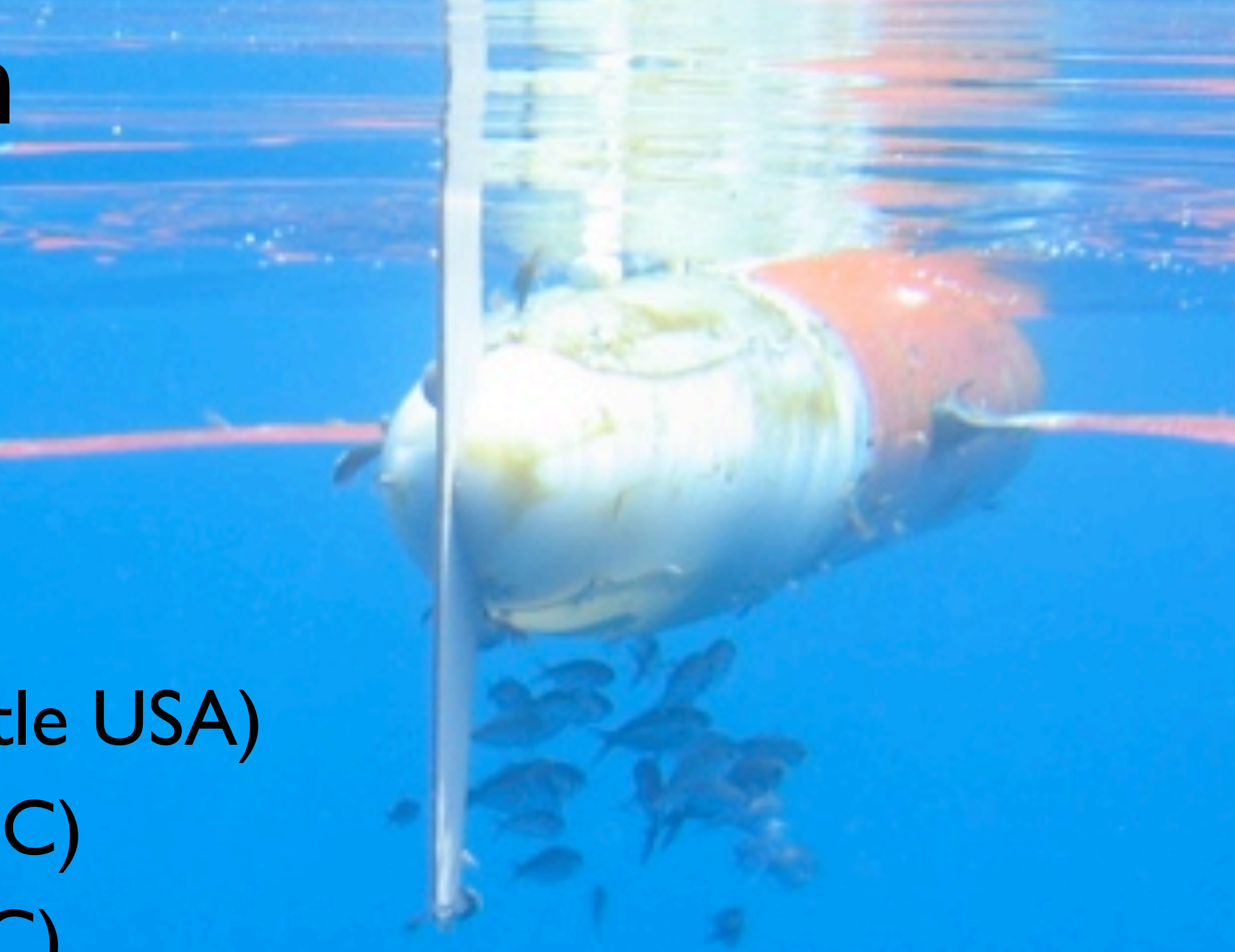
Circulation through the Solomon Sea ... origins and consequences



William S. Kessler (U. Washington, Seattle USA)
Sophie Cravatte (IRD, Nouméa NC)
Frédéric Marin (IRD, Nouméa NC)
Russ Davis (Scripps, La Jolla USA)

Davis, R.E., W.S. Kessler and J.T. Sherman, 2012: Gliders measure western boundary current transport from the South Pacific to the equator. *J.Phys.Oceangr.*, 42(11), 2001-2013.

Cravatte, S., W.S. Kessler and F. Marin, 2012: Intermediate jets in the tropical Pacific Ocean observed by Argo floats. *J.Phys.Oceanogr.*, 42(9), 1475-1485.

Kessler, W.S. and S. Cravatte, 2013: ENSO and short-term variability of the South Equatorial Current entering the Coral Sea. *J.Phys.Oceanogr.*, in press.

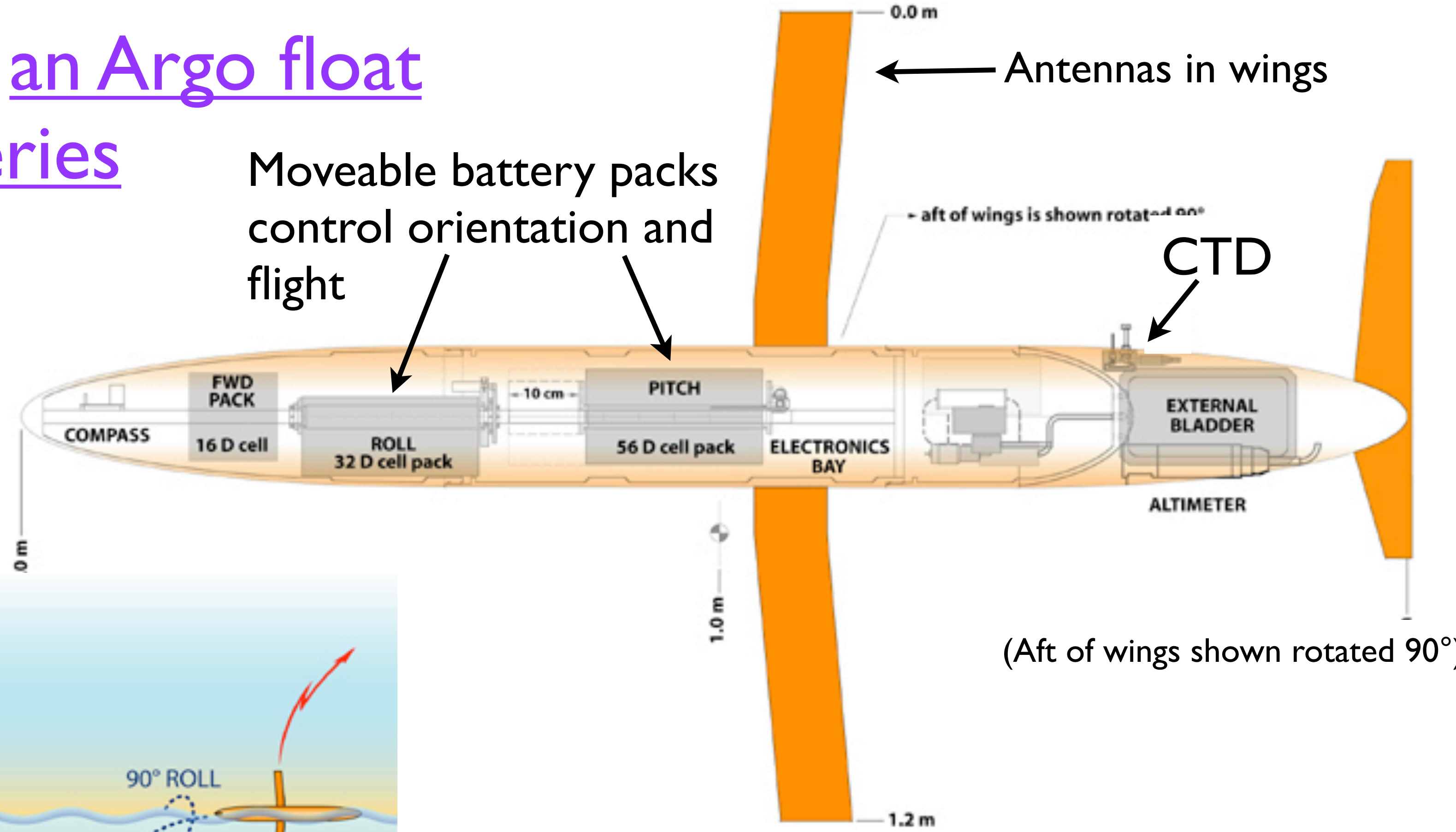
Kessler, W.S. and S. Cravatte, 2013: Mean circulation of the Coral Sea. *J.Geophys.Res.*, submitted.

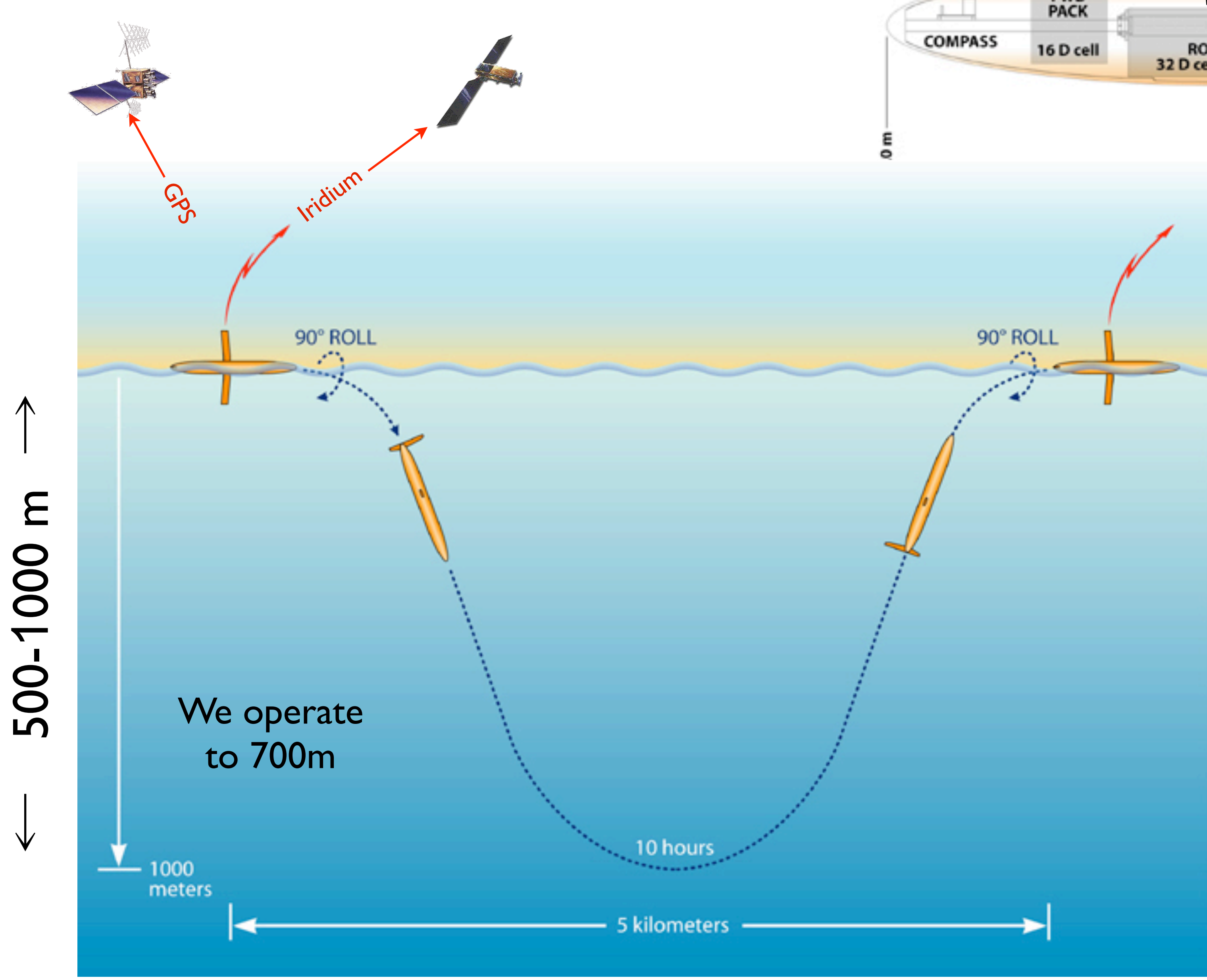
With thanks to Stuart Godfrey, Ernest Frohlich, and CSIRO Hobart .... who started me on this path in 2001

Collaborators:
- Solomon Islands Meteorological Service
- University of Papua New Guinea
- Bureau of Meteorology (Australia)

The Spray glider is essentially an Argo float with wings and movable batteries

The Spray glider is developed and built by the Instrument Development Group at Scripps.





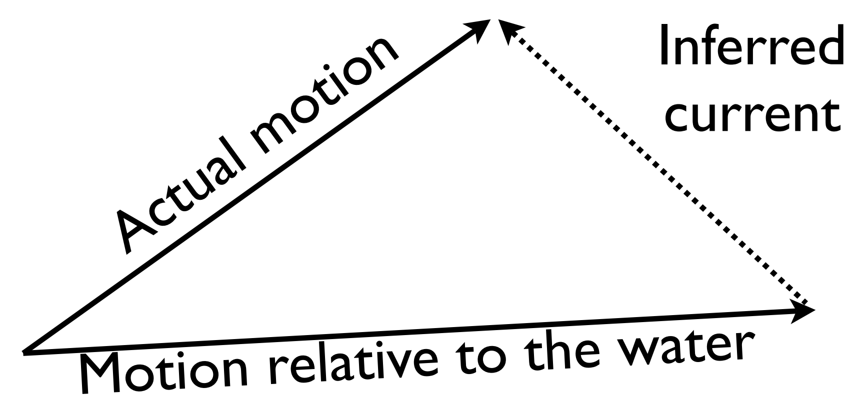
← 3 km (3-4 hr) →

Range 4-5 months at 20 cm/s = 2000+km

Very dense sampling (~ resolve tides)

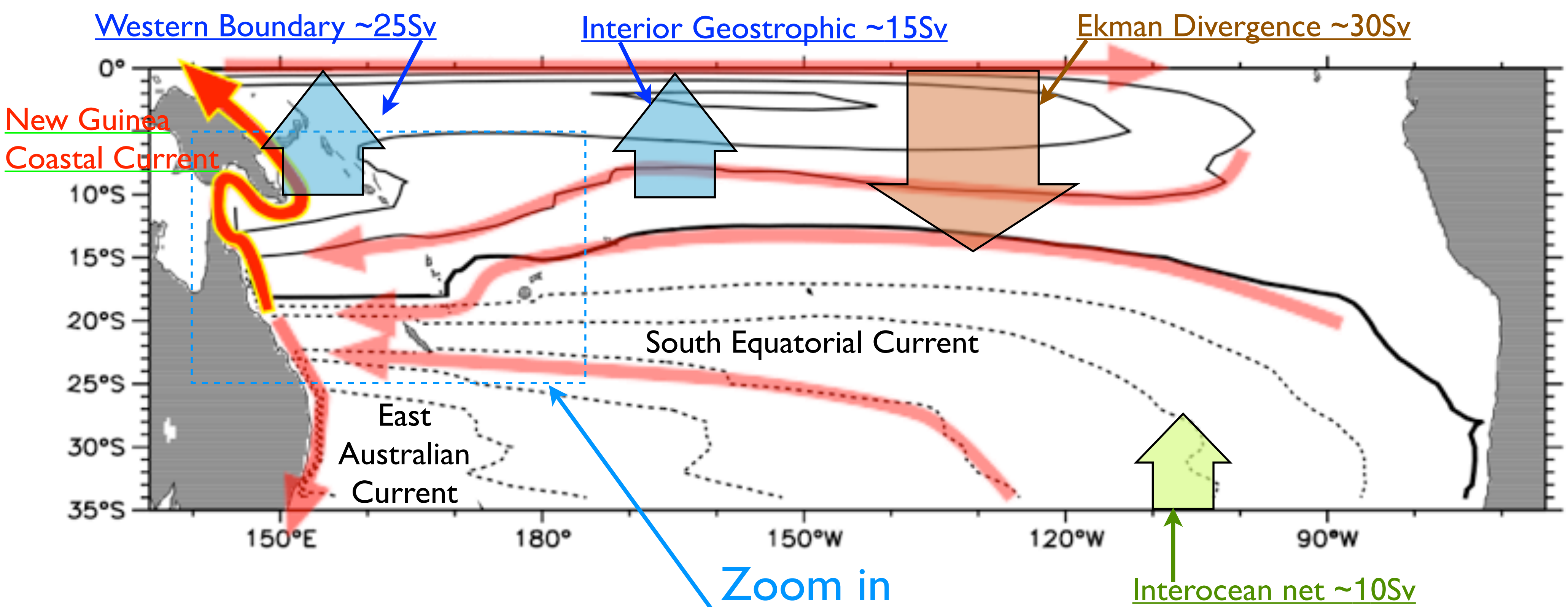
Argo-comparable T-S profiles:
geostrophic relative currents

Infer vertical-average absolute currents by the glider's drift:

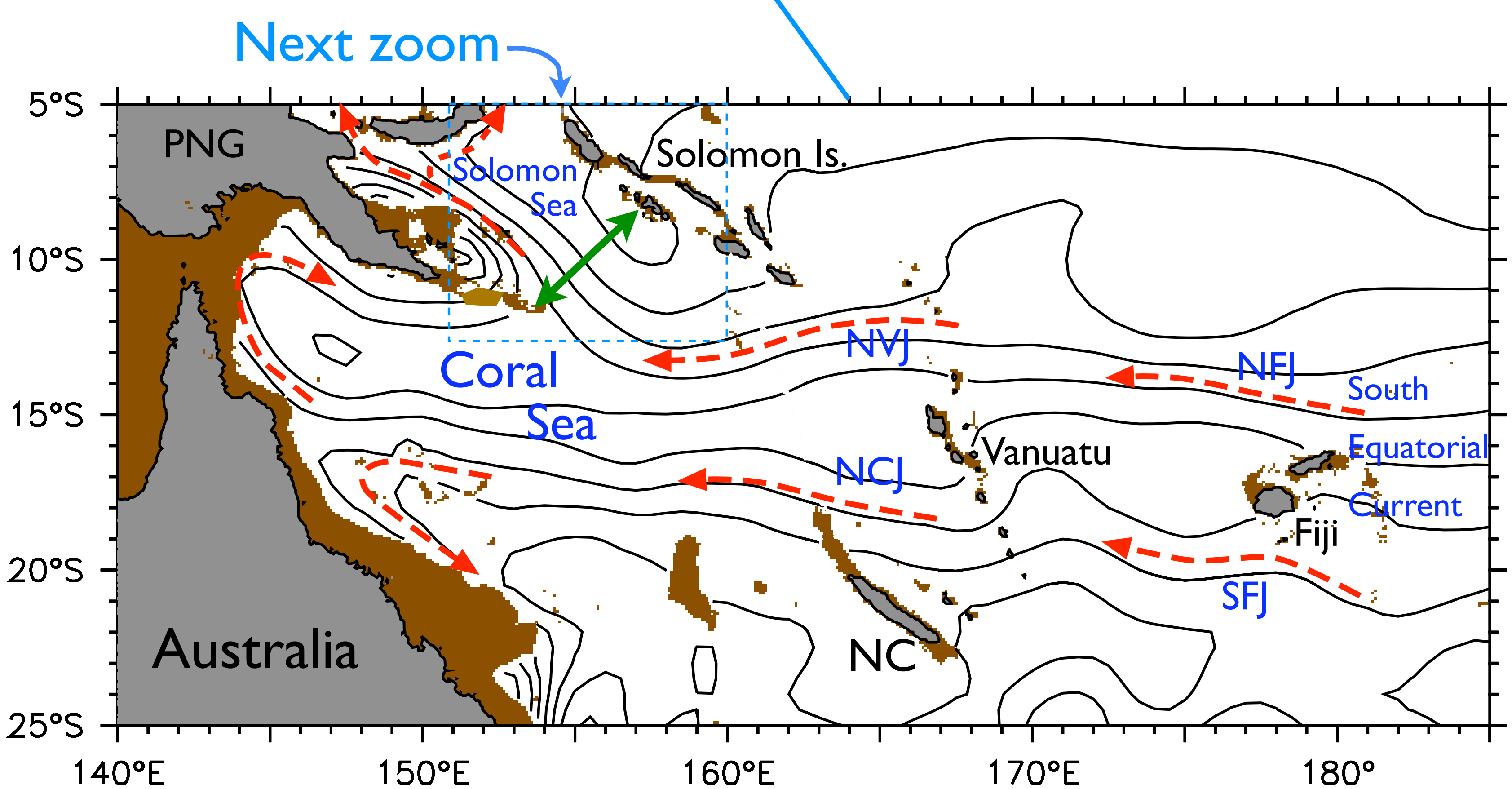


Davis, Kessler and Sherman (2012)

South Pacific average circulation

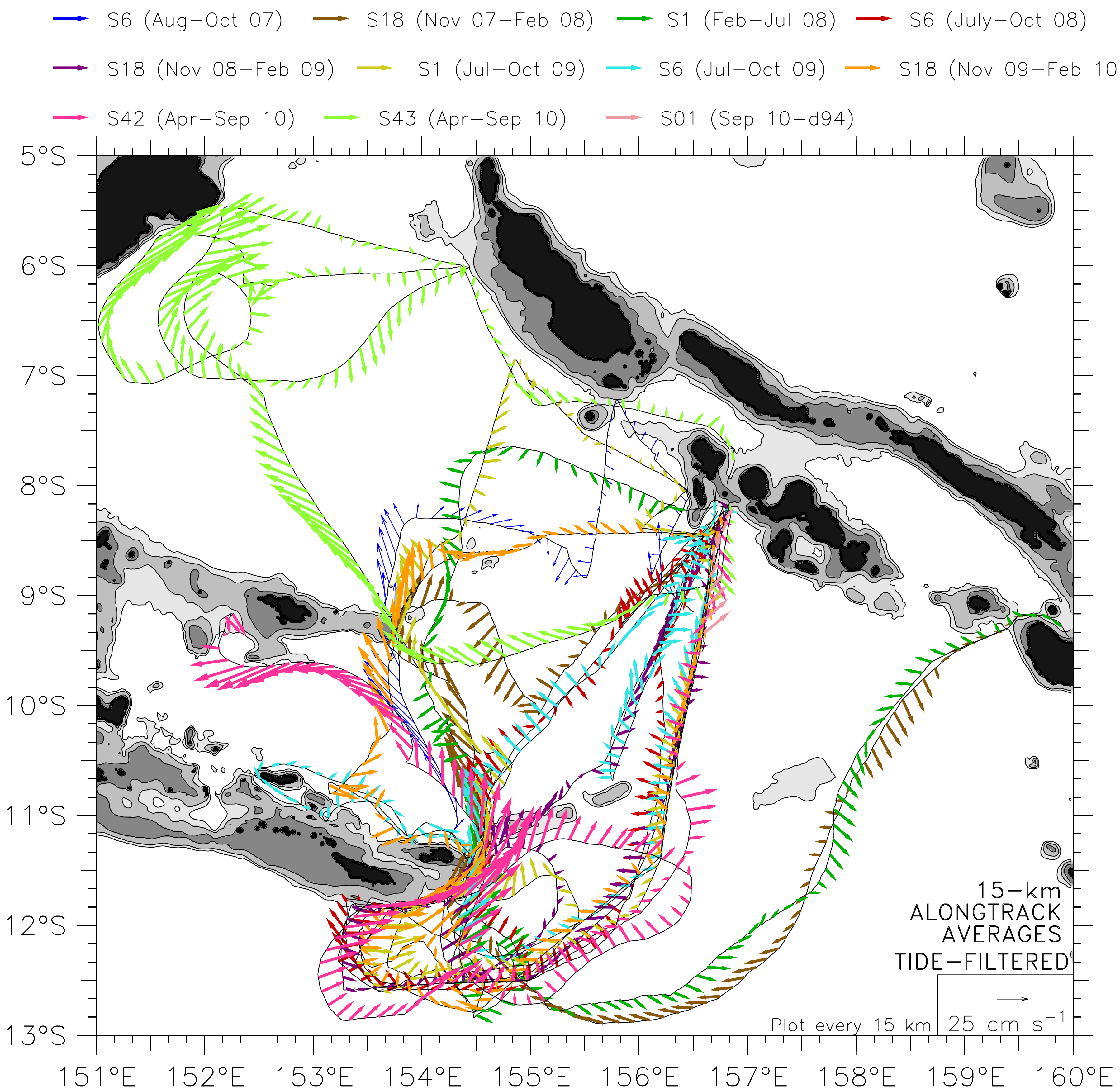


Island Rule (ERS winds)



Glider experiments cross the Solomon Sea and measure the flow towards the equator.

Glider currents in the Solomon Sea

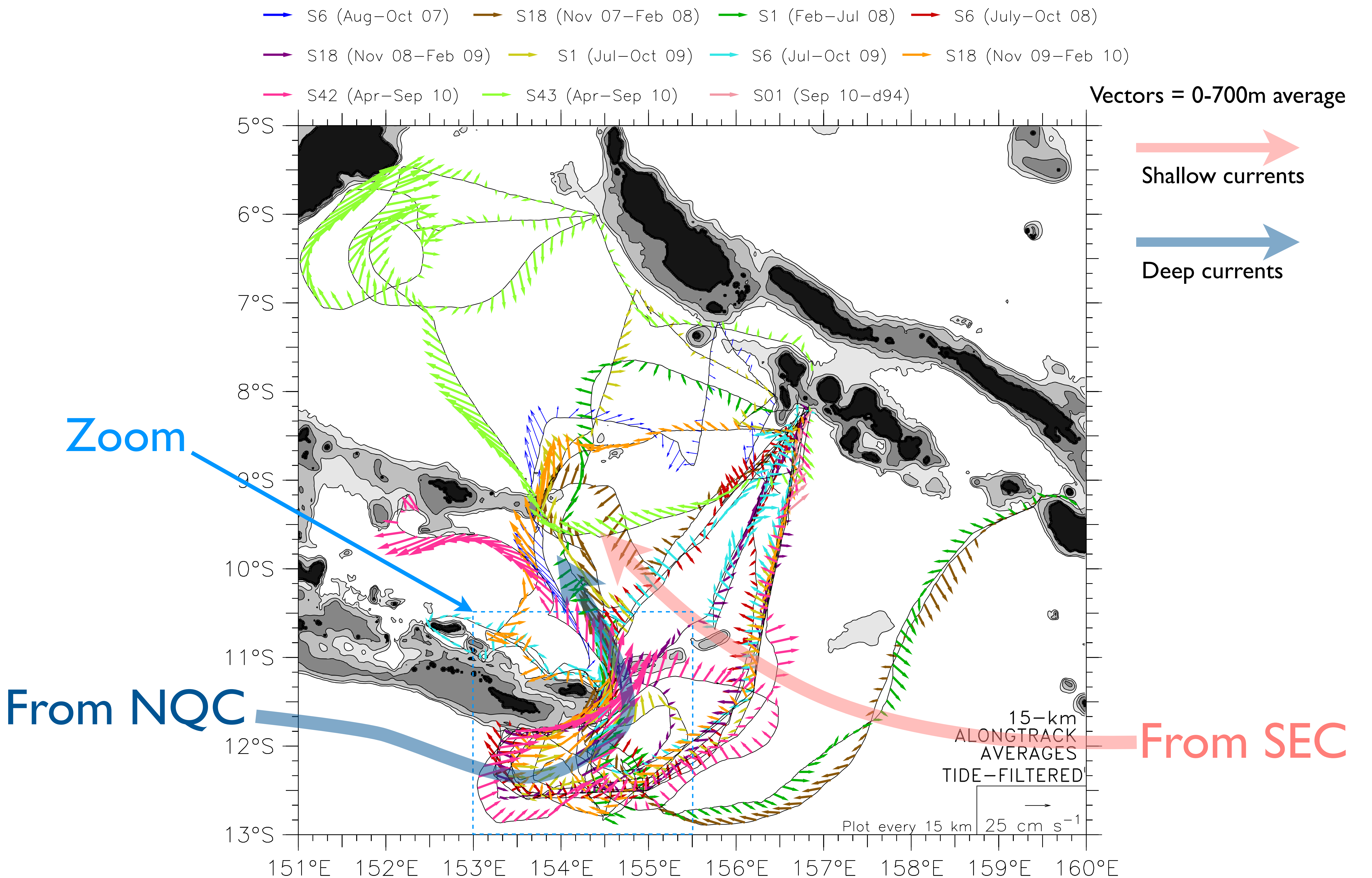


21 missions since mid-2007 (just deployed #22-23)

(2 failures ... but recovered the gliders)

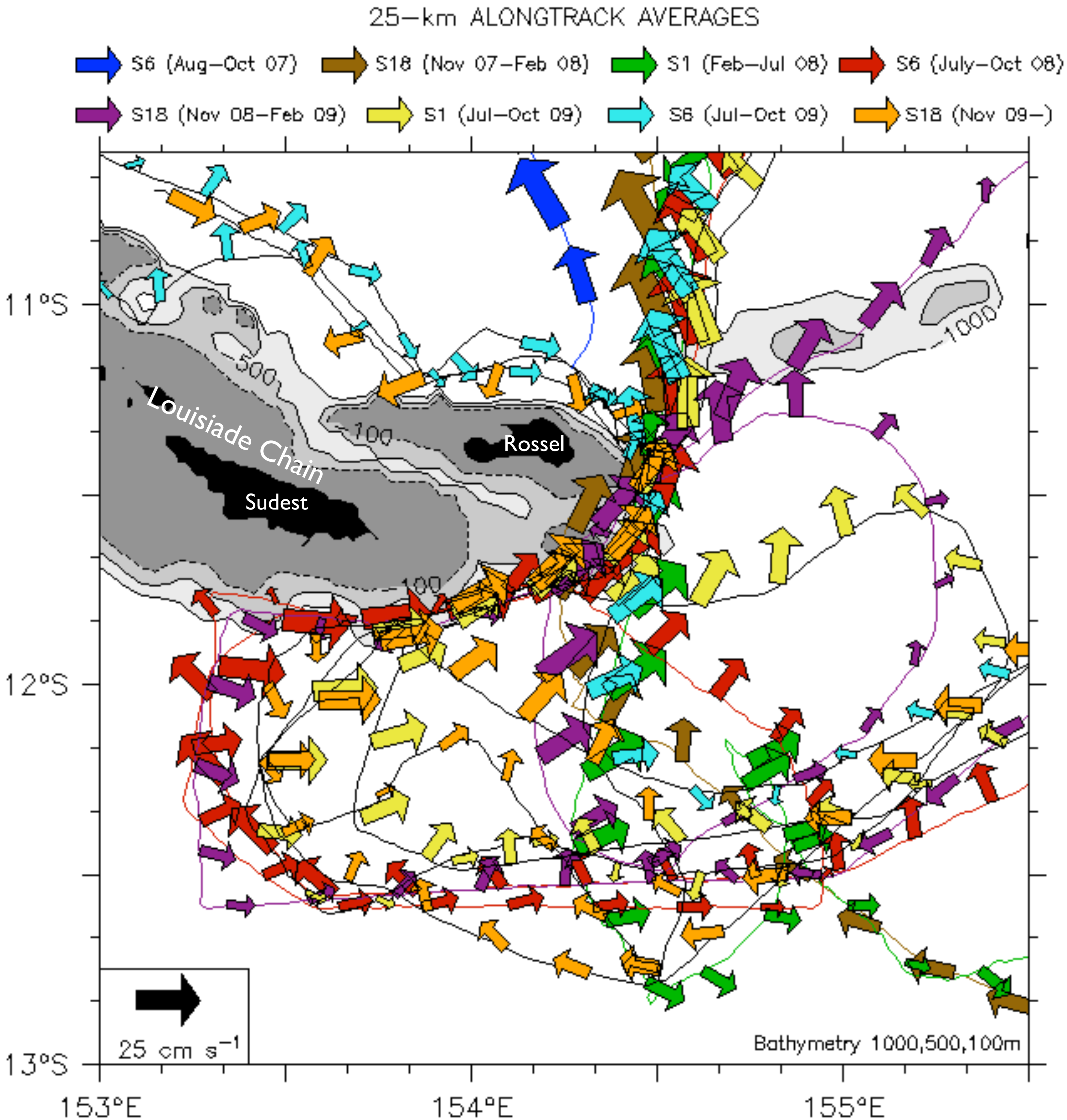
Davis, Kessler and Sherman (2012)

Glider currents in the Solomon Sea



Davis, Kessler and Sherman (2012)

Vertical-average currents at the tip of PNG

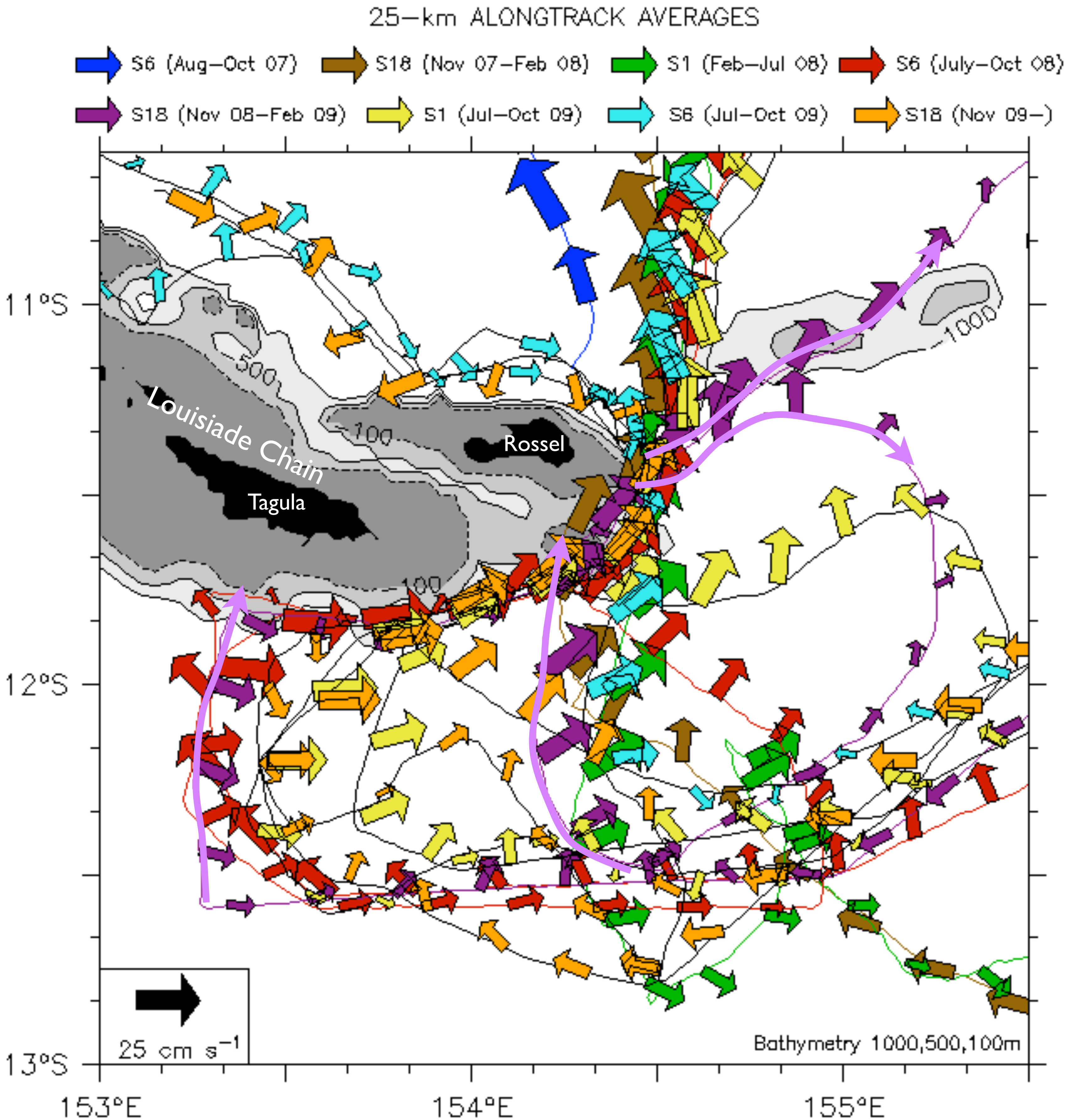


The most consistent observation is a strong current towards the equator at the tip of the Louisiades.

The current is very close to the reef line.

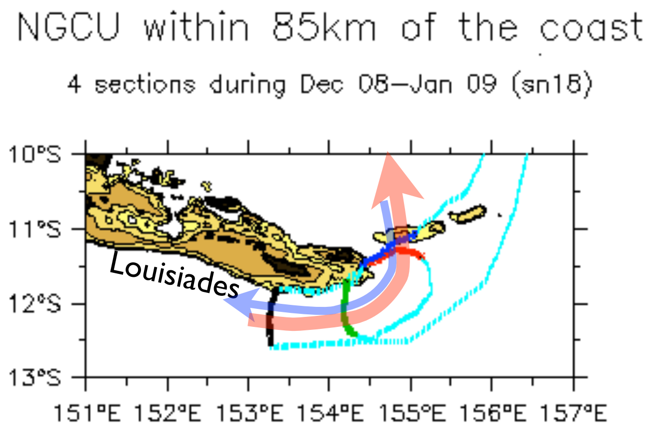
Davis, Kessler and Sherman (2012)

Vertical-average currents at the tip of PNG



Now, we'll look at the vertical structure of the NGCU .... four 100km sections (light purple lines)

Davis, Kessler and Sherman (2012)



The equatorward flow is an <u>undercurrent</u>

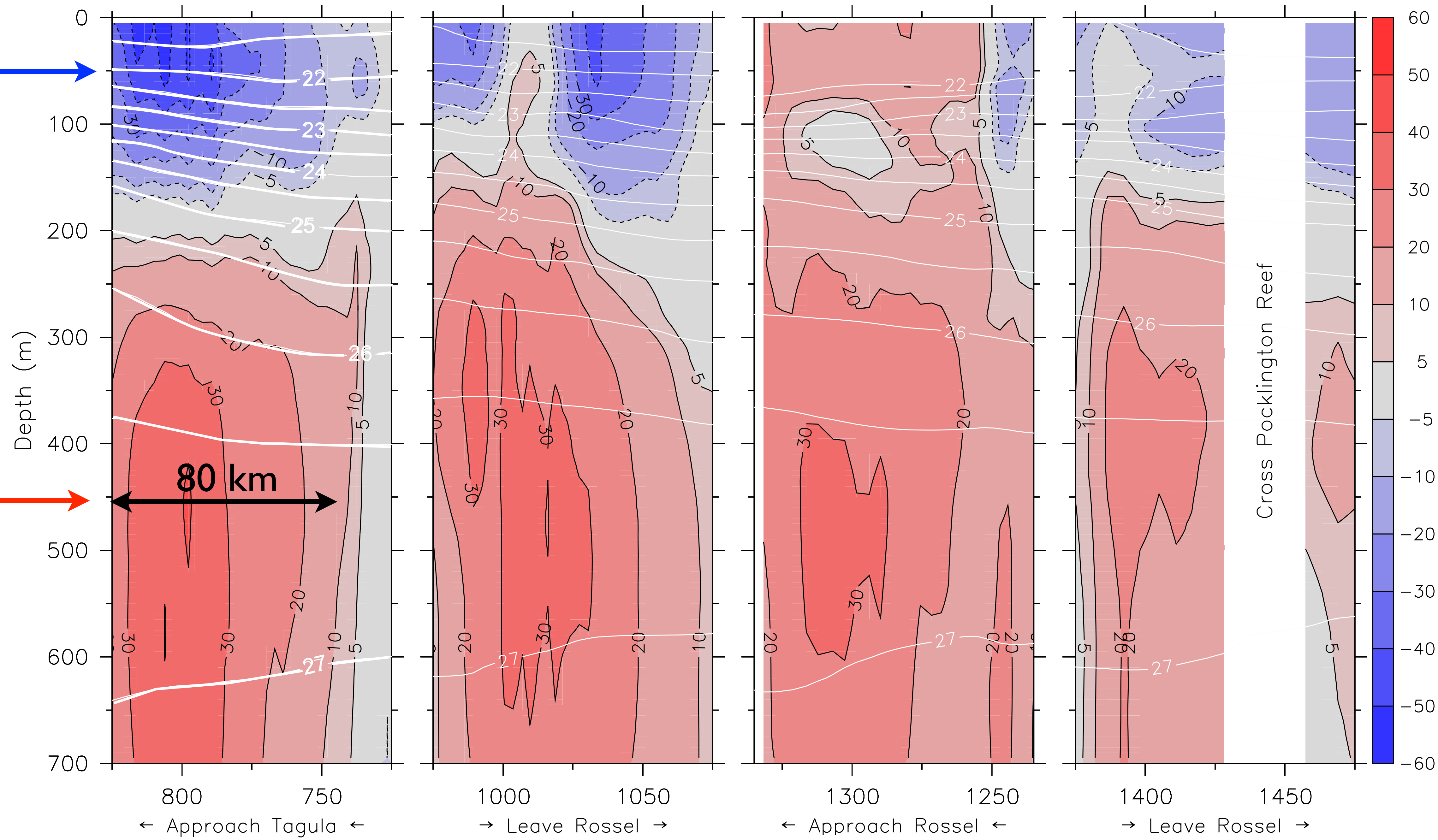
Currents at the tip of the Louisiades

Each section shows 100km from the coast on the left. Glider obs Dec 08-Jan 09

Opposite flow in upper layer

Note isopycnal spreading at the coast (white)

Maximum near 450m



Positive (red) = Equatorward

Davis, Kessler and Sherman (2012)

How to be quantitative with the irregularly-distributed glider tracks?

Define a function Φ, such that: $\nabla^2\Phi=0$, and:

$\Phi=0$ at PNG coast, $\Phi=1$ at Solomons coast.

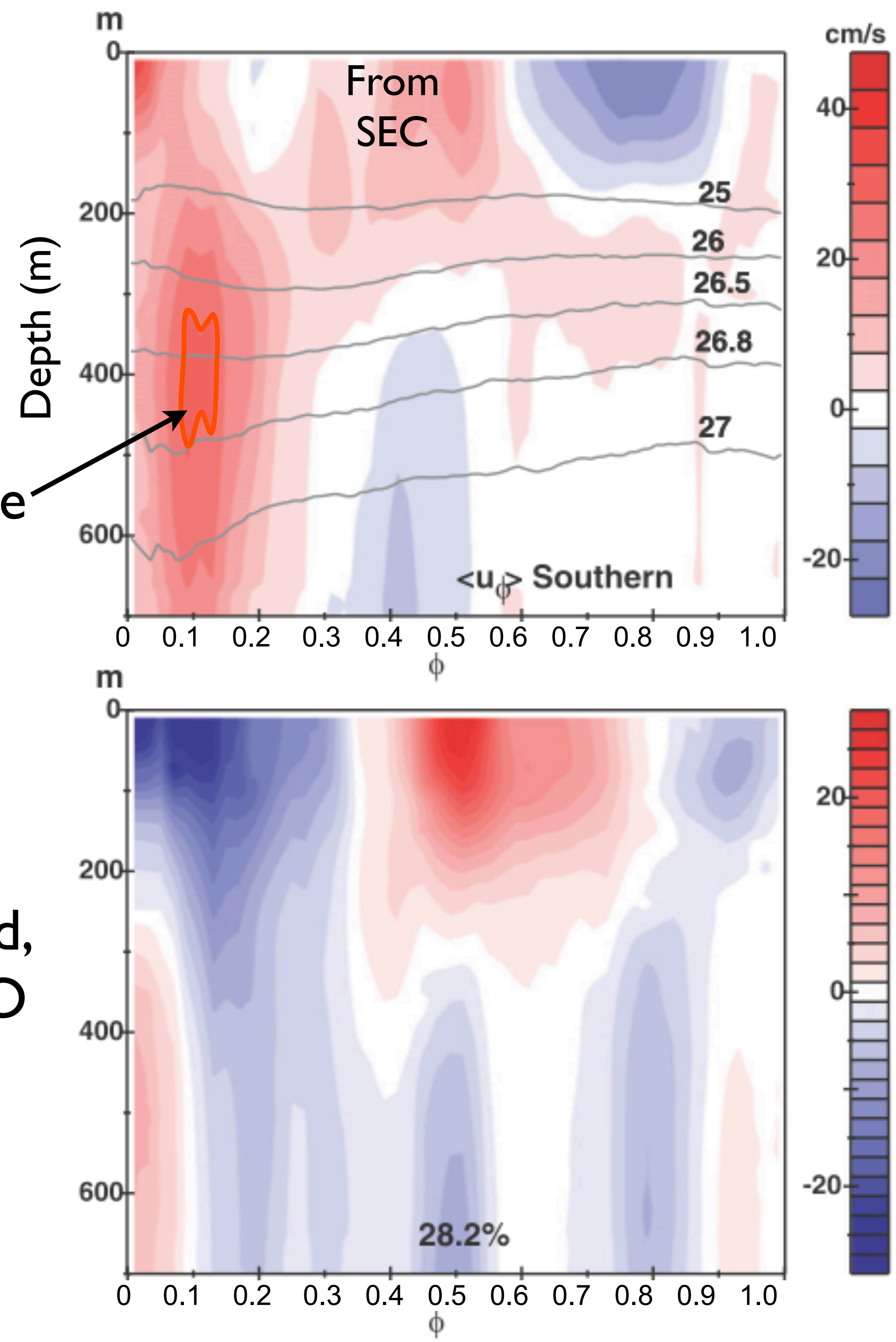
Consider velocity parallel to Φ contours "equatorward"

Mean eq-ward u_ϕ

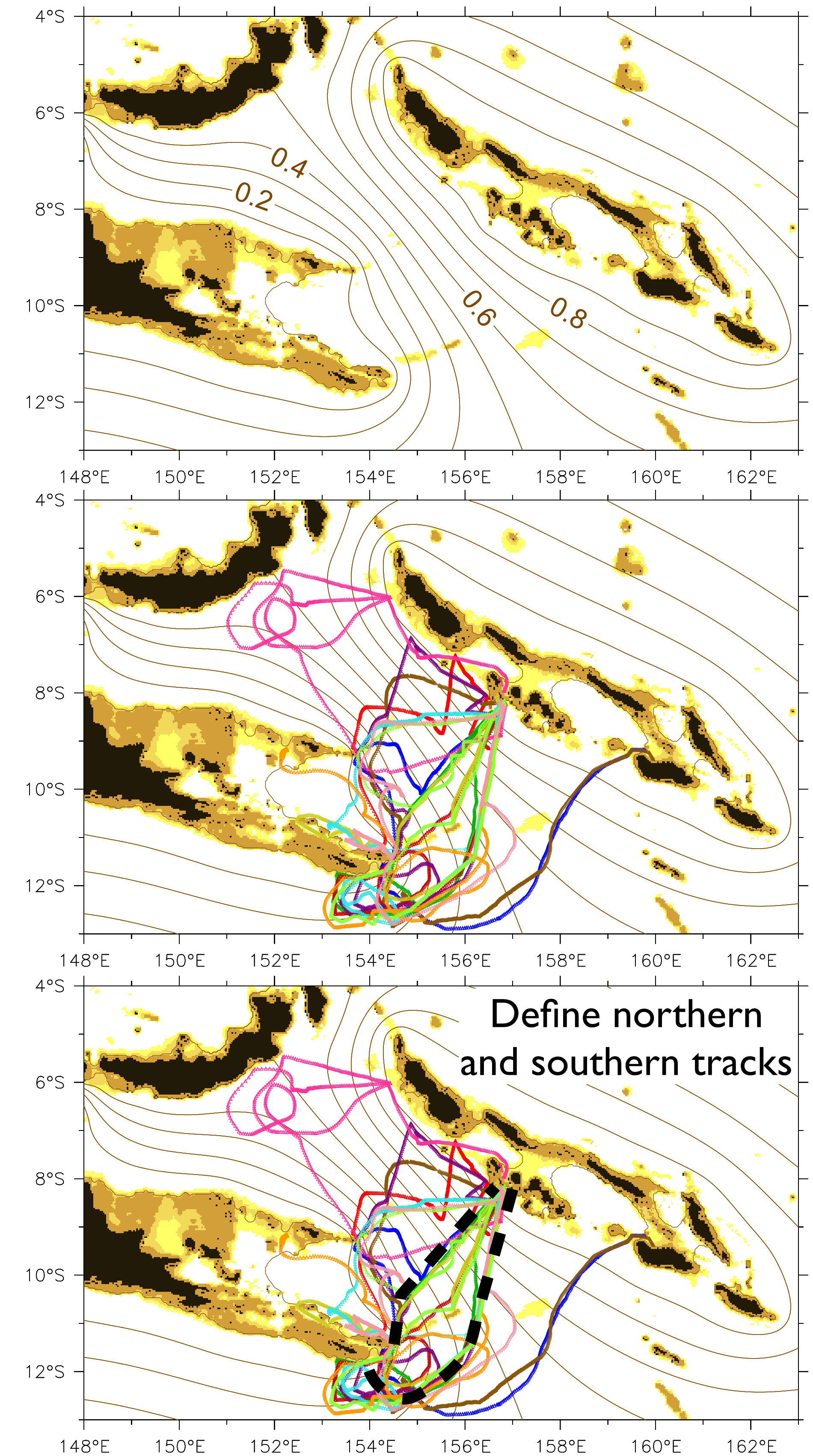
NGCU core

EOF 1

Variability is surface-intensified, dominantly ENSO



Contours of Φ (by 0.1)



Davis, Kessler and Sherman (2012)

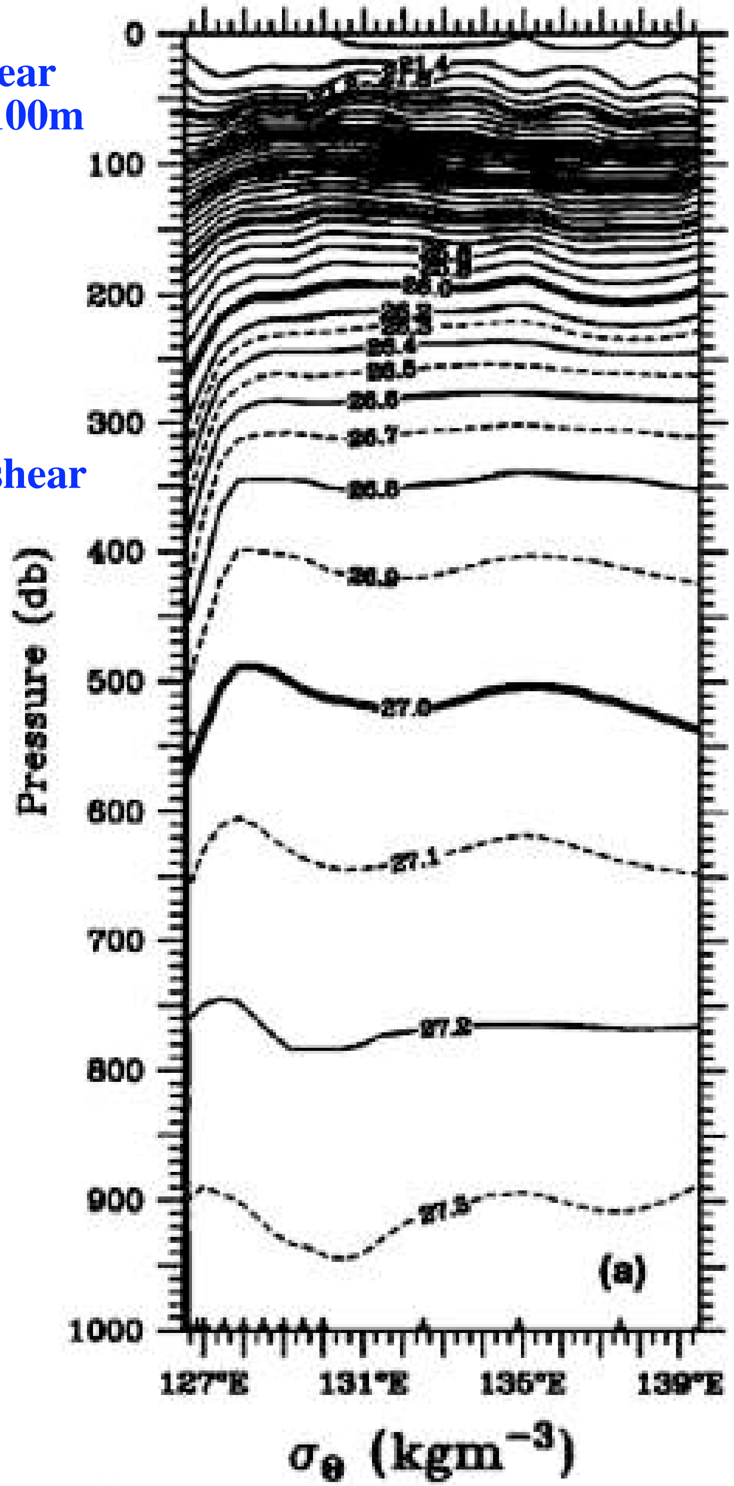
By contrast,

the Mindanao Current is surface-trapped, and shallow

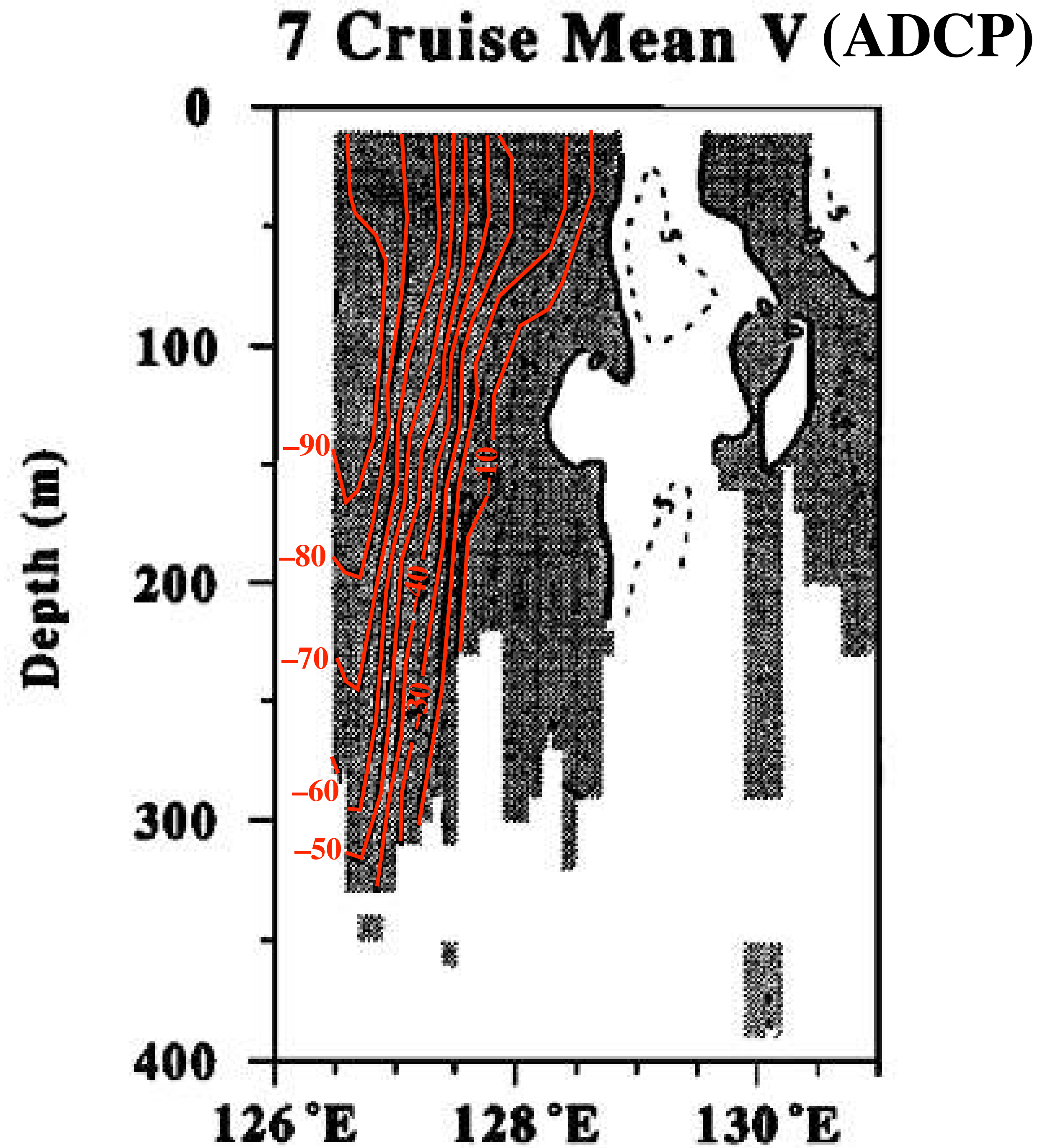
Average σ_θ

Reversed shear only above 100m

Southward shear at 250-550m



←13°→

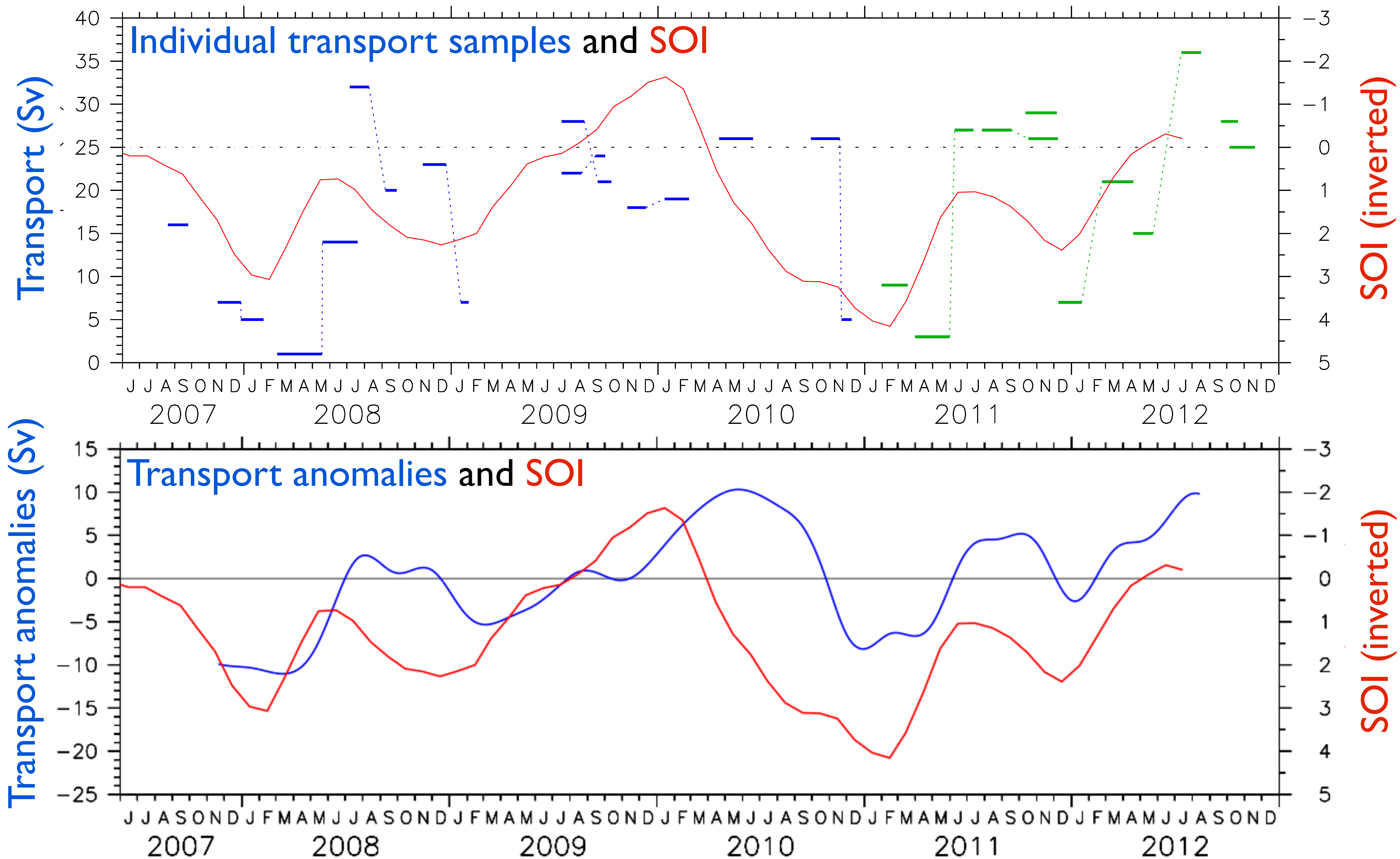


←5°→

Wijffels, Firing and Toole (1995)

Solomon Sea transport has a strong ENSO cycle

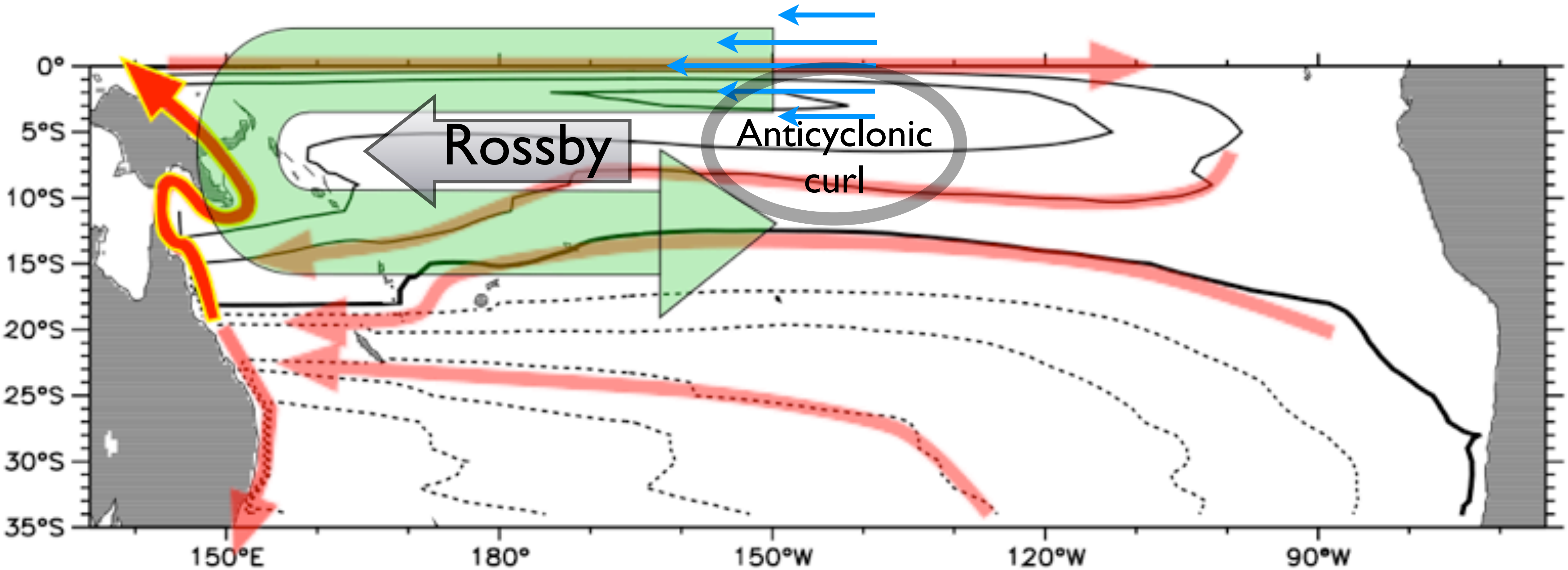
Lags SOI by "a few months"



(Also high correlation between glider transport anomalies and AVISO velocity)

La Niña transport anomalies

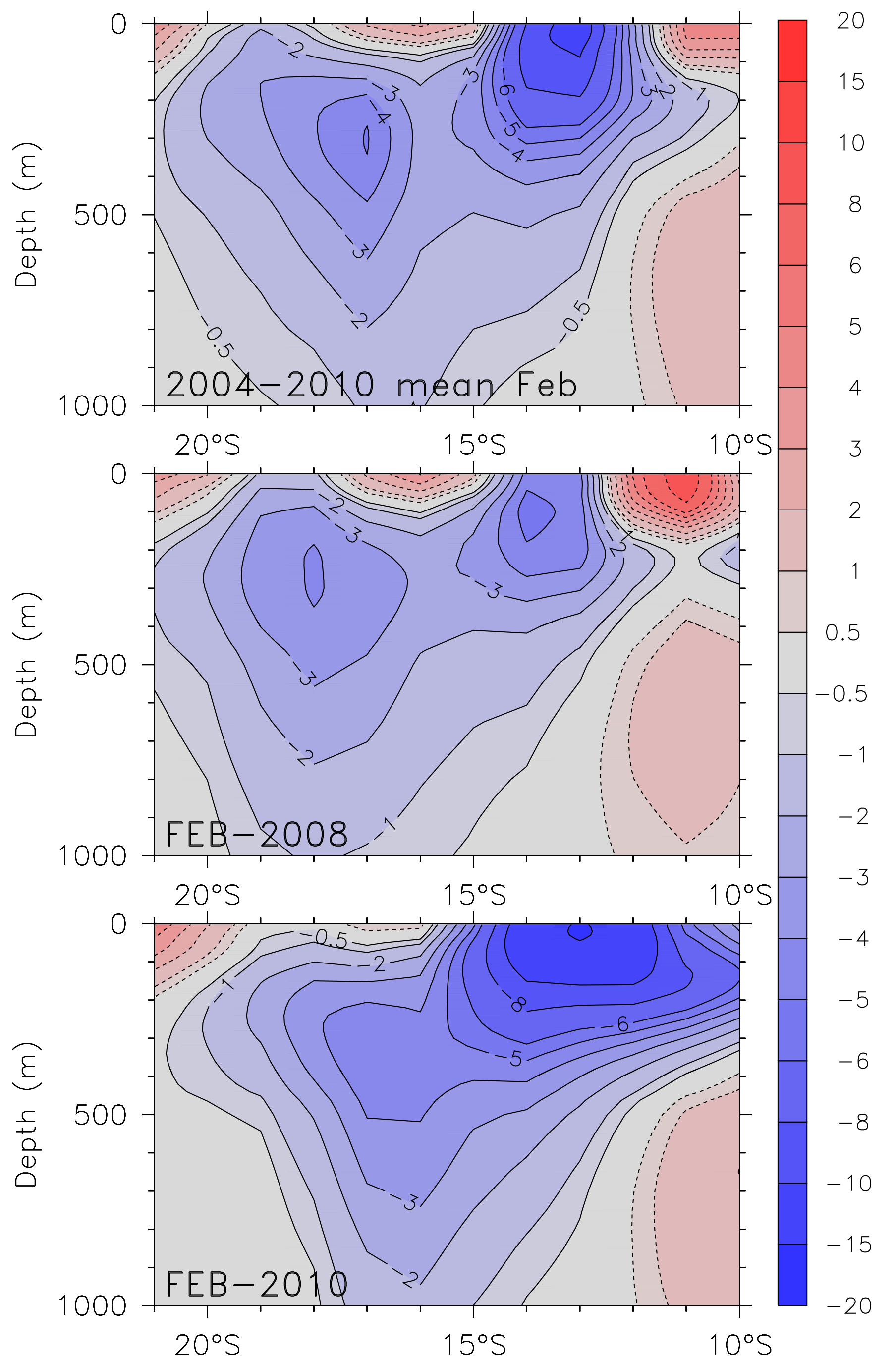
ENSO modifies western boundary transports:
La Niña tends to weaken the WBC in the west

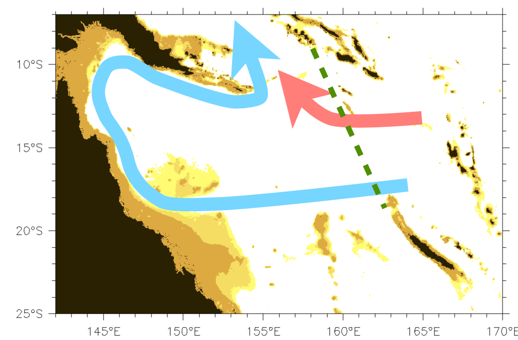


Downwelling curl east of the Solomon Sea during La Niña: northward interior Sverdrup flow ... Rossby waves ... → expect southward WBC anomalies a few months later.

ENSO variation of SEC at ~160°E is surface-intensified

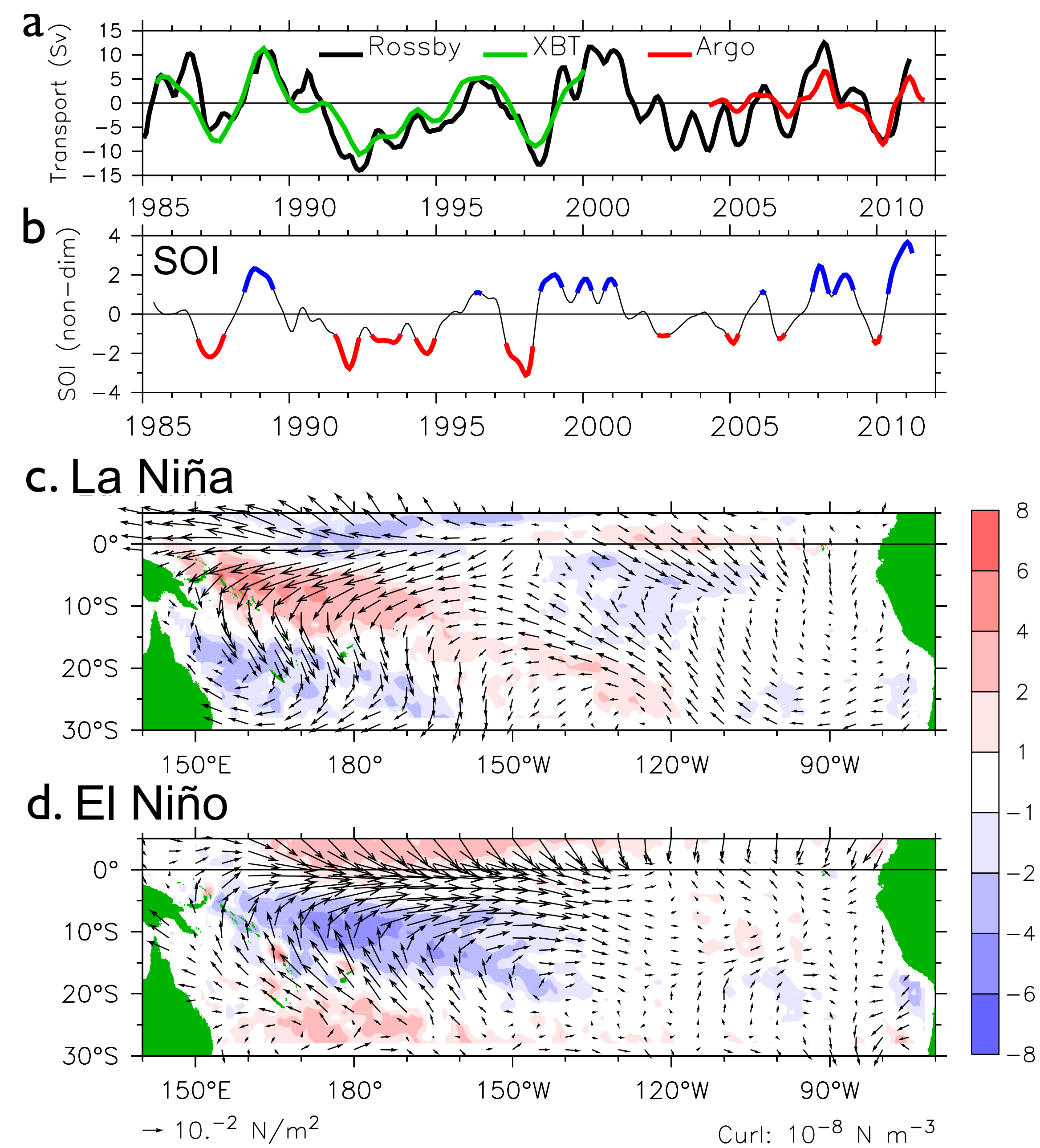
Examples of ENSO signal ($u_{g160°E}$)





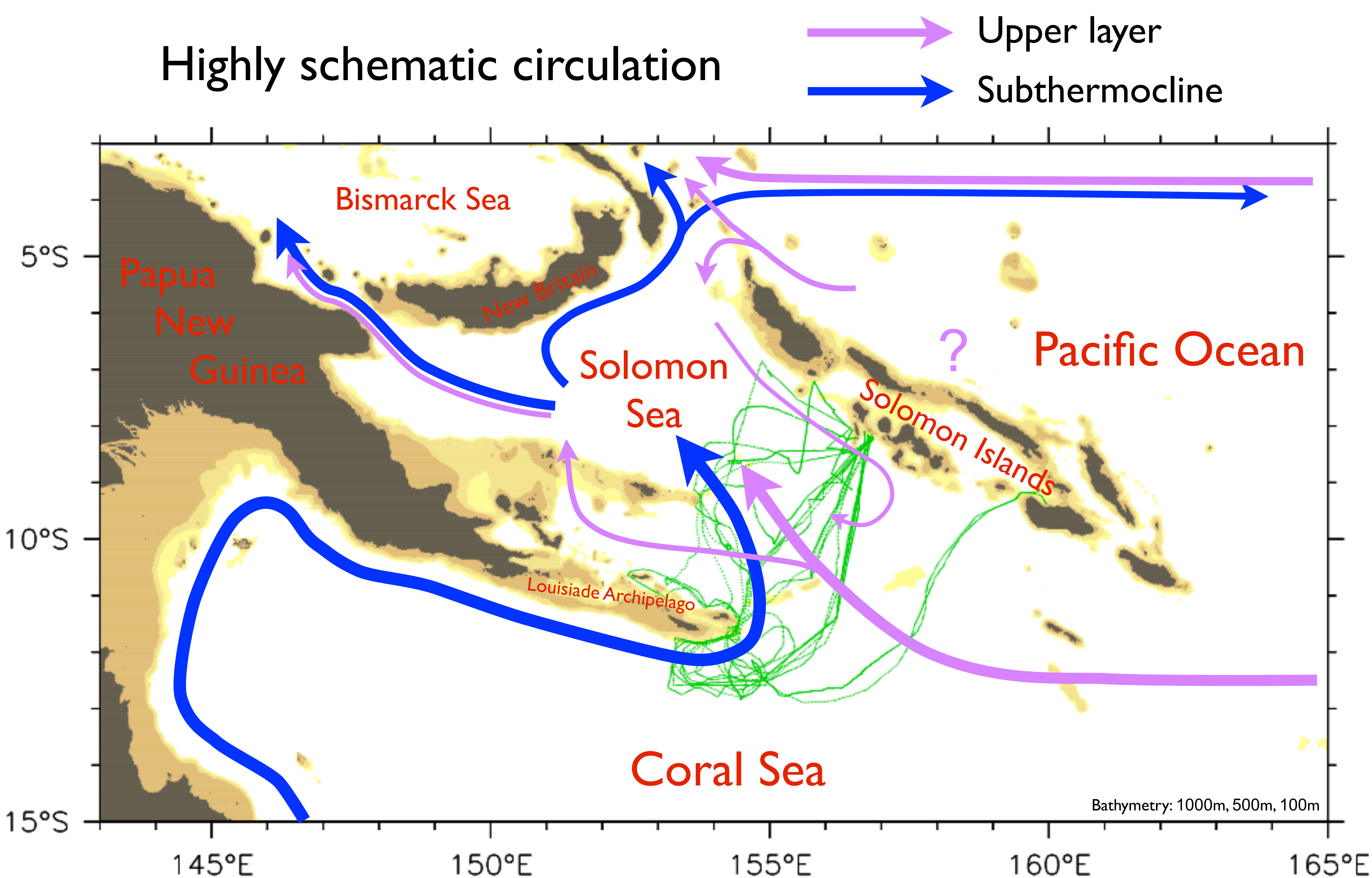
XBT line (green) and schematic circ.

1.5-layer Rossby model gives much of the transport



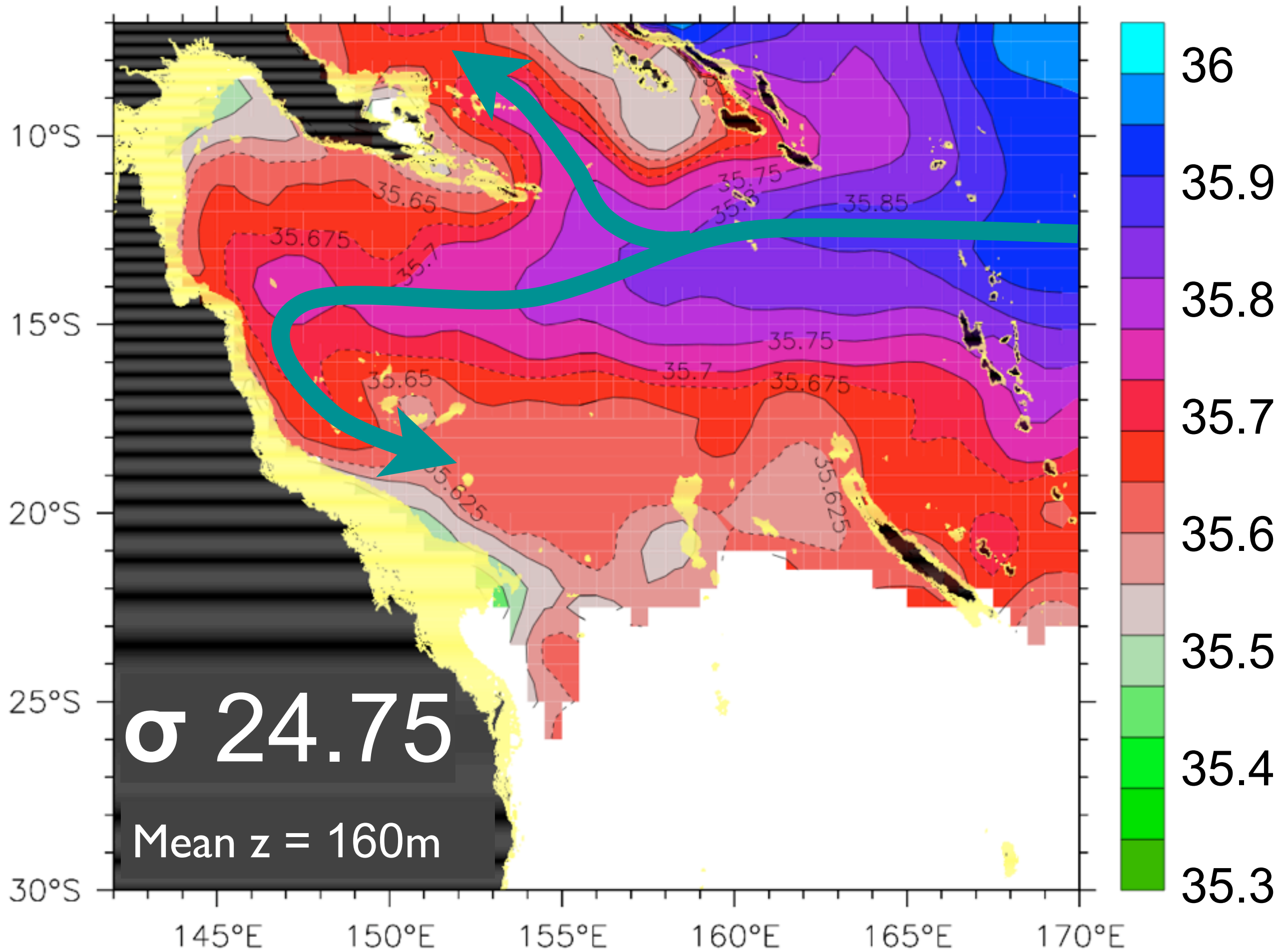
Kessler and Cravatte (2013)

What are the sources of the two Solomon Sea inputs?



Two distinct high-salinity tongues

At the level of the subtropical high-S max (NVJ)



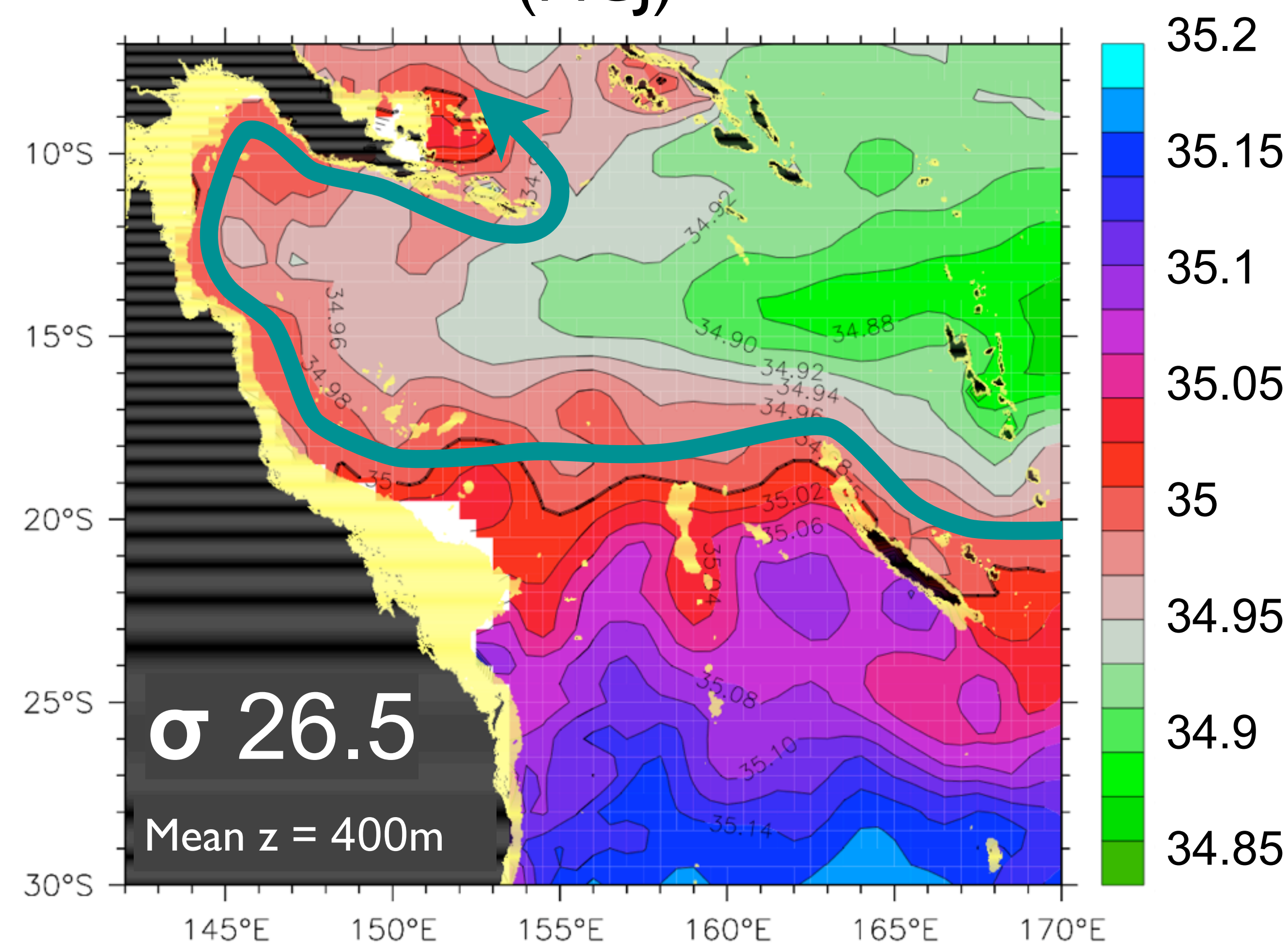
Subducted in the eastern subtropics (~ 20°S,120°W)

Enters the Coral Sea north of Vanuatu

Splits, flowing:

- directly into the Solomon Sea, and
- south into the EAC.

At the base of the thermocline (NCJ)



Subducted in the Tasman Front (~ 35°S,160°W)

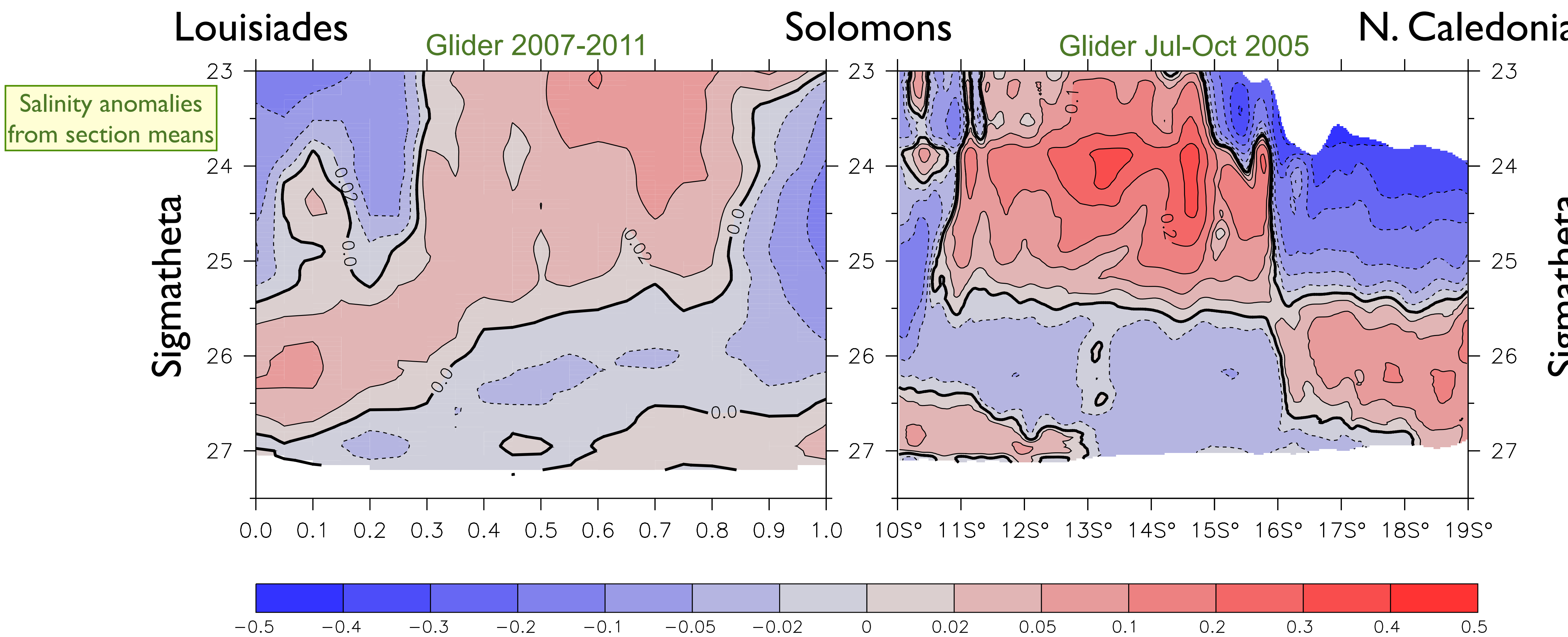
Enters the Coral Sea in the N. Caledonian Jet

Flows as a western boundary current

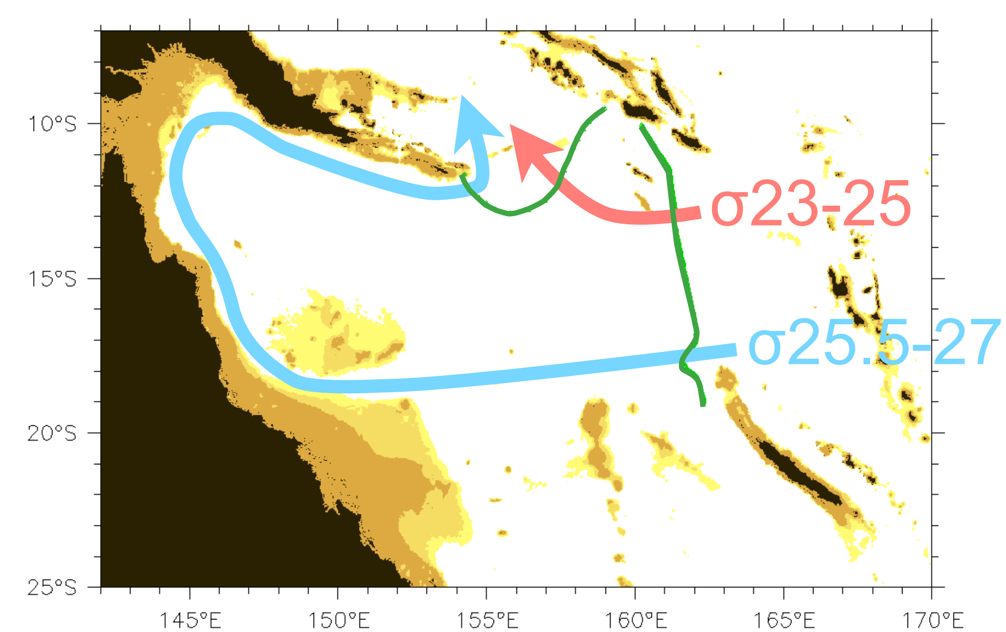
- along the Queensland and PNG coasts into the Solomon Sea.

Kessler and Cravatte (2013)

Salinity anomalies on isopycnals: 2 glider sections from the Solomons



Glider sections from the Solomons to:
- New Caledonia (Jul-Oct 2005)
- Louisiades (15 sections, 2007-ongoing) (green lines at right)

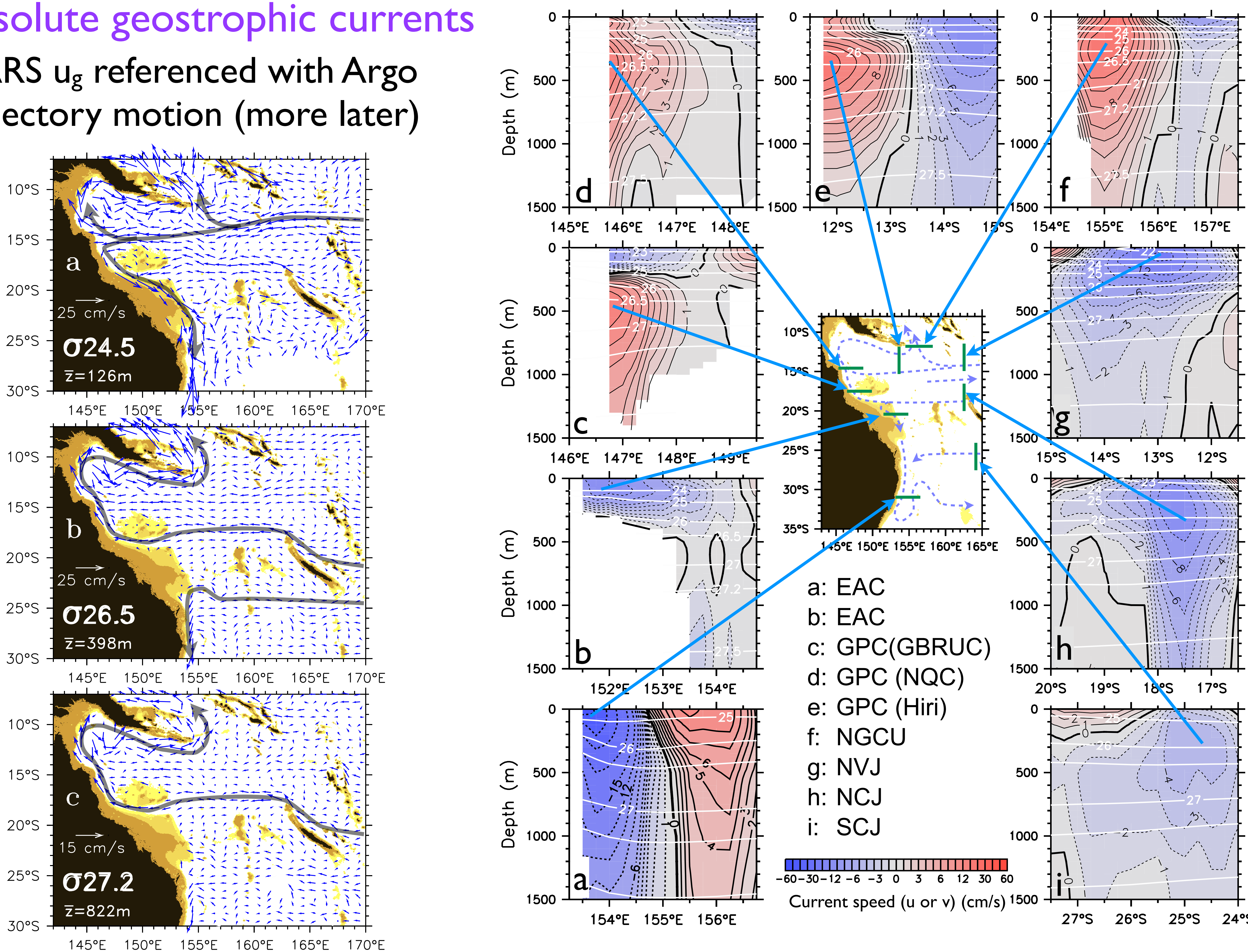


High-S tongues carried across and around the Coral Sea at shallow and mid-depth isopycnals

Kessler and Cravatte (2013)

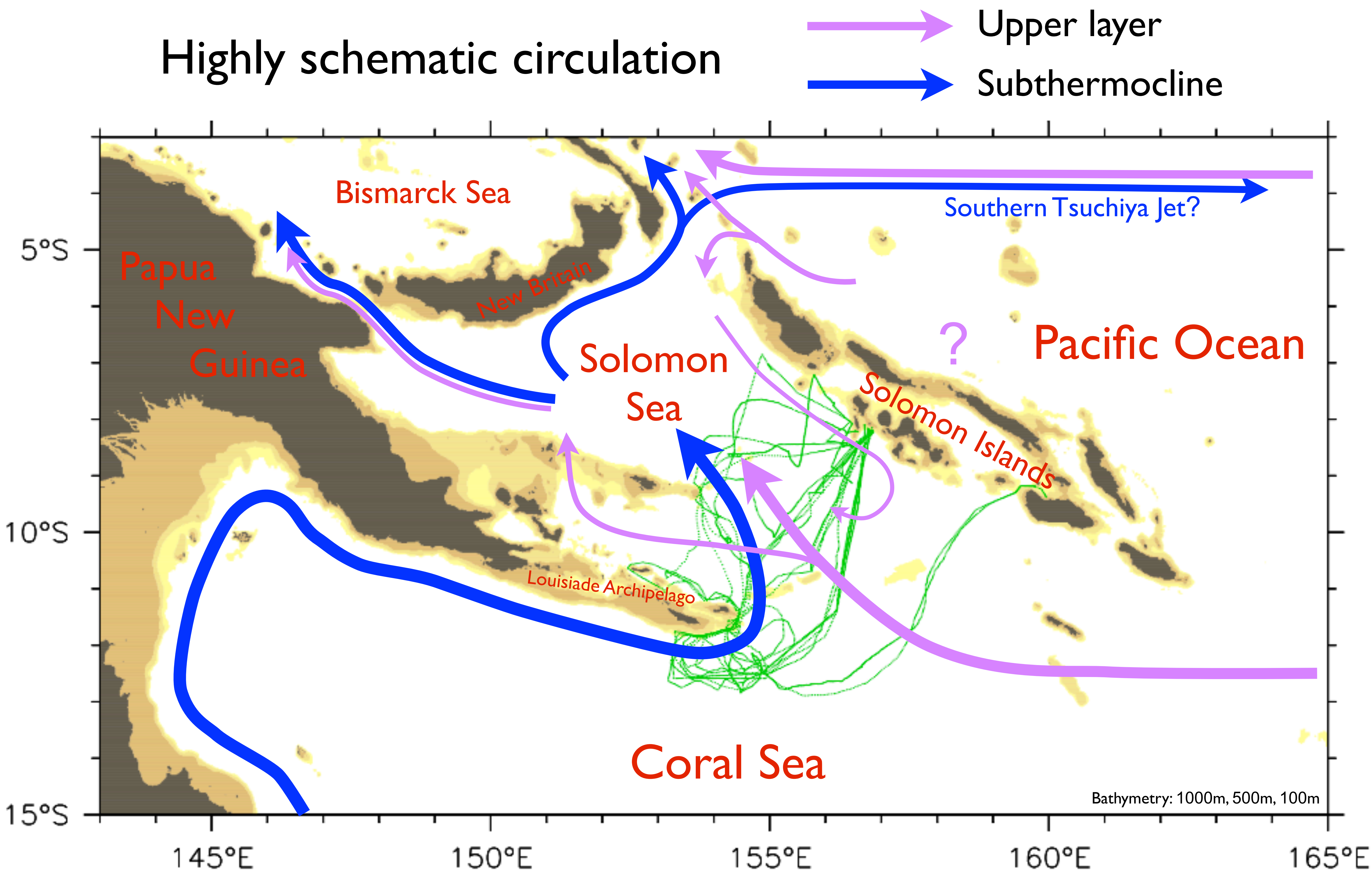
Absolute geostrophic currents

CARS u_g referenced with Argo trajectory motion (more later)



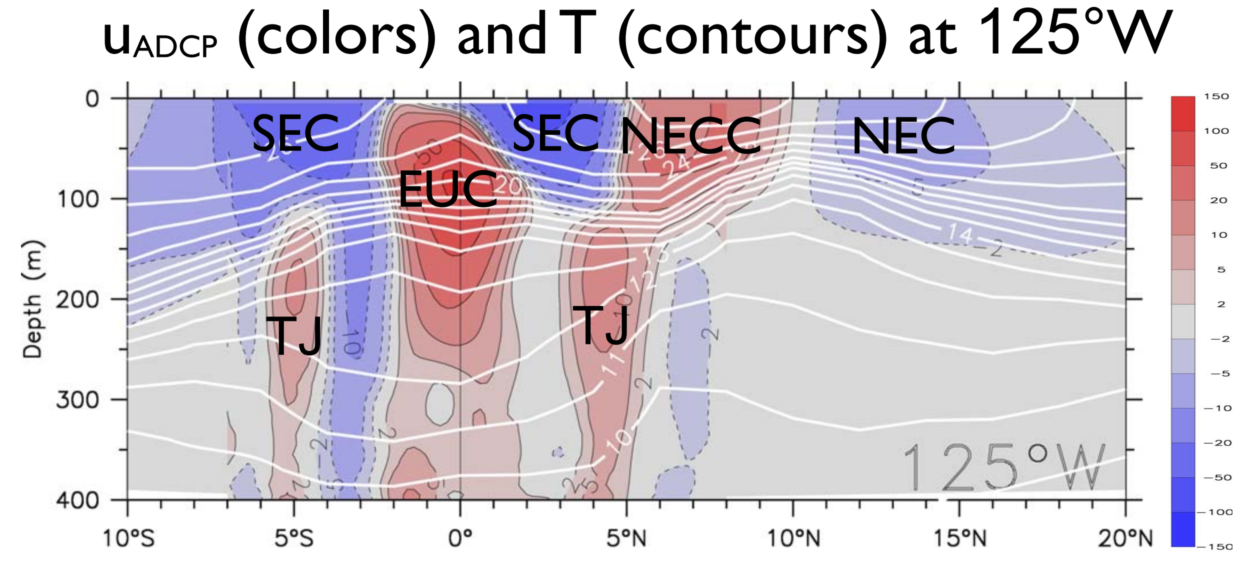
Kessler and Cravatte (2013)

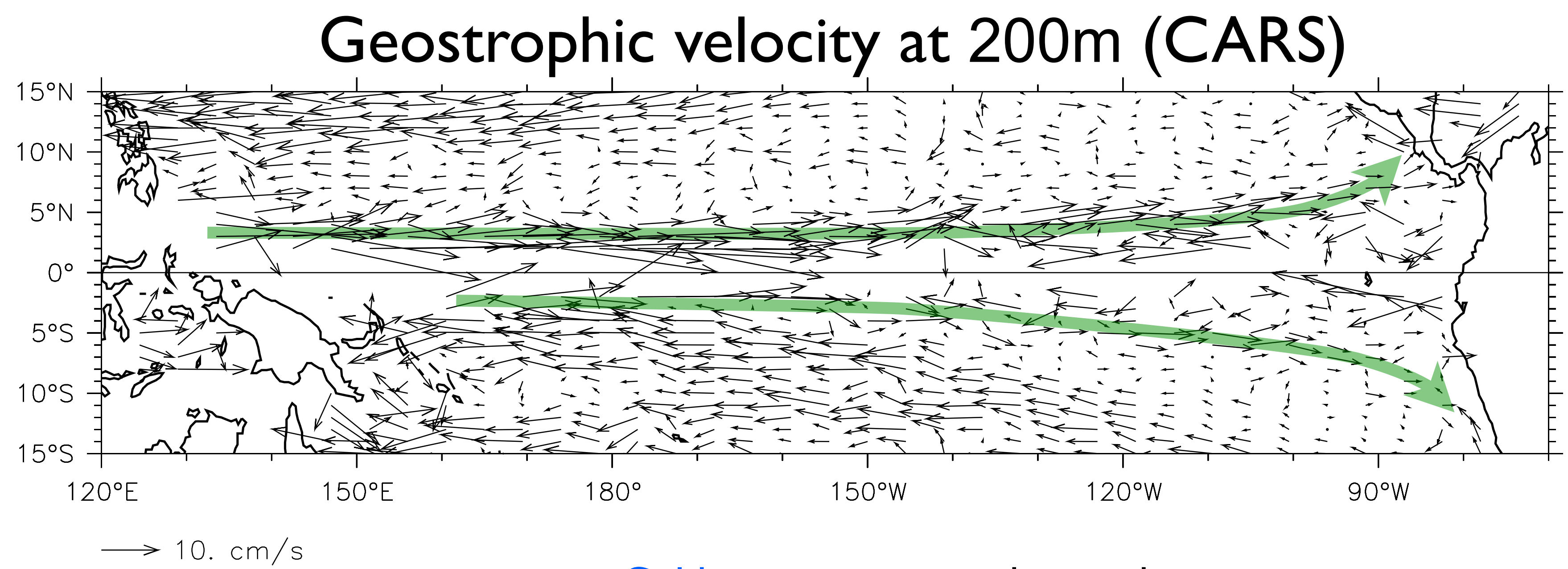
If NGCU is subthermocline, and (relatively) invariant at ENSO timescales, where does that water go?



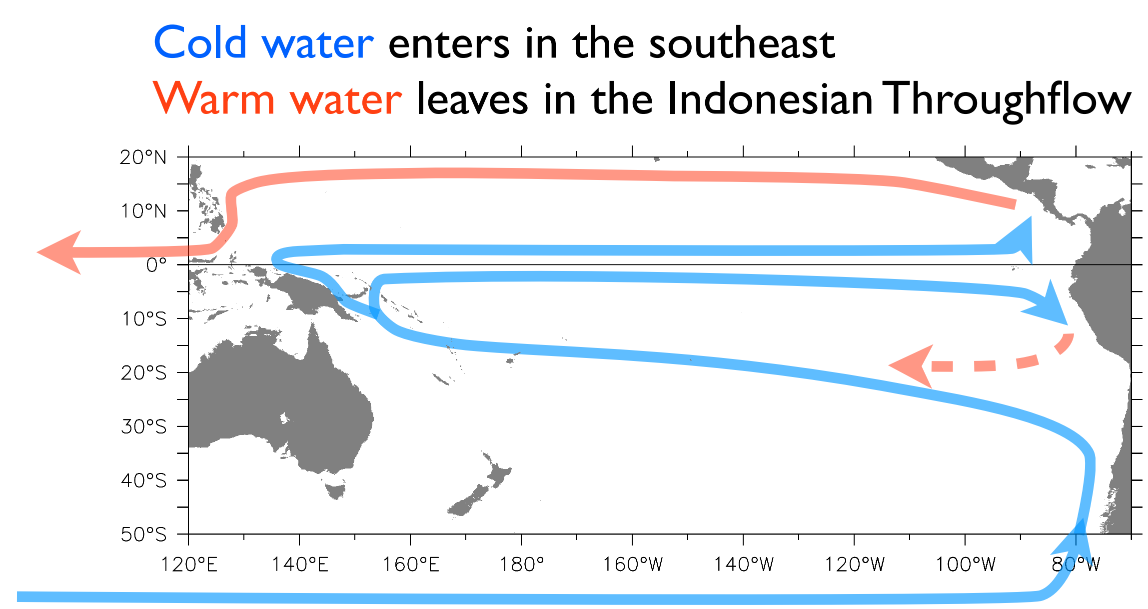
Tsuchiya Jets overview

Tsuchiya Jets flow across the entire Pacific at about 13°C (2-300m), feeding upwelling in the Costa Rica Dome and Peru coast.

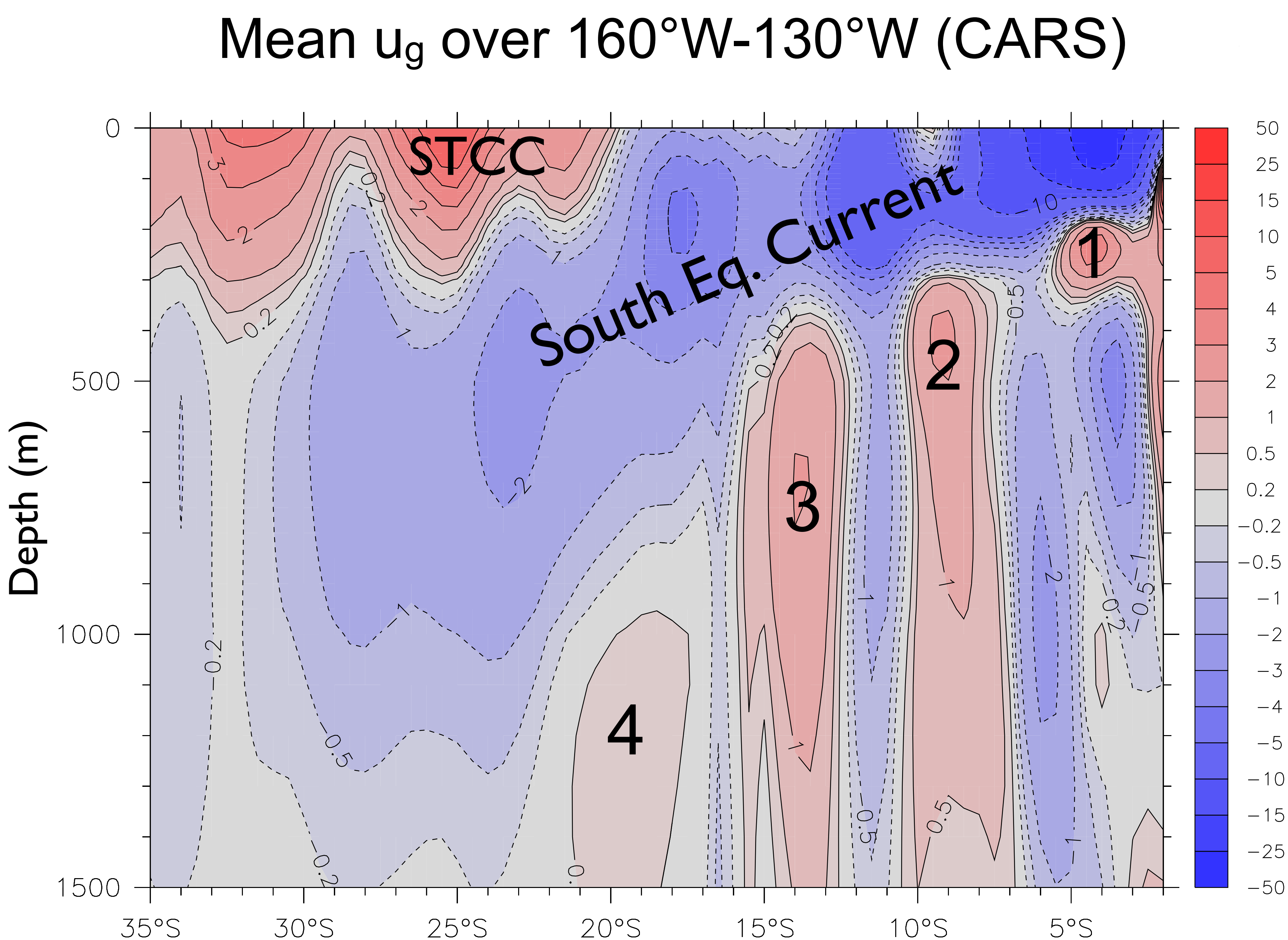




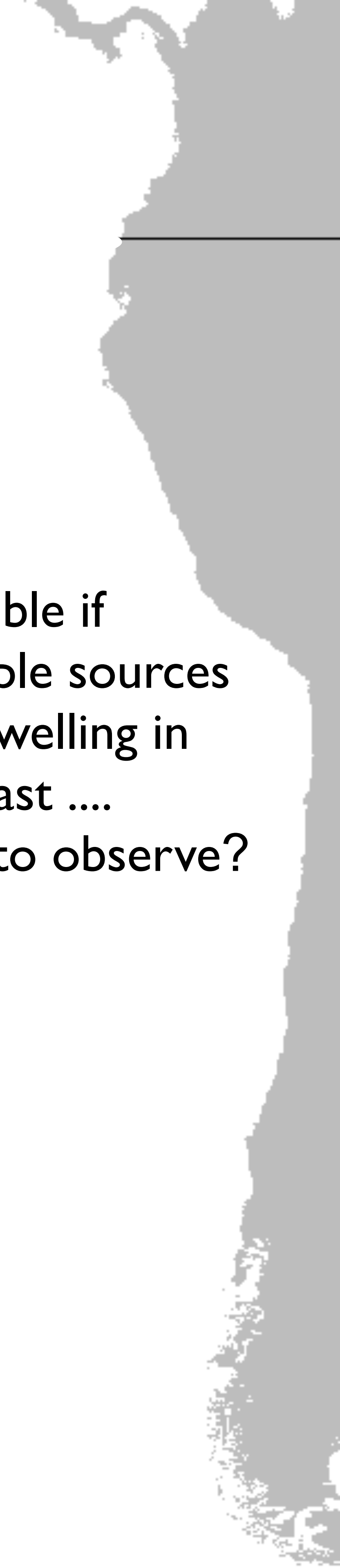
Water entering the South Pacific must
(a) be lifted through the thermocline, and
(b) cross the equator
Equatorial upwelling is shallow (next slide), but CR Dome and Peru upwelling reaches much deeper (β-plume).



Secondary, tertiary, quaternary Tsuchiya Jets?



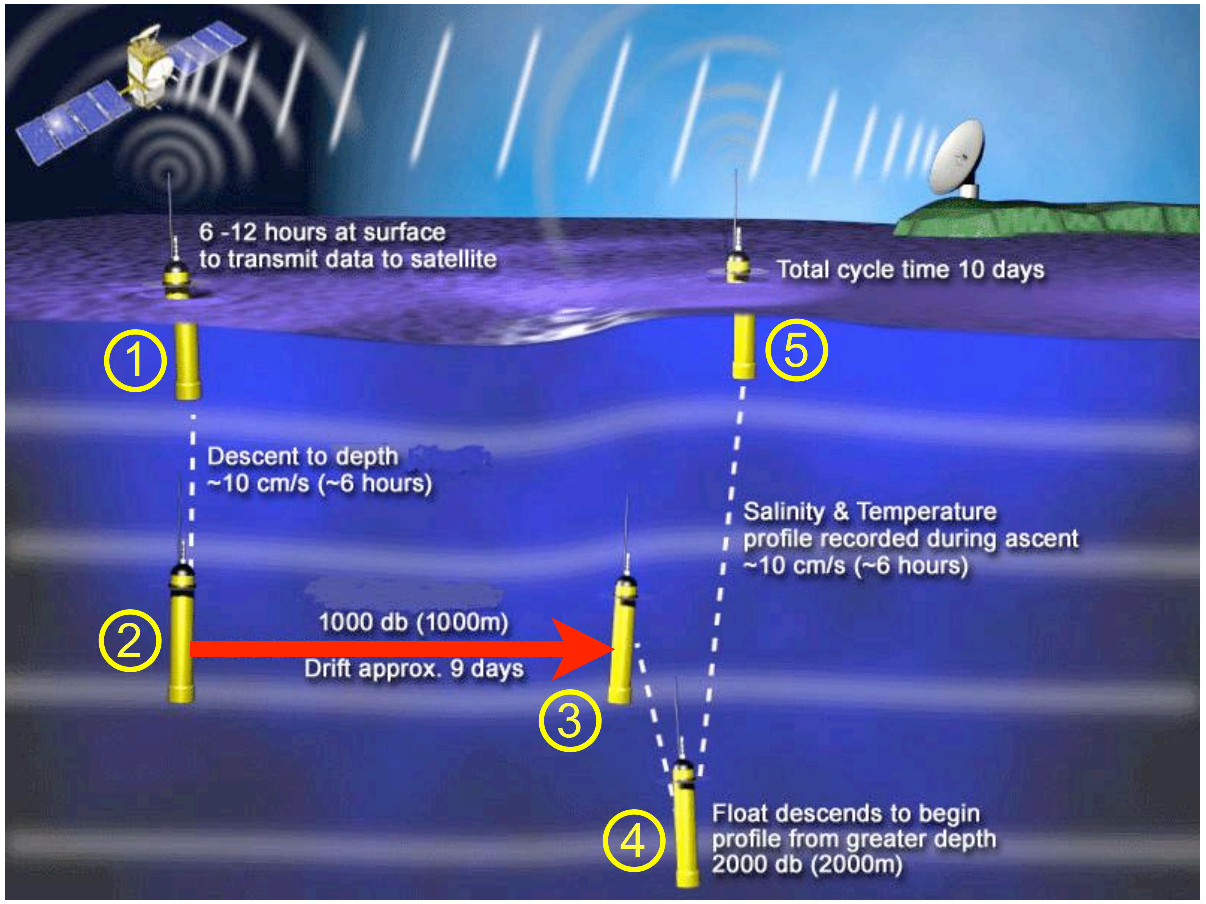
Plausible if multiple sources of upwelling in the east ....
how to observe?



Treatment of Argo trajectory data

1 - Select all (892) Argo floats in the box 120°E-80°W, 12°S-12°N, from 1/2003 à 8/2011

2 - Calculate subsurface velocities from float motion (Park et al., 2005) ...



IF:

- Times of all 5 "events" are known

... and if ...

- Advection during ascent, descent and surface drift can be estimated (usually geostrophy + Ekman drift)

THEN:

Subsurface advection (red arrow) can be estimated.

BUT:

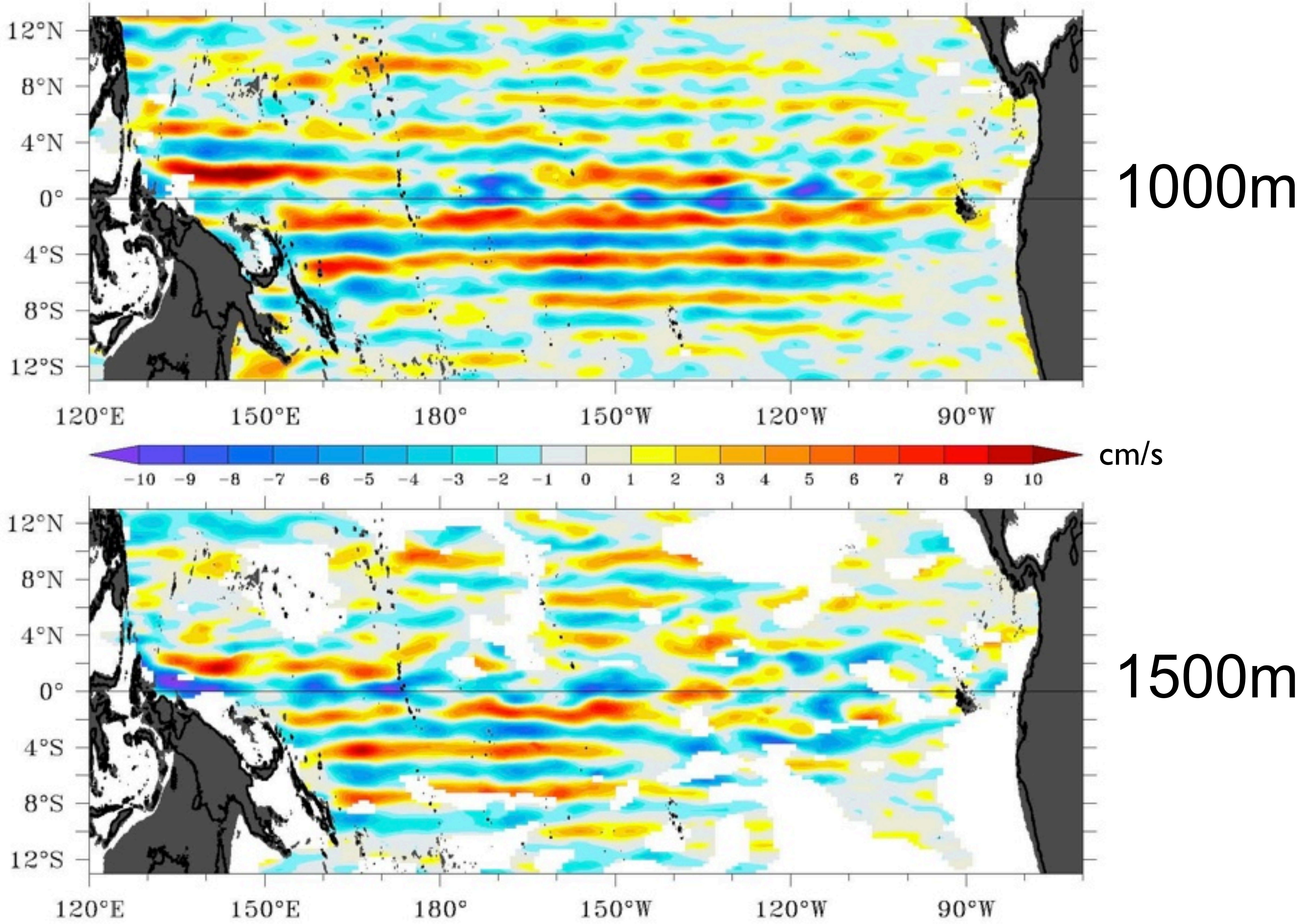
This information is often missing.

3 - Quality control (vital!): bad GPS hits, too-high speeds, grounding, ...

many visual and statistical checks (about 87% of 107k values eventually accepted).

Estimate median error ~0.4 cm/s from unsampled motion during ascent and descent.

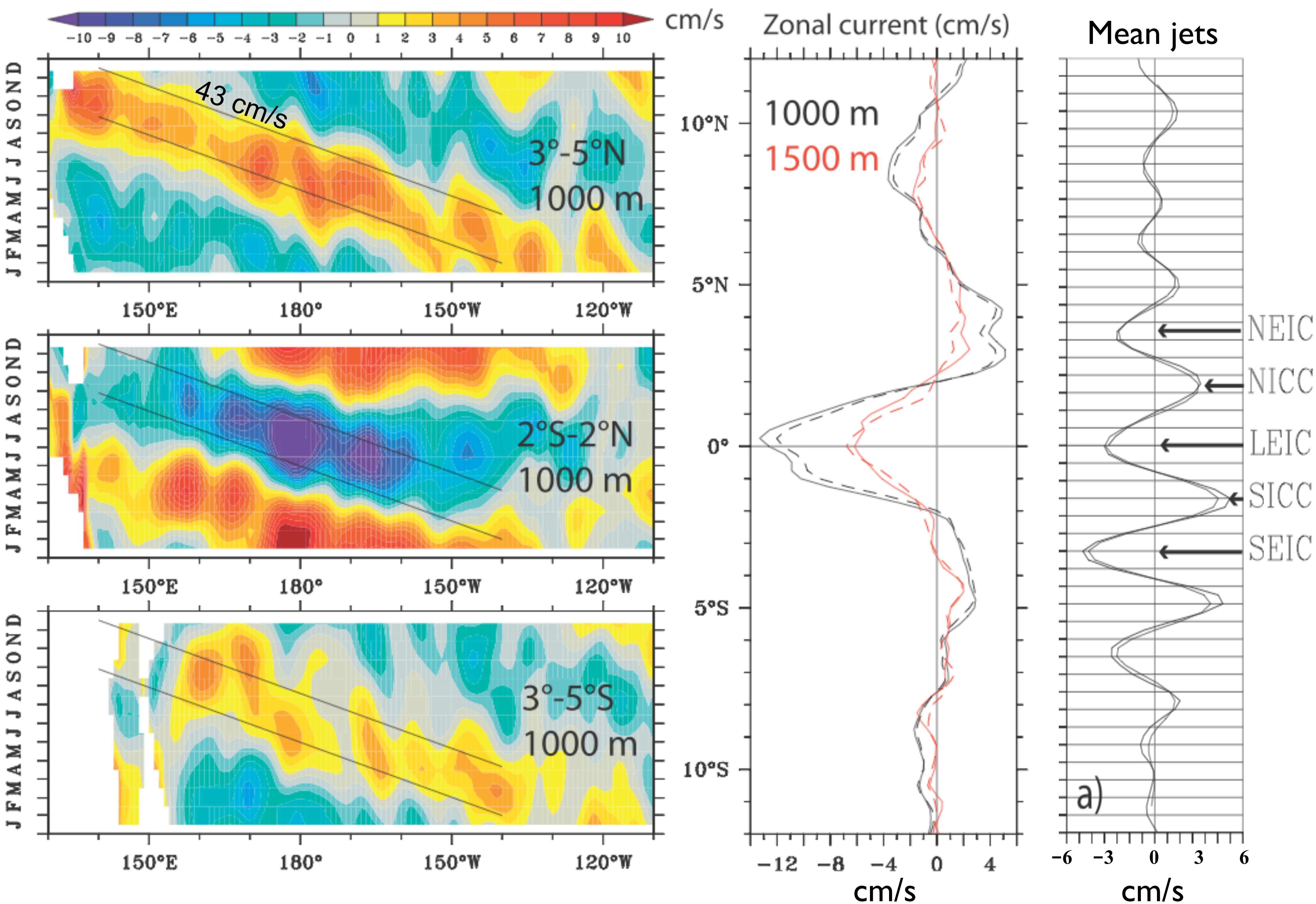
Mapped u at 1000 and 1500m



Cravatte, Kessler and Marin (2012)

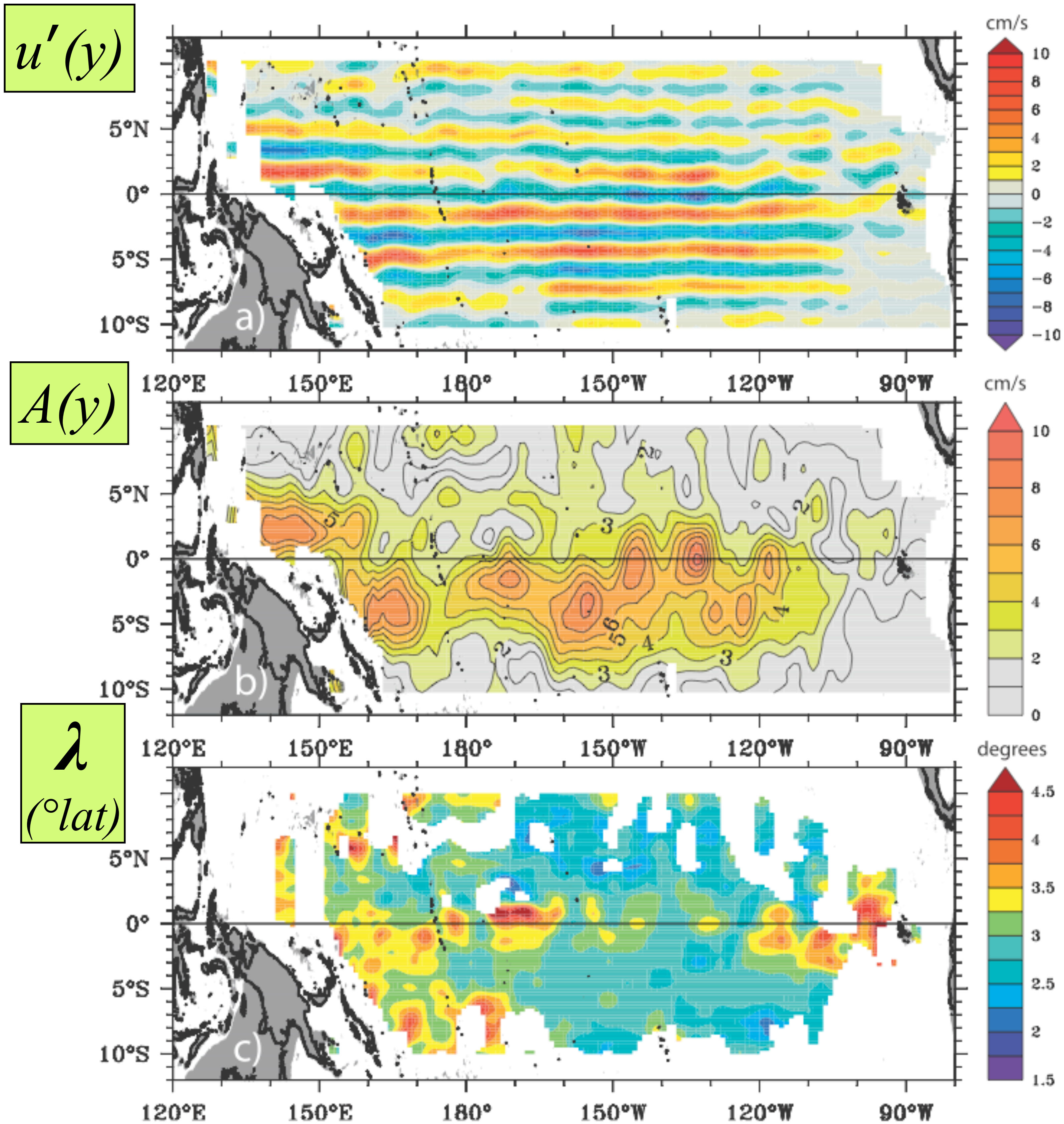
Annual cycle of u is the well-known vertically-propagating Mode 1 Rossby wave

- Annual propagation at same speed as found from earlier studies (of temperature variance)
- Annual cycle variance has different meridional structure from the background mean jets
- Large annual amplitude (implies jets can transiently "reverse")



Cravatte, Kessler and Marin (2012)

Meridional scale: ~300 km between crests



Complex demodulation: → LOCAL wavelength

$$u'(y) \sim A(y)cos(ky+\phi(y)) + Z(y)$$

Initial guess for k,

Solve for $A(y)$ and $\phi(y)$.

Interpret $\phi(y)$ as a slowly-varying wavenumber modification.

Results:

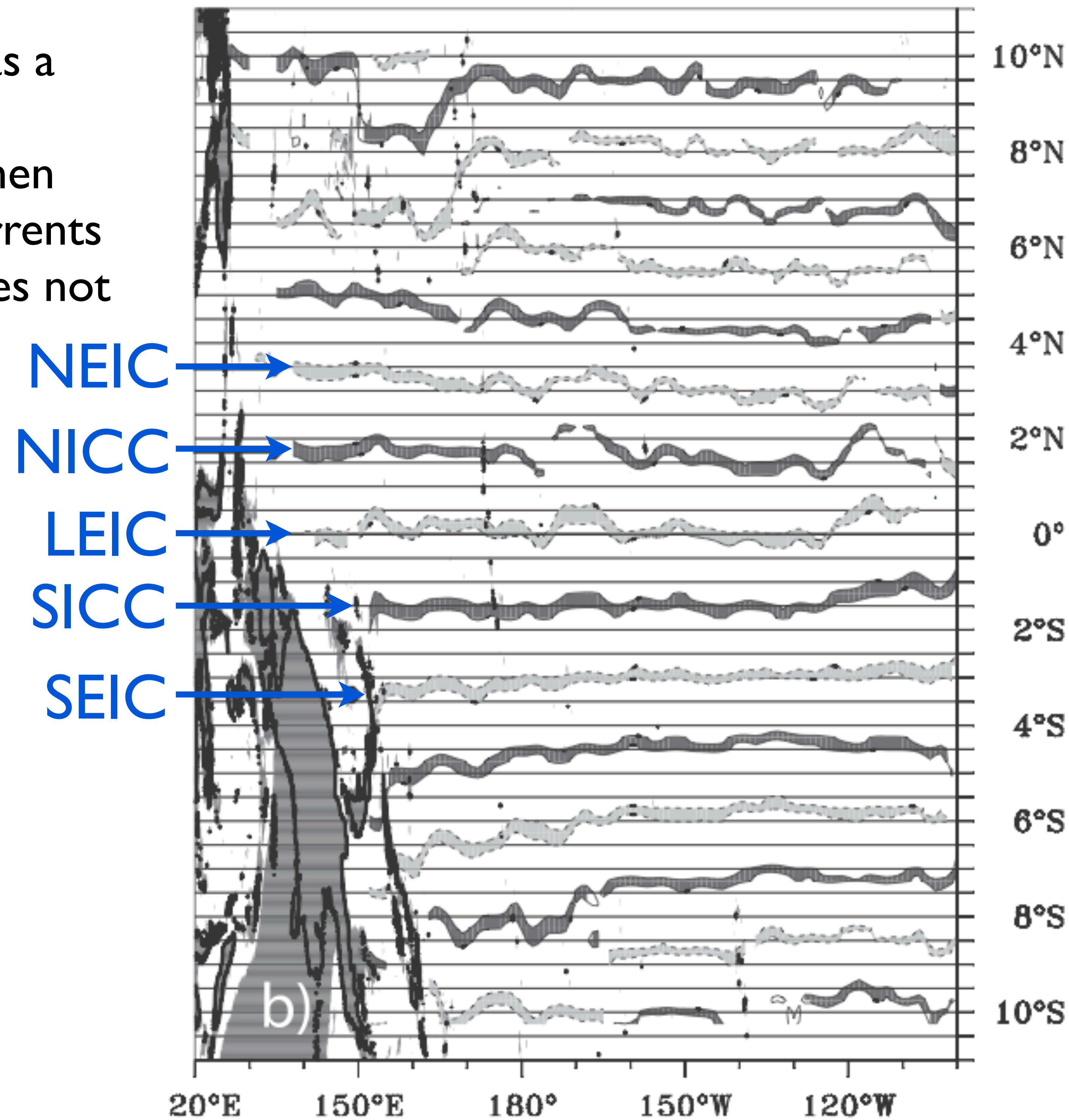
- Larger amplitude in the south (about ±5 cm/s)
- Meridional scale: about 300km (slightly larger in the west)
- Slant poleward in the west

Cravatte, Kessler and Marin (2012)

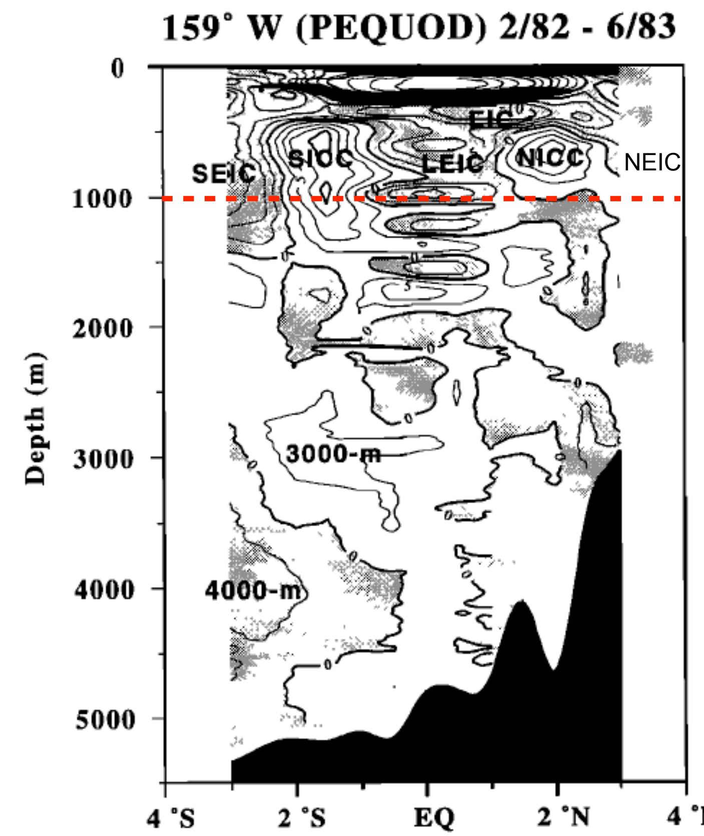
Jets slant poleward in the west

Eastward (dark) and westward (light) crests

If the pattern as a whole is a unit (I think it is), then naming the currents individually does not make sense.



(Firing et al. 1998)

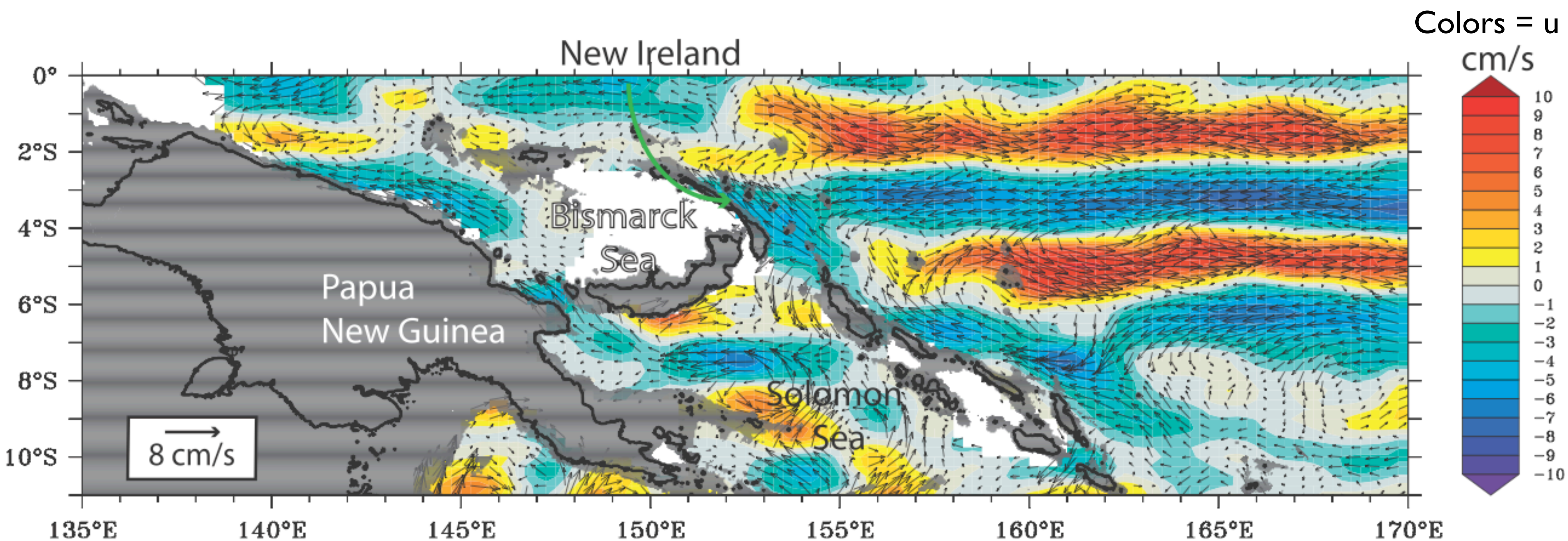


Northern jets shallower (why?). This might be why they appear weaker at 1000m.

Cravatte, Kessler and Marin (2012)

Jets arise close to the western boundary

They are connected by narrow western boundary currents



(Not enough data in the far western northern hemisphere)

Cravatte, Kessler and Marin (2012)

Ideas about "striations"

1) β-plume. A vorticity source (meridional flow past a topographic feature, or forced upwelling) generates a horizontal circulation much larger than the initial impulse. It produces a pair of opposite jets extending west. This is thought to be the origin of the striations seen in SSH west of California. (Maximenko)
Unlikely: No eastern source or features on the short meridional scale of the jets.

2) Rectified (dissipating), vertically-propagating equatorial waves (Ascani)
Monthly-period Yanai waves break, Stokes drift rectifies into a true mean flow.
Unlikely (?): Would be confined to near the equator (3 jets).
Does not explain why the jets increase in speed to the west.

3) Sampling artifact of a train of eddies on a latitude line (Chelton)
Unlikely (?): Would need a generation mechanism for eddies on this merid. scale.

4) Self-advection of relative vorticity on the flanks of a forced jet. (Kessler/Moore)
The EUC advects cyclonic ζ on both sides eastward: increases both the initial jet and opposite-sign jets on both sides.
Unlikely (?): Hard to account for many reversals, does not explain western increase.

Conclude

- Gliders (4-6 RT/yr) sample the absolute transport through the Solomon Sea
- Strong ENSO signal, mostly in the upper layer, lagged behind ENSO indices consistent with linear theories.
- The NGCU core is deeper than the ENSO signal, and less variable.

- Argo float trajectories are a useful source of mid-depth flow (much QC)
- A zonal jet or striation pattern spans the tropical Pacific:

➔ The jet region is broader than equatorial (at least 20° latitude)

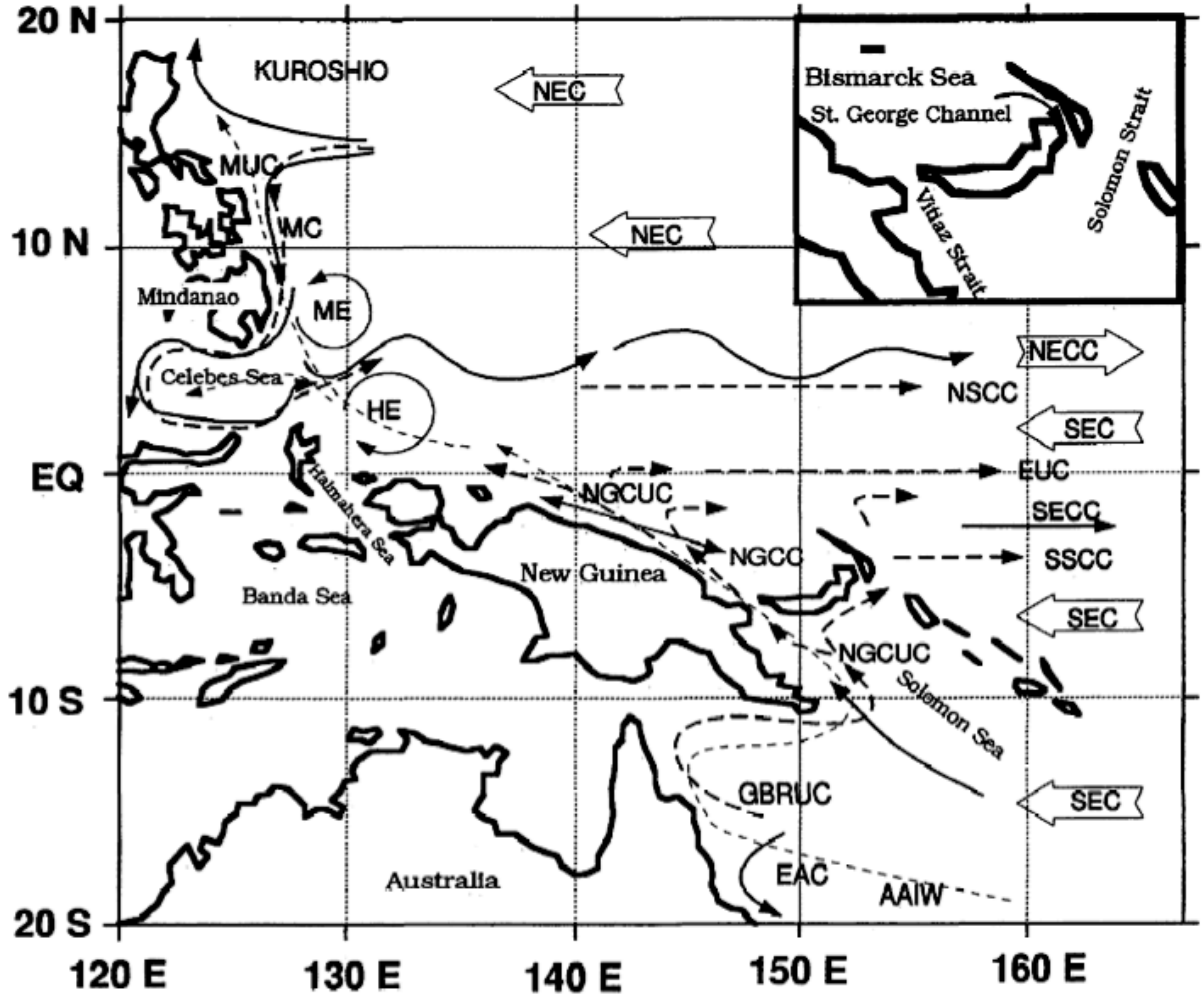
➔ The jets do not begin at the eastern boundary or topographic features

➔ Crest to crest scale ~300km;
slant poleward in the west, stronger in the west (and south?)

➔ We cannot detect time-dependence (about 6 years of data)

- Present theories do not account for this unified pattern spanning this wide latitude range.

Extra
figures
below

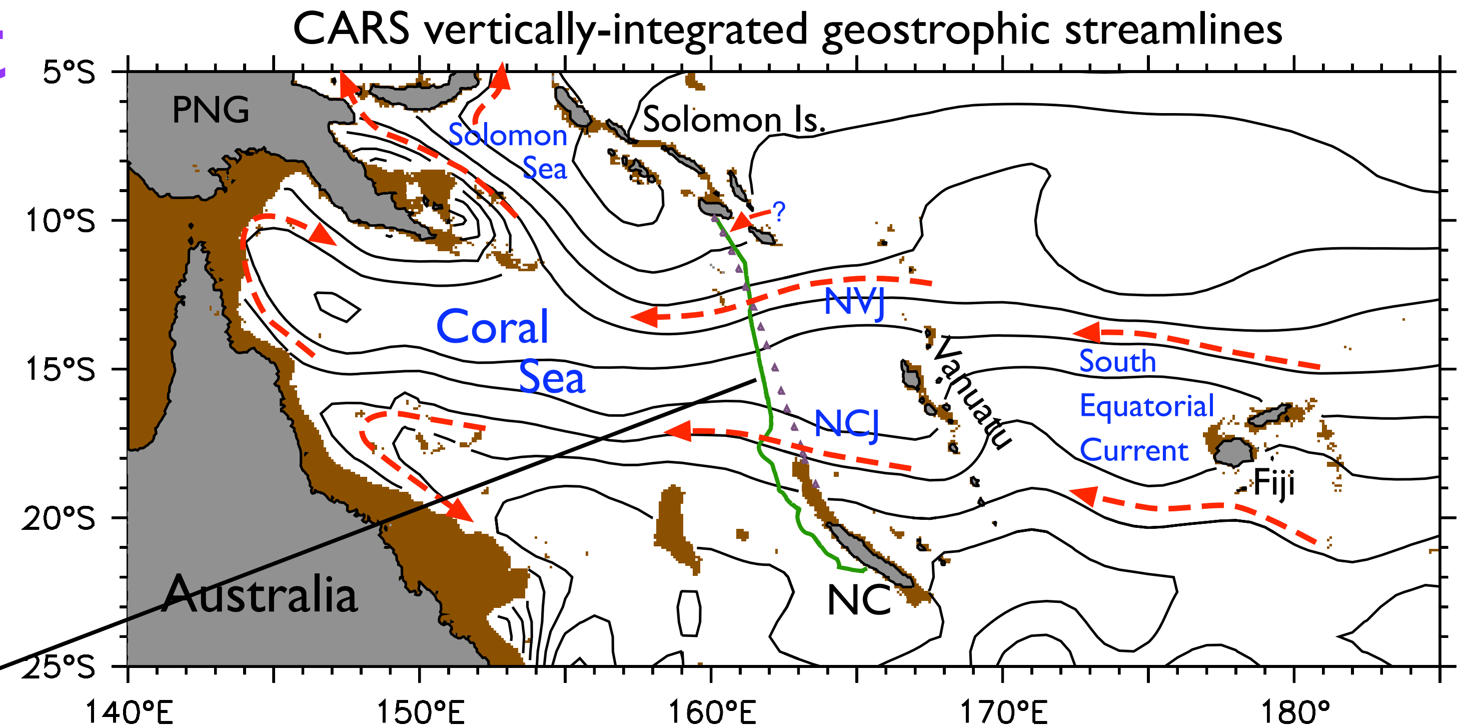


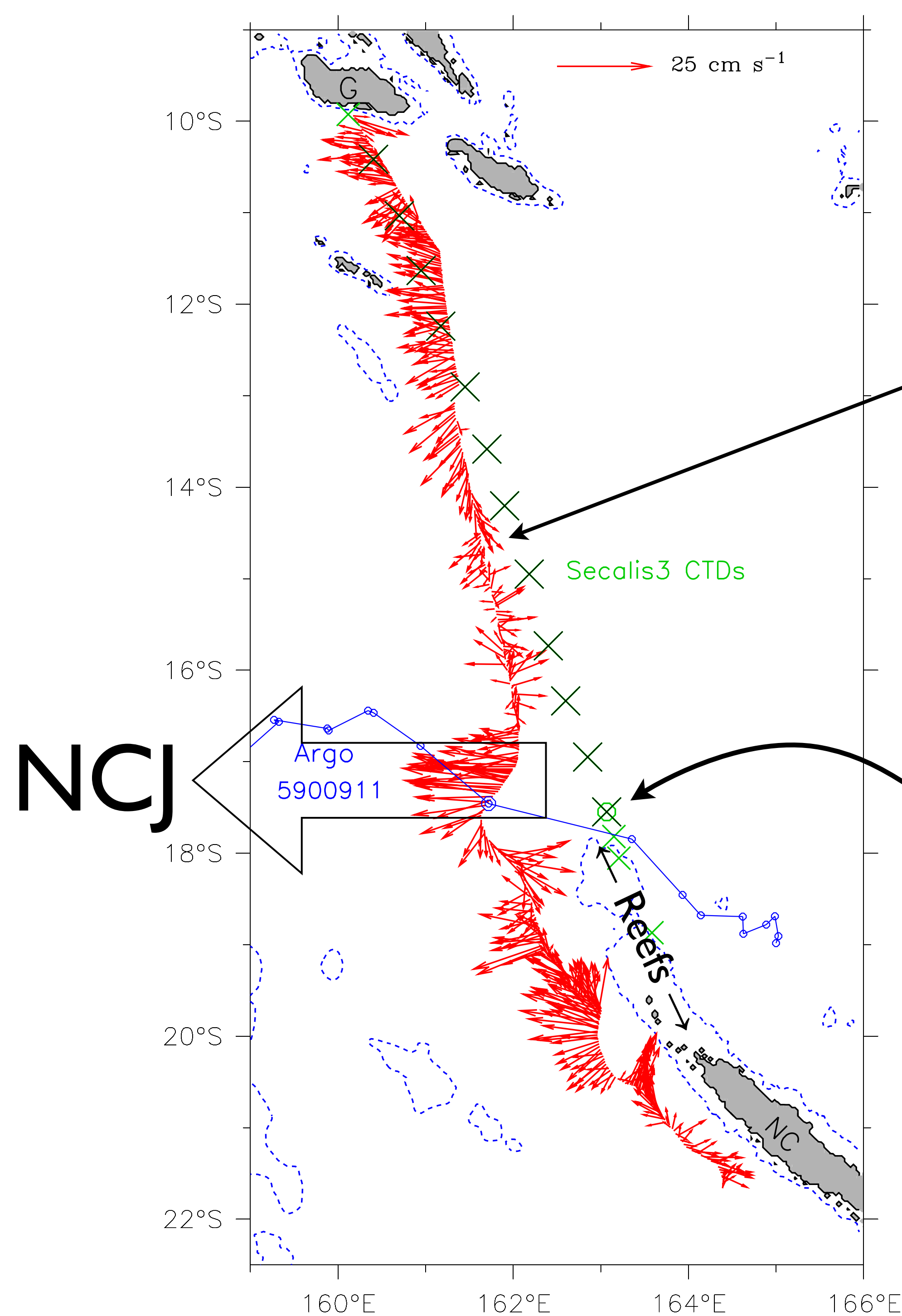
Fine et al., JGR 1994)

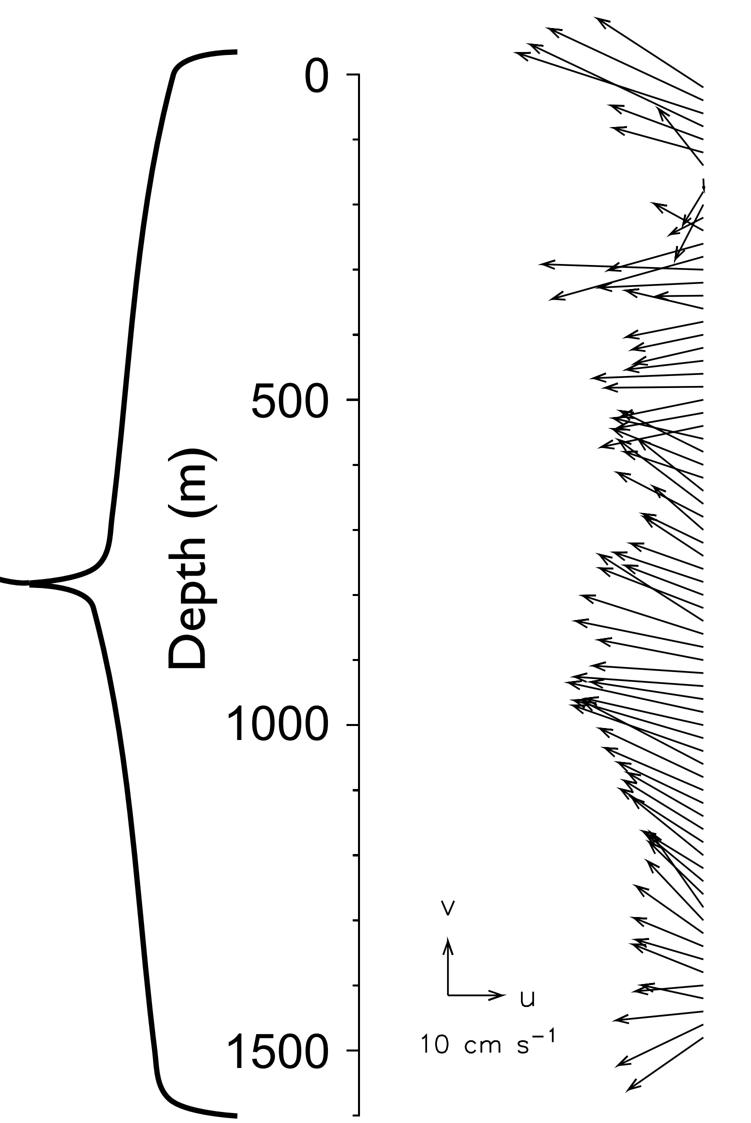
The North Caledonian Jet

precursor to the NGCU?

Gourdeau et al (2008)





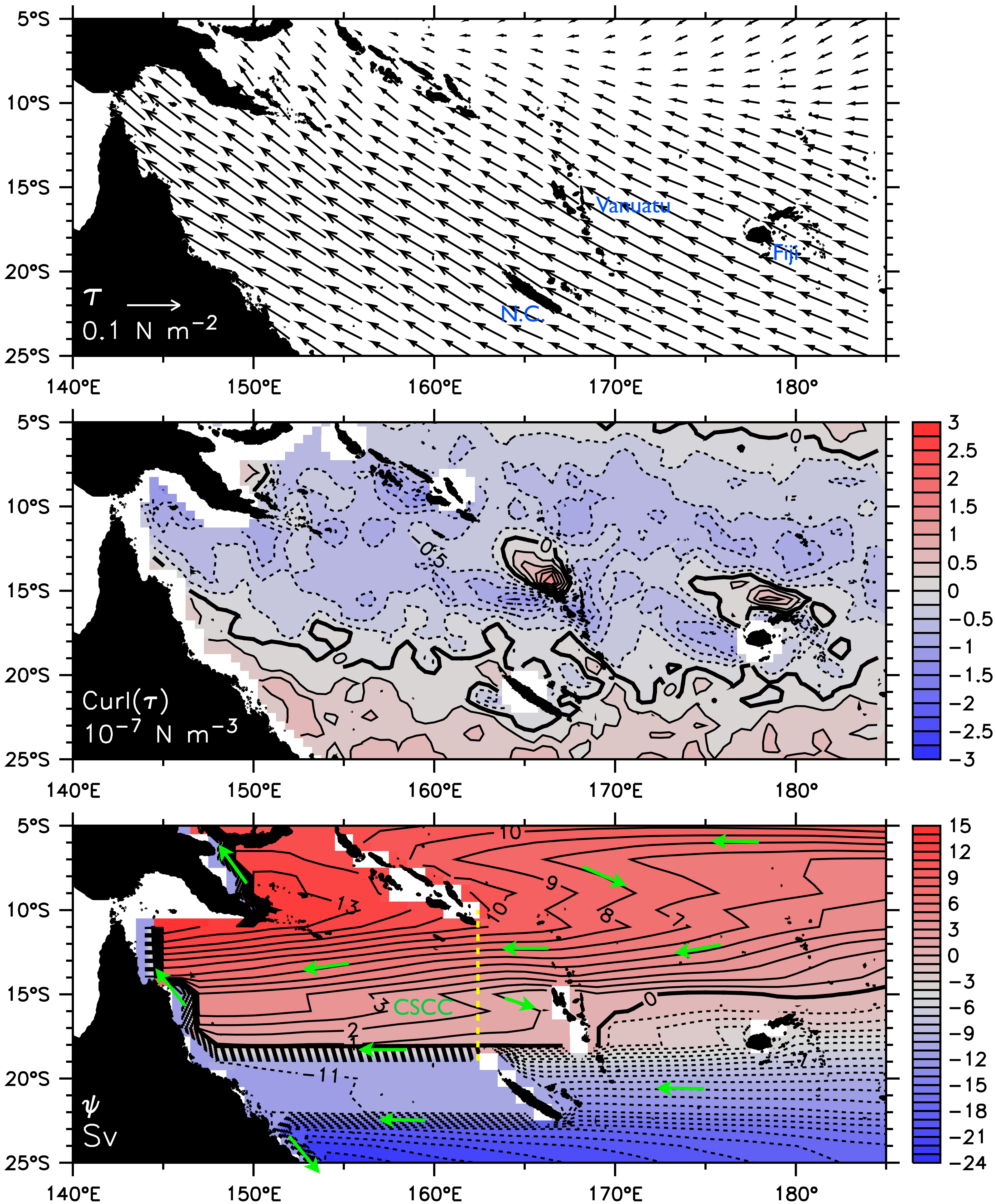


L-ADCP

in the center of the NCJ:

u > 20cm/s to 1500+m

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.

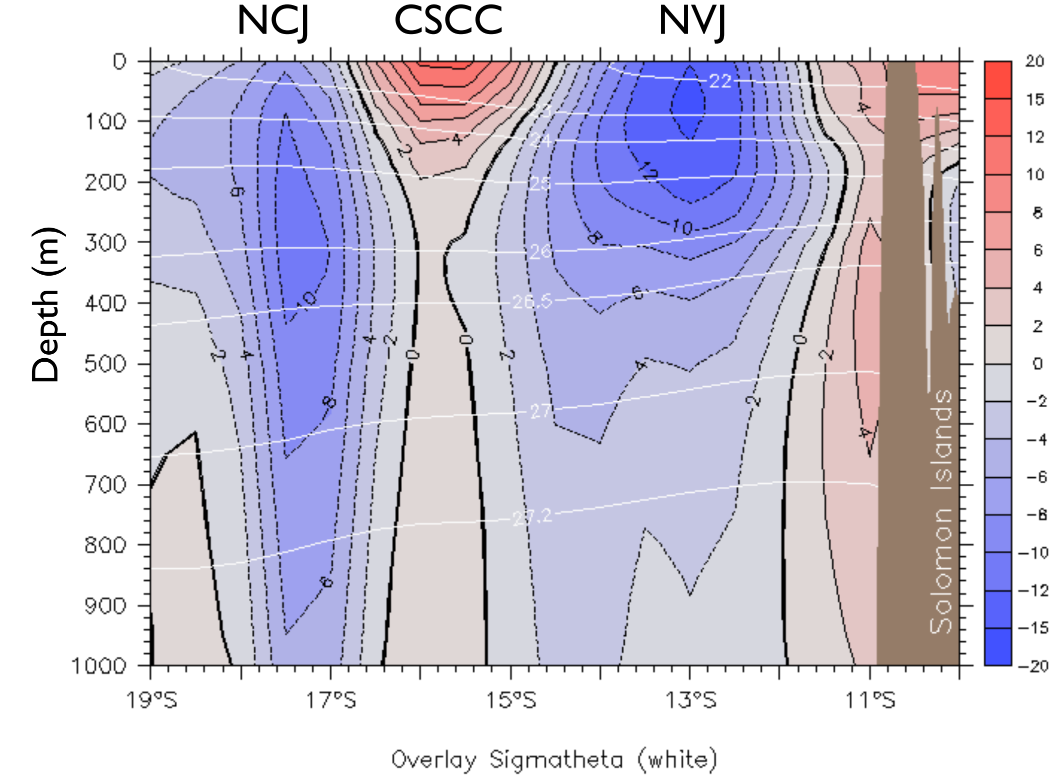
Two separate jets feed the Coral Sea:

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)

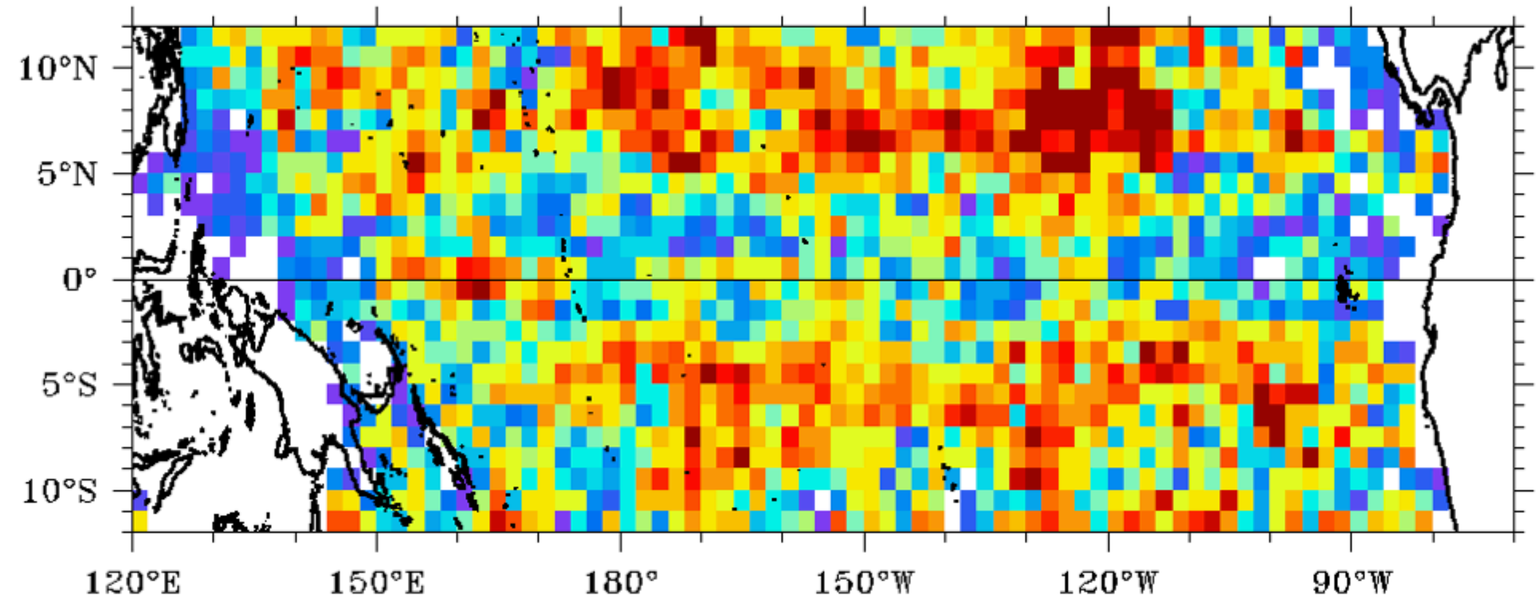
Mapped zonal current at 162.5°E



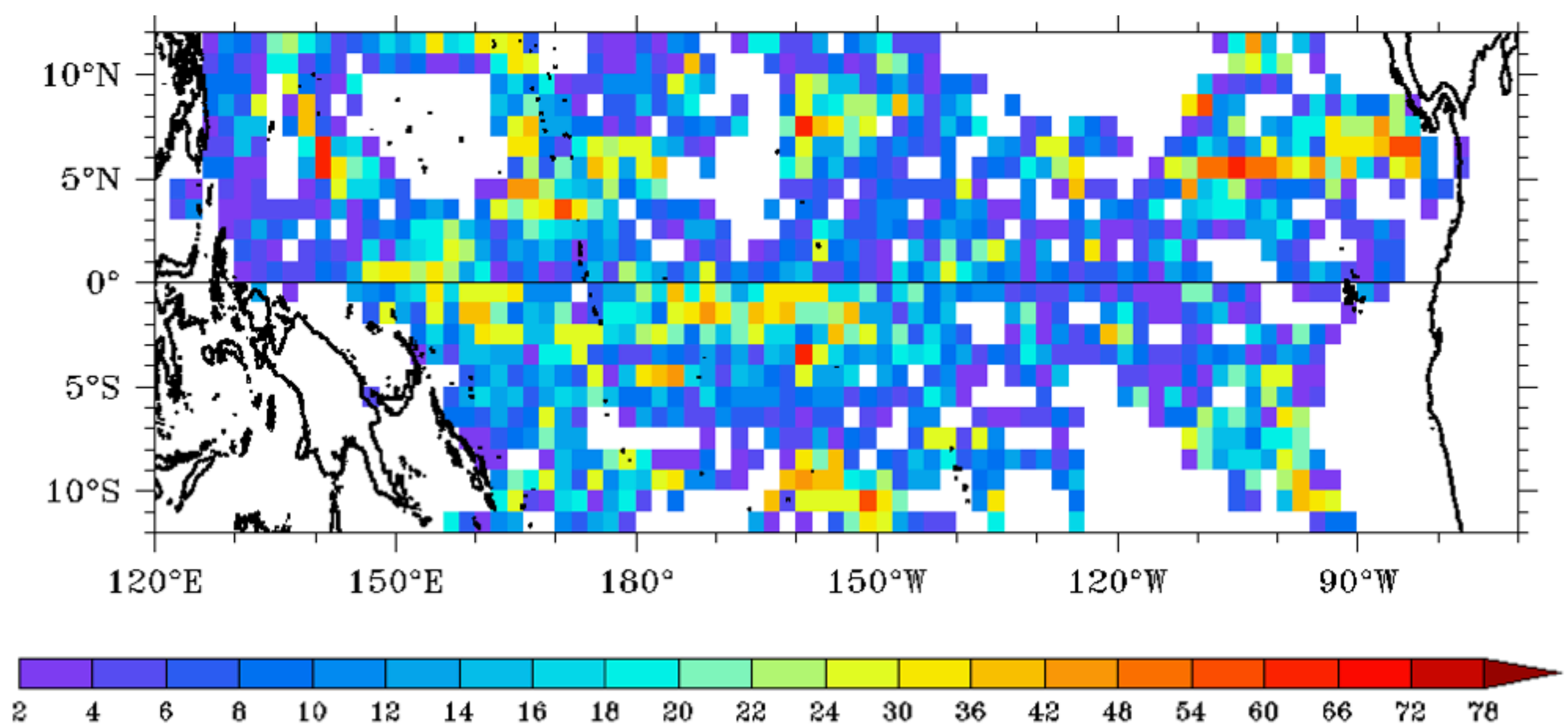
Argo data distribution

Number of velocity values in 2°x1° boxes
January 2003-August 2011

“1000m floats”: 950-1050m (68k samples)



“1500m floats”: 1450-1550m (15k samples)



Objective analysis of u and v:
Decorrelation scales:
x=330 km, y=55 km, t=3 mon

Get mean seasonal cycle:
Fields of (u,v) on a grid of
1° longitude by 1/4° latitude

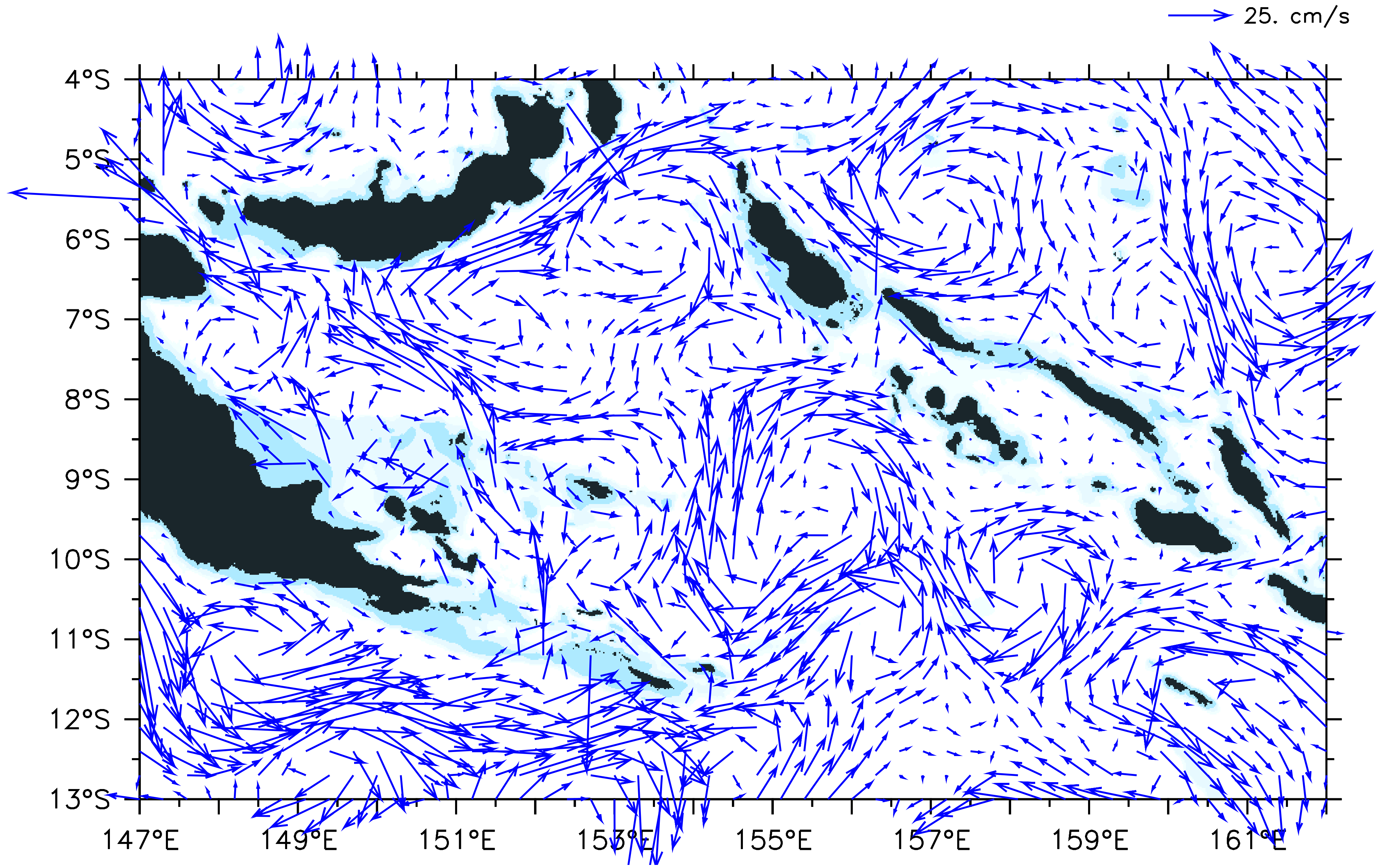
Cravatte, Kessler and Marin (2012)

Ocean model solutions show intense eddies.

⇒ Collaboration with modelers!

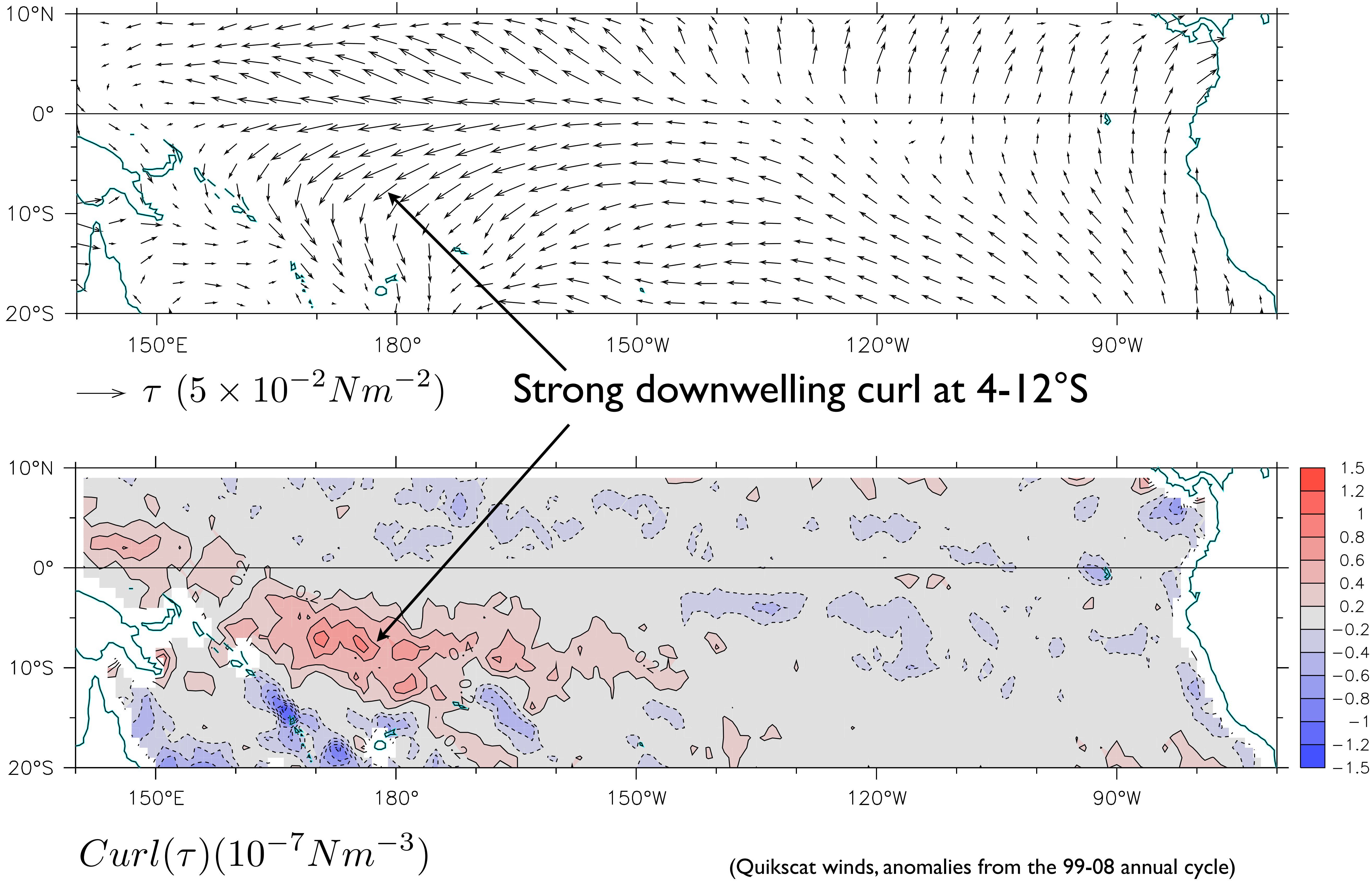
⇒ Altimetry to detect eddies.

Example of velocity from the Bluelink model (BOM)



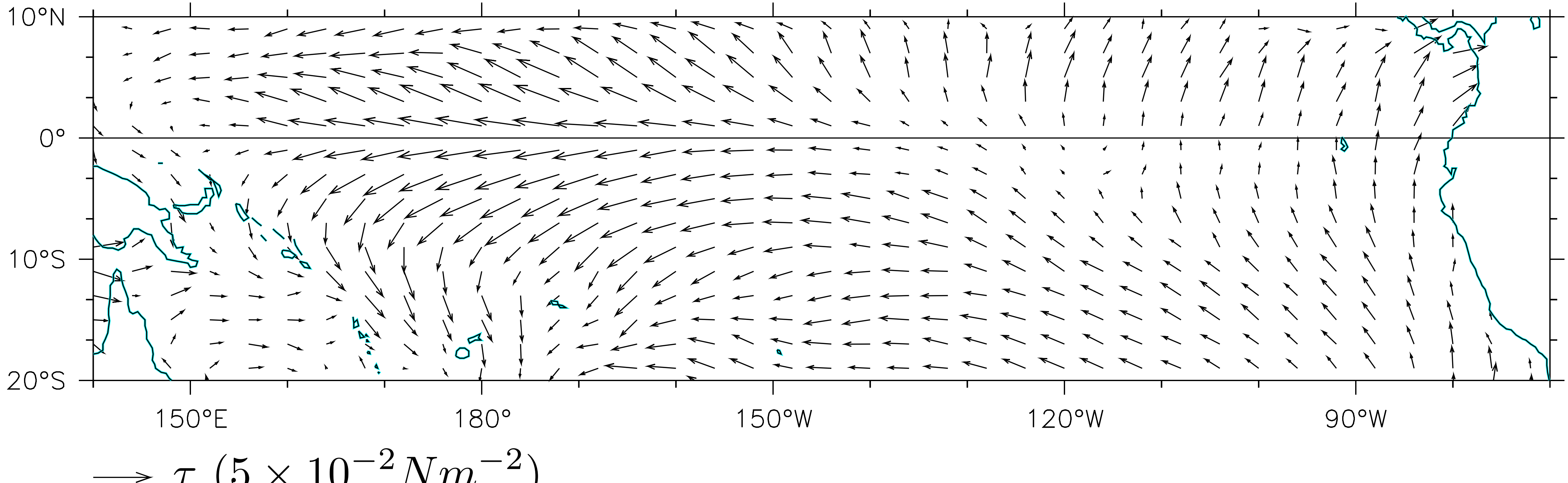
Bluelink example for 15-20 Oct 07

Anomalous winds and curl during Aug 07-Mar 08: La Niña

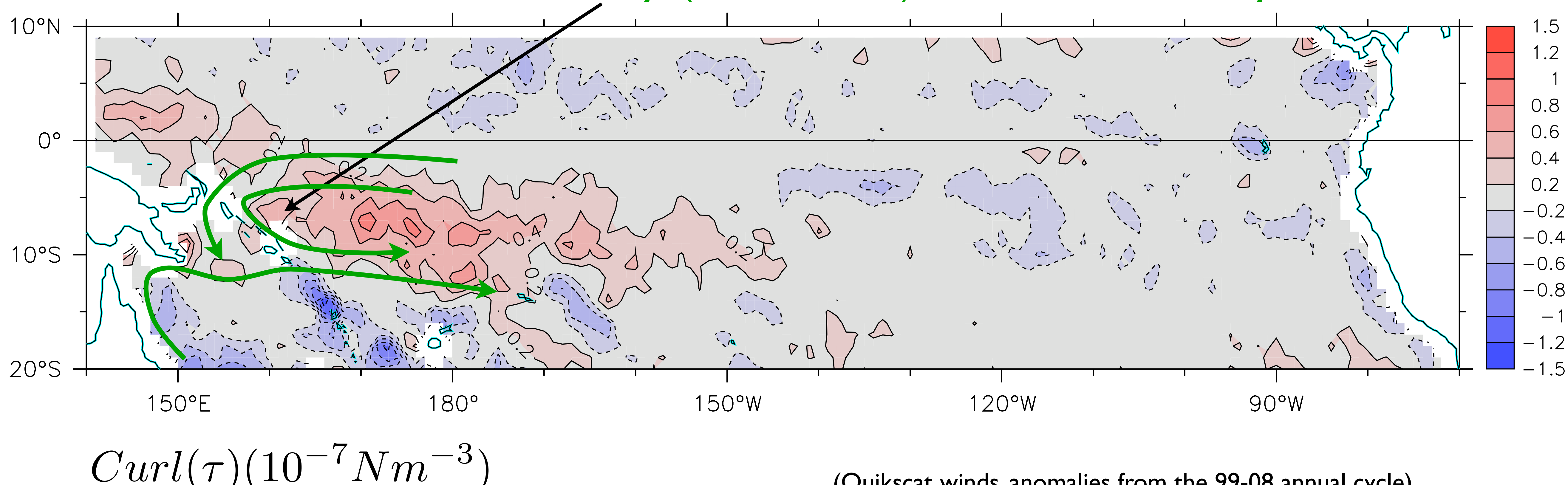


(Quikscat winds, anomalies from the 99-08 annual cycle)

Anomalous winds and curl during Aug 07-Mar 08: La Niña



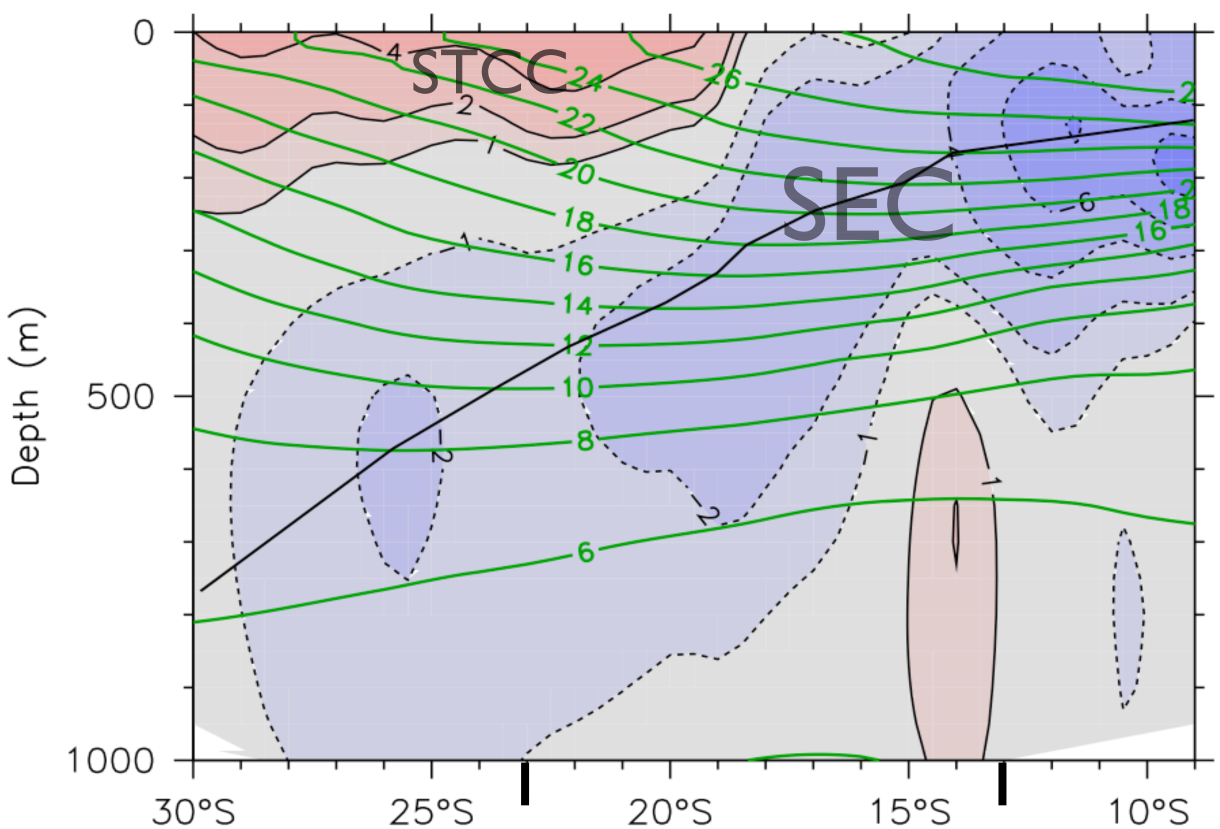
Rossby (Island Rule) solution driven by these winds



(Quikscat winds, anomalies from the 99-08 annual cycle)

Tilted subtropical gyre, tilted WBC bifurcation

175°W: Mean zonal current (color) and temperature (green contours)
→ SubTropical CounterCurrent ←



The bowl of the gyre tilts:
westward shear below,
eastward shear above.

CARS climatology (Ridgway & Dunn 2003)

An independent estimate of climatological alongshore velocity along the coast of Australia

Qu and Lindstrom (2002 JPO)

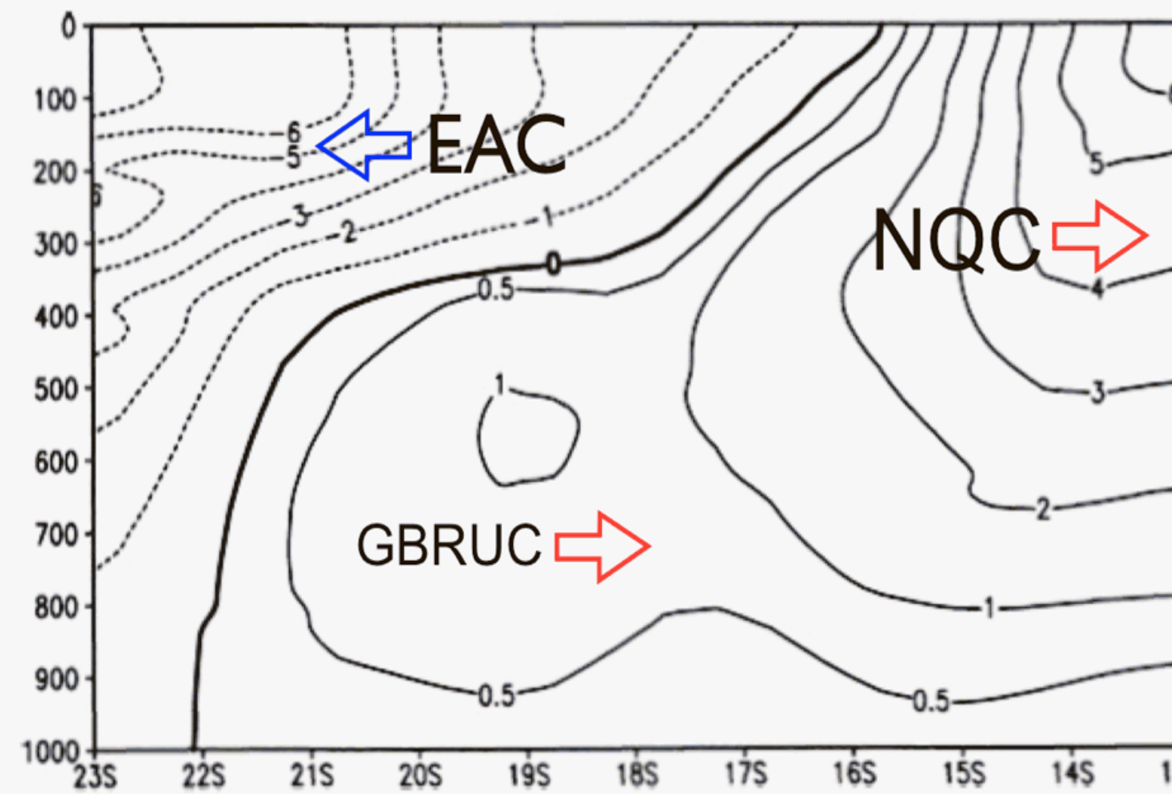


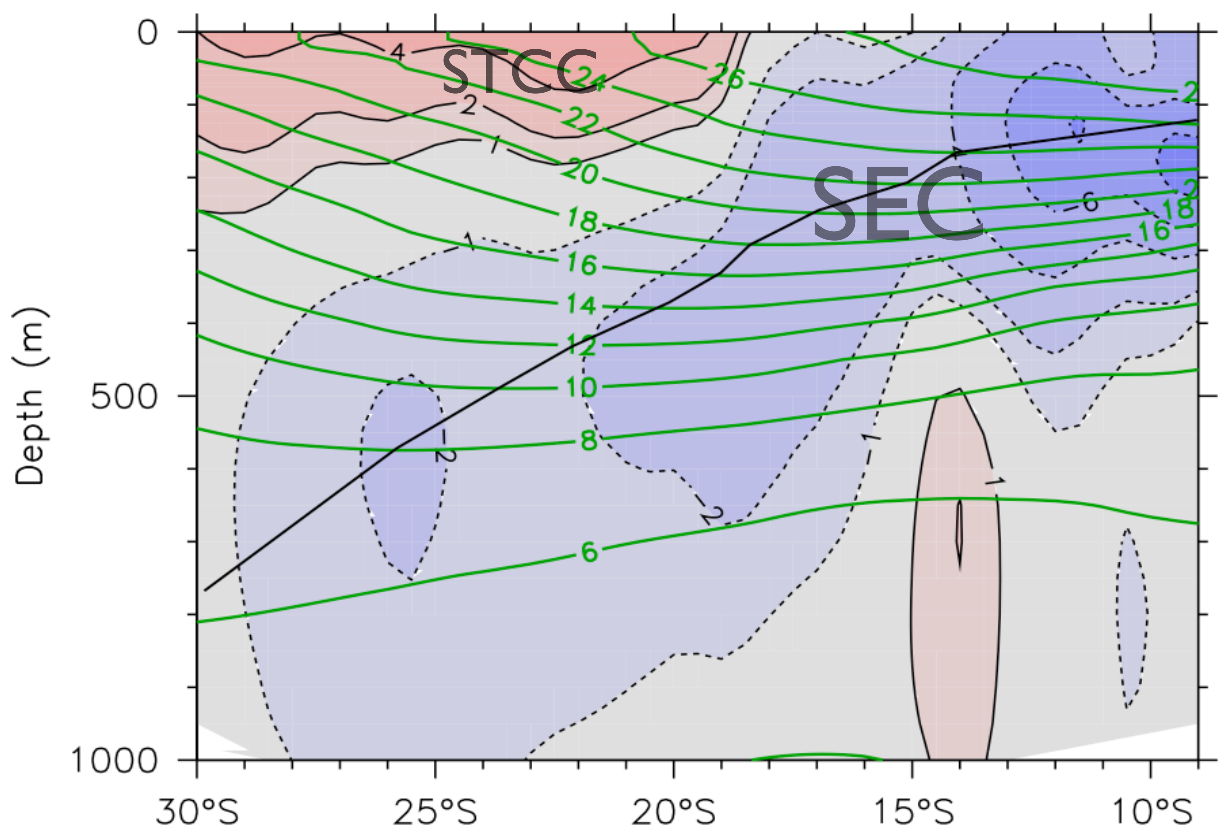
FIG. 9. Alongshore velocity (cm s^{-1}) averaged within 2° from the coast. Positive values are northwestward, and the contour of zero velocity indicates the bifurcation of the SEC.

From Qu and Lindstrom (2002 JPO)

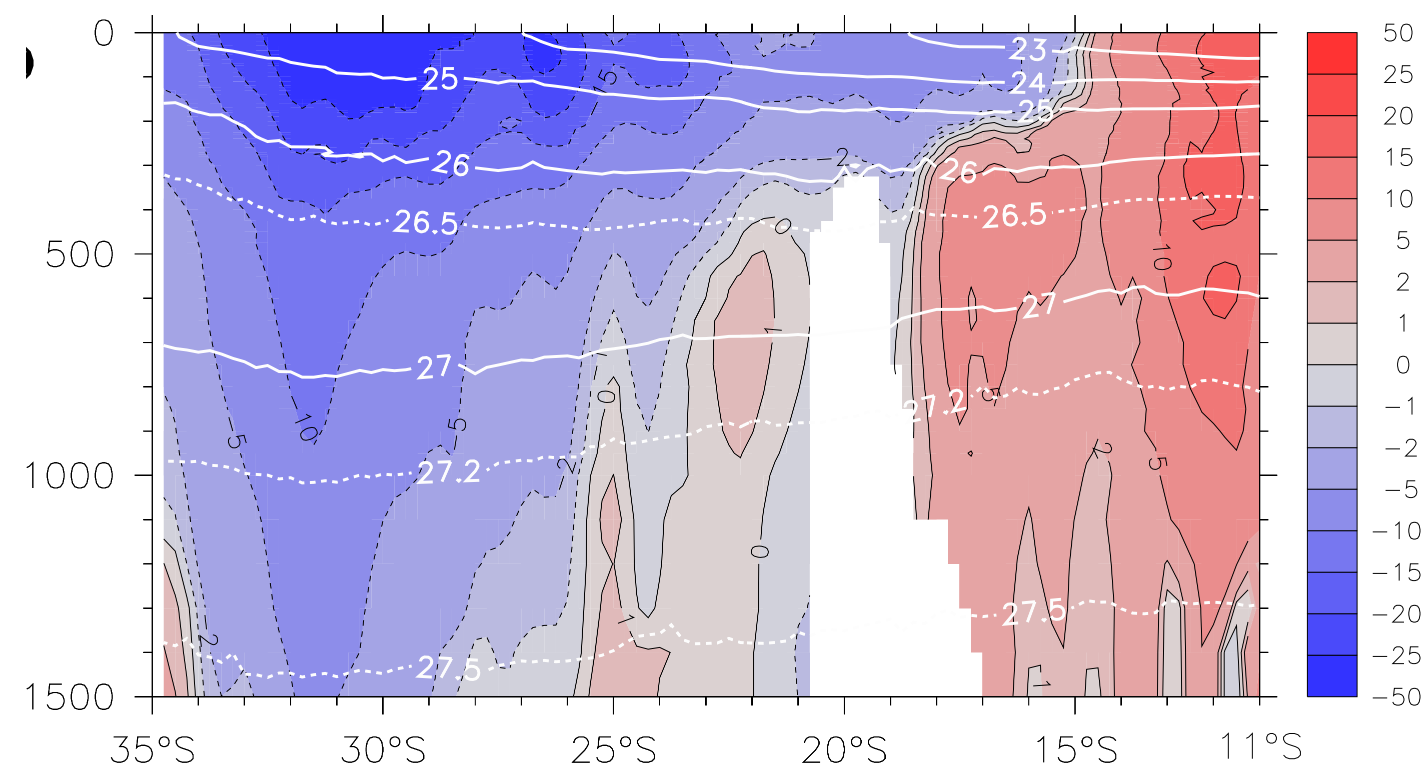
→ What is the connection between these two?

Tilted subtropical gyre, tilted WBC bifurcation

175°W: Mean <u>zonal current</u> (color) and temperature (green contours)
→ SubTropical CounterCurrent ←



An independent estimate of climatological <u>alongshore velocity</u> along the coast of Australia
Kessler and Cravatte (2013)



The bowl of the gyre tilts:
westward shear below,
eastward shear above.

CARS climatology (Ridgway & Dunn 2003)

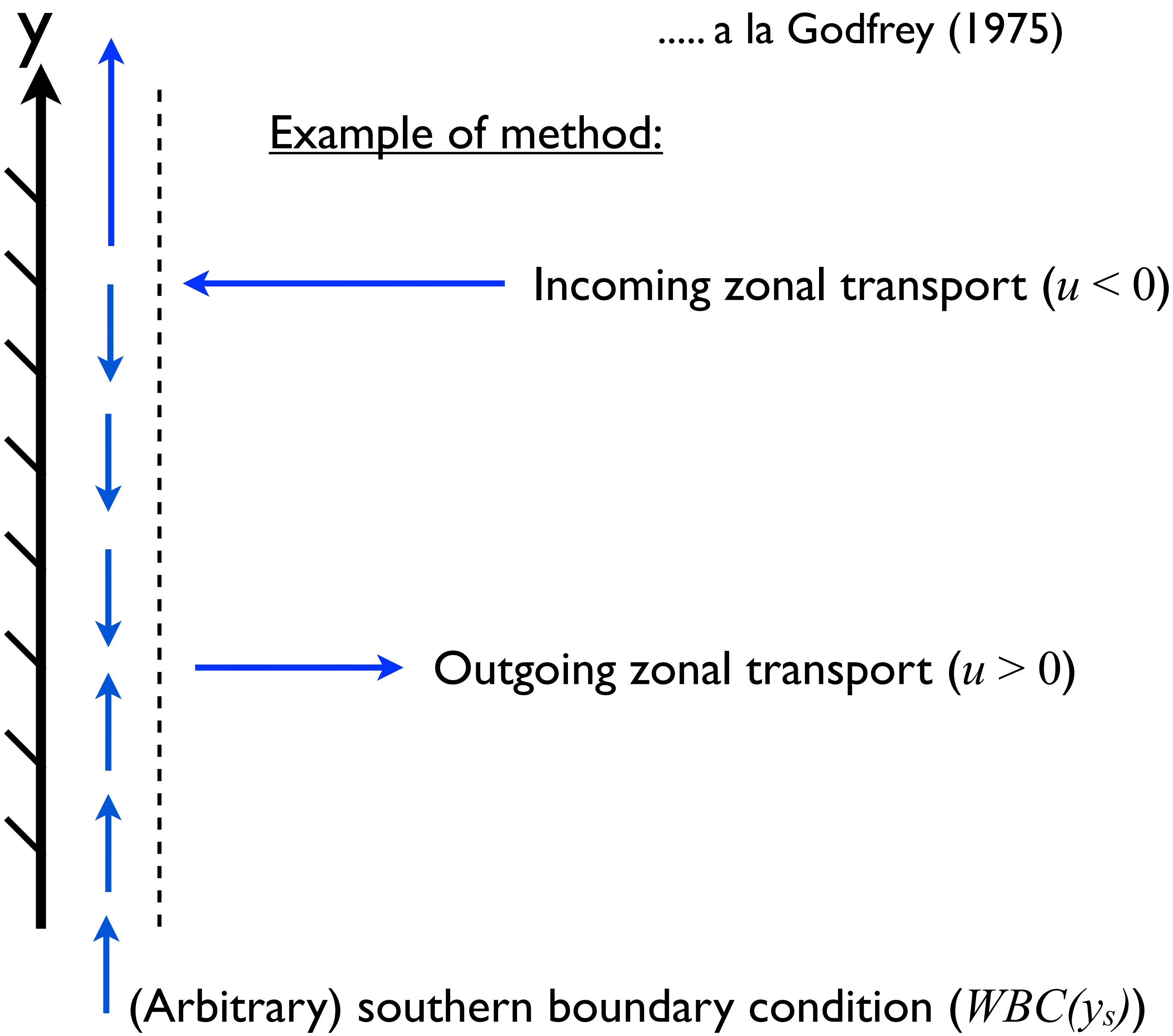
→ What is the connection between these two?

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:



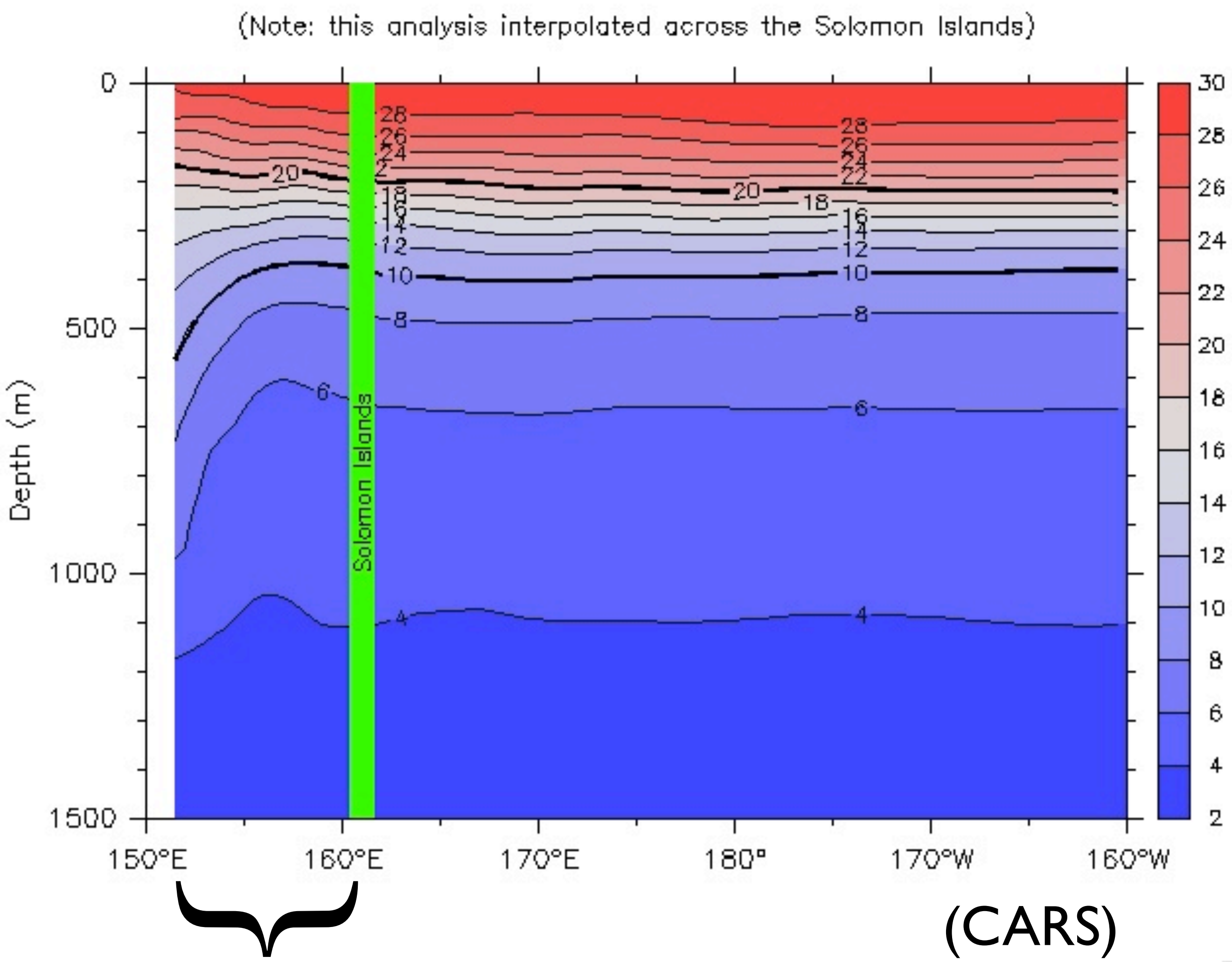
{ Incoming zonal transport
→ Eq-ward WBC tendency

{ Outgoing zonal transport
→ poleward WBC tendency

Isotherm spreading at western boundary

Poleward shear above NGCU: Undercurrent

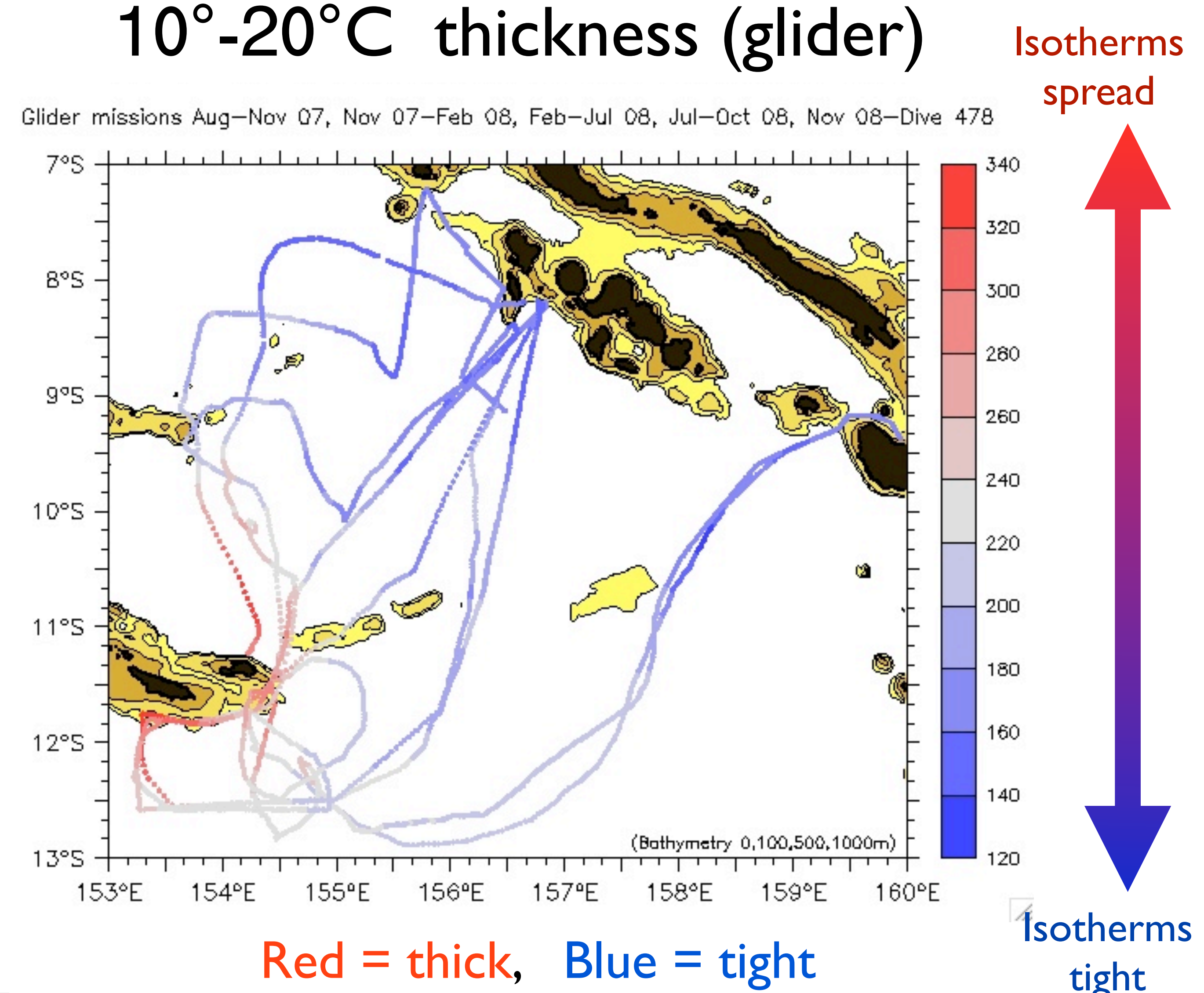
Climatological temperature at 10°S



Solomon Sea

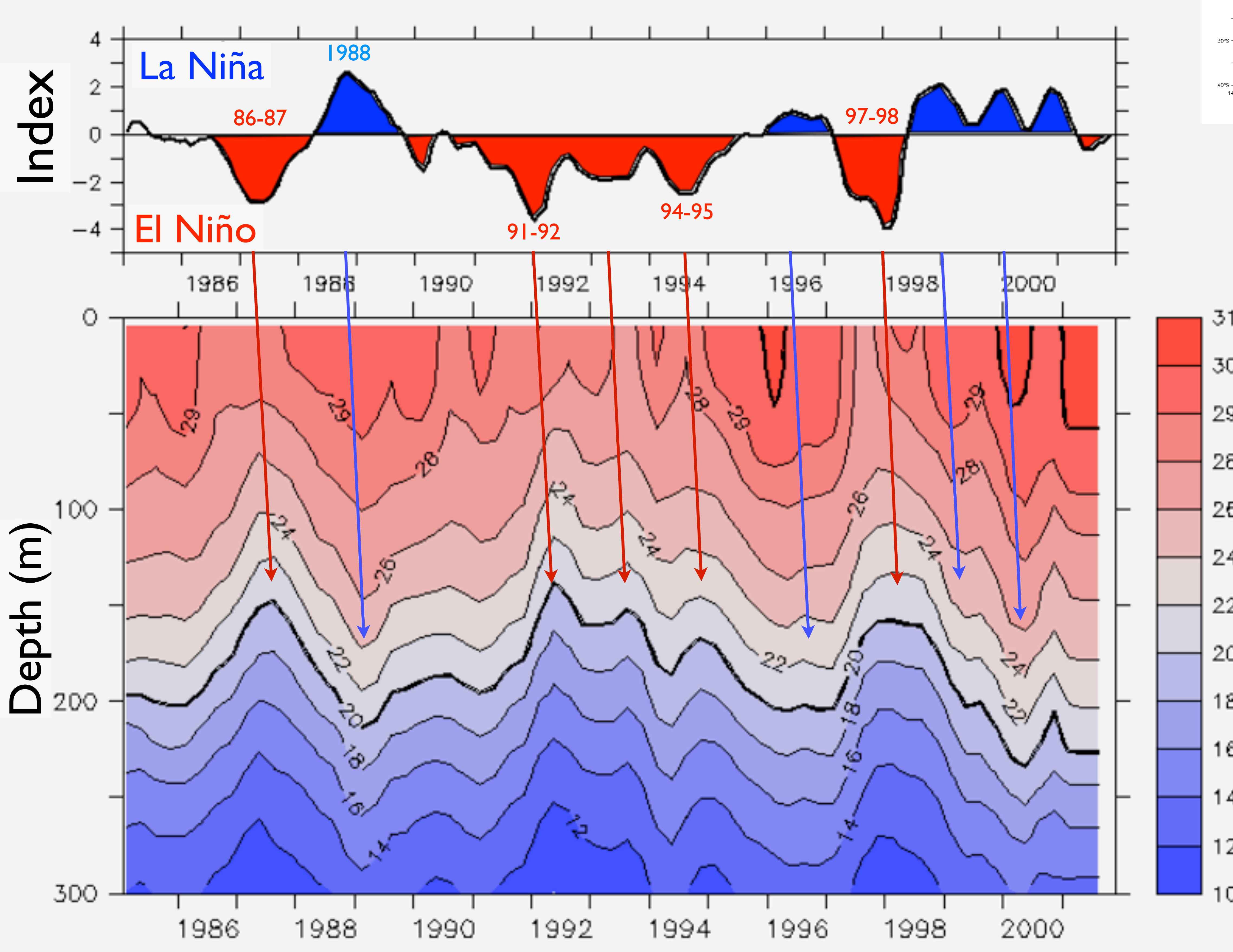
(CARS)

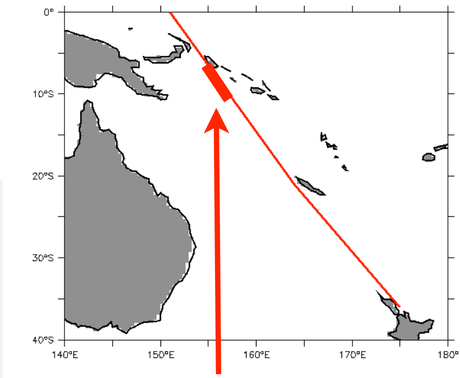
10°-20°C thickness (glider)



Red = thick, Blue = tight

Solomon Sea temperatures and El Niño / La Niña



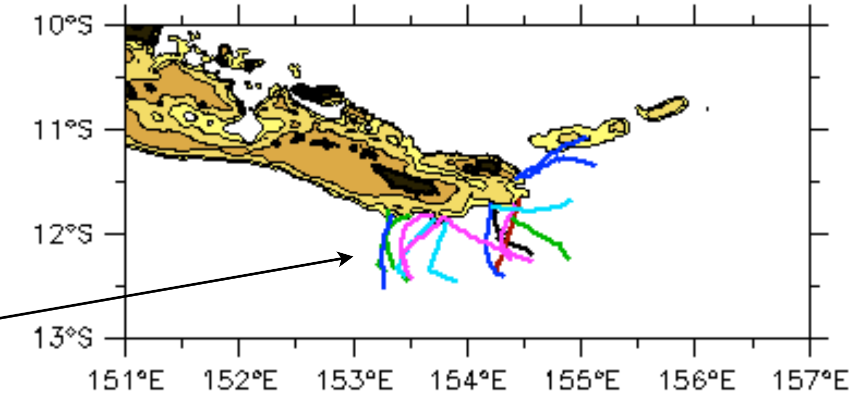


XBT track
(Merchant ship)
Sampled from 6-10°S

Velocity and salinity profiles in the NGCU

Map showing section locations

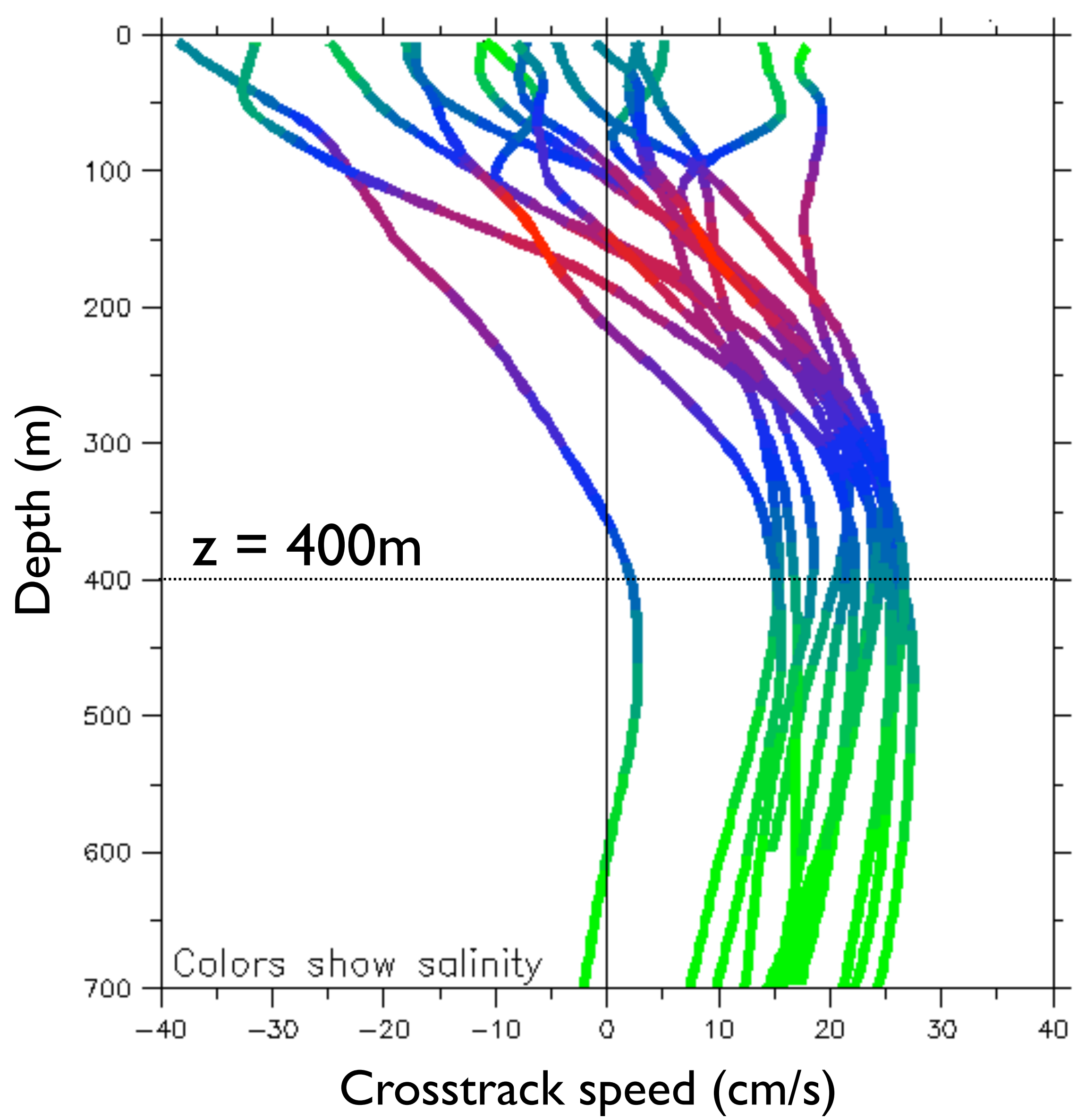
16 sections during Dec 07-Jan 10

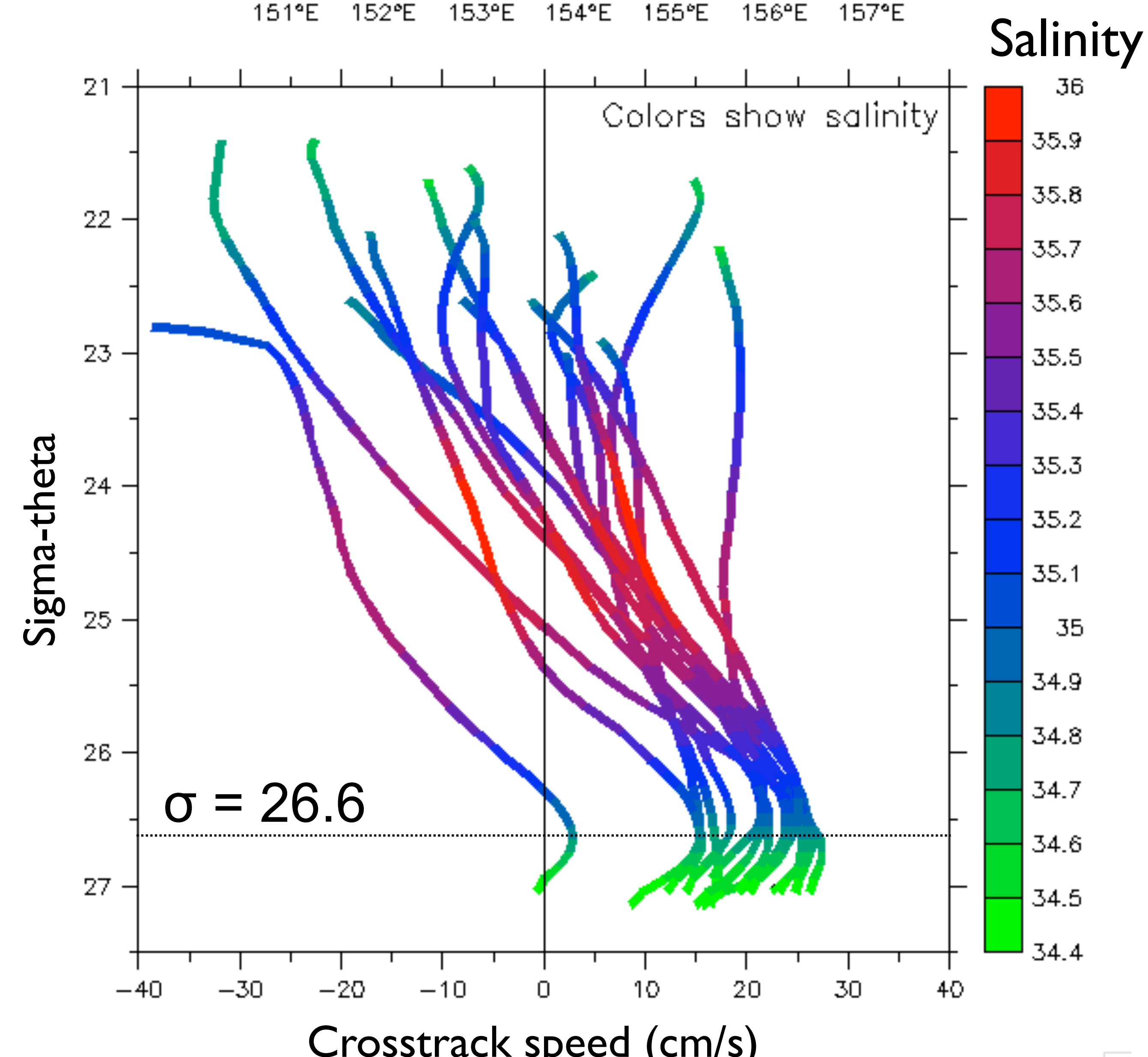


Speed vs depth (left), density (right)

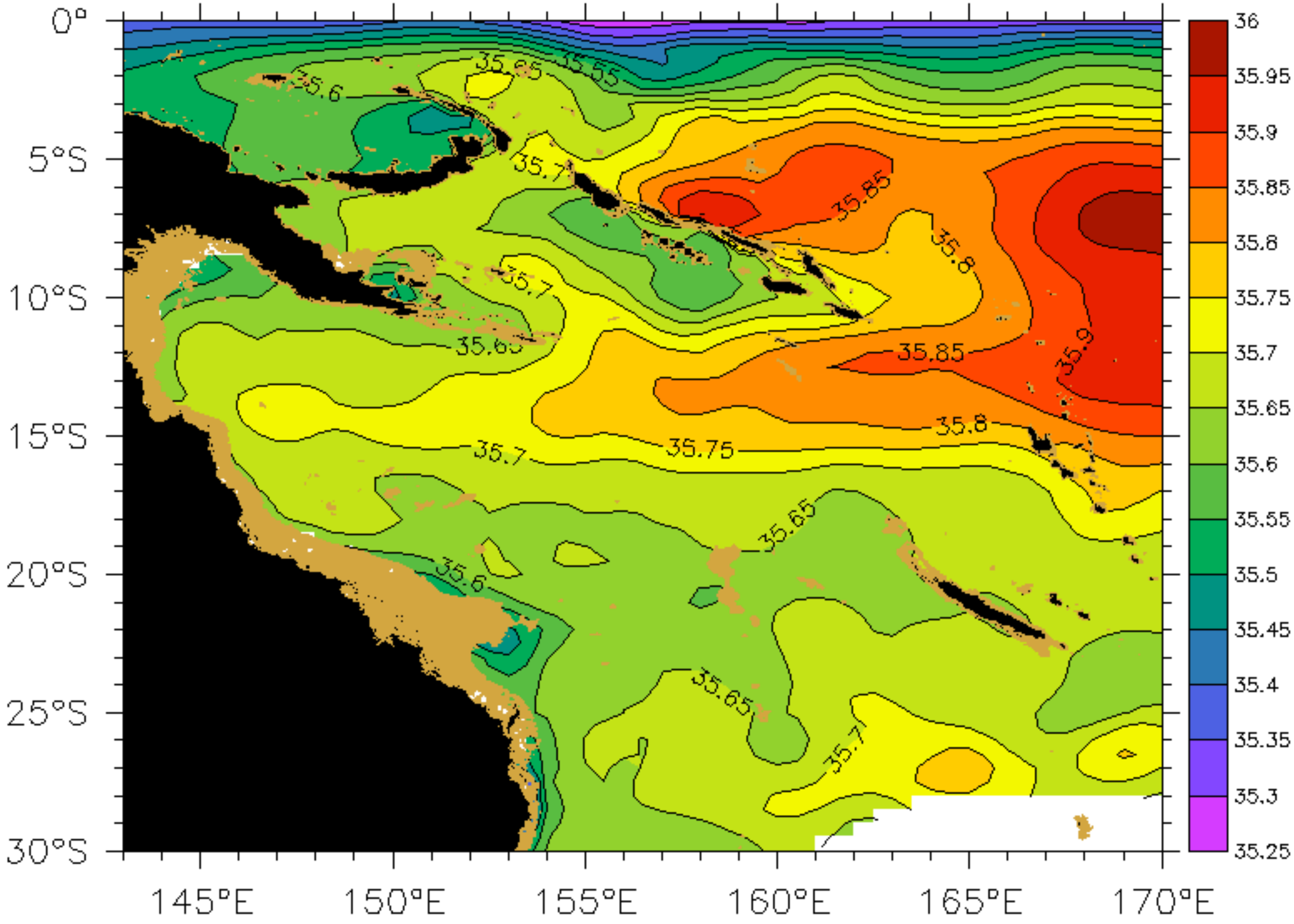
Colors show salinity

Sections are averages within 85km of the coast





A highly-sheared system. NGCU is below the EUC and salinity maximum.



0°
5°S
10°S
15°S
20°S
25°S
30°S
145°E
150°E
155°E
160°E
165°E
170°E
36
35.95
35.9
35.85
35.8
35.75
35.7
35.65
35.6
35.55
35.5
35.45
35.4
35.35
35.3
35.25

Mean and Variability of v_ϕ