# The Effects of Jet-Scale Overturning Circulations on the Air-Sea $CO_2$ Flux and Chlorophyll in the Southern Ocean and Gulf Stream Extension

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PennState
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Department of Meteorology and Atmospheric Science

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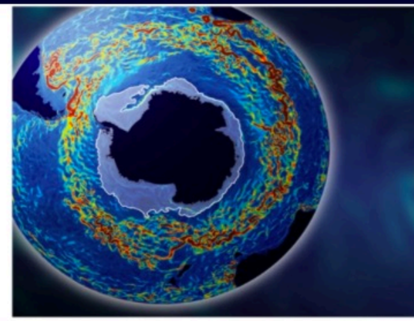

Estimating the Circulation and Climate of the Ocean — ECCO — National Oceanographic Partnership Program

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SOCCOM — Unlocking the mysteries of the Southern Ocean

## Biogeochemical Southern Ocean State Estimation

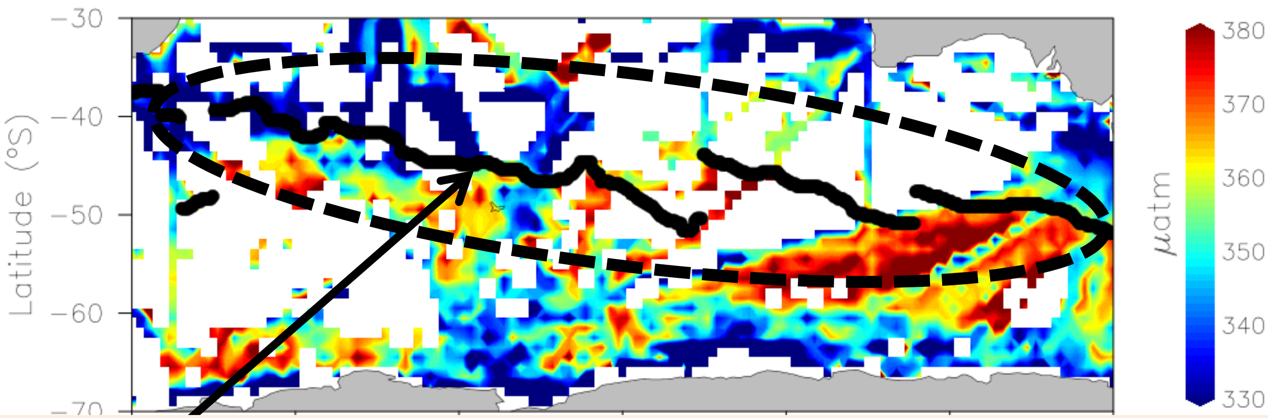
The links below take you to files containing the Iteration 105 solution of the Biogeochemical Southern Ocean State Estimate (B-SOSE), including the state variables, air-sea fluxes, and various diagnostics. Be sure to adhere to our disclaimer and terms of use. If you are a new user please let us know that you will be using our product. All users are encouraged to contact us for a description of methodology, file formats, assistance closing budgets, or with any other questions you may have. And please let us know if you require diagnostics not presently hosted on this site. contact us

B-SOSE is a contribution of the Southern Ocean Carbon and Climate Observations and Modeling project (SOCCOM) program. SOCCOM is an NSF-sponsored program focused on unlocking the mysteries of the Southern Ocean and determining its influence on climate.

A. Verdy and M. Mazloff, 2017: A data assimilating model for estimating Southern Ocean biogeochemistry. J. Geophys. Res. Oceans., 122, doi:10.1002/2016JC012650.

# Jet-scale Structure in the Surface Ocean $CO_2$ in the Indo-western Pacific Southern Ocean

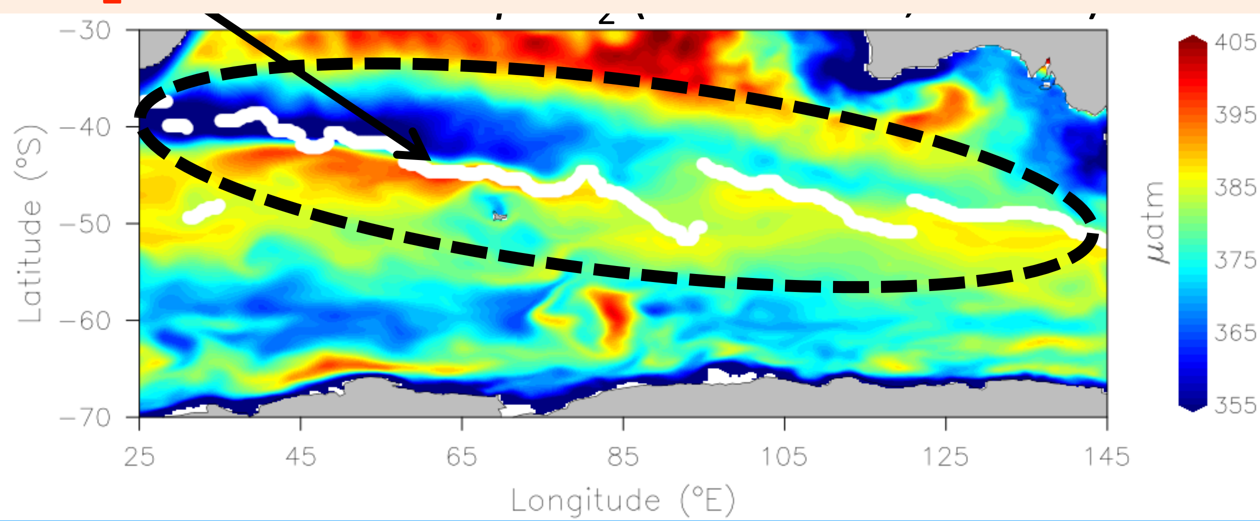
Mean annual $fCO_2$ (1970-2016; SOCATv5)



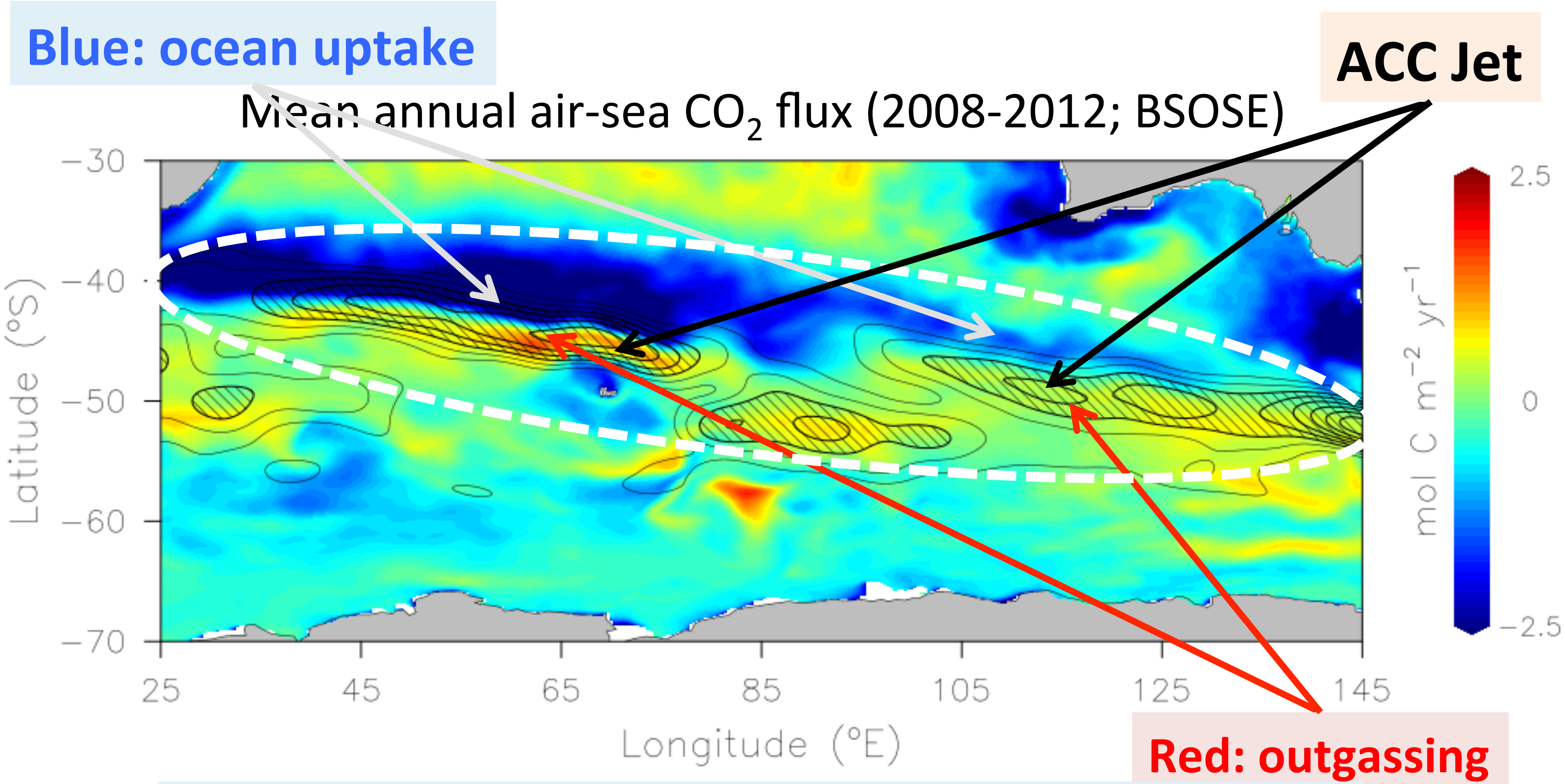

**Antar**

**Low $fCO_2$/$p$CO2** on the **equatorward** flank of the ACC jet;

**High $fCO_2$/$p$CO2** on the **poleward flank** of the ACC jet.



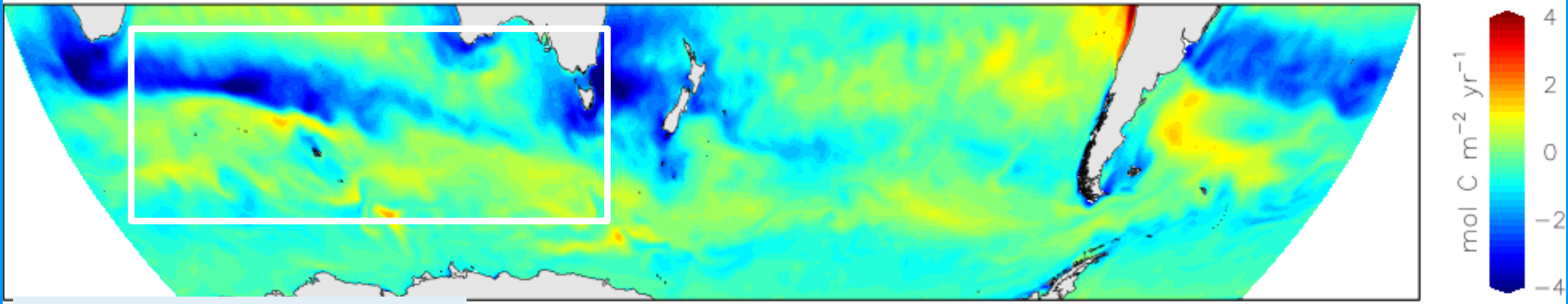
# Jet-scale Structure in the air-sea $CO_2$ flux in the Indo-western Pacific Southern Ocean




- $CO_2$ **uptake** on the **equatorward** flank of the ACC jet
- $CO_2$ **outgassing** on the **poleward** flank of the ACC jet

# Model Simulated Southern Ocean Air-Sea $CO_2$ Flux (2008-2012)

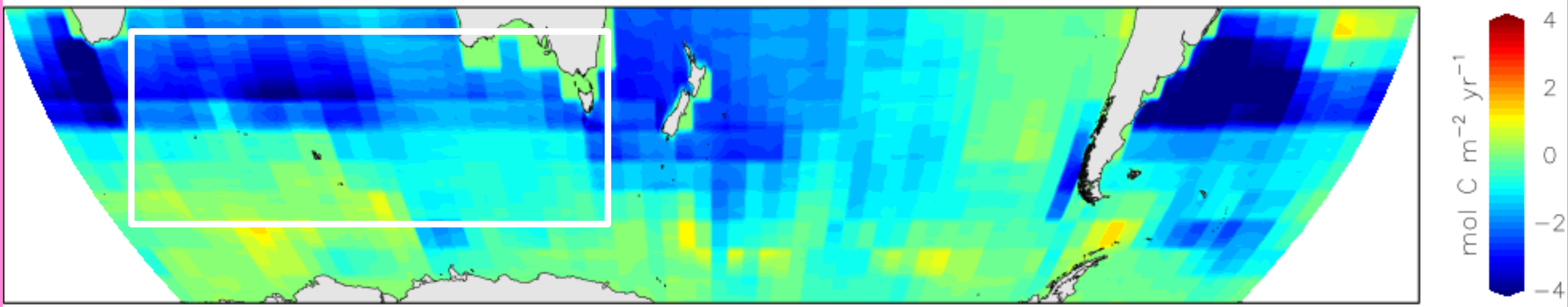
(**1/3°×1/3°**) Biogeochemical Southern Ocean State Estimation (BSOSE)




**Blue: ocean uptake**

(**1°×1°**) Inversion from NOAA's Carbon Tracker (version CT2016)

https://www.esrl.noaa.gov/gmd/ccgg/carbontracker/index.php

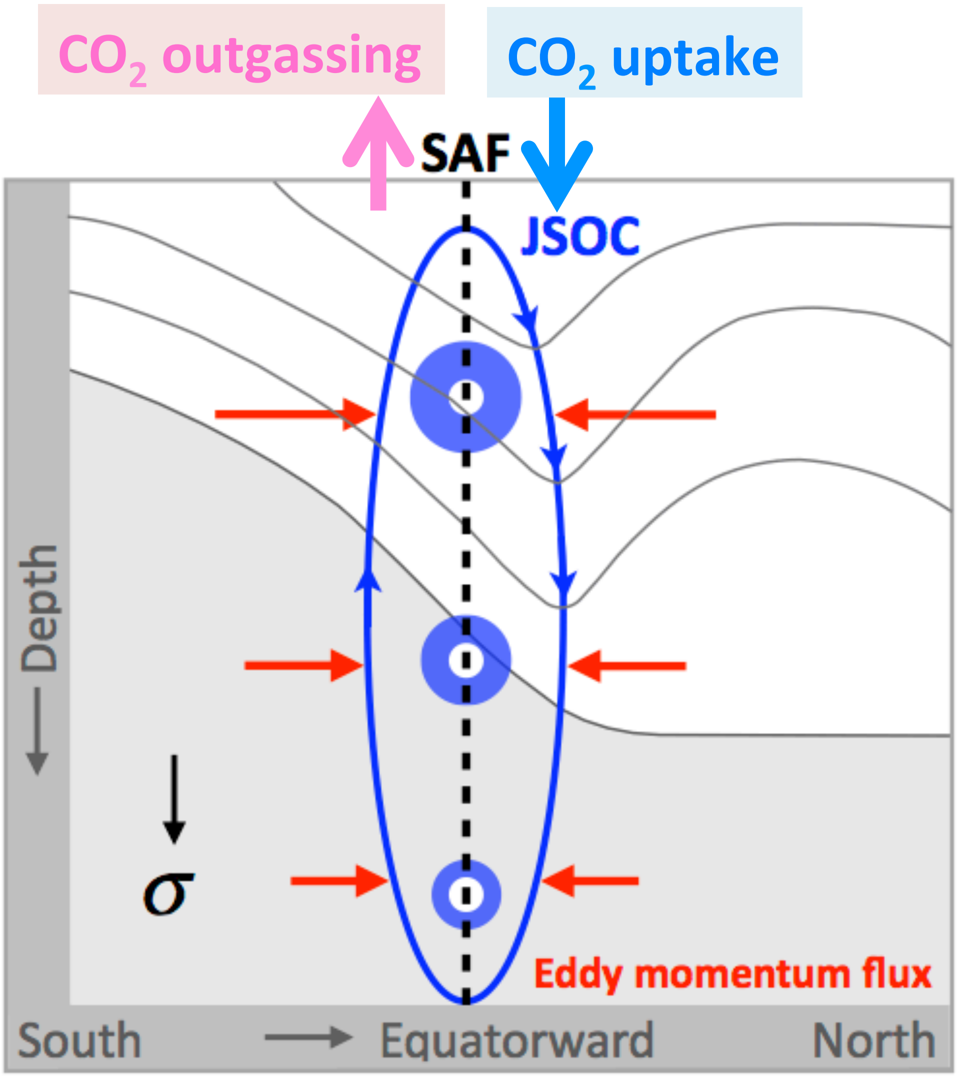



- **Oceanic mesoscale eddies** are important in air-sea carbon exchange

# <u>Question</u>:

What mechanism accounts for this fine ***jet-scale structure*** in the surface ocean *p*$CO_2$ and air-sea $CO_2$ flux in the Indo-western Pacific Southern Ocean?

# Hypothesis: The Jet-scale Overturning Circulation (JSOC) is responsible for the fine jet-scale structure in the air-sea carbon exchange




SAF = Subantarctic Front

Li and Lee (2017, JPO, in press)

On the equatorward flank of the jet:

JSOC brings down light water
↓
destratifies the water column
↓
deepens the mixed layer

Poleward flank:

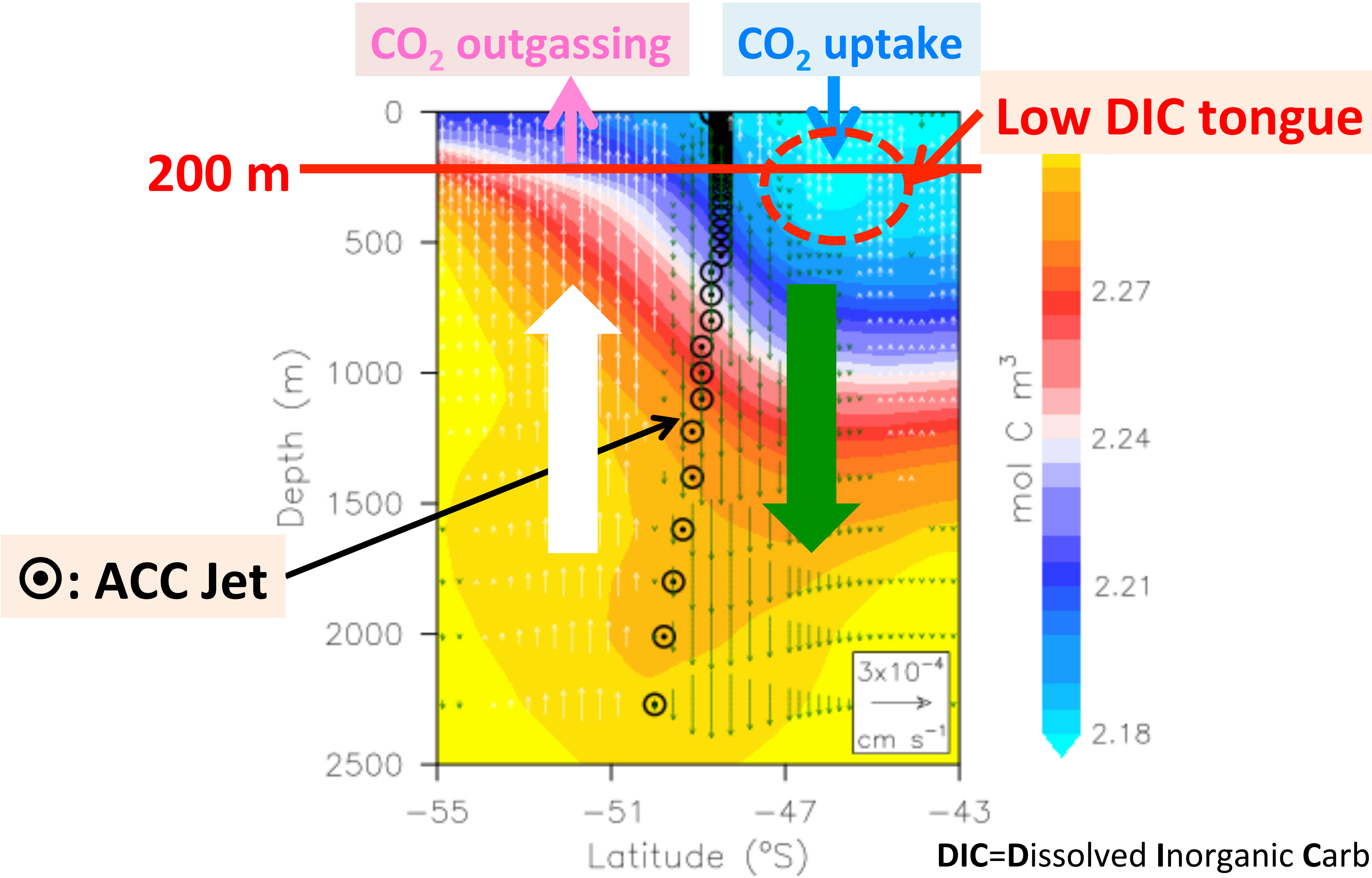
JSOC brings up DIC-rich water
↓
surface ocean high $pCO_2$
↓
$CO_2$ outgassing

Equatorward flank:

JSOC suppresses upwelling DIC-rich water
↓
Surface ocean low $pCO_2$
↓
$CO_2$ uptake

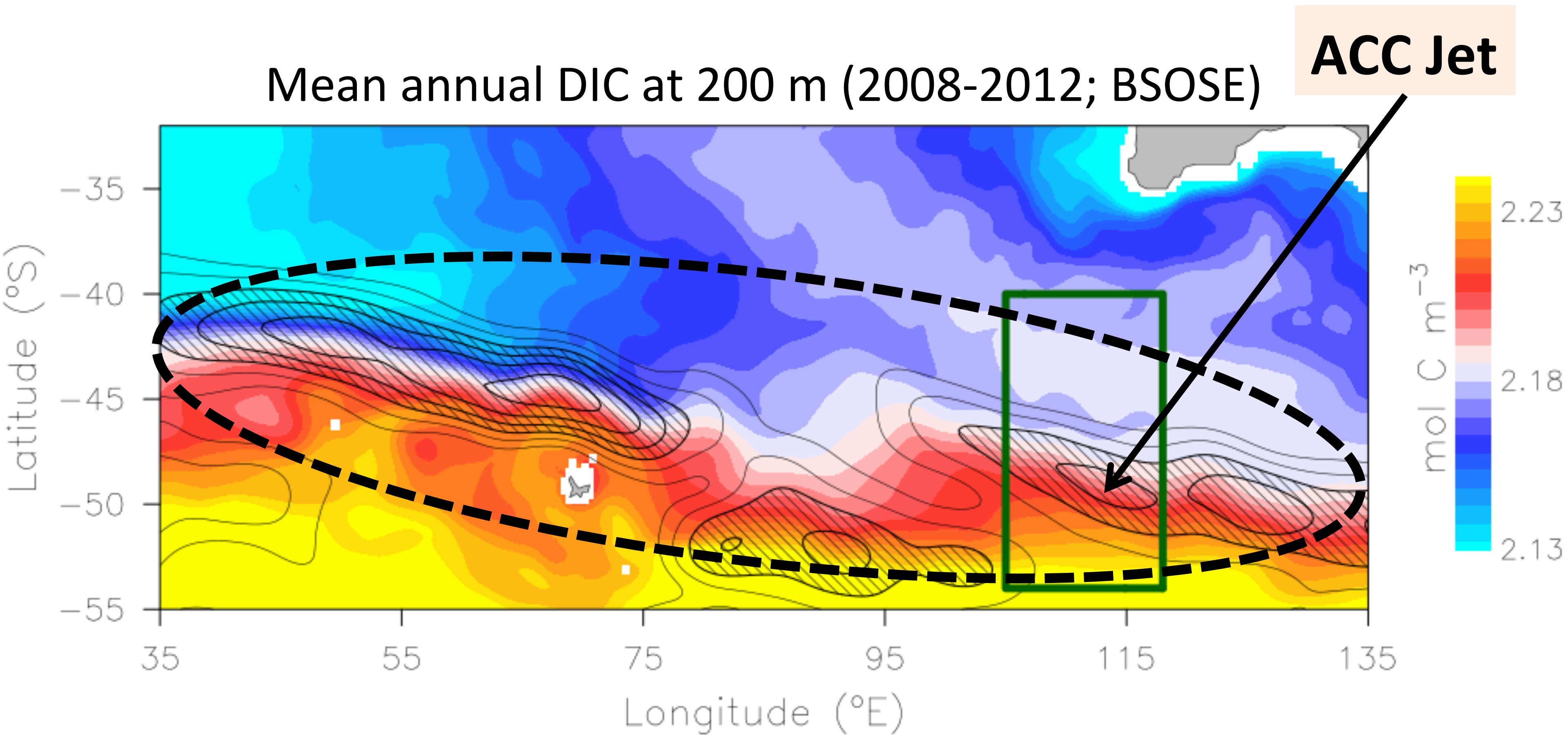
# Vertical Cross-section of Mean Annual DIC (color) and Vertical Velocity (vectors) from BSOSE

Sector of 105°E-118°E in the Indo-western Pacific Southern Ocean



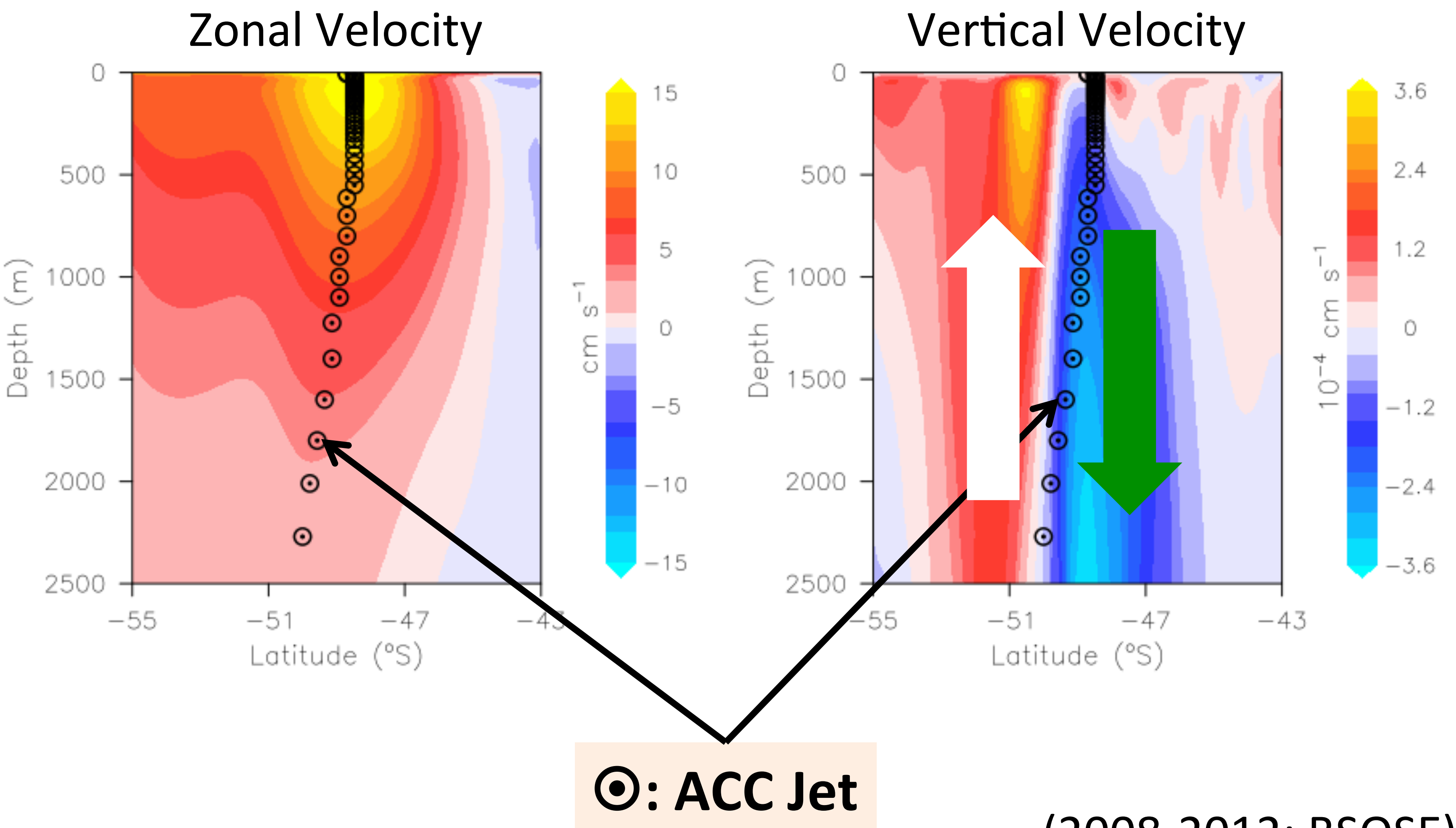

DIC=Dissolved Inorganic Carbon

# Jet-scale Structure in the DIC distribution in the Indo-western Pacific Southern Ocean




**Low DIC concentration** on the **equatorward** flank of the ACC jet;
**High DIC concentration** on the **poleward flank** of the ACC jet.

# Jet-Scale Overturning Circulations (JSOC) in the Indo-western Pacific Southern Ocean




(2008-2012; BSOSE)

## *What are the dynamics of the JSOC?*

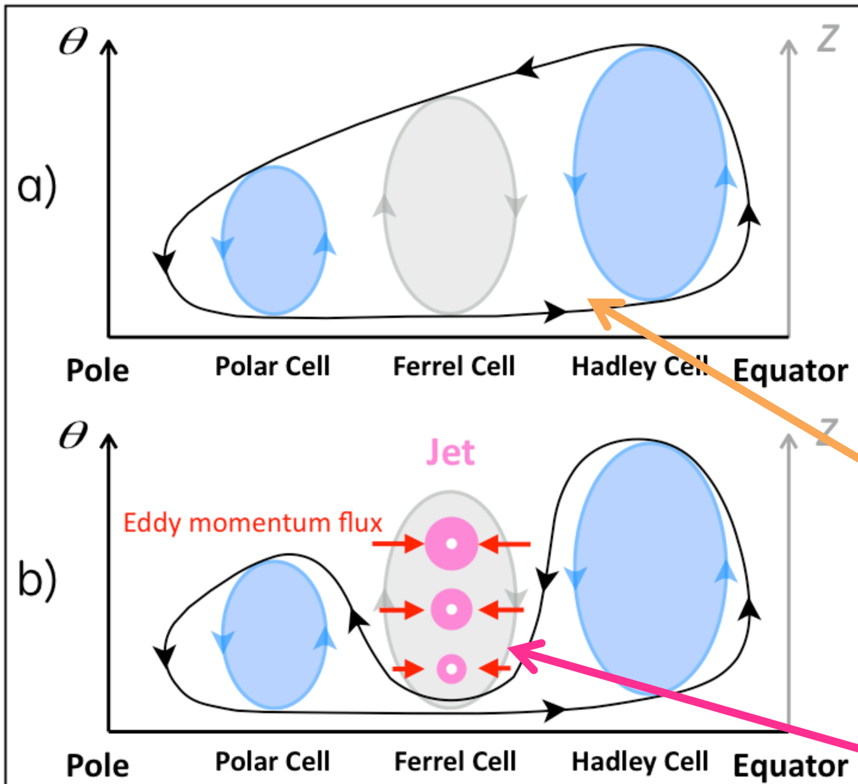
# The JSOC dynamics:

*Eulerian vs. Lagrangian*

## Eddy momentum flux can drive Jet-Scale Overturning Circulation (JSOC)

*JSOC is strong enough to show in the transformed Eulerian mean (TEM) circulation*

- Example from the atmosphere:




Li, Lee, Griesel (2016, JPO)

### *Lagrangian View*

- **Residual-mean meridional circulation:**

$$[v^\dagger] = [v] - \frac{\partial}{\partial z}\left[\frac{1}{N^2}v^*b^*\right]$$

$$[w^\dagger] = [w] + \frac{\partial}{\partial y}\left[\frac{1}{N^2}v^*b^*\right]$$

- **Quasi-geostrophic (QG) zonal momentum and buoyancy equations:**

$$\frac{\partial [u]}{\partial t} = f_0[v^\dagger] - \frac{\partial}{\partial y}[u^*v^*] + \frac{\partial}{\partial z}\left[\frac{f_0}{N^2}v^*b^*\right] + [F]$$

$$\frac{\partial [b]}{\partial t} = -N^2[w^\dagger] + [Q]$$

**Thermal wind balance**

- **Residual-mean meridional circulation:**

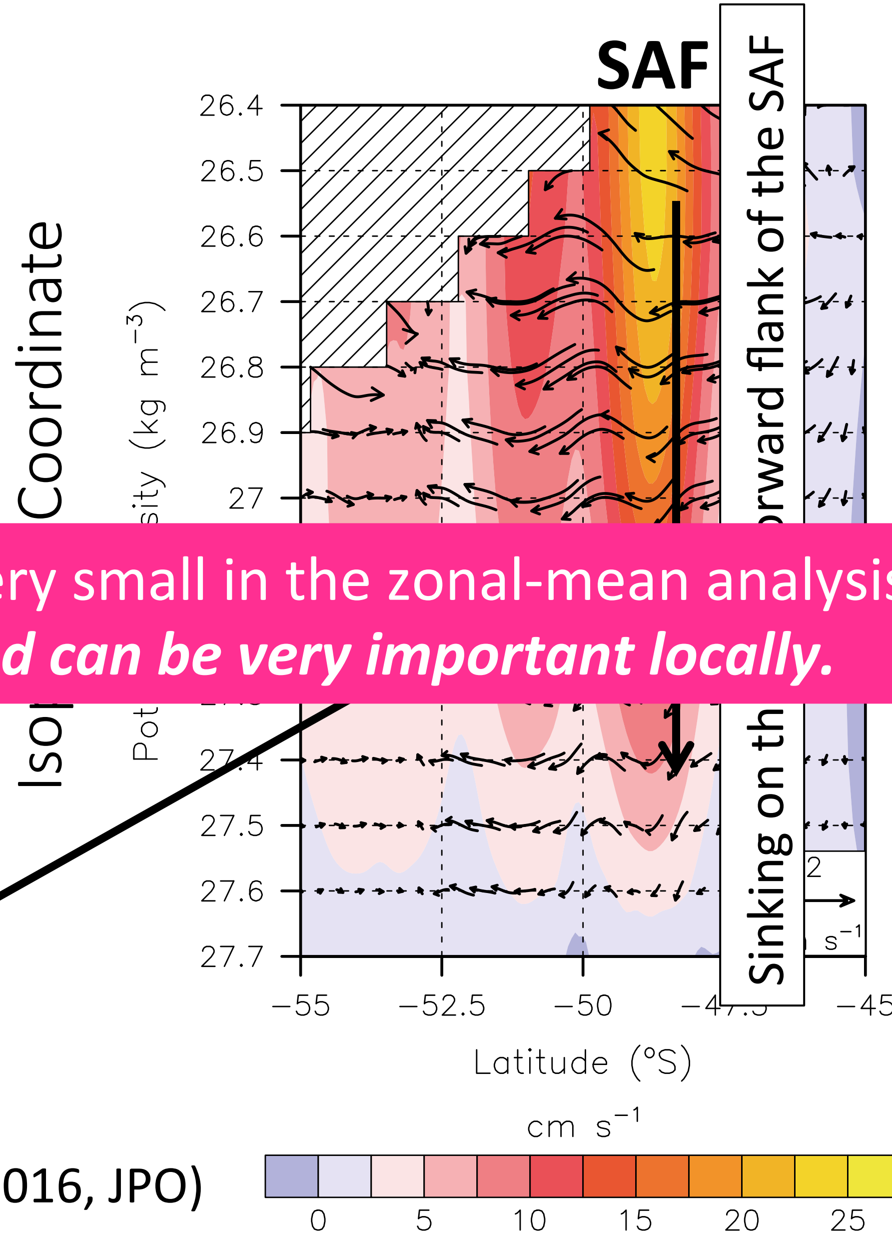
$$N^2\frac{\partial [w^\dagger]}{\partial y} - f_0^2\frac{\partial [v^\dagger]}{\partial z} = \underbrace{-f_0\frac{\partial}{\partial z}\frac{\partial}{\partial y}[u^*v^*]}_{\text{A}} + \underbrace{f_0\frac{\partial^2}{\partial z^2}\left[\frac{f_0}{N^2}v^*b^*\right]}_{\text{B}}$$

# JSOCs are found in model and observations

Vertical Cross-section of Mean Annual Zonal Velocity (color) and Vertical Velocity (vectors)

Sector 120E°-144°E
from an ***eddy-resolving***
(**0.1°x0.1°**) POP simulation

**Acknowledgements:**
Mat Maltrud, Elena Yulaeva, Julie McClean



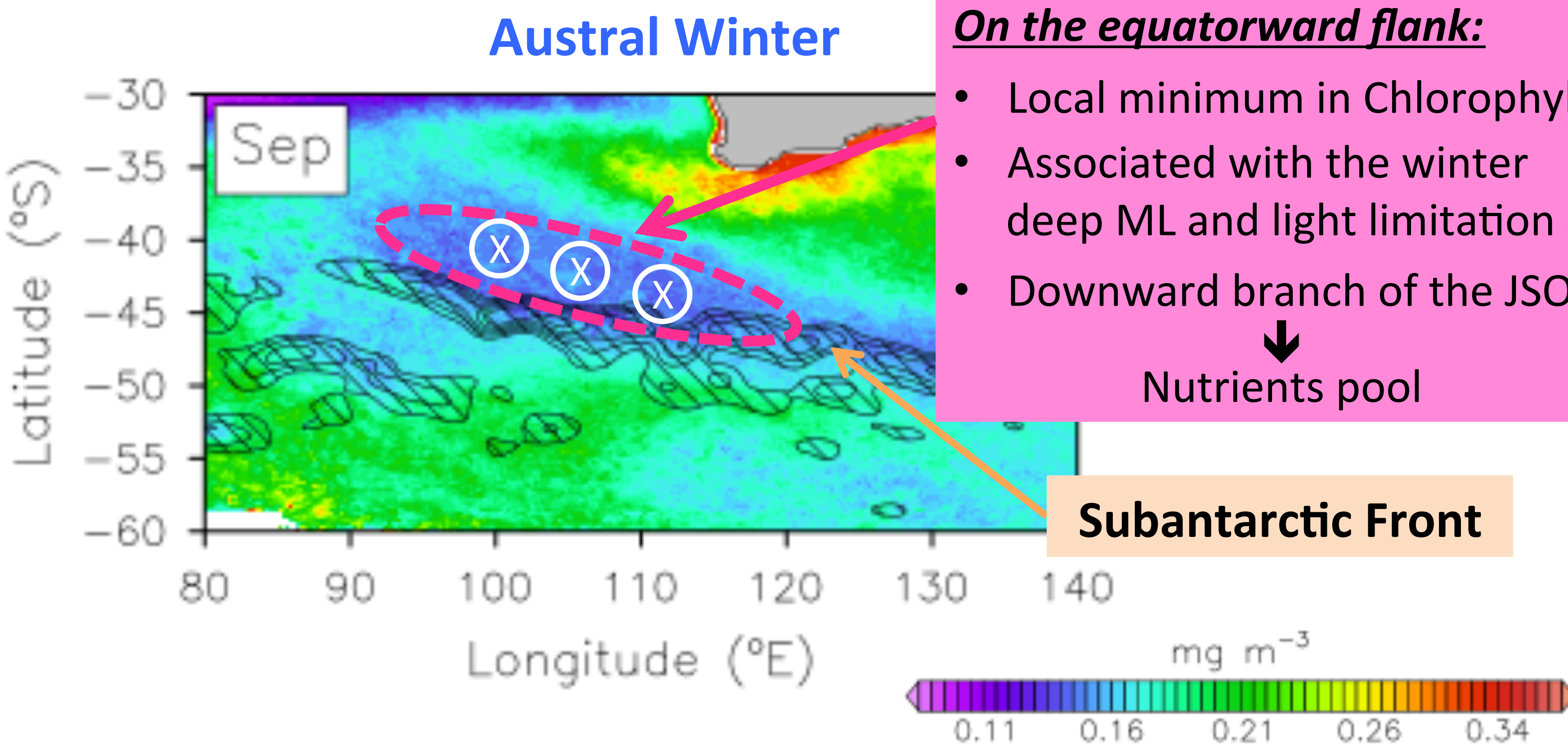

Eddy momentum flux is very small in the zonal-mean analysis.
***However, it is large and can be very important locally.***

Argo float trajectories show that JSOCs also exist in nature. (Li, Lee, Mazloff, 2017, in prep.)

Li, Lee, Griesel (2016, JPO)

***More evidence of the impact of the JSOC on biogeochemical process.***

# Jet-scale Structure in Chlorophyll (ocean color; SeaWiFS) in the Indo-western Pacific Southern Ocean




***On the equatorward flank:***

- Local minimum in Chlorophyll
- Associated with the winter deep ML and light limitation
- Downward branch of the JSOC

↓

Nutrients pool

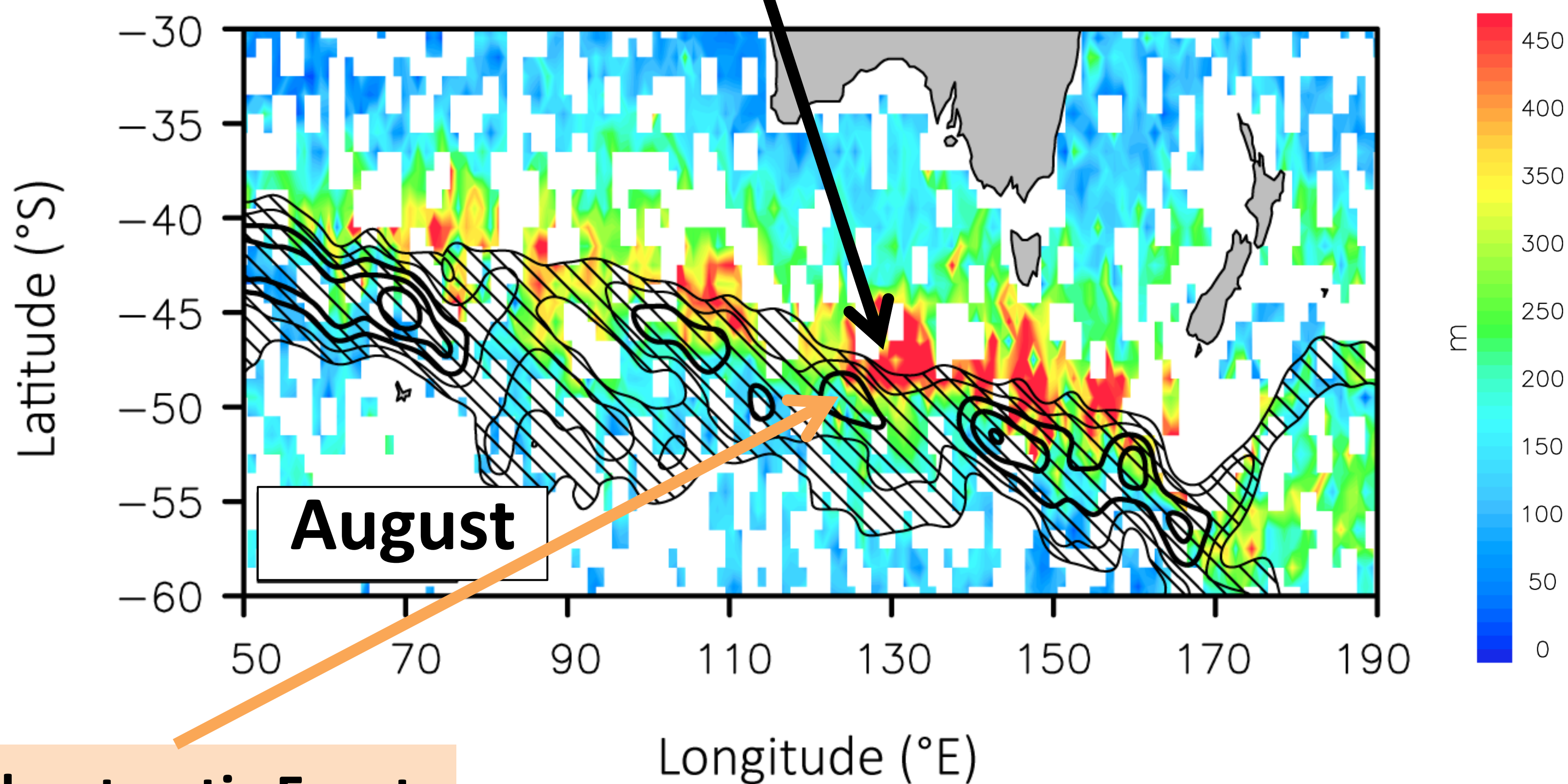
***Contours***: Smoothed **zonal velocity** from (**1/4°x1/4°**) Estimating the Circulation and Climate of the Ocean, phase II (ECCO2; http://ecco2.jpl.nasa.gov/).

***Ocean Color***: NASA Goddard Space Flight Center, Ocean Biology Processing Group; (2014): Sea-viewing Wide Field-of-view Sensor (**SeaWiFS**) Ocean Color Data, NASA OB.DAAC, Greenbelt, MD, USA.
Hu, C., Lee Z., and Franz, B.A. (2012). Chlorophyll-a algorithms for oligotrophic oceans: A novel approach based on three-band reflectance difference, J. Geophys. Res., 117, C01011.

# Jet-scale Structure in the Mixed Layer Depth (MLD) in the Indo-western Pacific Southern Ocean

Mixed layer is deepest on the equatorward flank of the jet

Observation-based MLD (Argo floats) during austral winter




Subantarctic Front

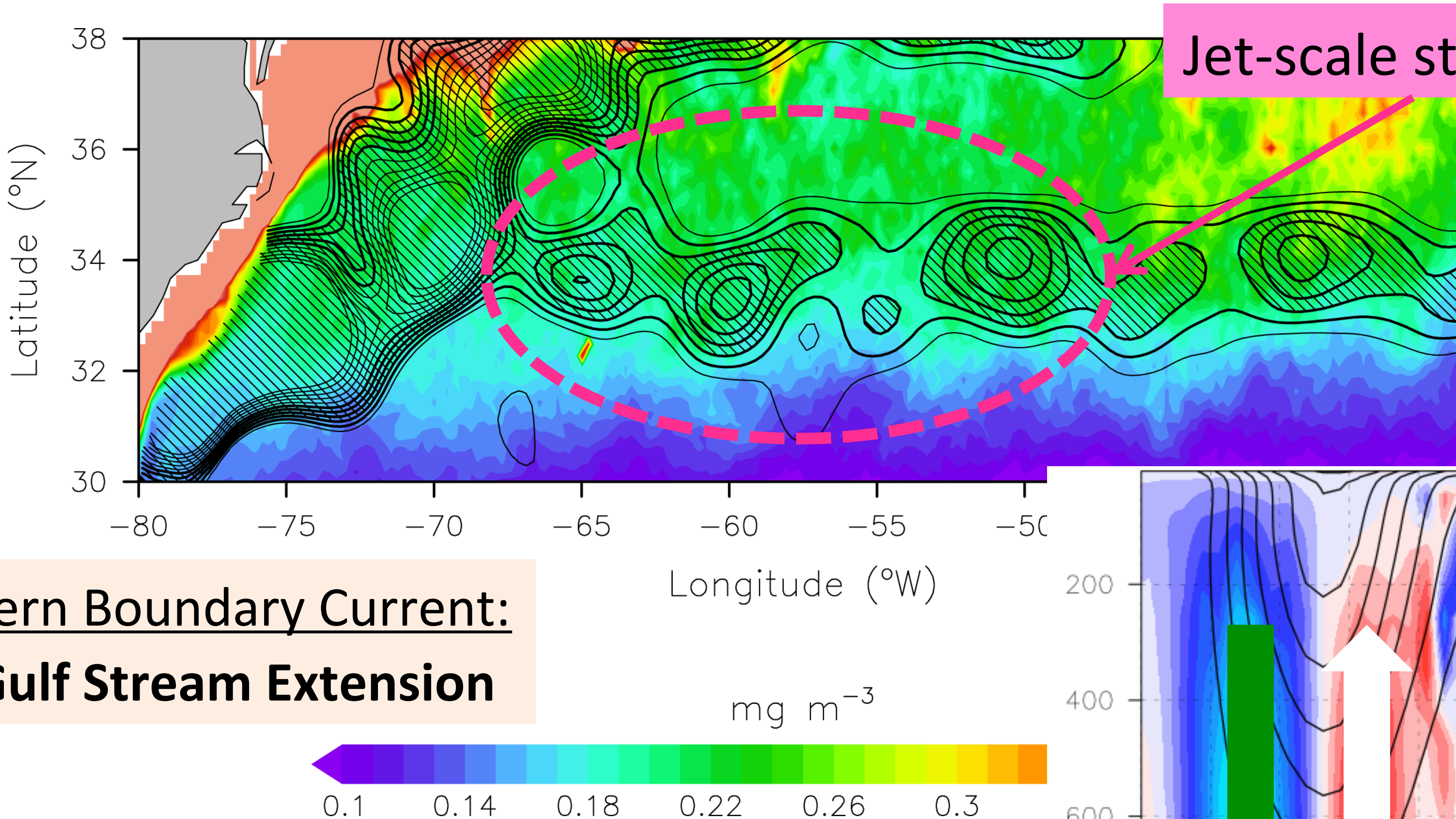
***Color***: Argo-based **MLD** (*Holte and Talley 2009*)

***Contours***: Smoothed **zonal velocity** from SOSE

Li and Lee (2017, JPO, in press)

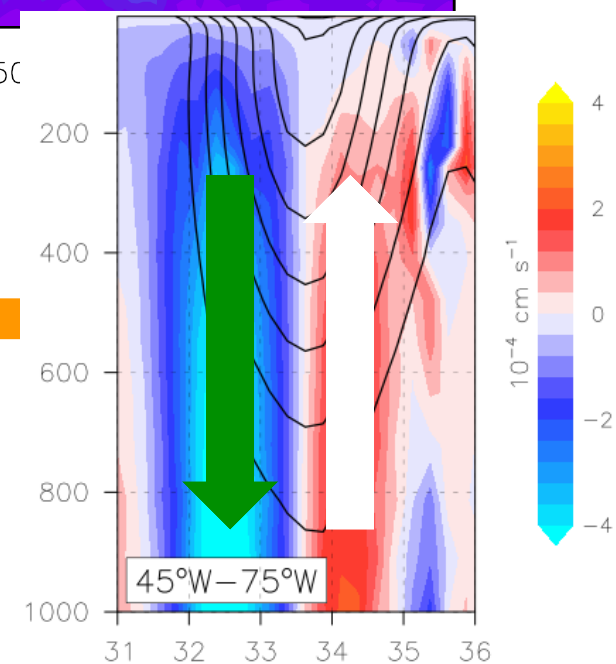
# Jet-scale Structure in Chlorophyll (ocean color) in the North Atlantic Ocean (SeaWiFS; Hu, Lee, and Franz, 2012)

Contours: depth-averaged zonal velocity (above 1 km ;ECCO2)




**Western Boundary Current:**

**The Gulf Stream Extension**




Vertical cross-sections of ***vertical velocity*** (color) and ***zonal velocity*** (contours) from ECCO2

# Conclusion

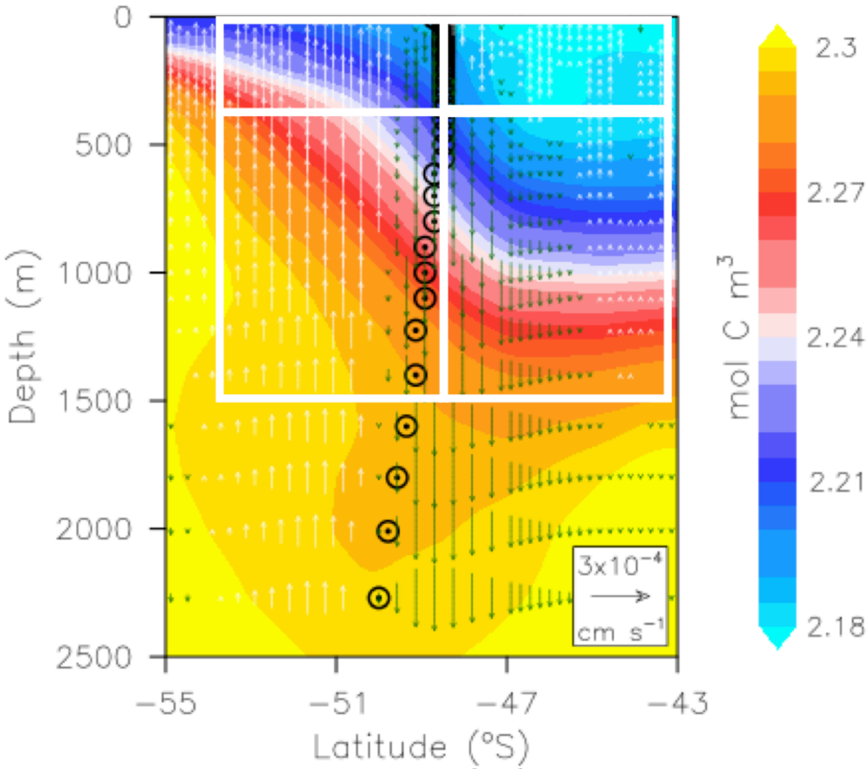
- The ***eddy-momentum-flux-driven*** JSOC has a potential impact on carbon hot spots in the Southern Ocean.
- The JSOC also influences the mixed layer formation and Chlorophyll.
- **Future work:** Given this evidence, we will further investigate the physical and biogeochemical processes associated with the strong jets.

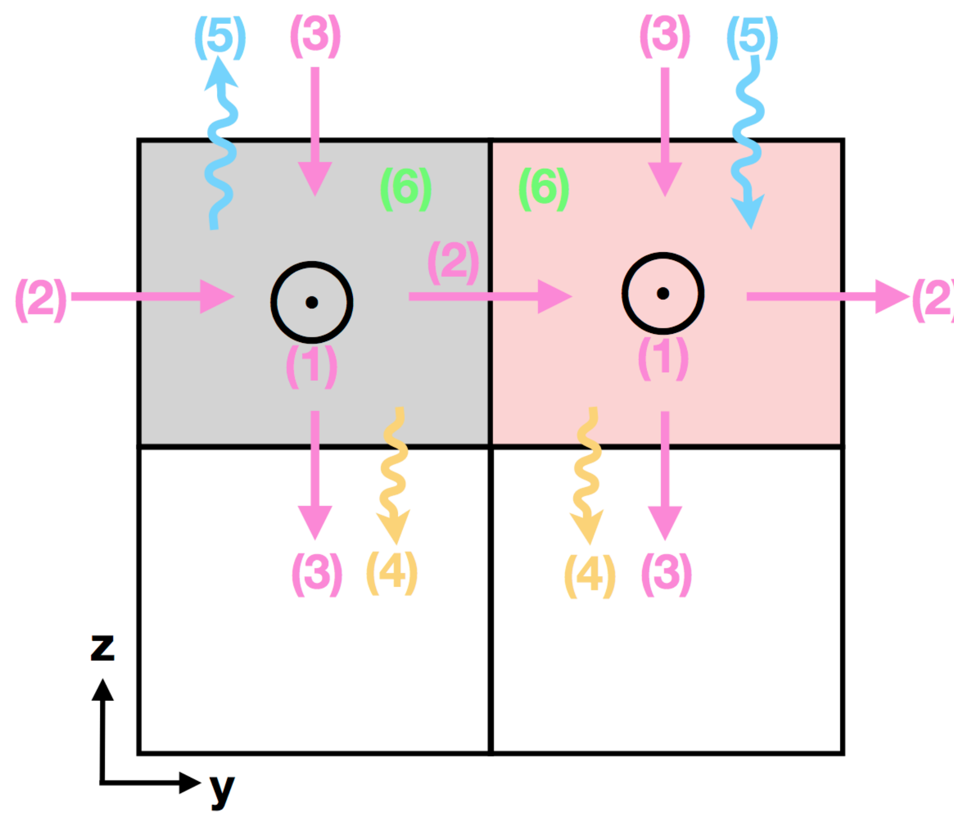
# Carbon Budget:

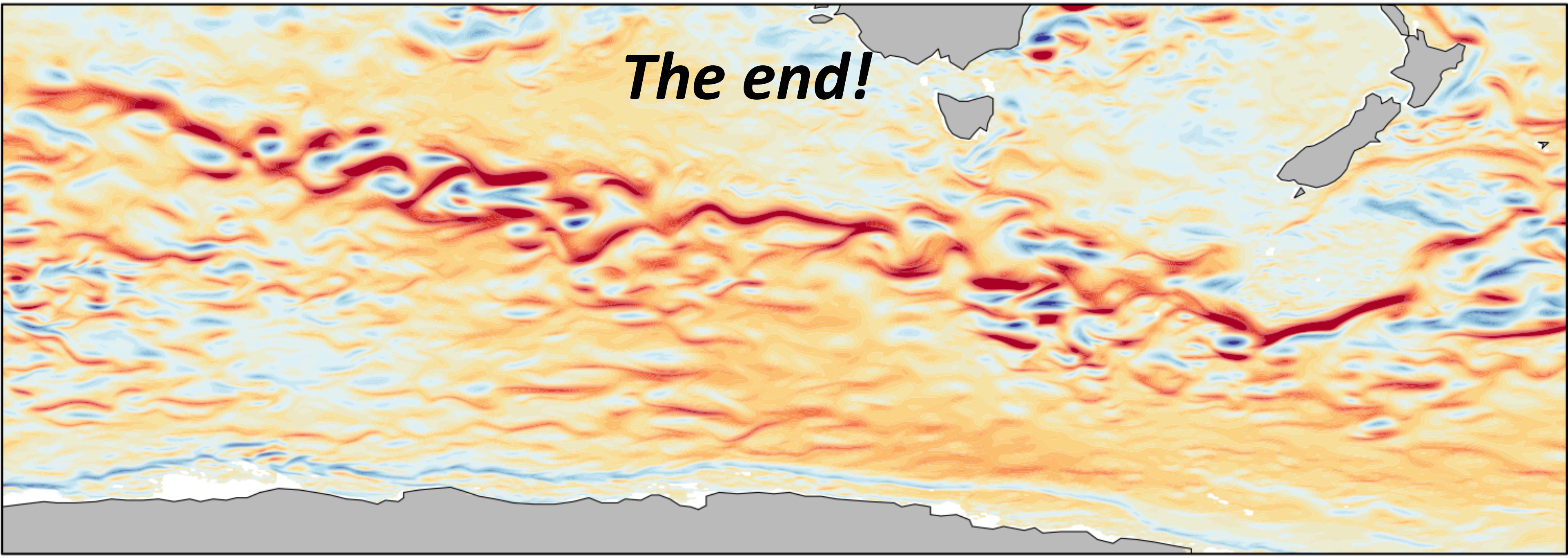
$$\frac{\partial C}{\partial t} = \underbrace{-\overbrace{\frac{\partial uC}{\partial x}}^{(1)} - \overbrace{\frac{\partial vC}{\partial y}}^{(2)} - \overbrace{\frac{\partial wC}{\partial z}}^{(3)}}_{advection} + \underbrace{\overbrace{\frac{\partial}{\partial z}\left(\kappa \frac{\partial C}{\partial z}\right)}^{(4)}}_{vertical\ diffusivity} + \underbrace{\overbrace{\gamma \cdot \Delta pCO_2}^{(5)}}_{air-sea\ flux} + \overbrace{NCP}^{(6)}$$

(1) zonal advection
(2) meridional advection
(3) vertical advection
(4) vertical diffusivity
(5) outgassing/uptake
(6) Net Community Production (NCP)

## Vertical Cross-section of Mean Annual DIC






**Reference:**

Li, Q., S. Lee, and A. Griesel, 2016: Eddy fluxes and jet-scale overturning Circulations in the Indo-western Pacific Southern Ocean. Journal of Physical Oceanography, 46, 2943-2959.

Li, Q. and S. Lee, 2017: A mechanism of mixed-layer formation in the Indo-western Pacific Southern Ocean: preconditioning by an eddy-driven jet-scale overturning circulation, in press.

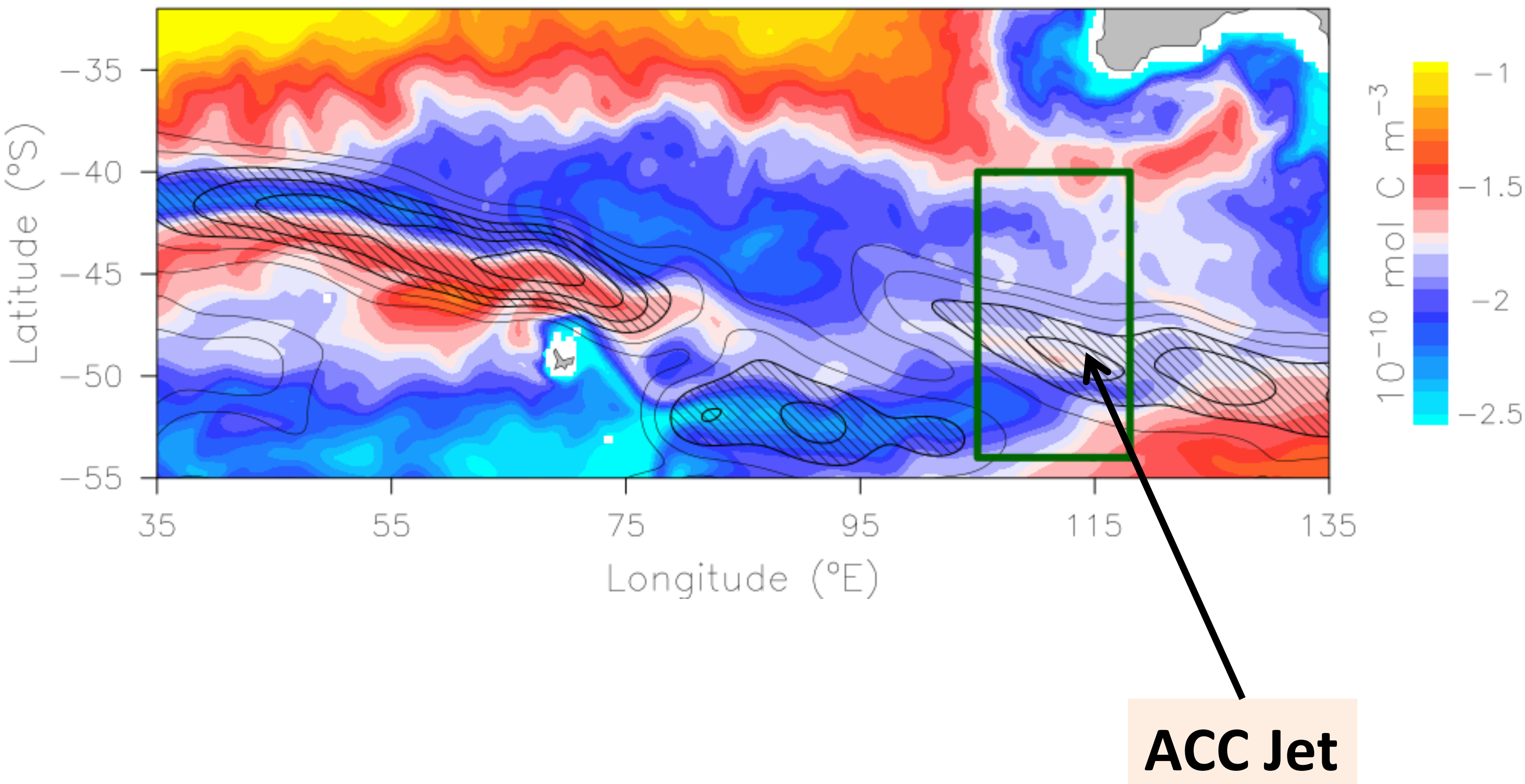
Li, Q., S. Lee, and M. Mazloff, 2017: Evidences of JSOC in Argo Trajectories, in preparation.

**Acknowledgement:**

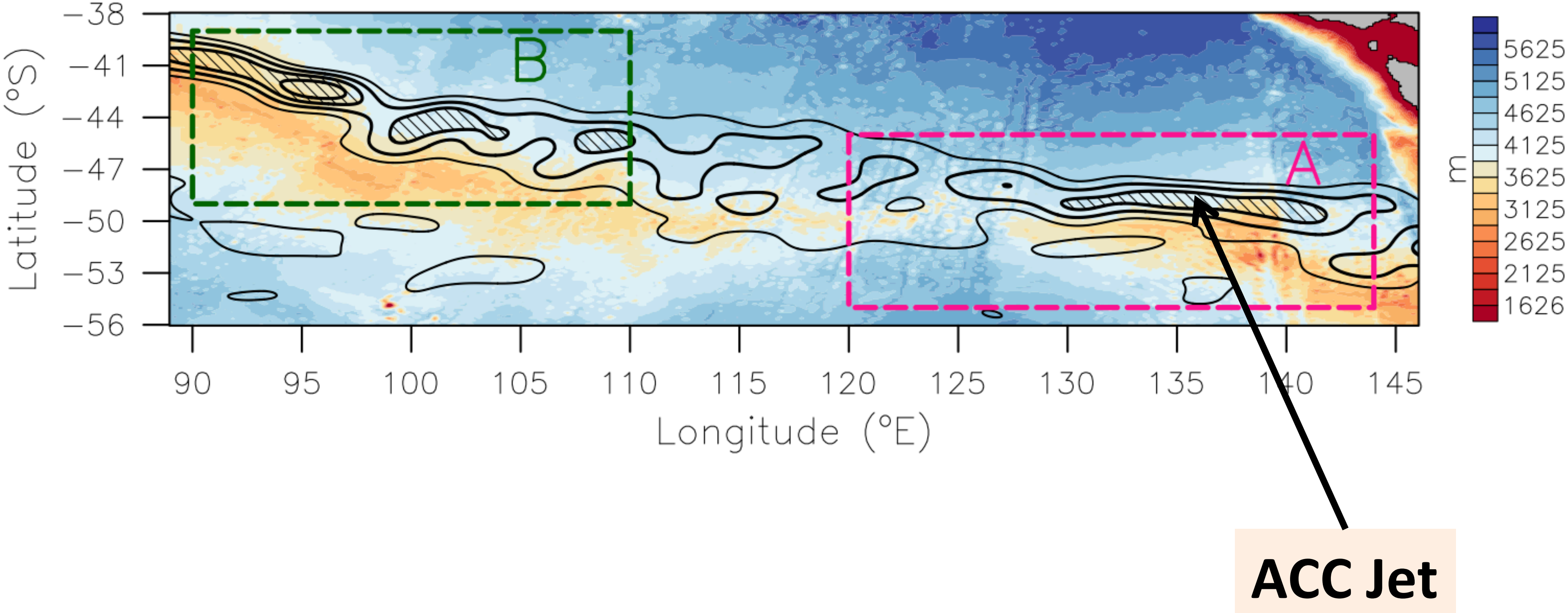
We thank Matt Mazloff for proving information about using BSOSE.

NSF for funding; NASA and NOAA for data.

Mean annual Net Community Production (NCP) at 200 m (2008-2012; BSOSE)

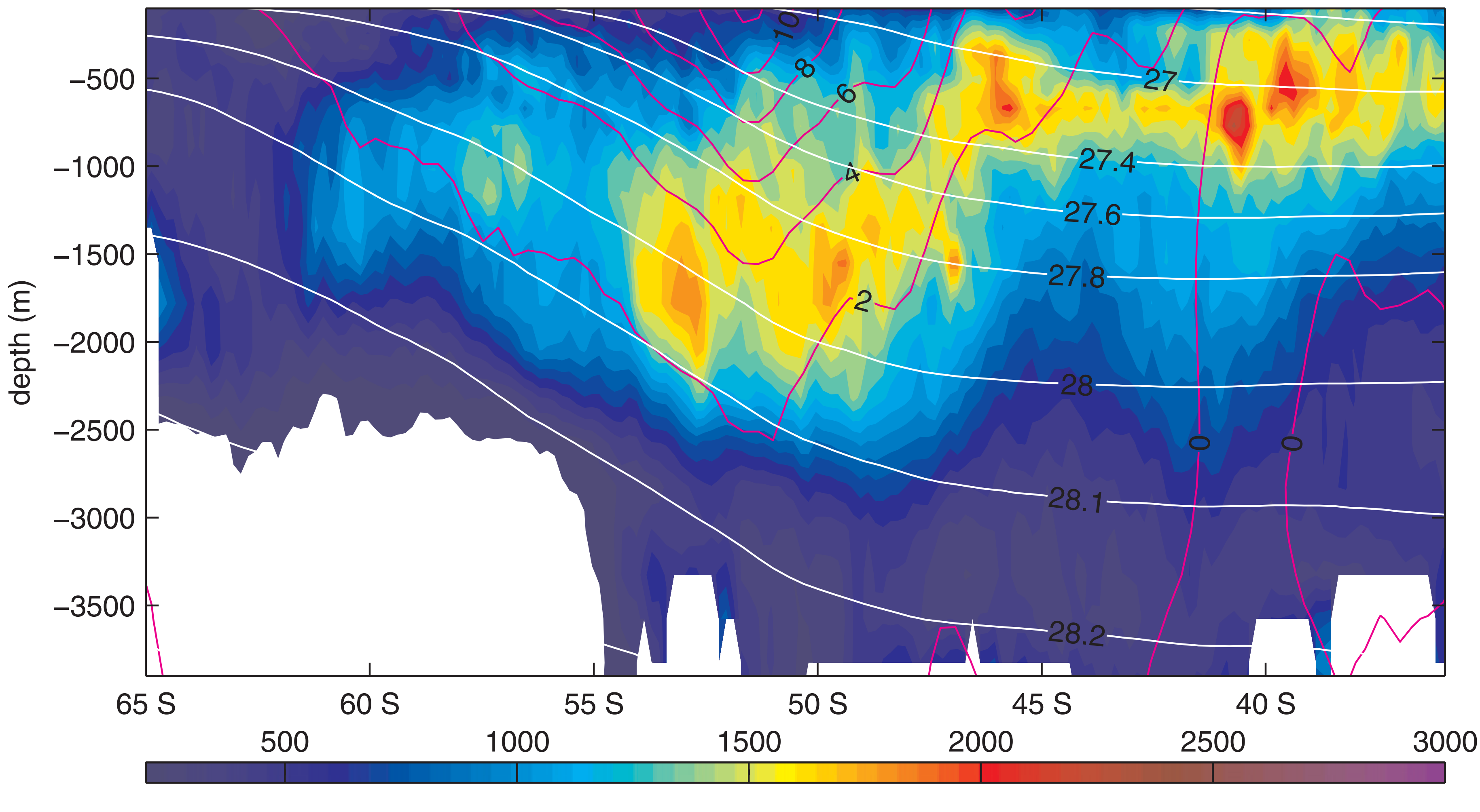


# Topography in the Indo-western Pacific Southern Ocean



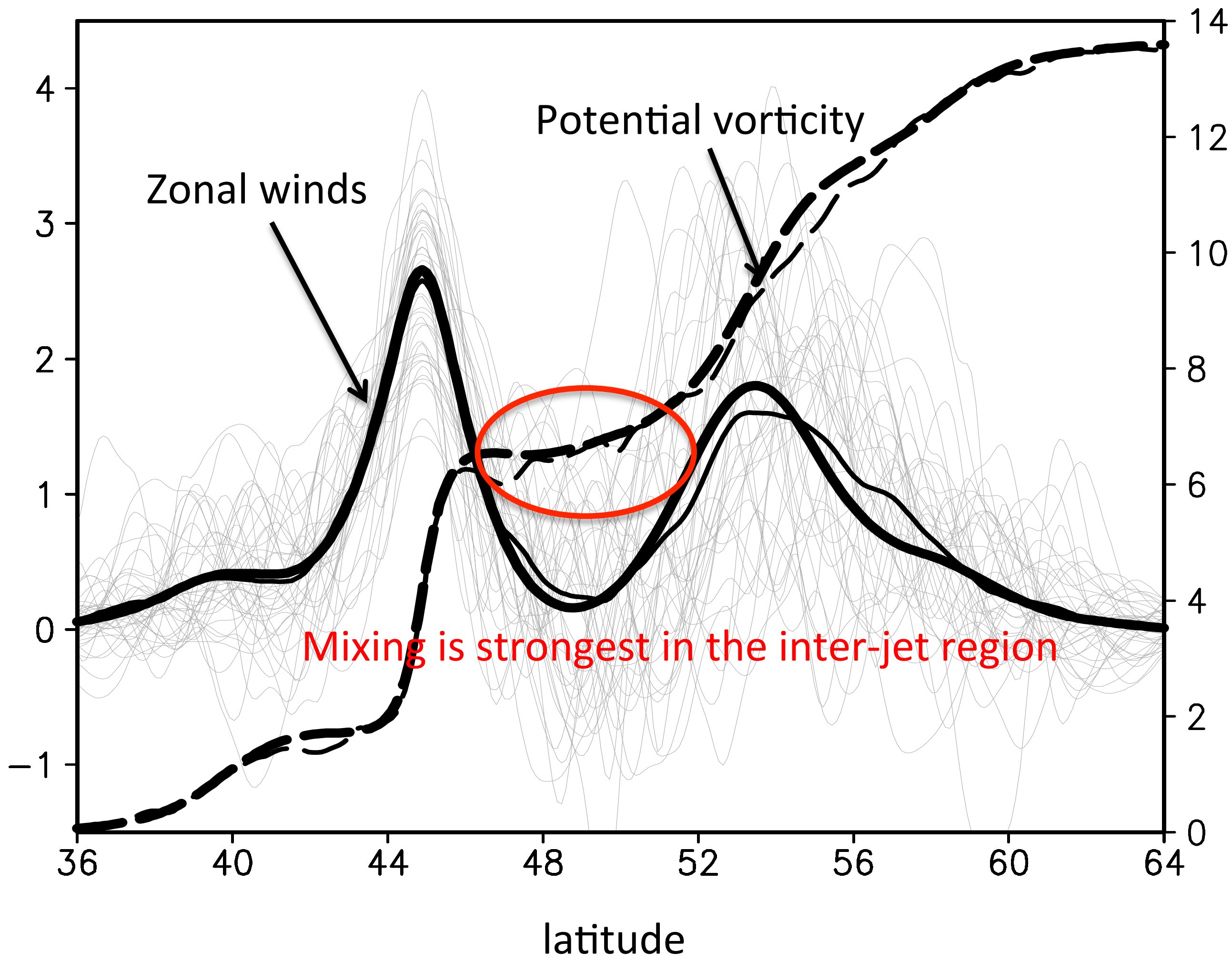
# Effective diffusivity (Abernathey, Marshall, Mazloff, JPO, 2010)

data source: SOSE (Southern Ocean State Estimate)



# Multiple jets and potential vorticity mixing in a two-layer quasi-geostrophic model

source: Yoo and Lee (2010, JAS)



# Preconditioning role of the JSOC on the mixed layer wedge formation

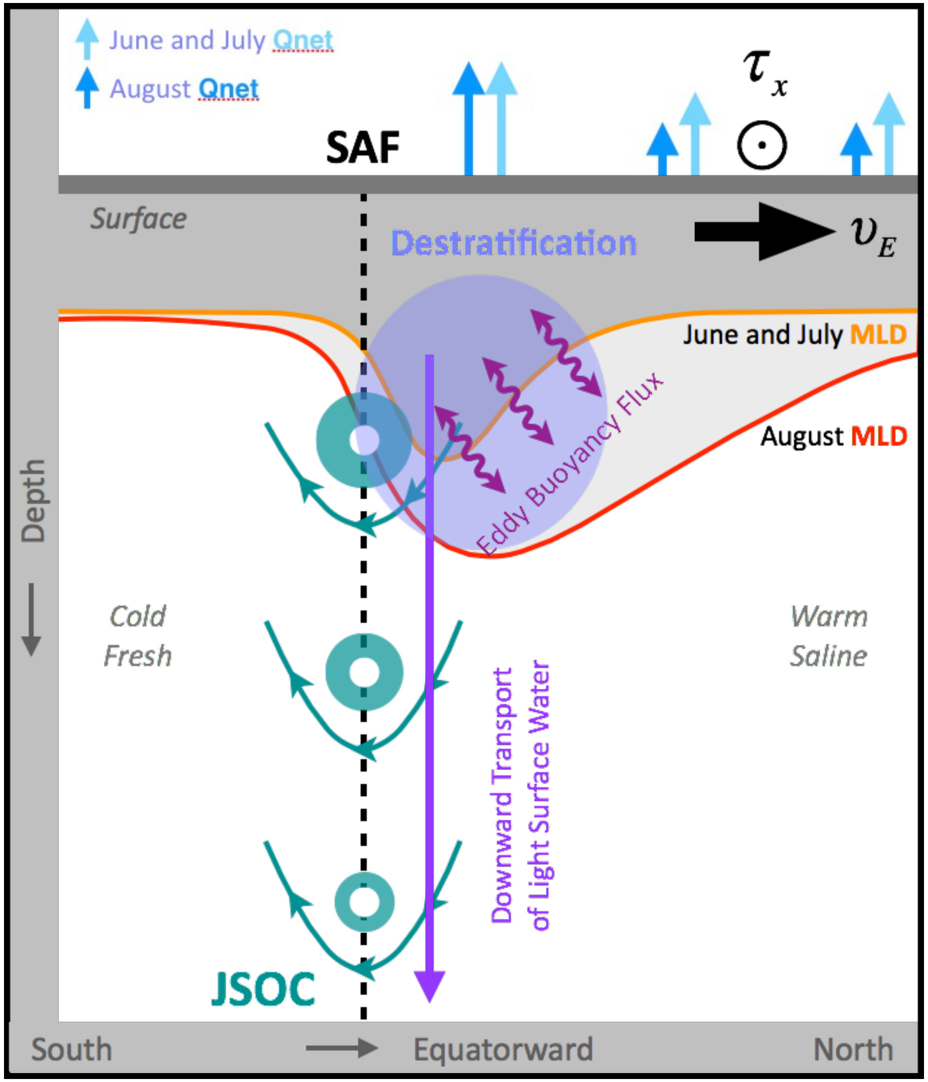
① ***Ekman advection*** contributes to the formation of the mixed layer, but further north of where the mixed layer initially deepens;

② ***Net air-sea heat flux*** reveals a similar wedge-like feature, but this feature is preconditioned by the JSOC;

③ The formation of the winter narrow mixed layer coincides with *destratification underneath the summer mixed layer*;

④ This destratification can be attributed primarily to the *downwelling branch of JSOC*, which occurs on the warmer equatorward flank of the SAF, promoting destratification during the warm season, hence ***preconditioning*** for the deep mixed layer;

⑤ *Eddy buoyancy flux* also contributes to this destratification.



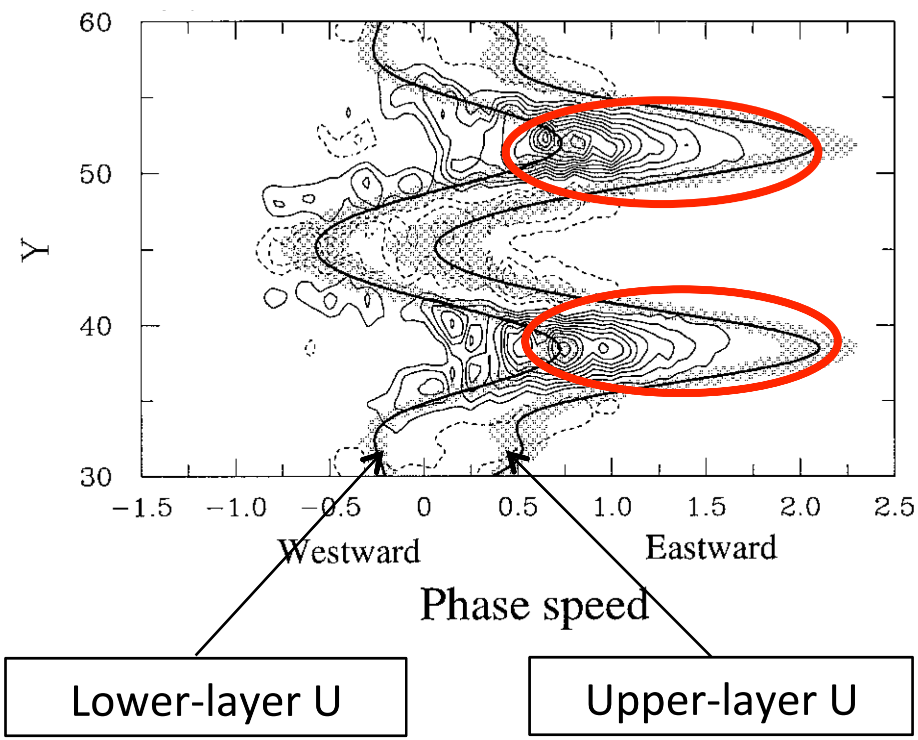
# ***The JSOC dynamics:***

## Eddy momentum flux can drive multiple jets and JSOCs

***JSOC is strong enough to show in the transformed Eulerian mean (TEM) circulation***

2-Layer QG Model

**Eddy Momentum Flux Convergence**




Lee (1997)

**Residual-mean meridional circulation:**

$$N^2\frac{\partial[w^\dagger]}{\partial y} - f_0^2\frac{\partial[v^\dagger]}{\partial z} = \underbrace{-f_0\frac{\partial}{\partial z}\frac{\partial}{\partial y}[u^*v^*]}_{\mathrm{A}} + \underbrace{f_0\frac{\partial^2}{\partial z^2}\left[\frac{f_0}{N^2}v^*b^*\right]}_{\mathrm{B}}$$