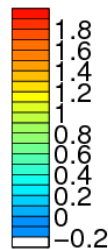
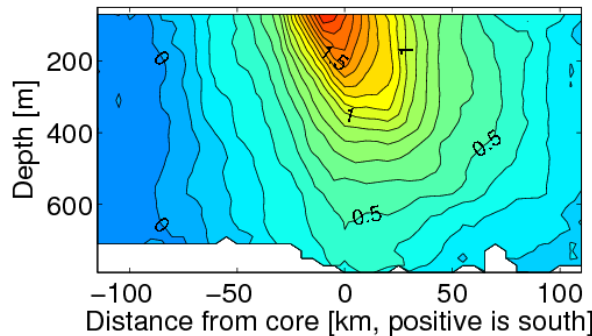


Averaging east-west velocities by latitude...

or as a function of distance from core...

...smears out structure.

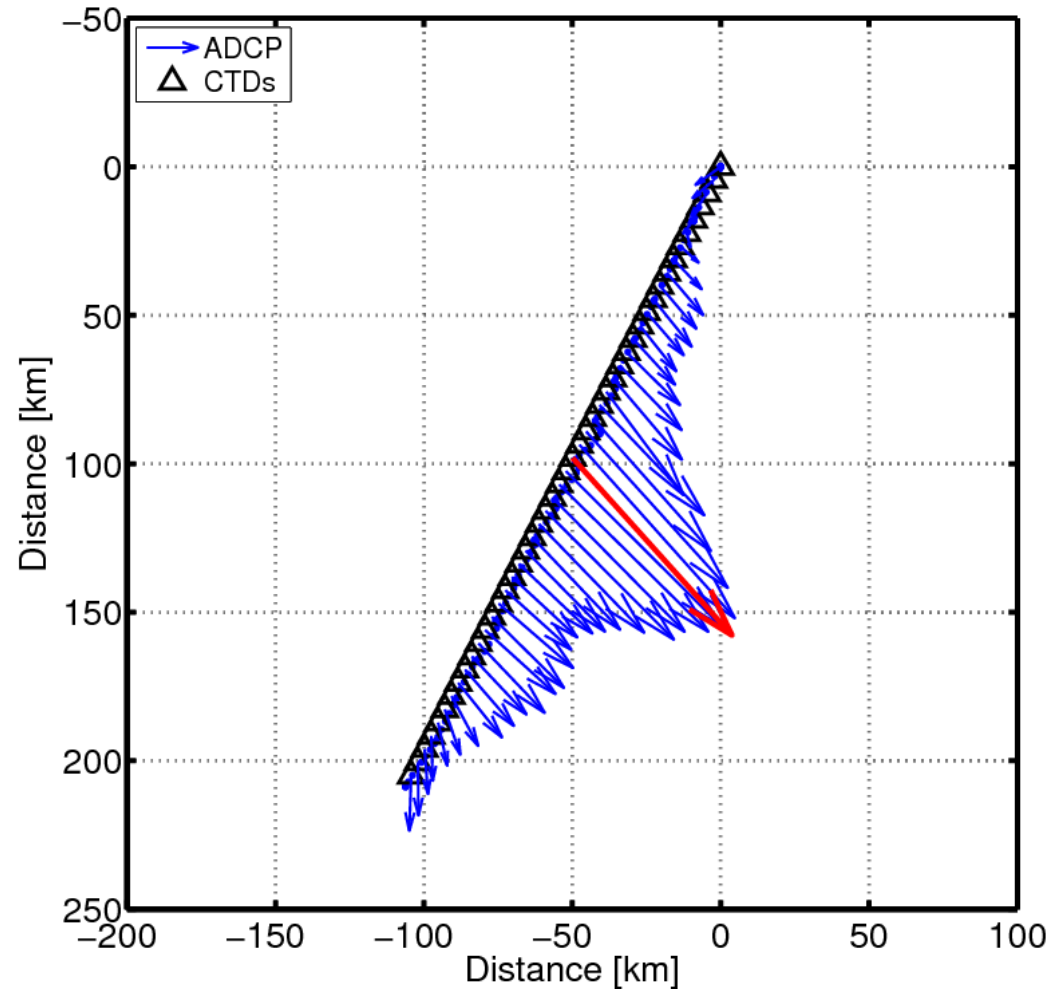
c) Down–stream Velocity [m/s]



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

Defining the Stream-Coordinate System

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

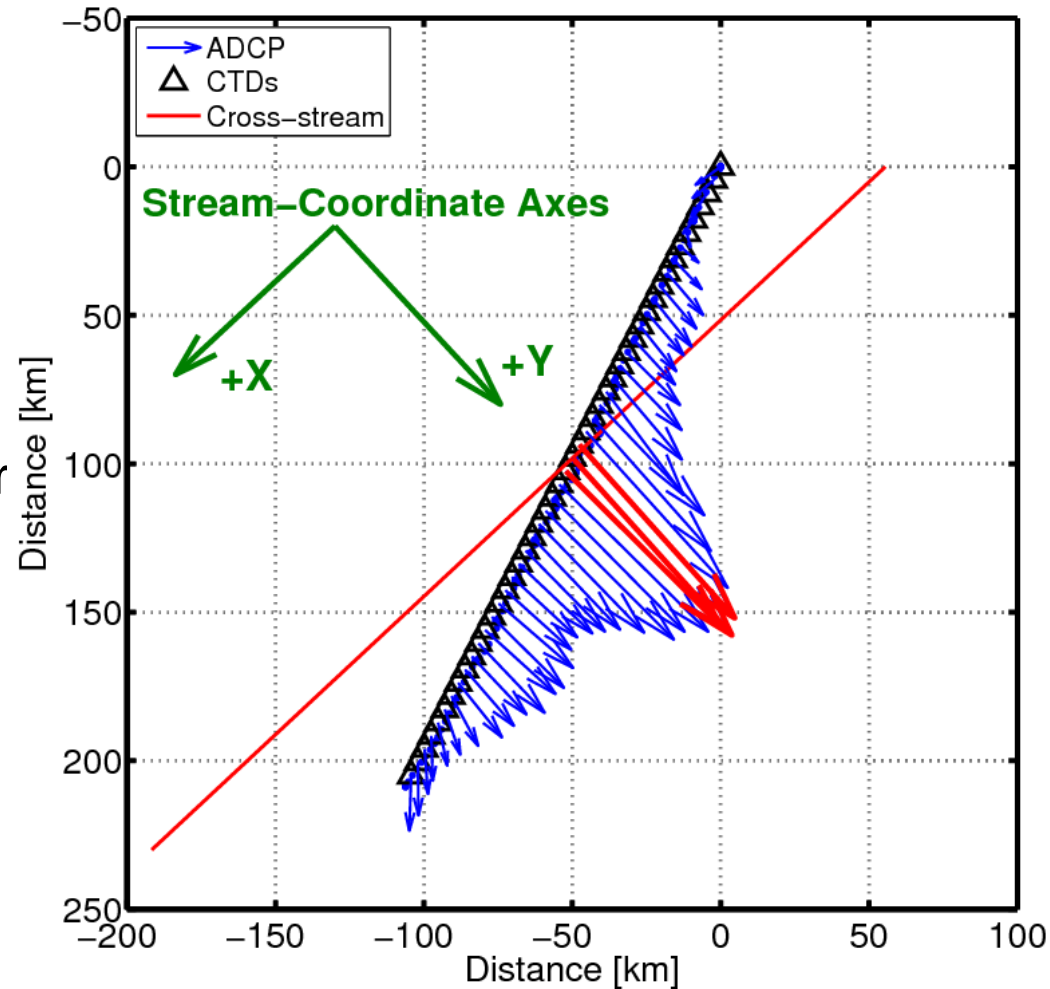


Sample transect

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

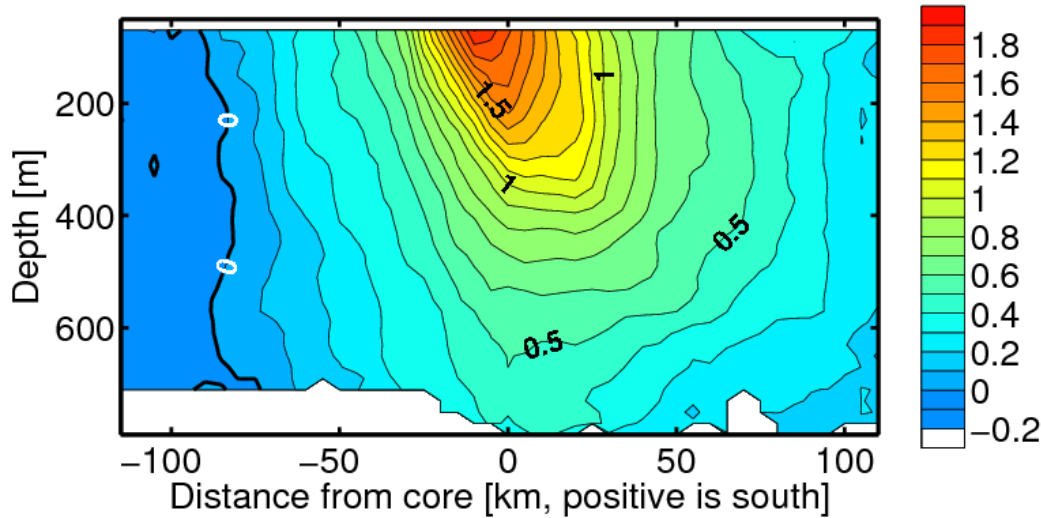


Sample transect

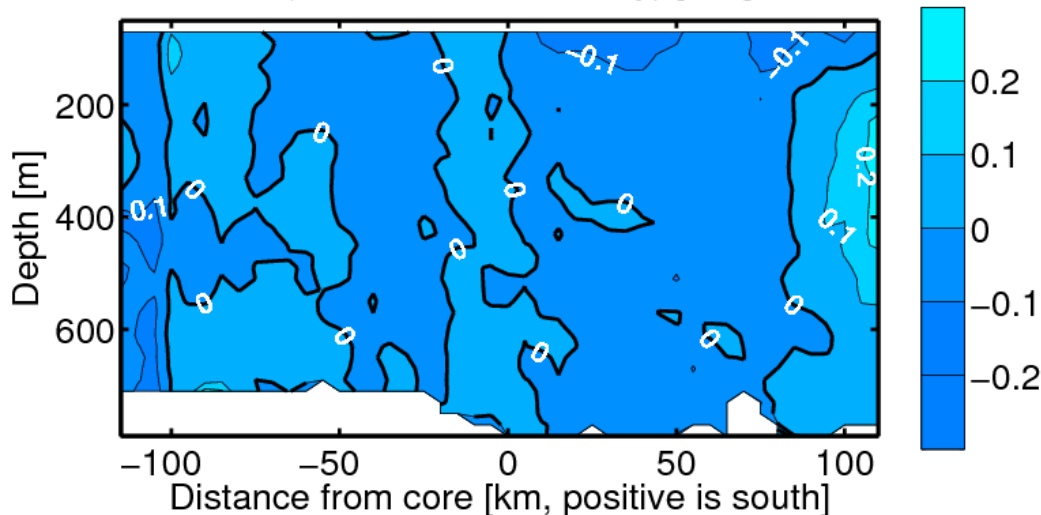
5 km gridded, 100-300 m averaged ADCP

Mean Down- and Cross-stream Velocity

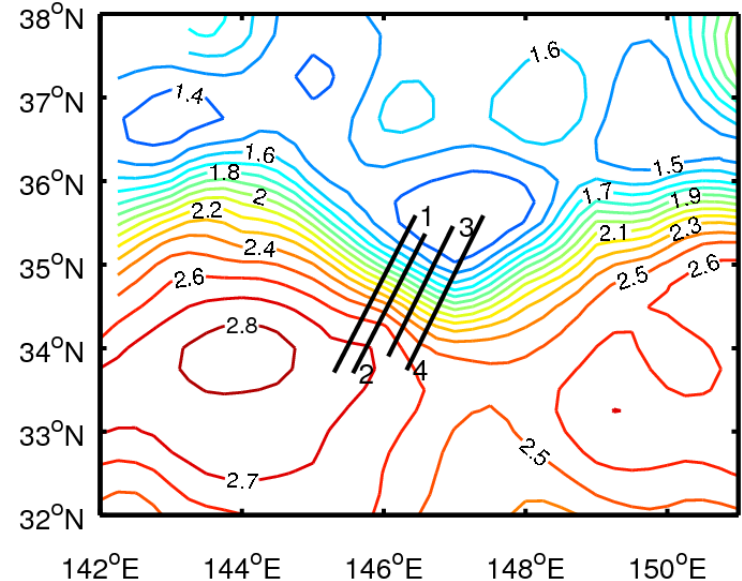
V (Down-stream velocity) [m/s]



U (Cross-stream velocity) [m/s]



- 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



Location of transects included in mean

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*):

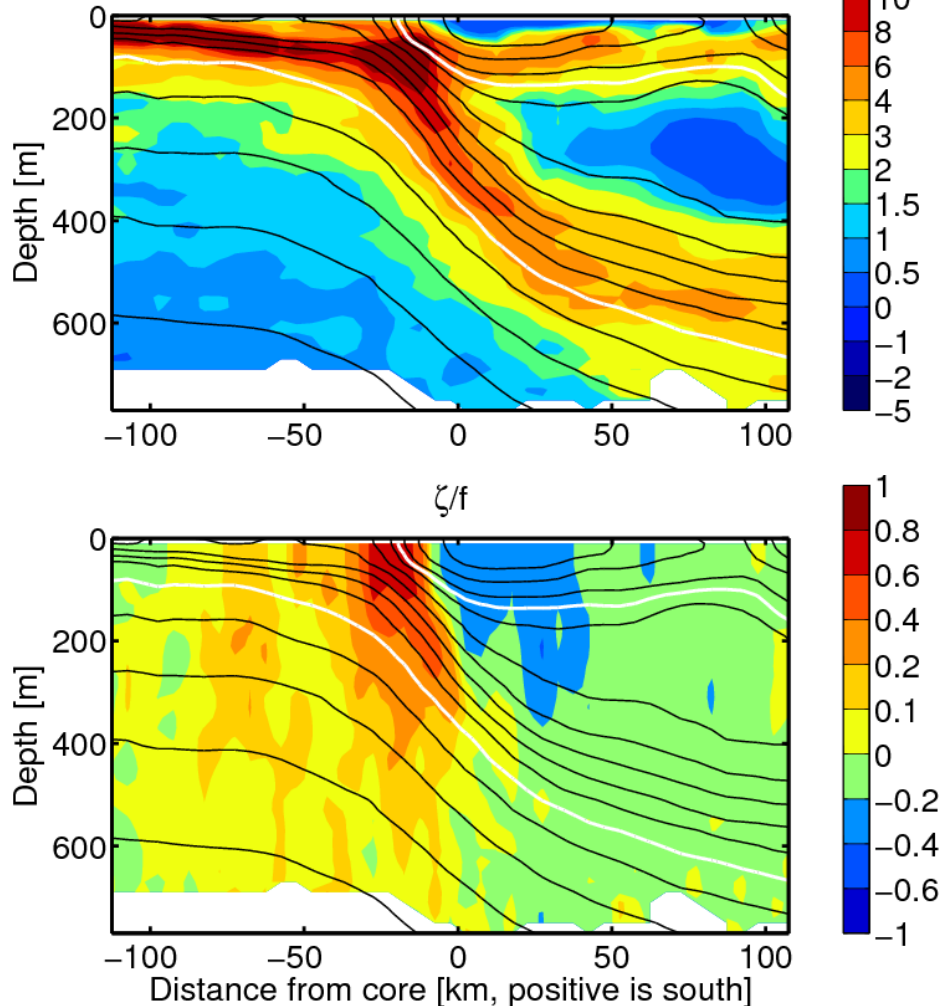
$$\frac{D}{Dt} \left(\vec{\zeta}_a \cdot \frac{\nabla \rho}{\rho} \right) = 0 \quad \longrightarrow \quad Q = - \underbrace{\frac{1}{\rho} \frac{\partial \rho}{\partial x} \frac{\partial v}{\partial z}}_{\text{"twisting"}} + \frac{1}{\rho} \frac{\partial \rho}{\partial z} \left(\underbrace{f}_{\text{"thickness"}} + \underbrace{\frac{\partial v}{\partial x}}_{\text{"cross-stream shear"}} + \underbrace{\kappa v}_{\text{"curvature"}} \right)$$

Mean Potential Vorticity Structure

Total PV

$$(q = -1/\rho \, dp/dx \, dv/dz + (f + dv/dx + \kappa v) * N^2/g)$$

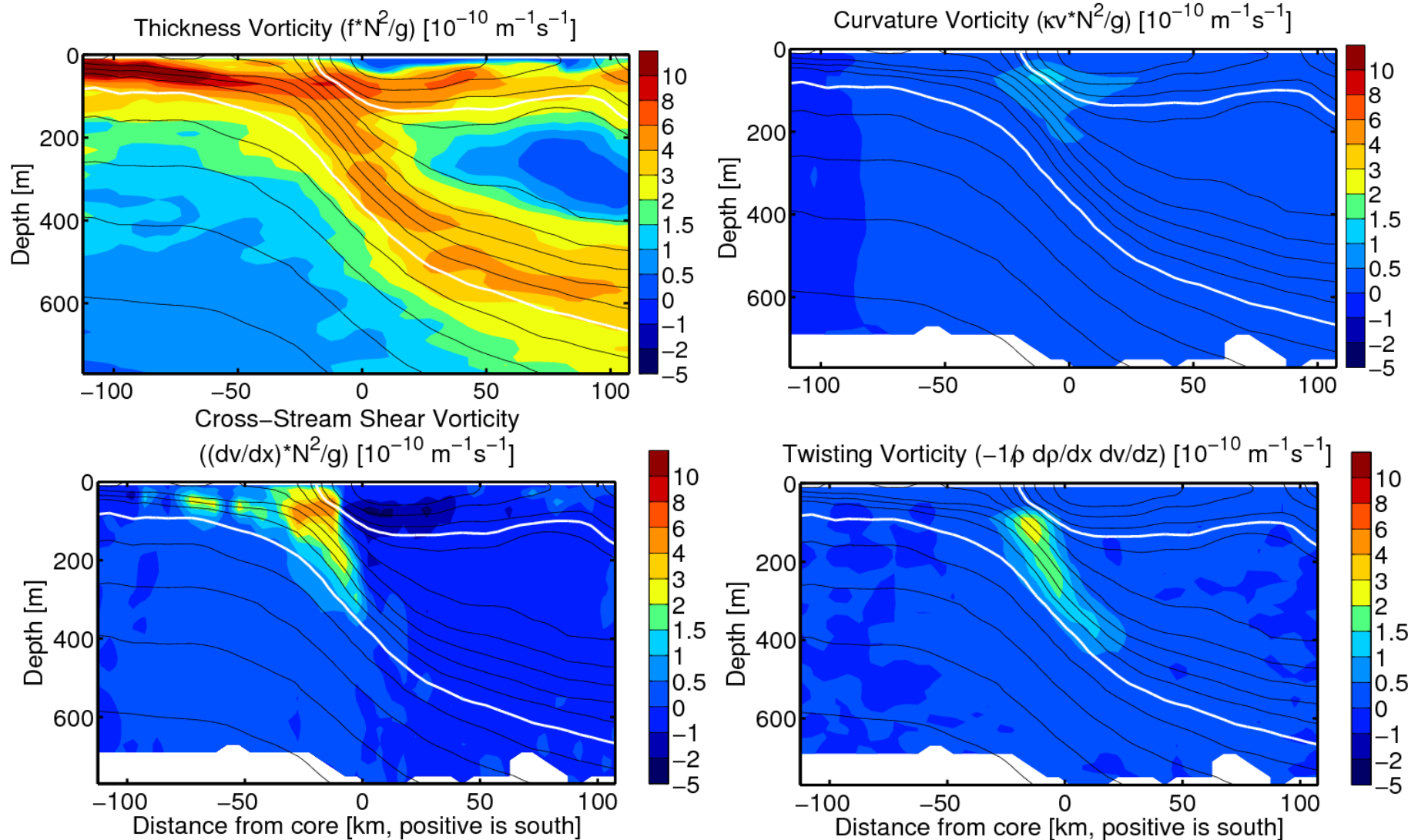
[$10^{-10} \text{ m}^{-1} \text{ s}^{-1}$]



- 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) ~ 0.8** just north of core, weakly negative south of core

Colors are PV, contour lines are σ_θ

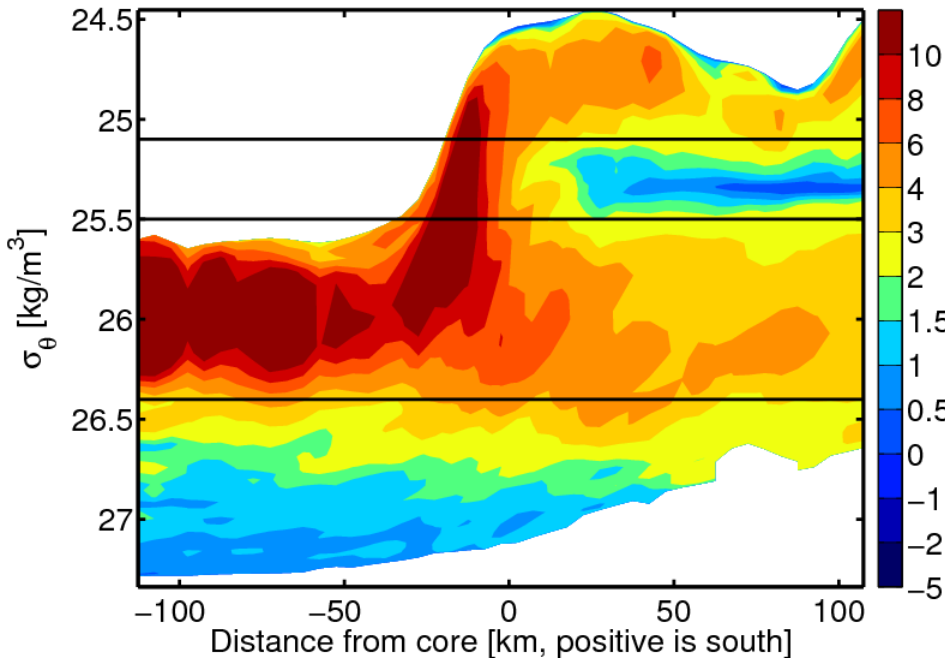
Does Shear Vorticity Matter?



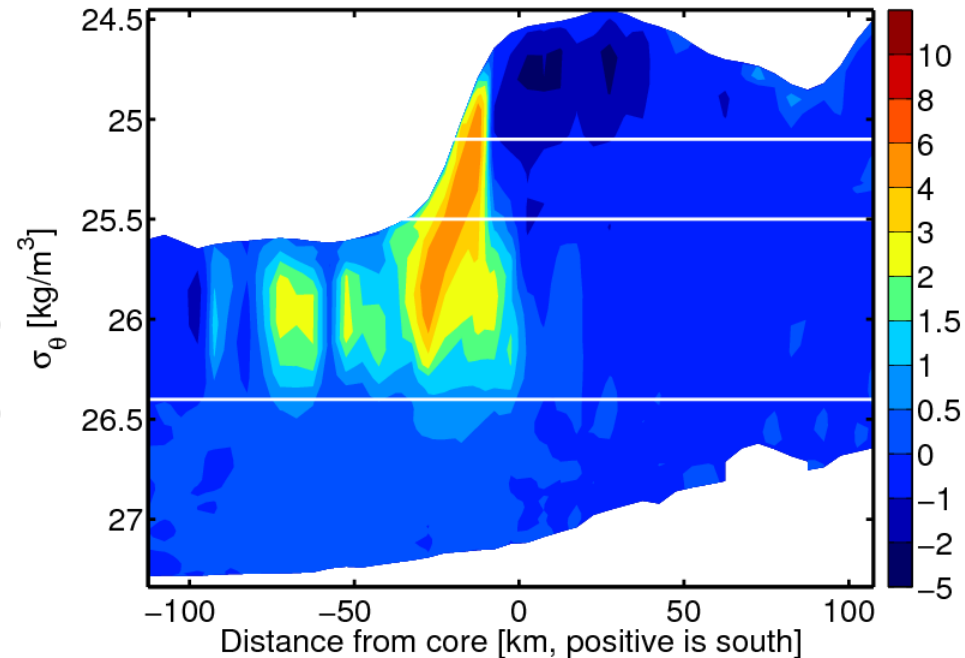
- **Cross-stream shear** ~40% of total PV (~80% of f) at shallow depths north of core
- **Twisting vorticity** ~15-20% of total PV (~30% of f) north of core

PV as a Function of Density

Total PV as a Function of σ_θ [$10^{-10} \text{ m}^{-1} \text{ s}^{-1}$]



Relative Vorticity as a Function of σ_θ [$10^{-10} \text{ m}^{-1} \text{ s}^{-1}$]

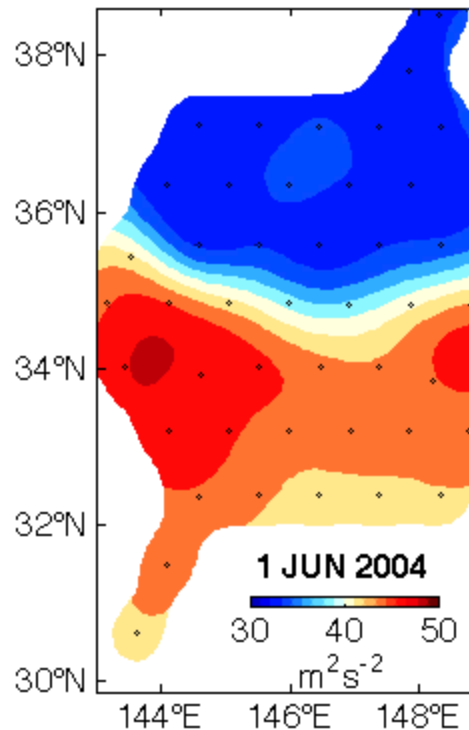


Where are PV gradients?

- $\sim \sigma_\theta = 25.1$ - 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?

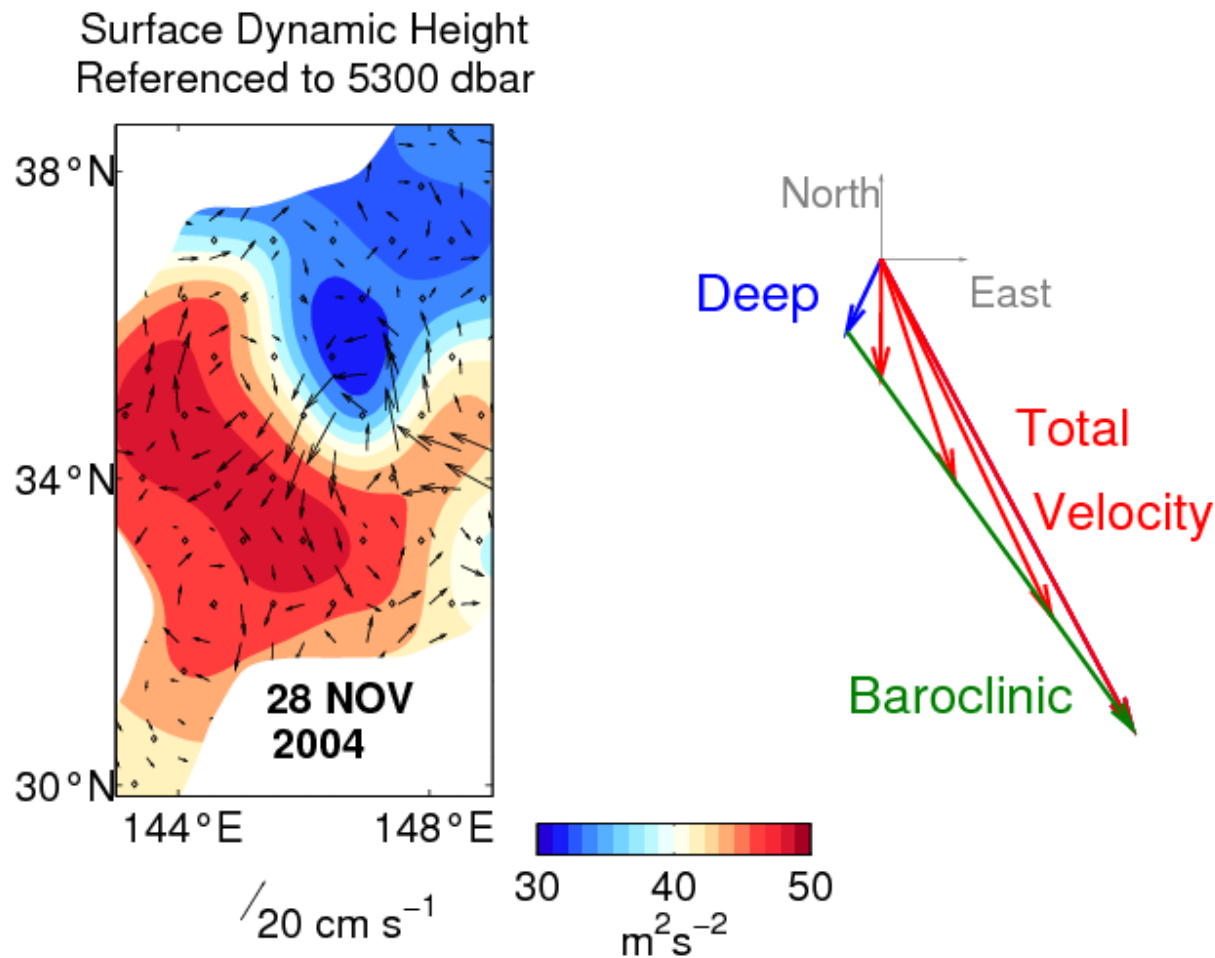
- **CPIES** provide a **longer time series** of geopotential height...



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

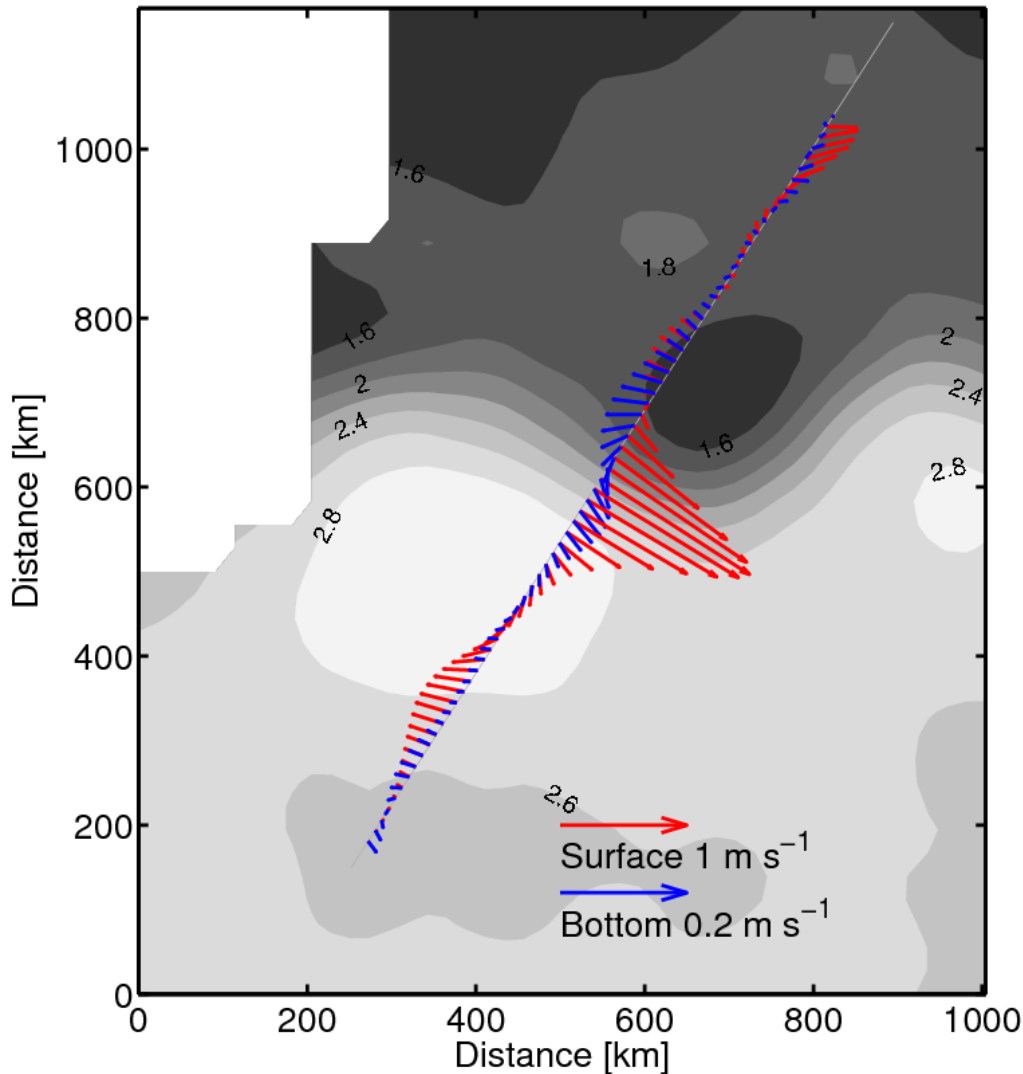
CPIES

- **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



Stream-Coordinate Mean from CPIES

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



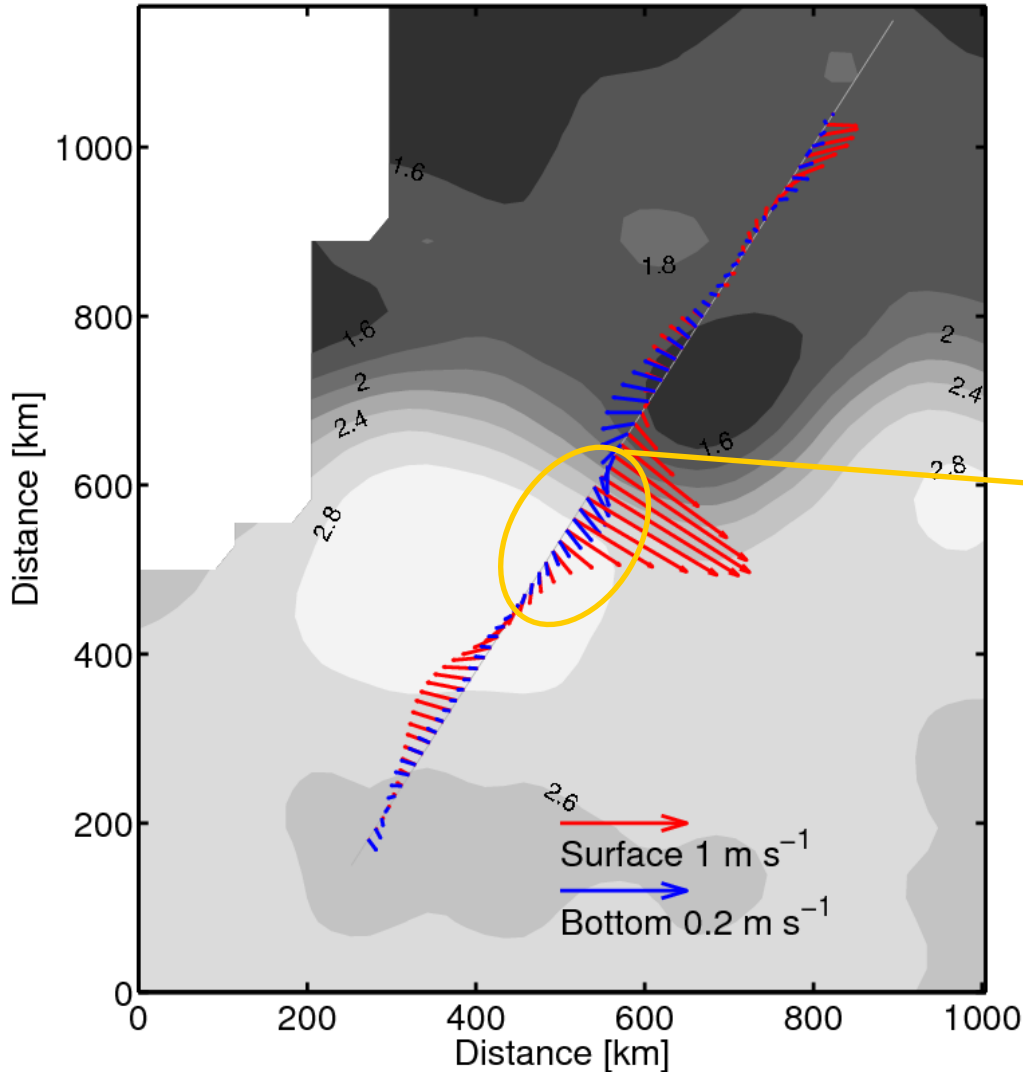
To generate **6-month stream-coordinate mean at a longitude:**

- **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

Stream-Coordinate Mean from CPIES

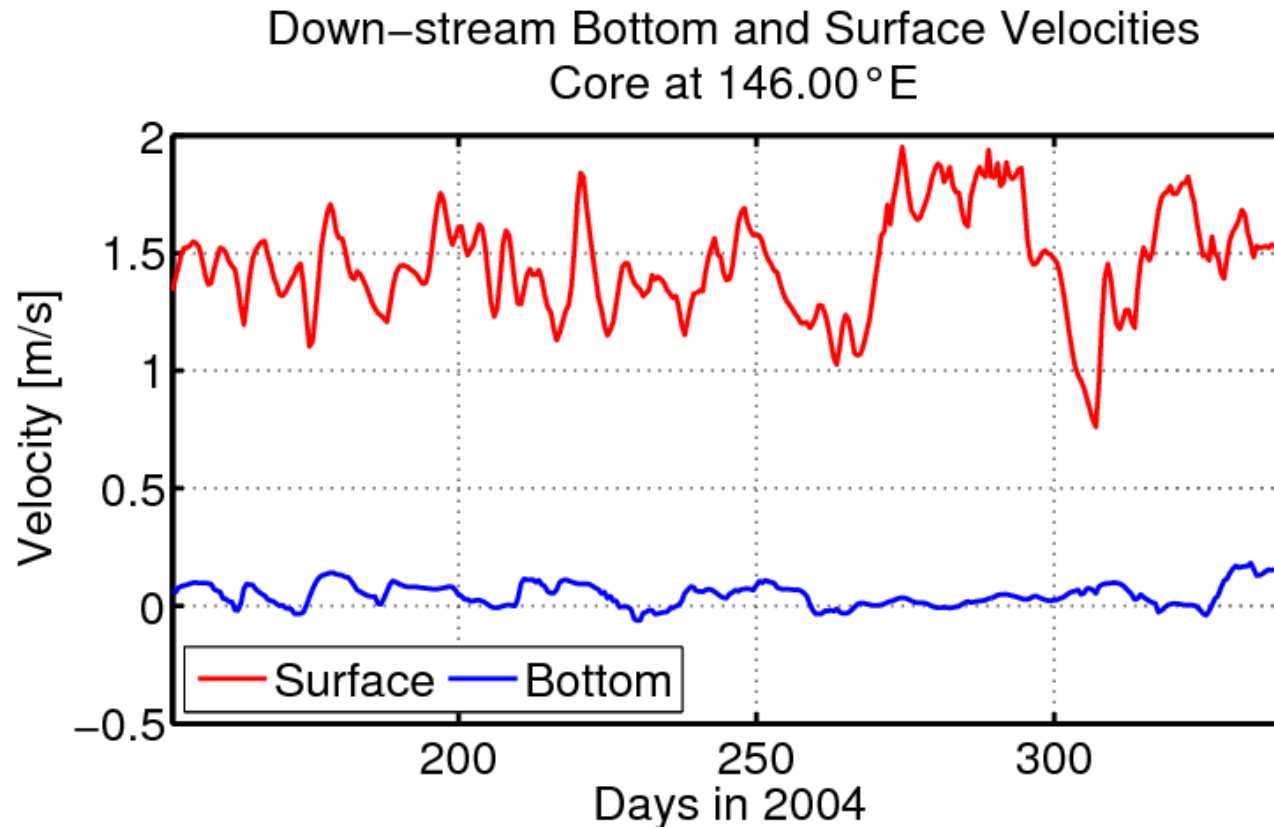
Mean Absolute Velocities In Increments of 15 km from the Core
2004/06/01 to 2004/12/01



Clockwise rotation of velocity with depth at and south of core

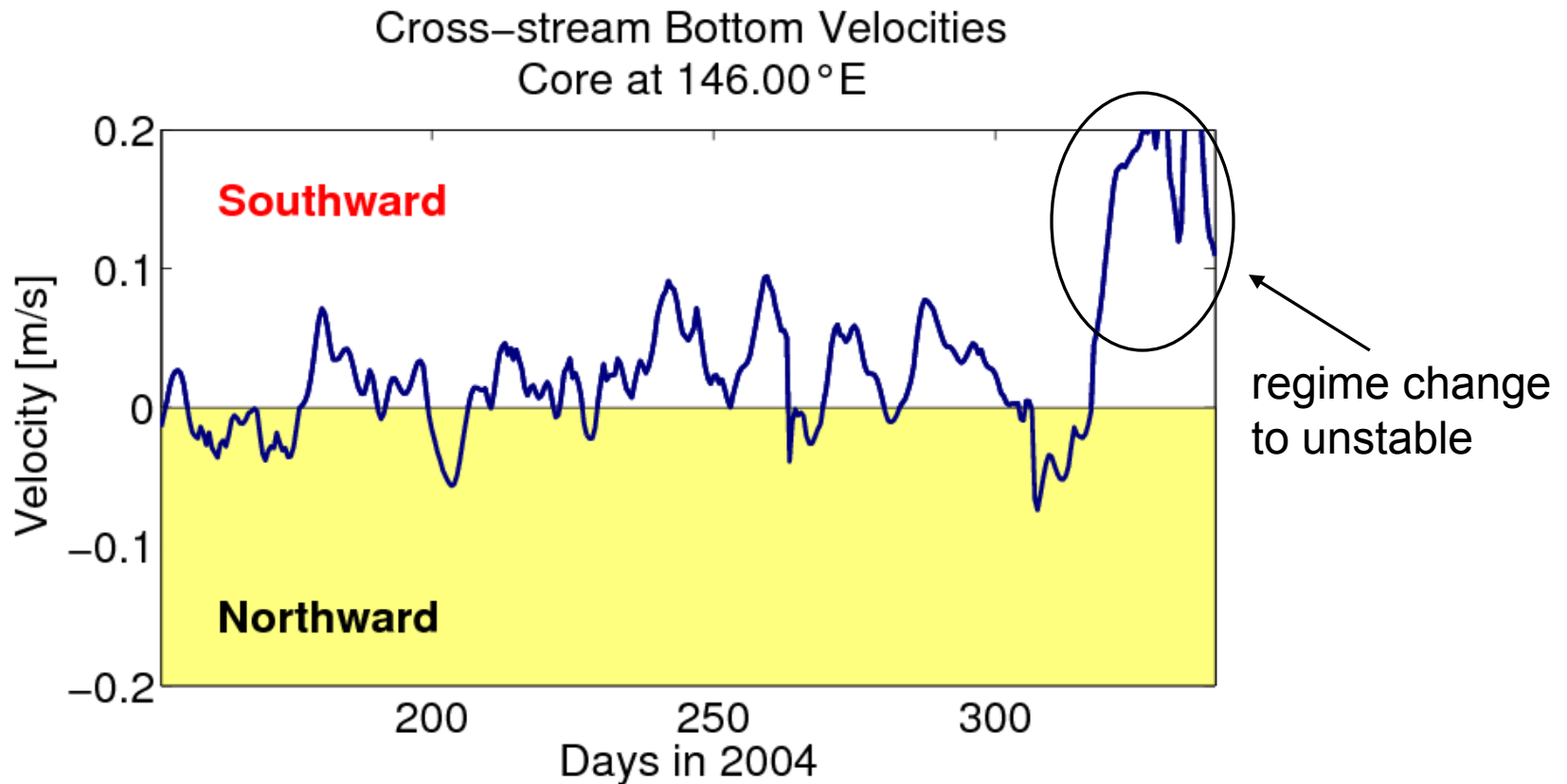
- Implies **southward cross-frontal flux** and subpolar-to-subtropics **downwelling**

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

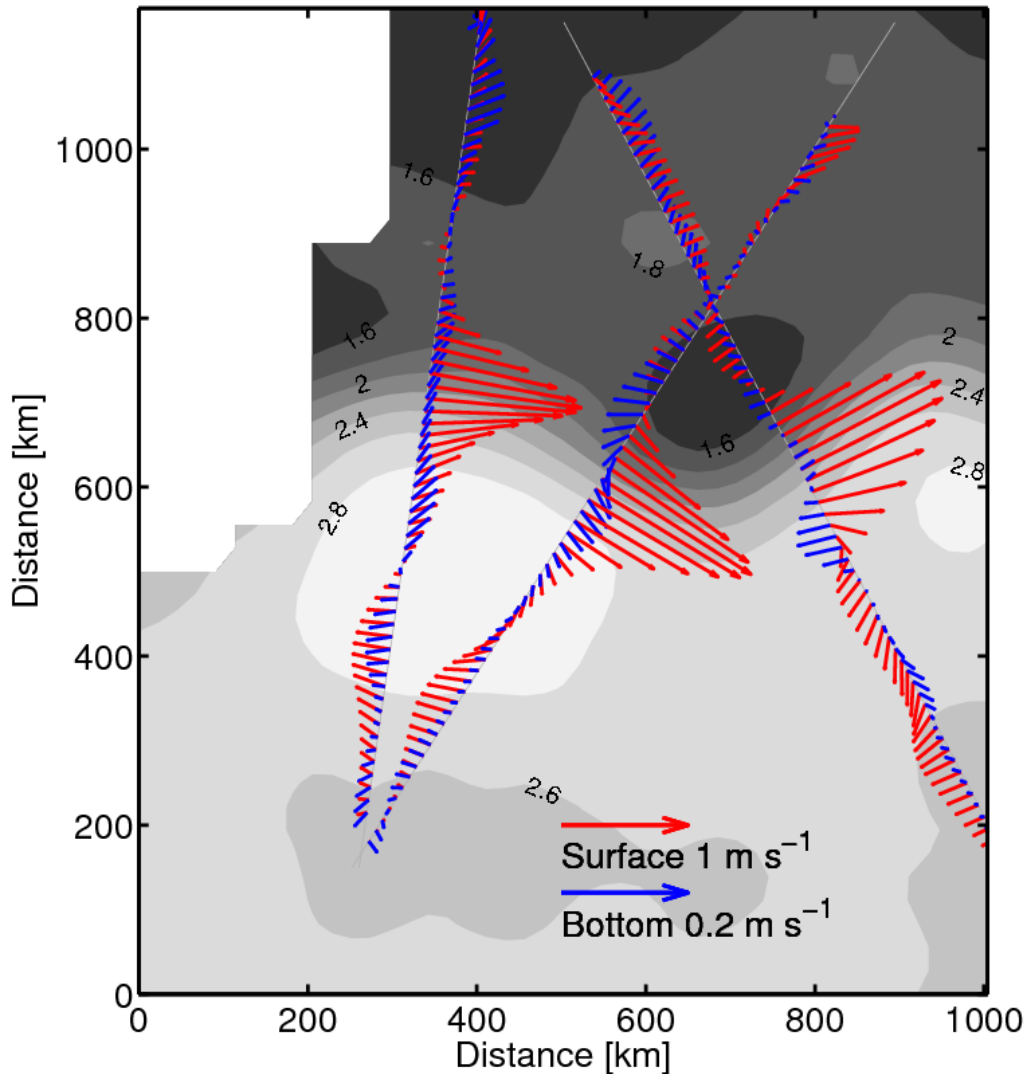
Core Cross-stream Flow Variability



- 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?

Structural Changes: Crest-Trough-Crest

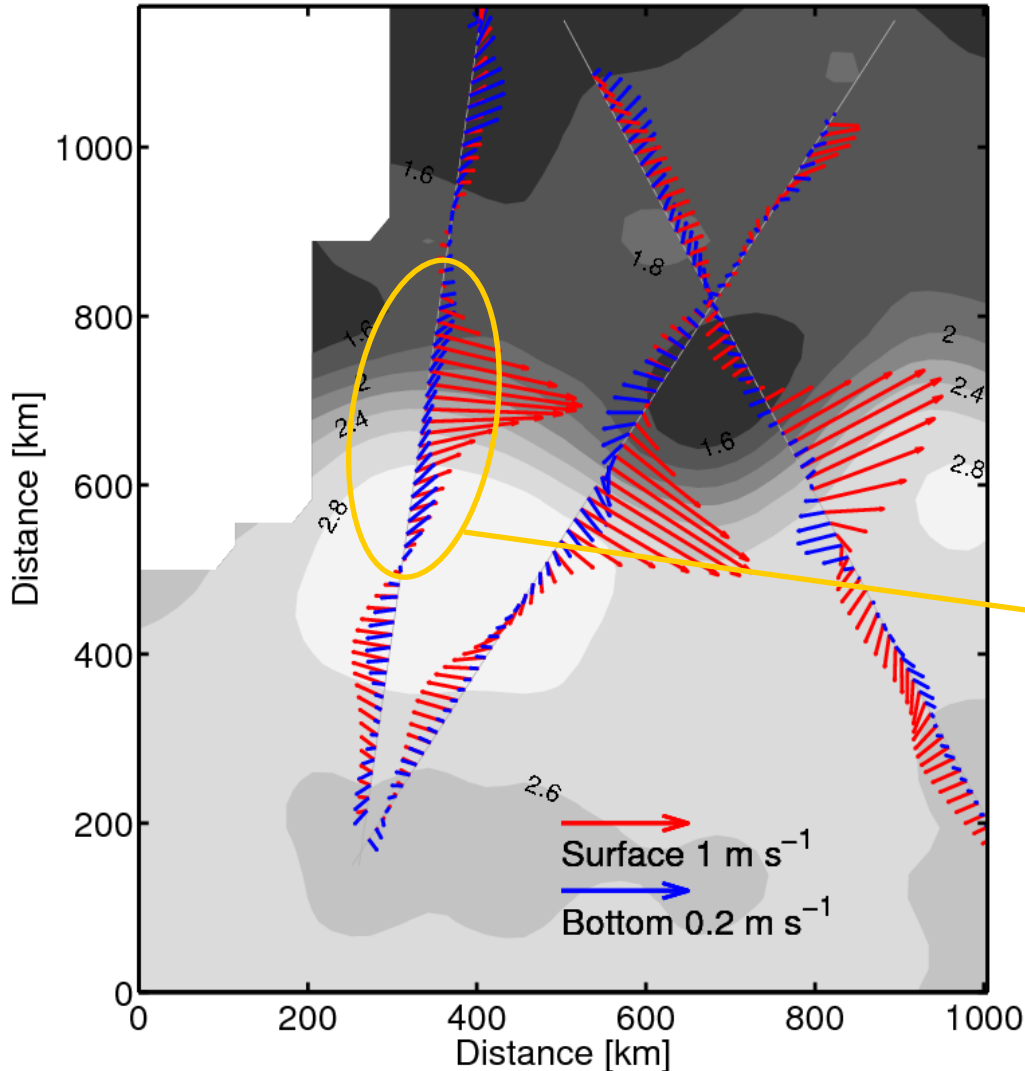
Mean Absolute Velocities In Increments of 15 km from the Core
2004/06/01 to 2004/12/01



- 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

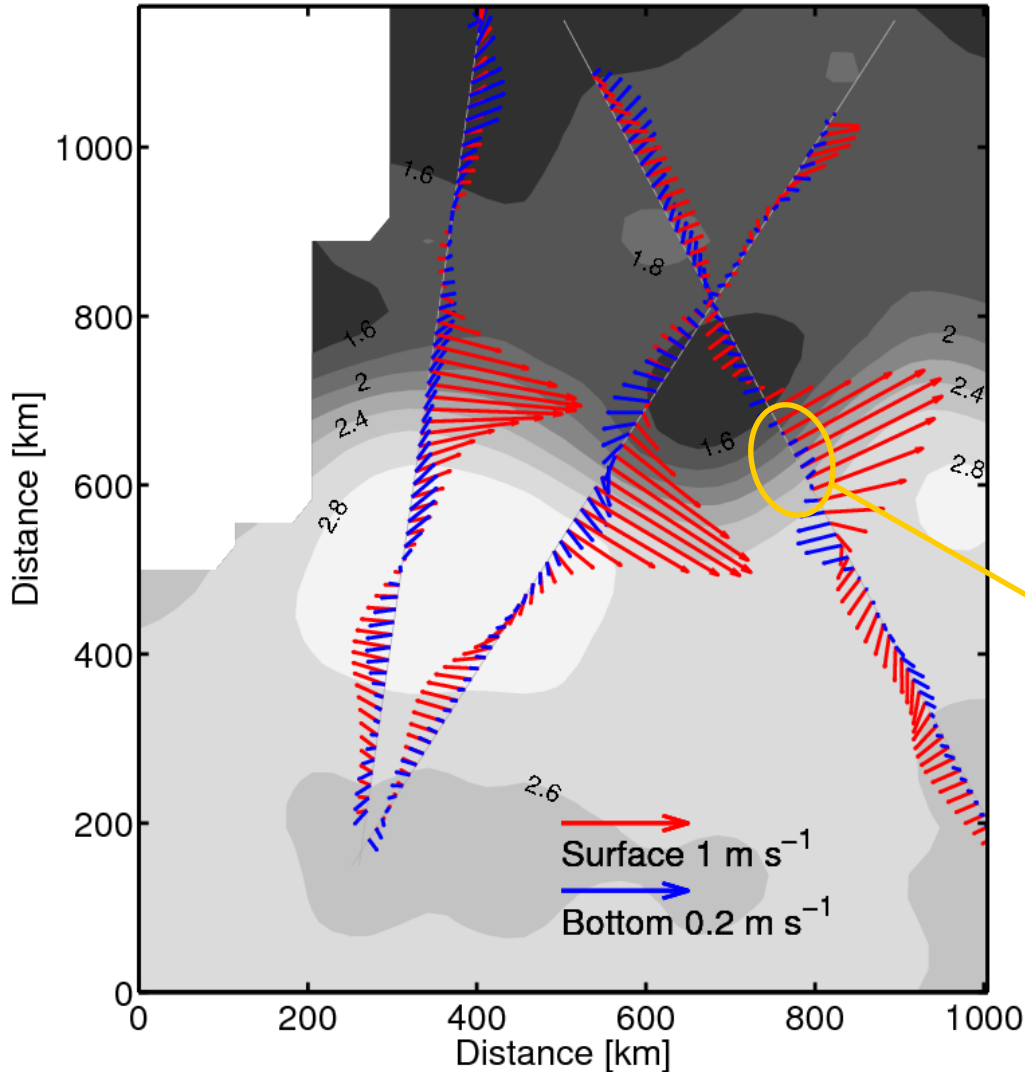


Counter-clockwise rotation with depth at first meander crest

- Implies **northward cross-frontal flux** and subtropics-to-subpolar upwelling

Structural Changes: Crest-Trough-Crest

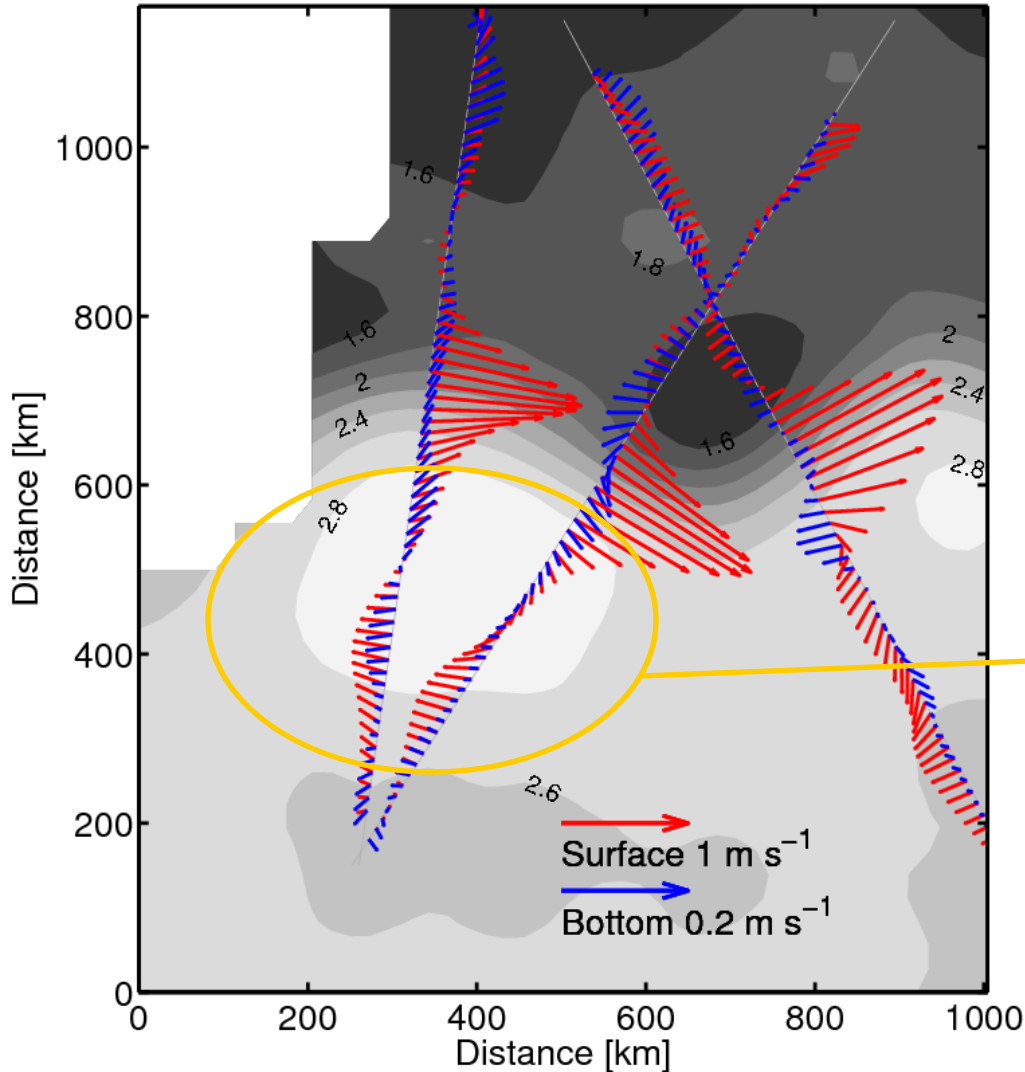
Mean Absolute Velocities In Increments of 15 km from the Core
2004/06/01 to 2004/12/01



- 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

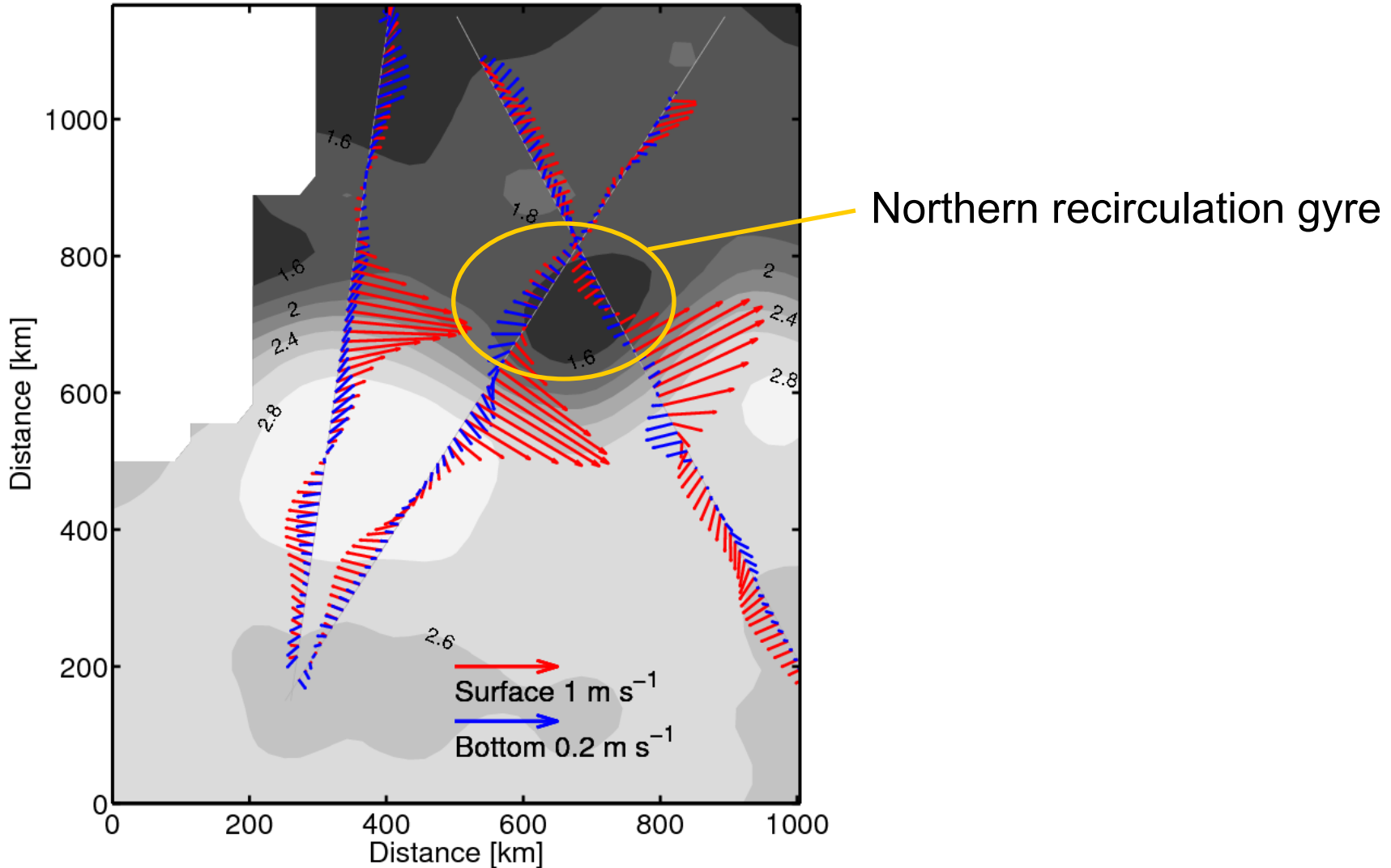


Southern recirculation gyre

- 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



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

	Gulf Stream	Kuroshio
Down-stream Velocity	Maximum averages around 2 m/s, varying between 1.5-2.5 m/s ^{1,2,3,4}	Maximum averages around 1.5 m/s, varying between 1-2 m/s
Stream Width	214 km between lines of 0 transport over 0-2000 m ³ , narrower in troughs than crests ¹	~150-200 km between lines of 0 down-stream velocity estimated from surveys and CPIES
Total PV	$O(10^{-10})^1$	$O(10^{-10})$
Contribution of Lateral Shear Vorticity	In steepening crest, up to 120% of f on cyclonic side, ~-40% of f on anticyclonic side ¹	Entering trough, >80% of f on cyclonic side, ~-30% of f on anticyclonic side

¹Liu and Rossby, 1993; ²Rossby and Gottlieb, 1998; ³Halkin and Rossby, 1985;

⁴Rossby and Zhang, 2001