Evidence of Jet-Scale Overturning Ocean Circulations in Argo Float Trajectories

Qian Li
University of New South Wales, Sydney, Australia

in collaboration with:

Sukyoung Lee (Penn State University)
Matthew Mazloff (Scripps Institution of Oceanography)

Sources and Sinks Ocean Mesoscale Eddy Energy Workshop, Tallahassee
March 12, 2019
Filamented Southern Ocean MLD (color) at the early stage of austral winter (July)

The deepest MLDs are located just on the equatorward flank of the ACC jets.

Indo-western Pacific SO

Model-simulated MLD (0.1°-resolution POP)

Eastern Pacific SO

Contours: zonal current speed indicating the ACC Jets

Observation-based MLD (Argo floats; Holte et al. 2017)
The JSOC is responsible for the formation of the deep mixed layers.

Mechanisms for the winter mixed layer formation in the SO:

- **Air-sea buoyancy loss** (Sallée et al. 2006; Dong et al. 2008; Hogg 2010)
- **Ekman advection of buoyancy** (Rintoul and England 2002)
- **Mesoscale eddy buoyancy transport** (Sallée et al. 2010)
- **Langmuir turbulence associated with the Stokes drift** (Belcher et al. 2012)

At the early stage of austral winter

On the equatorward flank of the jet:

- JSOC brings down light water
- destratifies the water column
- deepens the MLD

[Li & Lee 2017, *JPO*]
Background about Jet-Scale Overturning Ocean Circulation (JSOC):

The JSOC is responsible for the formation of the deep mixed layers.

Mechanisms for the winter mixed layer formation in the SO:

- Air-sea buoyancy loss (Sallée et al. 2006; Dong et al. 2008; Hogg 2010)
- Ekman advection of buoyancy (Rintoul and England 2002)
- Mesoscale eddy buoyancy transport (Sallée et al. 2010)
- Langmuir turbulence associated with the Stokes drift (Belcher et al. 2012)

[Li & Lee 2017, JPO]
Eddy momentum flux can drive multiple jets and JSOCs

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

Residual-mean meridional circulation:

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

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

QG zonal momentum and buoyancy equations:

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

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

Thermal wind balance

Residual-mean meridional circulation:

$$N^2 \frac{\partial [w^I]}{\partial y} - f_0 \frac{\partial [v^I]}{\partial z} = -f_0 \frac{\partial}{\partial z} \frac{\partial}{\partial y} [u^* \nu^*] + f_0 \frac{\partial^2}{\partial z^2} \left[ \frac{f_0}{N^2 \nu^* b^*} \right]$$
Background about Jet-Scale Overturning Ocean Circulation (JSOC):

**Eddy momentum flux can drive multiple jets and JSOCs**

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

- Example from the atmosphere:

Residual-mean meridional circulation:

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

\[
[w^i] = [w] + \frac{\partial}{\partial y} \left[ \frac{1}{N^2} u^* b^* \right]
\]

QG zonal momentum and buoyancy equations:

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

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

Thermal wind balance

Residual-mean meridional circulation:

\[
N^2 \frac{\partial [w^i]}{\partial y} - f_0 \frac{\partial [v^i]}{\partial z} = -f_0 \frac{\partial}{\partial z} \left[ u^* v^* \right] + f_0 \frac{\partial^2}{\partial z^2} \left[ \frac{f_0}{N^2} u^* b^* \right]
\]
**Background about Jet-Scale Overturning Ocean Circulation (JSOC):**

Eddy momentum flux can drive multiple jets and JSOCs. 

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

- Example from the atmosphere:

**Residual-mean meridional circulation:**

\[
[v^i] = [v] - \frac{\partial}{\partial z} \left( \frac{1}{N^2 v^* b^*} \right) 
\]

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

**QG zonal momentum and buoyancy equations:**

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

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

**Thermal wind balance**

**Residual-mean meridional circulation:**

\[
N^2 \frac{\partial [w^i]}{\partial y} - f_0 \frac{\partial [v^i]}{\partial z} = f_0 \frac{\partial}{\partial z} \frac{\partial [u^* v^*]}{\partial y} + f_0 \frac{\partial^2}{\partial z^2} \left[ f_0 \frac{\partial}{N^2 v^* b^*} \right] 
\]

(A) - (B)
Background about Jet-Scale Overturning Ocean Circulation (JSOC):

Eddy momentum flux can drive multiple jets and JSOCs

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

Example from the atmosphere:

Residual-mean meridional circulation:

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

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

QG zonal momentum and buoyancy equations:

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

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

Thermal wind balance

Residual-mean meridional circulation:

\[
N^2 \frac{\partial [w^i]}{\partial y} - f_0 \frac{\partial [v^i]}{\partial z} = -f_0 \frac{\partial}{\partial z} \frac{\partial [u^* v^*]}{\partial y} + f_0 \frac{\partial^2}{\partial z^2} \left[ f_0 \frac{N^2}{N^2} v^* b^* \right] \]

Example from the ocean:

ACC scale
Eddy momentum flux can drive multiple jets and JSOCs

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

Residual-mean meridional circulation:

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

\[
[w^\prime] = [w] + \frac{\partial}{\partial y} \left[ \frac{1}{N^2} u^* b^* \right]
\]

QG zonal momentum and buoyancy equations:

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

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

Thermal wind balance

Residual-mean meridional circulation:

\[
N^2 \frac{\partial [w^\prime]}{\partial y} - f_0 \frac{\partial [v^\prime]}{\partial z} = -f_0 \frac{\partial}{\partial z} \left[ u^* v^* \right] + f_0 \frac{\partial^2}{\partial z^2} \left[ \frac{f_0}{N^2} u^* b^* \right]
\]
Eddy momentum flux can drive multiple jets and JSOCs

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

Residual-mean meridional circulation:

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

QG zonal momentum and buoyancy equations:

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

Thermal wind balance

Residual-mean meridional circulation:

\[
N^2 \frac{\partial [w^i]}{\partial y} - f_0 \frac{\partial [v^i]}{\partial z} = -f_0 \frac{\partial}{\partial z} \frac{\partial}{\partial y} [u^* v^*] + f_0 \frac{\partial^2}{\partial z^2} \left[ \frac{f_0}{N^2} u^* b^* \right]
\]

Jet scale

[Li, Lee, Griesel 2016, JPO]
Background about Jet-Scale Overturning Ocean Circulation (JSOC):

**JSOCs are found in the 0.1°-resolution ocean model**

- The POP model forced by CORE-IAF
- Horizontal resolution: ~1/10°
- Vertical resolution: 42 levels
- Period: 1994-2007 (14 years)
- Acknowledgements: Matt Maltrud, Elena Yulaeva, Julie McClean

**Analysis region:**
Indo-western Pacific Southern Ocean

**120E-144E:**
Zonal velocity (color)
Meridional and vertical velocities (vectors)

Zonal Current Speed
**Background about Jet-Scale Overturning Ocean Circulation (JSOC):**

JSOCs are found in the 0.1°-resolution ocean model

- The POP model forced by CORE-IAF
- Horizontal resolution: ~1/10°
- Vertical resolution: 42 levels
- Period: 1994-2007 (14 years)
- Acknowledgements: Matt Maltrud, Elena Yulaeva, Julie McClean

**Analysis region:**
Indo-western Pacific Southern Ocean

**Zonal Current Speed**

[Image of zonal current speed with analysis region indicated]

**Zonal velocity (color)**
Meridional and vertical velocities (vectors)

**Isopycnal Coordinate**

**Potential Density (kg m⁻³)**

**Sinking on the equatorward flank of the SAF**

[Graph showing potential density with sinking indicated]

[Li, Lee, Griesel 2016, *JPO*]
Background about Jet-Scale Overturning Ocean Circulation (JSOC):

JSOCs are found in the 0.1°-resolution ocean model

Analysis region:
Indo-western Pacific Southern Ocean

Do JSOCs exist in nature?

- The POP model forced by CORE-IAF
- Horizontal resolution: ~1/10°
- Vertical resolution: 42 levels
- Period: 1994-2007 (14 years)
- Acknowledgements: Matt Maltrud, Elena Yulaeva, Julie McClean

[Li, Lee, Griesel 2016, JPO]
Argo: **Observing** the Ocean in Real Time

3913 Floats
1-11 Mar, 2019

http://www.argo.ucsd.edu/
The **Observed** Ocean Current Velocities

**An Argo Float Mission**

• **Subsurface** velocities at ~1 km (Argo parking level)

\[
\begin{align*}
    u_p &= \frac{x_{asc} - x_{des}}{t_{asc} - t_{des}} \\
    v_p &= \frac{y_{asc} - y_{des}}{t_{asc} - t_{des}}
\end{align*}
\]

[Schmid et al. 2007]

**Descending:** \( x_{des}, y_{des}, t_{des} \)

**Ascending:** \( x_{asc}, y_{asc}, t_{asc} \)
The **Observed** Ocean Current Velocities

An Argo Float Mission

**Descending:** $X_{\text{des}}, Y_{\text{des}}, t_{\text{des}}$

**Ascending:** $X_{\text{asc}}, Y_{\text{asc}}, t_{\text{asc}}$

- **Subsurface** velocities at $\sim 1$ km (Argo parking level)

\[
\begin{align*}
    u_p &= \frac{X_{\text{asc}} - X_{\text{des}}}{t_{\text{asc}} - t_{\text{des}}} \\
    v_p &= \frac{Y_{\text{asc}} - Y_{\text{des}}}{t_{\text{asc}} - t_{\text{des}}}
\end{align*}
\]

- **Surface** geostrophic velocity:

\[
\begin{align*}
    u_g &= -\frac{g}{f} \frac{\partial \eta}{\partial y} \\
    v_g &= \frac{g}{f} \frac{\partial \eta}{\partial x}
\end{align*}
\]

Sea Surface Height

---

[Schmid et al. 2007]
The **Observed** Ocean Current Velocities

- **Contours:** AVISO SSH-based *surface geostrophic current speed* (above 5 cm s\(^{-1}\))
- **Vectors/color:** Argo-float-trajectories-based *subsurface (at ~1 km) velocity/magnitude*

[Li, Lee, Mazlo 2018, GRL]

0.5° x 0.5° resolution

**Indo-western Pacific Southern Ocean**

**Eastern Pacific Southern Ocean**
Structure of the Theoretical JSOC

Schematic diagram of the SAF (→) and JSOC (→)
ACC Jets are tilted

Streamwise Coordinate

Streamwise velocity

\[ u_s = u_p \cos \alpha - v_p \sin \alpha \]

Cross-stream velocity

\[ v_s = u_p \sin \alpha + v_p \cos \alpha \]

- **Dots**: Daily positions of the speed maxima in the AVISO SSH-based surface geostrophic current speed.
Detecting Horizontal Motion by Argo Float Trajectories

Indo-western Pacific Southern Ocean

Negative cross-stream motion across the jets

[Li, Lee, Mazloff 2018, GRL]

Lines: Streamwise velocity ($u_s$)
Bars: Cross-stream velocity ($v_s$)
Detecting Horizontal Motion by Argo Float Trajectories

**Eastern Pacific Southern Ocean**

**Negative cross-stream motion across the jets**

[Li, Lee, Mazloff 2018, GRL]

**Lines:** Streamwise velocity ($u_s$)

**Bars:** Cross-stream velocity ($v_s$)
Conclusions

- In the Indo-western Pacific SO, where the jets are relatively well-defined, the analysis shows that **eddy momentum fluxes** drive the ACC jets and **jet-scale overturning circulations (JSOCs)**.

- Analogous to the Ferrel Cell, the JSOCs are **thermally indirect** with sinking/rising motions on the equatorward/poleward flank of the jets.

- The **negative cross-stream motion** is revealed across the jets by Argo float trajectories. It suggests that **the JSOCs indeed exist in nature**.

- The eddy-driven JSOC associated with the SAF plays an important role in **initiating the narrow and deep mixed layer wedge** that forms north of the SAF.
Reference:

