# Observed circulation in the Coral Sea

William S. Kessler and Sophie Cravatte

## Work in progress!!!

Motivations:

1. Background for major fieldwork (French/Australian/US "Solwara")
2. Very thick currents and strong topography in South Pacific:
   → need supplement to reference-level geostrophy
3. Role of Coral Sea processes modifying water masses to Equator
4. Tilted WBC bifurcation: special dynamics of the South Pacific?

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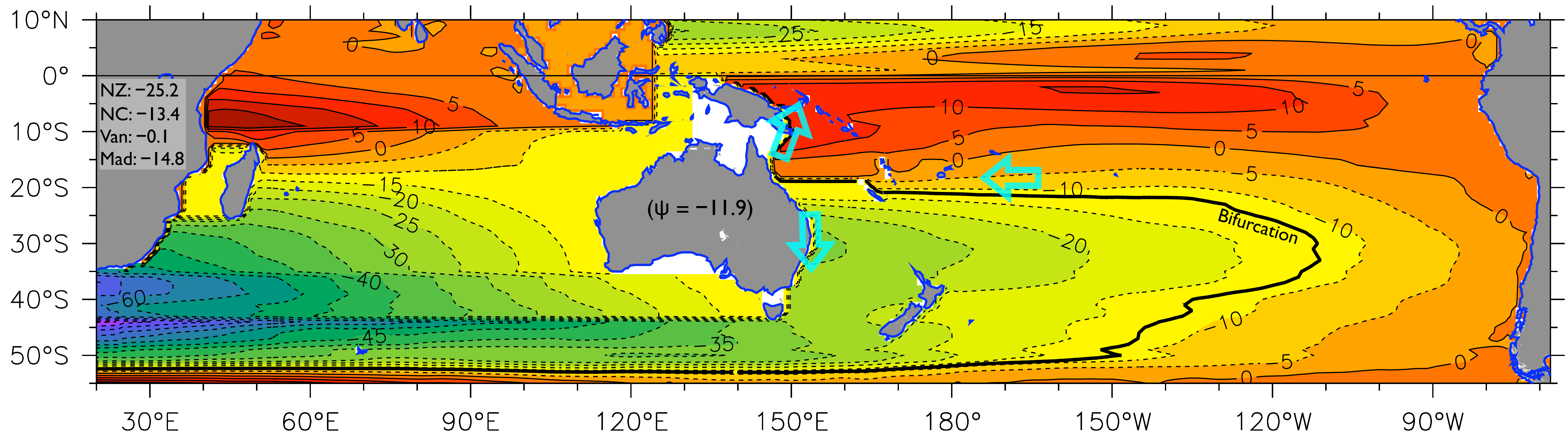
4. Tilted WBC bifurcation: special dynamics of the South Pacific?

# Why do we care about the Coral Sea?

## Island Rule (generalized Sverdrup) streamfunction




(ERS winds)

- "Southern hemisphere supergyre"
- Bifurcation streamline divides water that (mostly) goes to the Indonesian Throughflow from water that (mostly) forms SW Pacific mode water or goes into the Indian Ocean.
- If the Indonesian Throughflow were closed, the zero contour would be the bifurcation streamline (about 2° further north at the coast of Australia).
  In the Sverdrup sense, all the ITF transport comes from this change in WBC transport.

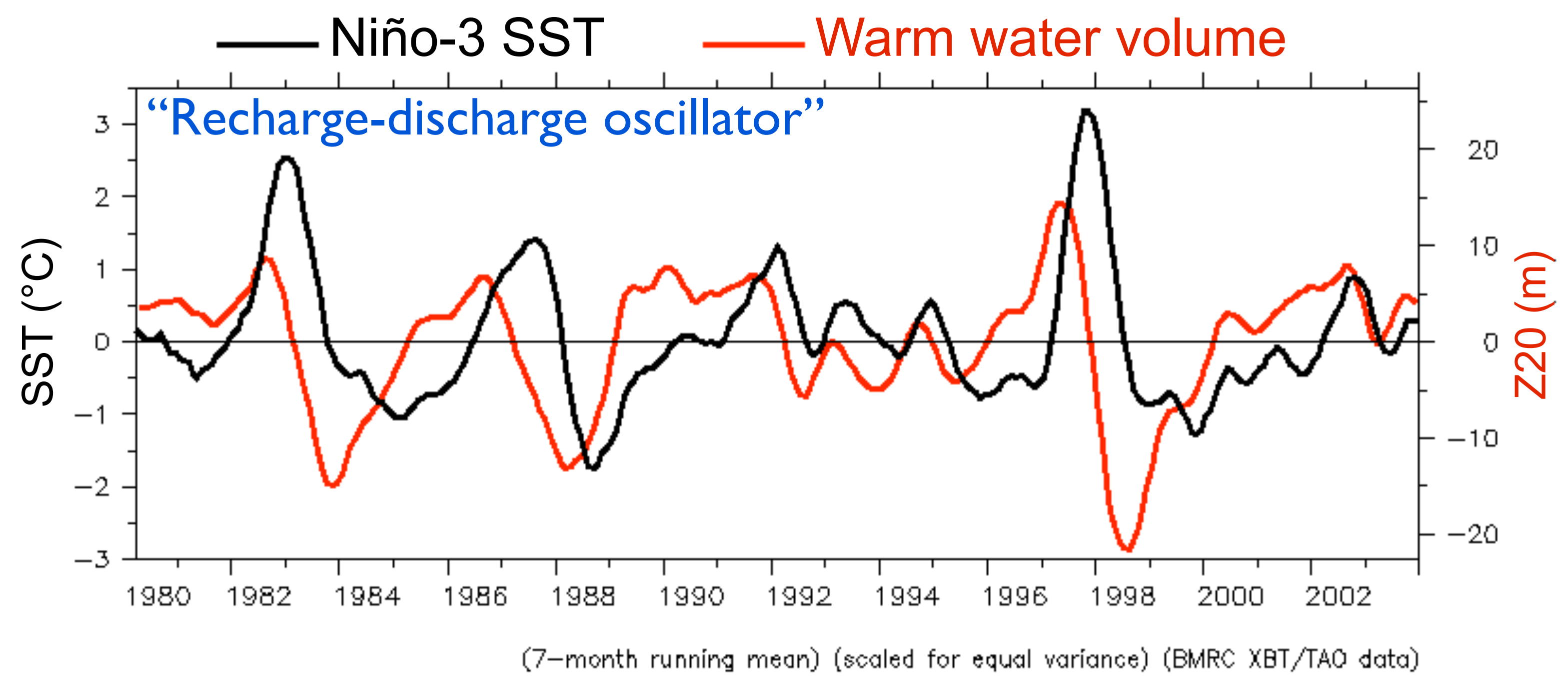
# Strong ENSO variability in the Coral Sea (WBCs) … and consequences

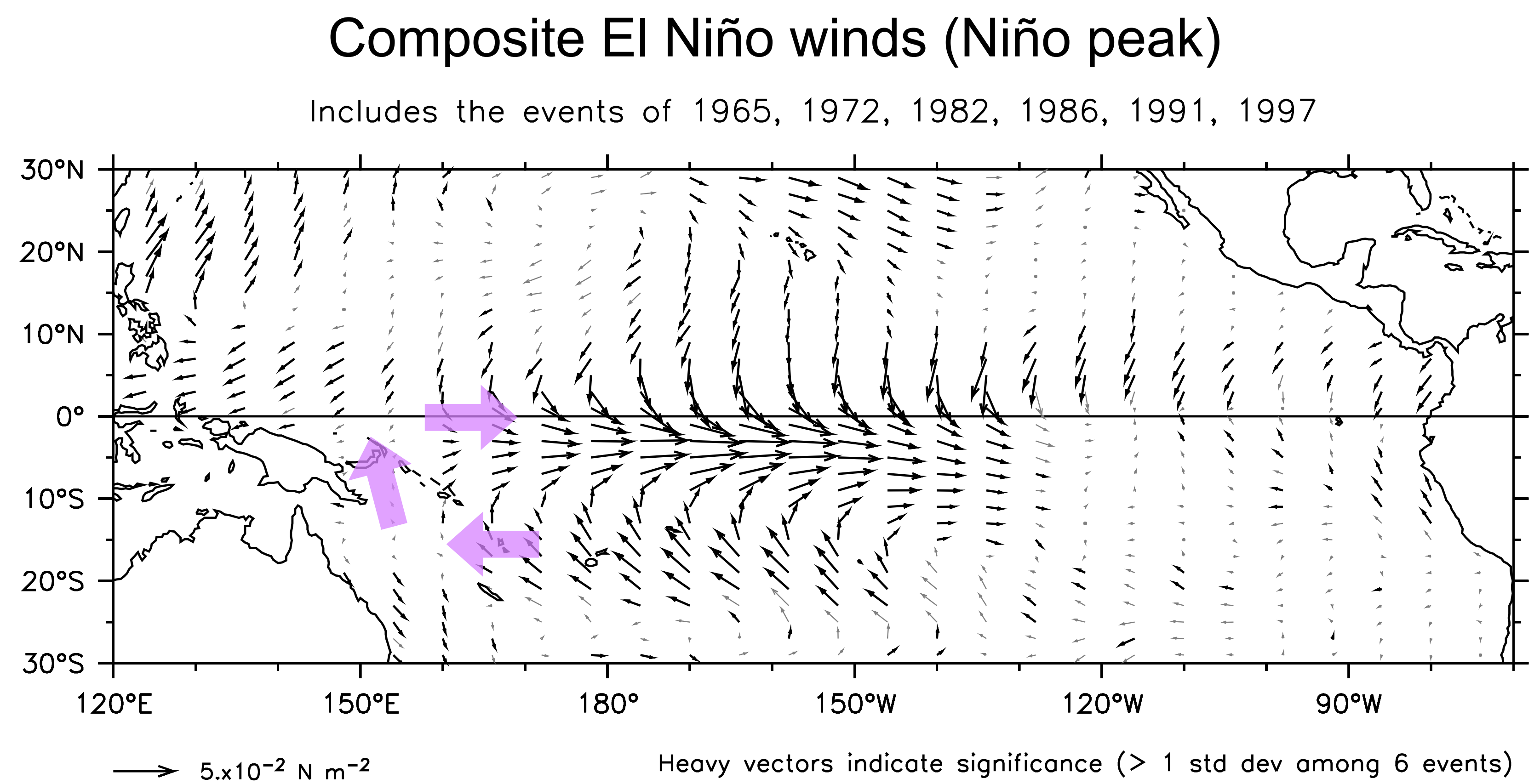
The Coral Sea WBCs play a large role in the ENSO “recharge-discharge oscillator”.

ENSO wind stress curl signals occur in the central Pacific, but the effects propagate west via Rossby waves.

A few months after El Niño winds peak, equatorward western boundary transport increases (greatly: O(100%)).

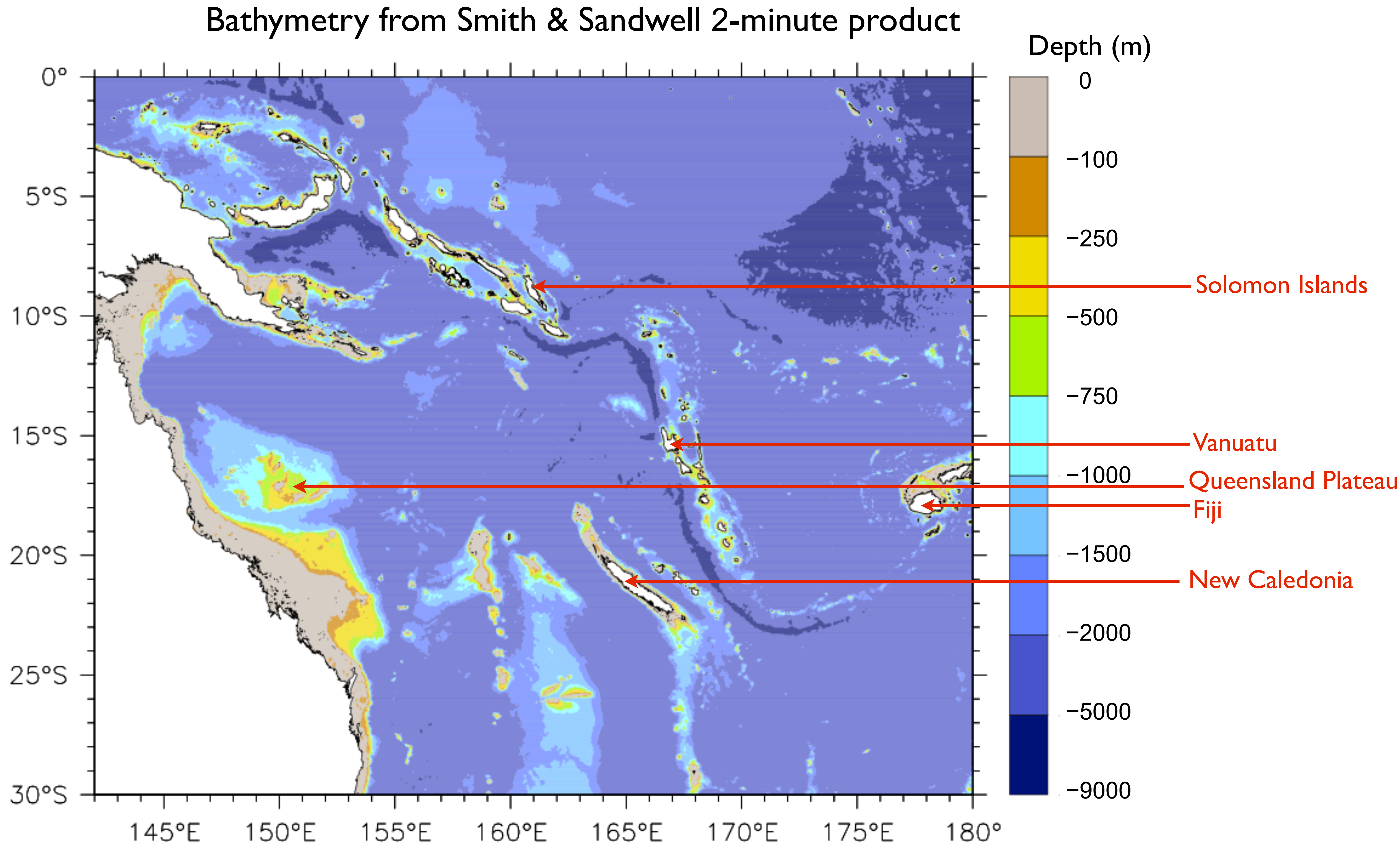
The anomalous WBC is a major part of the “recharge” of the west Pacific warm pool following an El Niño event.
(And vice versa for La Niña).




Rossby waves carry curl signal west (Eq-ward WBC a few months lagged).
Purple arrows show anomalous post-El Niño circulation.

# Complex bathymetry with islands and near-islands



# Data sources

## Argo trajectory files

All floats that ever entered the region 140°E-180°, 30°S-Equator

## CARS (CSIRO Atlas of Regional Seas) climatological T,S

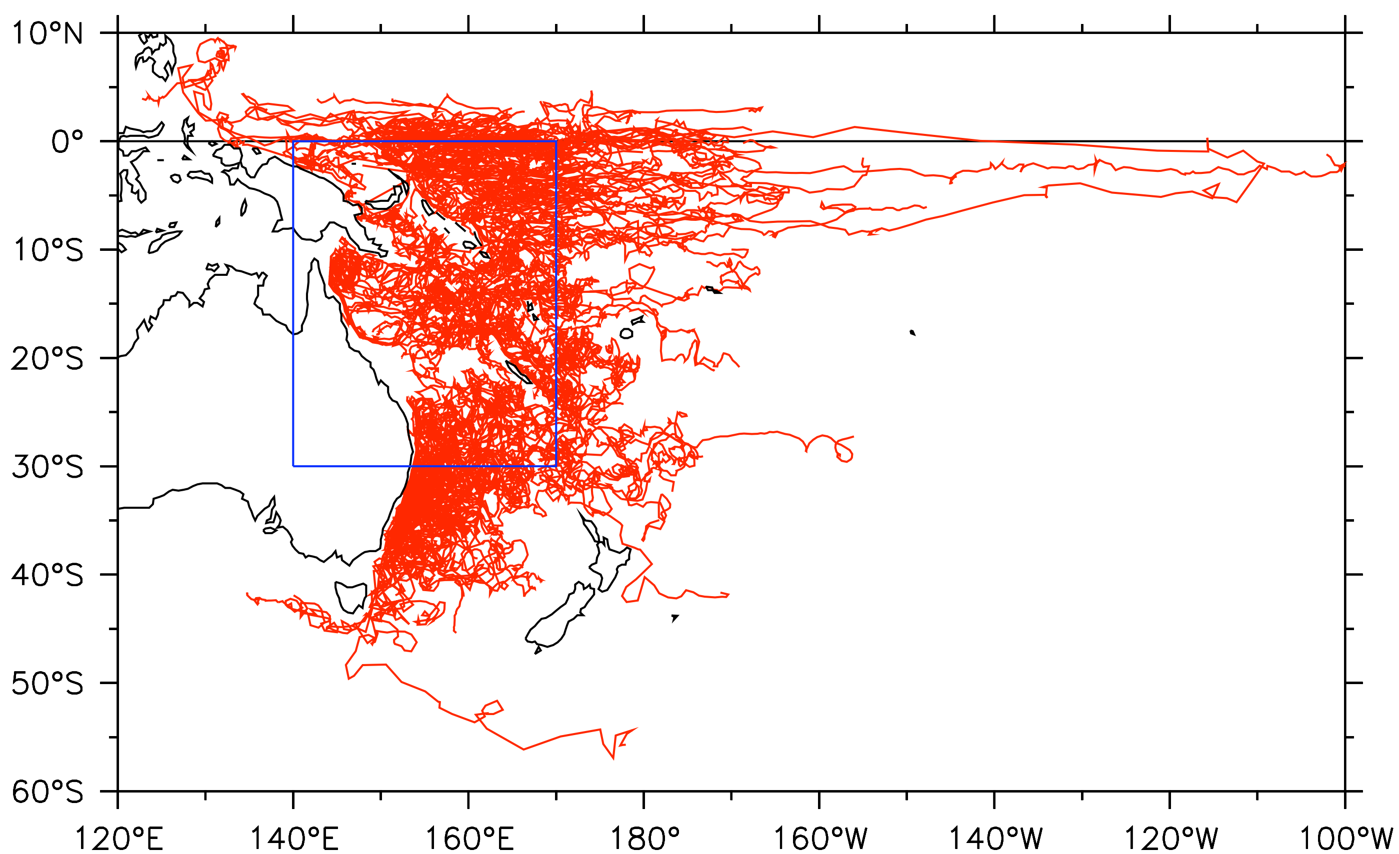
Mean and annual harmonics from all sources (Argo, CTD, XBT, TAO), carefully mapped (Ridgway and Dunn, Prog.Oc. 2003, and updated)

Also use the CARS gridded $O_2$ product (historical $O_2$ profiles very messy).

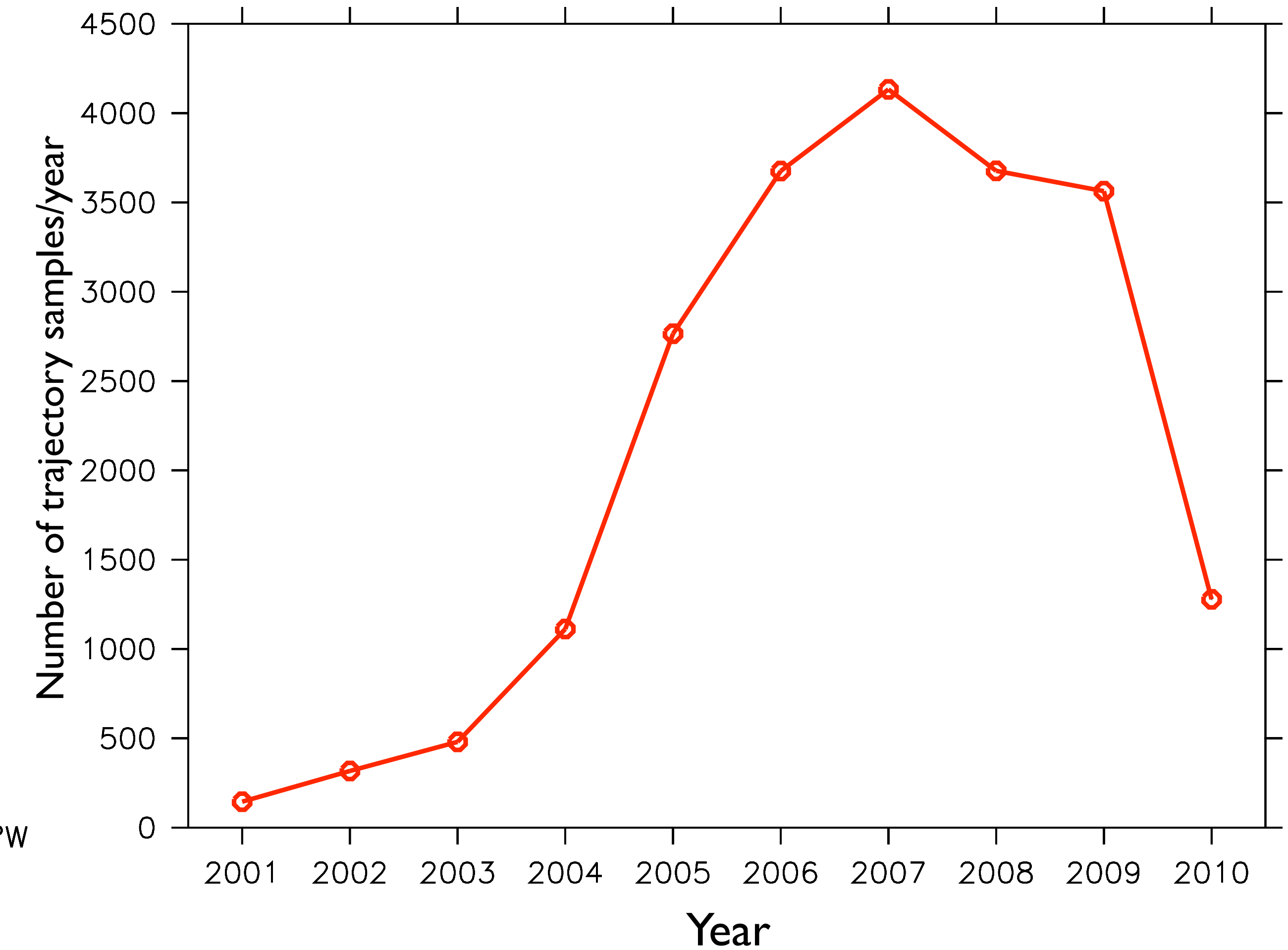
And note that the "Argo Atlas" (Roemmich and Gilson 09) is too coarse to resolve the boundary currents and jets.

# Mapping the Argo drift velocity

Trajectories of floats entering the blue box




Trajectory samples per year

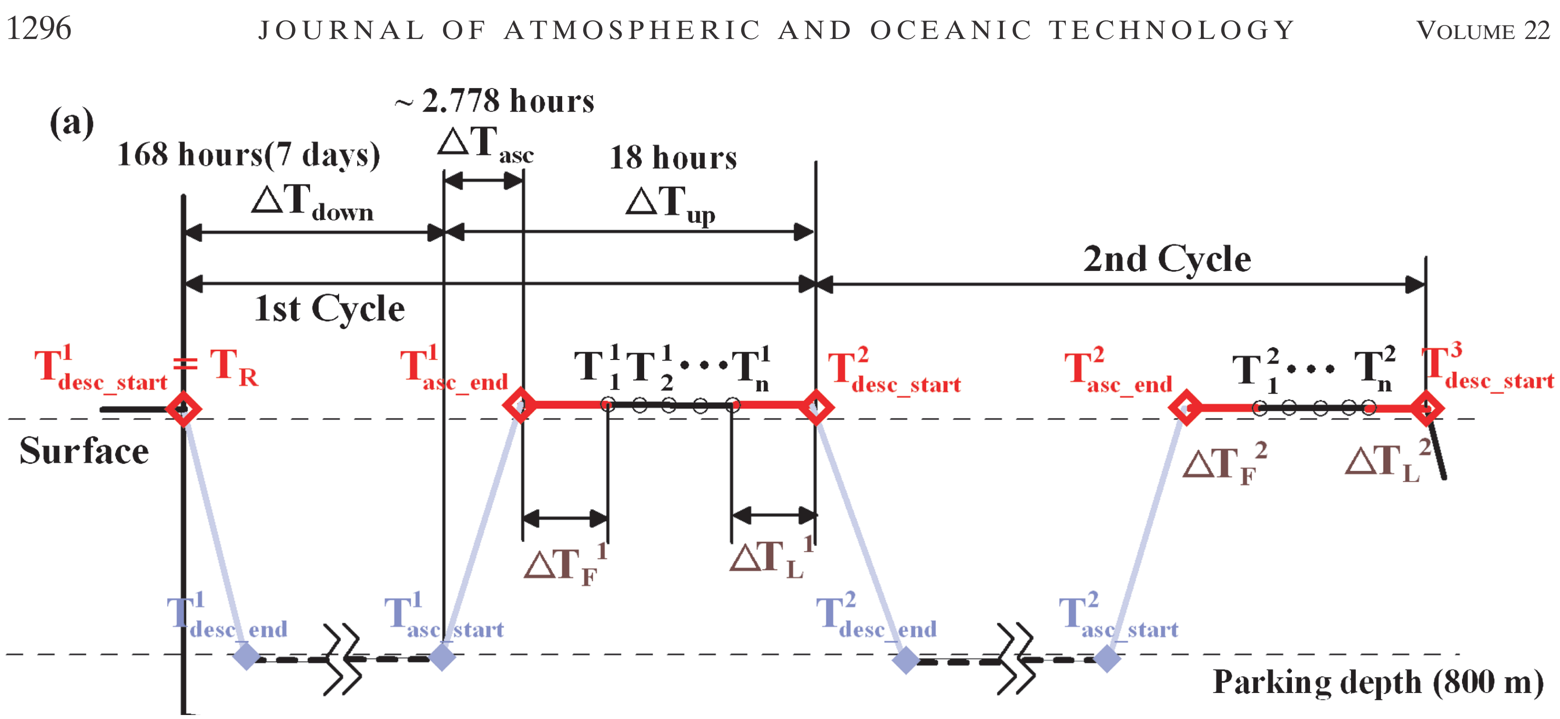



187 floats ever entered the region 140°E-180°, 30°S-Eq, to March 2010

# The right way to estimate the subsurface drift

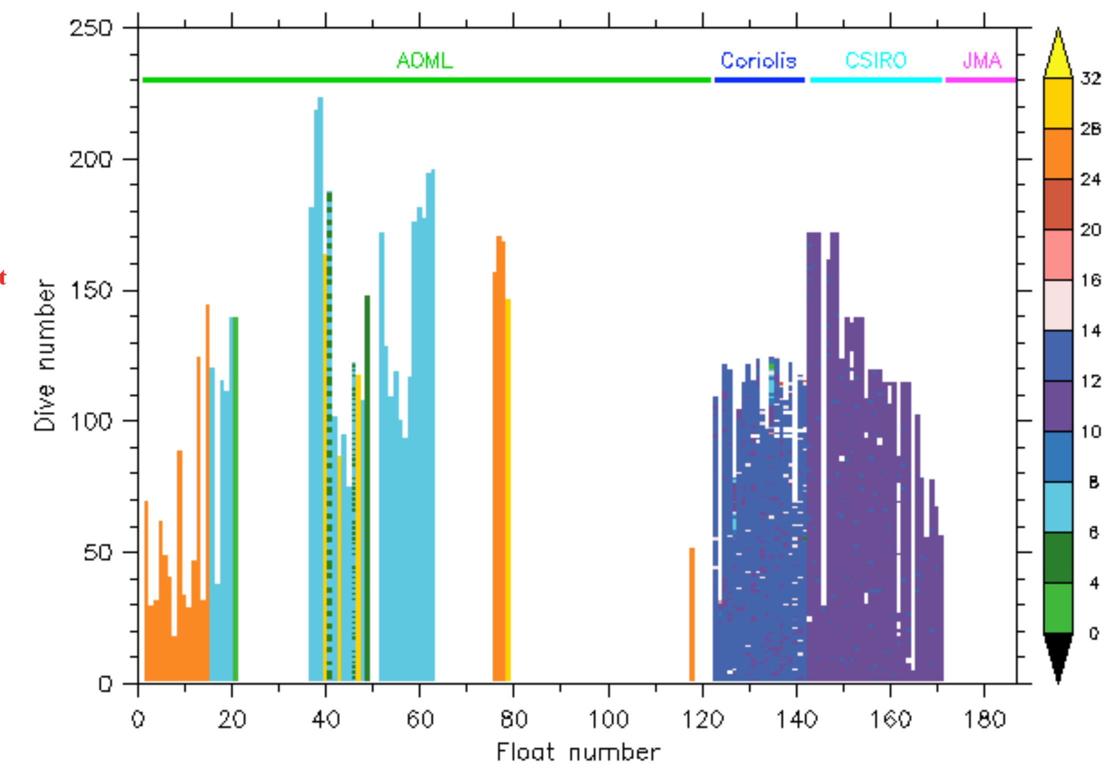
## (if all information is available)

**The ideal** (Park et al. 2005)




**The reality**

Argo float descent+ascent times in the Coral Sea




Times in hours

If the times of all events are available (departing/arriving at the surface and parking depth);

And if the motion at the surface and during ascent/descent can be estimated (Ekman and inertial surface motion, and shear relative to the parking depth);

Then a best estimate of the parking depth drift can be made.

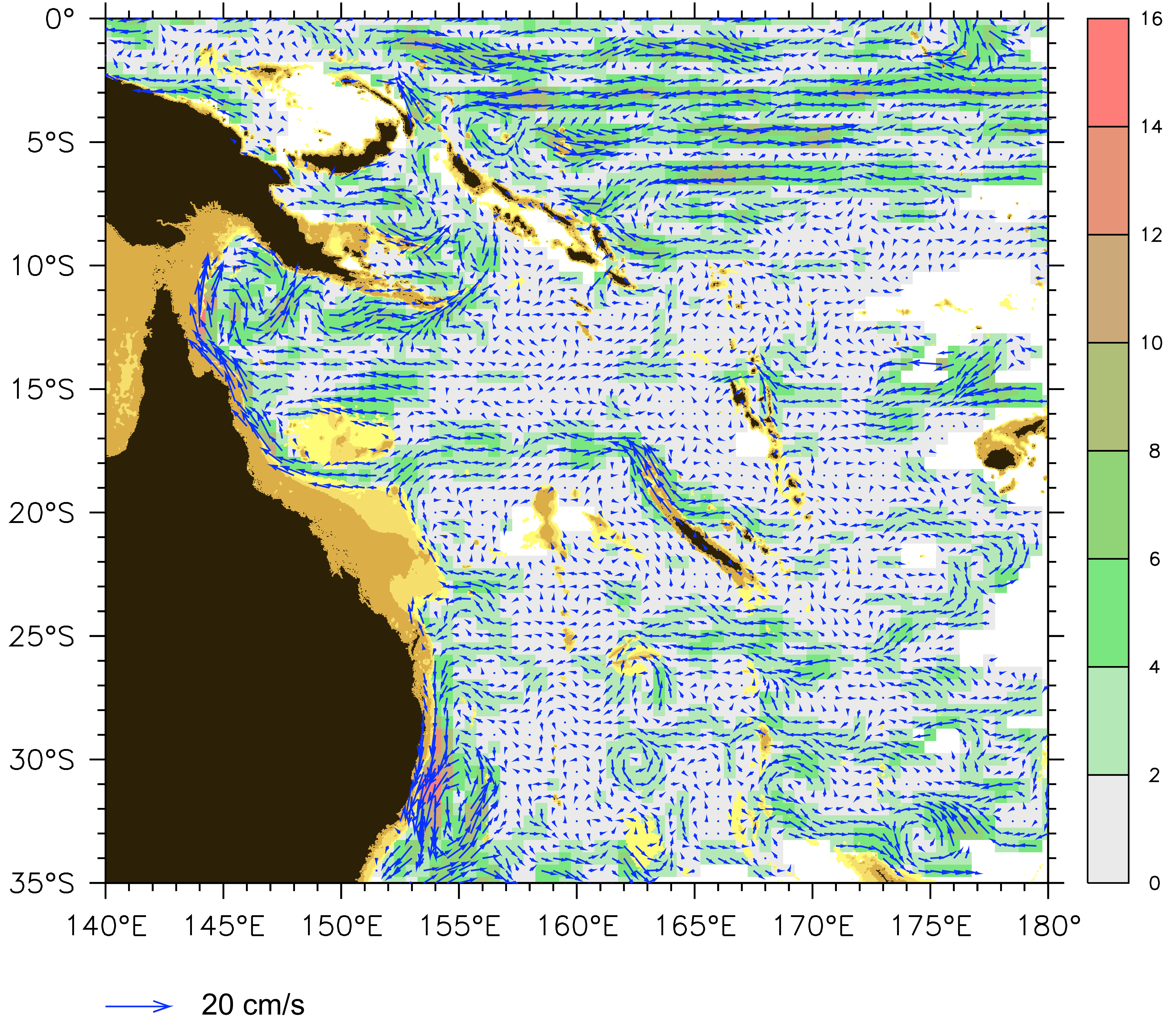
➡ But, this information is often missing from the Argo trajectory files.

# Mapping method (owes much to Willis and Fu, JGR 2008)

1. Manual QC (bad GPS hits, grounded floats, ....)
2. Use CARS $u_g$ shear to reference all floats to 1000m
3. In the absence of complete information, choose:
   4 hours unsampled surface time, 12 hours ascent/descent time
   (Averages over the floats with known values.)
   Project surface velocity 4 extra hr, use CARS shear for ascent/descent
4. Do NOT correct for poorly-known influences: Ekman, inertial motion
5. Objectively-map (u,v) drift components to a ½°×½° grid
   - Mapping scales 100km in (x,y)
   - Accept mapped values with estimated error < 0.4×variance
   → Get a field of mean Argo parking-depth drift velocity
6. Take the mapped float drifts as 1000m reference for CARS $u_g$ shear
7. For bottom depths < 1000m, find CARS $u_g$ relative to the bottom

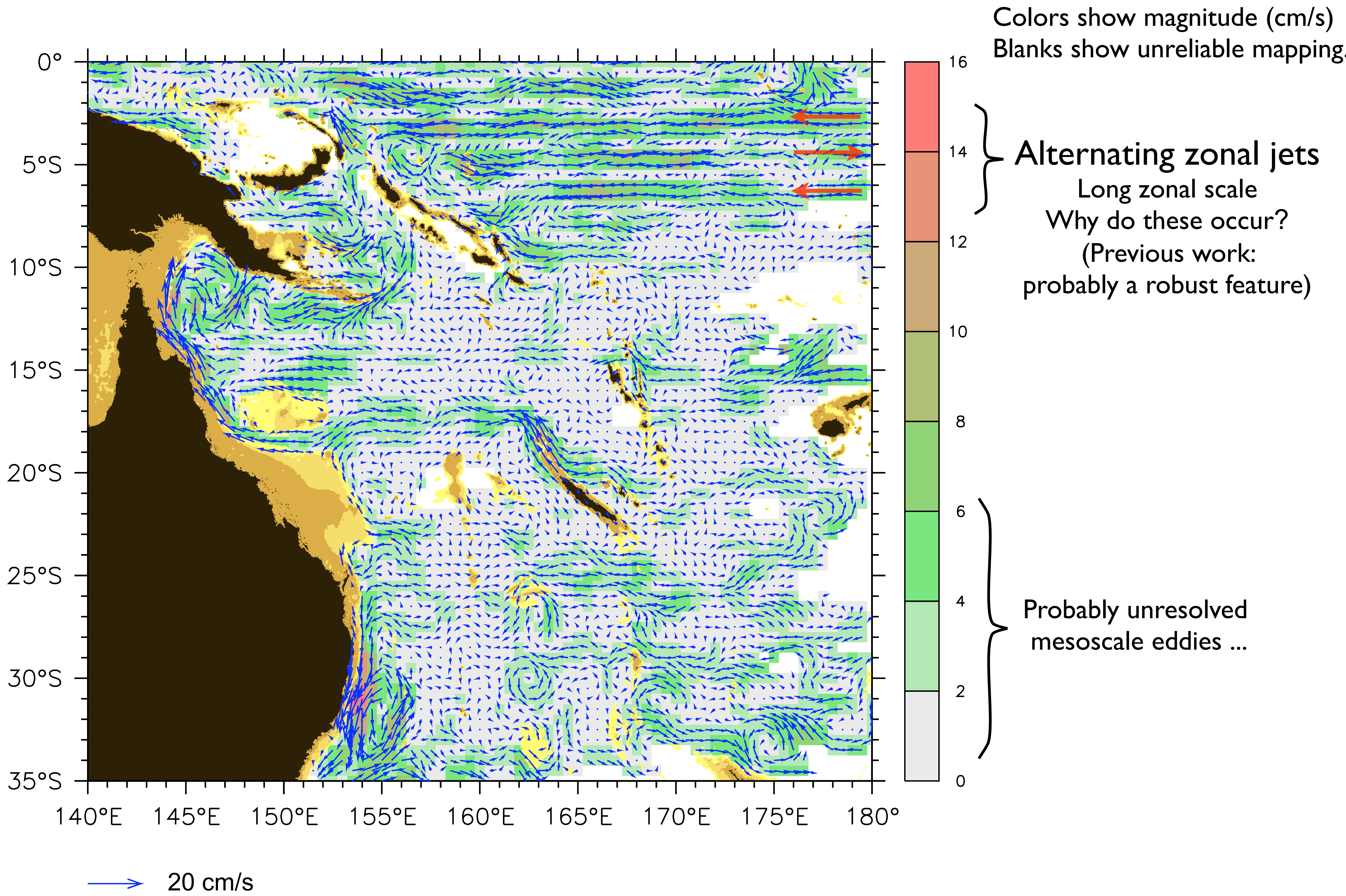
⇨ **The result is a 3-D field of mean (u,v) to 2000m**

# Mapped 1000m Argo drift velocity



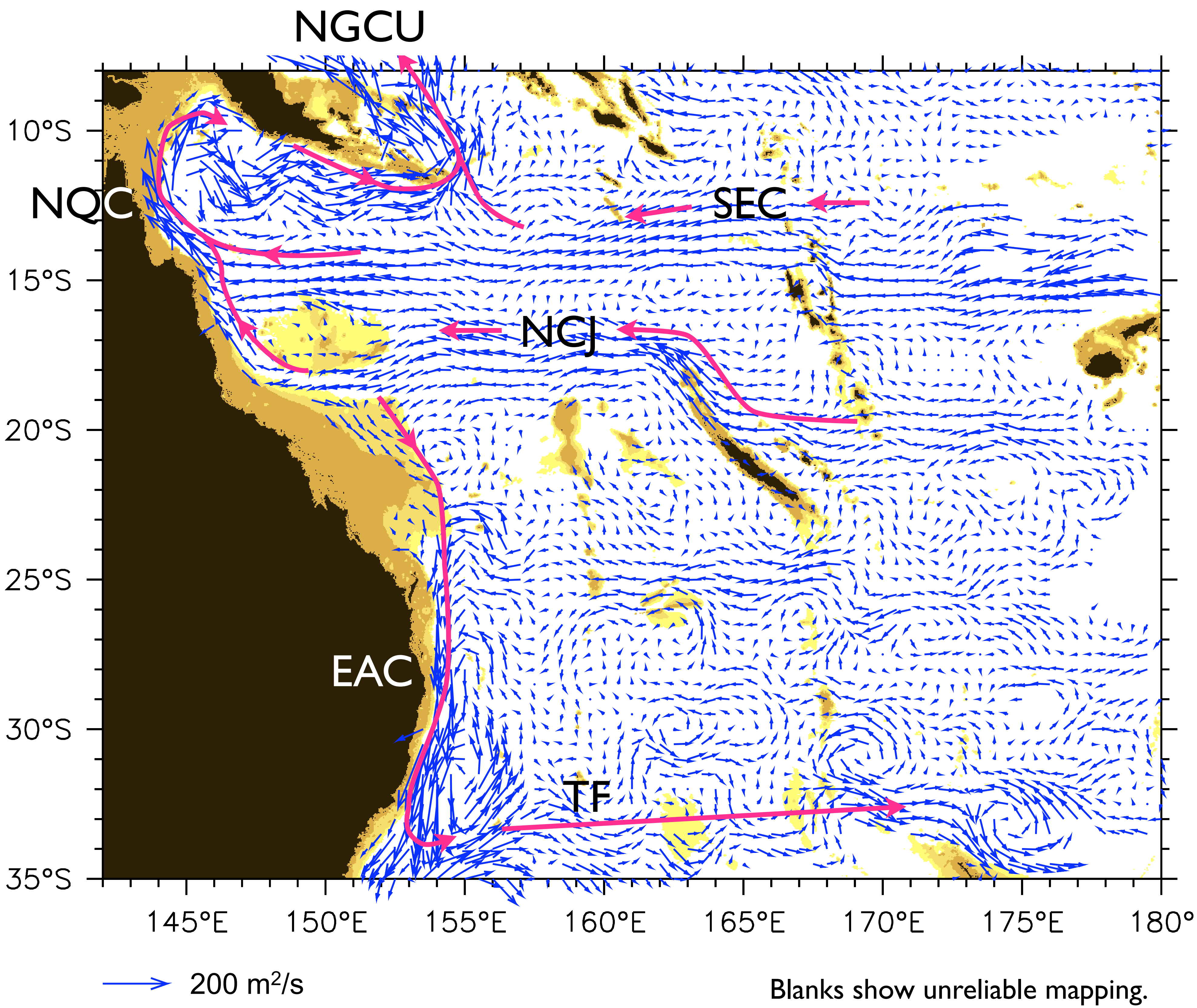

Colors show magnitude (cm/s)
Blanks show unreliable mapping.

# Mapped 1000m Argo drift velocity



# Combined Argo/CARS 0-1000m transport

Most of the Coral Sea inflow occurs across 162°E between the Solomons and New Caledonia: SEC and NVJ




## Current names

SEC: South Equatorial Current

NCJ: North Caledonian Jet

NQC: North Queensland Current

EAC: East Australian Current

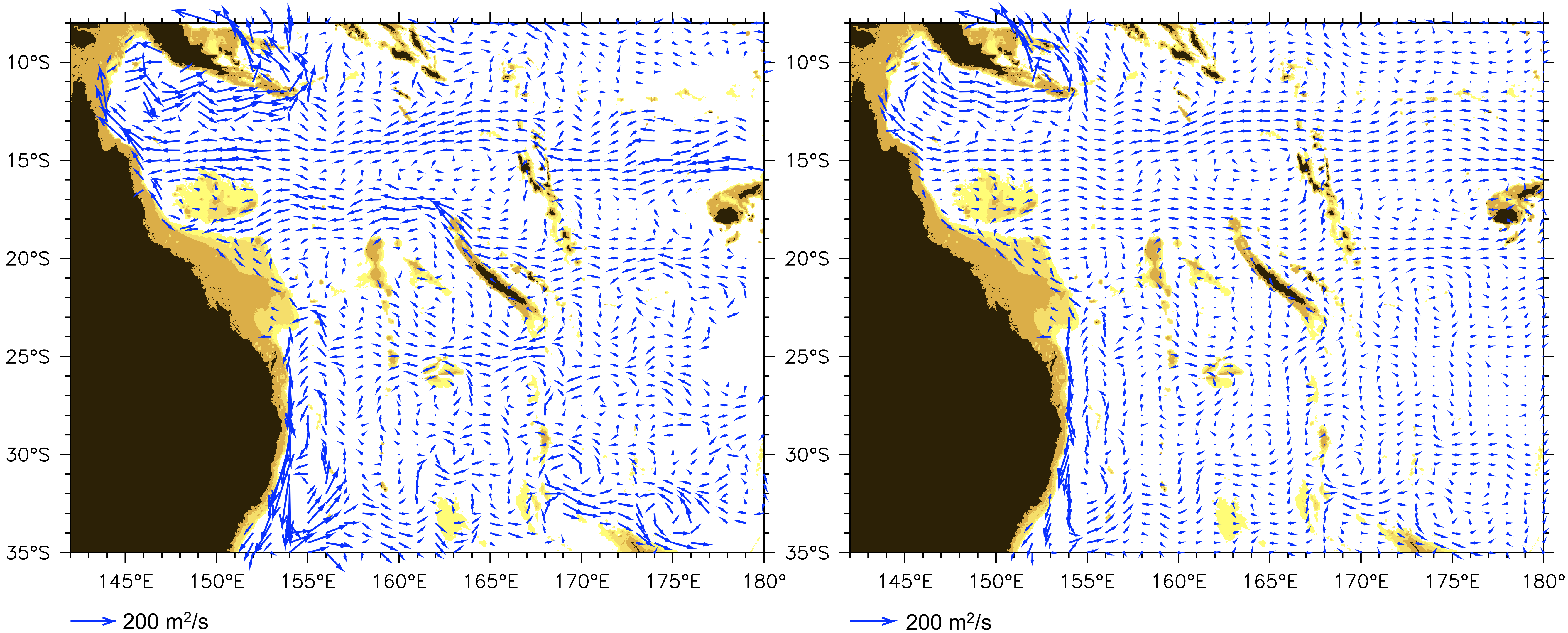
TF: Tasman Front

NGCU: New Guinea Coastal Undercurrent

Blanks show unreliable mapping.
Bathymetry at 0,100,500,1000m.

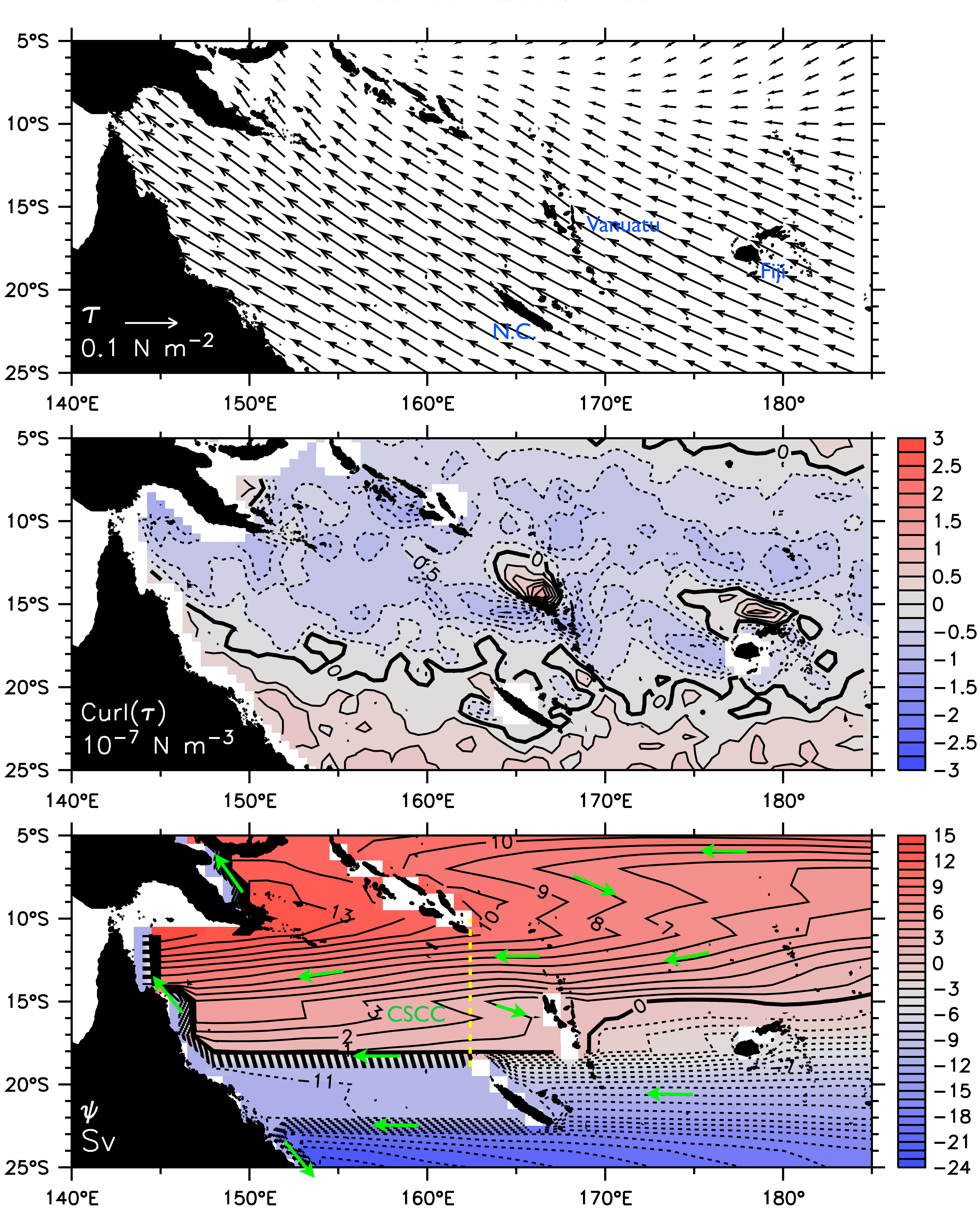
# Effect of Argo drift:
## (Compare relative $u_g$)

Integrated total u | Integrated $u_g$ relative to 1000m




- Impact of mapped Argo drift is largest for the NCJ.
- It also increases WBC transport (both directions).
- SEC is relatively unchanged (shallow current due to slope of tropical thermocline).

# Island Rule (Sverdrup) solution




Qiu et al. 2010

The islands affect the circulation two ways:
- Mountains block the wind, change the curl,
- The islands block the currents.

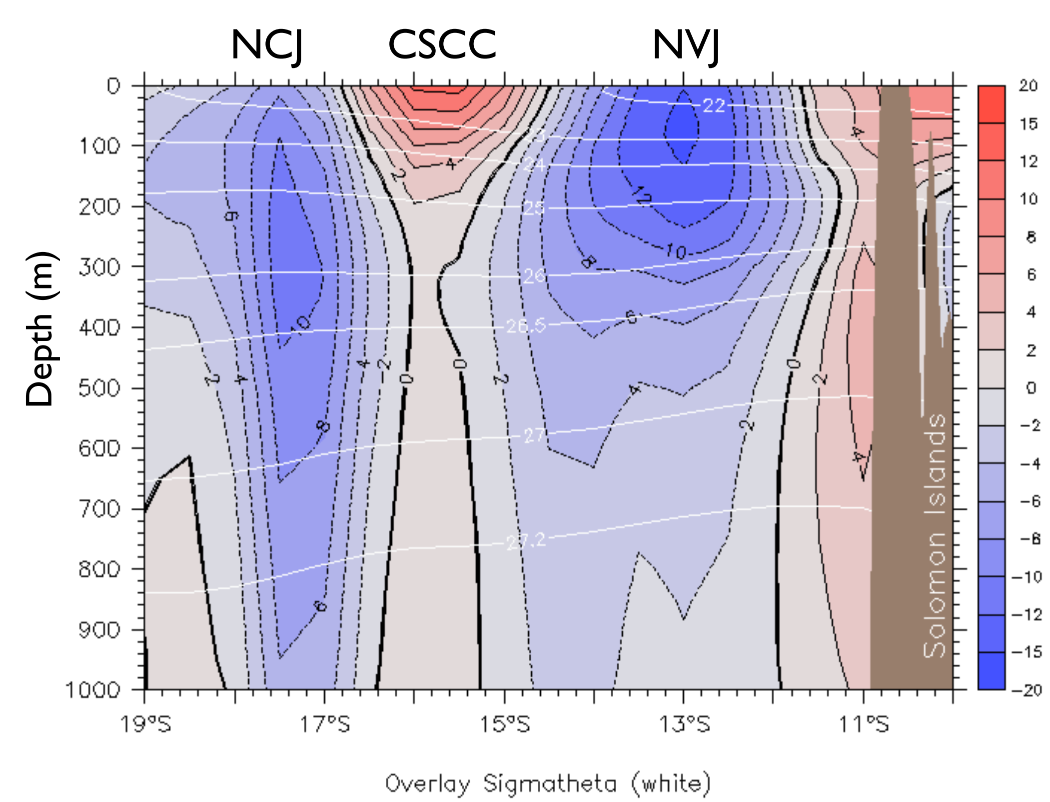
Two separate jets feed the Coral Sea:

S. Equatorial Cur. (broad current at 11°-14°S),
=> slope of the main thermocline

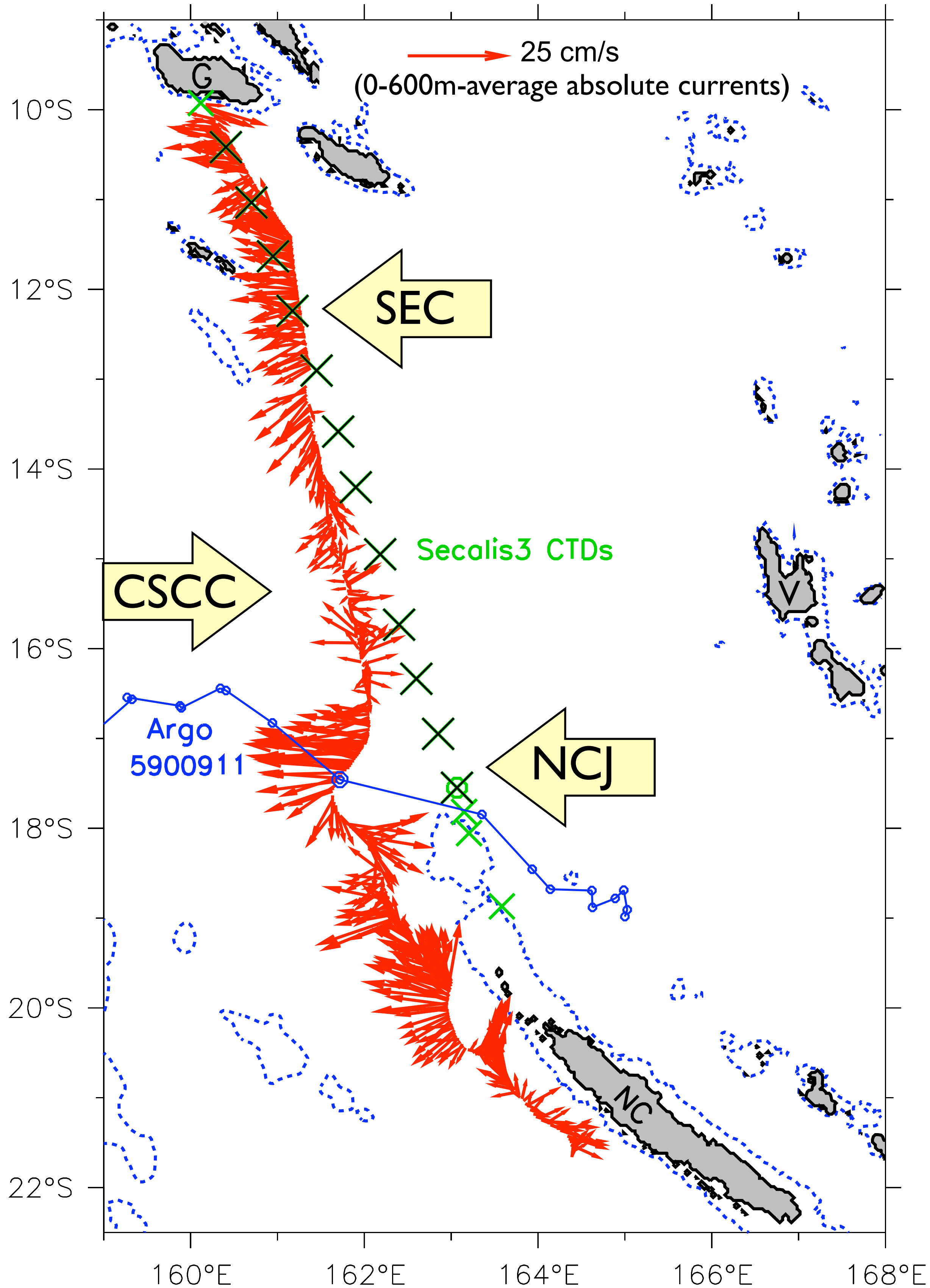
N. Caledonian Jet (narrow jet at 18°S),
=> shear only below ~600m

Curl around Vanuatu mountains produces
Coral Sea Countercurrent (shallow)

Mapped zonal current at 162.5°E

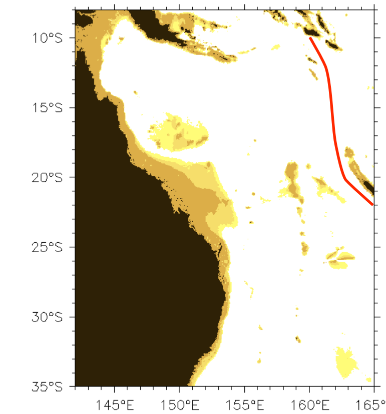


# Coral Sea input: Observations during 2005: glider, cruise, Argo




Gourdeau et al (2008)

| | |
|---|---|
| Glider: | Jul-Sep 2005 (red vectors) |
| Secalis3: | Jul 2005 (green crosses) |
| Argo: | May-Aug 2005 (blue dots) |



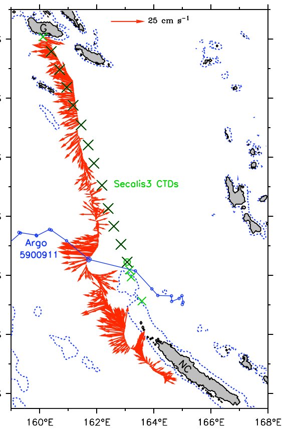

The glider showed 3 distinct currents:

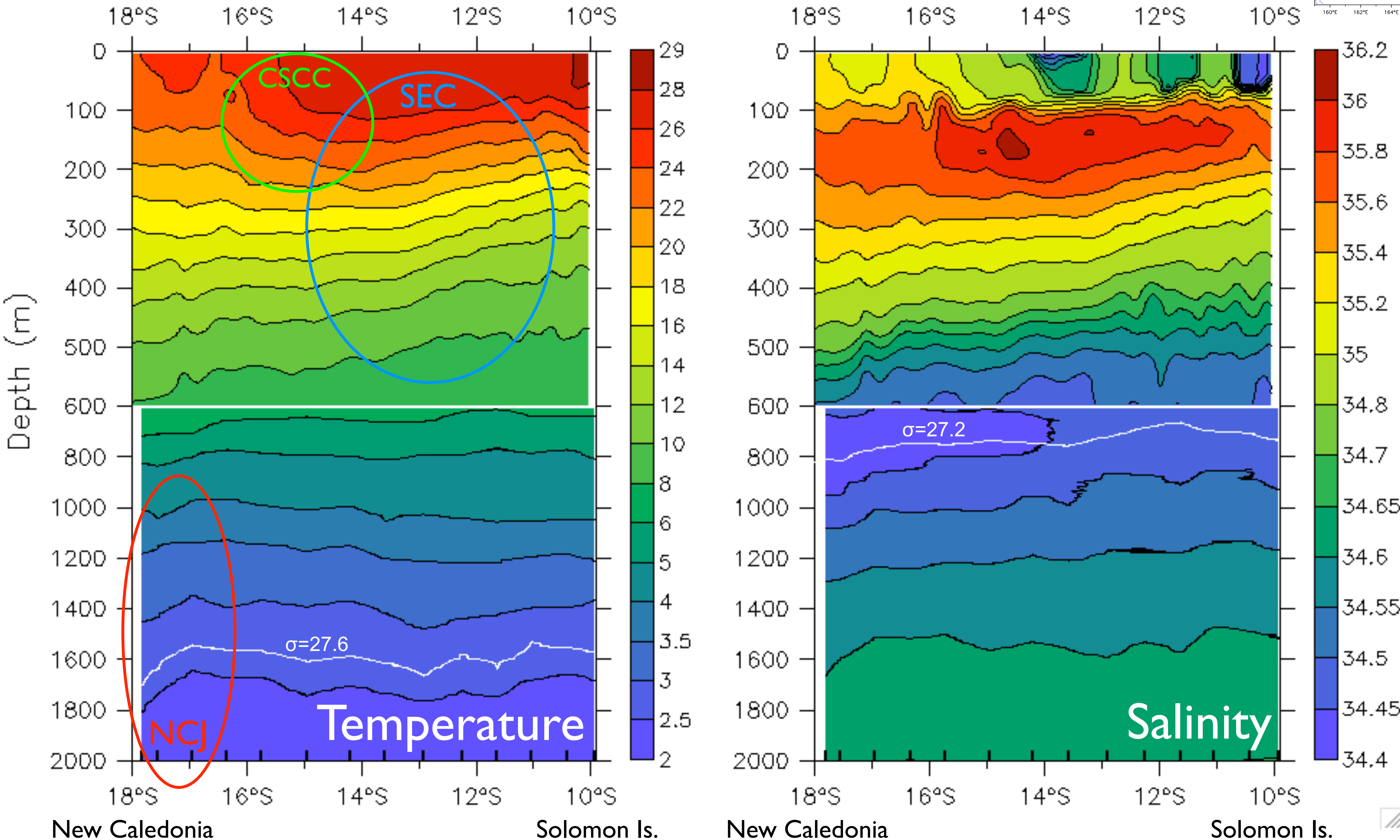
- Broad SEC at 11-14°S
- Narrow, fast NCJ at 17-18°S
- Separated by the weak CSCC
  in the wake of Vanuatu.

Argo float 5900911 crossed the glider track 48 days previously.
It drifted at <u>20.2 cm/s</u> for this dive.

# T and S observations during 2005 glider and cruise

Glider (0-600m, top), Secalis3 cruise (600-2000m, bottom)

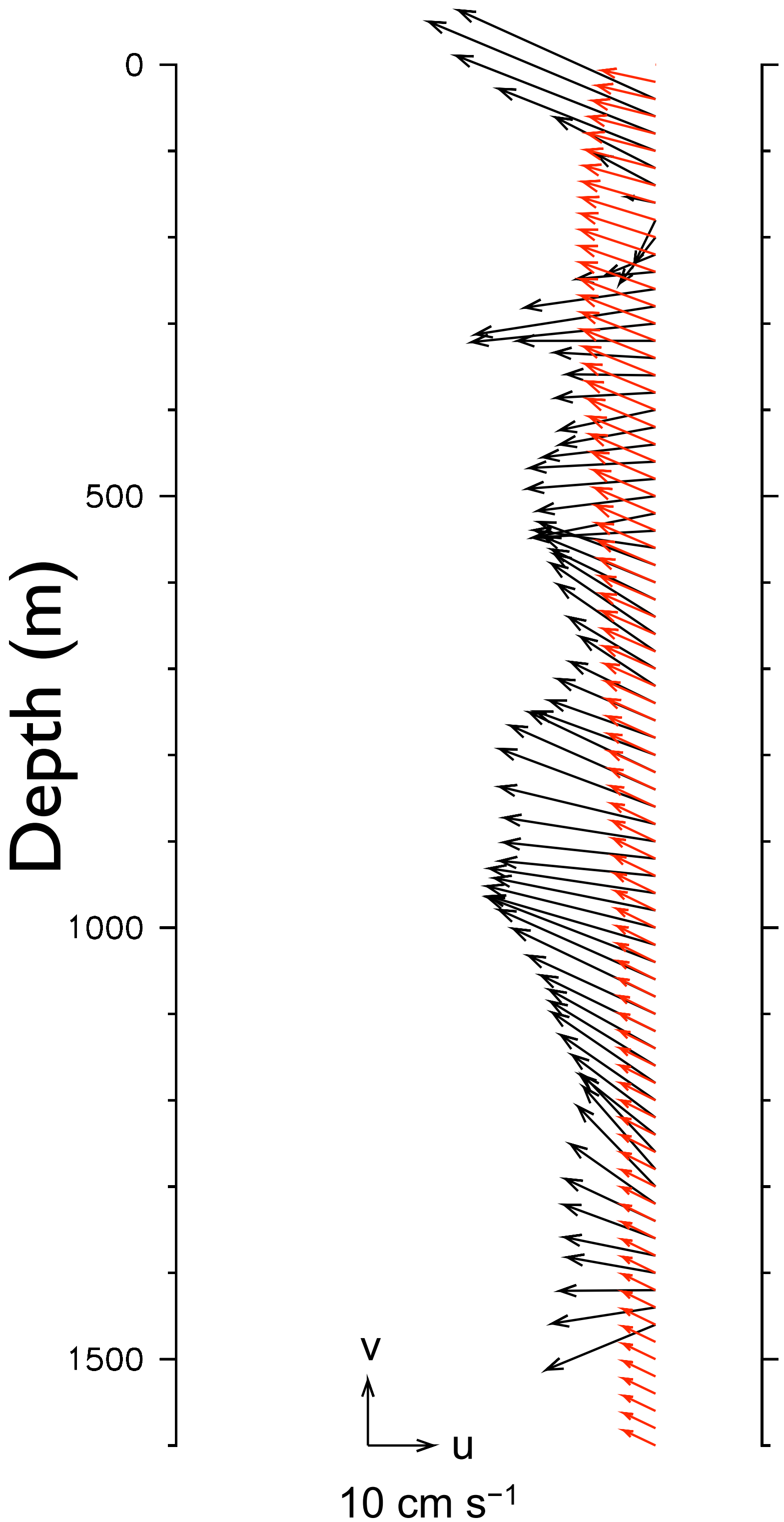



Gourdeau et al (2008)

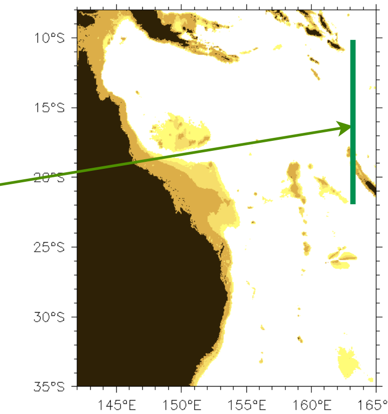
# Effect of mapping: Compare $u_g$ (NCJ is very thick!)

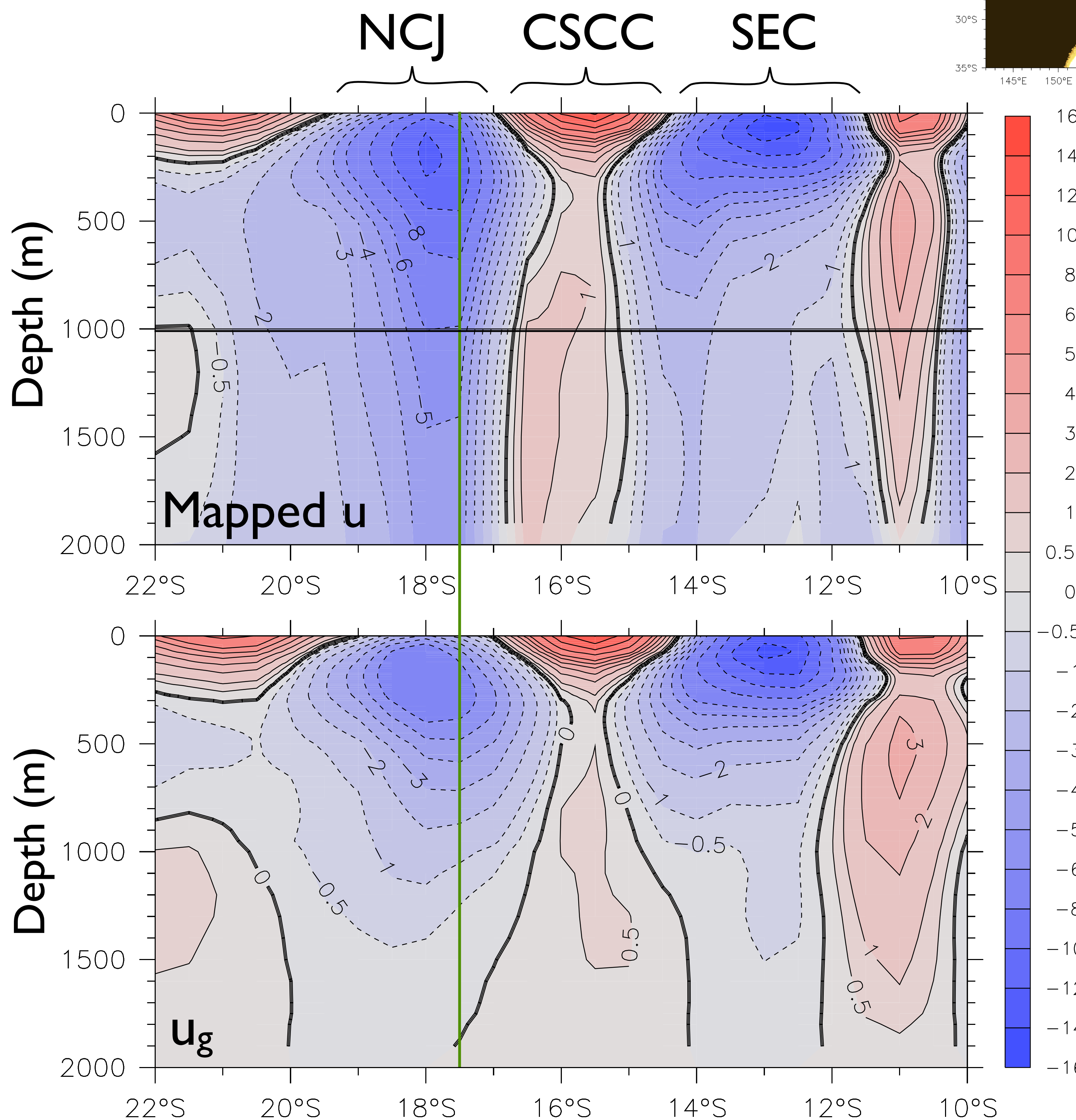
LADCP profile at 17.5°S,163°E

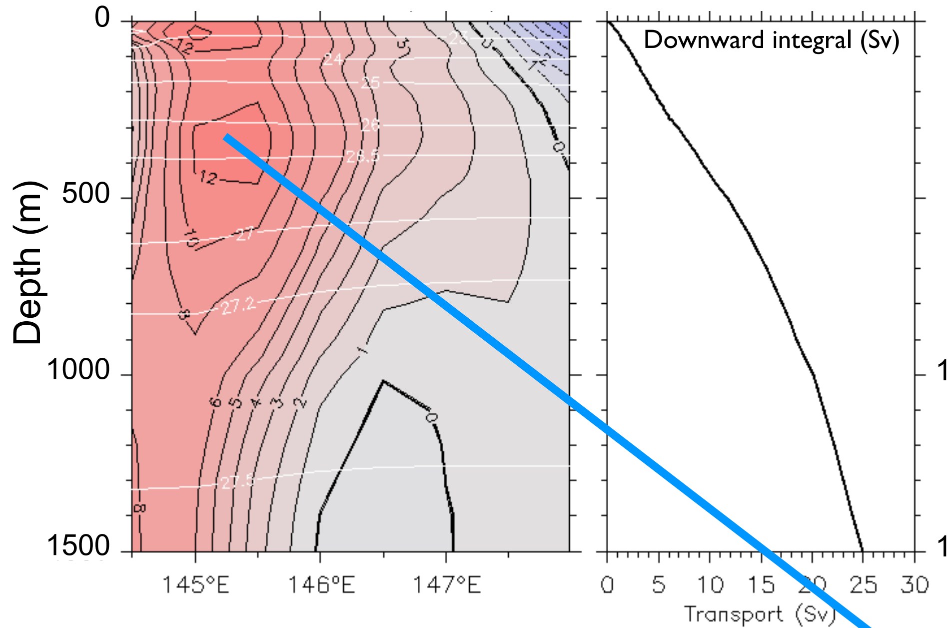


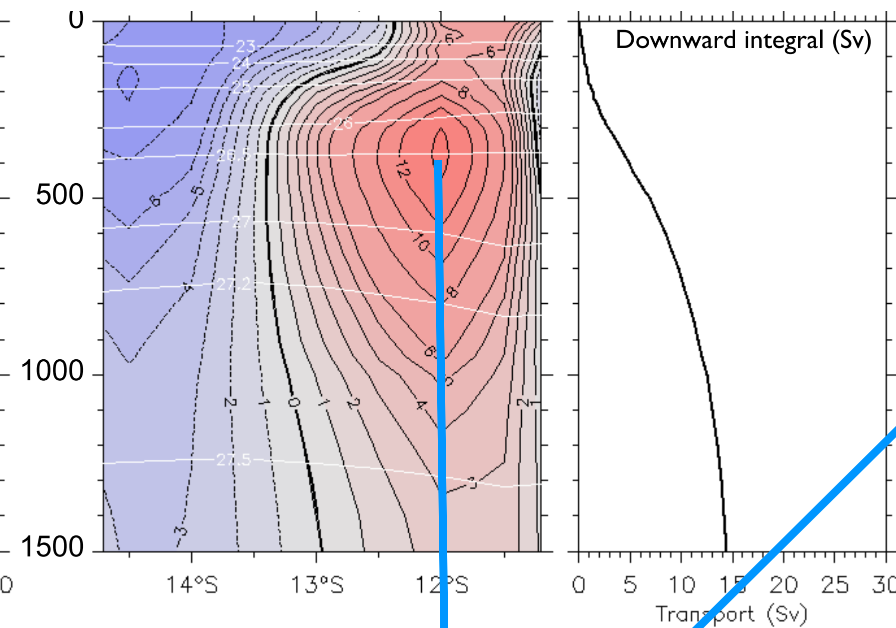

Black=LADCP (Jul 2005)
Red=Mapped velocity

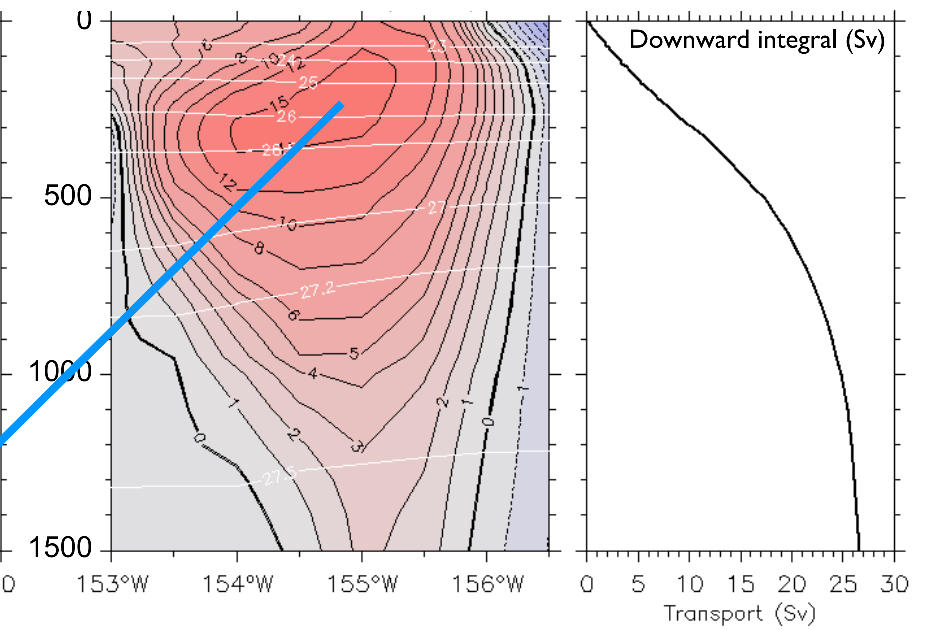
Sections along 163°E





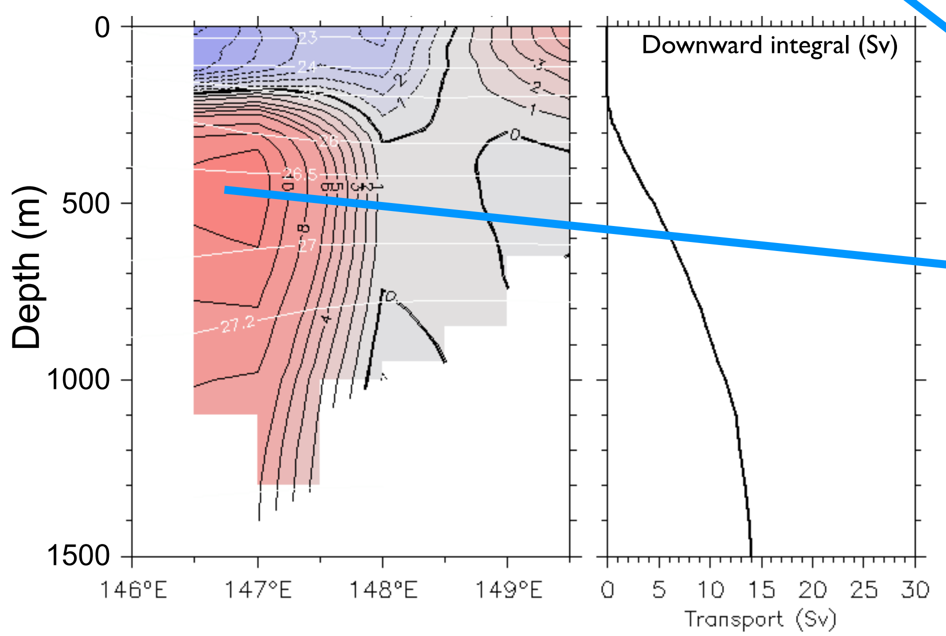


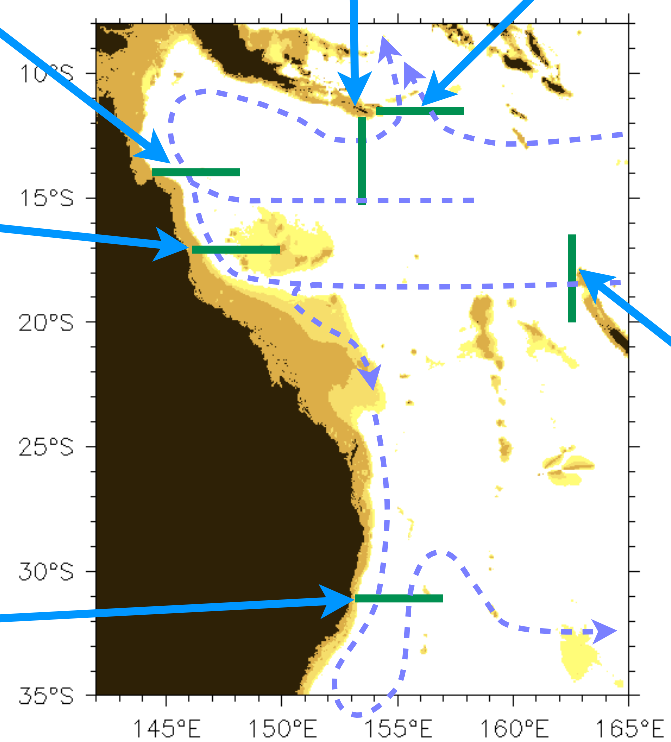



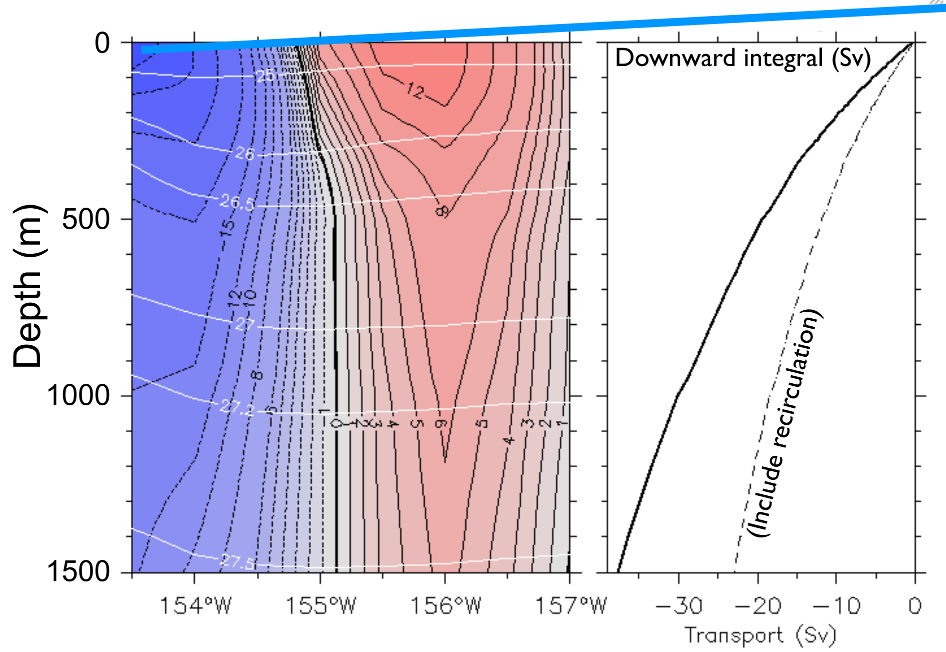

# Many thick jets in the Coral Sea

(all x-EAC with subsfc cores)

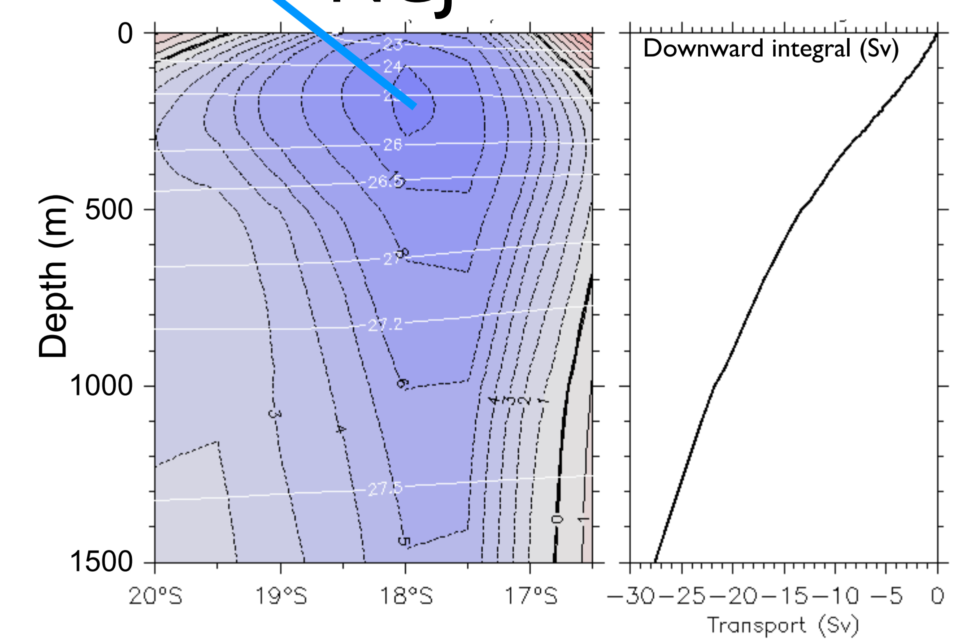



NCJ

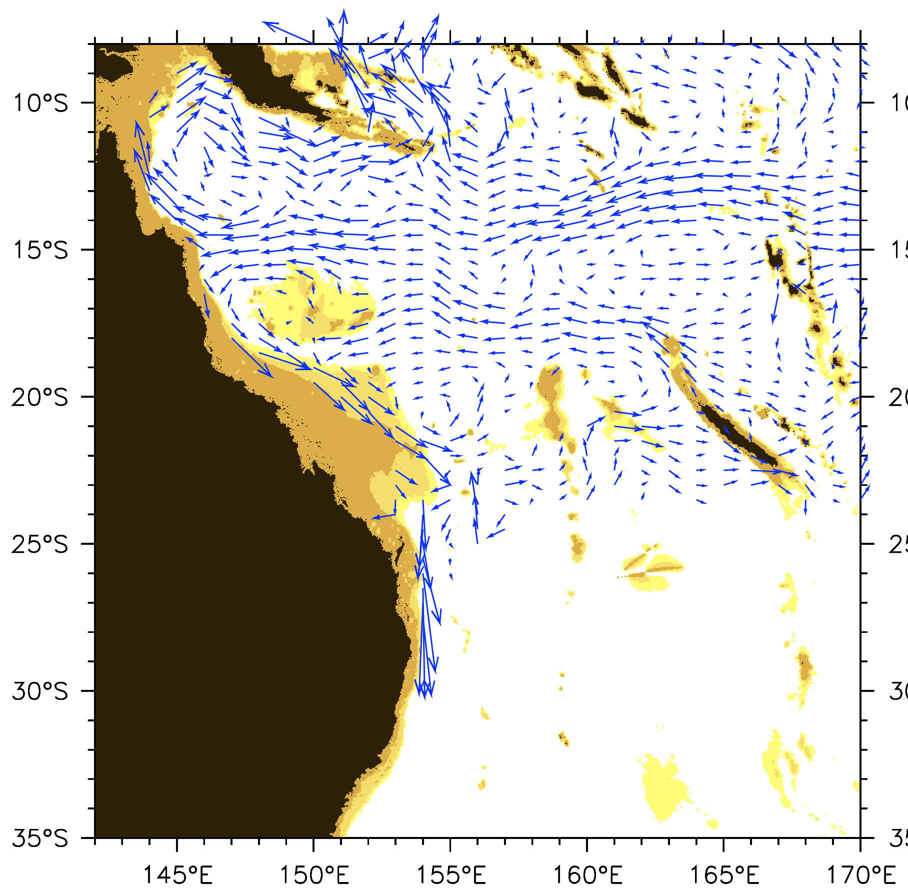



All plots have the same widths (3.5°), contours, scales (x EAC transport!)
Red = E-ward/N-ward
Blue = W-ward/S-ward



# Circulation on isopycnals

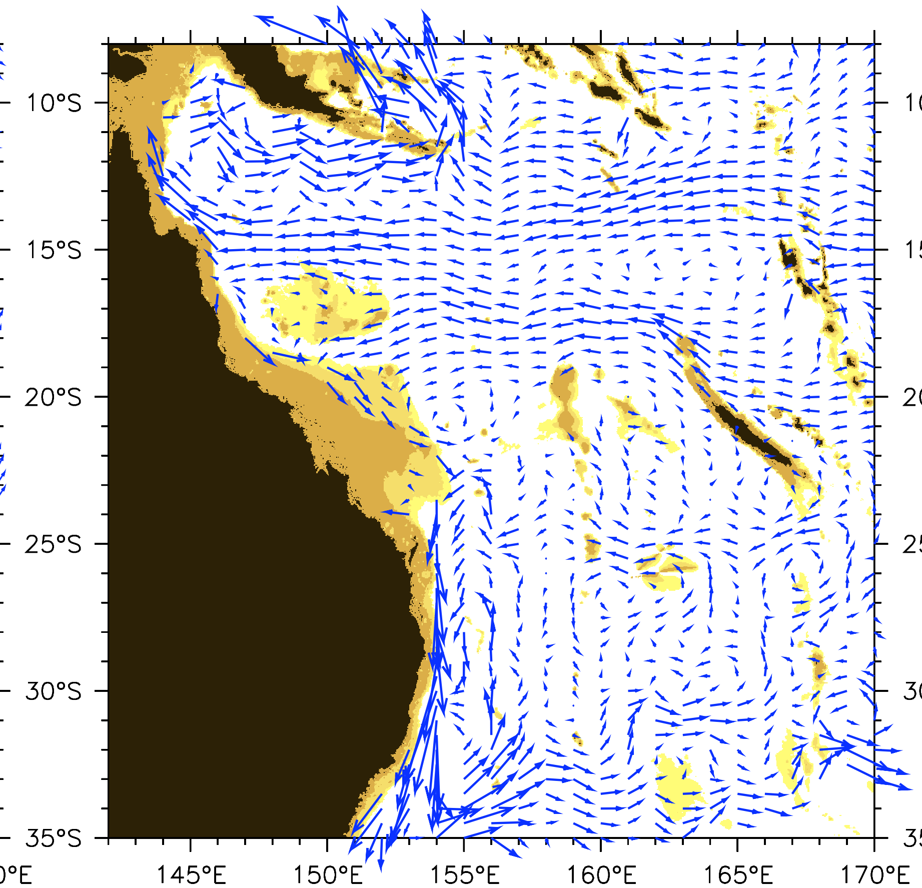
## Sigma 24.0




25. cm/s

Mean depth 102m

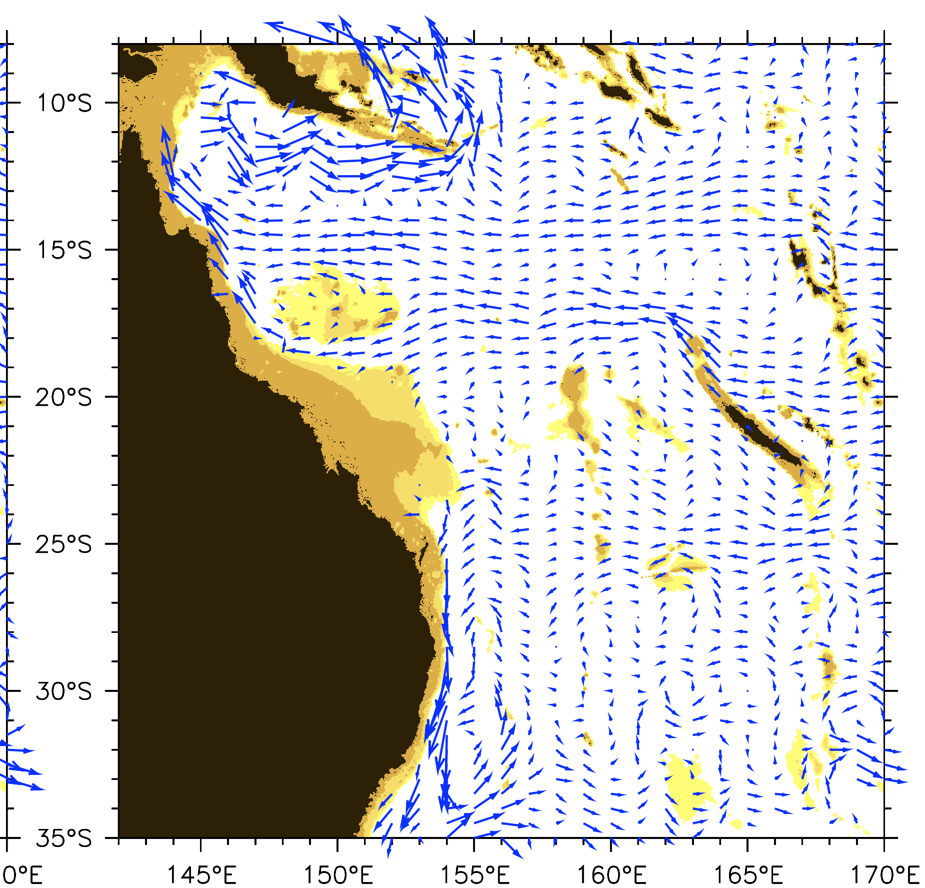
## Sigma 25.5




25. cm/s

Mean depth 197m

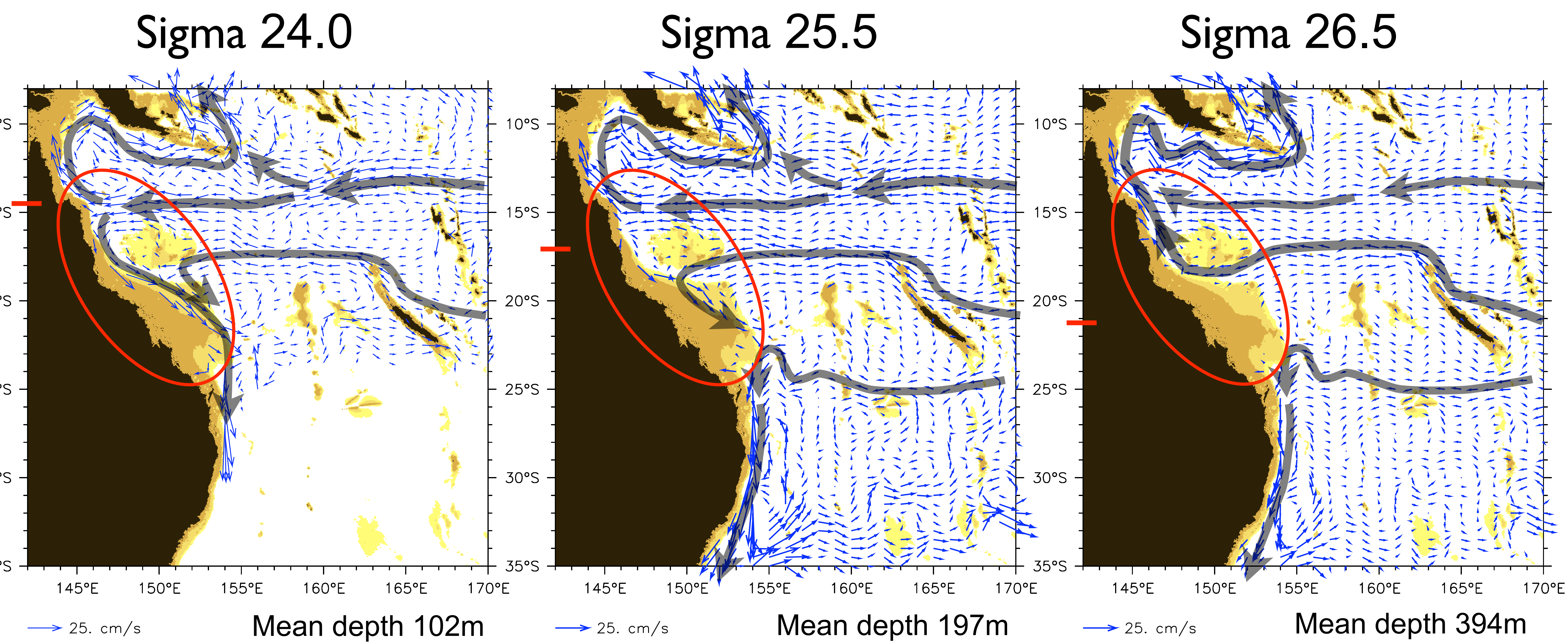
## Sigma 26.5




25. cm/s

Mean depth 394m

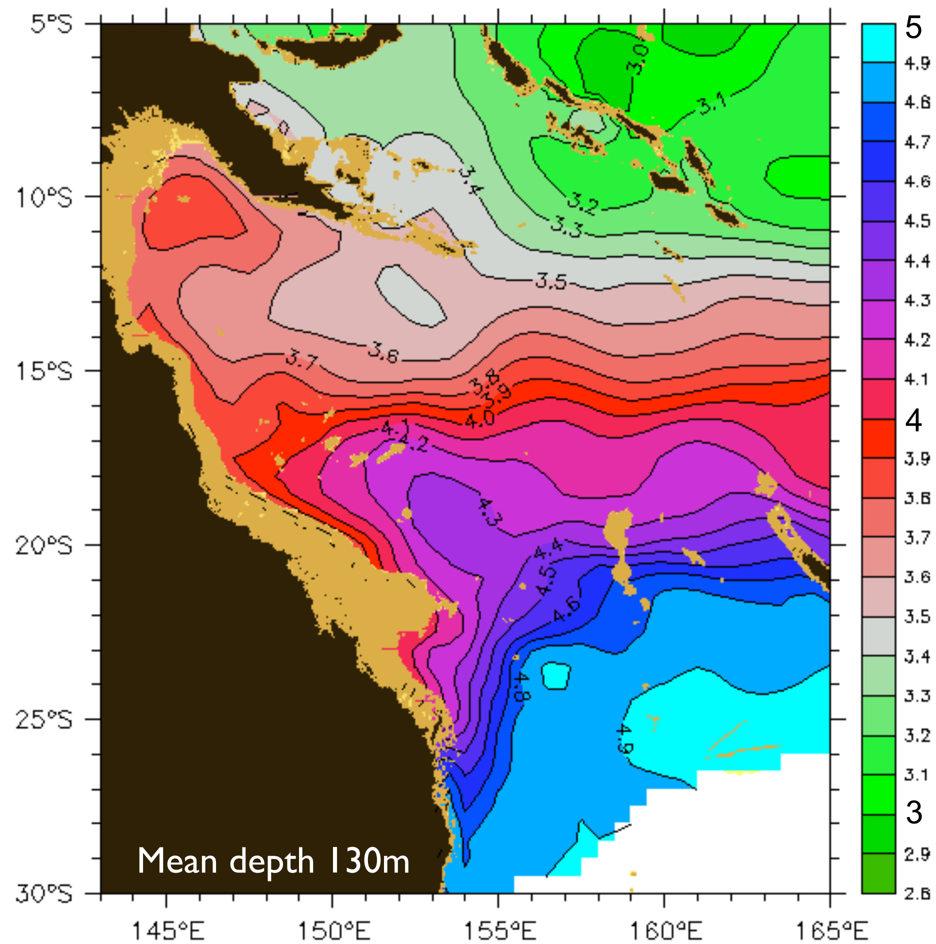
# Circulation on isopycnals




WBC bifurcation moves south with depth (density)

# Oxygen as a tracer of Coral Sea currents

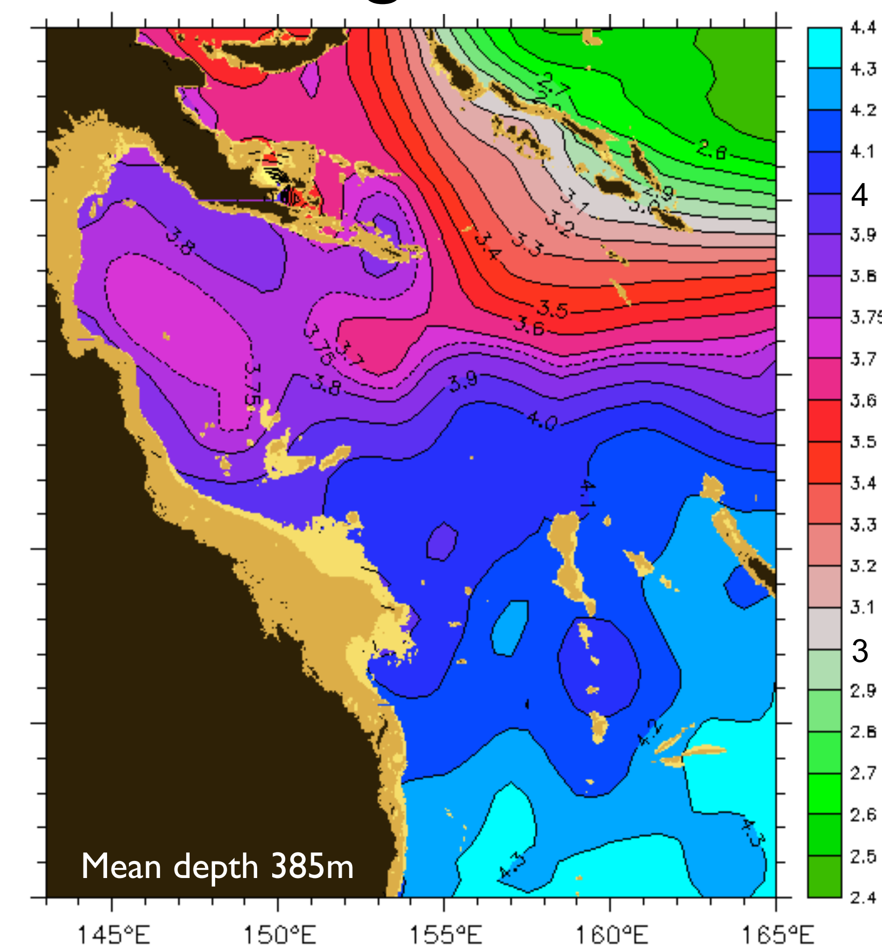
## On sigma 24.5




Low-$O_2$ SEC water

- flows south in the EAC
- fills the Solomon Sea
- High-$O_2$ southern water blocked in the Coral Sea

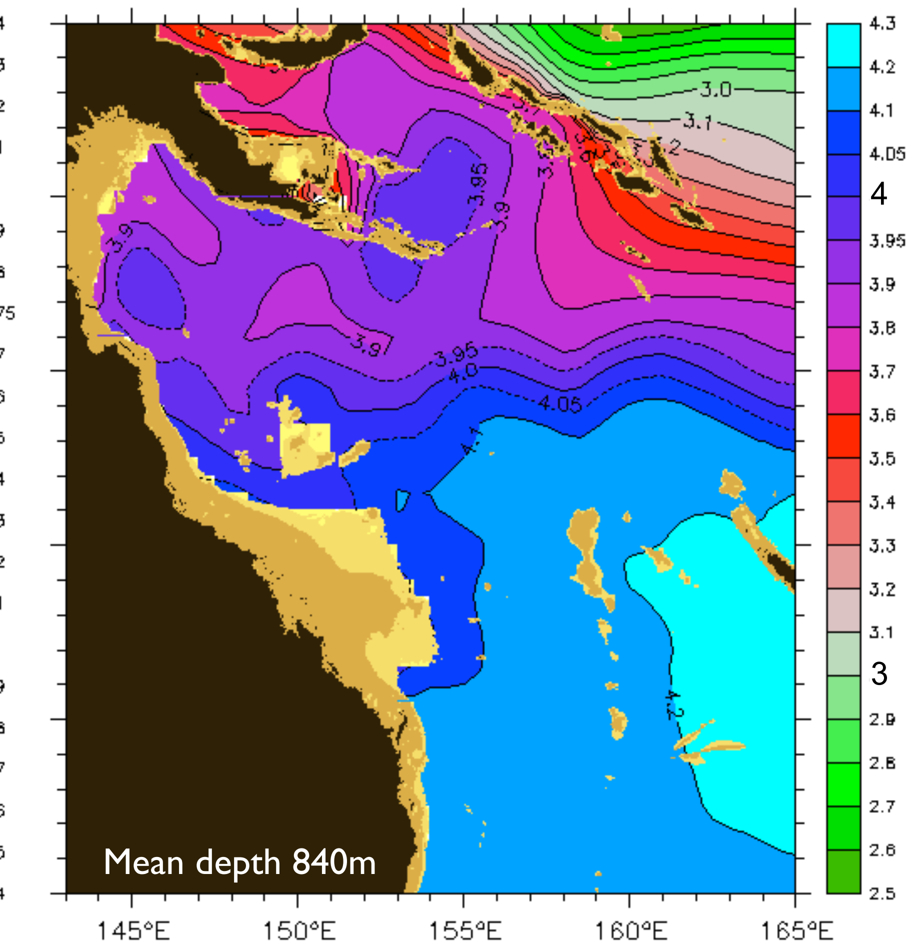
## On sigma 26.5




High-$O_2$ NCJ water

- flows north in the WBC
- joins with Low-$O_2$ SEC water in the Solomon Sea

## On sigma 27.2

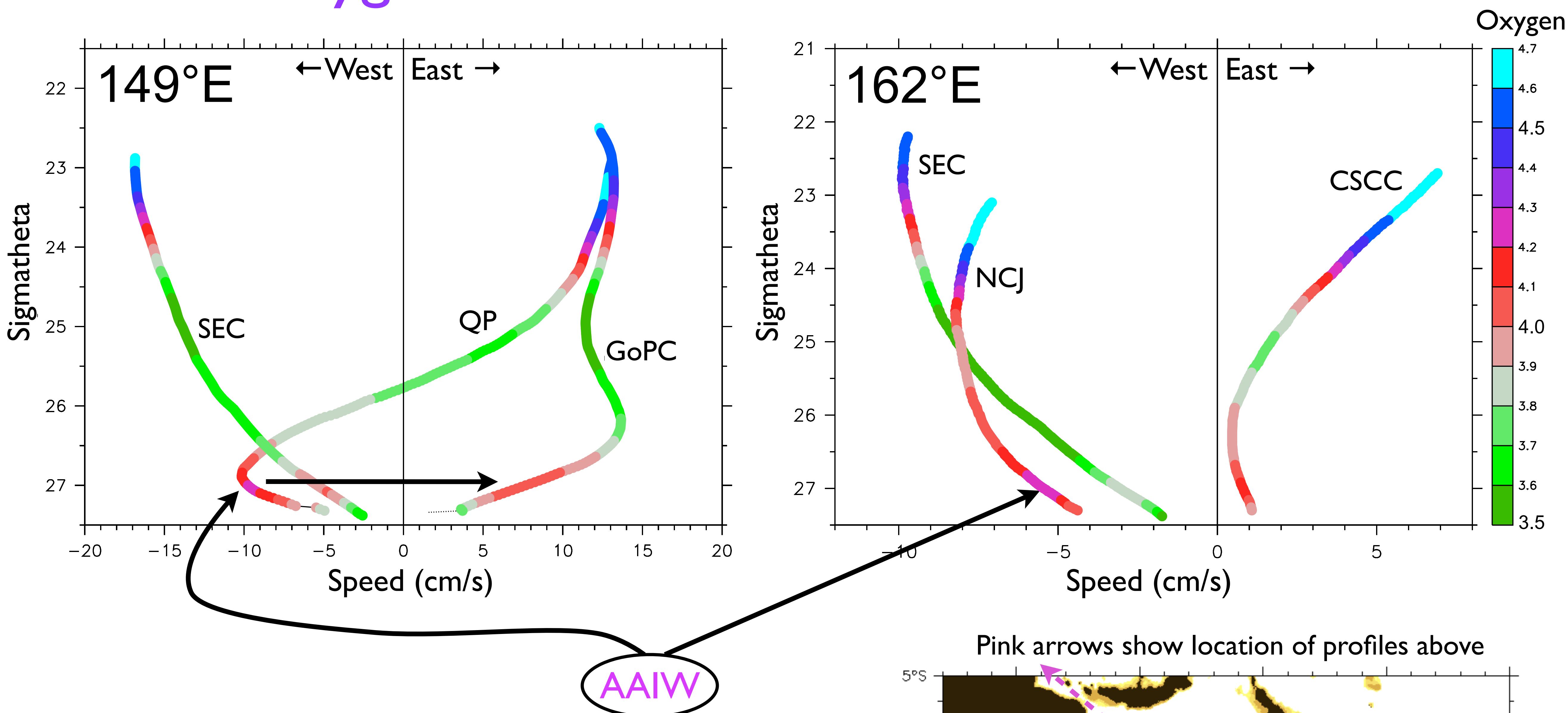



High-$O_2$ AAIW

- fills the Coral Sea from the southeast
- fills the Solomon Sea

CARS gridded T, S, $O_2$
Bathymetry shown where it is shallower than the isopycnal (0,100,500,1000m)

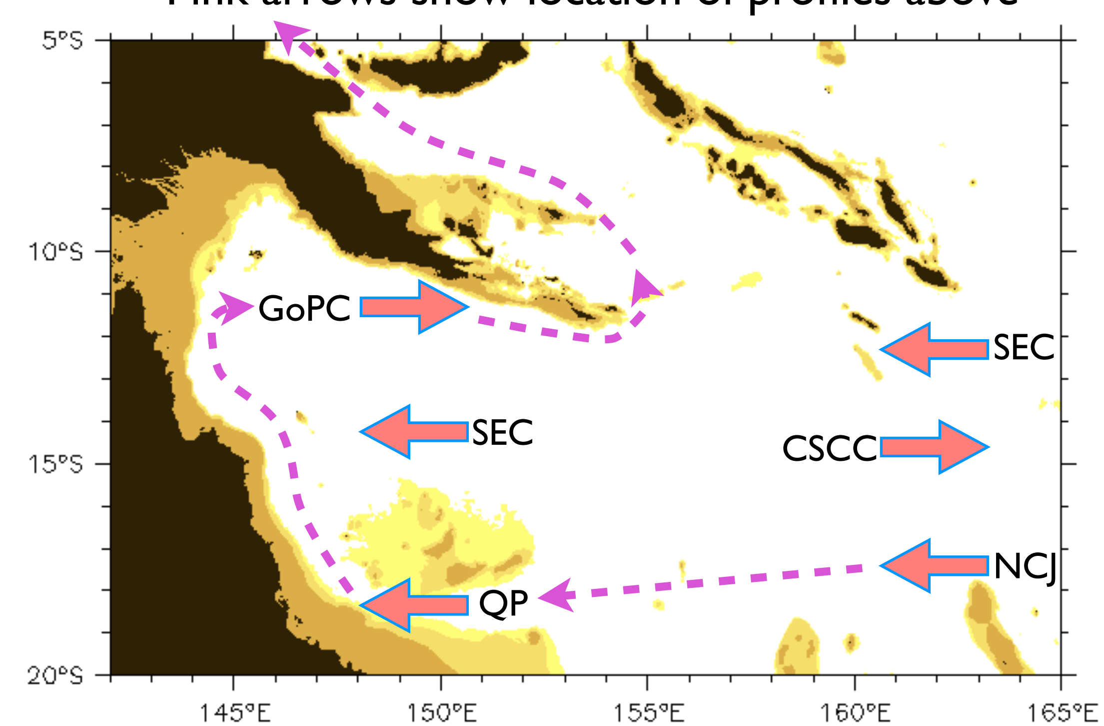
# Oxygen as a tracer of Coral Sea currents



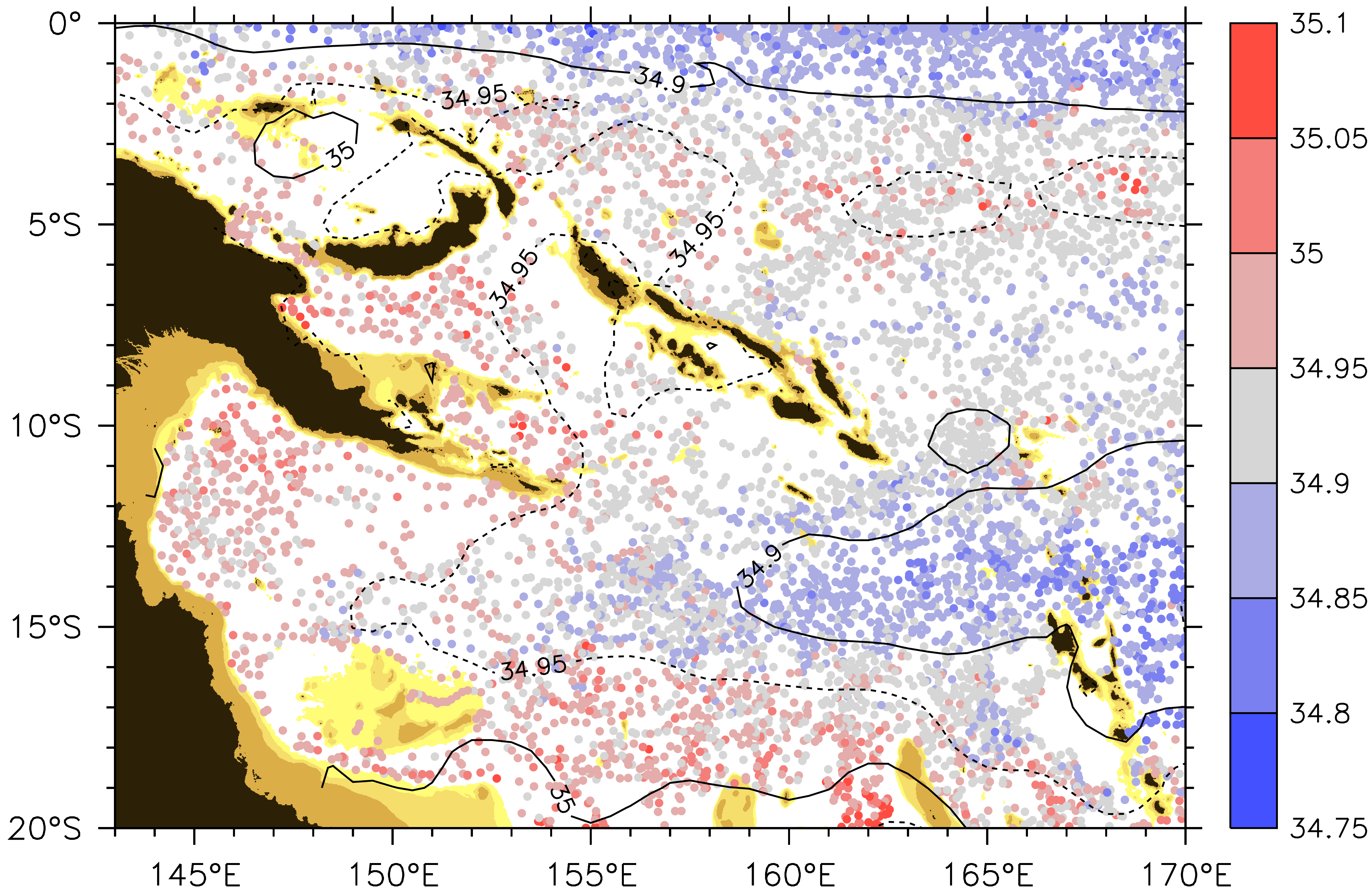

High-$O_2$ AAIW enters the Coral Sea mainly via the NCJ, then is carried in the WBC to the Solomon Sea.

(Then through Vitiaz St to the NW Pacific: Qu et al., JPO '99).

Pink arrows show location of profiles above



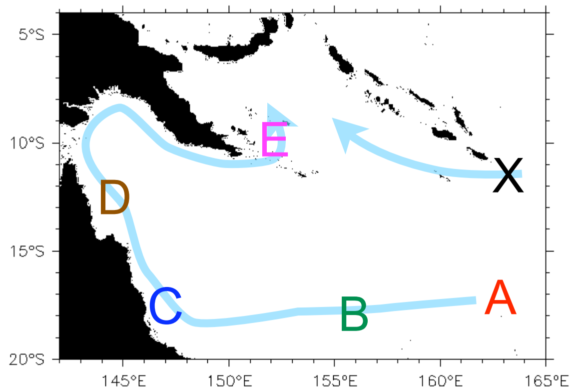
# Argo salinity on sigmatheta 26.5



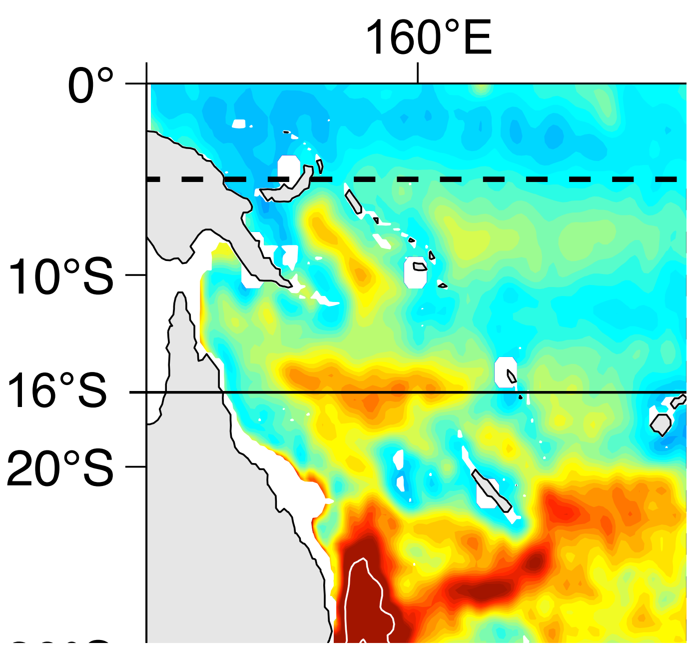

Mean(Argo) = 34.925 RMS = 0.141

Overlay CARS 09 contours
Bathymetry: 100, 500, 1000m

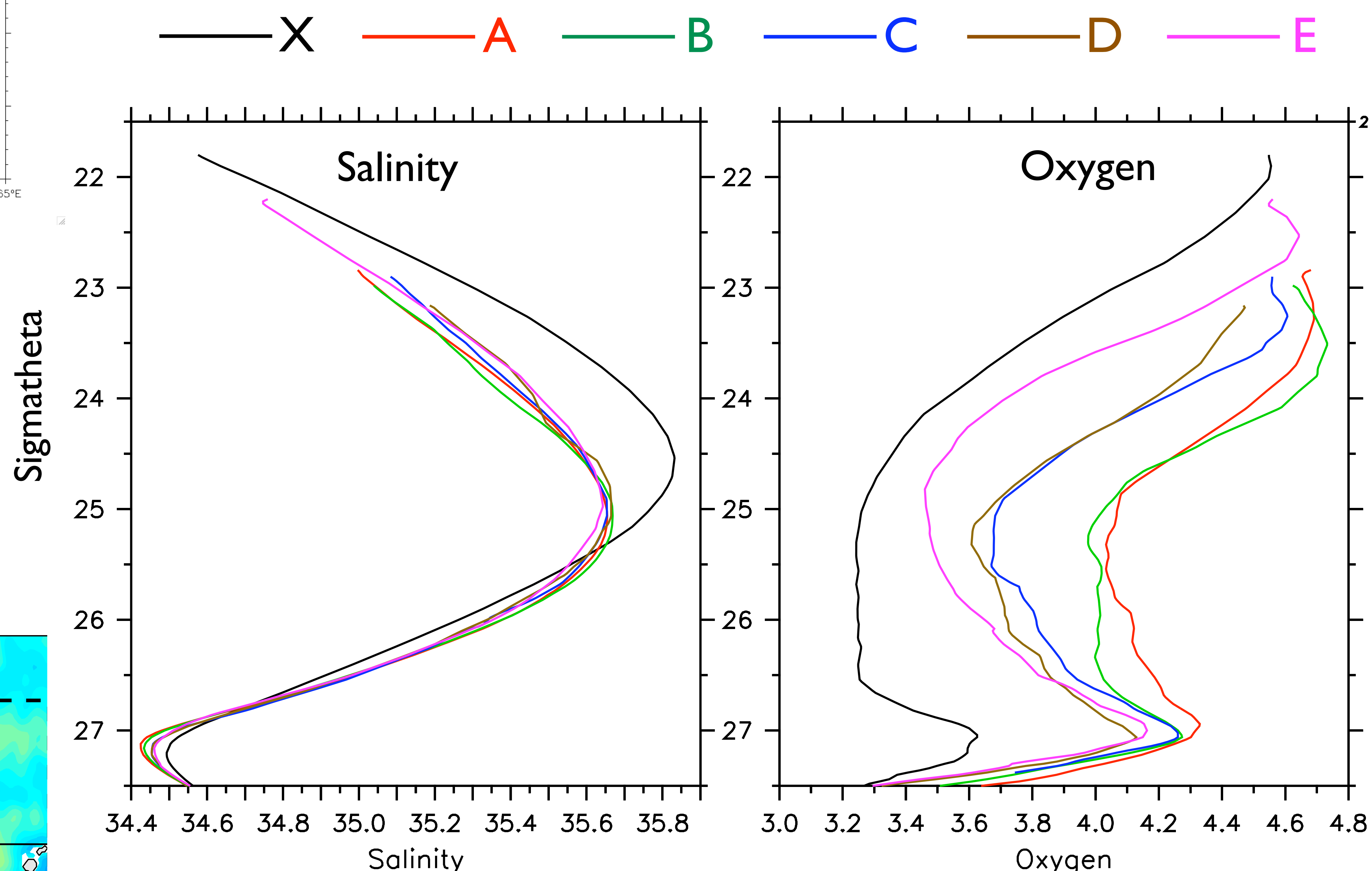
# Where does the mixing happen?




Eddies generated along 16°S due to shear between the NCJ and CSCC. (Qiu et al 2009)



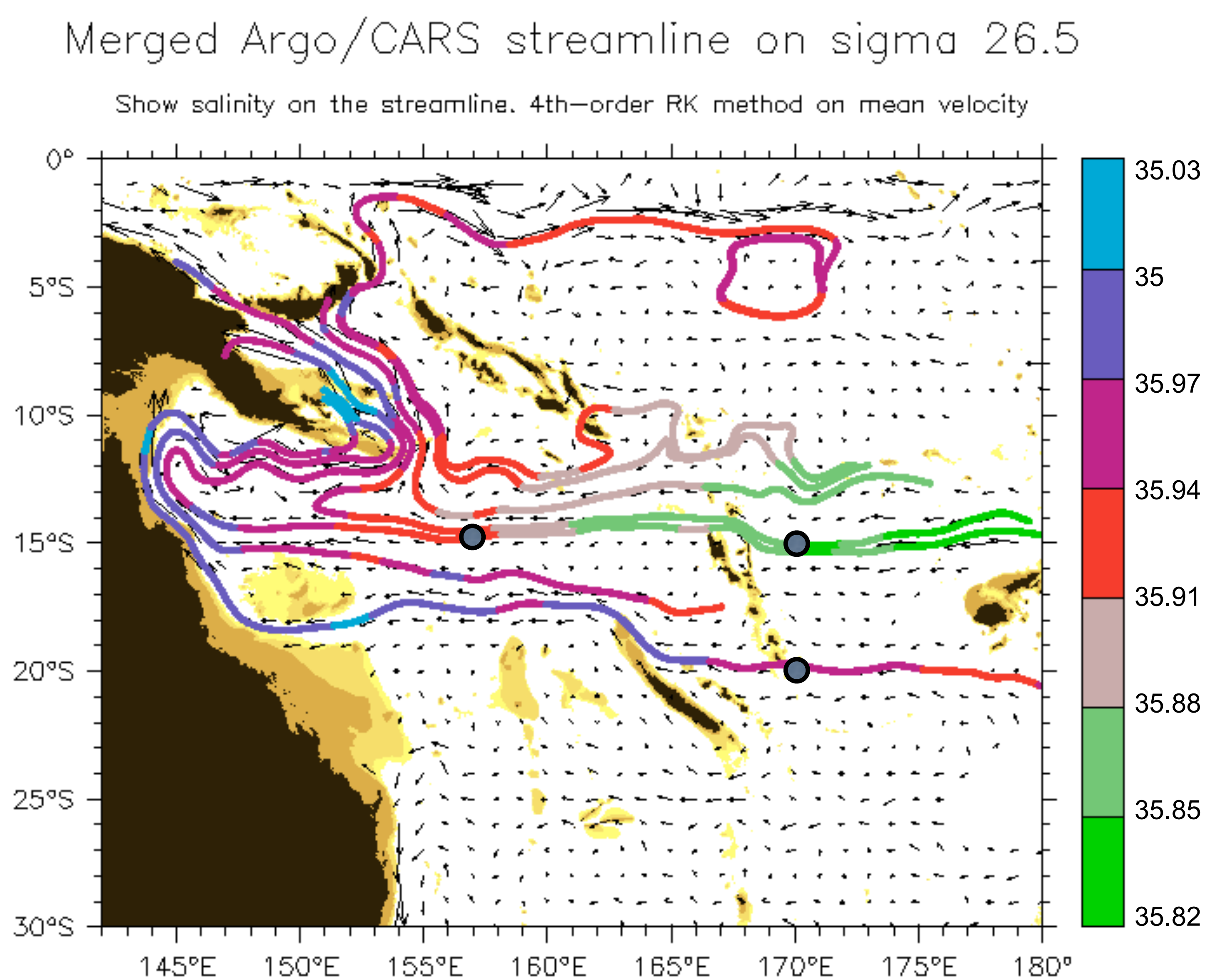

RMS amplitude of high-pass-filtered SSH from weekly AVISO data.



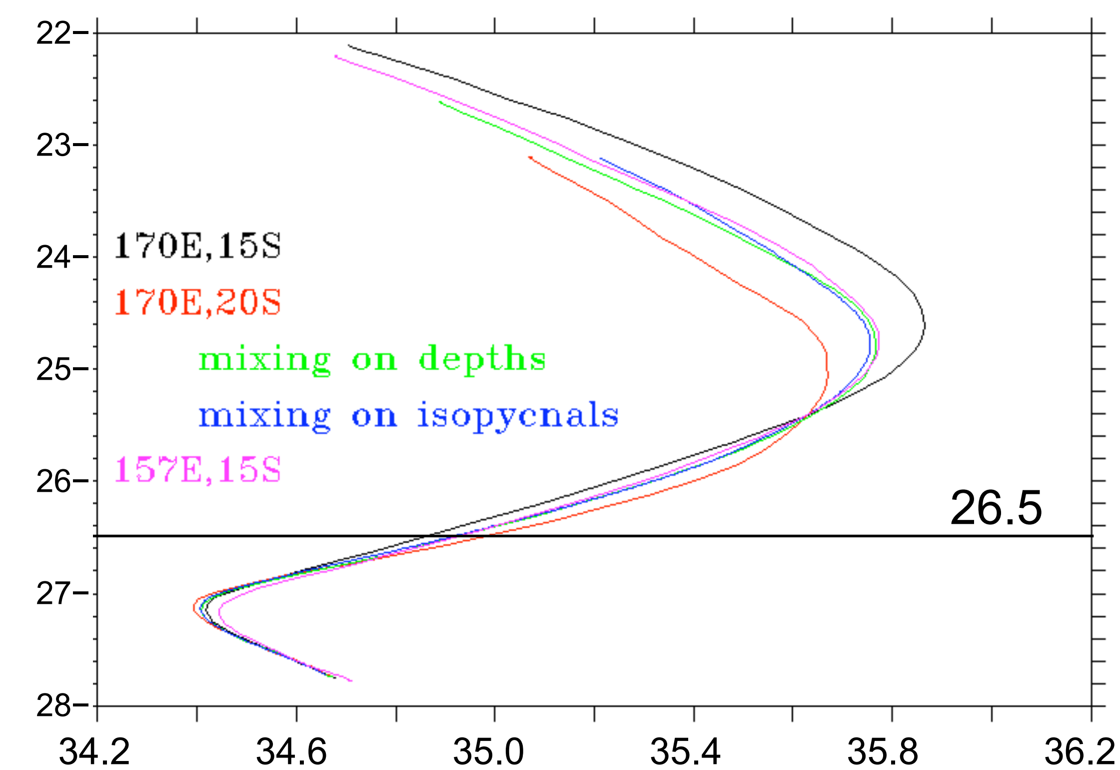

Progressive erosion of $O_2$ max along pathway A→B→C→D→E (west along 18°S, then around the western boundary)
Point X (SEC) is completely different.

# Mixing between the low-S SEC and high-S NCJ?

Eddies in the CSCC along 16-17°S, west of Vanuatu




CARS salinity vs sigmatheta: estimate end-member from mixing



# Tilted gyre: the zonal current “input” is sheared

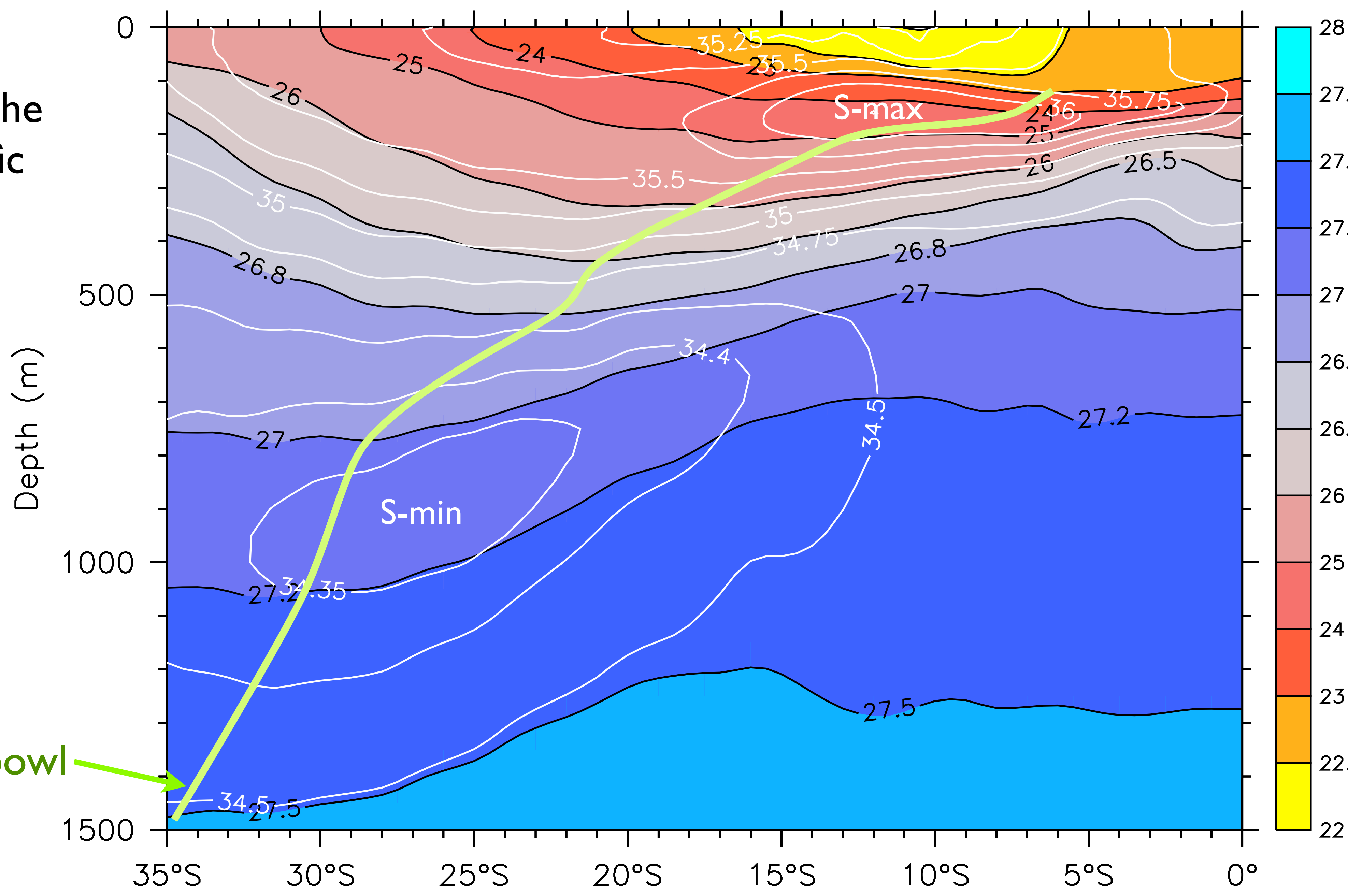
S-max formed at the surface in SE Pacific

S-min is ~ AAIW

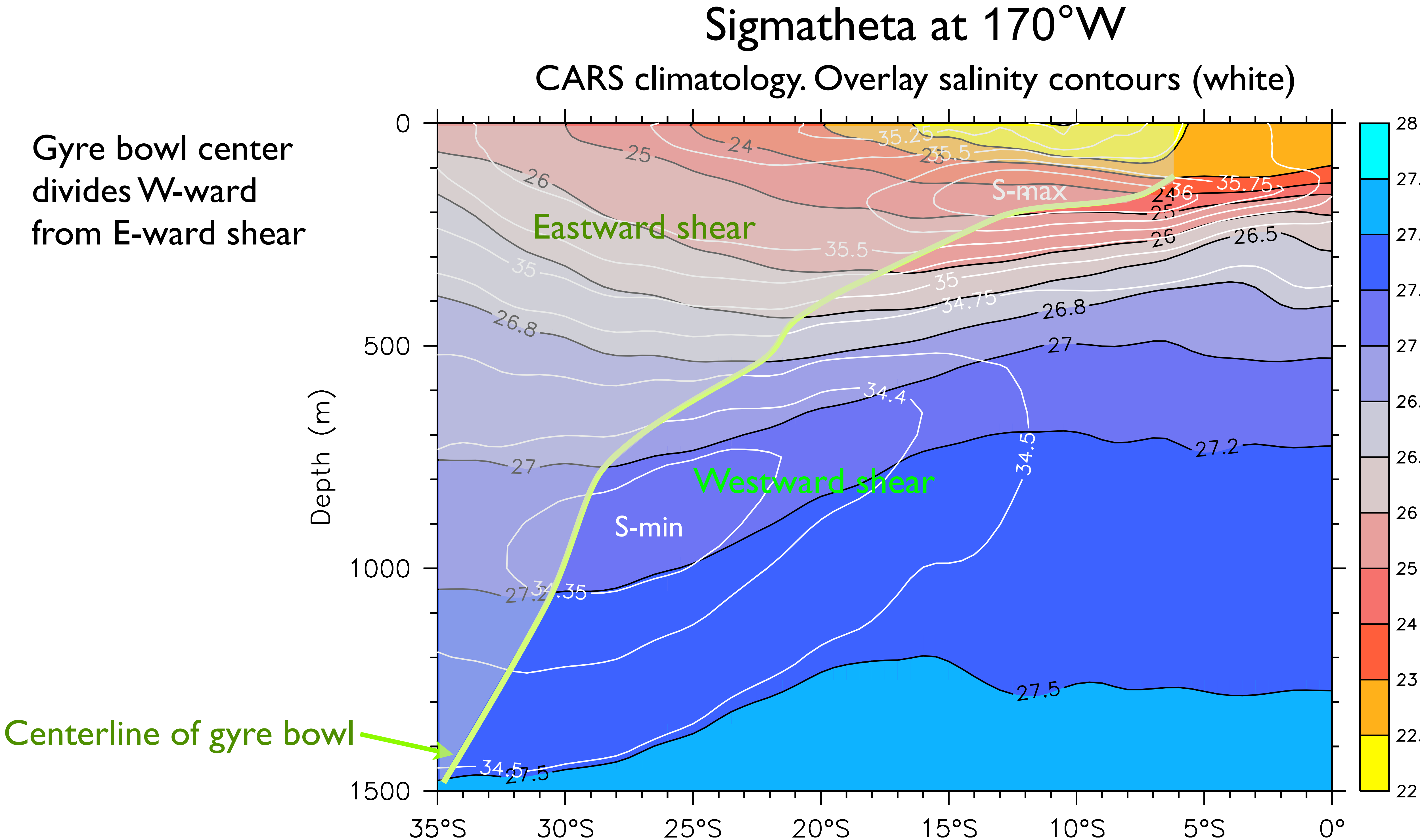
Centerline of gyre bowl

## Sigmatheta at 170°W

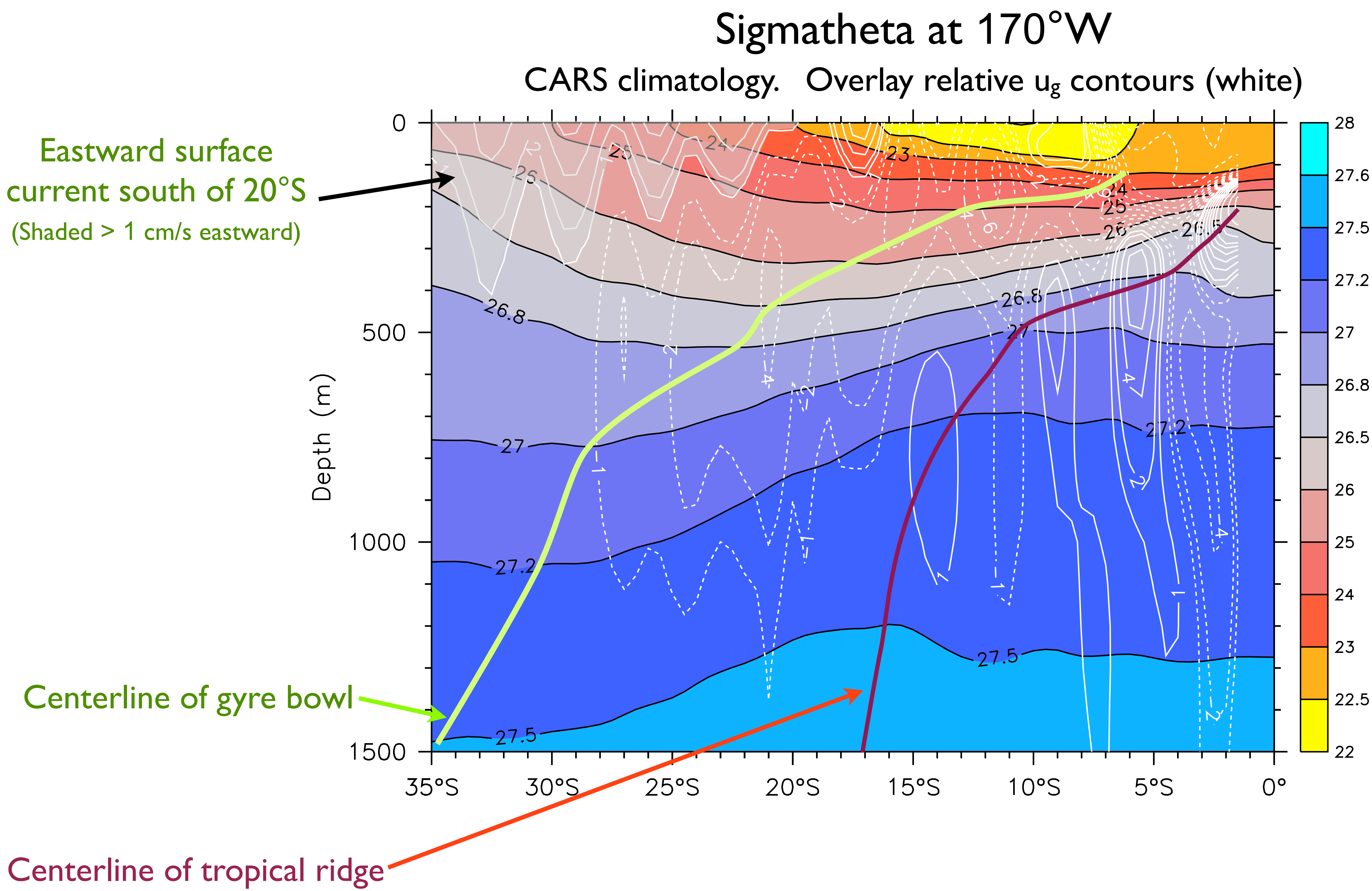
CARS climatology. Overlay salinity contours (white)



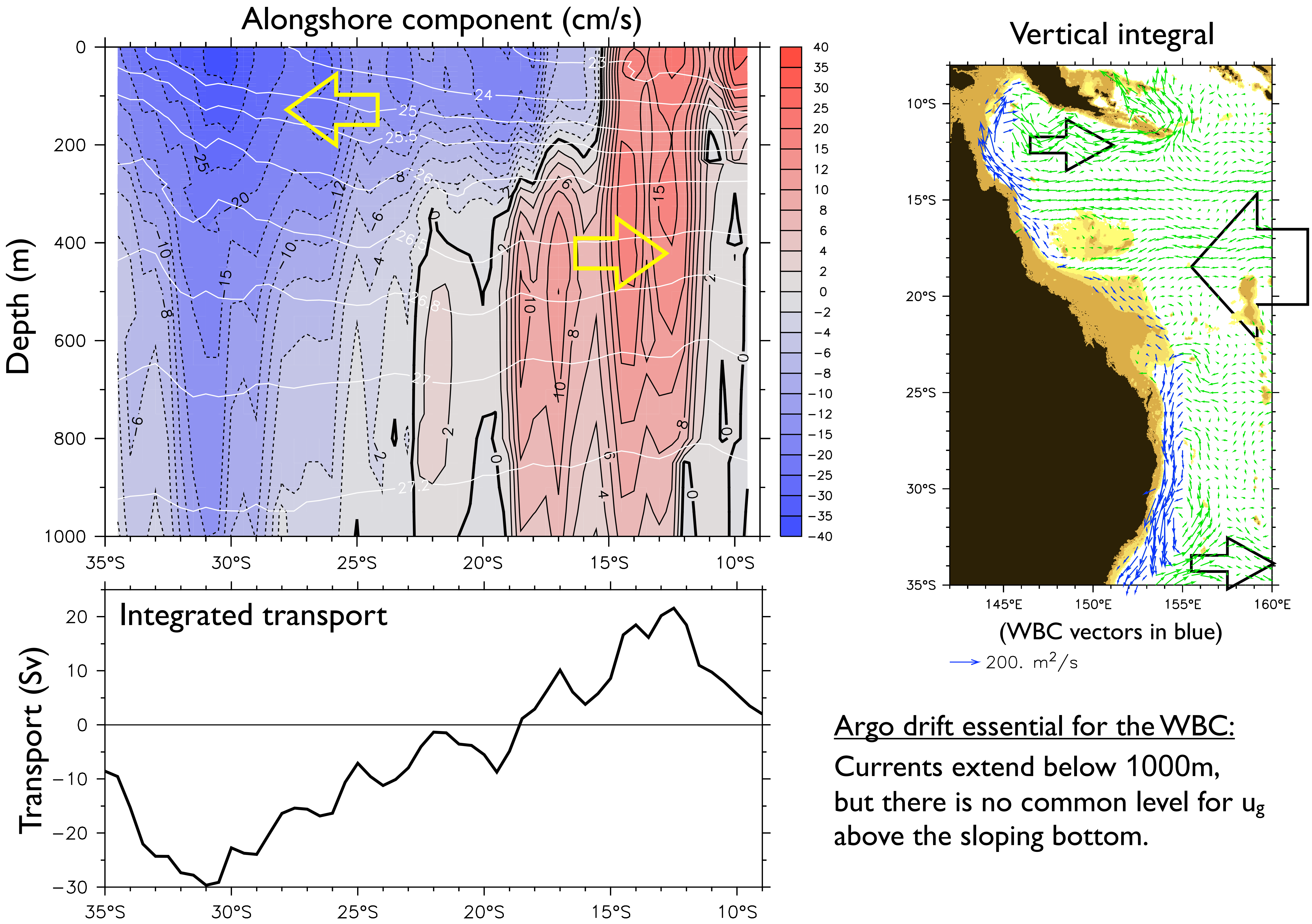
# Tilted gyre: the zonal current "input" is sheared



# Tilted gyre: the zonal current "input" is sheared



# Australian coastal western boundary current




Argo drift essential for the WBC:

Currents extend below 1000m, but there is no common level for $u_g$ above the sloping bottom.

# Conclude ... with questions not answers

Argo trajectories are (potentially) an excellent source of information on the mid-depth circulation.

Using these velocities to reference geostrophy gets us closer to absolute velocities.

Better documentation would improve this resource.

Why does the South Pacific support these very thick jets?

EAC recirculation gyre producing thick mode water?

What is the implication for the interocean circulation (Indonesian Throughflow)?

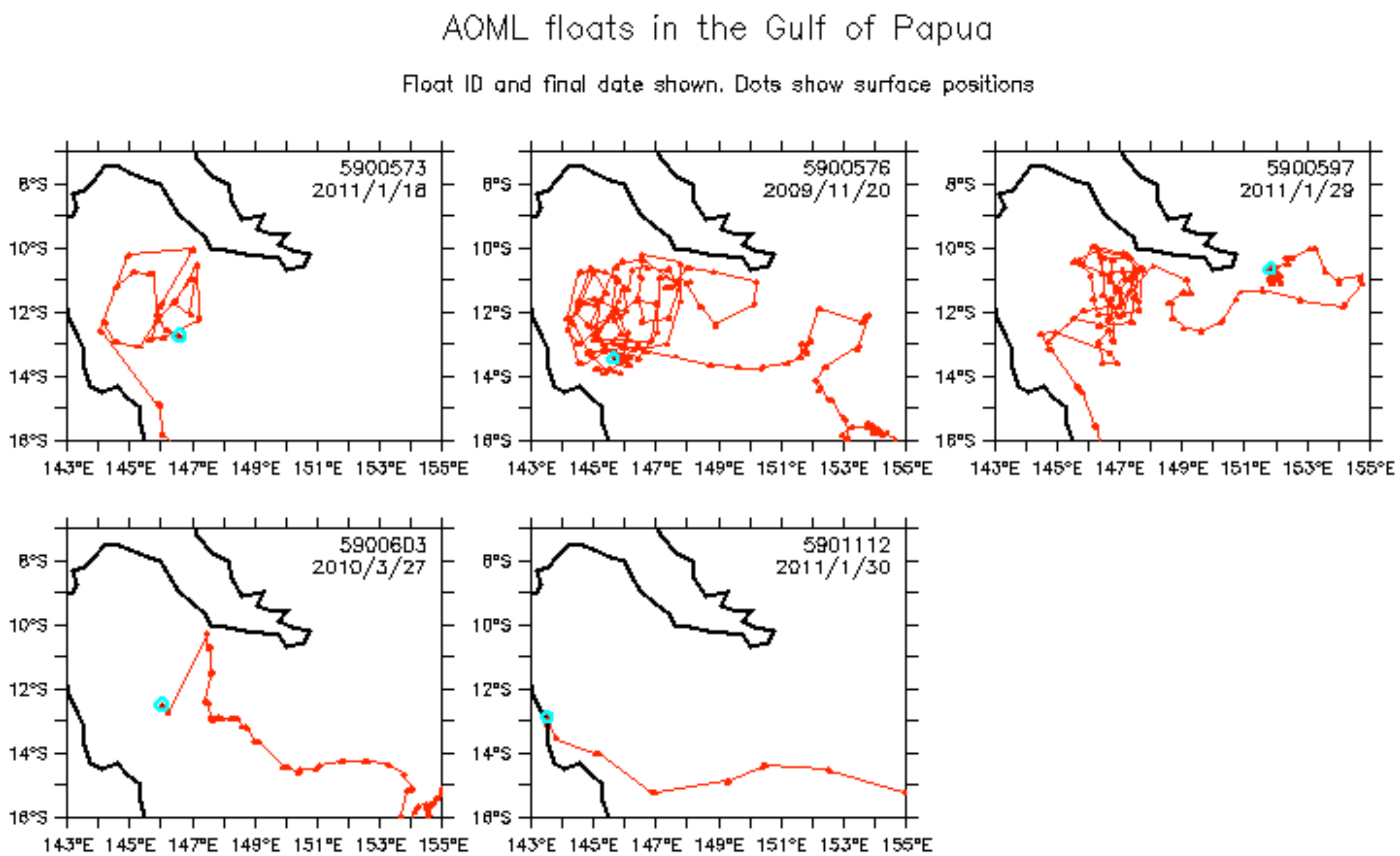
Where is the mixing that produces the characteristics of mid-depth (high-$O_2$) water entering the N. Pacific?

What is the mechanism?

Coral Sea eddies? Or is it mostly on the western boundary?

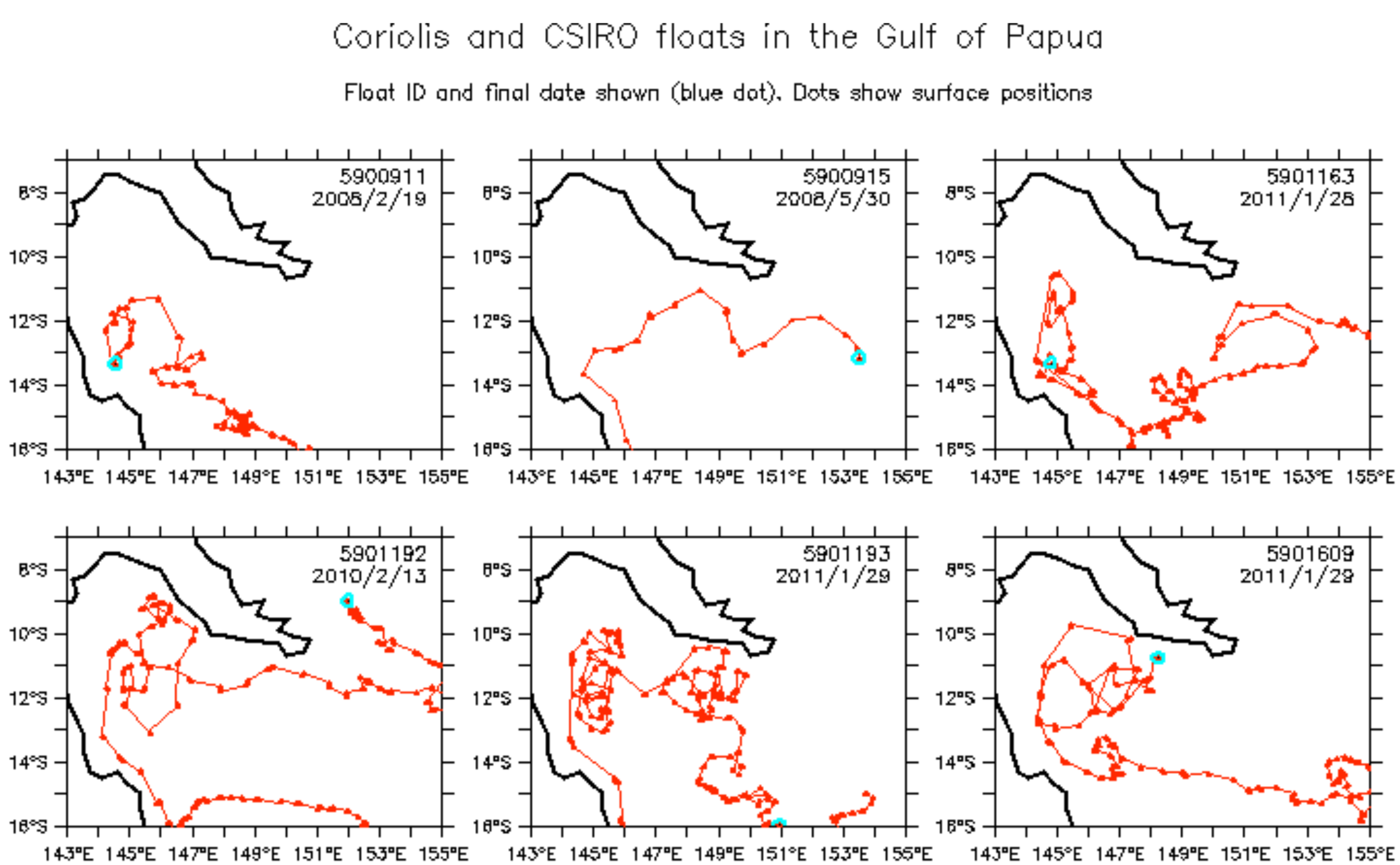
# Extra figures follow

# Persistent eddy in the Gulf of Papua

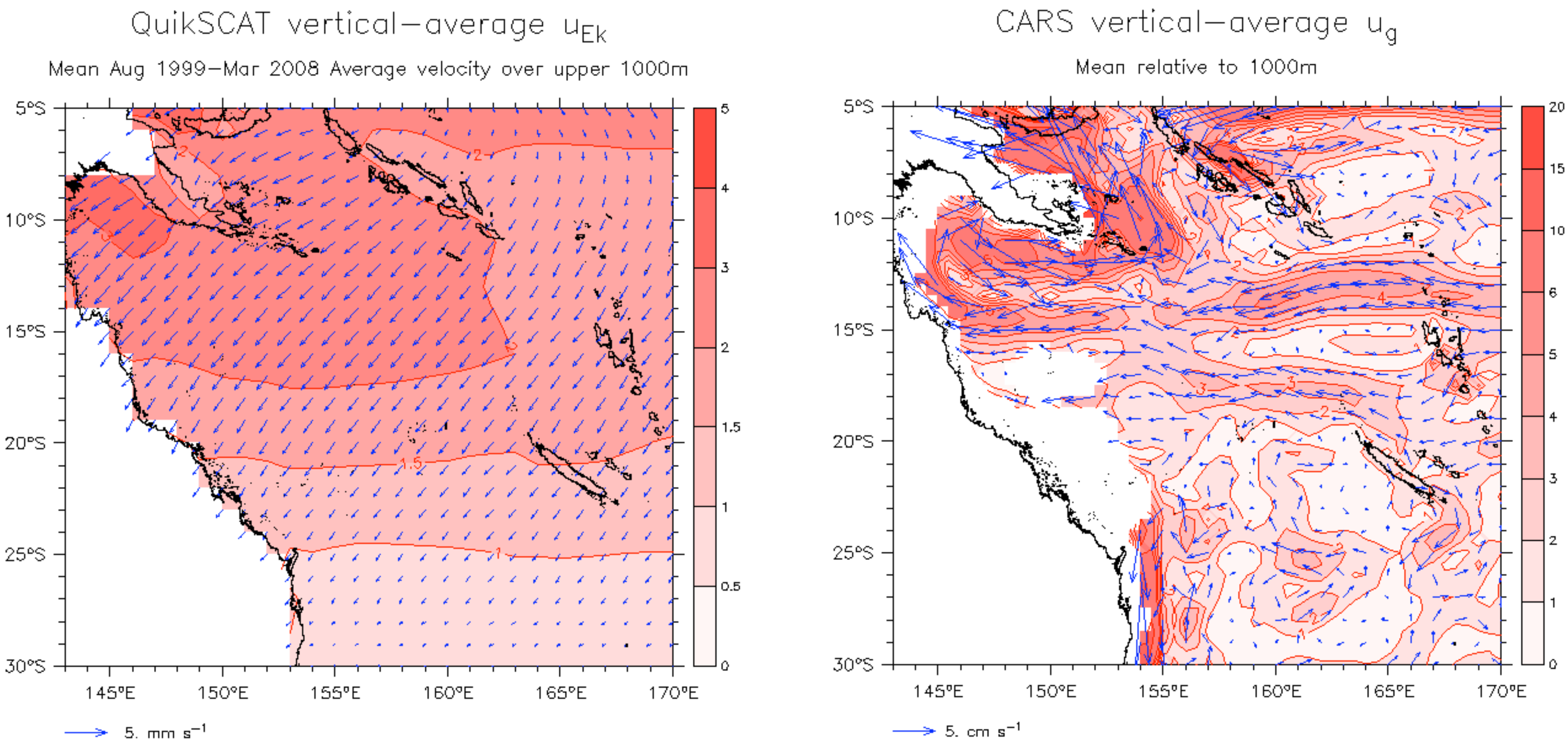



Floats often drift rapidly westward, then northward in the WBC,

but then circulate around the Gulf of Papua for many months.



# Account for these in computing the drift?




16 hours average time in unsampled surface drift (4 hours) plus ascent plus descent (12 hours).

⇒ about 1/14 of the time at parking depth.

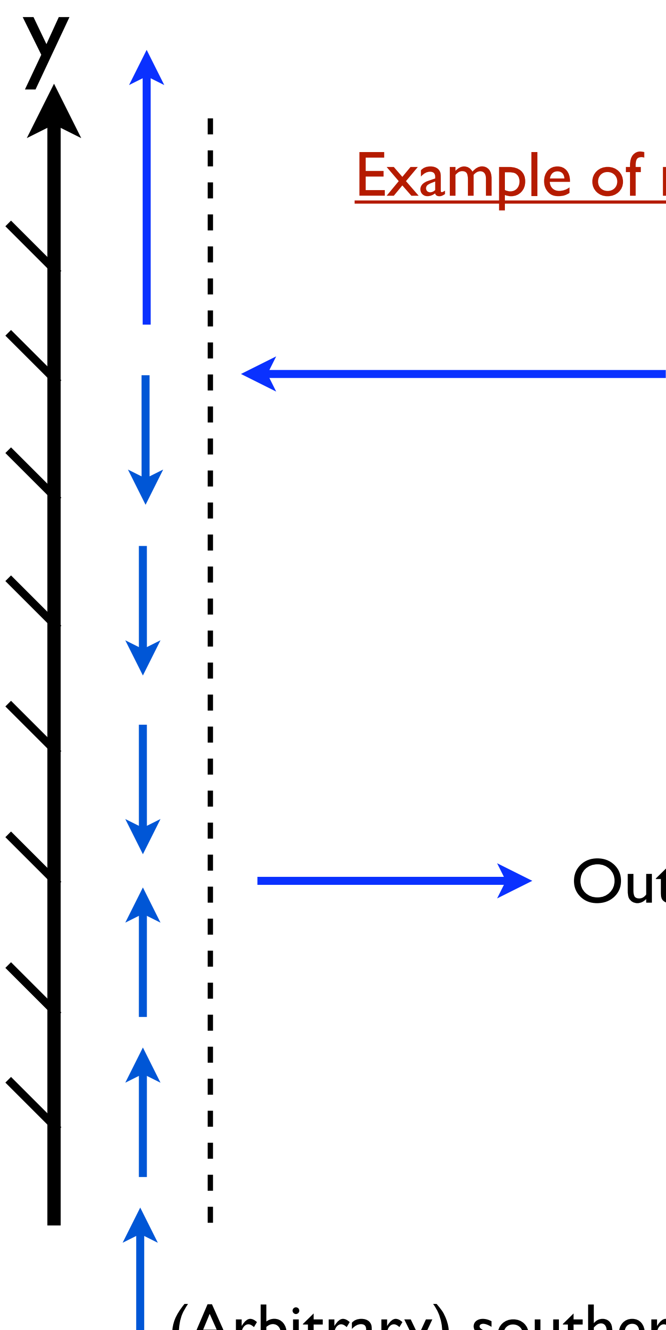
Mean Ekman drift is negligible (might not be in particular times).

Mean geostrophic shear is about 10 times larger (i.e., comparable to the drift velocity), but acts over only 15th of the cycle.

# Conserve mass in western boundary layer.
# → WBC is equatorward integral of incoming/outgoing transport.

$$WBC(y) = WBC(y_s) - \int_{y_s}^{y} u_g dy'$$

The WBC integrates the incoming zonal transport equatorward (because information travels equatorward on a western boundary). Need a southern boundary condition: $WBC(y_s)$.
..... a la Godfrey (1975)




Example of method:

Incoming zonal transport $(u < 0)$

Incoming zonal transport
→ Eq-ward WBC tendency

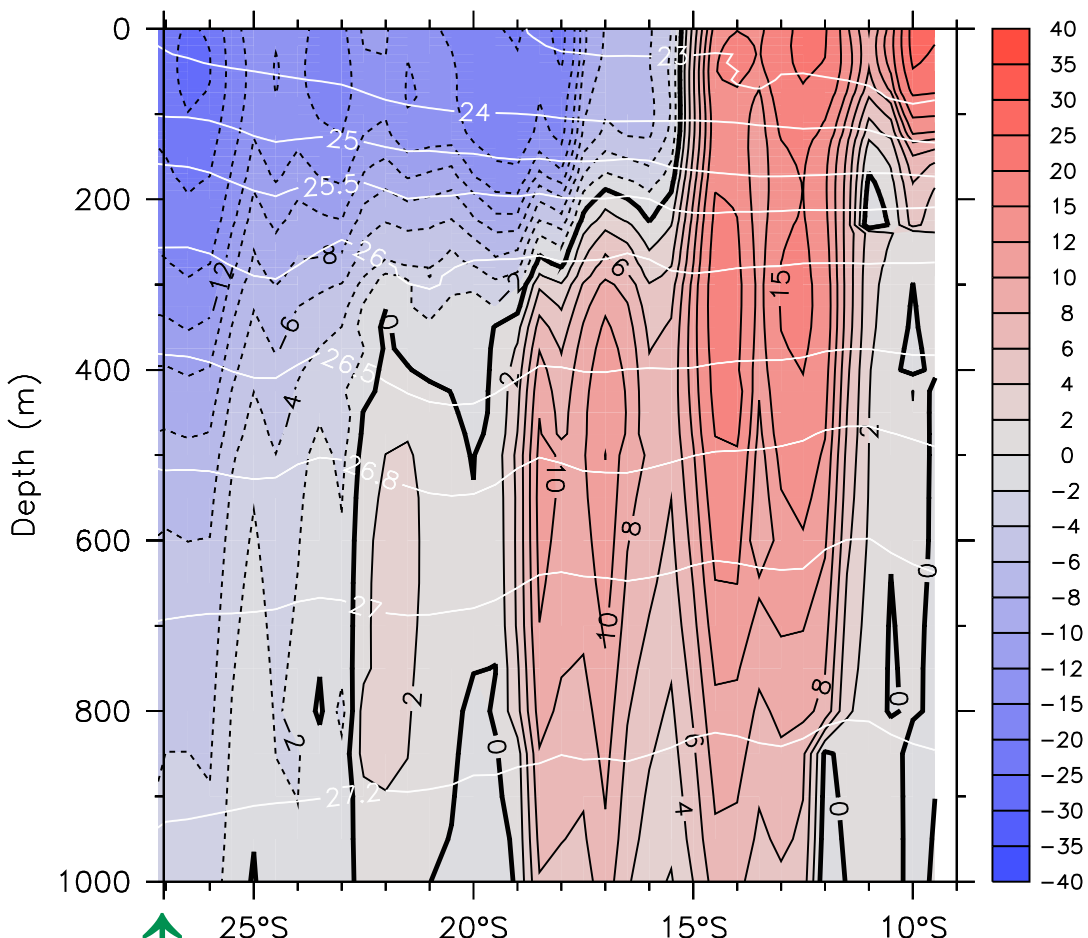
Outgoing zonal transport $(u > 0)$

Outgoing zonal transport
→ poleward WBC tendency

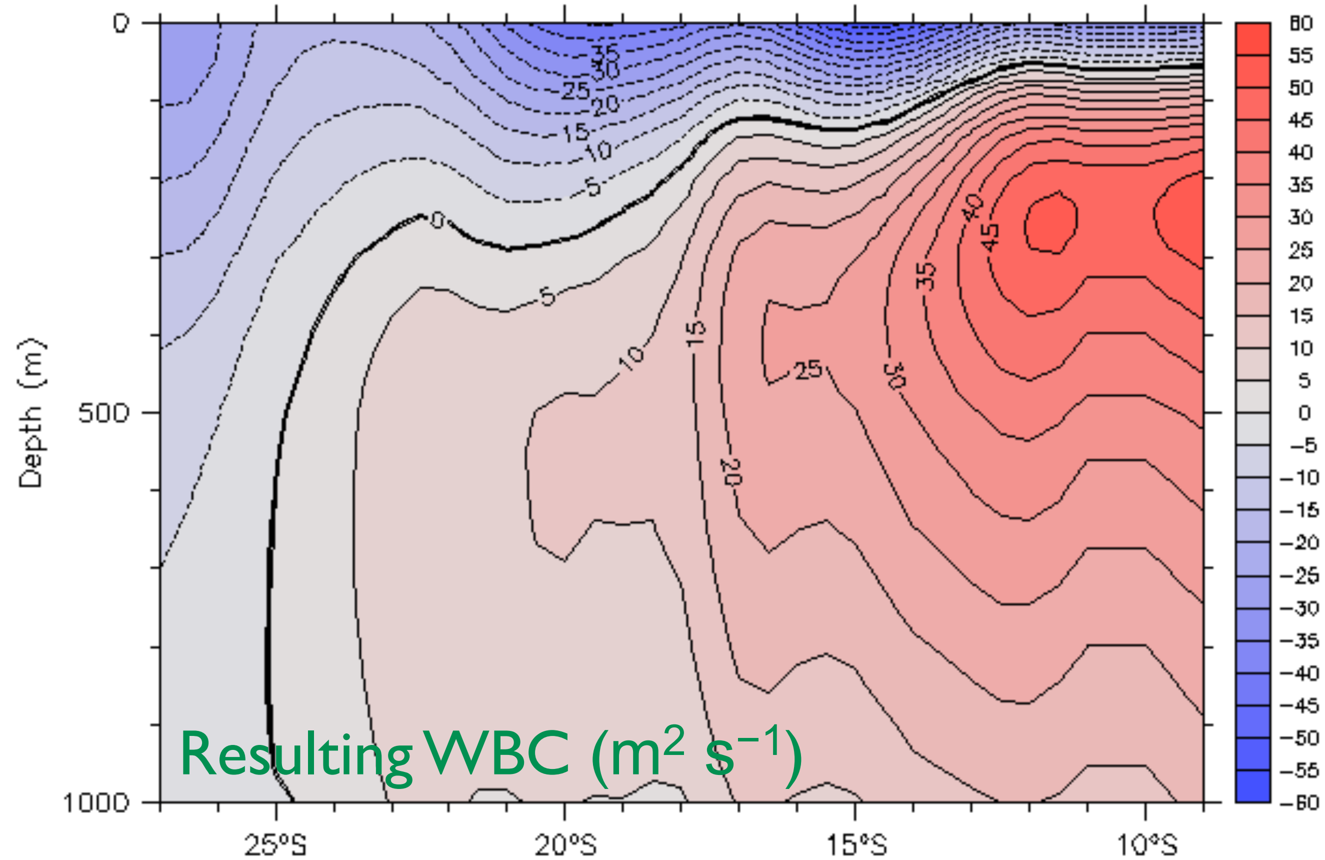
(Arbitrary) southern boundary condition ($WBC(y_s)$)

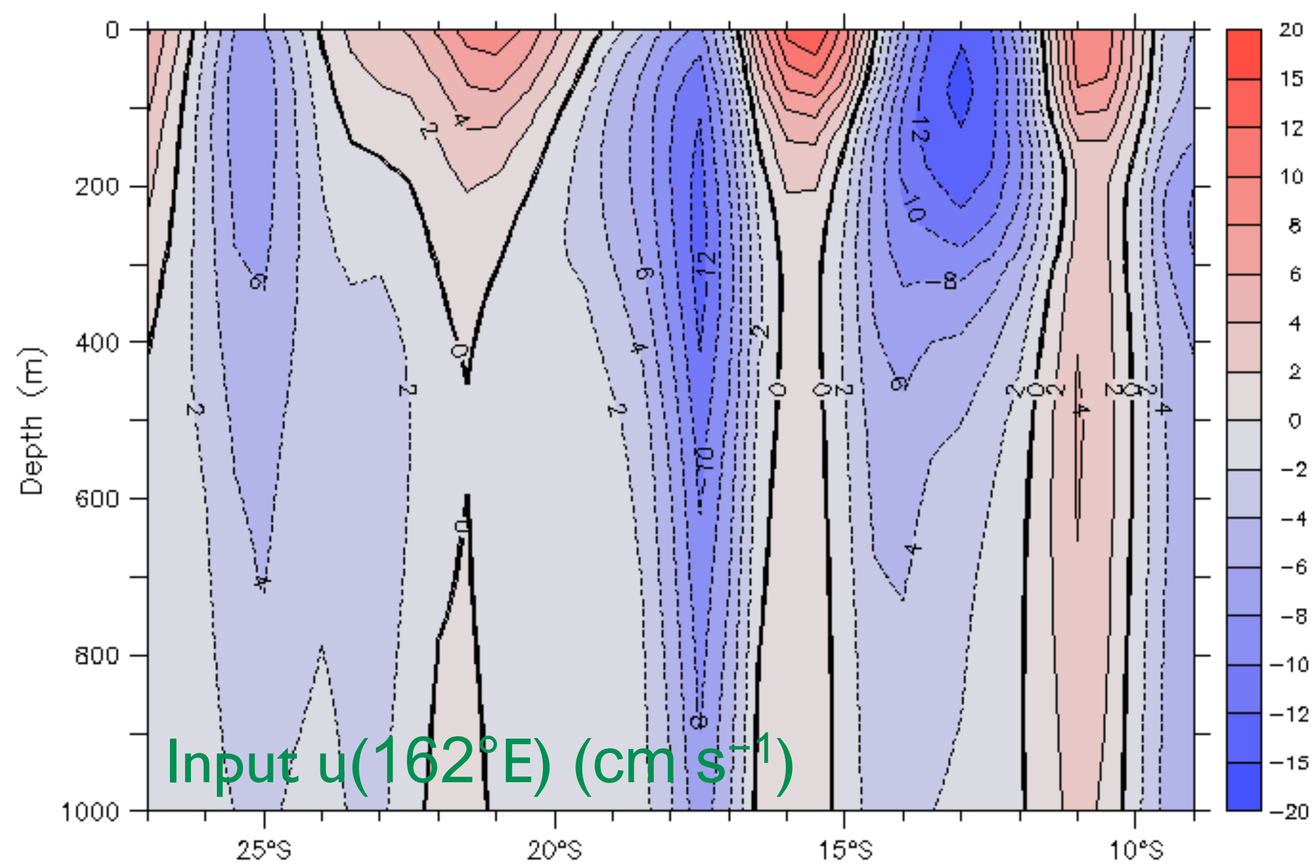
# The tilted gyre implies a tilted WBC bifurcation

## Observed WBC




Use v(27°S) as $v_s$



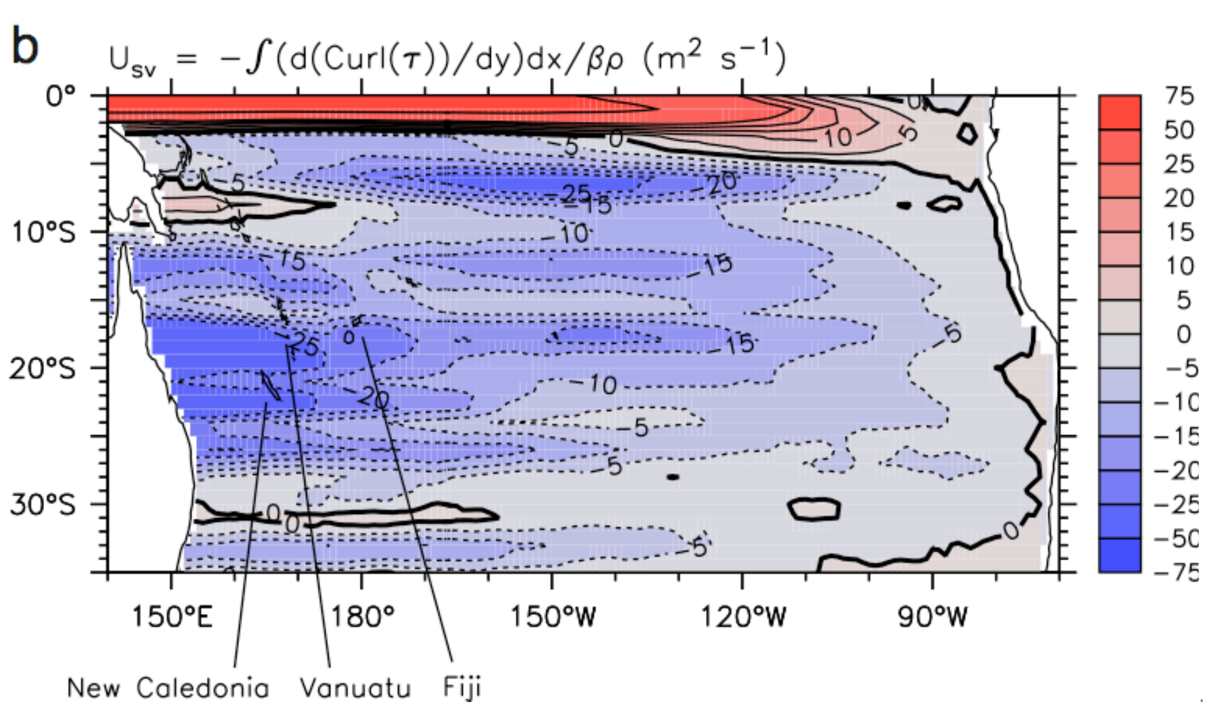
# Multiple Tsuchiya Jets?

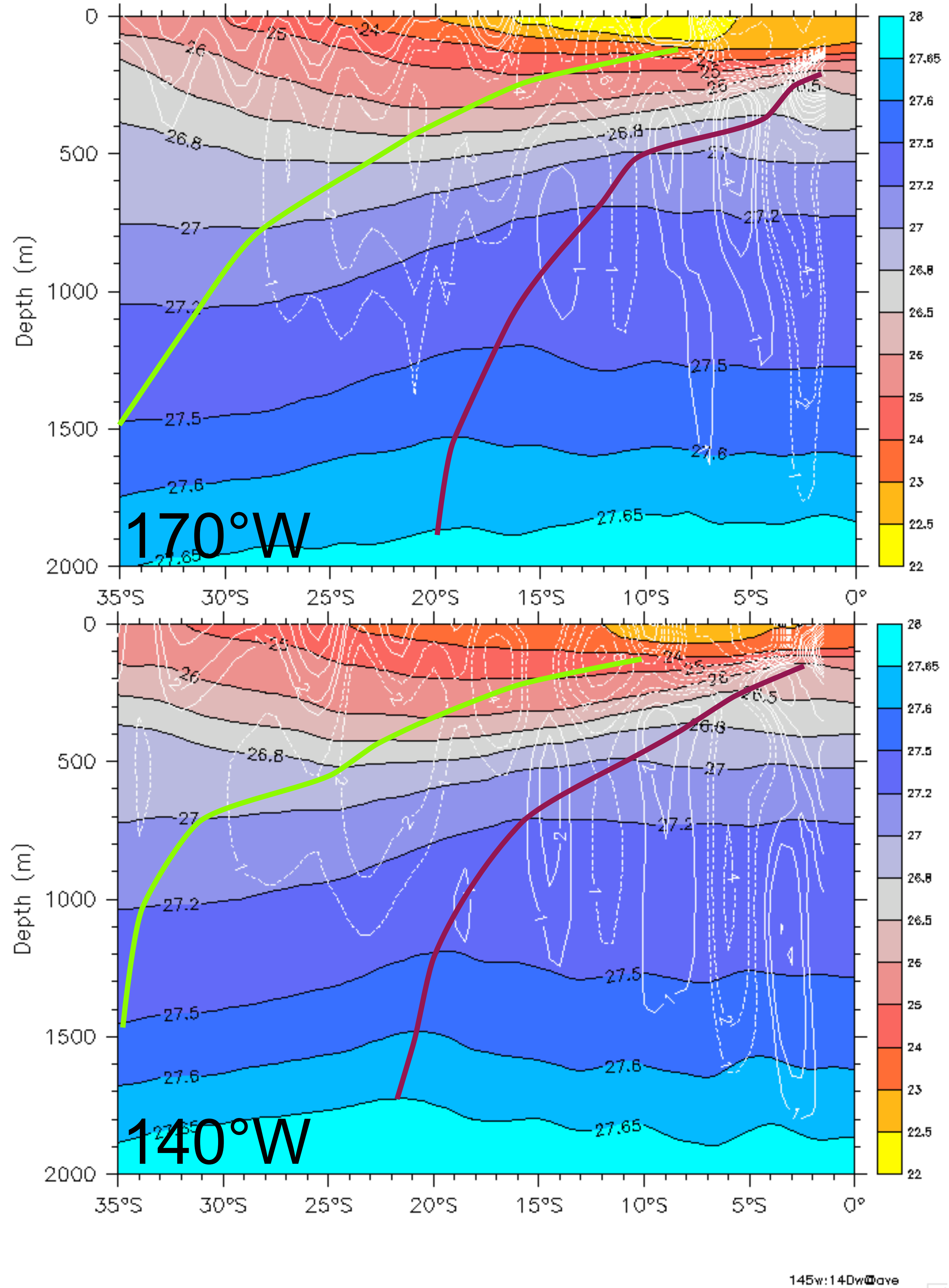
The subtropical gyre is tilted (no surprise), but the tropical (cyclonic) gyre is also tilted. Surprising?

The apparent multiple TJs seem to occur only in the South Pacific. Why?

They are a robust feature, seen over a wide range of longitudes, and in other data sets (Levitus, GRACE geoid).

Kessler and Gourdeau (GRL 2006) suggested that the long zonal jets are wind-driven (!). (They appear in the Sverdrup transport).



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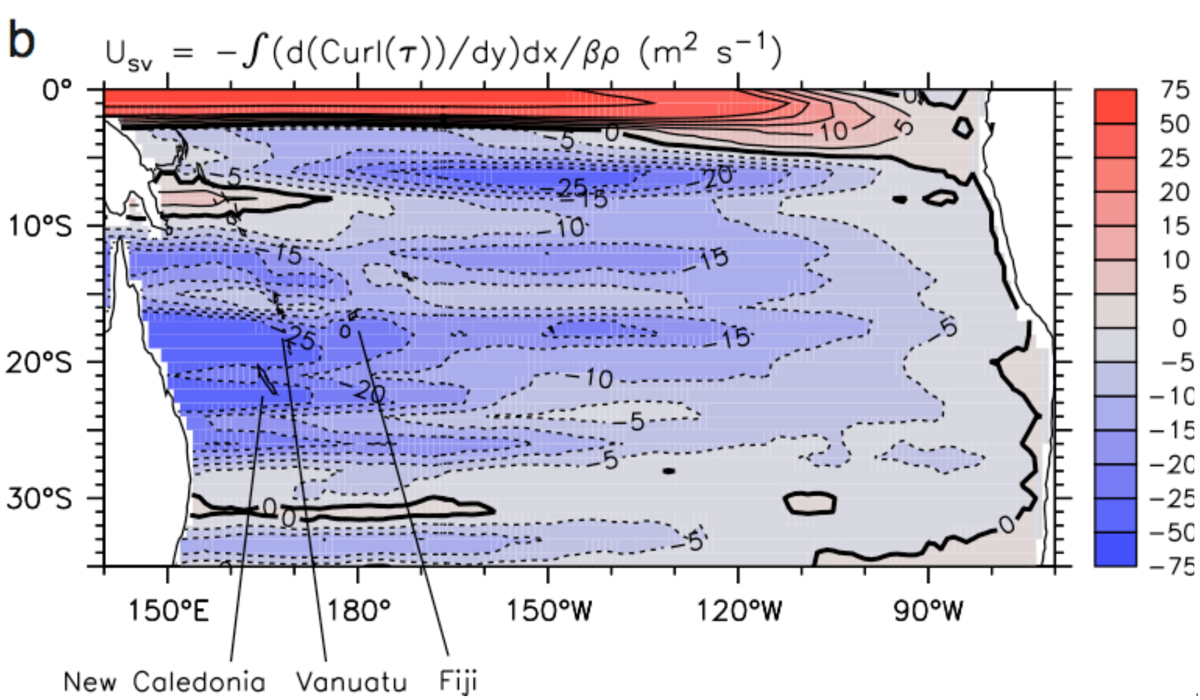
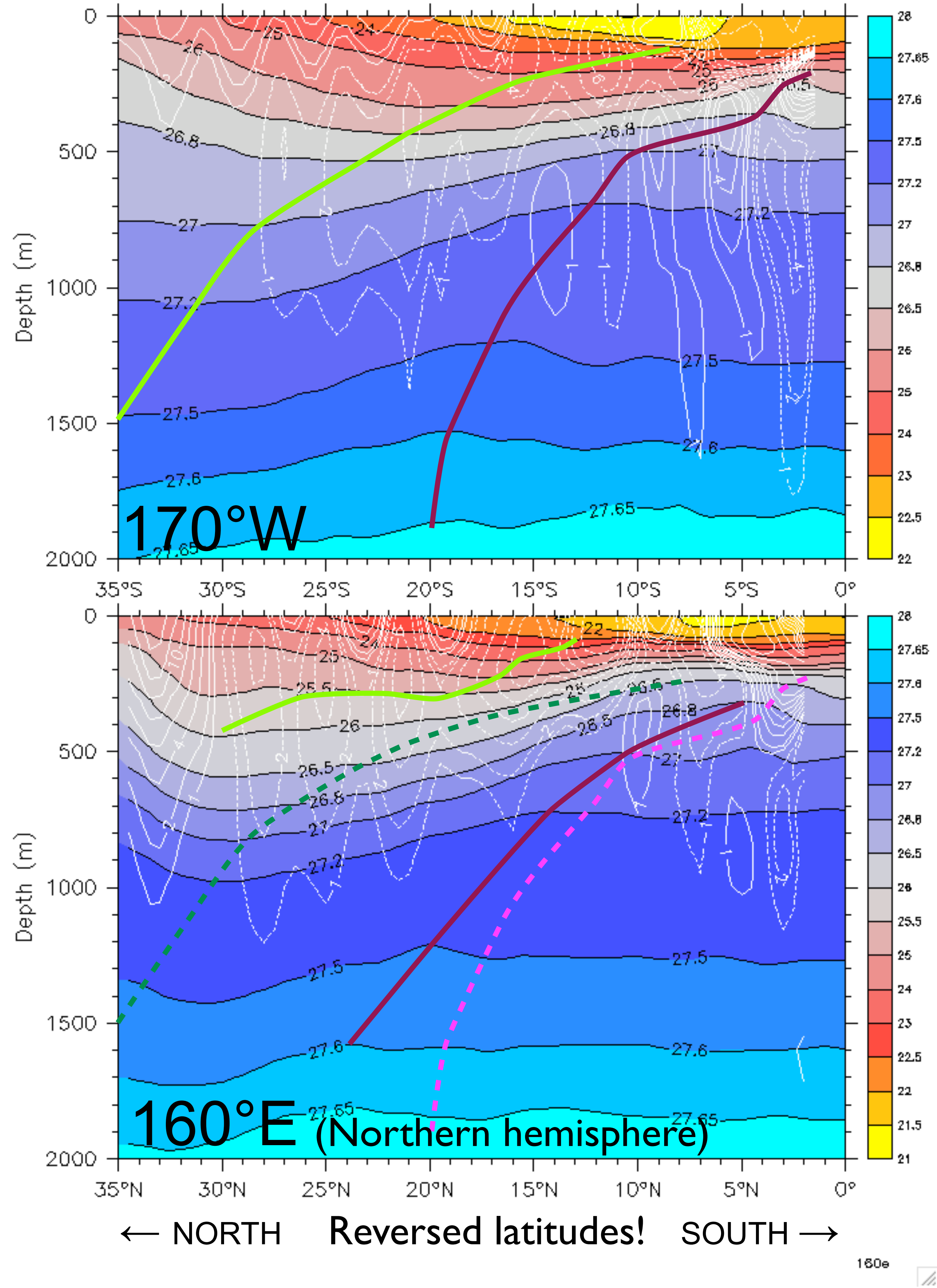
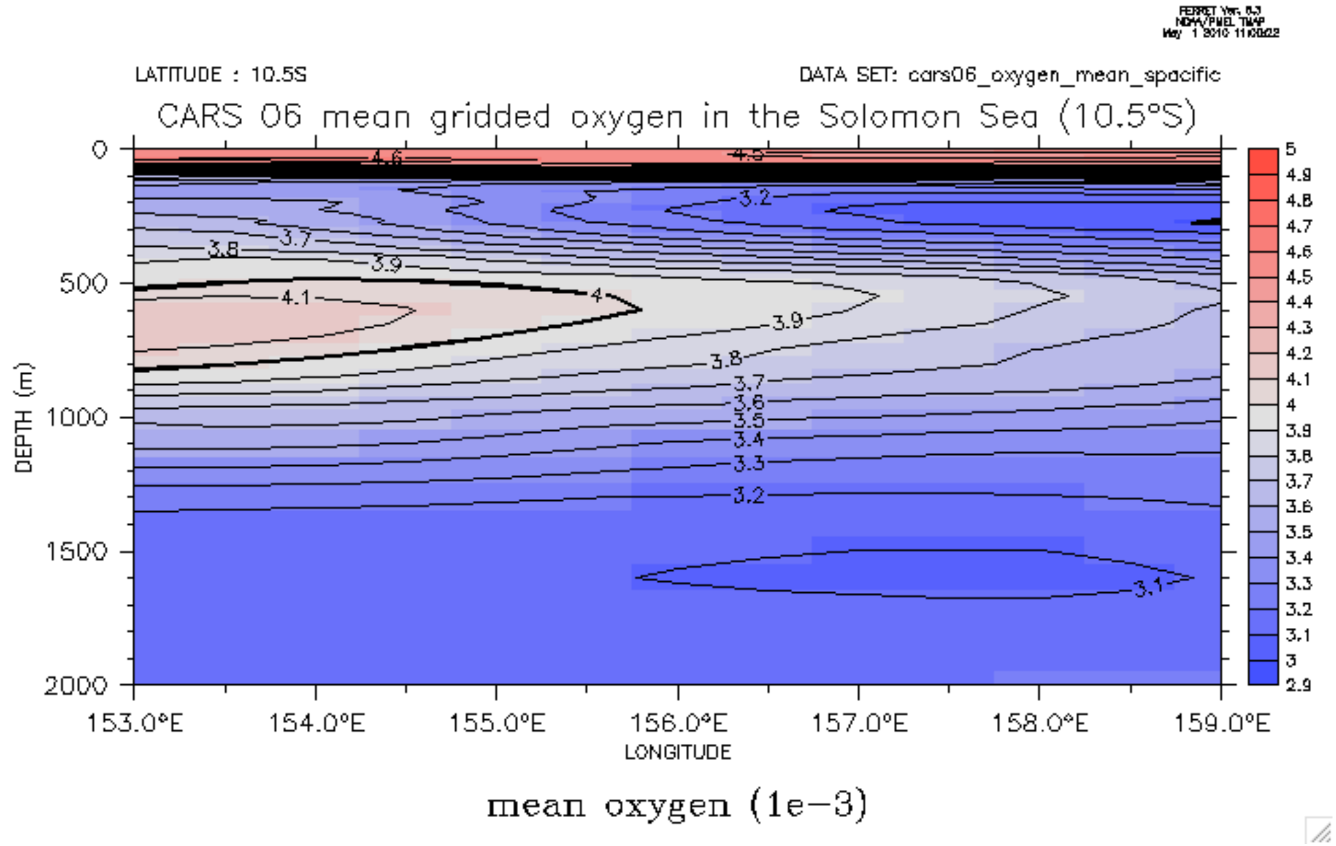
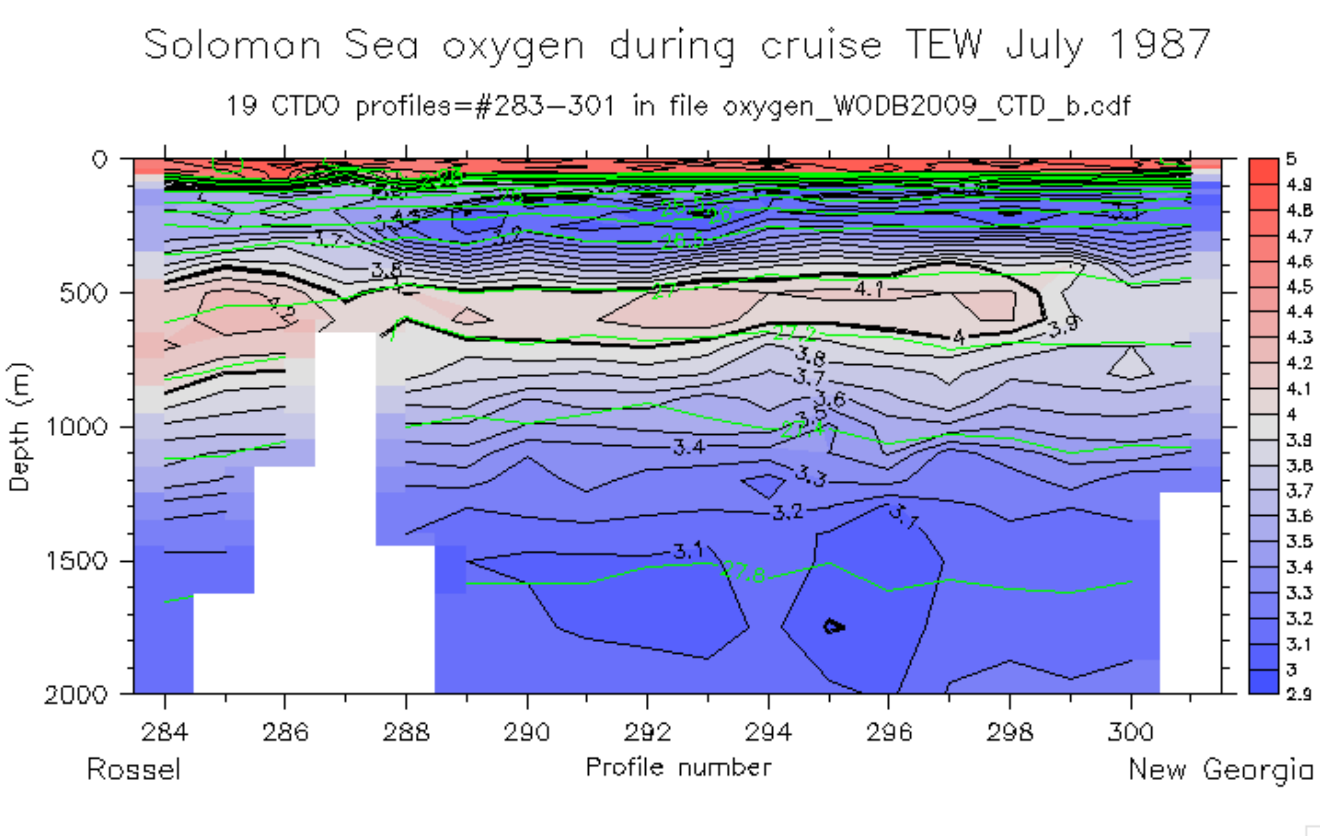
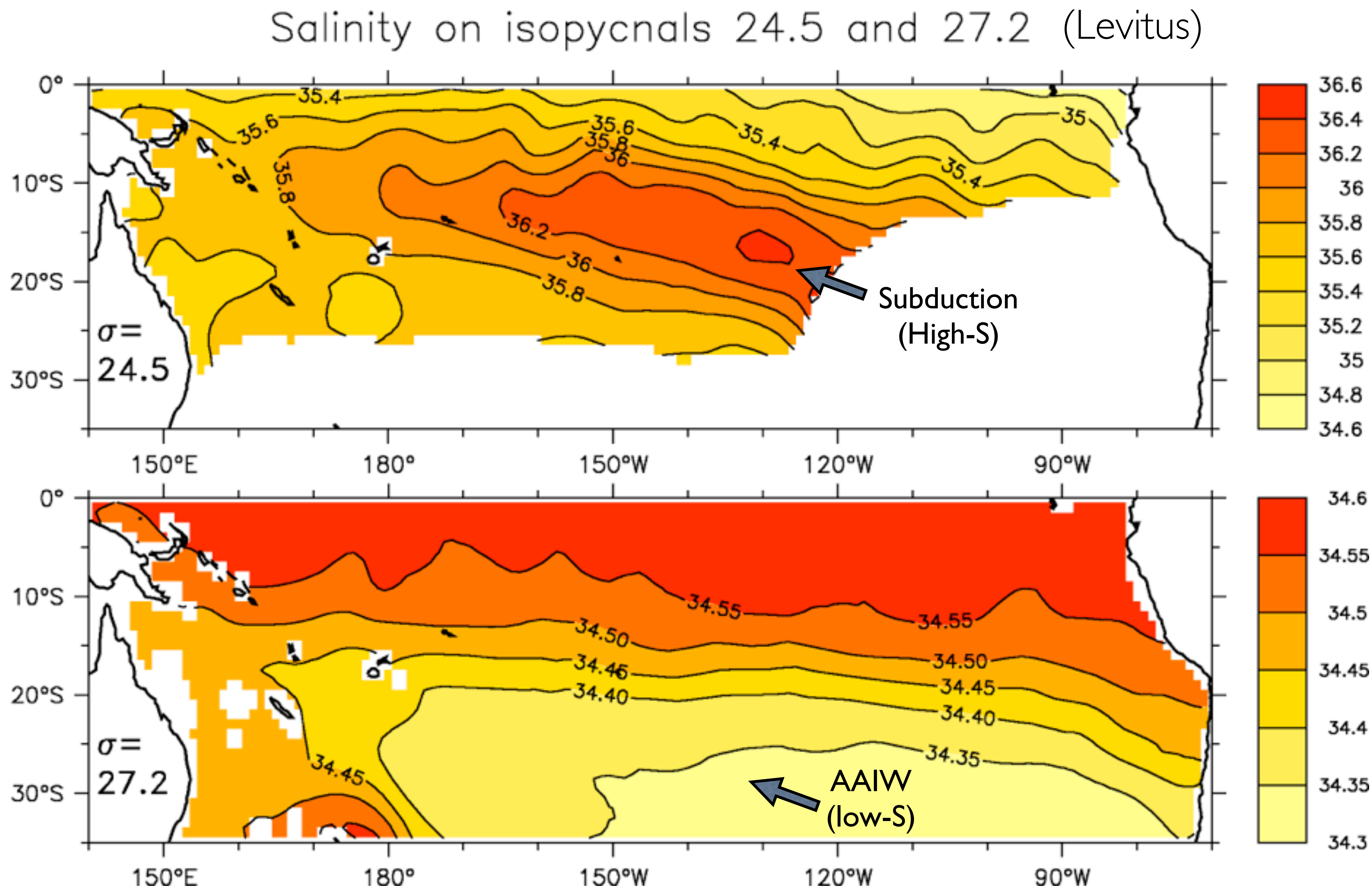


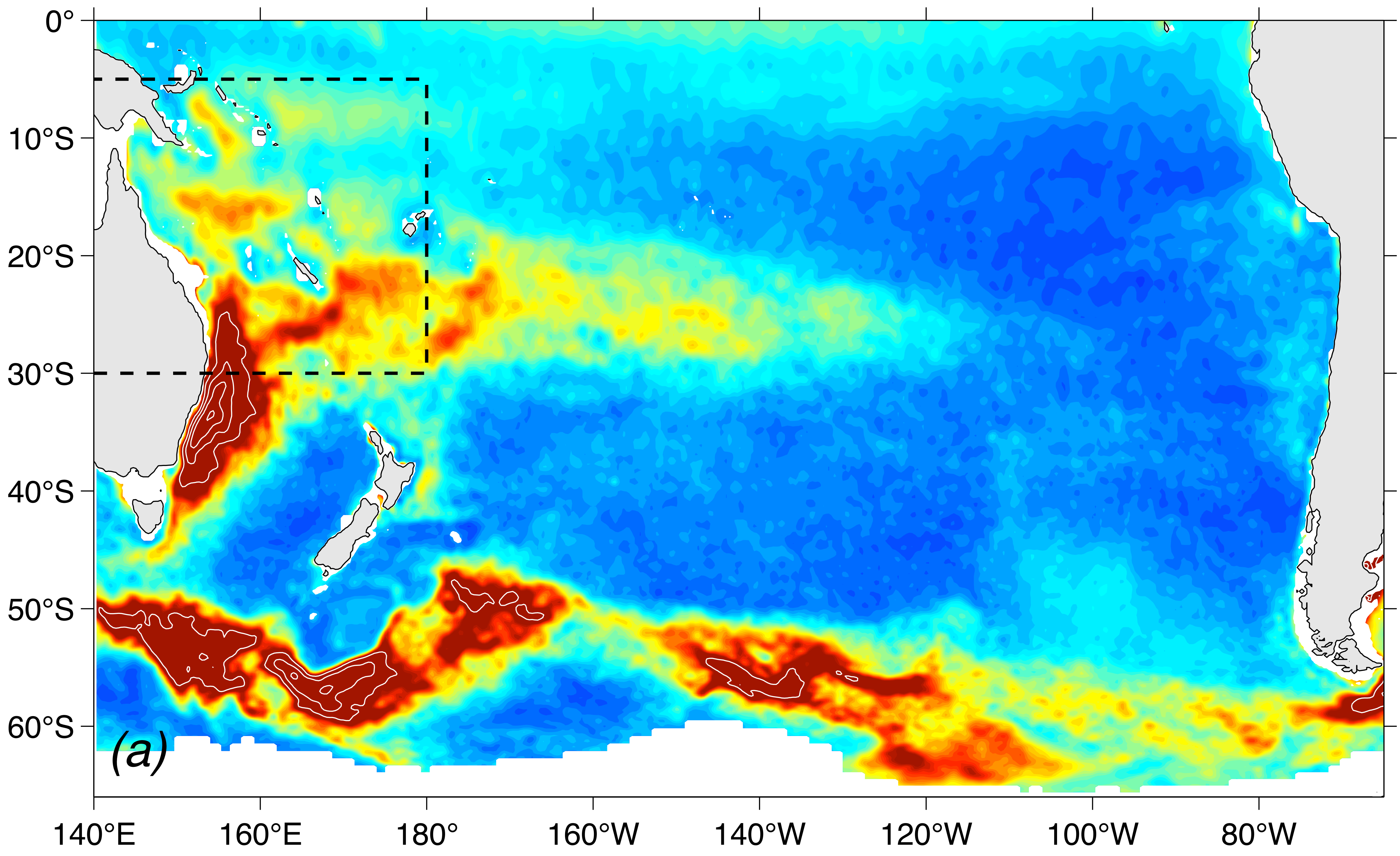

FERRET Ver. 6.3 NOAA/PMEL TMAP May 1 2010 11:09:22
LATITUDE : 10.5S
DATA SET: cars06_oxygen_mean_spacific
CARS 06 mean gridded oxygen in the Solomon Sea (10.5°S)
DEPTH (m)
LONGITUDE
153.0°E
154.0°E
155.0°E
156.0°E
157.0°E
158.0°E
159.0°E
mean oxygen (1e−3)


Solomon Sea oxygen during cruise TEW July 1987
19 CTDO profiles=#283–301 in file oxygen_WODB2009_CTD_b.cdf
Depth (m)
Profile number
Rossel
New Georgia

# Water masses in the SW subtropical Pacific

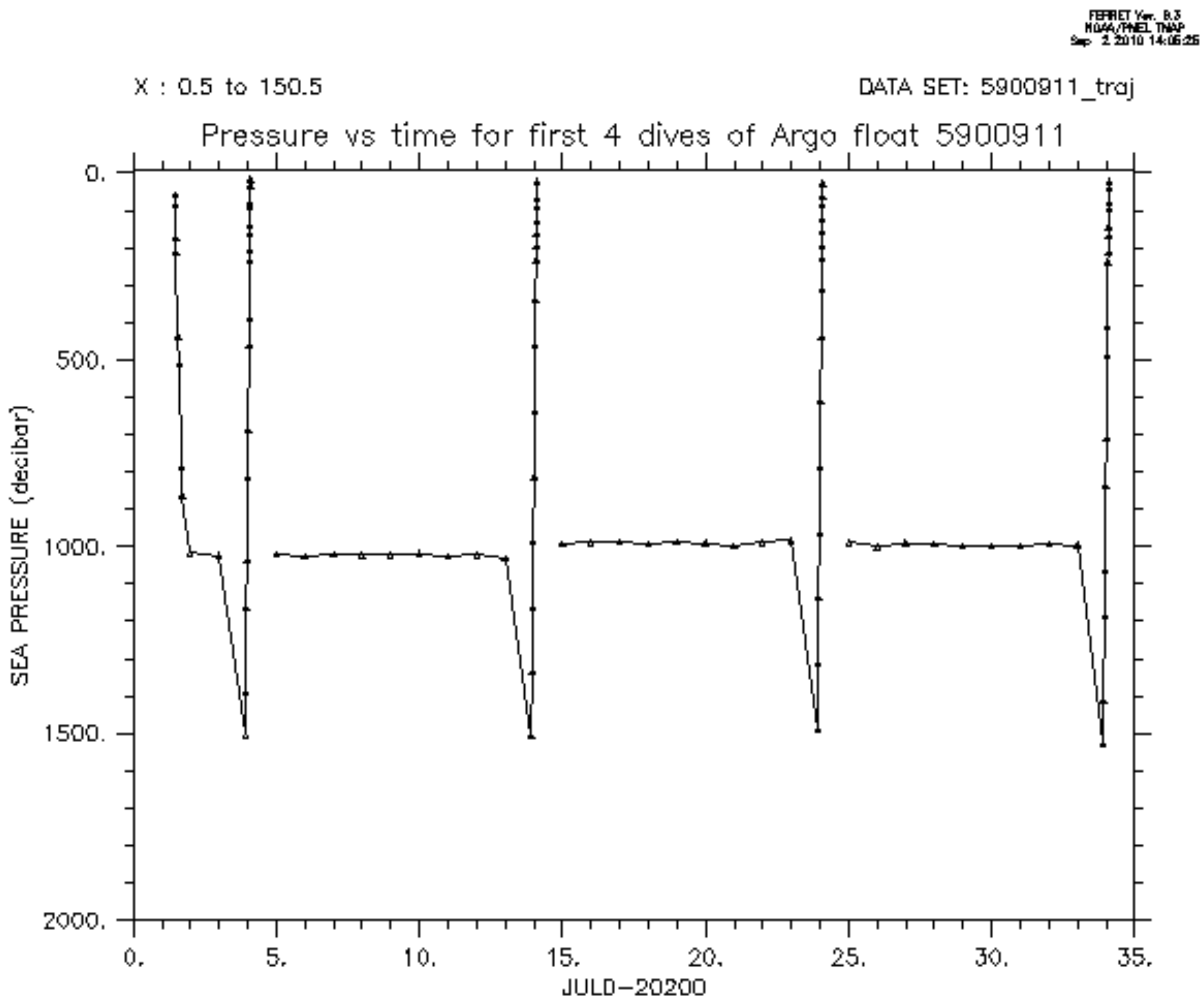


# High eddy variability west of Vanuatu




Rms amplitude of the high-pass-filtered SSH field in the South Pacific Ocean based on weekly AVISO data.
The high-pass filter has a half-power at 180 days. Thin white lines have a contour interval of 0.05 m starting from 0.1 m.

Qiu et al.,(2009)


FERRET Ver. 6.3
NOAA/PMEL TMAP
Sep 2 2010 14:05:25
X : 0.5 to 150.5
DATA SET: 5900911_traj
Pressure vs time for first 4 dives of Argo float 5900911
SEA PRESSURE (decibar)
0.
500.
1000.
1500.
2000.
0.
5.
10.
15.
20.
25.
30.
35.
JULD-20200

## Previous work:


Cravatte, S., A. Ganachaud, Q.-P. Duong, W.S. Kessler, G. Eldin and P. Dutrieux (2010): Observed circulation in the Solomon Sea from SADCP data. *Prog. Oceanogr*, accepted.
Qiu, B., S. Chen, and W.S. Kessler (2009): Source of the 70-day mesoscale eddy variability in the Coral Sea and the North Fiji Basin. *J. Phys. Oceanogr.*, 39, 404-420.
Ganachaud, A., L. Gourdeau, and W. S. Kessler (2008): Bifurcation of the subtropical South Equatorial Current against New Caledonia in December 2004 from a hydrographic inverse box model. *J. Phys. Oceanogr.*, 38(9), 2072-2084.
Gourdeau, L., W.S. Kessler, R.E. Davis, J. Sherman, C. Maes and E. Kestenare (2008): Zonal jets entering the Coral Sea. *J.Phys.Oceanogr.*, 38(3), 715-725.
Kessler, W.S. and L. Gourdeau (2007): The annual cycle of circulation of the southwest subtropical Pacific, analyzed in an ocean GCM. *J.Phys.Oceanogr.*, 37(6), 1610-1627.
Kessler, W.S. and L. Gourdeau (2006): Wind-driven zonal jets in the South Pacific Ocean *Geophys.Res.Lett.*, 33, L03608, doi:10.1029/2005GL025084.