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

6 March, 2008

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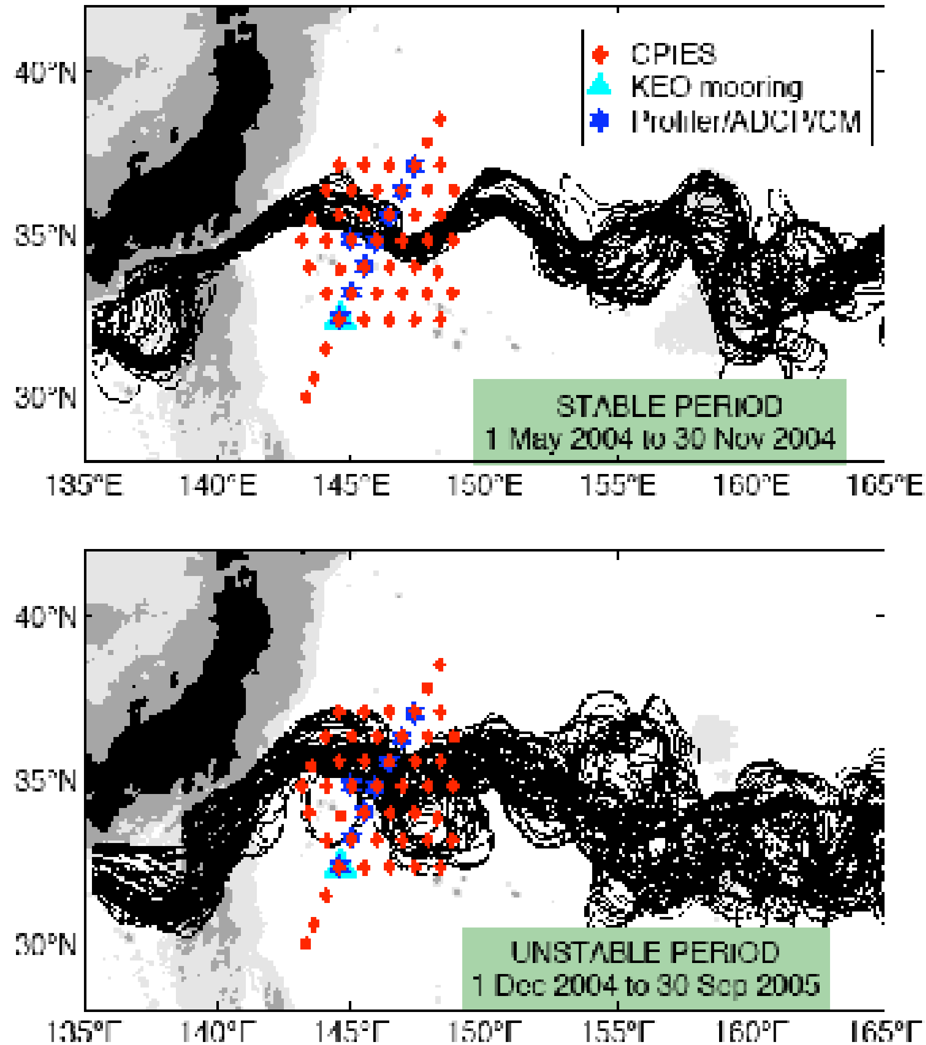
Kuroshio Extension System

• 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**

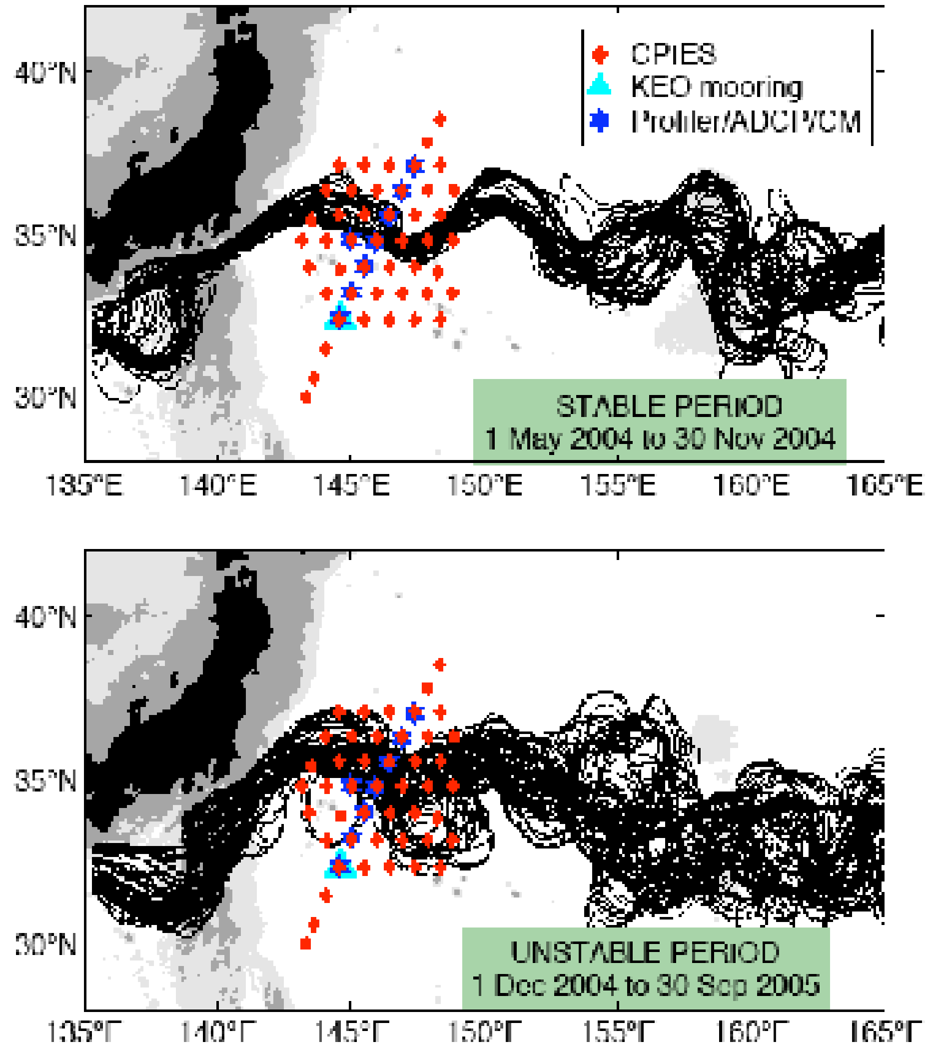


After *Qiu and Chen, 2005*

Kuroshio **E**xtension **S**ystem **S**tudy

KESS:

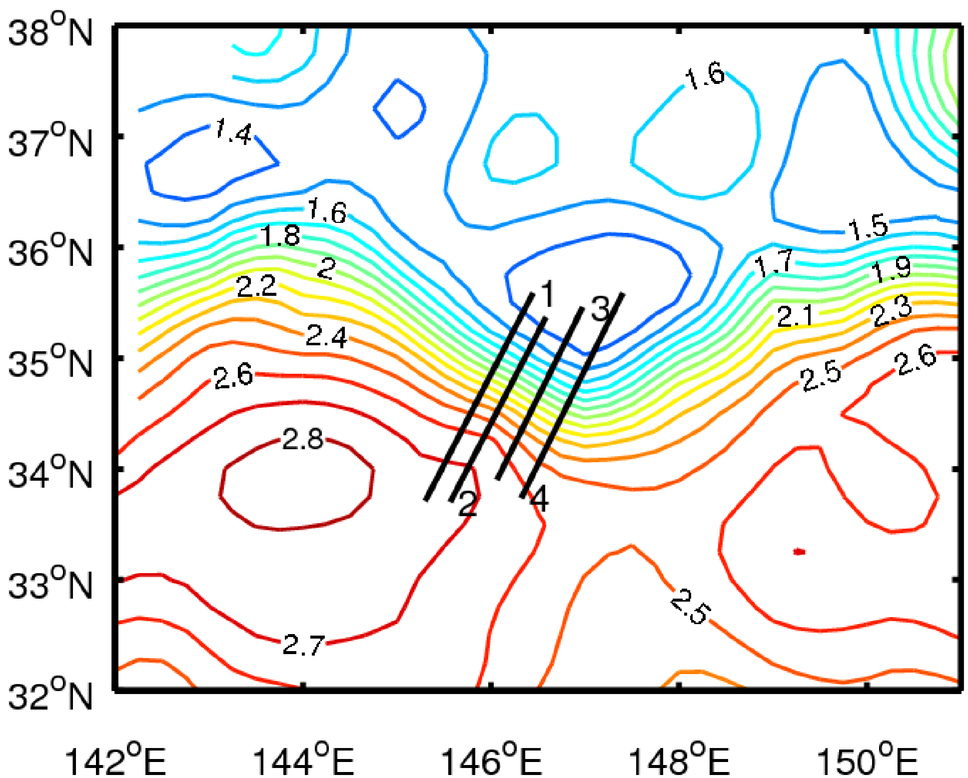
- 46 Current and Pressure sensor-equipped Inverted Echo Sounders (CPIES)
- June 2004 - June 2006
- First meander crest and trough
- Stable for first 6 months
- Unstable thereafter



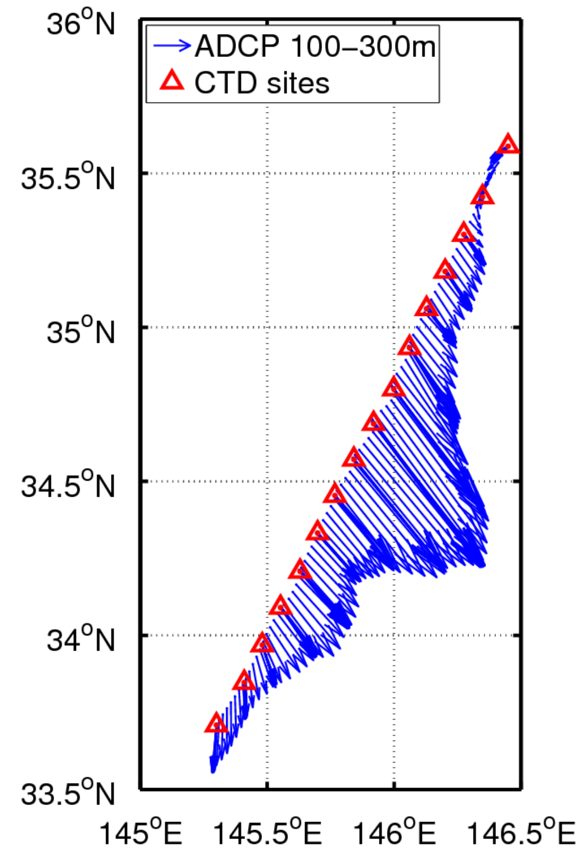
After *Qiu and Chen, 2005*

Feature Surveys

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



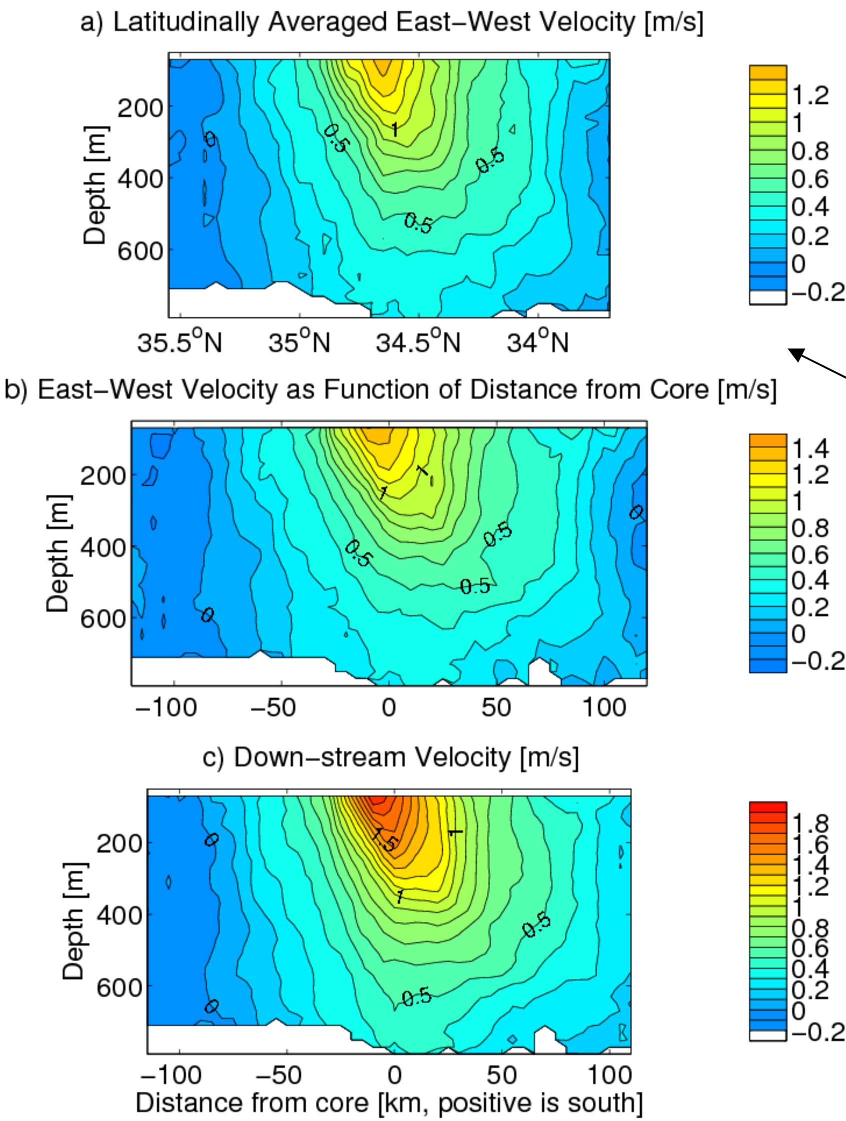
- Transects 1-4 over mean SSH contours for time of surveys (5/2-5/6)



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**

Averaging east-west velocities by latitude…

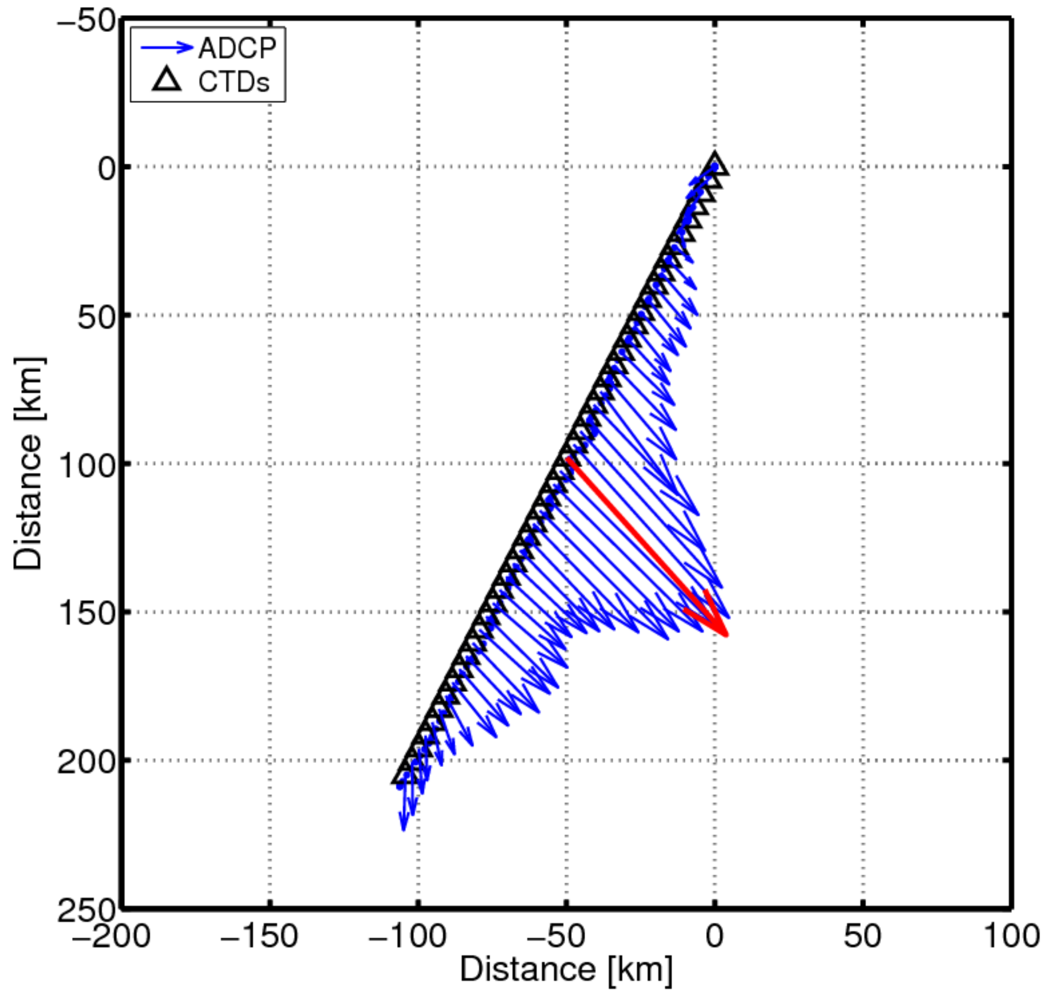
or as a function of distance from core…

…smears out structure.

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

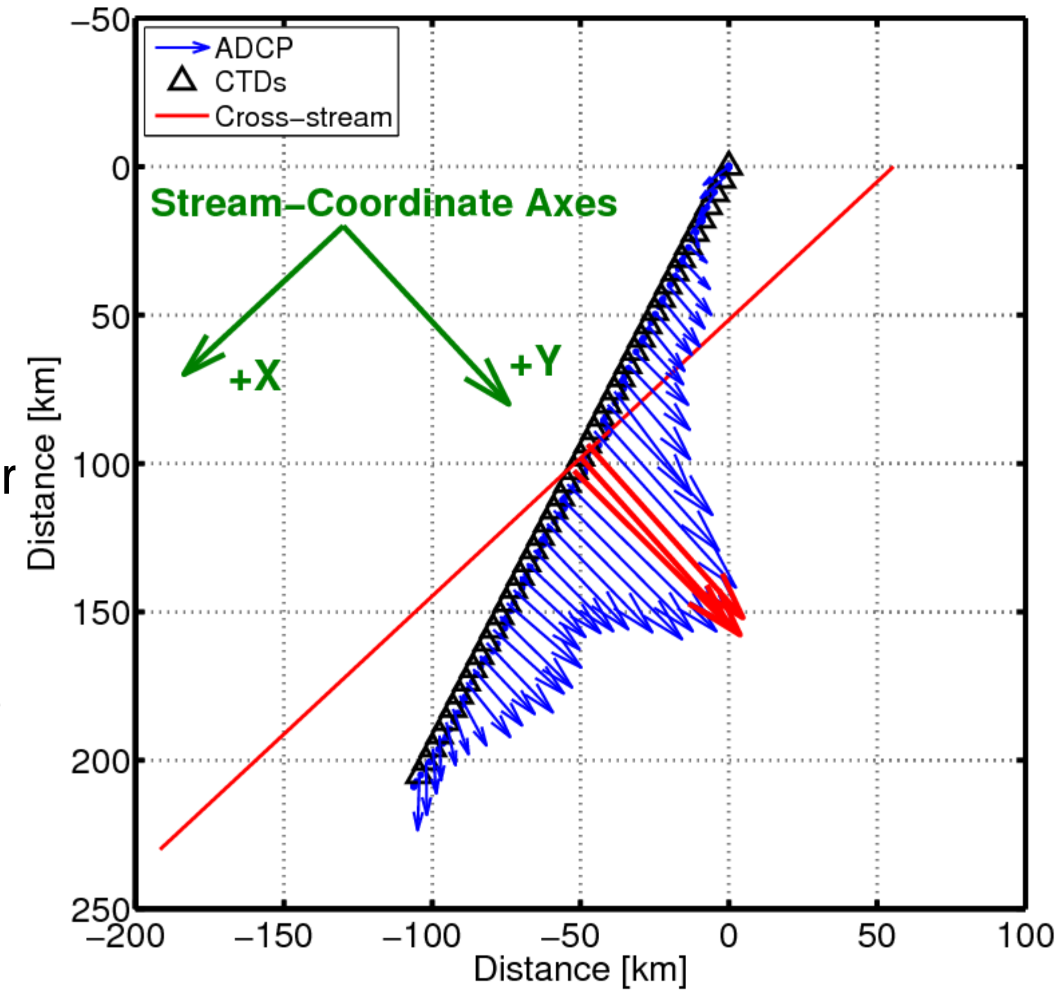


Sample transect

5 km gridded, 100-300 m averaged ADCP

Defining the Stream-Coordinate System

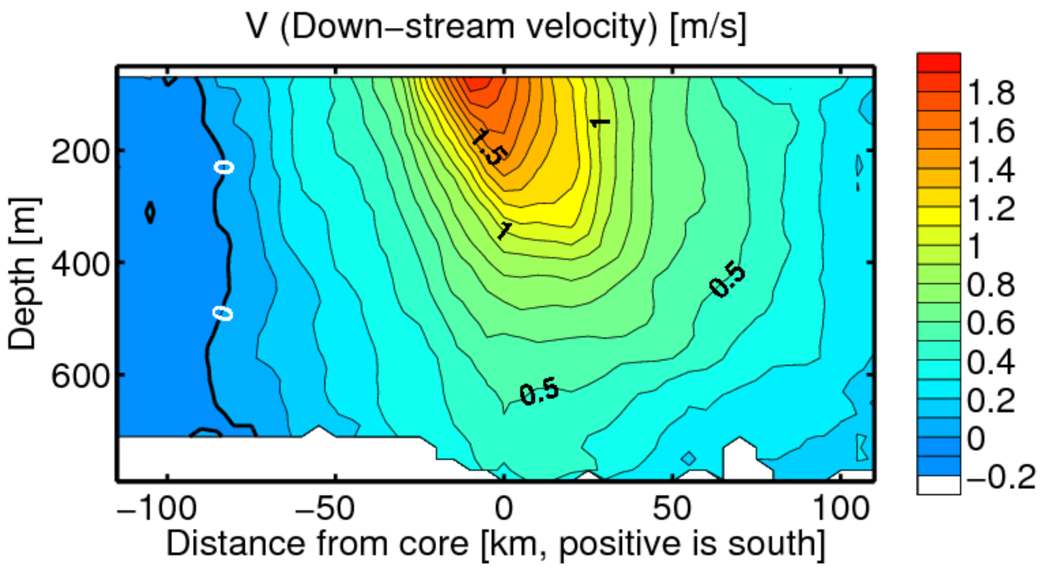
- ADCP data averaged over 100-300 m depth range
- **Core** = location of maximum velocity
- **Down-stream direction** = vector average of **three** central ADCP vectors
- Project data to cross-stream line
- Rotate to down- and cross-stream components

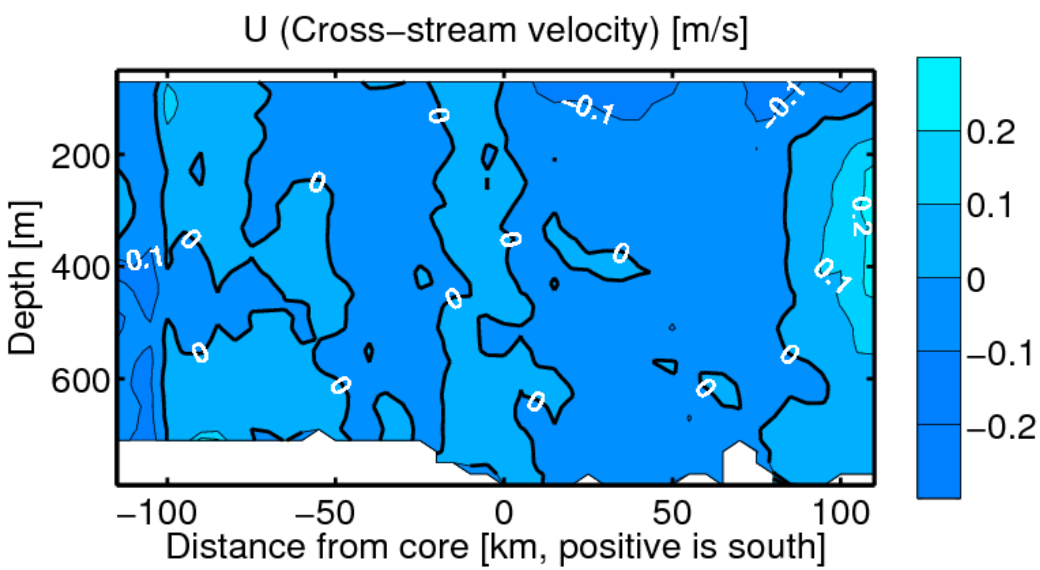


Sample transect

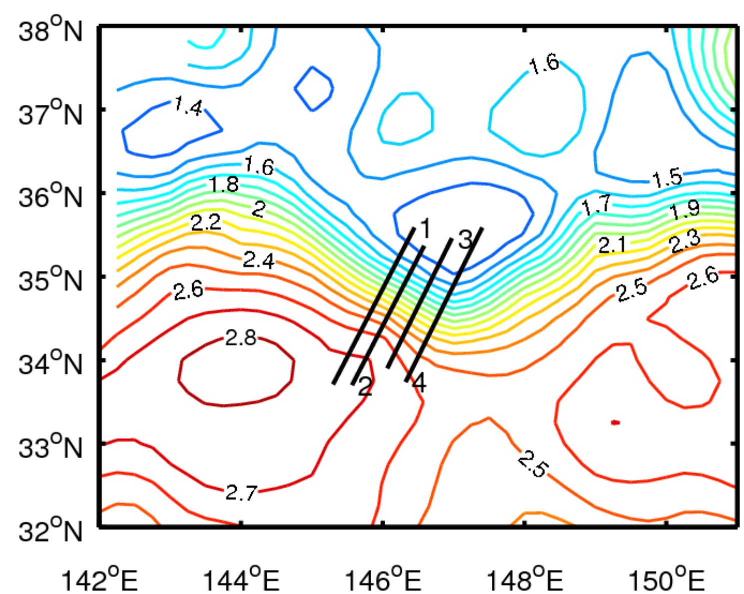
5 km gridded, 100-300 m averaged ADCP

Mean Down- and Cross-stream Velocity





- 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)*:

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

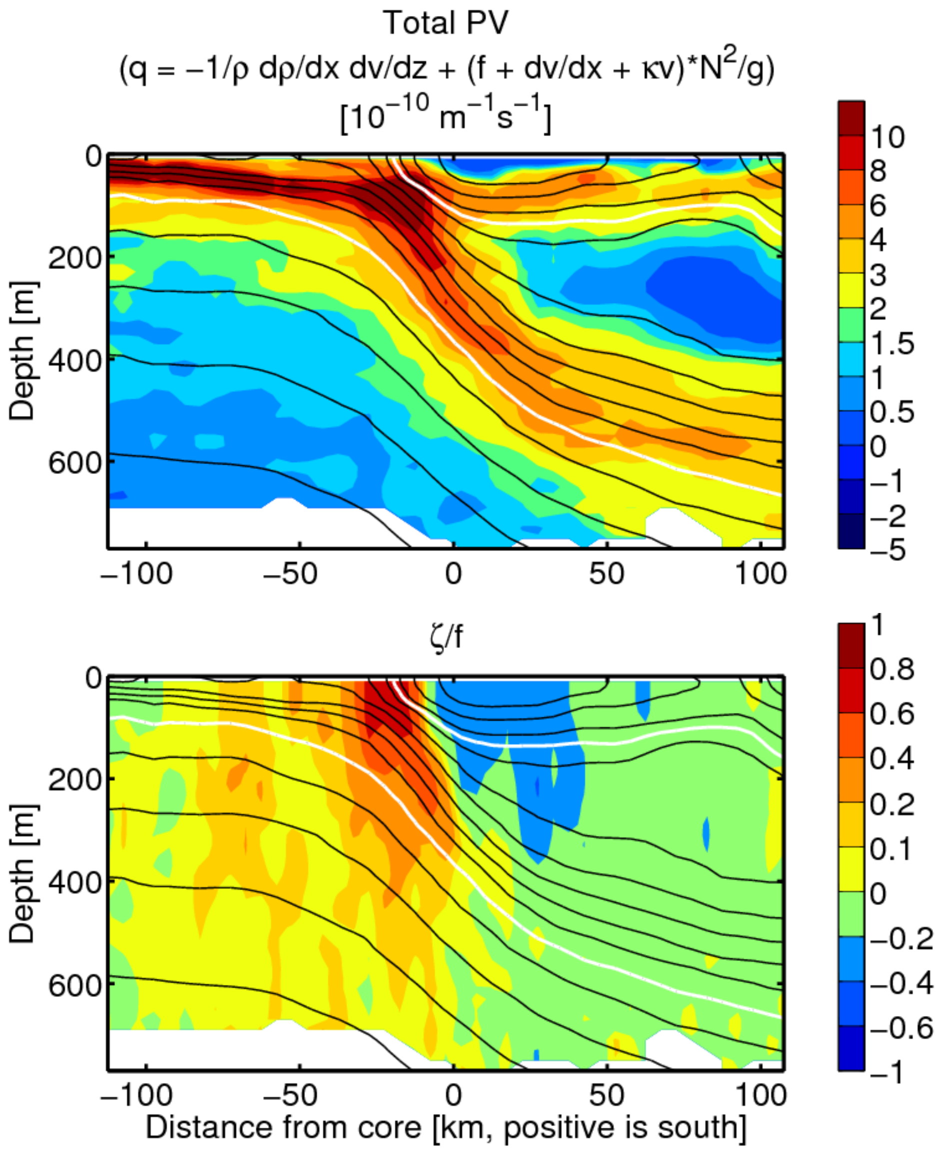
"twisting"

"thickness"

"cross-stream shear"

"curvature"

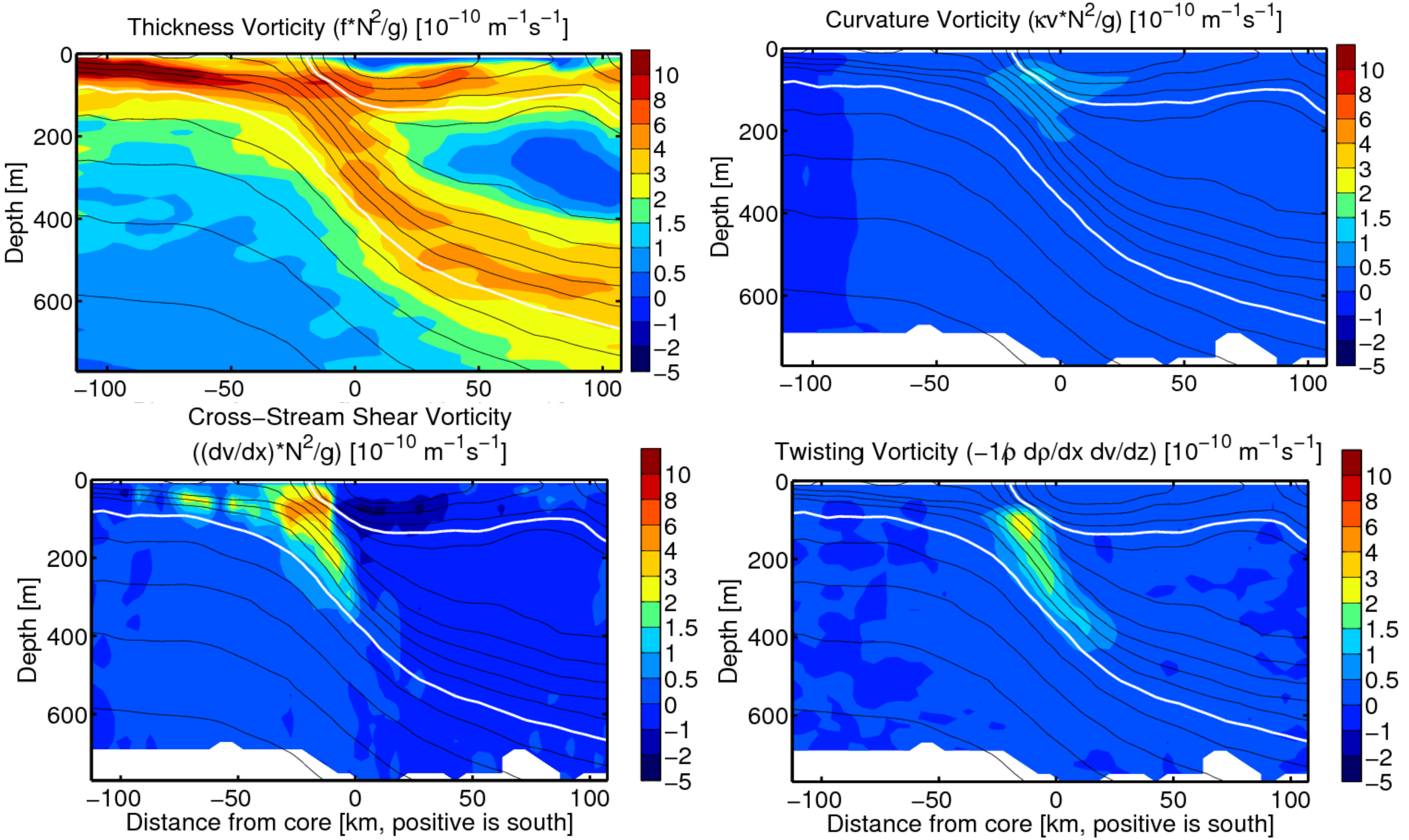
Mean Potential Vorticity Structure



Colors are PV, contour lines are σ_θ

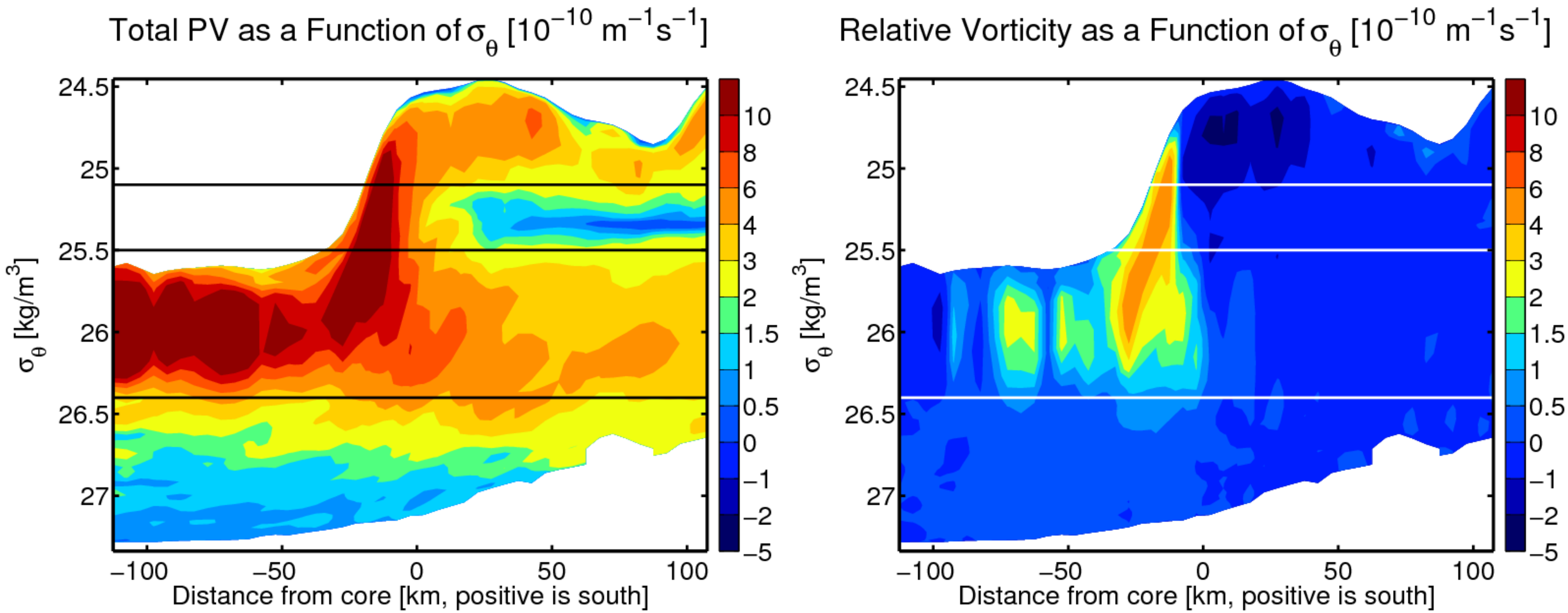
- CTD data: surface-1200m
- ADCP data extrapolated to surface
- Strong band of high-PV water follows isopycnals down from north to south of core
- Low-PV **mode water** evident
- **(Ro) ~ 0.8** just north of core, weakly negative south of core

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

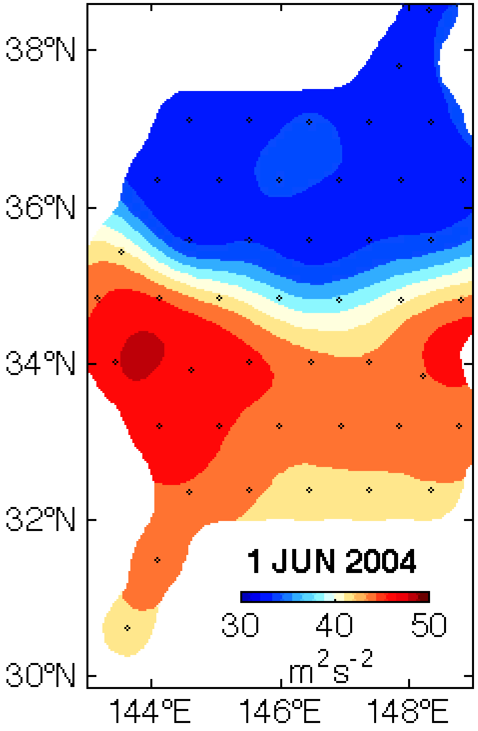


Where are PV gradients?

- ~σ_θ = 25.1-25.5, **Mode water region: strong gradients, "barrier"**
- ~σ_θ = 25.5-26.4, **Main thermocline: weaker gradients**
- ~σ_θ > 26.4, **NPIW: no gradients, "blender"**

How Representative is the Survey Mean?

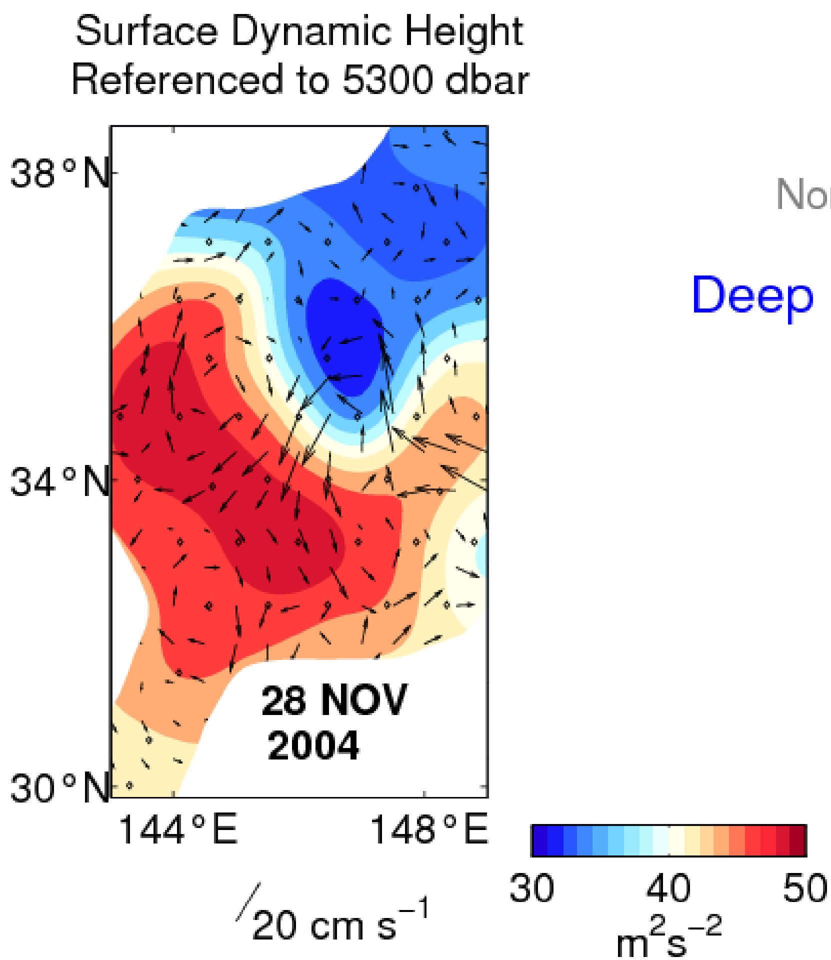
- **CPIES** provide a **longer time series** of geopotential height…

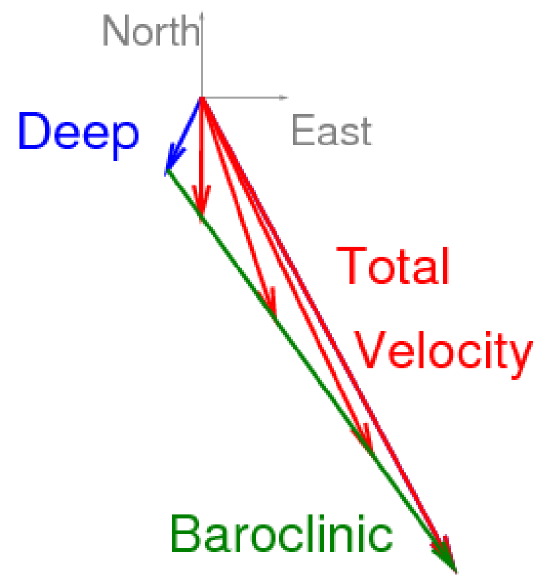


- **Frontal waves** may cause **variability** in flow speed and structure

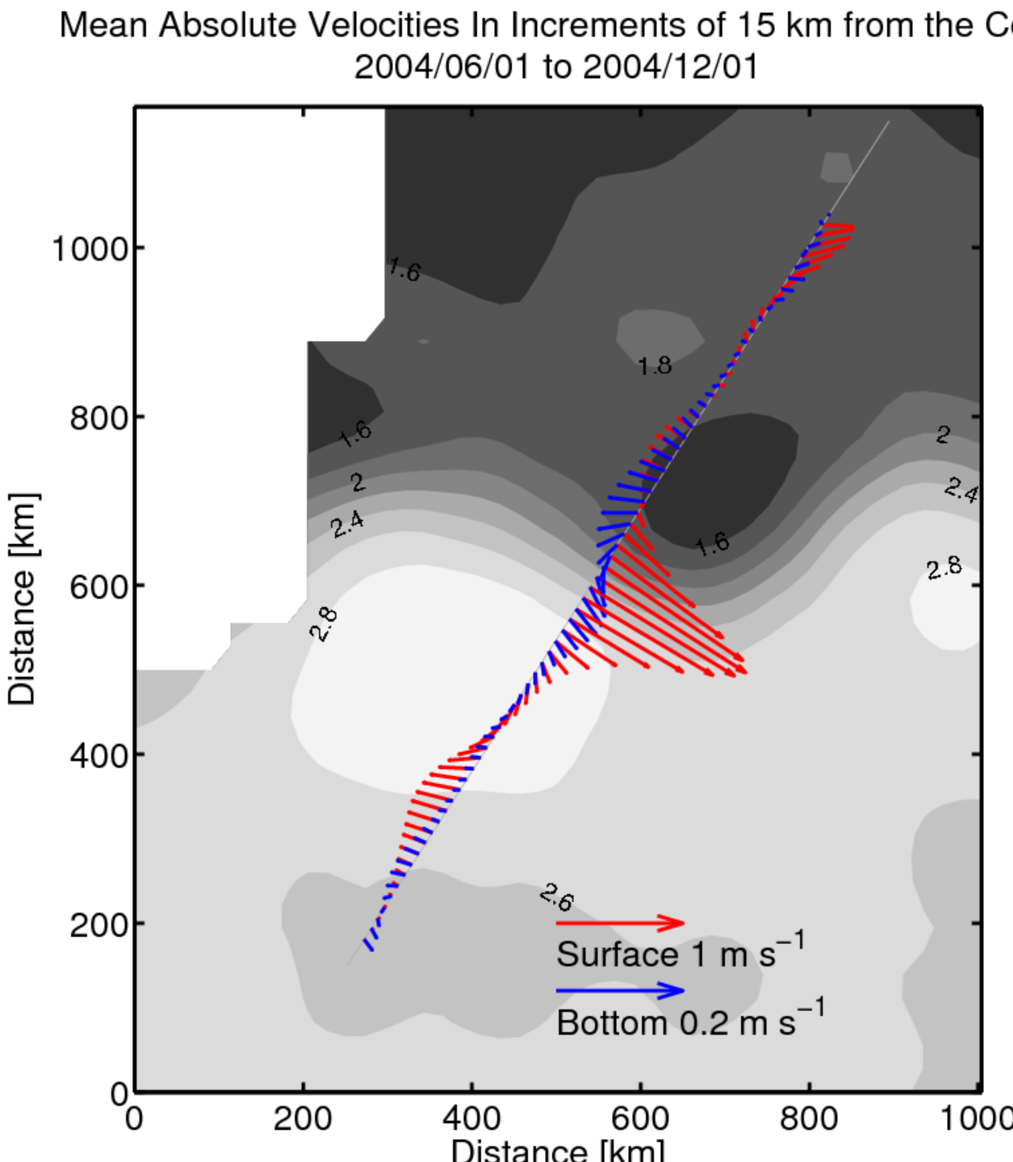
CPIES

- **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

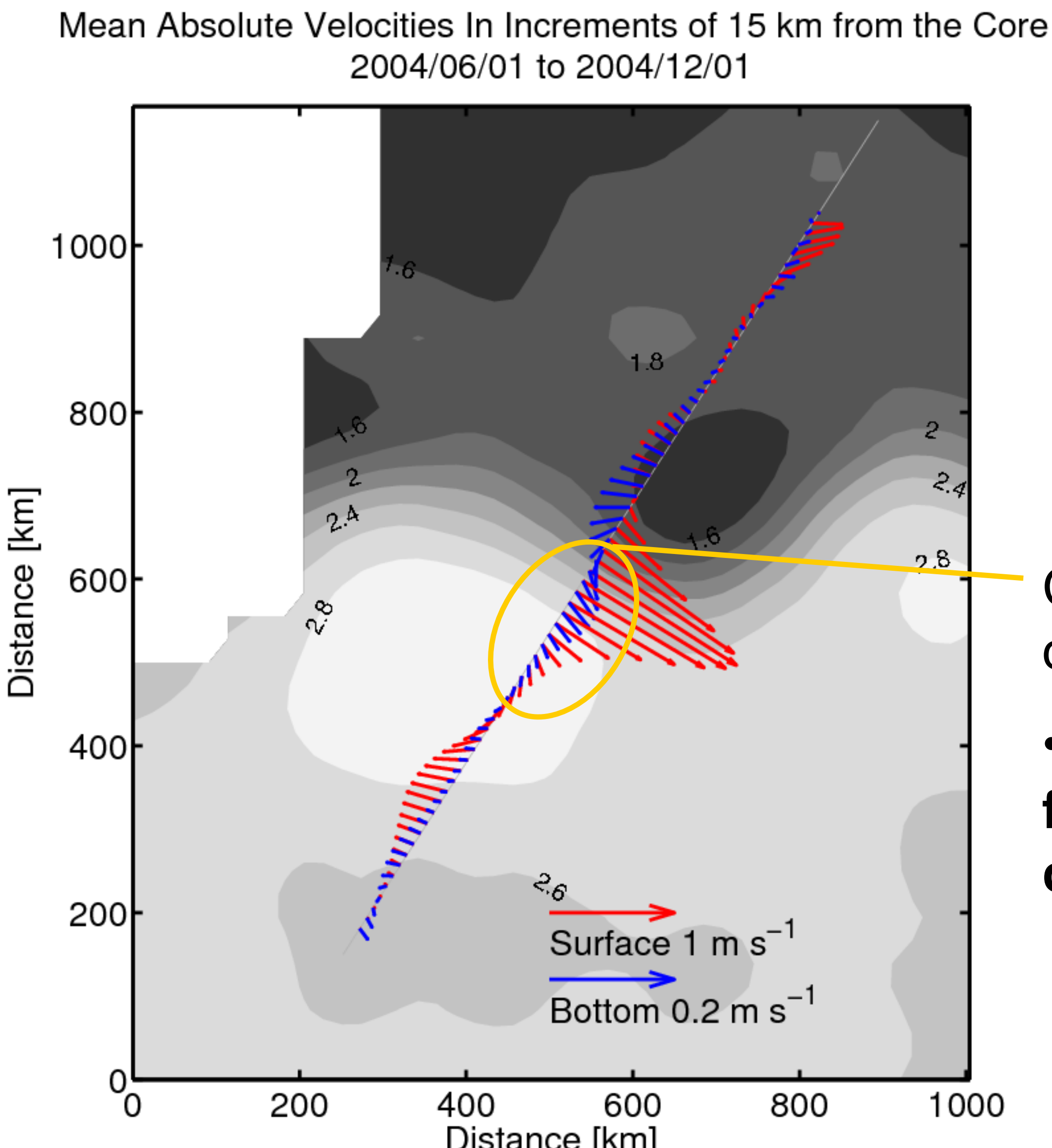


To generate **6-month stream-coordinate mean at a longitude:**

- **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

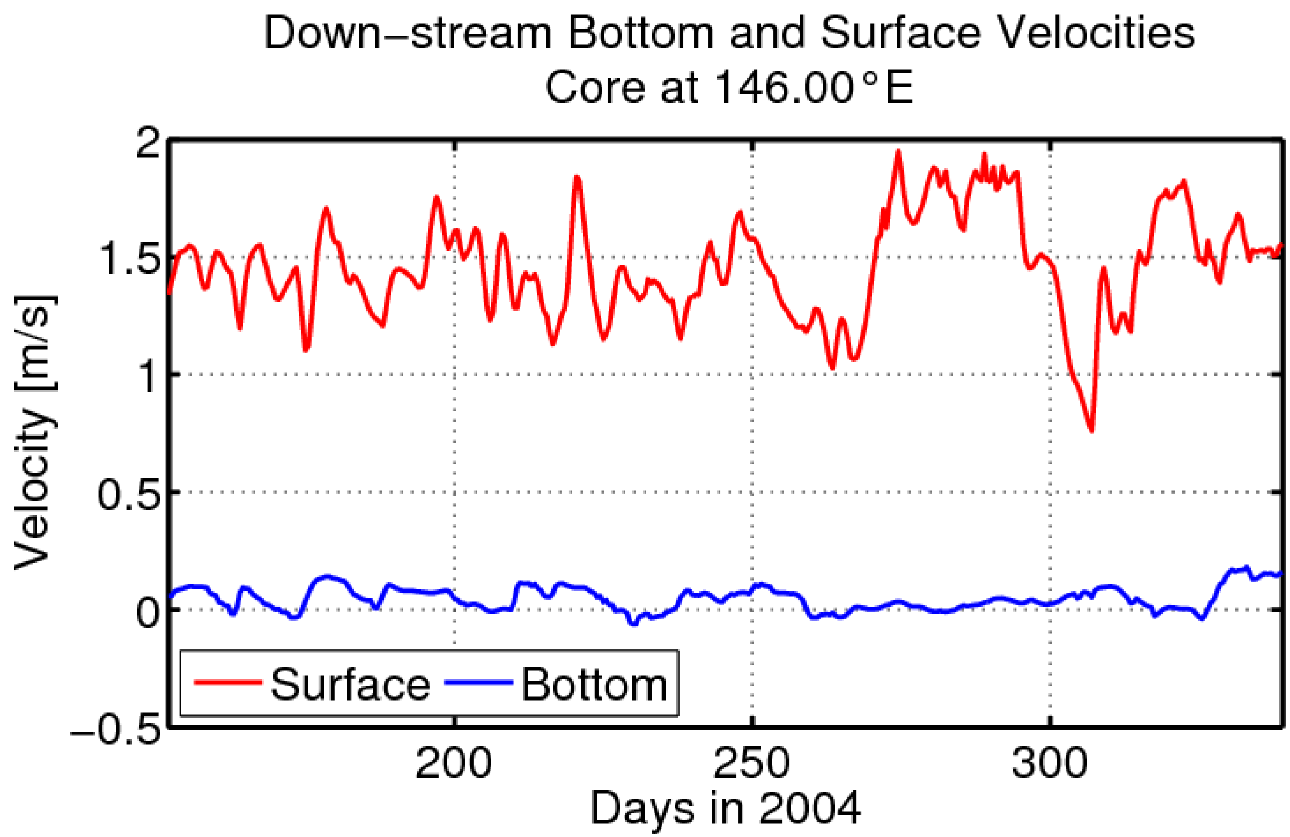
Stream-Coordinate Mean from CPIES



Clockwise rotation of velocity with depth at and south of core

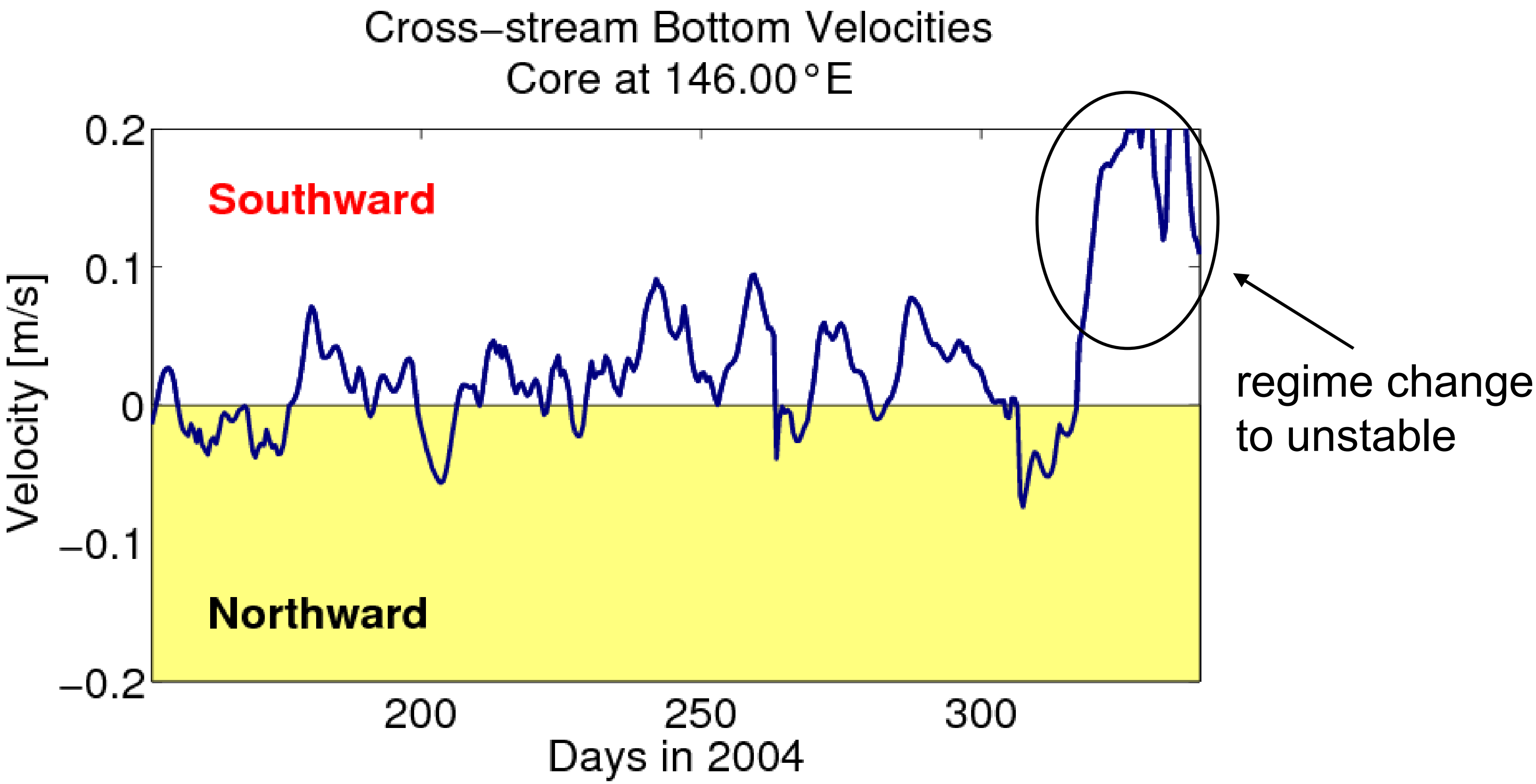
- Implies **southward cross-frontal flux** and subpolar-to-subtropics **downwelling**

Core Down-stream Velocity Variability



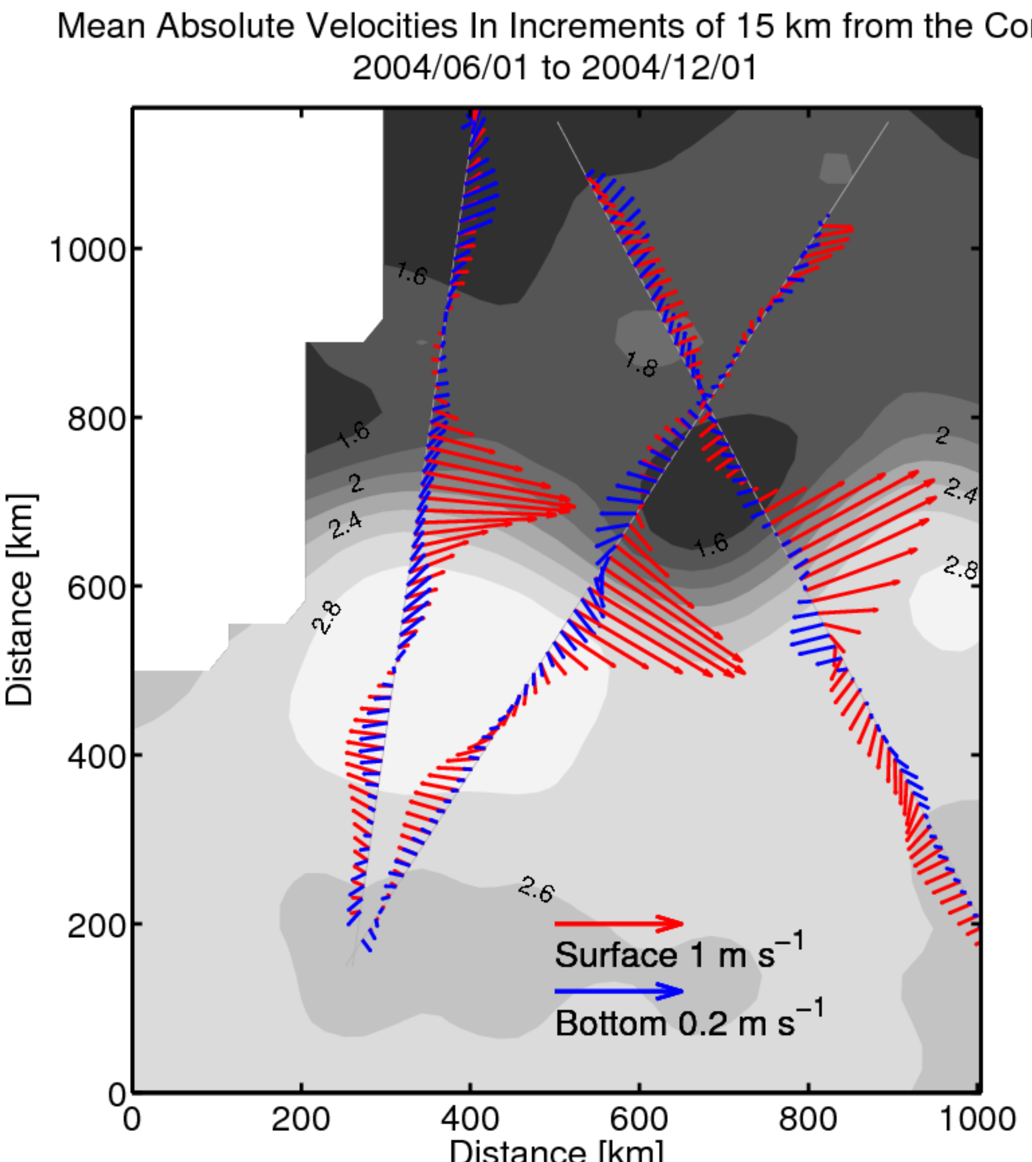
- Maximum **surface** down-stream velocities vary between **1-2 m/s**
- **Bottom** down-stream velocities at the core reach as high as **0.15 m/s** but are also negative at times
    - Deep flow direction reversal may be due to deep eddy activity

Core Cross-stream Flow Variability



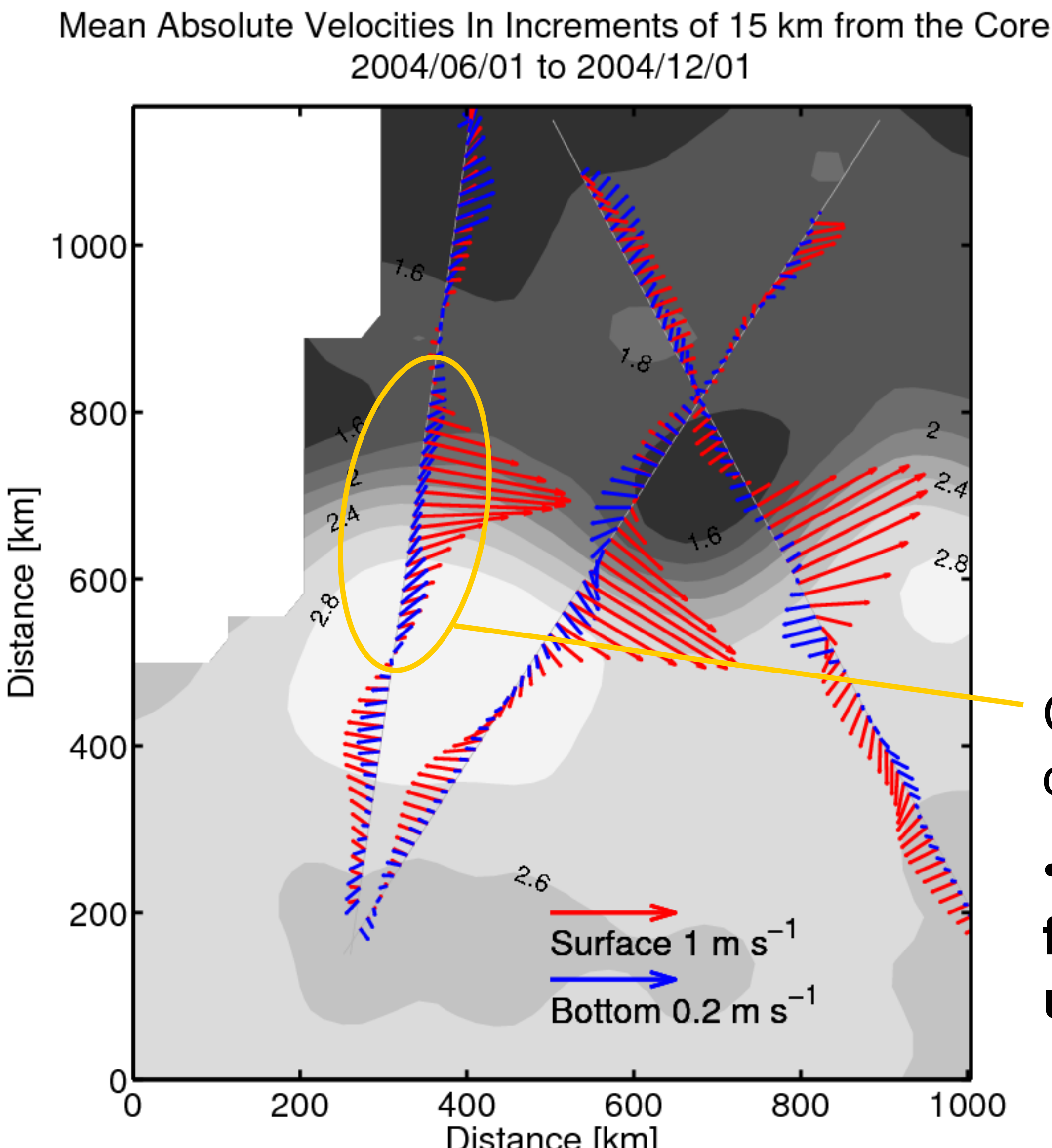
- Cross-stream bottom velocities show significant variability; southward cross-stream flow dominates at this location
- Suggestive of an event-driven process; mixture of remote and local forcing?

Structural Changes: Crest-Trough-Crest



- Repeat stream-coordinate averaging procedure at other longitudes…

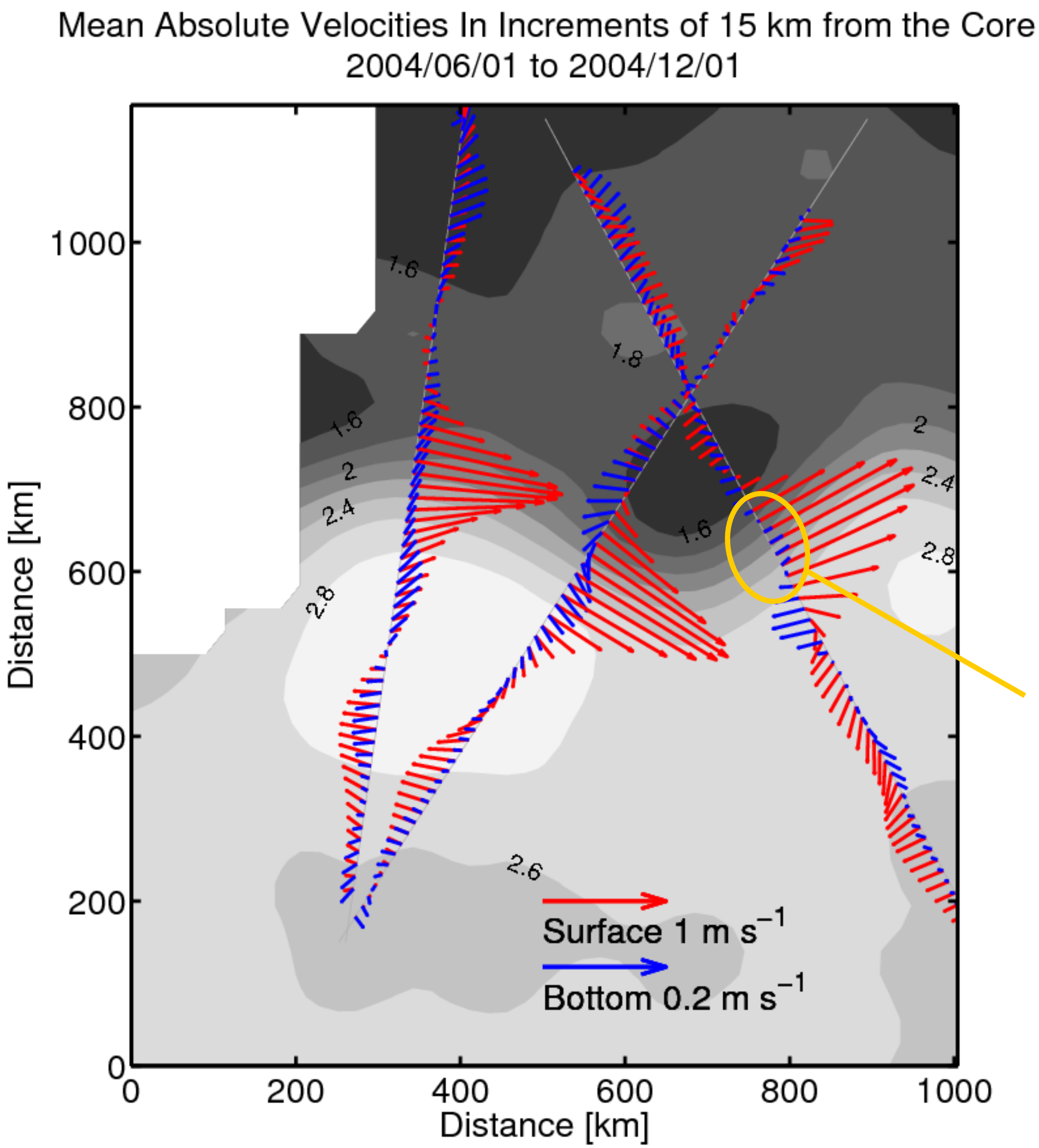
Structural Changes: Crest-Trough-Crest



Counter-clockwise rotation with depth at first meander crest

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

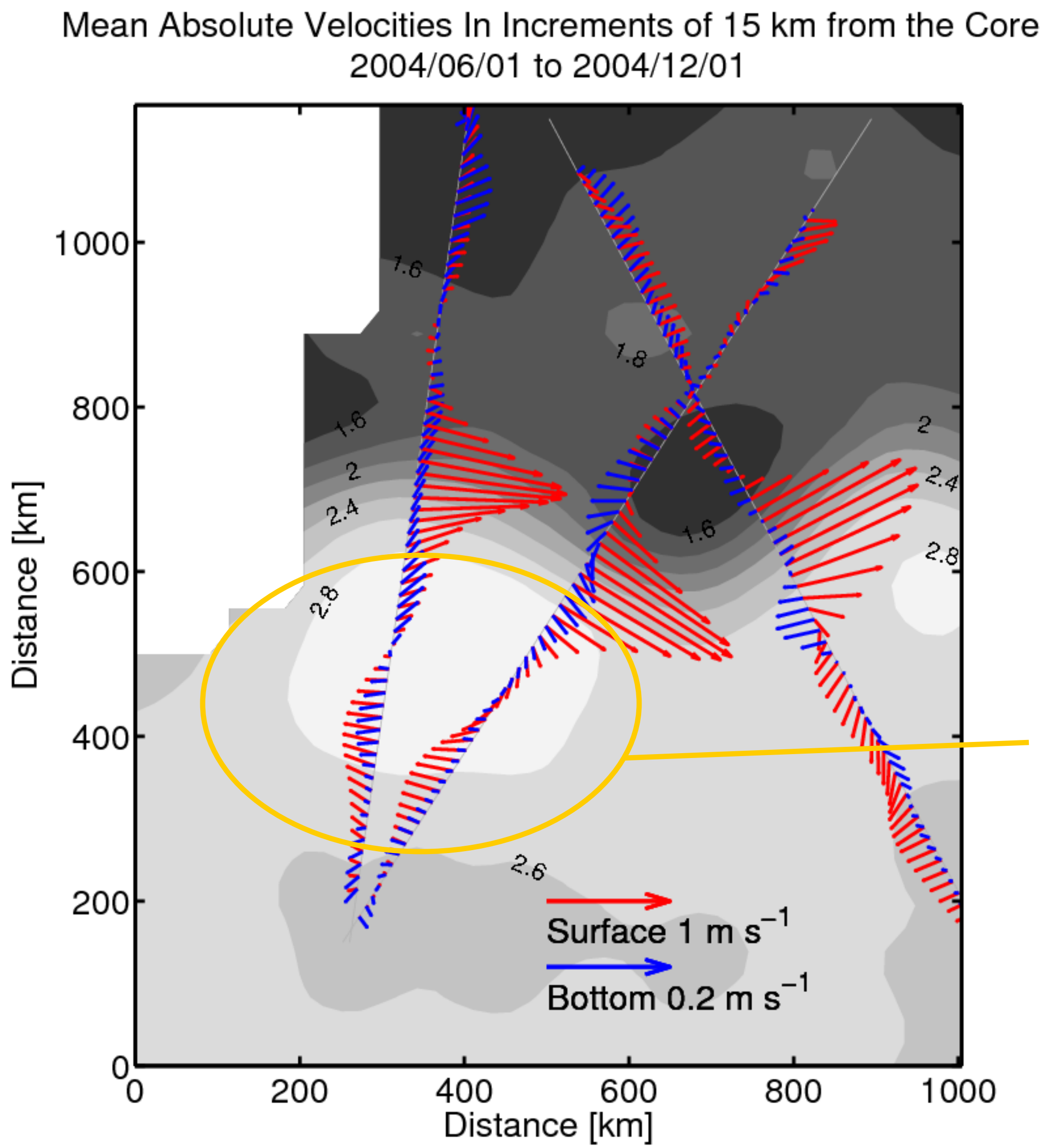
Structural Changes: Crest-Trough-Crest



Surface and deep currents aligned leaving meander trough

- Implies little cross-stream flux

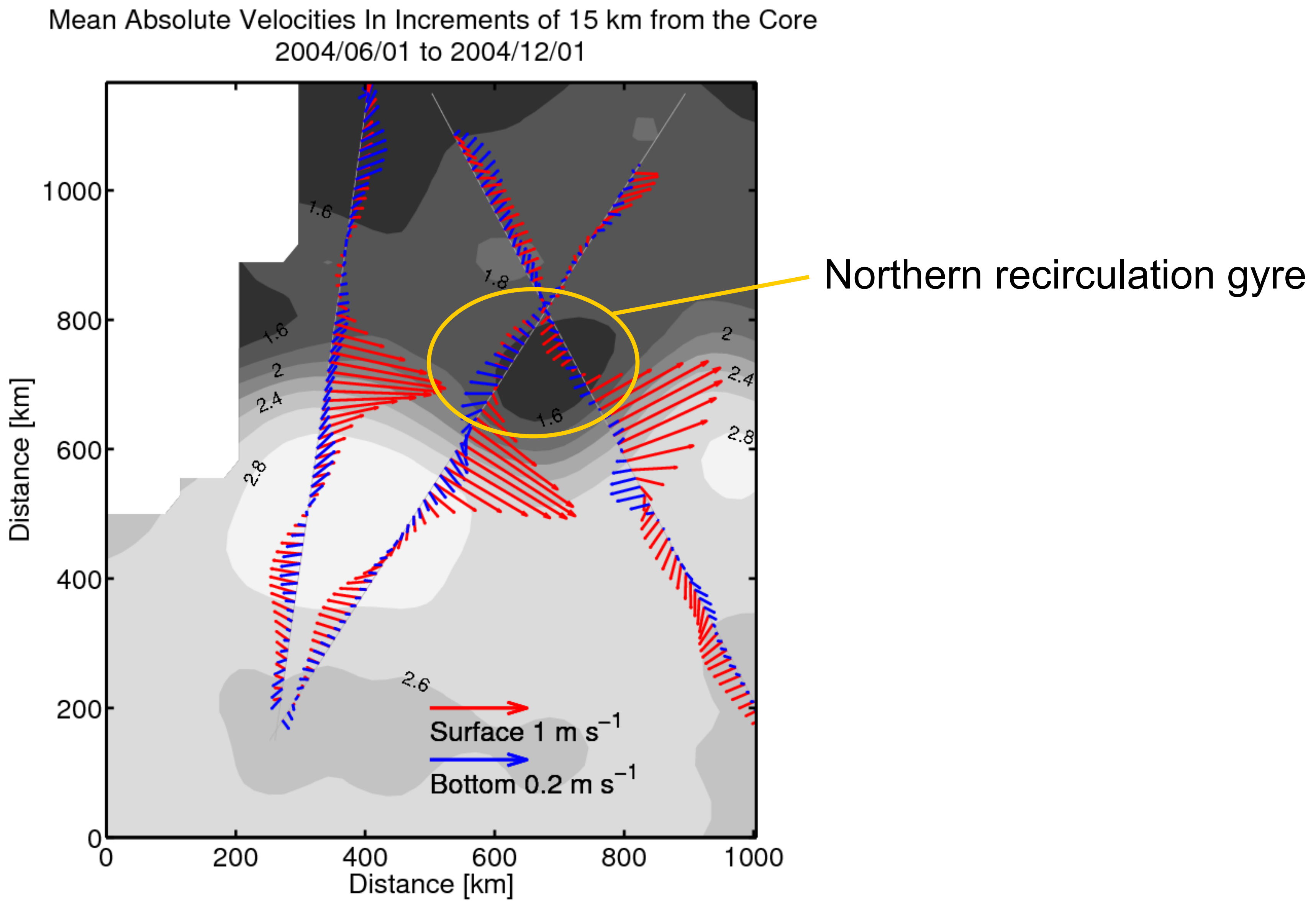
Structural Changes: Crest-Trough-Crest



Southern recirculation gyre

- Surface and deep currents not quite aligned implies interaction of gyre with KE jet

Structural Changes: Crest-Trough-Crest



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

[1]Liu and Rossby, 1993; [2]Rossby and Gottlieb, 1998; [3]Halkin and Rossby, 1985; [4]Rossby and Zhang, 2001