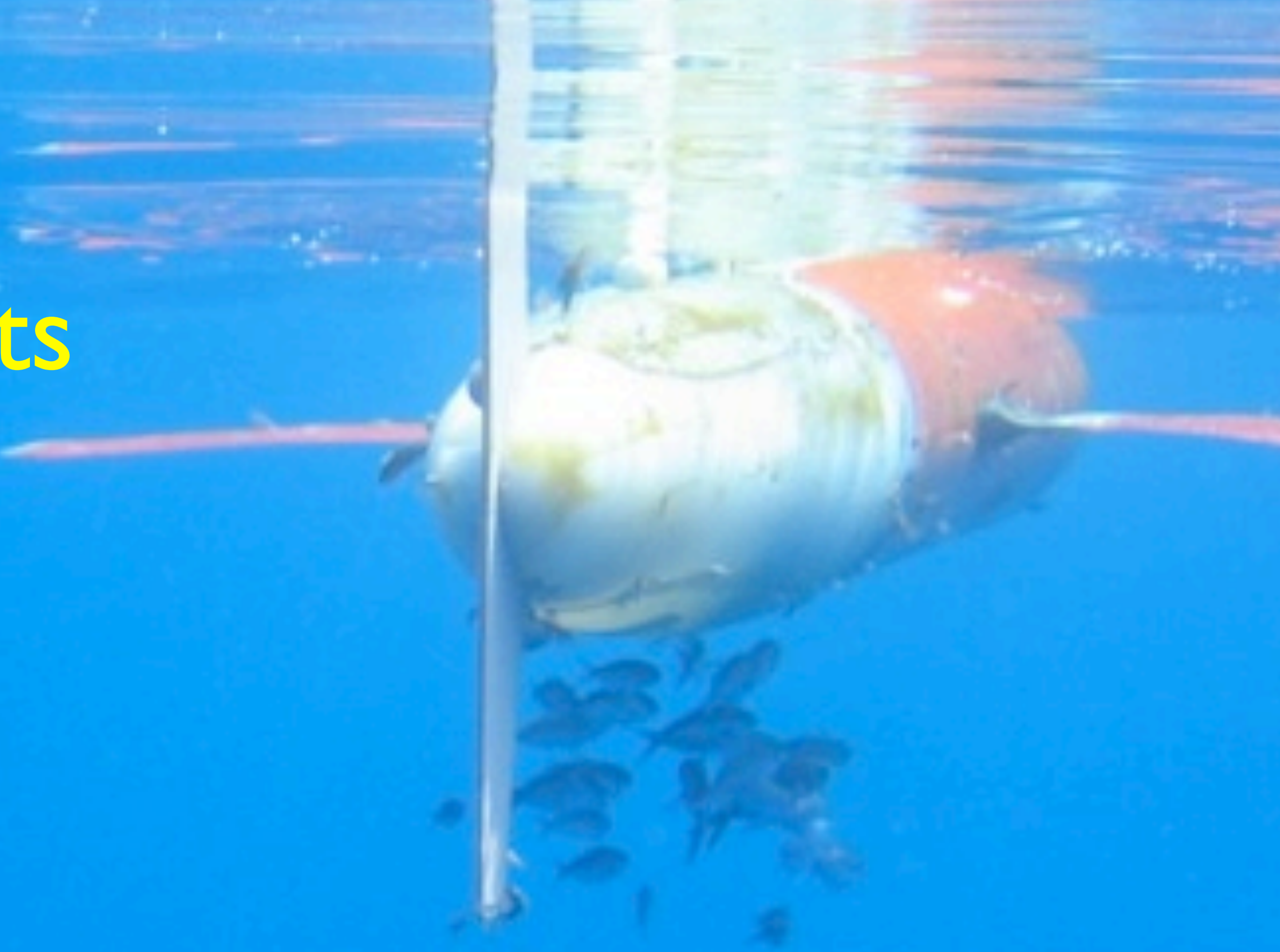
Measuring South Pacific low-latitude western boundary currents with ocean gliders: A pilot study



William S. Kessler
NOAA / PMEL, Seattle USA

Russ Davis and Jeff Sherman
(Scripps Institution of Oceanography, La Jolla USA)

Lionel Gourdeau
(Institut de Recherche pour le Developpement (IRD), Noumea, New Caledonia)

PMEL

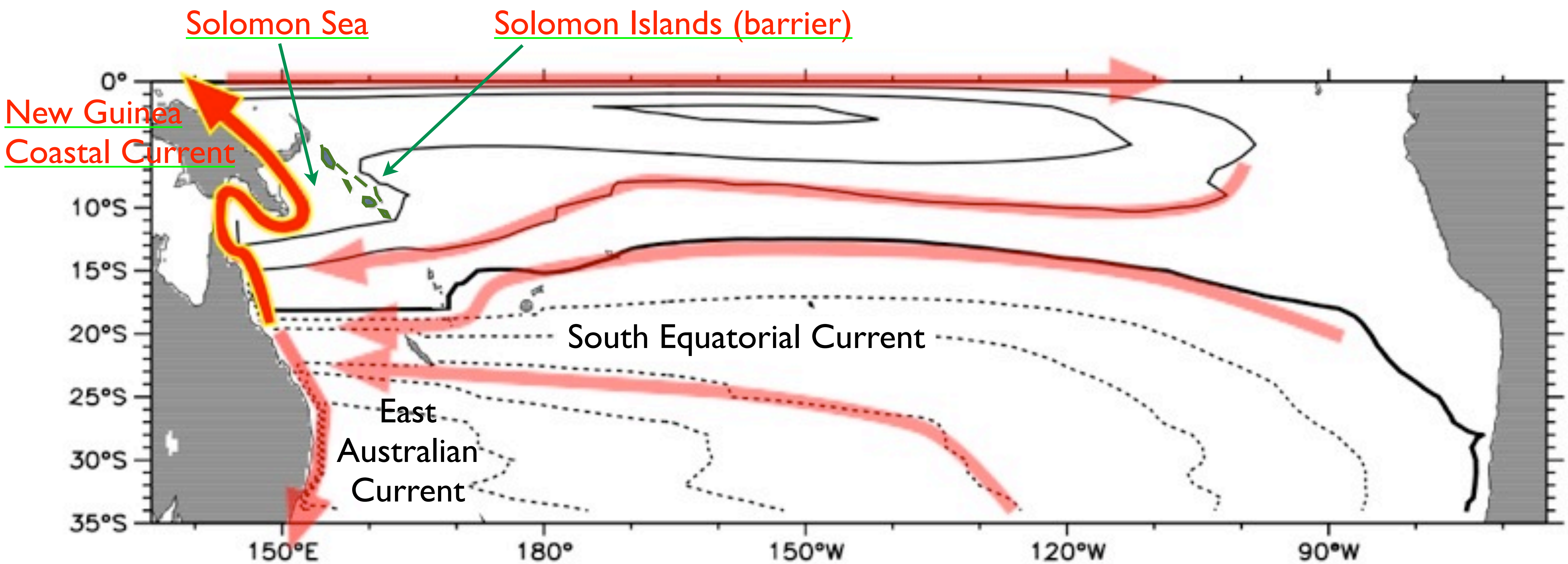
Institut de recherche pour le développement

Essential collaborators:

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

South Pacific mean circulation

(Sverdrup/Island Rule transport from scatterometer winds)



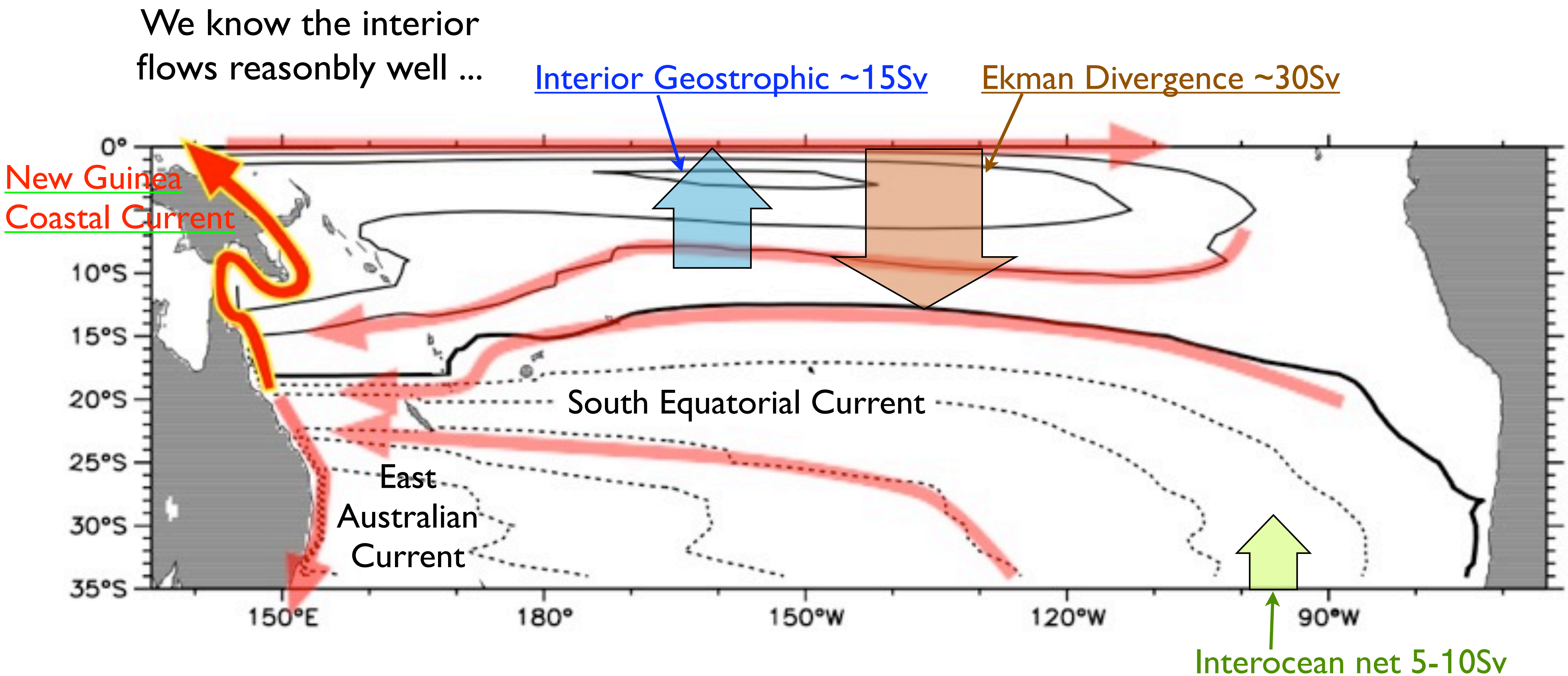
- The vertically-integrated circulation is two gyres with a bifurcation near 18°S.
- About half the SEC transport turns north through the Solomon Sea.

  → Mean Solomon Sea transport is 15-20 Sv.
- Unusual western boundary geometry:

  → 5° latitude barrier in front of continental boundary

  → WBC transport may be limited by narrow straits

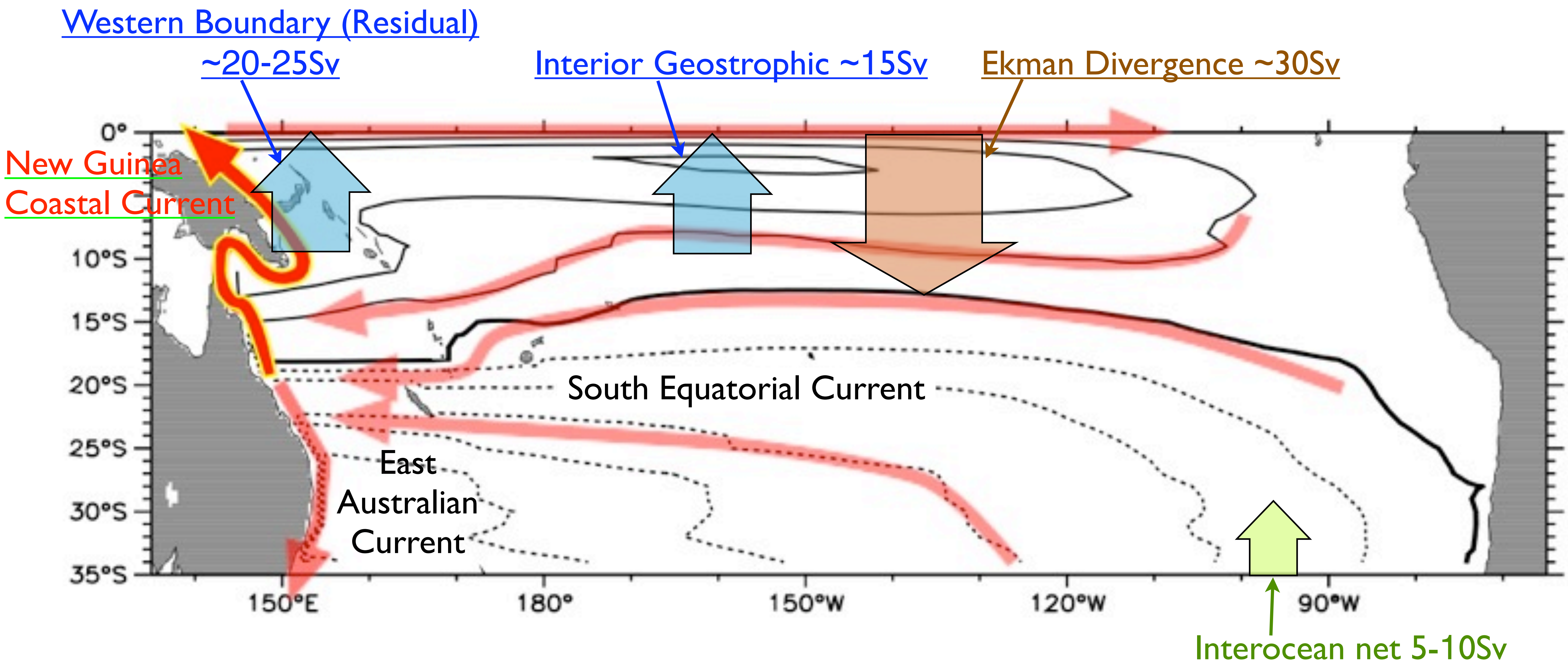
South Pacific mean circulation



Water property observations suggest that a large fraction of the water in the EUC passes through the Solomon Sea.

Determines the properties (T, S, carbon content) of the EUC and cold tongue.

South Pacific mean circulation

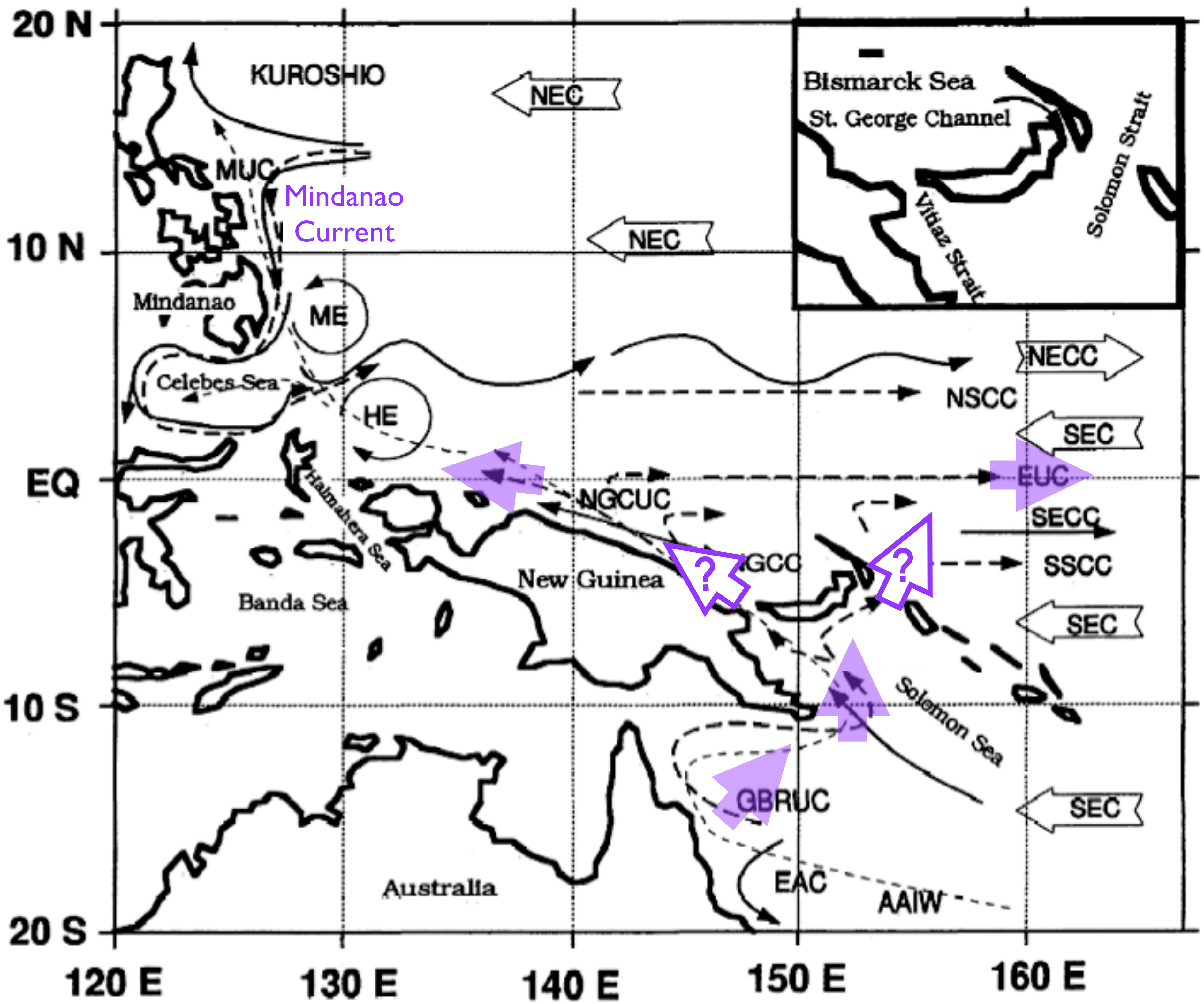


Water property observations suggest that a large fraction of the water in the EUC passes through the Solomon Sea.

Determines the properties (T, S, carbon content) of the EUC and cold tongue.

What is the source of the Equatorial Undercurrent?

Redistribution of the Solomon Sea inflow → Directly to the EUC at 155°E? → Or far to the west?

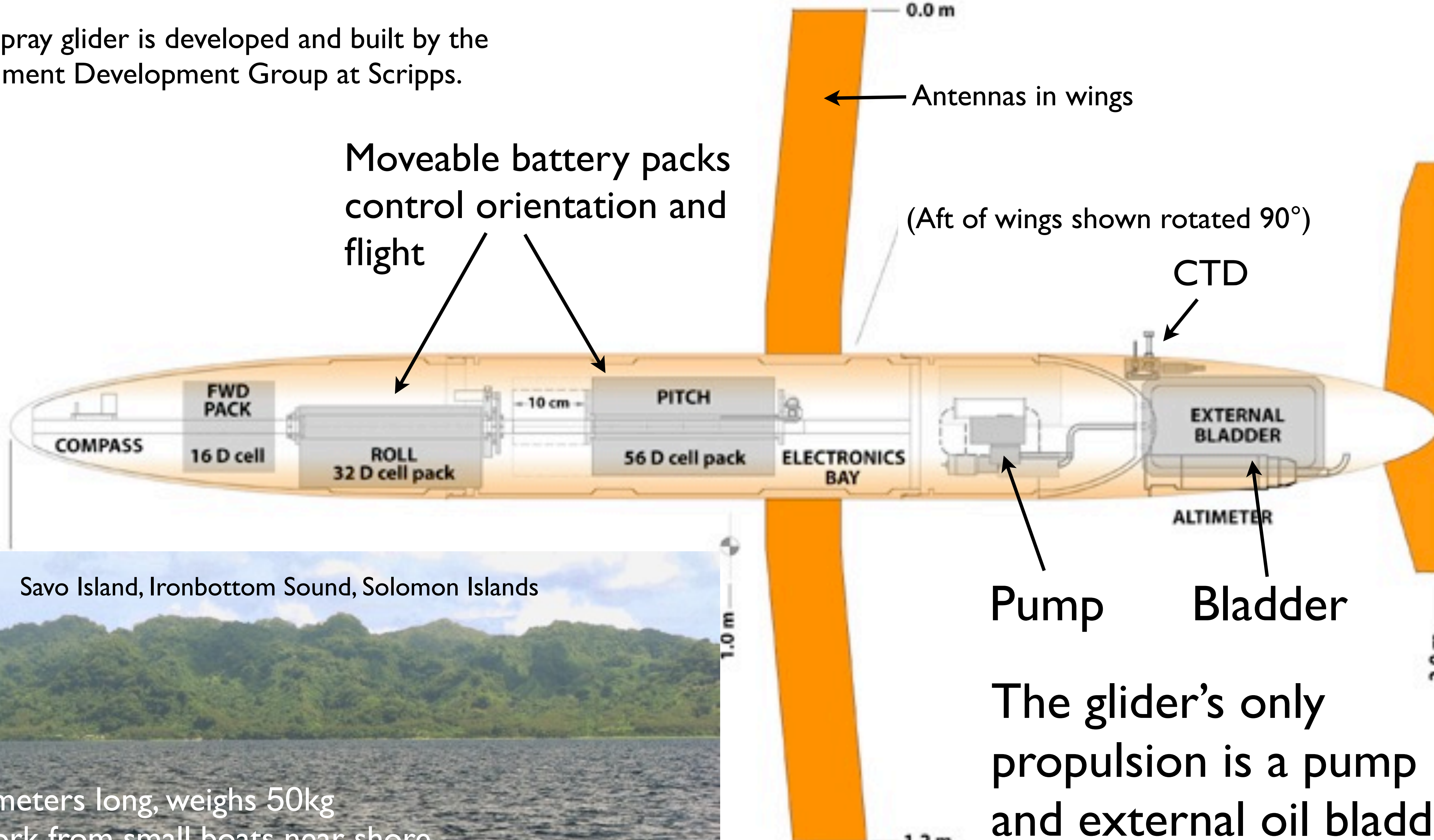


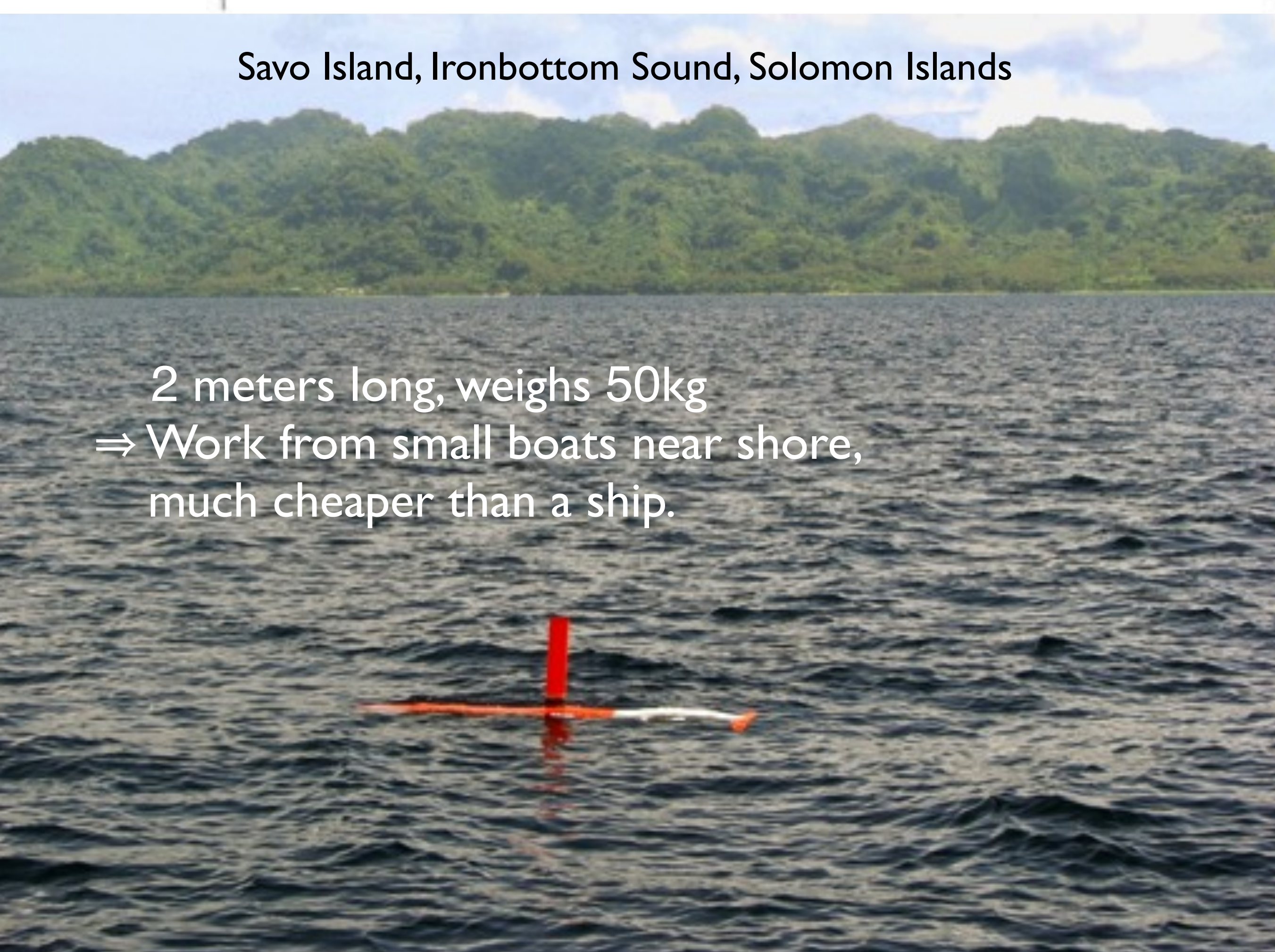
Fine et al. (JGR 1994)

Solid = surface layer
Dash = Thermocline
Thin dash = AAIW

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.

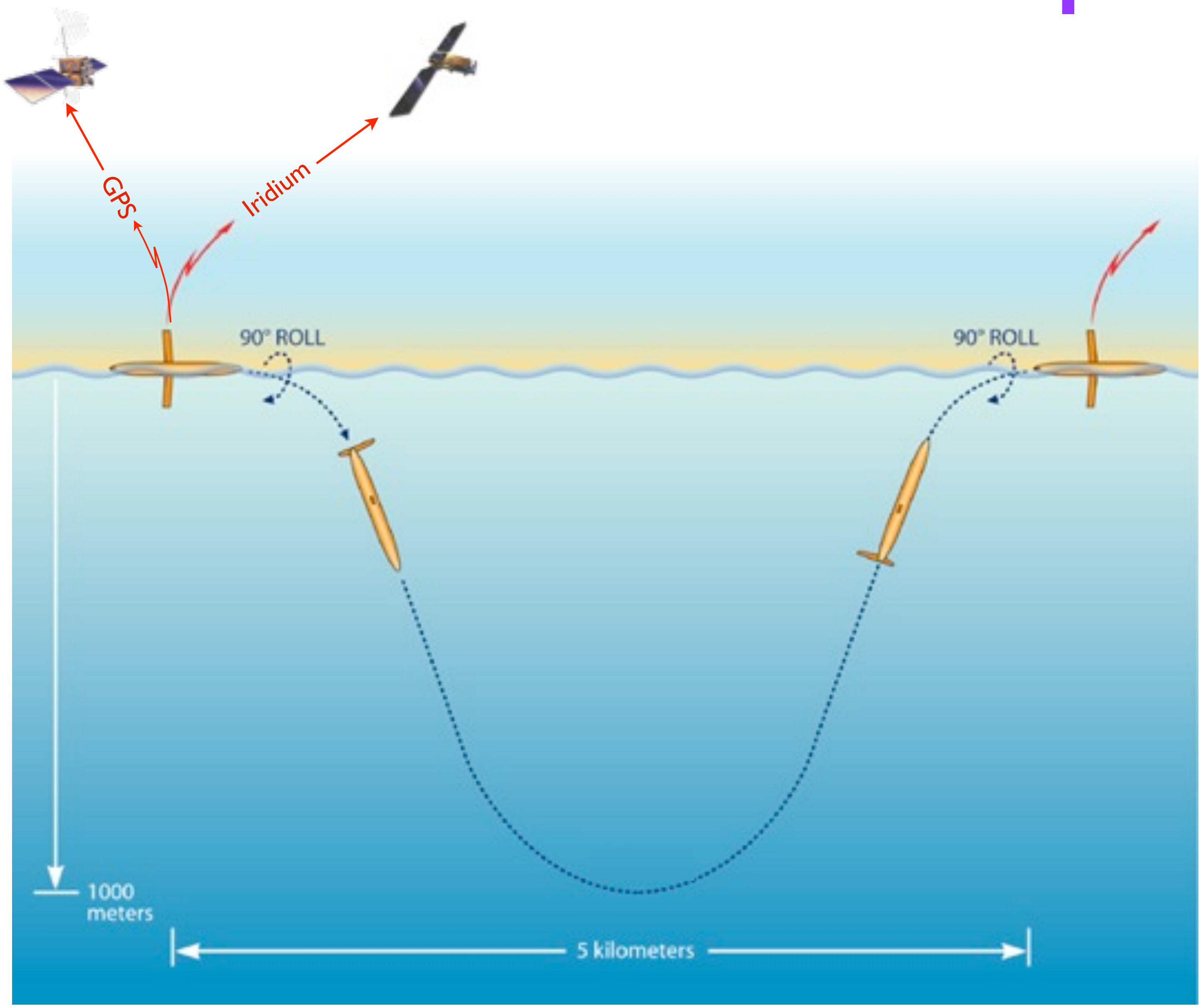




The glider's only propulsion is a pump and external oil bladder (flooded compartment). The pump inflates and deflates the bladder to change its buoyancy.

A dive of the Spray glider

↑ 500-1000 m ↓

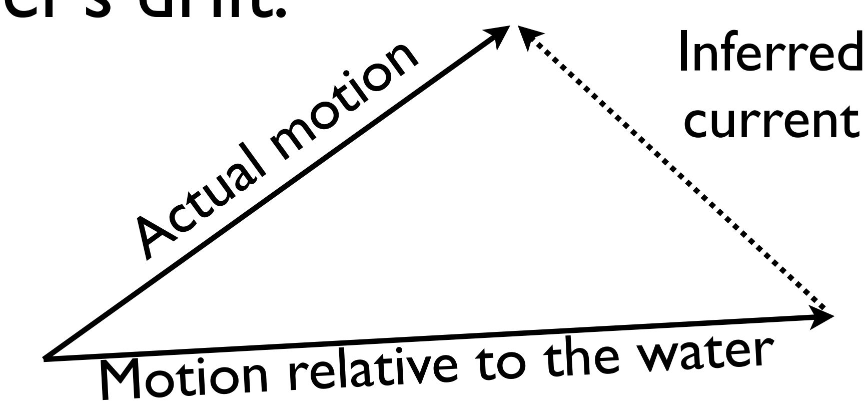


Very dense sampling
(~ resolve tides)

Data reported by Iridium satellite each time it surfaces

Argo-comparable T-S profiles: geostrophic relative currents

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

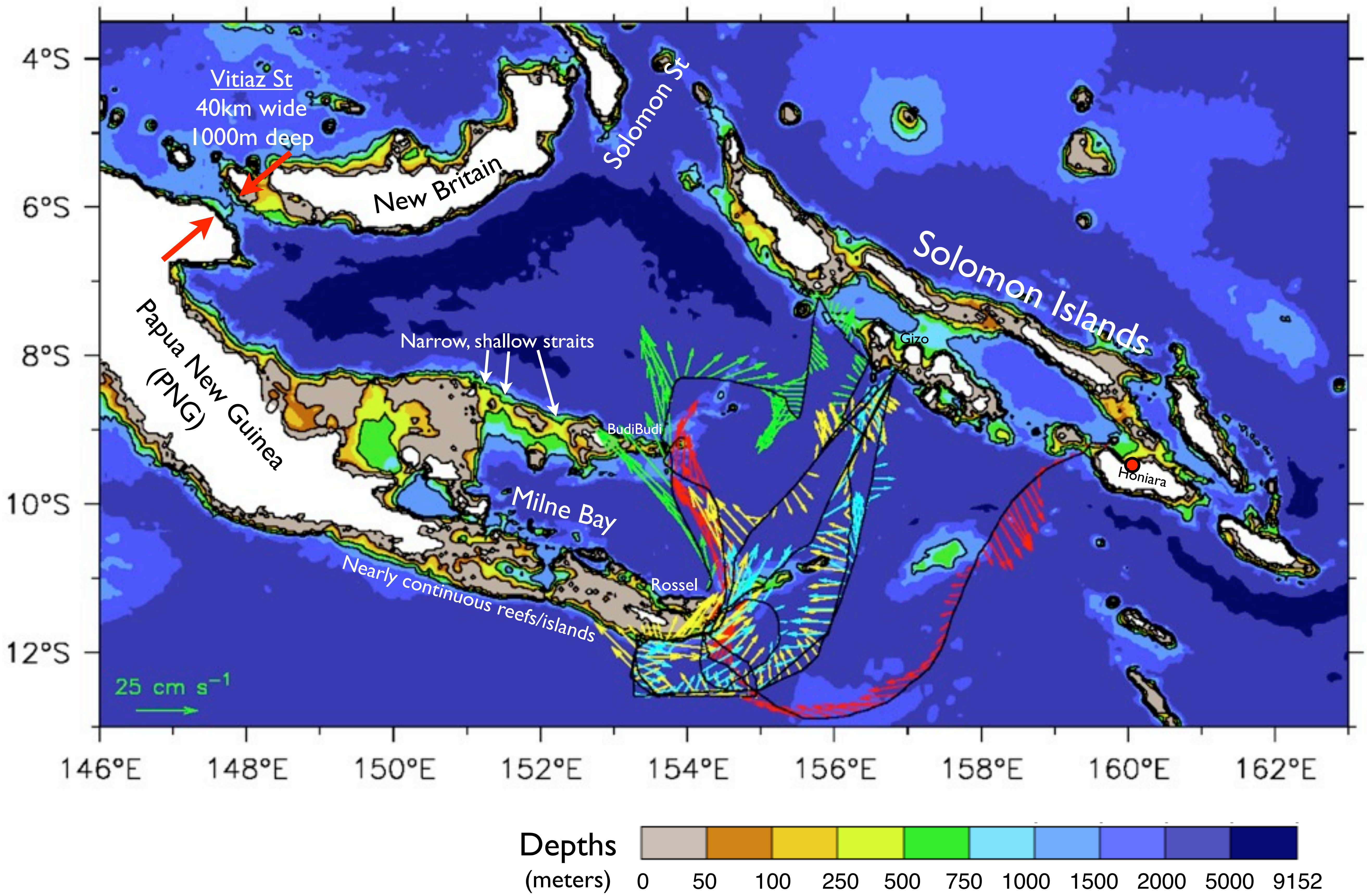


← 3 km (3-4 hr) →

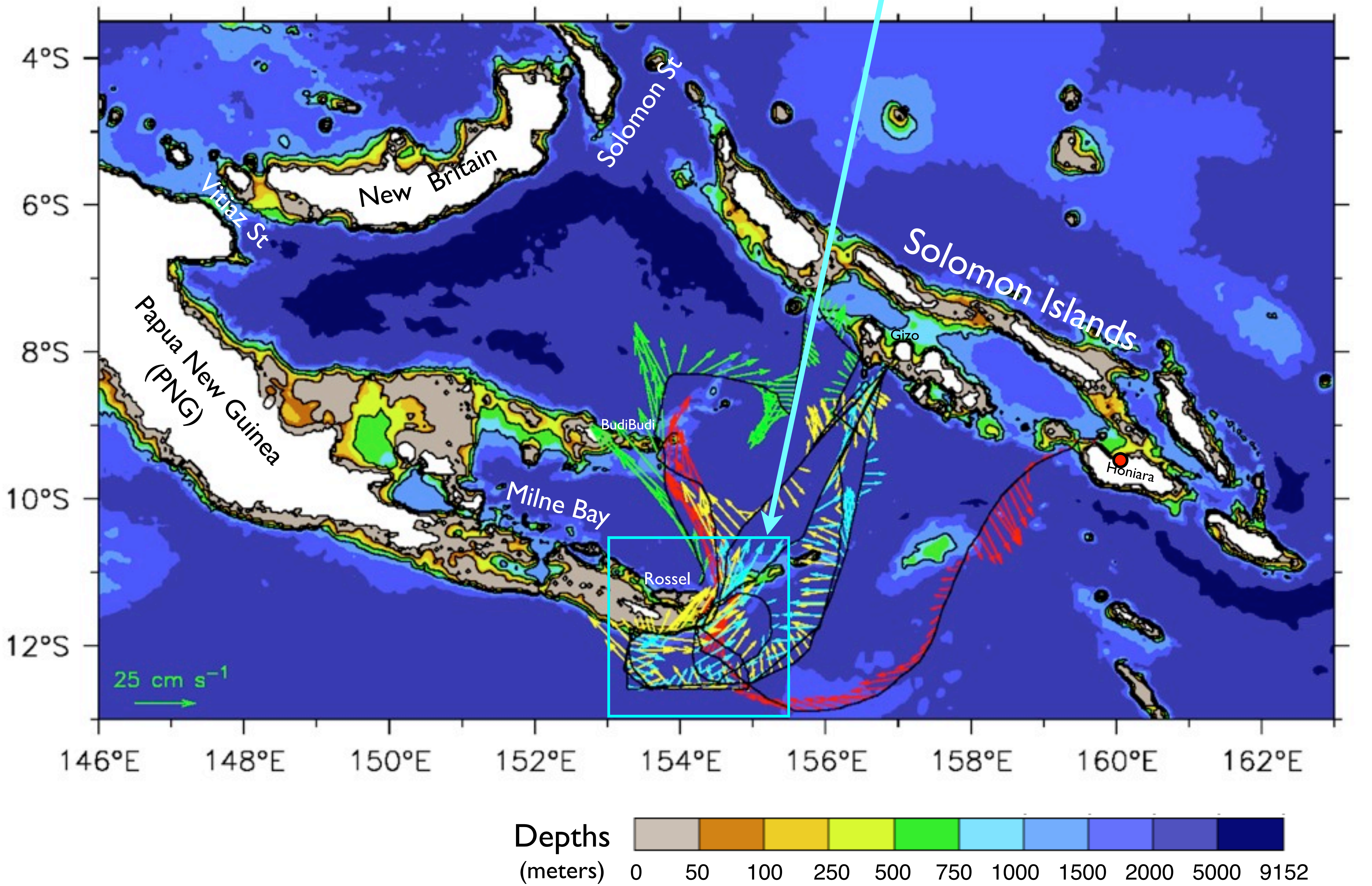
20 cm/s →

Range about 4 months = 2000+km

Solomon Sea bathymetry: islands, reefs and narrow straits

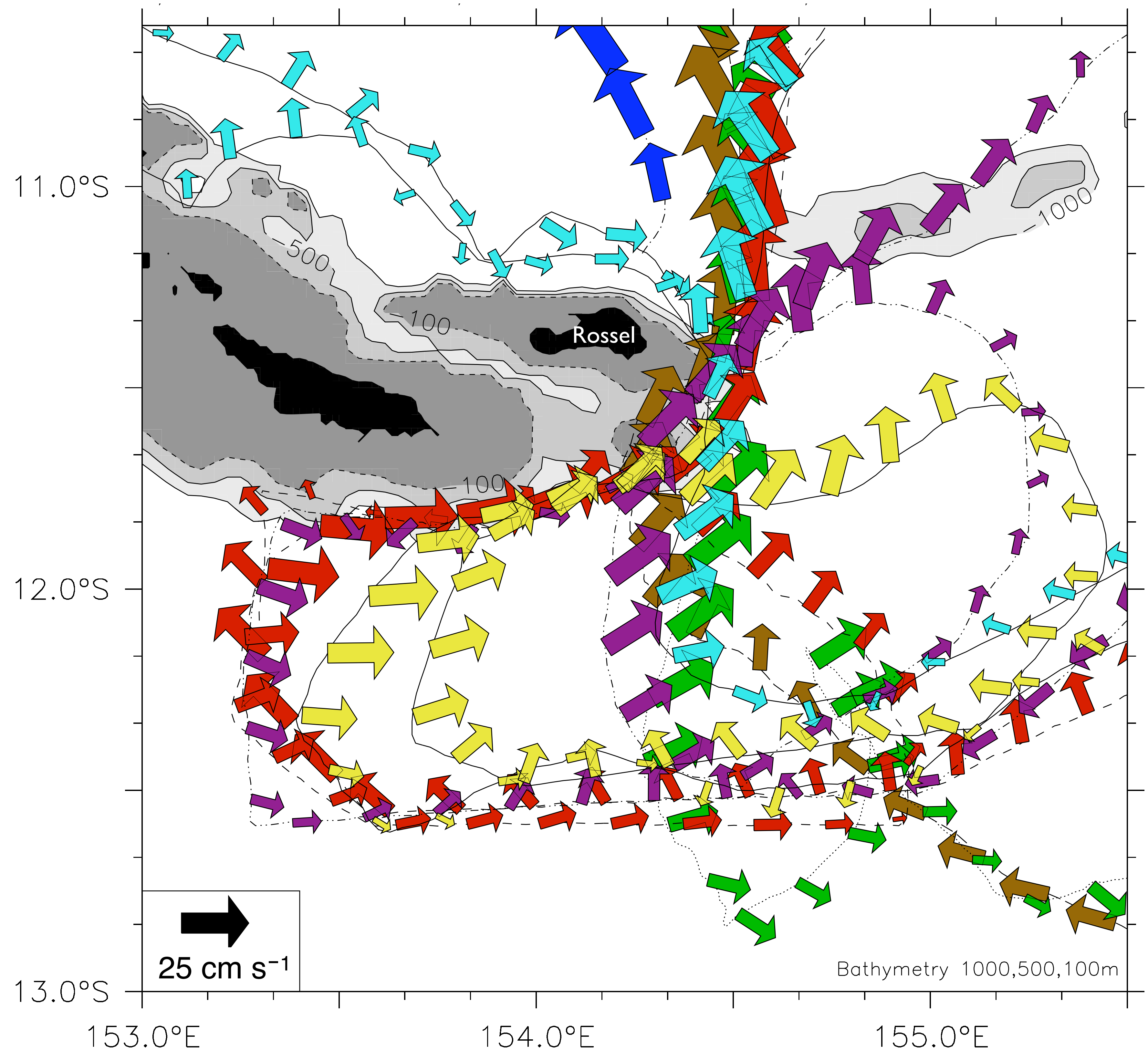


Western Boundary Current off the SE tip of New Guinea

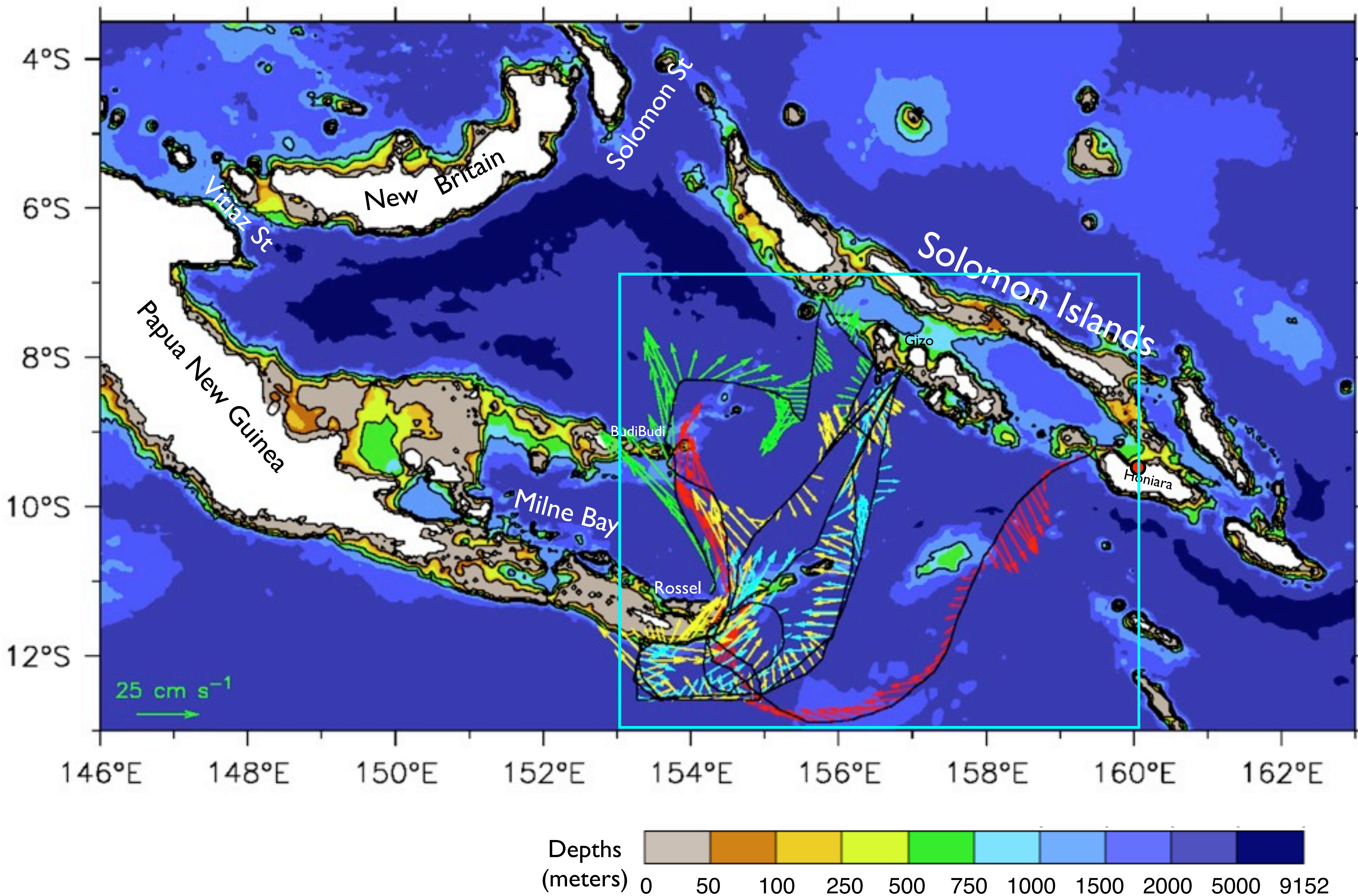


Vertical-average currents at the tip of PNG

20-km along-track averages.   Tide-filtered



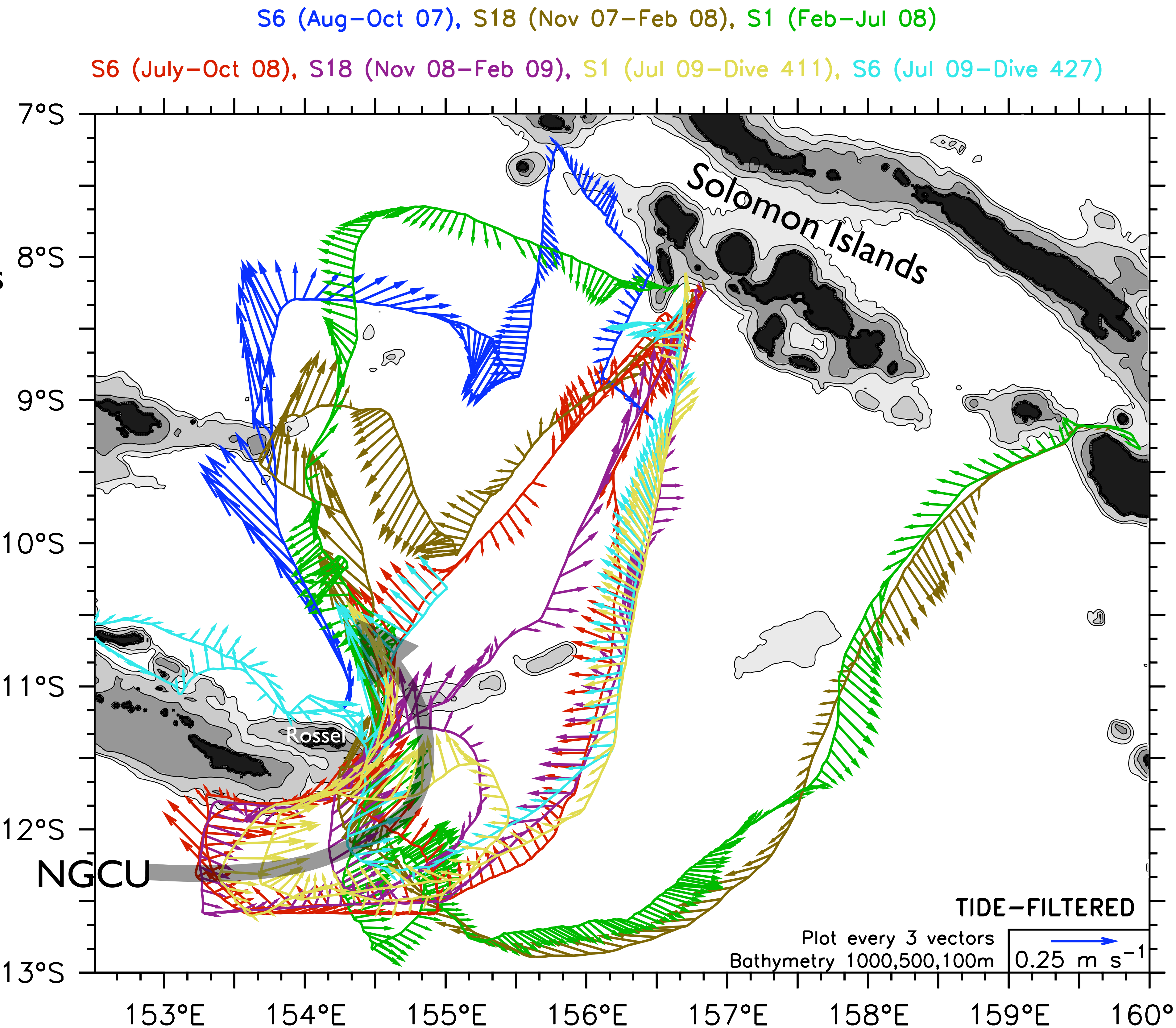
7 glider surveys so far (launches every 3-4 months)



Glider currents: 7 missions Aug 07 - Oct 09

After 7 missions, is there a discernable "background"?

One consistent feature is a strong NGCU



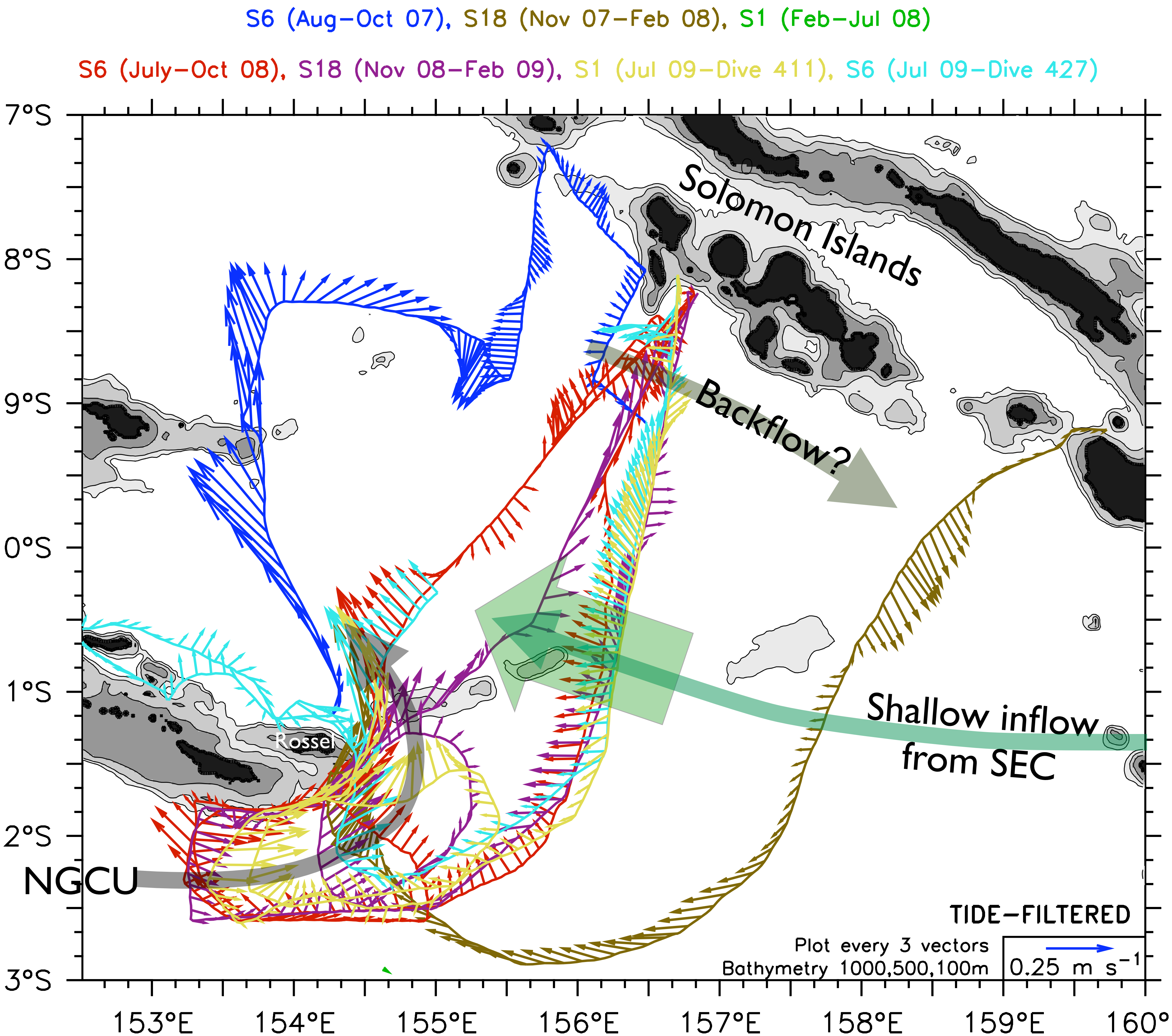
Glider currents: 7 missions Aug 07 - Oct 09

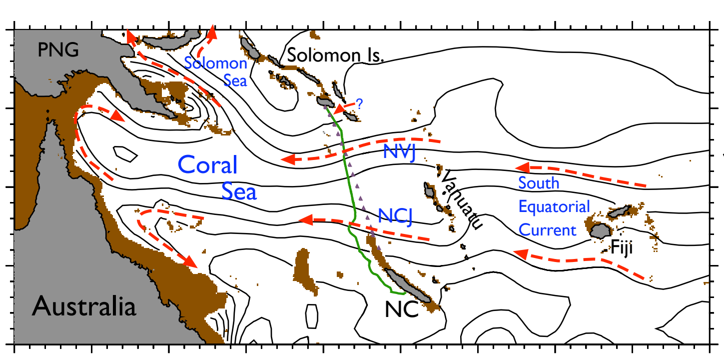
After 7 missions, is there a discernable "background"?

One consistent feature is a strong NGCU (Will show this to be a deep current).

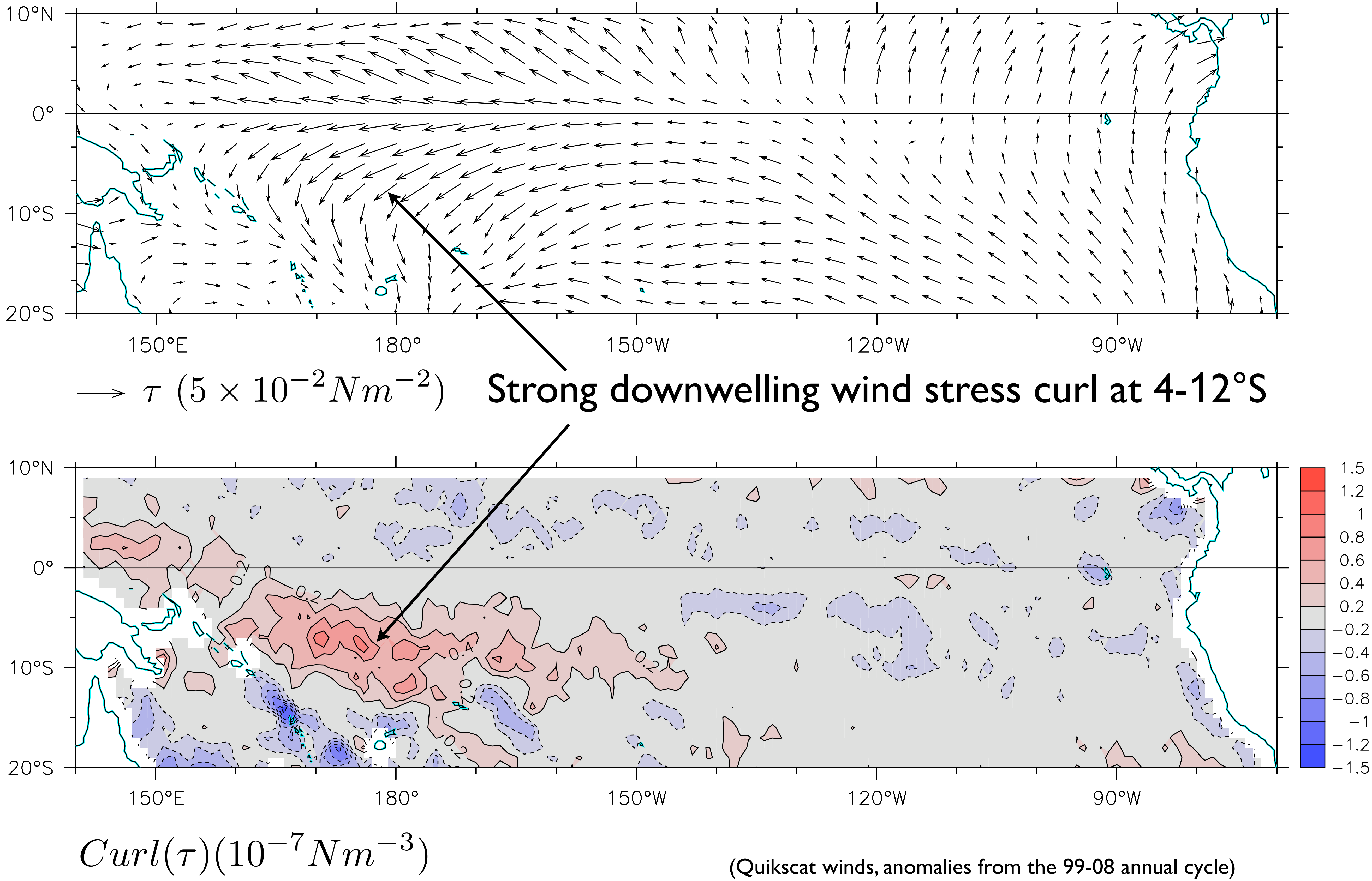
A second fairly consistent feature is a shallower inward flow in the central part of the basin.

There is often a southward flow in the east.



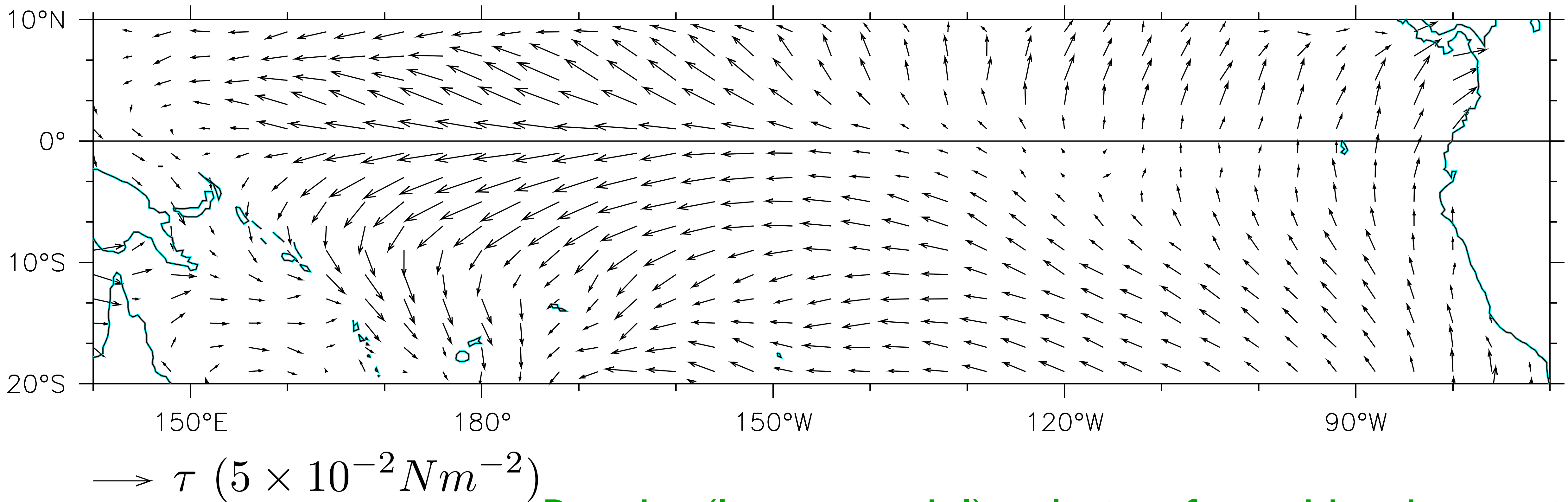


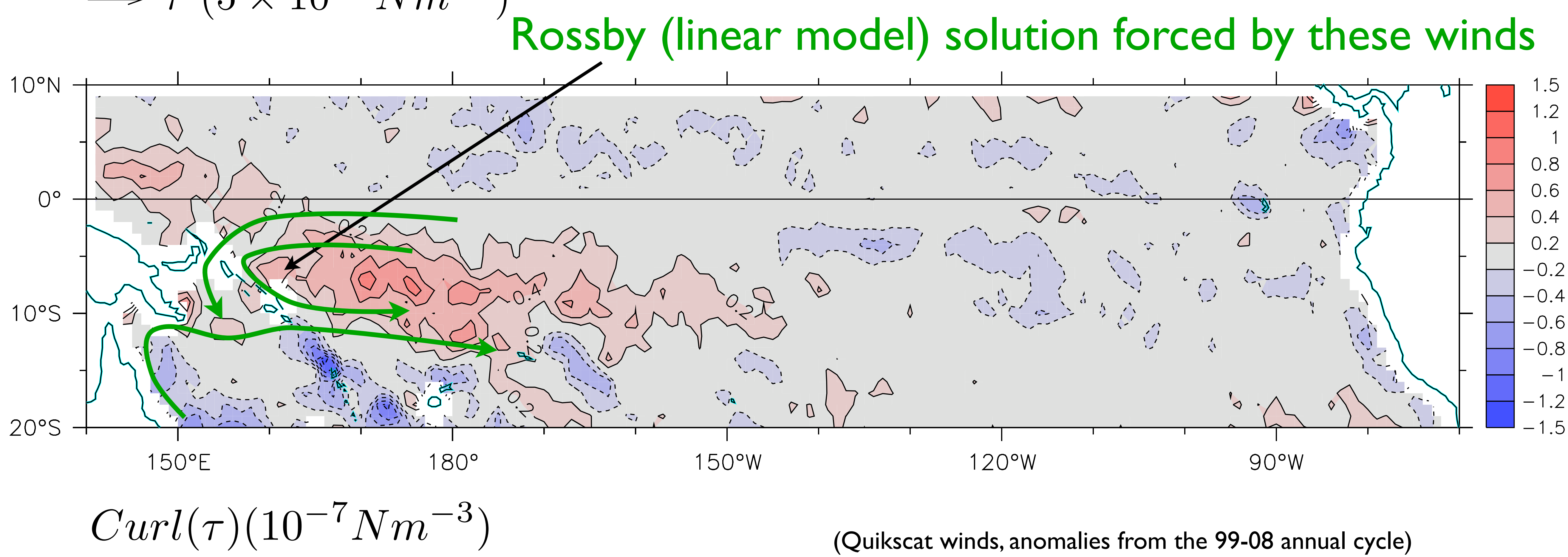
Anomalous winds and curl during Aug 07-Mar 08: La Niña



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

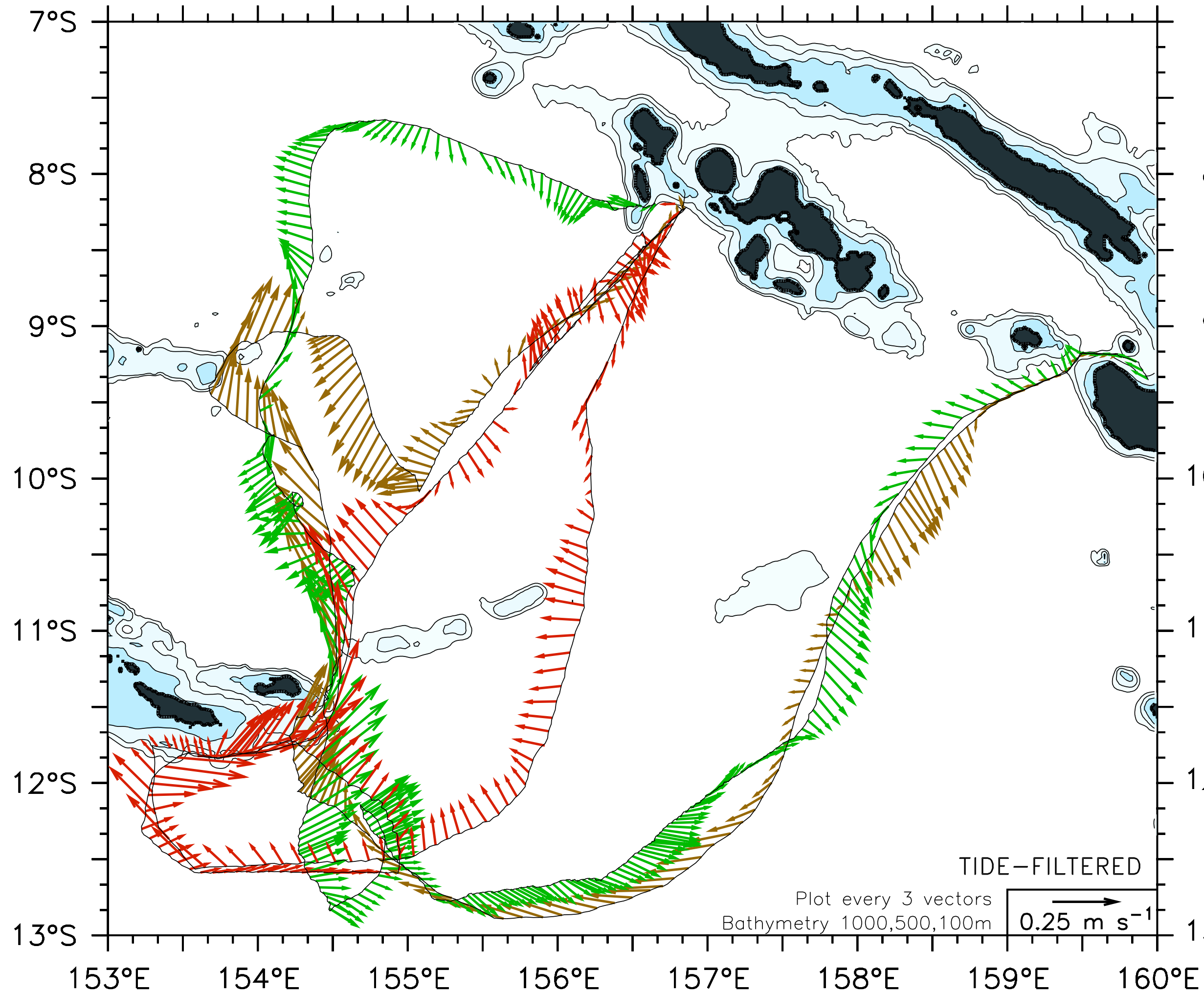
Anomalous winds and curl during Aug 07-Mar 08: La Niña





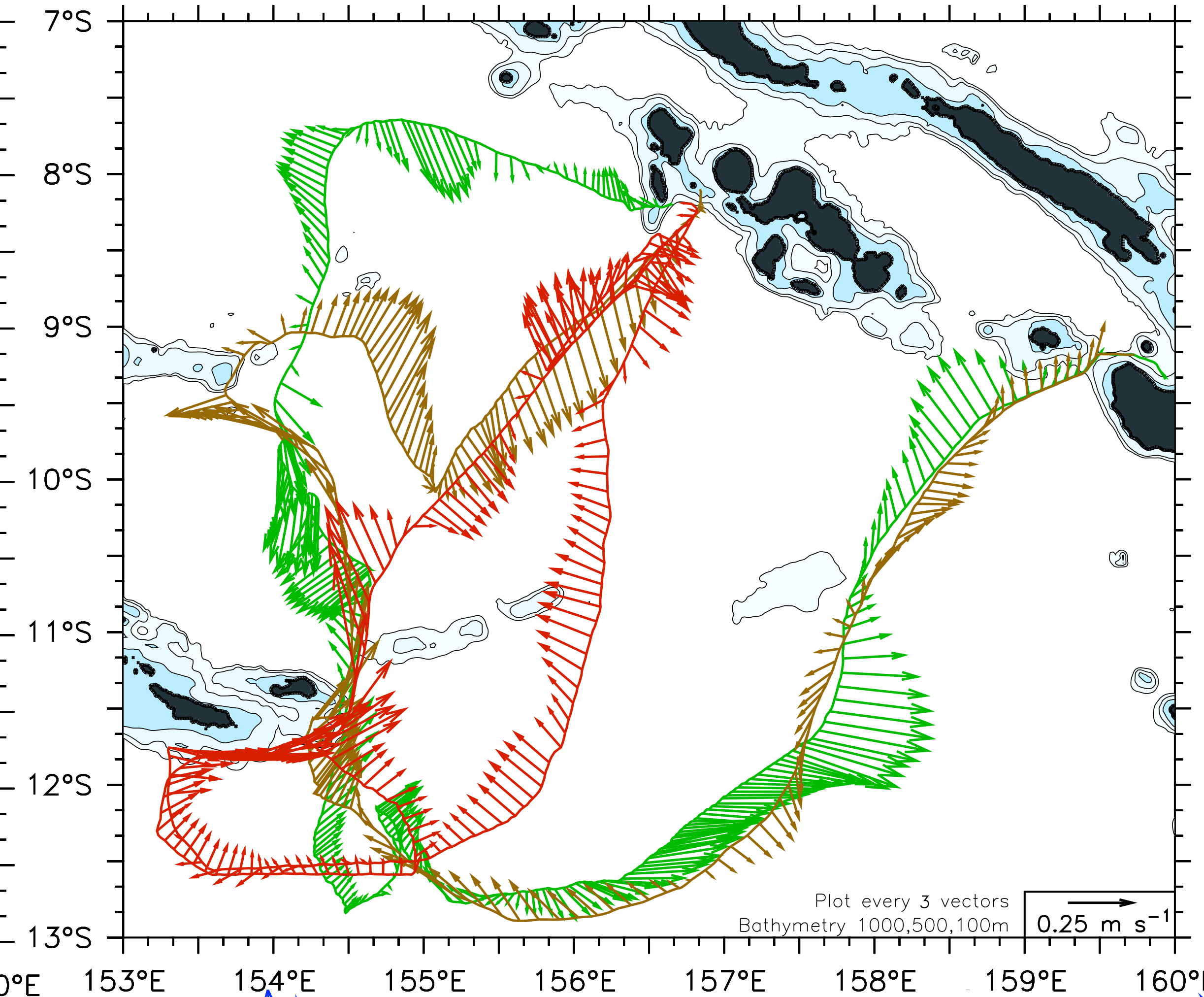
(Quikscat winds, anomalies from the 99-08 annual cycle)

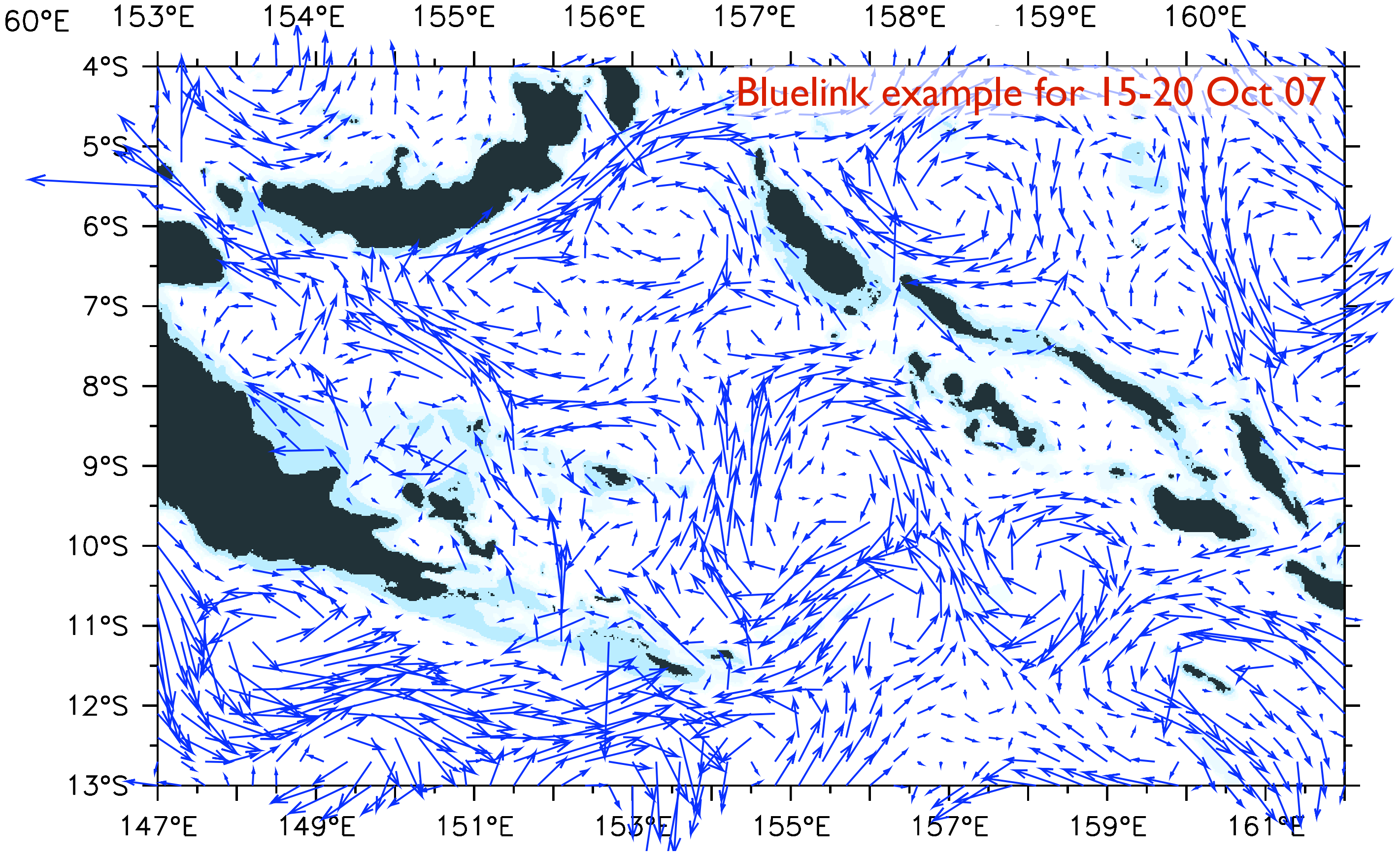
Observed currents



Bluelink (BOM: MOM4) model currents

Sampled at glider time/position

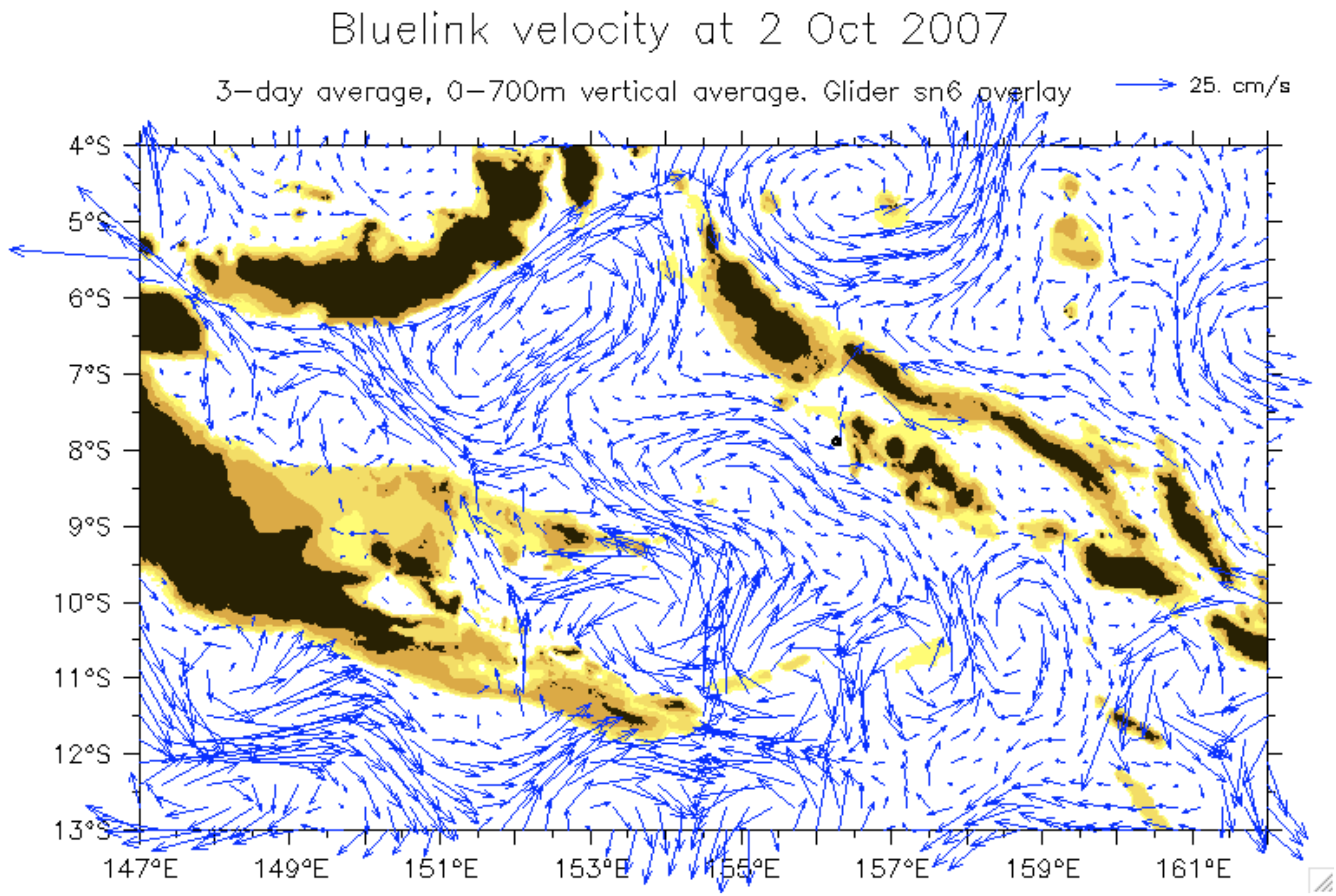




GCM solutions show eddy dominance.

⇒ Collaboration with modelers!

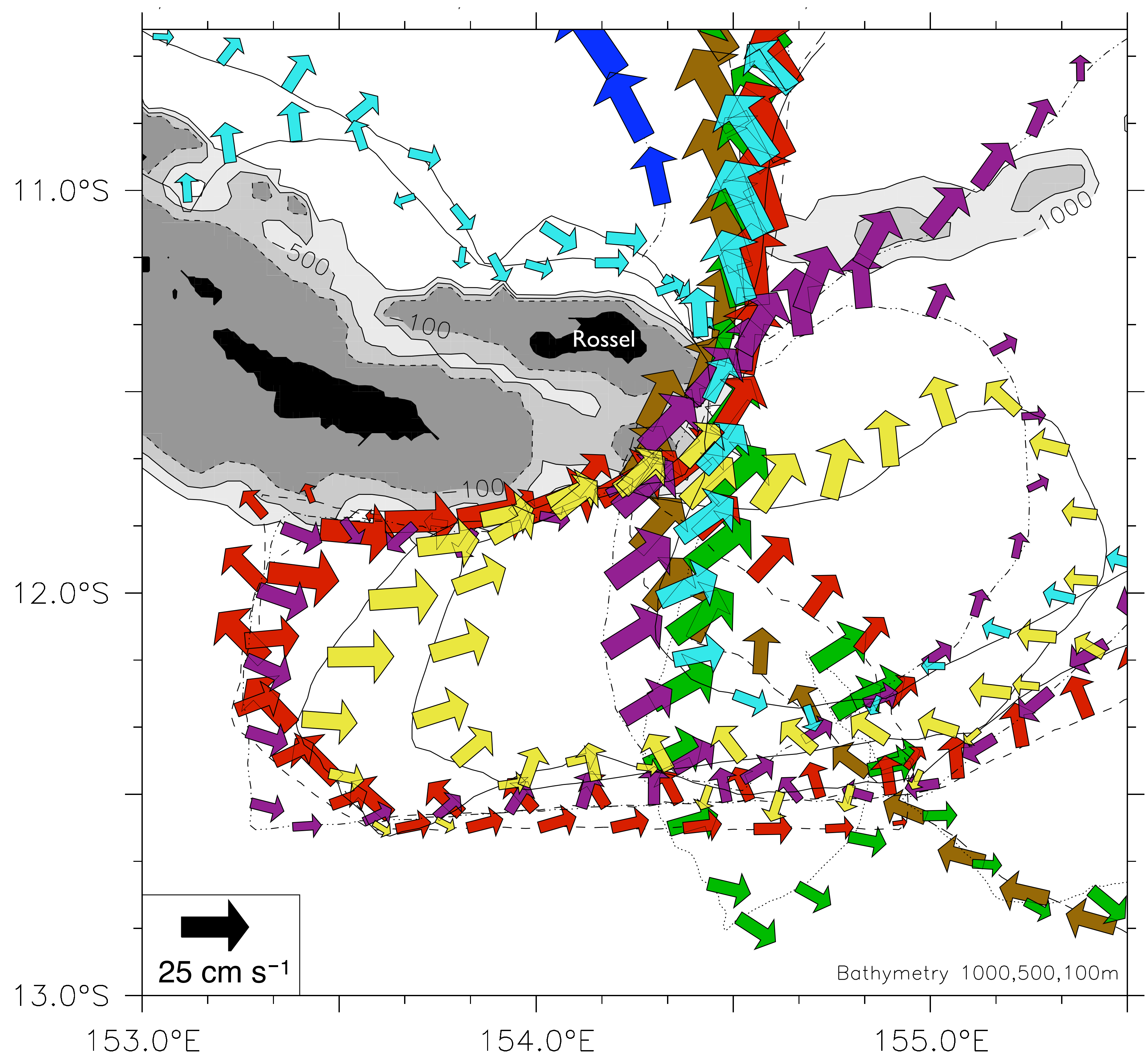
Model 0-700m velocity during glider obs: a daunting sampling problem



Bluelink: MOM4, BoM, Melbourne. 1/10th degree

Vertical-average currents at the tip of PNG

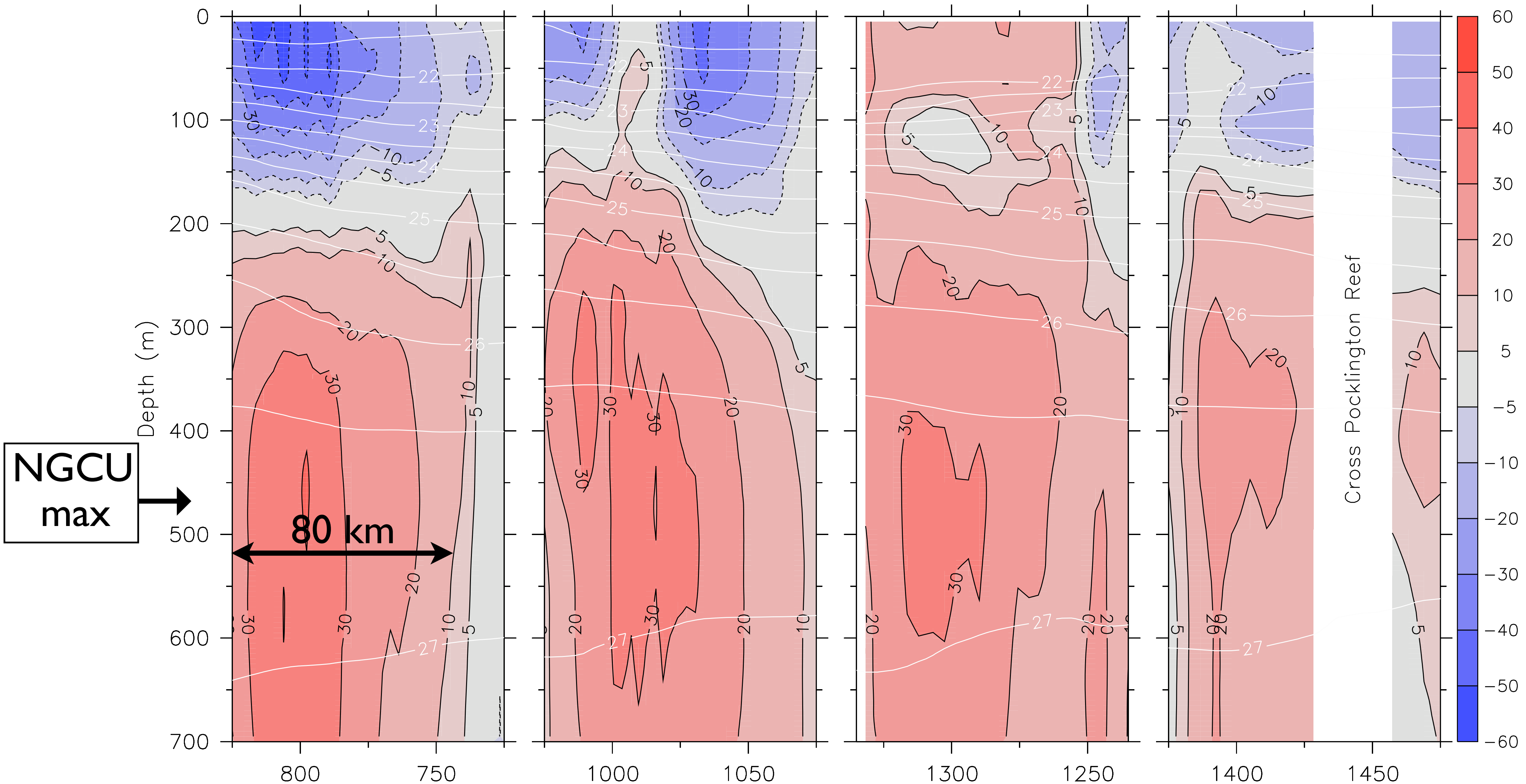
Now, we will look at the vertical structure of the NGCU ....



Absolute crosstrack geostrophic speed in the NGCUndercurrent

Positive equatorward

Each section shows 100km from the coast of PNG, with the coast on the left. (Dec 08-Jan 09)

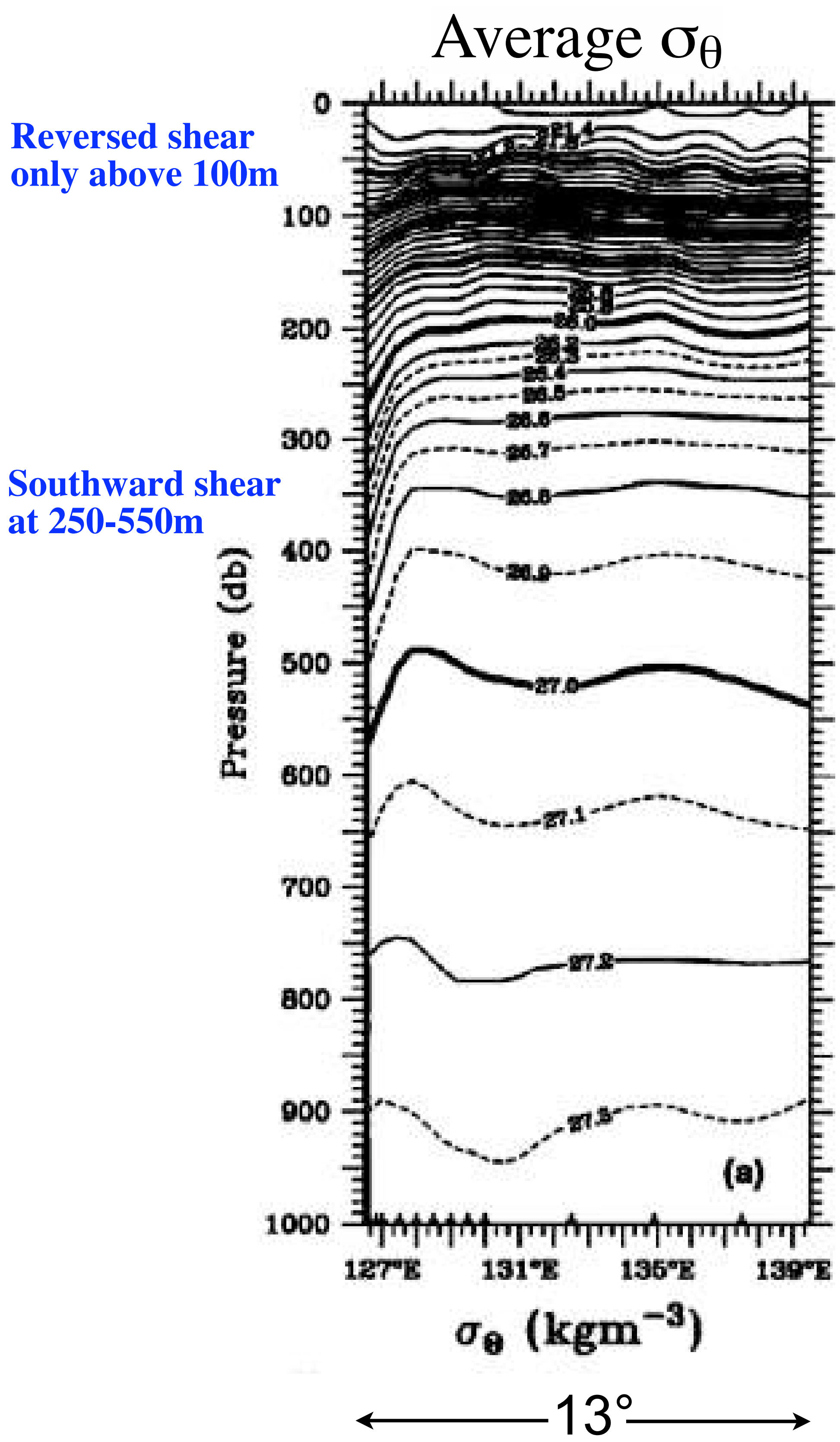


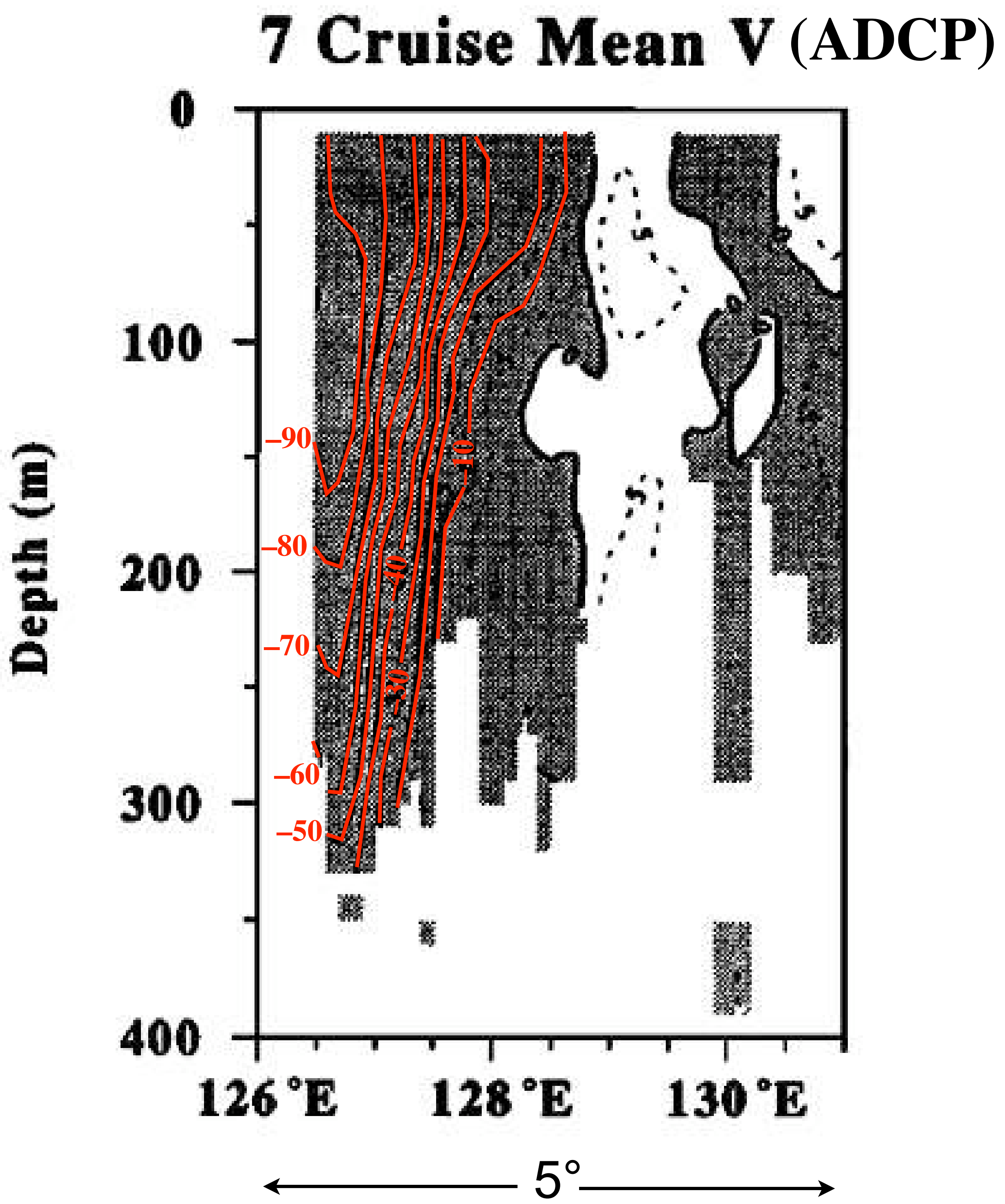
→ 1) Why is it so deep? Northward shear mostly below 700m

→ 2) Why is there reversed shear above 400m?

By contrast,

the Mindanao Current is surface-trapped, and shallow



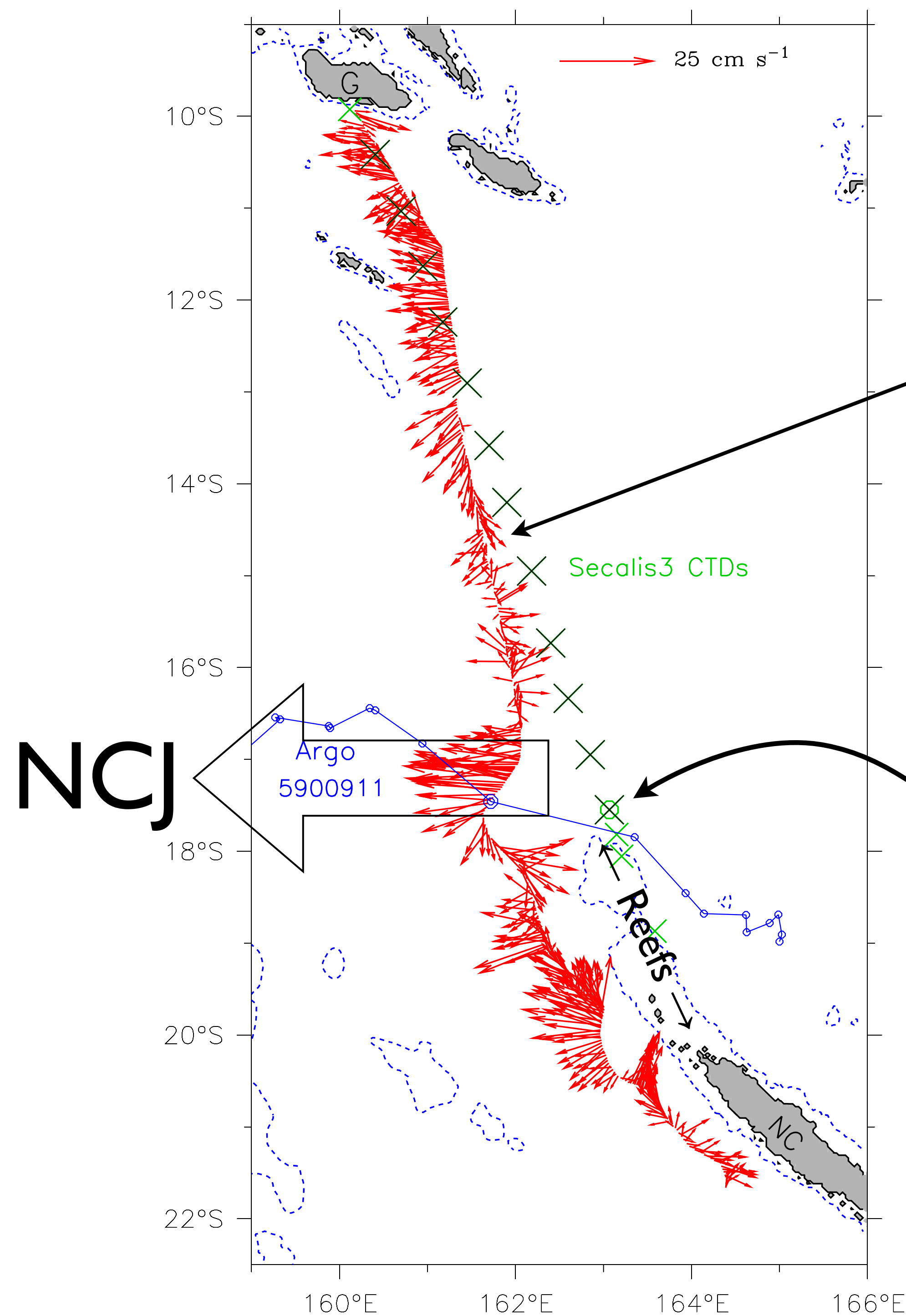


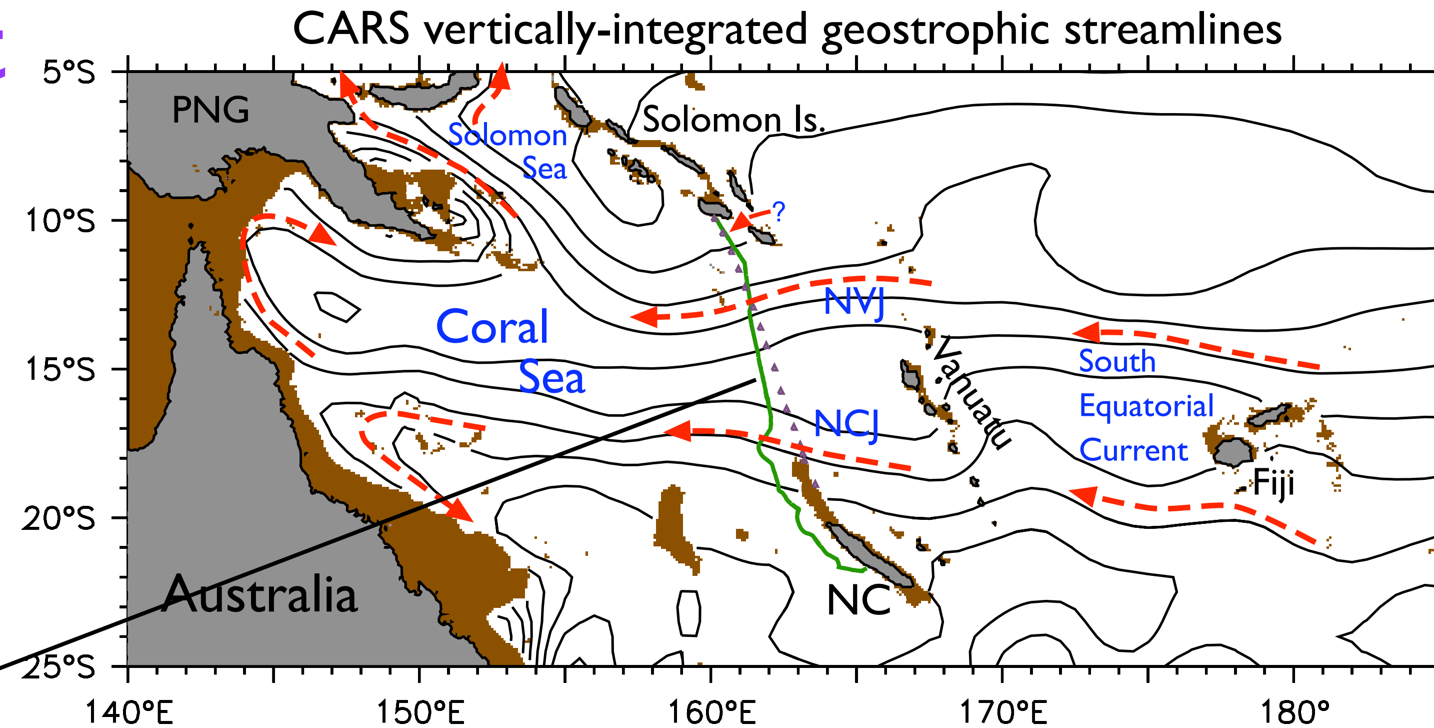
Wijffels, Firing and Toole (1995)

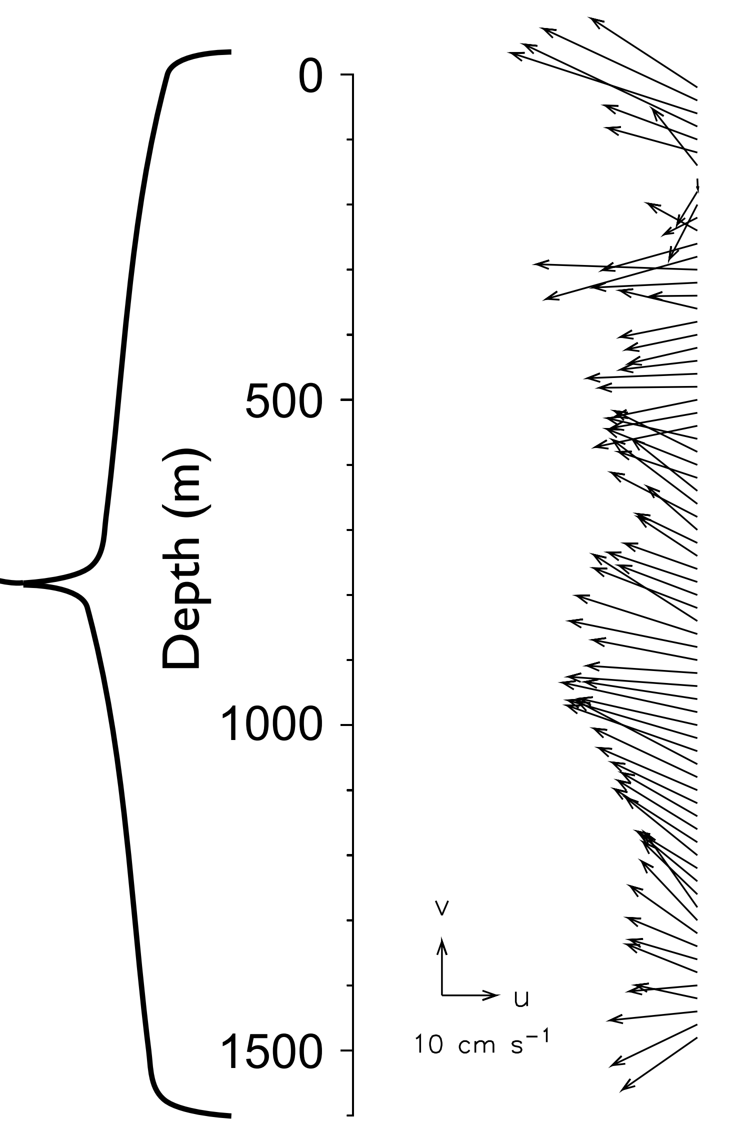
The North Caledonian Jet

precursor to the NGCU?

Gourdeau et al (2008)







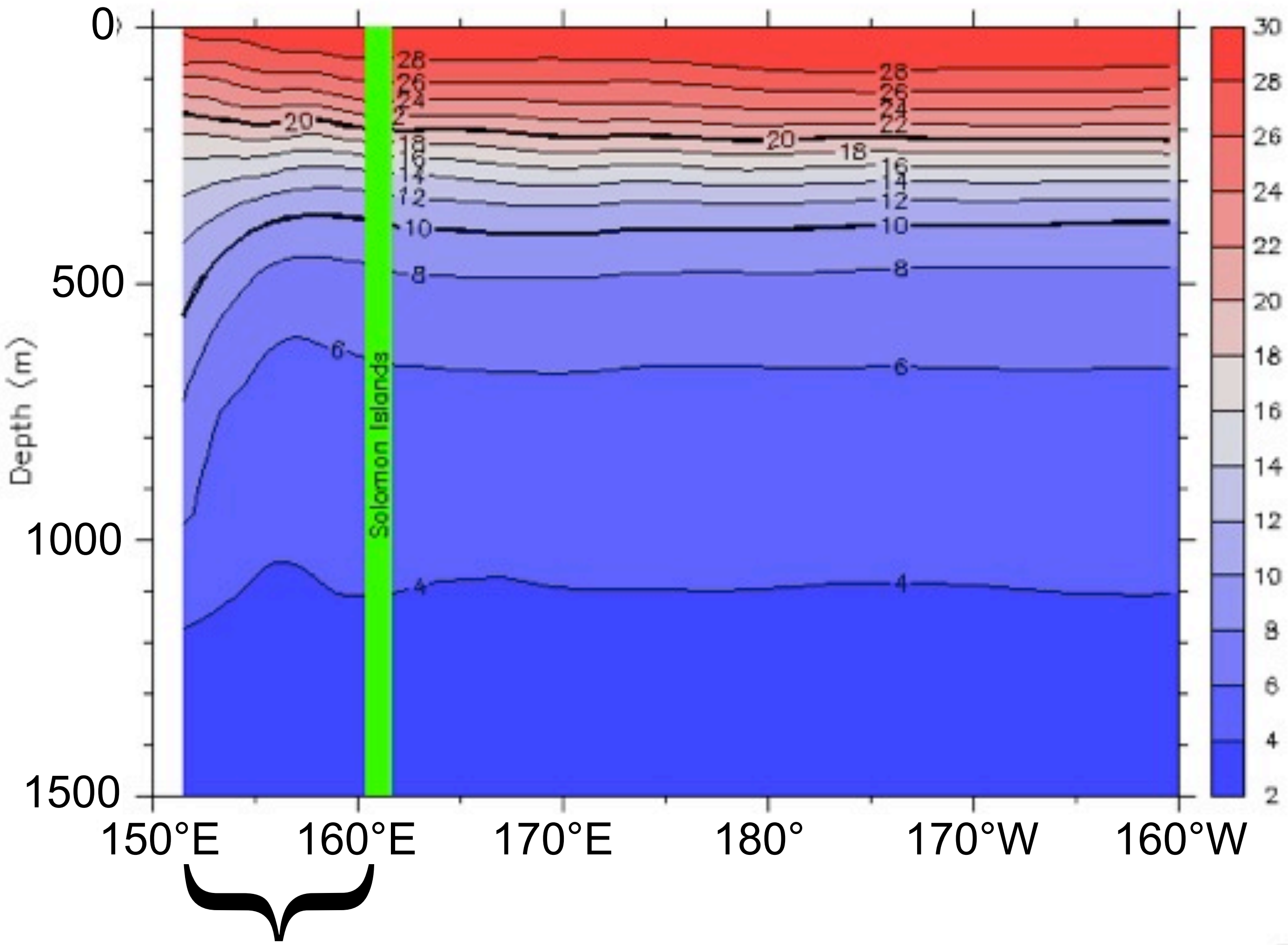
L-ADCP

in the center of the NCJ:

u > 20cm/s to 1500+m

Isotherm spreading at western boundary: South Pacific LLWBCs are undercurrents

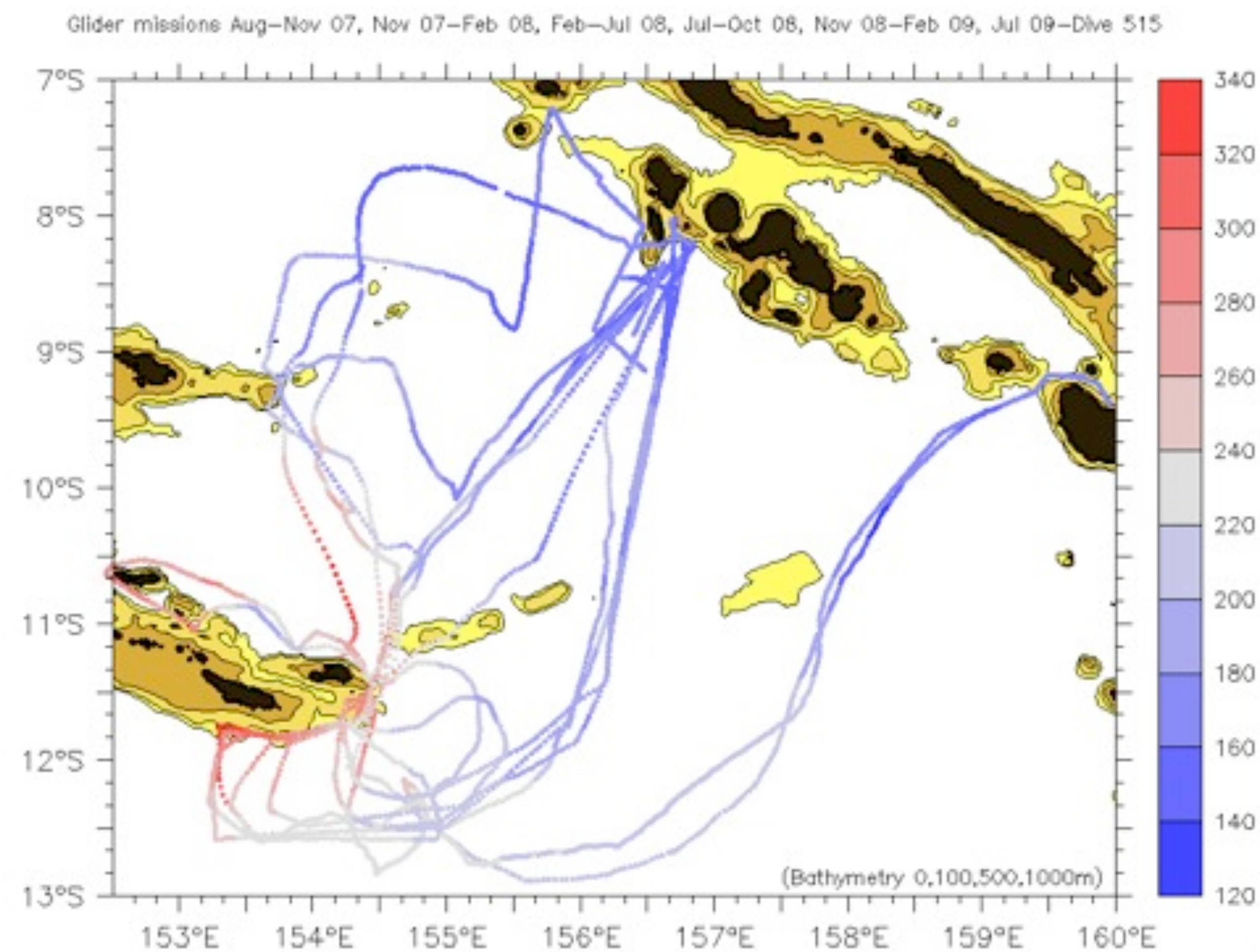
Climatological temperature at 10°S



Solomon Sea

(CARS)

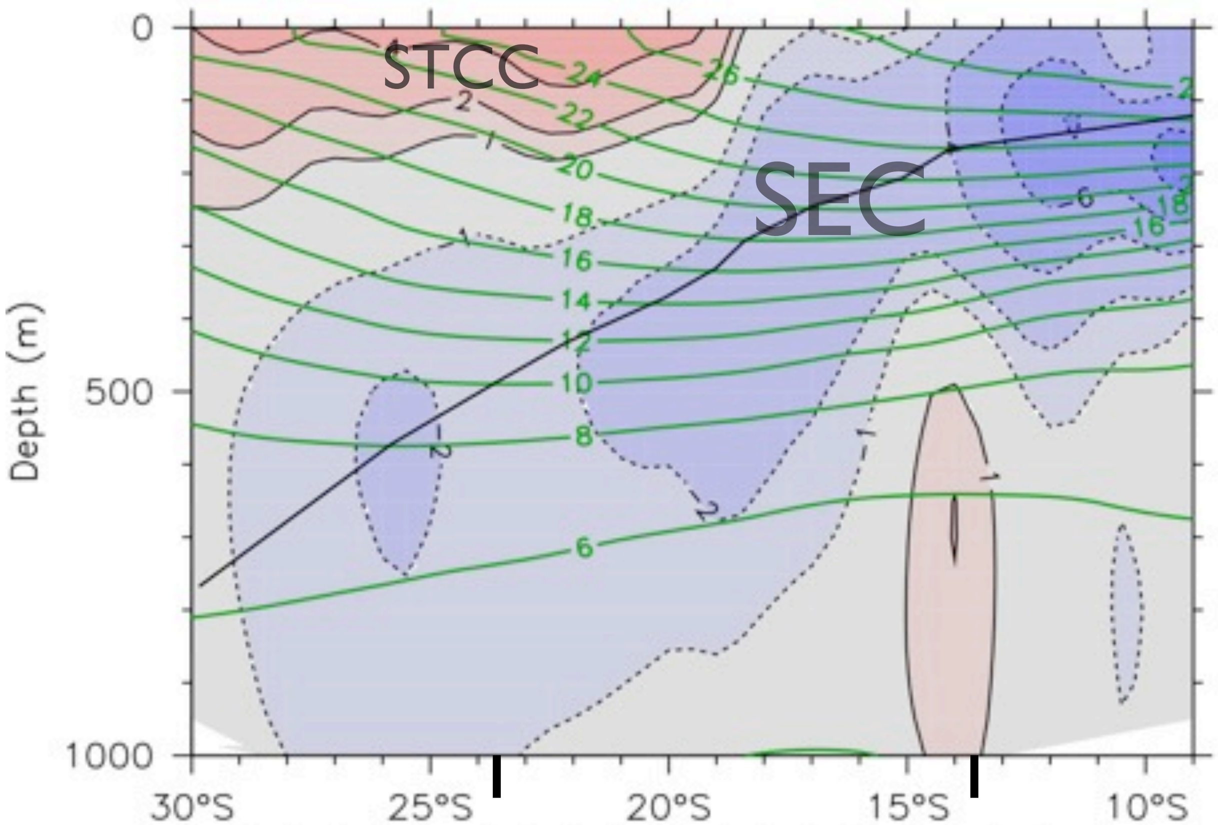
10°-20°C thickness (glider)



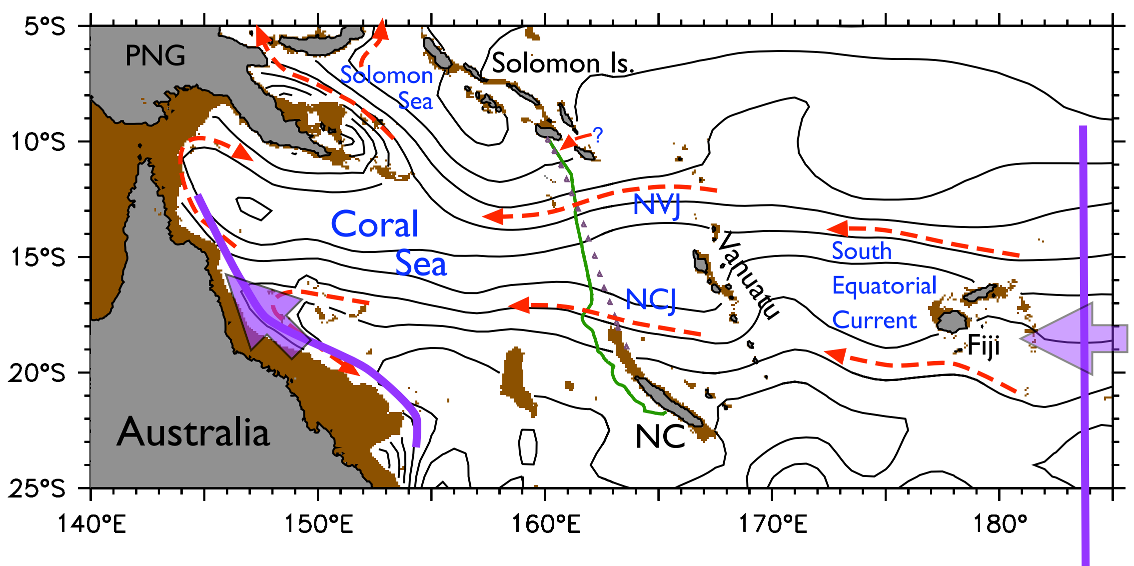
Red = thick, Blue = tight

Tilted subtropical gyre, tilted WBC bifurcation

Mean (y,z) section across the central basin:
u (color) and T° (green contours)
→ SubTropical CounterCurrent ←



Tilted gyre bowl: W shear below, E above.



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

Qu and Lindstrom (2002 JPO)

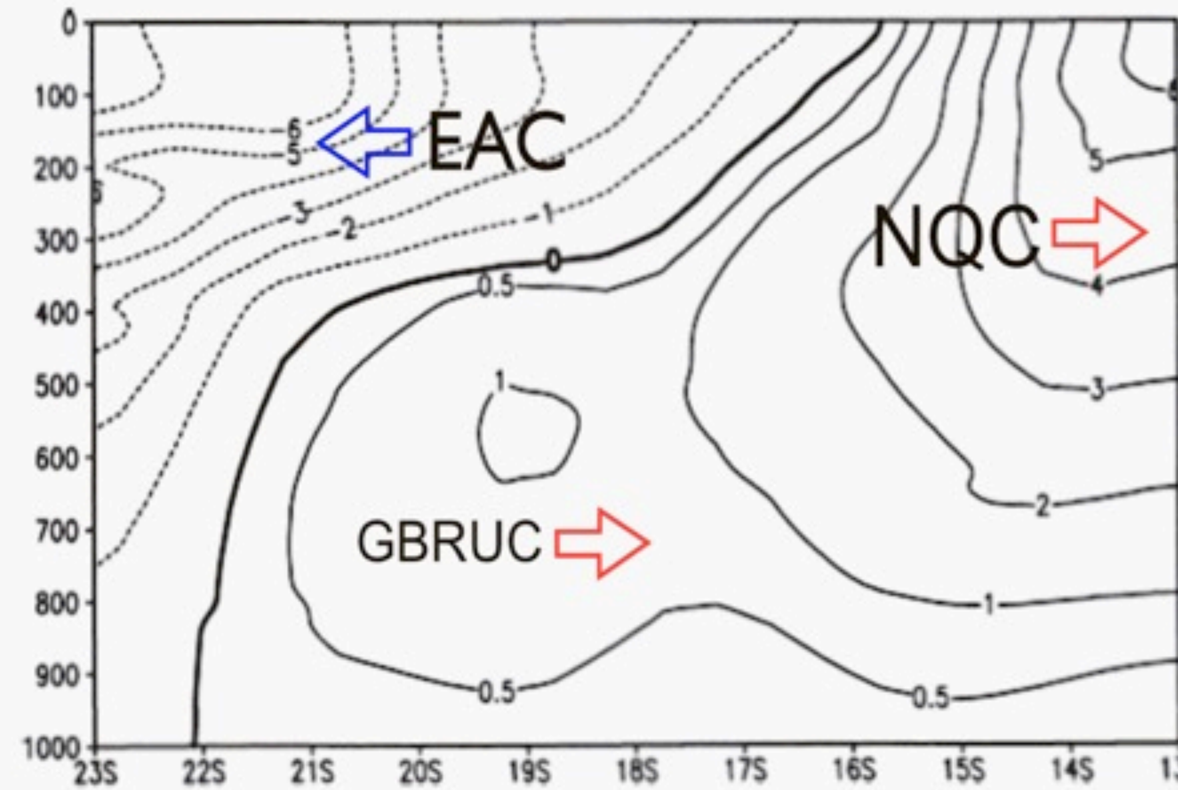


FIG. 9. Alongshore velocity (cm s^{-1}) averaged within 2° from the coast. Positive values are northwestward, and the contour of zero velocity indicates the bifurcation of the SEC.

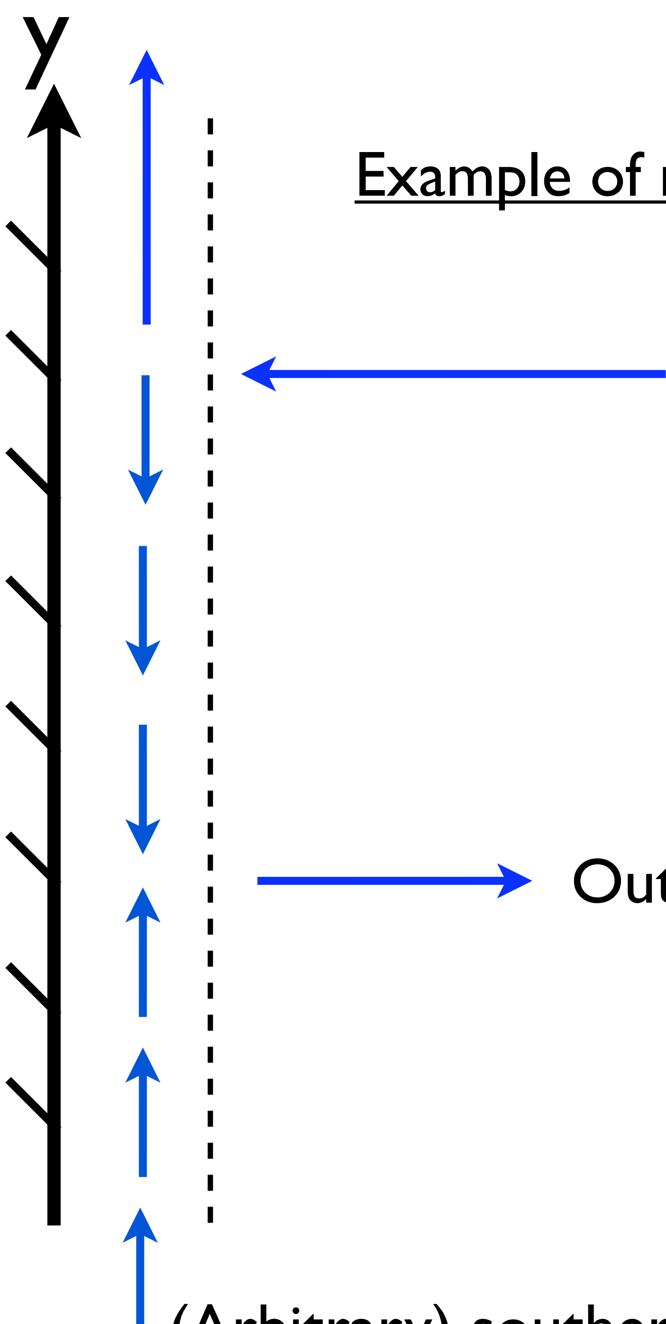
From Qu and Lindstrom (2002 JPO)

→ What is the connection between these two?

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

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

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 ($WBC(y_s)$)

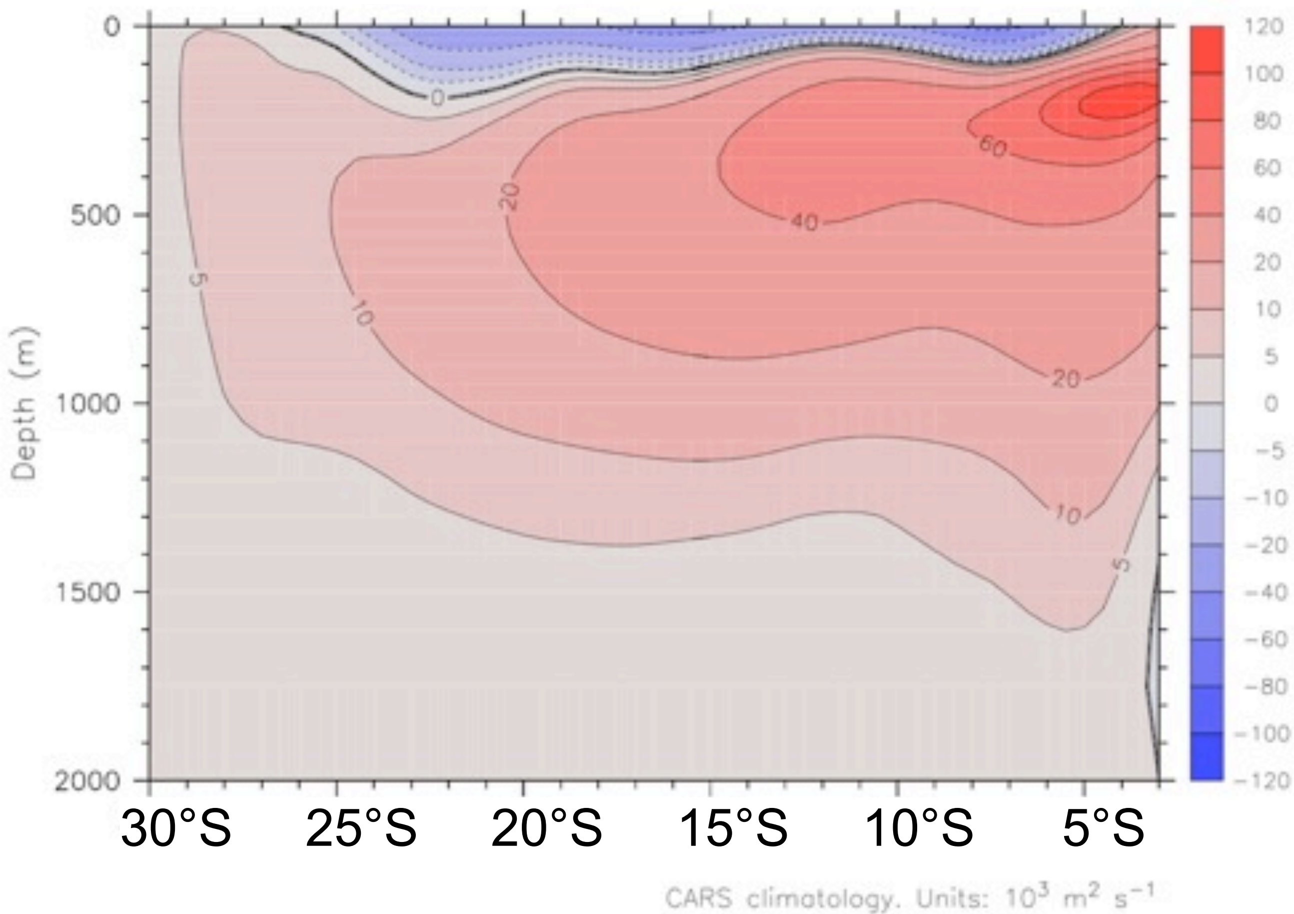
A kinematic estimate of the WBC a la Godfrey (1975)

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

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

Choose u_g at 170°E, integrate northward at each <u>z-level</u>.
Need a southern boundary condition: $WBC(y_s)$.

With zero southern BC



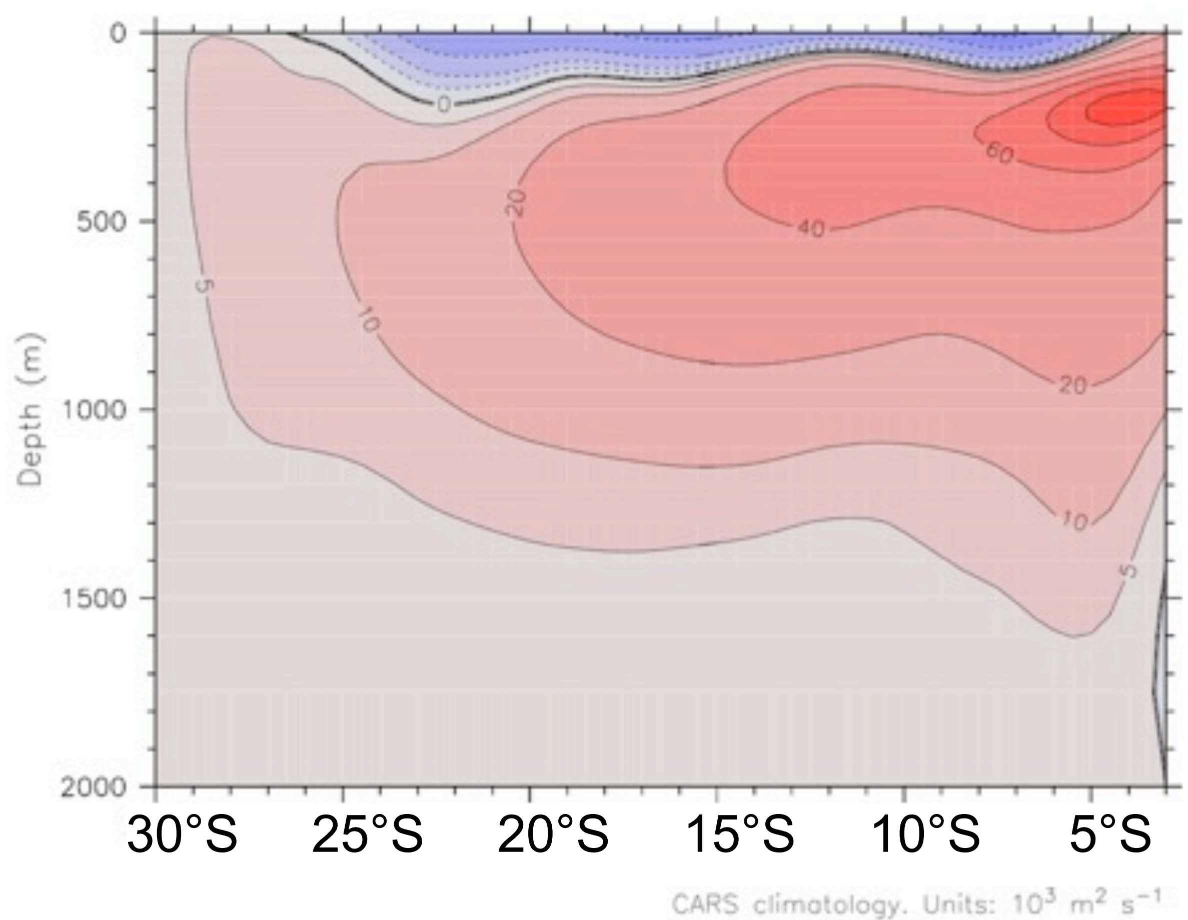
A kinematic estimate of the WBC a la Godfrey (1975)

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

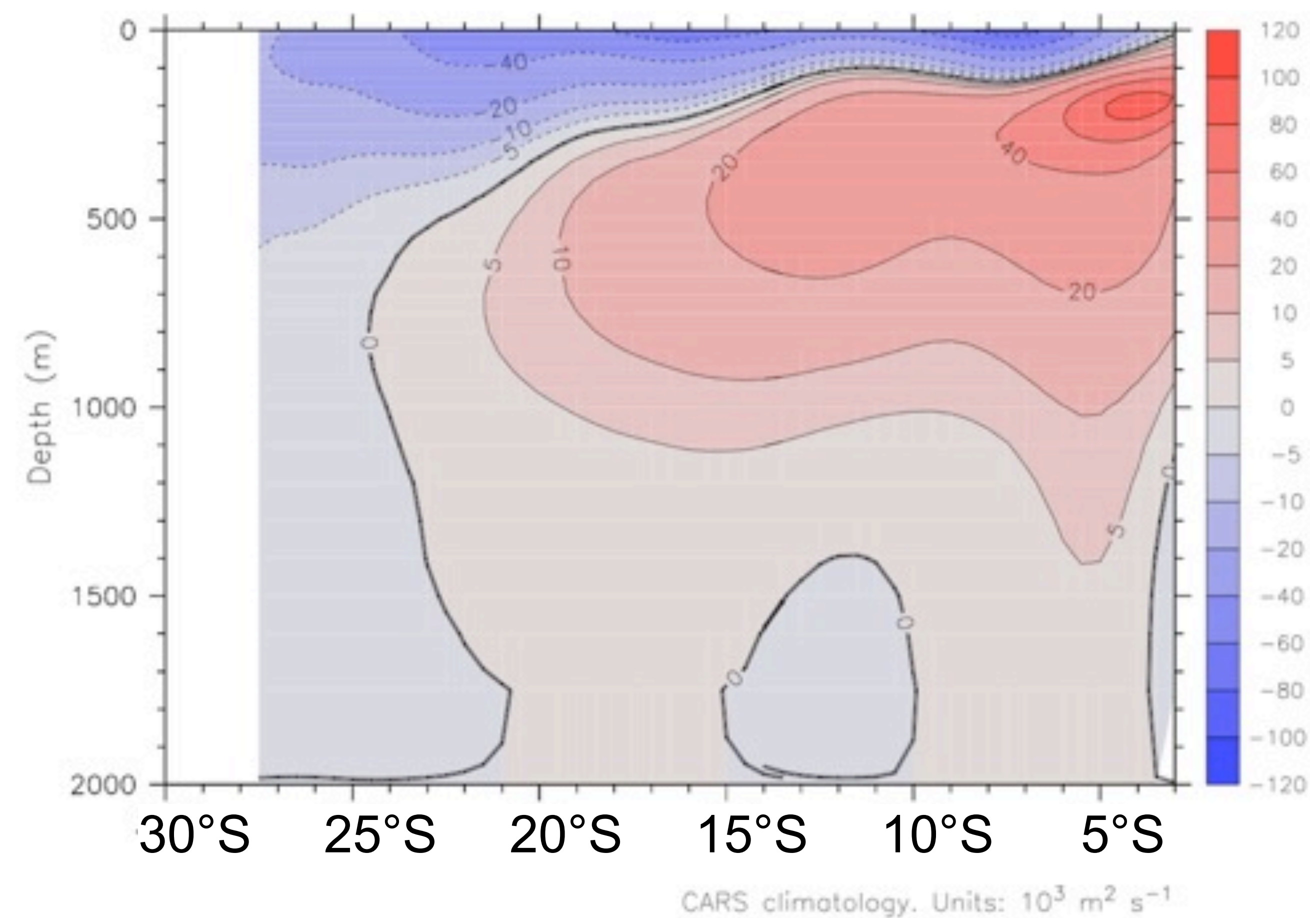
$$WBC(y) = WBC(y\ ) - \int_{y_s}^{y} u_g \, dy'$$

Choose u_g at 170°E, integrate northward at each <u>z-level</u>.
Need a southern boundary condition: $WBC(y_s)$.

With zero southern BC



Southern BC = CARS v_g at 25°-30°S



→ The near-surface shear is a function of the tilted gyre.
(But what is special about the South Pacific gyre?)

An LPS framework: solution along Rossby characteristics

(Luyten & Stommel 1986; McCreary & Lu 1994)

Sverdrupian (steady, linear momentum eqns)
  Layer 1 is geostrophic + Ekman
  Layer 2 is geostrophic

Nonlinear continuity eqns:

$$(h_1 u_1)_x + (h_1 v_1)_y = w_e \qquad (1)$$

$$(h_2 u_2)_x + (h_2 v_2)_y = 0 \qquad (2)$$

These lead to PV conservation along streamlines in layer 2:

$$\left(\frac{f}{h_2}\right)_x h_y - \left(\frac{f}{h_2}\right)_y h_x = 0 \qquad (3)$$

where $h = h_1 + h_2$. (Contours of h are streamlines of layer 2 u_g .)

} LPS

(1)-(3) and ... yield a characteristic equation (ray paths) for h:

$$\left[\underbrace{-\frac{\beta}{f^2} g'_{12} h_e}_{c_r} + \underbrace{-\frac{1}{h}\left(\Psi_y - \frac{\tau^y}{f}\right)}_{\overline{u_g}}\right] h_x + \left[\underbrace{\frac{1}{h}\left(\Psi_x + \frac{\tau^x}{f}\right)}_{\overline{v_g}}\right] h_y = \overrightarrow{C_g} \bullet \nabla h = 0 \qquad (4)$$

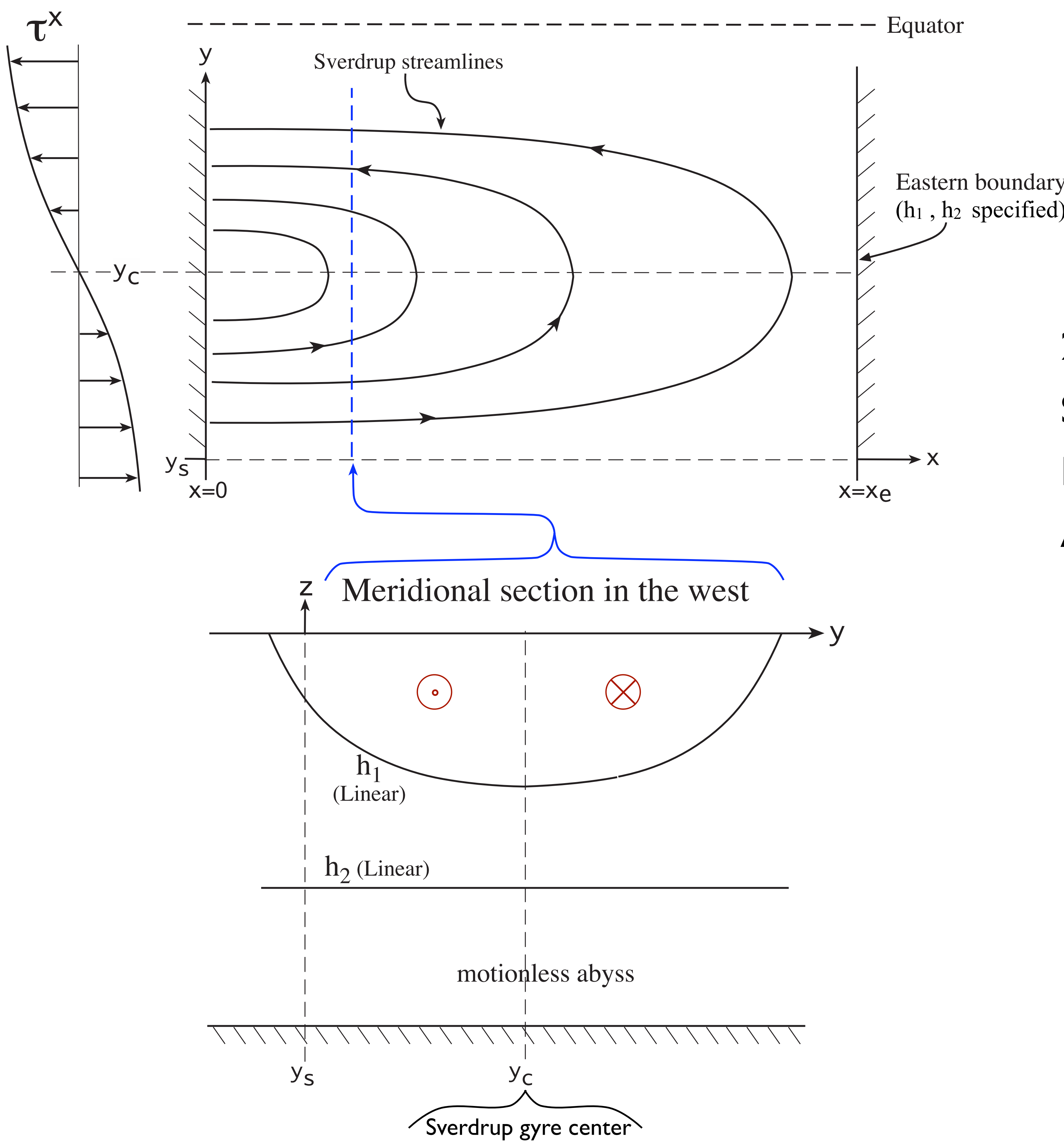
where $h_e = h_1(1-h_1/h)$, and Ψ is the Sverdrup streamfunction.

(Luyten & Stommel, 86 JPO; McCreary & Lu, 94 JPO)

(4) is a first-order PDE in h and known quantities:

→ find streamlines by integrating along background-flow-modified Rossby ray paths.

A linear southern subtropical gyre: no STCC



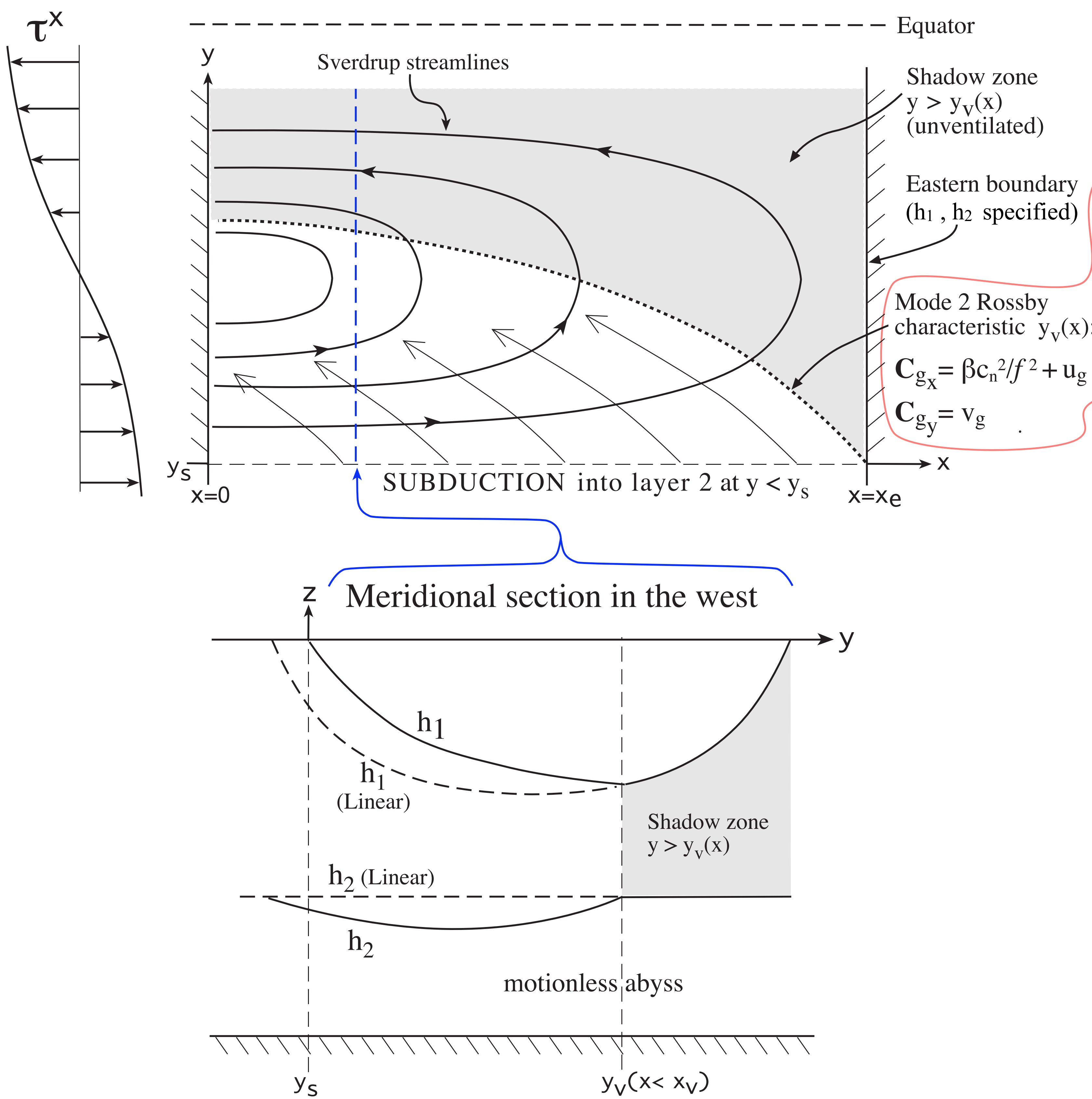
2.5 layers (but layer 2 is motionless)

Sverdrupian (in vertical integral)

Rossby characteristics are due west

All Sverdrup transport is in layer 1:
h_1 is a centered bowl.

An LPS southern subtropical gyre: generation of the STCC



2.5 layers (minimum)

Sverdrupian (in vertical integral)

Essential nonlinearity of LPS:

Rossby characteristics are (information pathways) bent by Sverdrup currents (equatorward ....)

In shadow zone, only layer 1 is active

In ventilated region, layer 2 “feels” the downwelling wind forcing

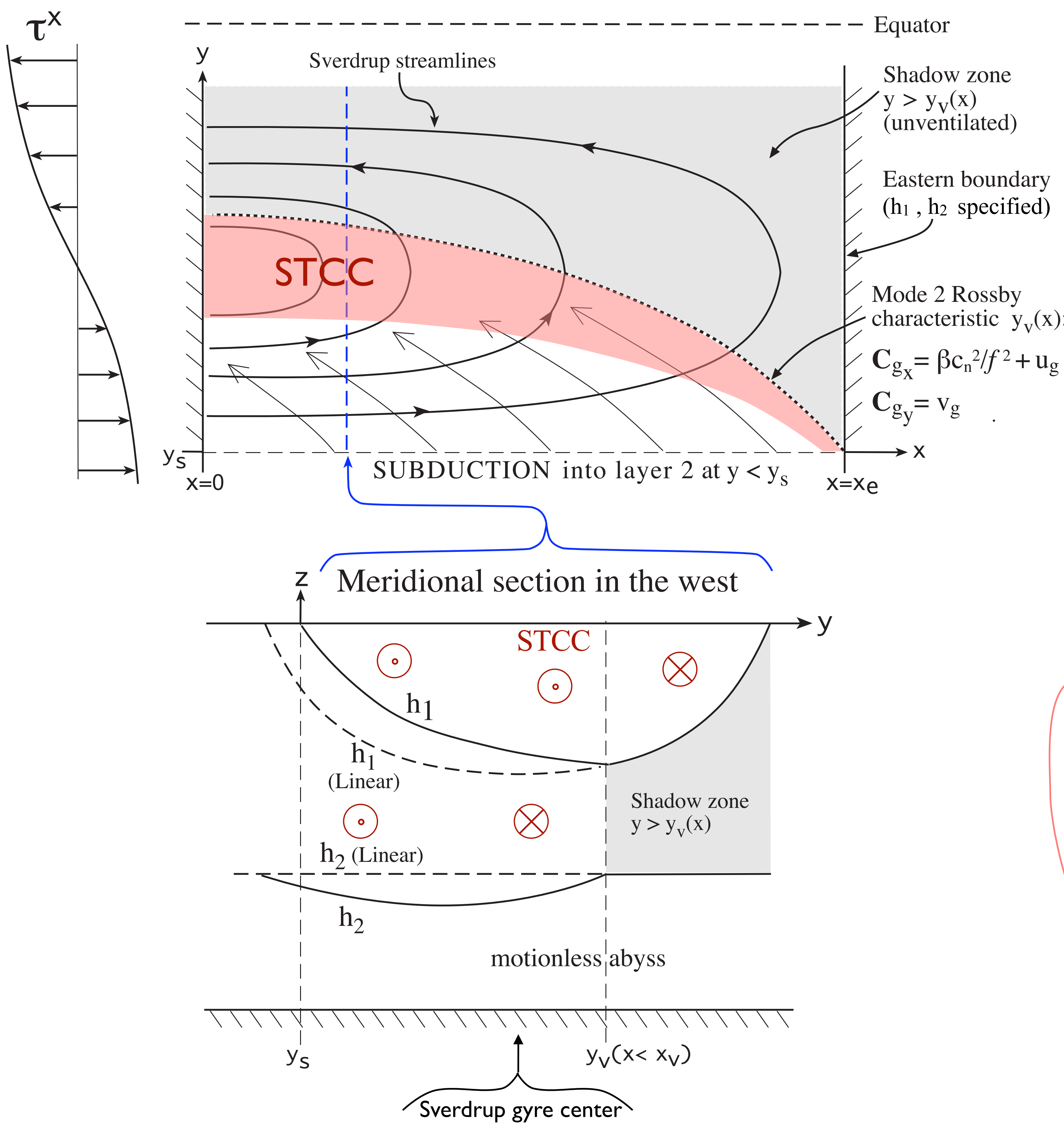
⇒ Upper gyre (h_1) shifted eq-ward
Lower gyre (h_2) shifted poleward

⇒ Tilted gyre, eastward sfc shear, SubTropical Counter Current

⇒ Sheared WBCs

⇒ NGCU shear depends on subduction .... Where?

An LPS southern subtropical gyre: generation of the STCC



2.5 layers (minimum)

Sverdrupian (in vertical integral)

Essential nonlinearity of LPS:

Rossby characteristics (information pathways) are
bent by Sverdrup currents
(equatorward ....)

In shadow zone, only layer 1 is active

In ventilated region, layer 2 "feels"
the downwelling wind forcing

⇒ Upper gyre (h_1) shifted eq-ward
Lower gyre (h_2) shifted poleward

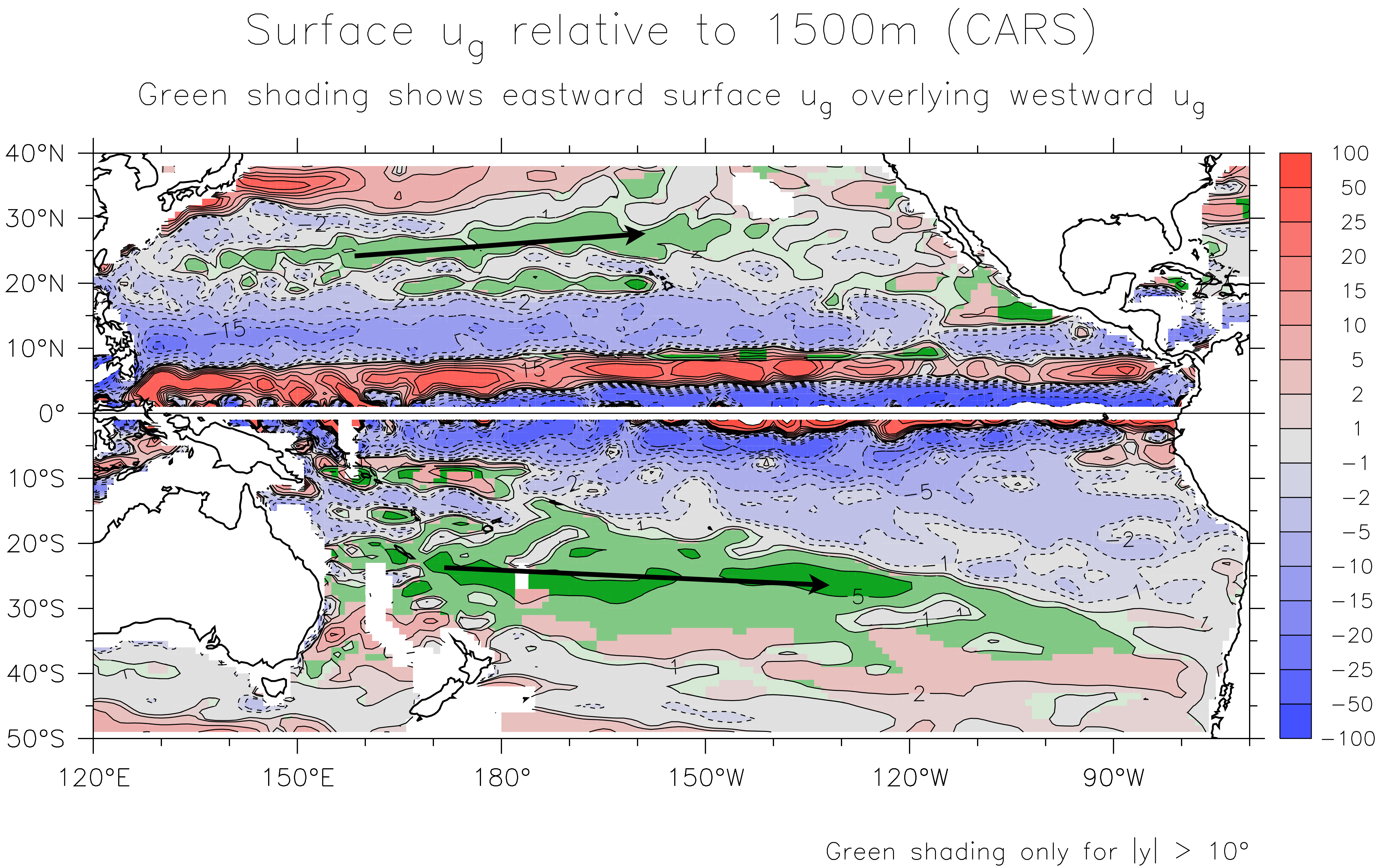
⇒ Tilted gyre, eastward sfc shear,
SubTropical Counter Current

⇒ Sheared WBCs

⇒ NGCU shear depends on
subduction .... Where?

Observed SubTropical Counter Currents

The STCC is stronger and extends further west in the South Pacific



Issues, problems and open questions:

- Strong western boundary current: 15-20+Sv
  - Scale width about 80km
  - Large and rapid interannual (ENSO) variability

  } Results

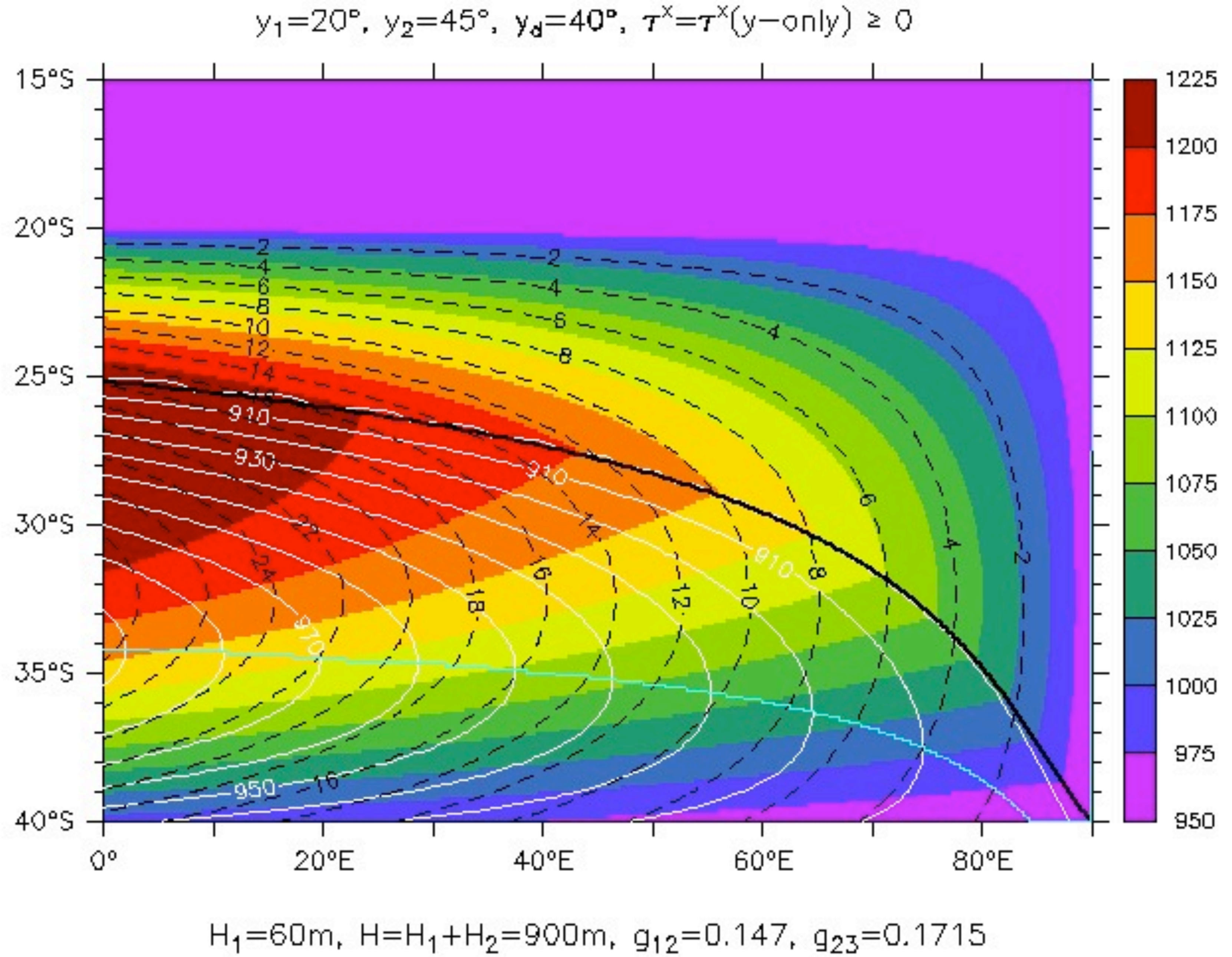
- Amazingly complex geometry/bathymetry:
  - Narrow straits at the equatorial exit
  - Large blocking island not far offshore (double WBC?)
- Intense eddies: How are they generated?
  - What sets their scale?
  - How can they be adequately sampled?
- Why is the NGCU an undercurrent?
  - Shear inherent in the shape of the S. Pacific gyre: STCC
    Implies strong subduction: Where? Why?
  - And why does the NGCU (and other S Pacific jets) extend so deep?

extra

figures

follow ....

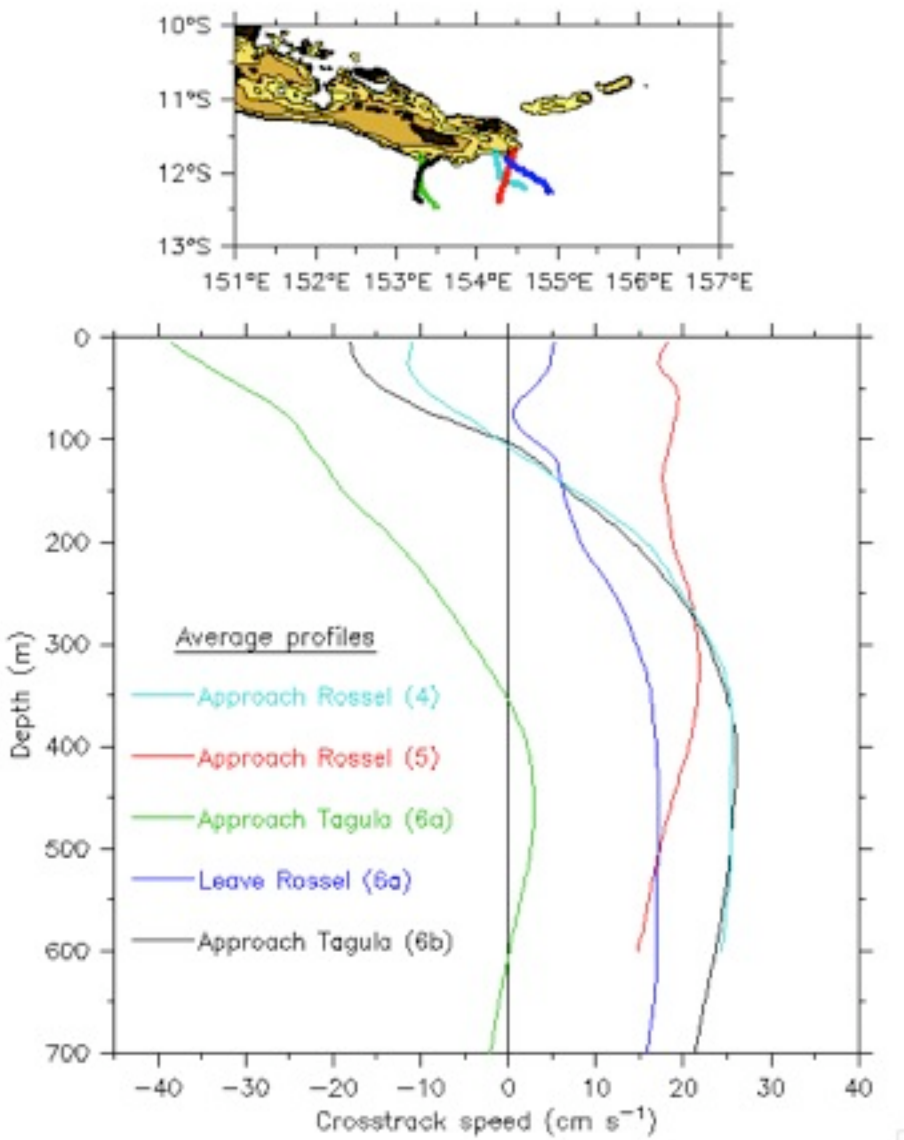
LPS solution for southern subtropical gyre



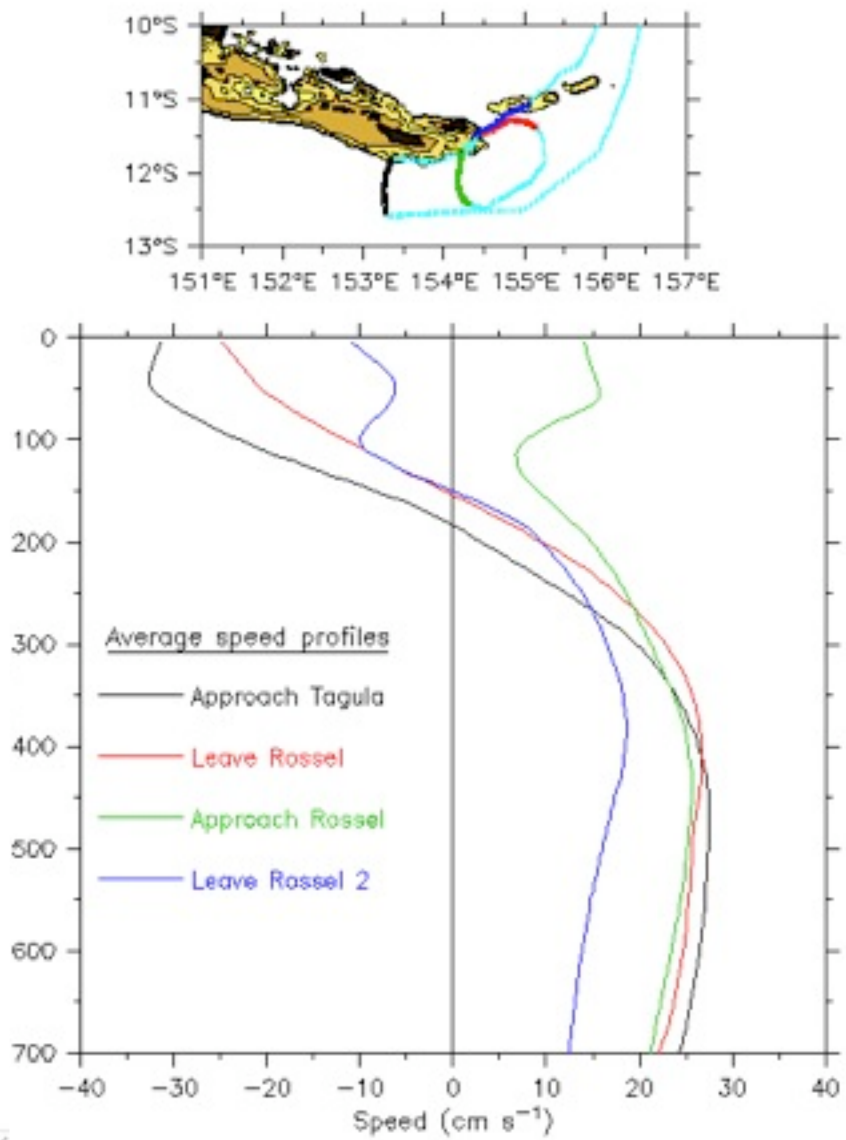
Eqns of McCreary and Lu (1994)

13 sections across the NGCU

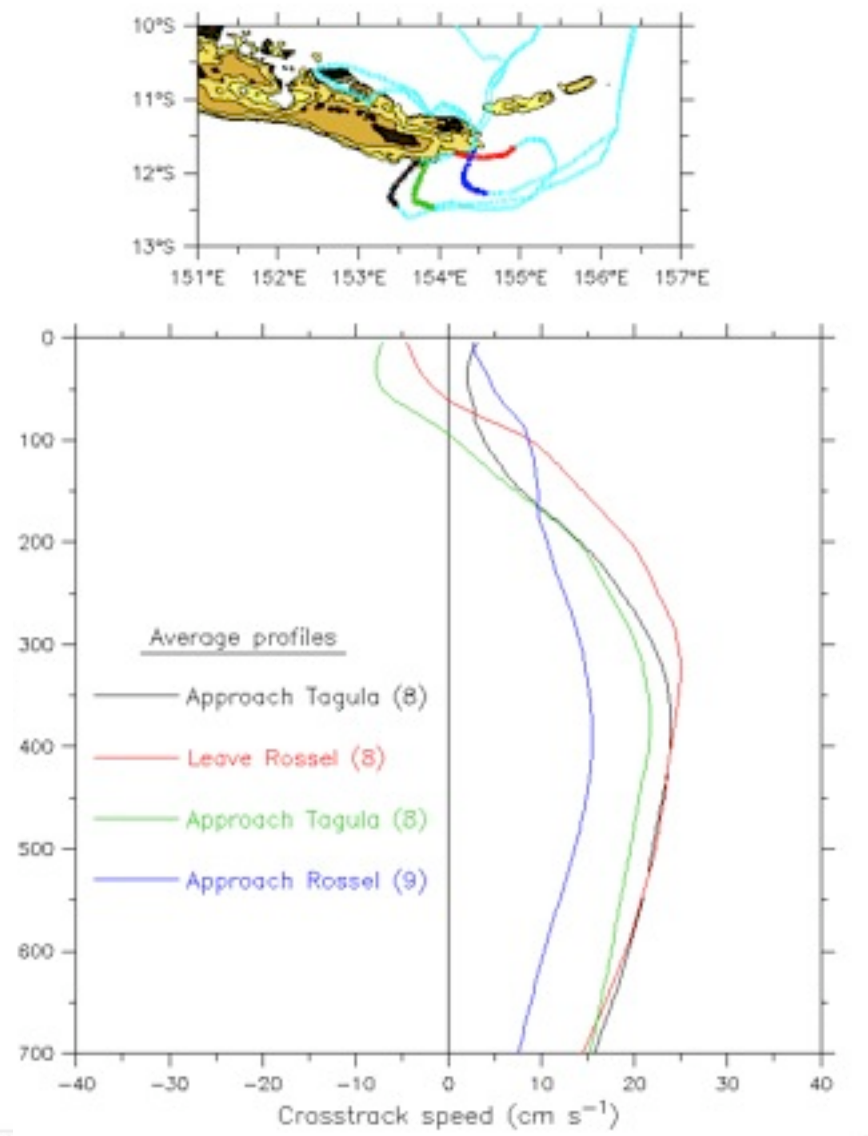
Dec 07-Sep 08



Dec 08-Jan 09

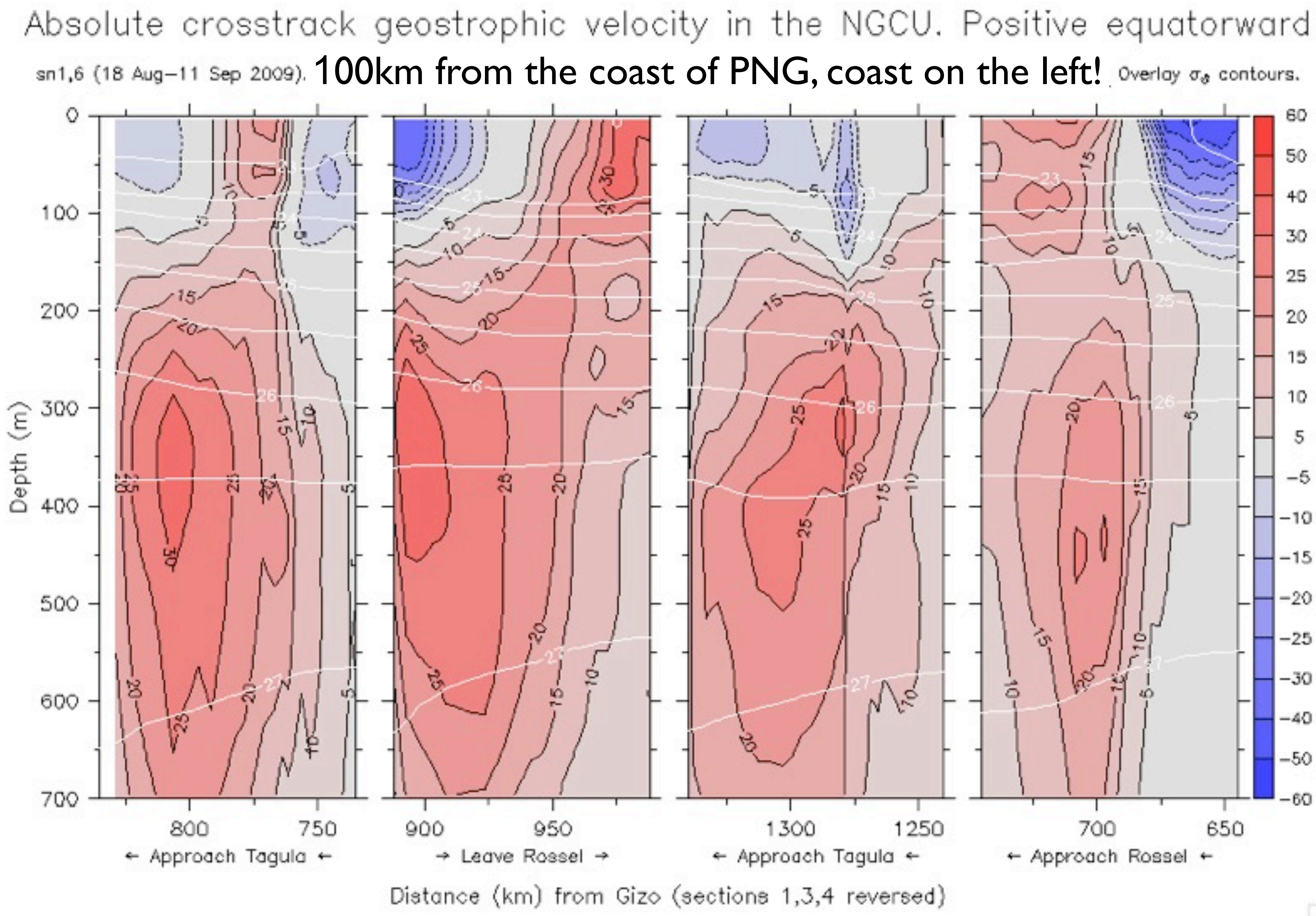


Aug-Sep 09



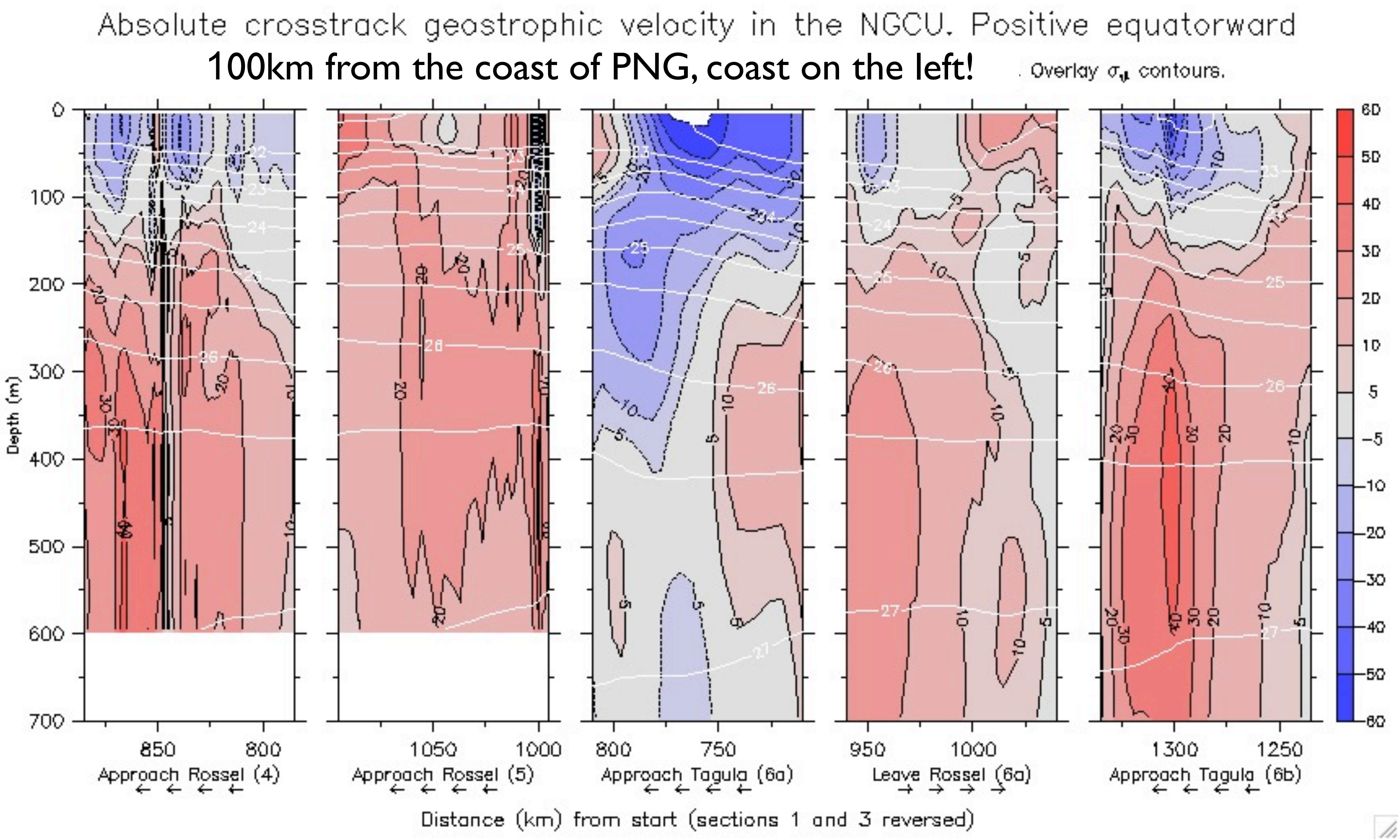
Average crosstrack speed within 85km of the coast.

Earlier sections across the NGCU



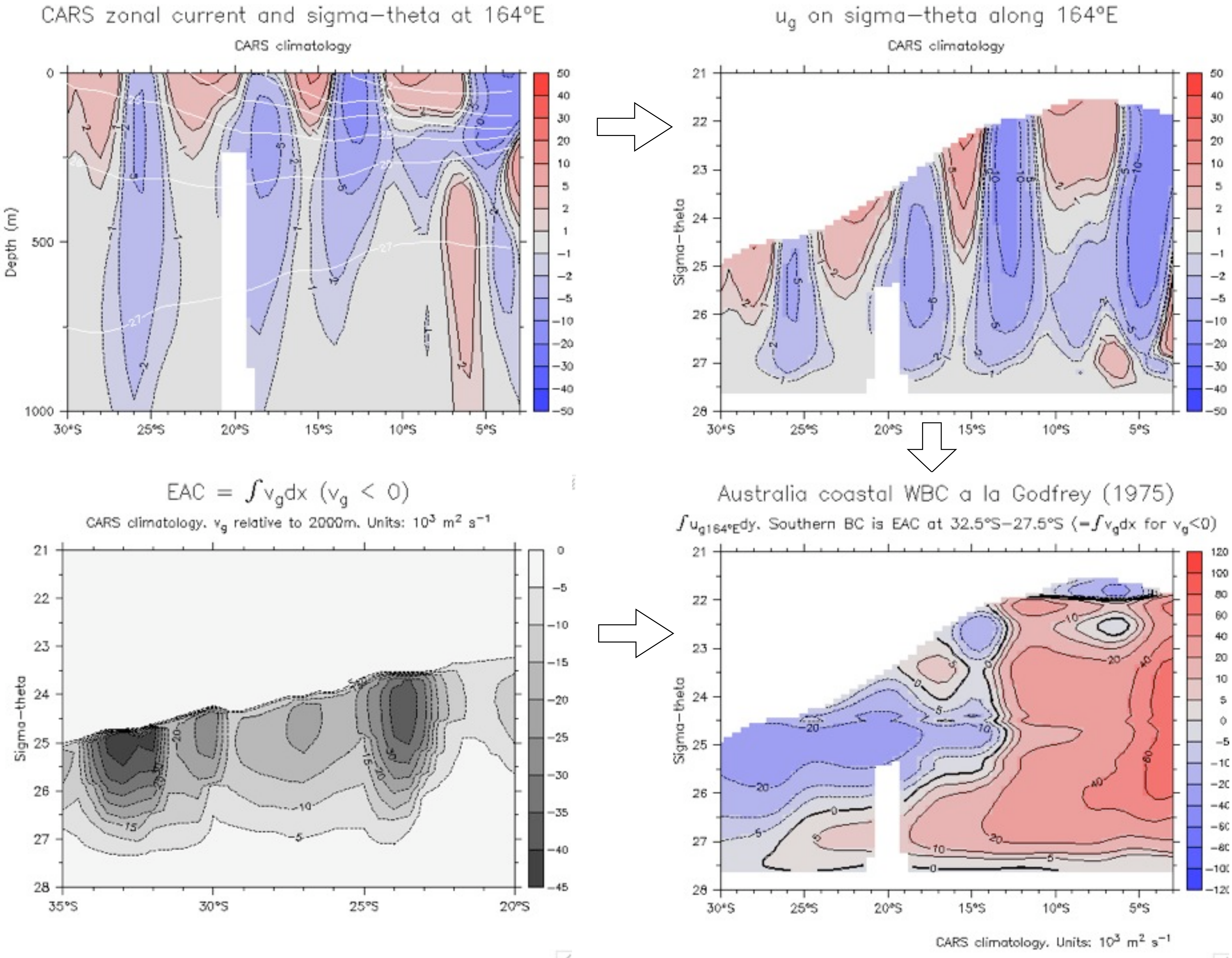
Aug - Sep 2009

Earlier sections across the NGCU



Dec 2007 - Sep 2008

WBC a la Godfrey, on density

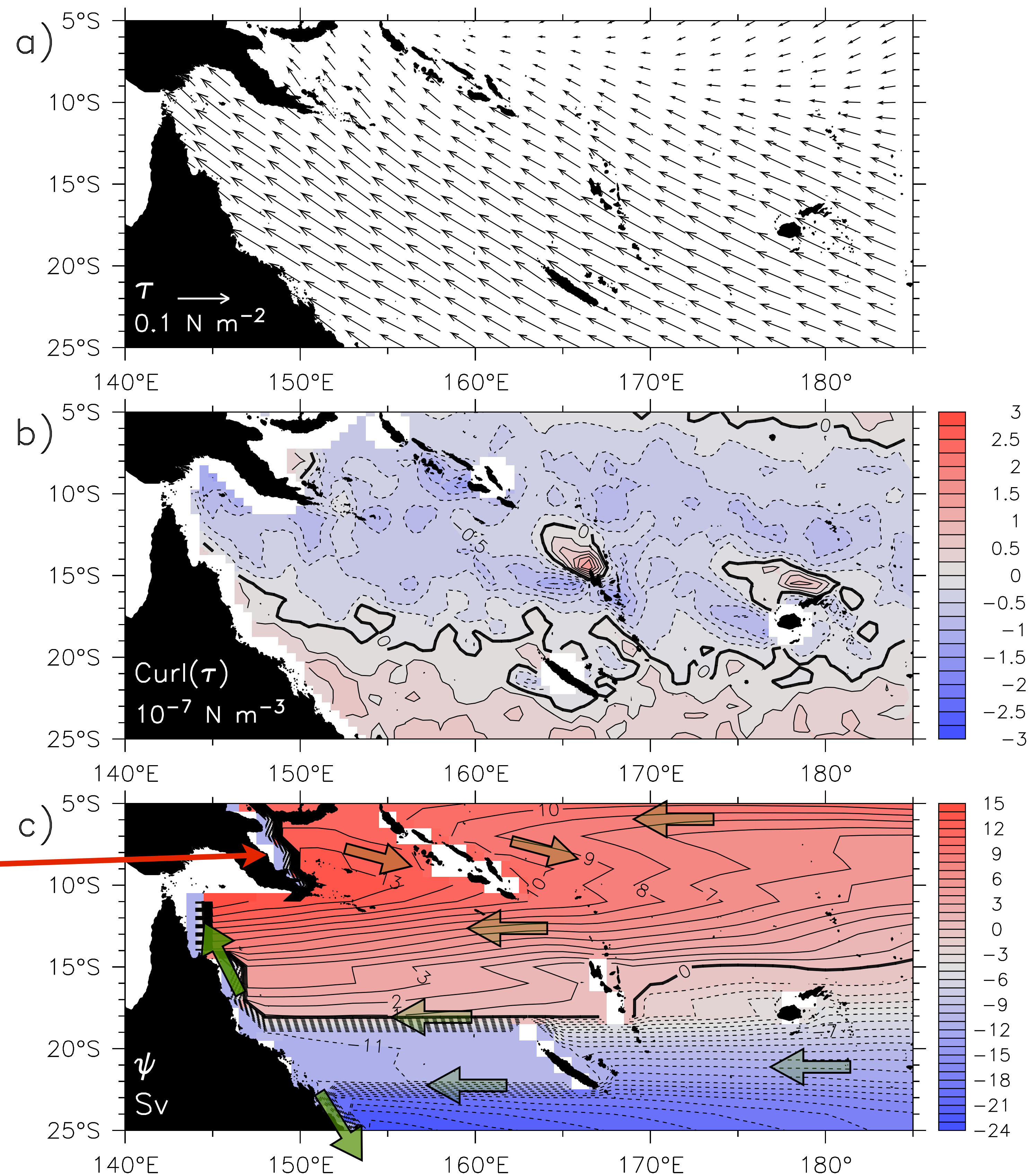


Mean wind stress, Curl(τ), Island Rule Streamfunction

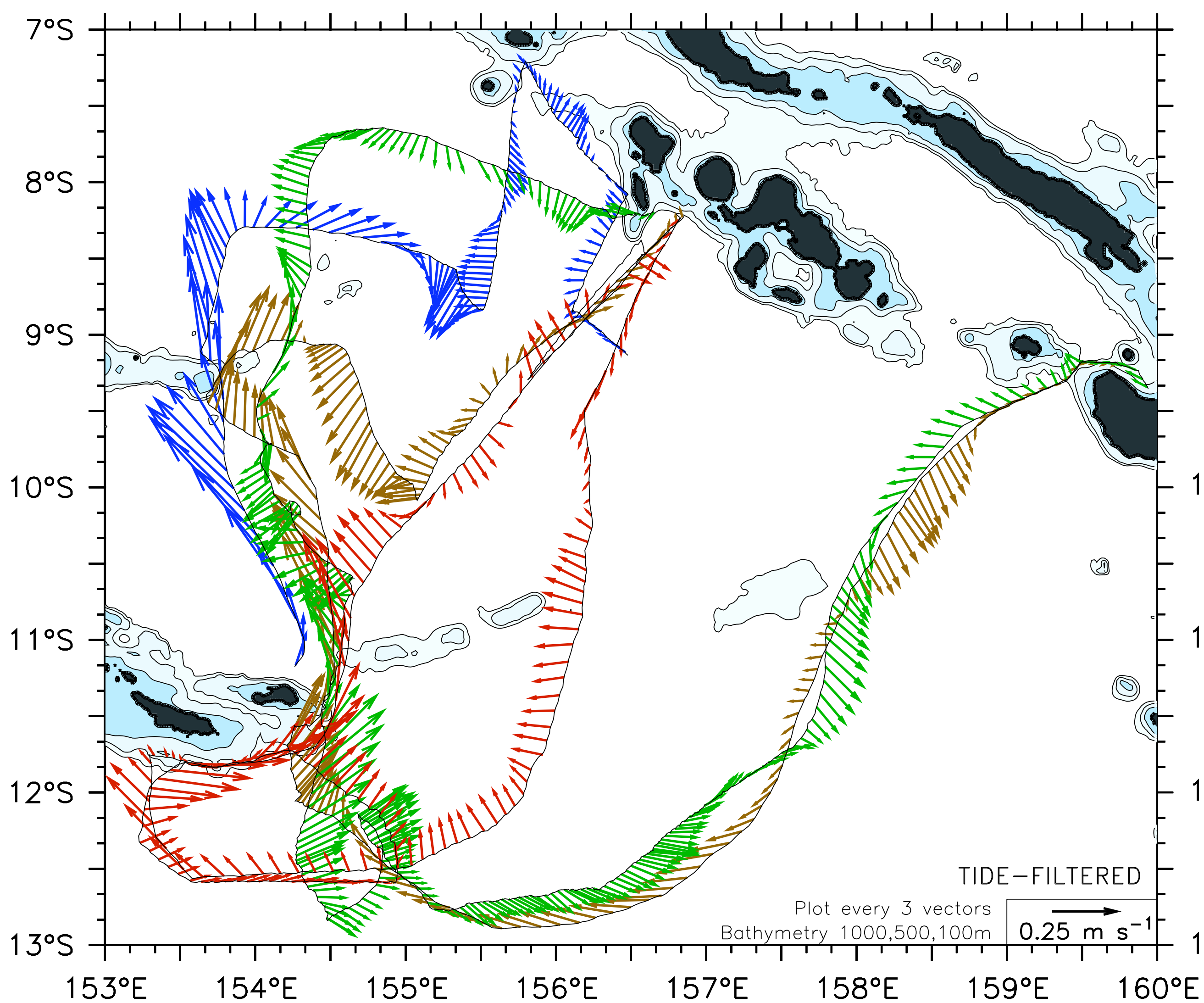
(ERS winds 1991-2000)

(Qiu et al 2009)

"Wind-driven" NGCU ≈ 24 Sv

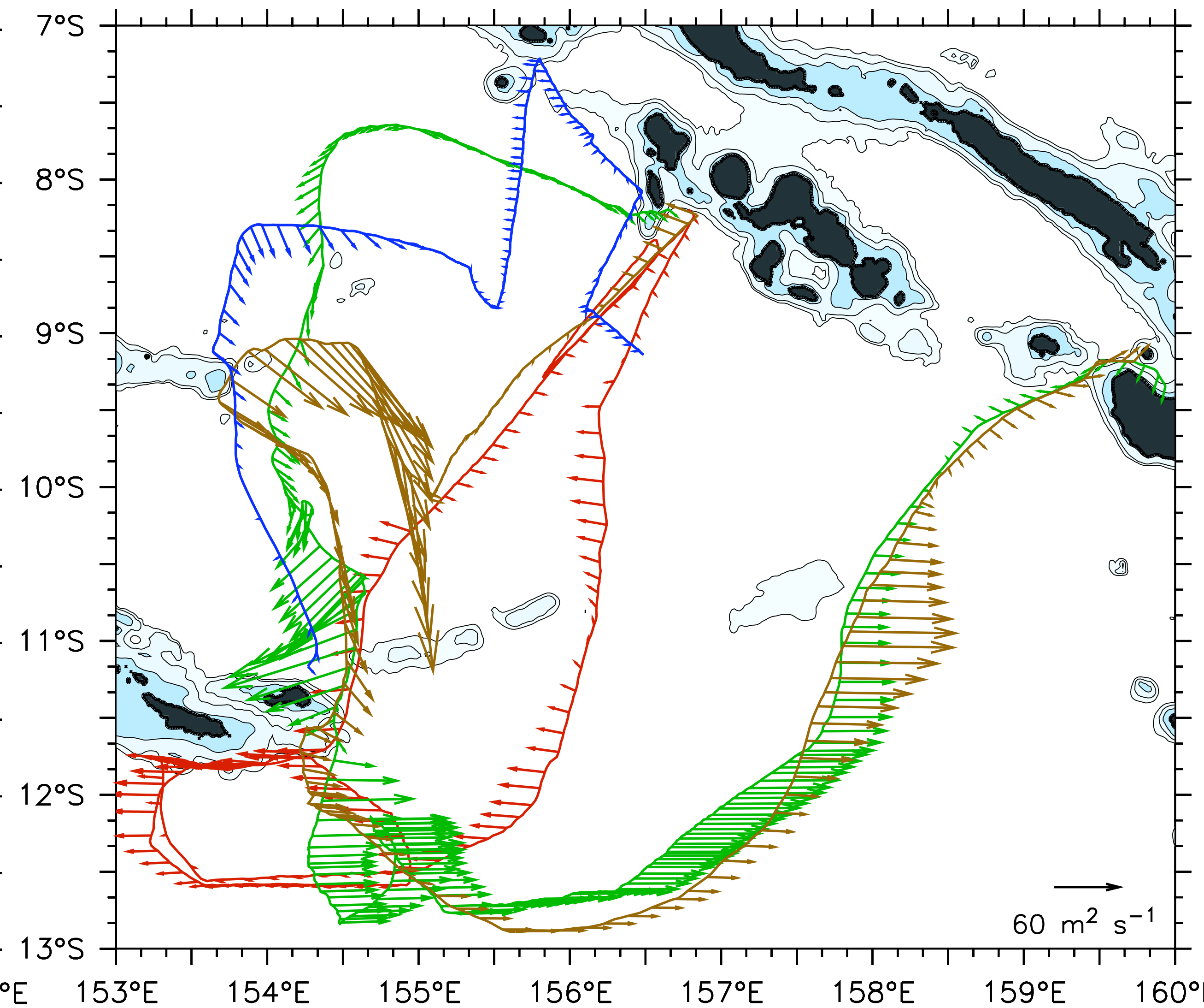


Observed Total currents



Anomalies simulated by a Rossby model

sampled on the glider time/position



The downwelling curl signature of the La Niña was strong.

Its remote effects were qualitatively simulated by a Rossby model,

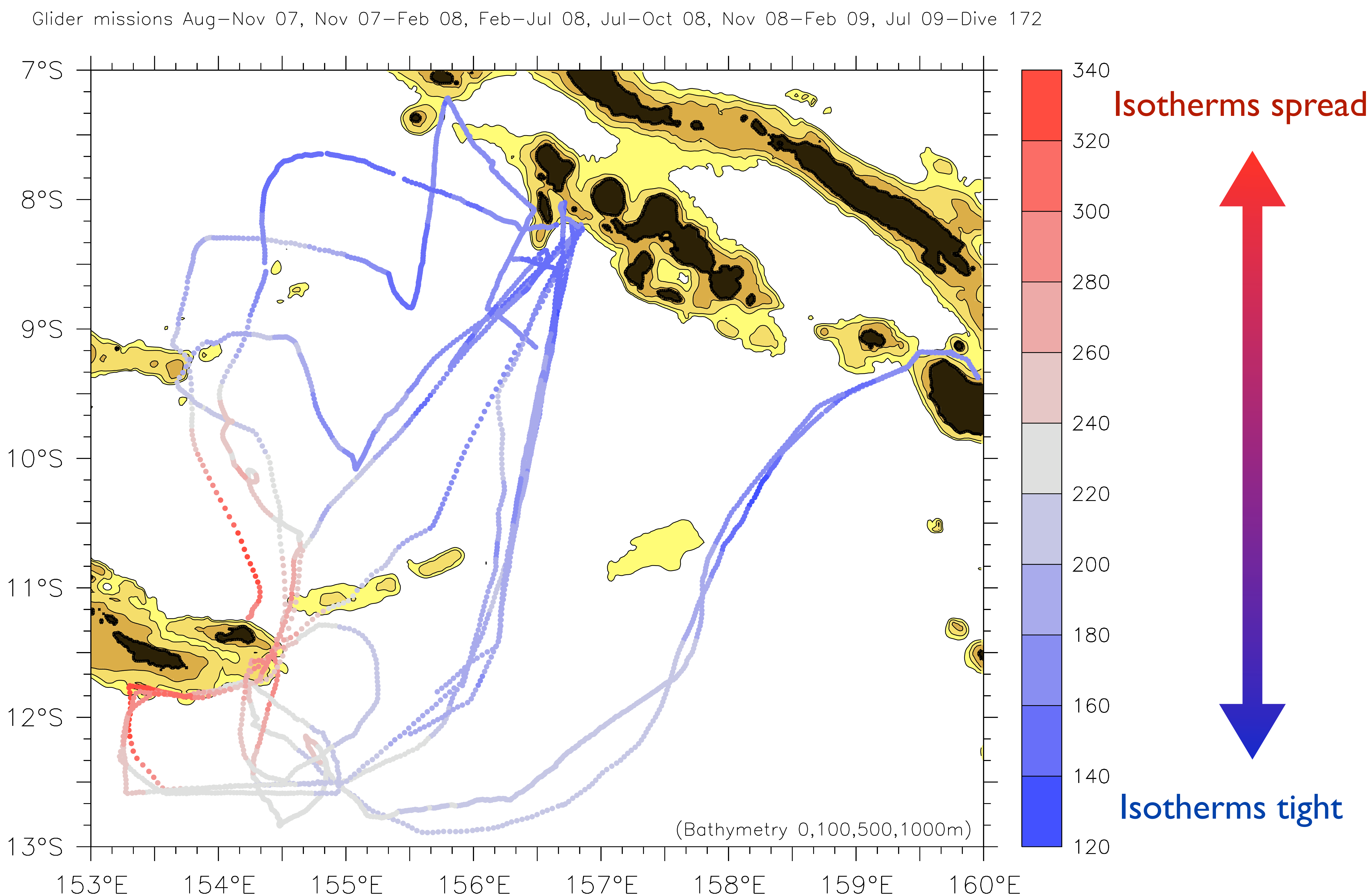
using the Firing et al (1999) Time-dependent Island Rule

and a Godfrey (1975) formulation for the Australia coastal signal.

(Many caveats ....)

10°-20°C thickness in the Solomon Sea

Isotherm spreading is boundary-intensified

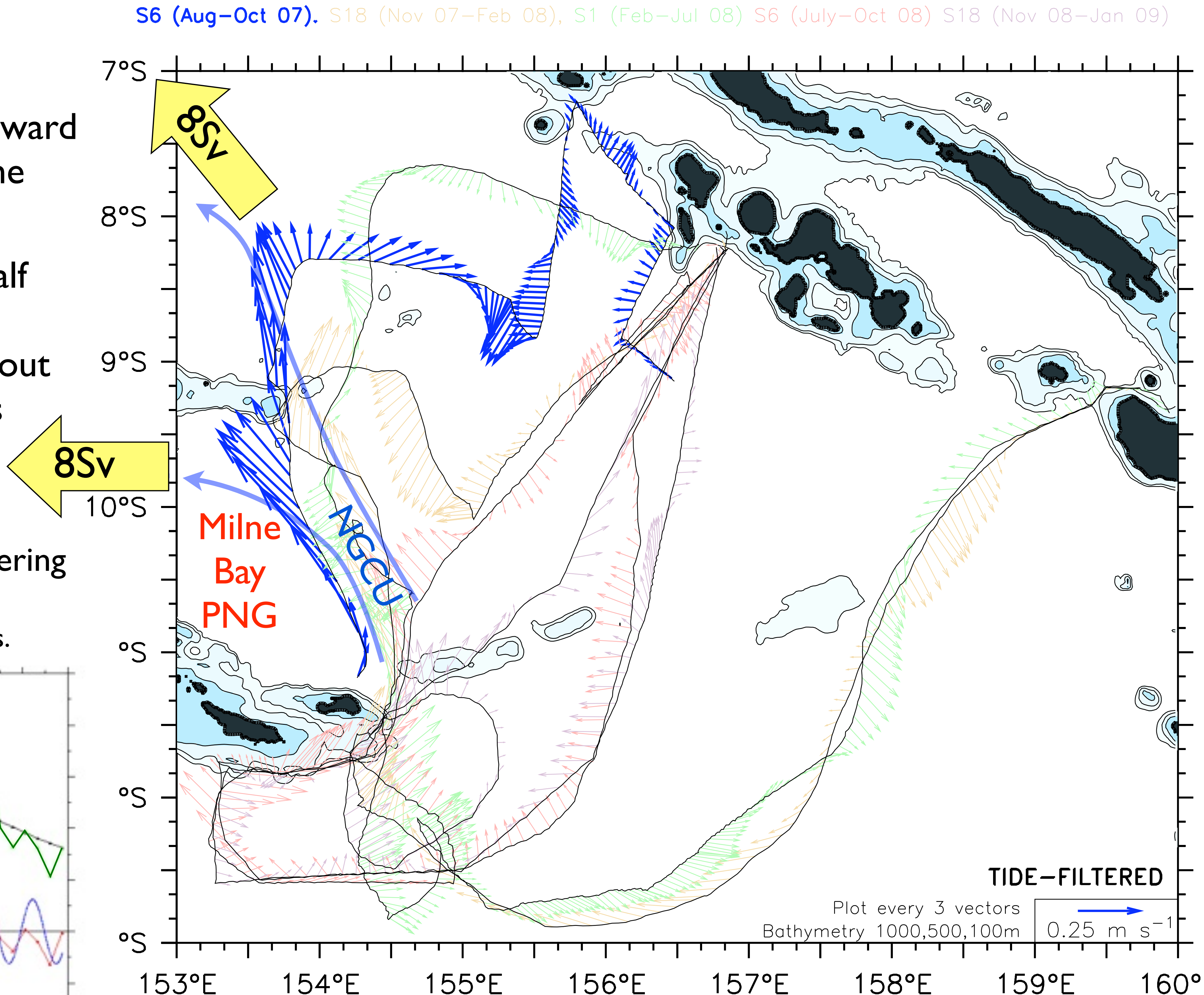


Aug-Oct 07: Pre-La Niña

First mission:

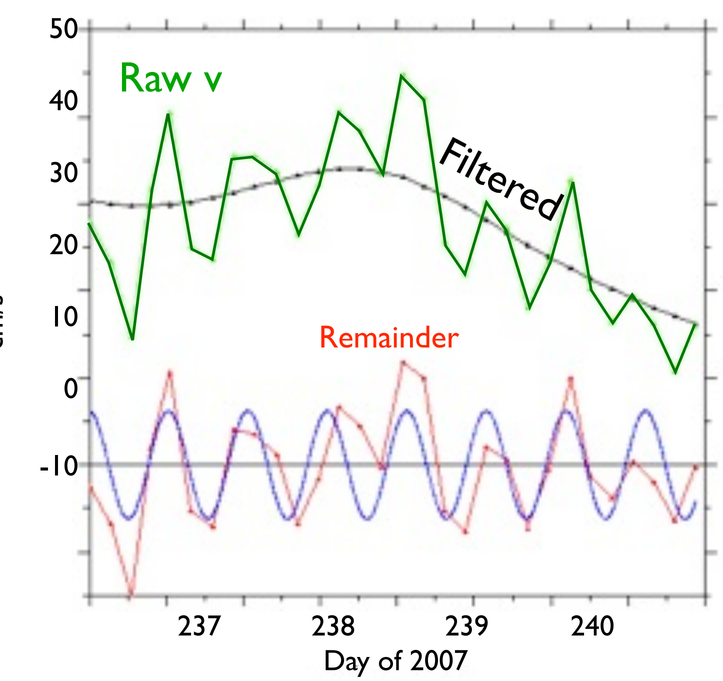
About 18Sv equatorward transport through the Solomon Sea.

Surprisingly, about half of this flowed into Milne Bay (and thus out the shallow channels to the northwest).



An example of tide-filtering

Gaussian objective mapping with a time-scale of 1.5 days.

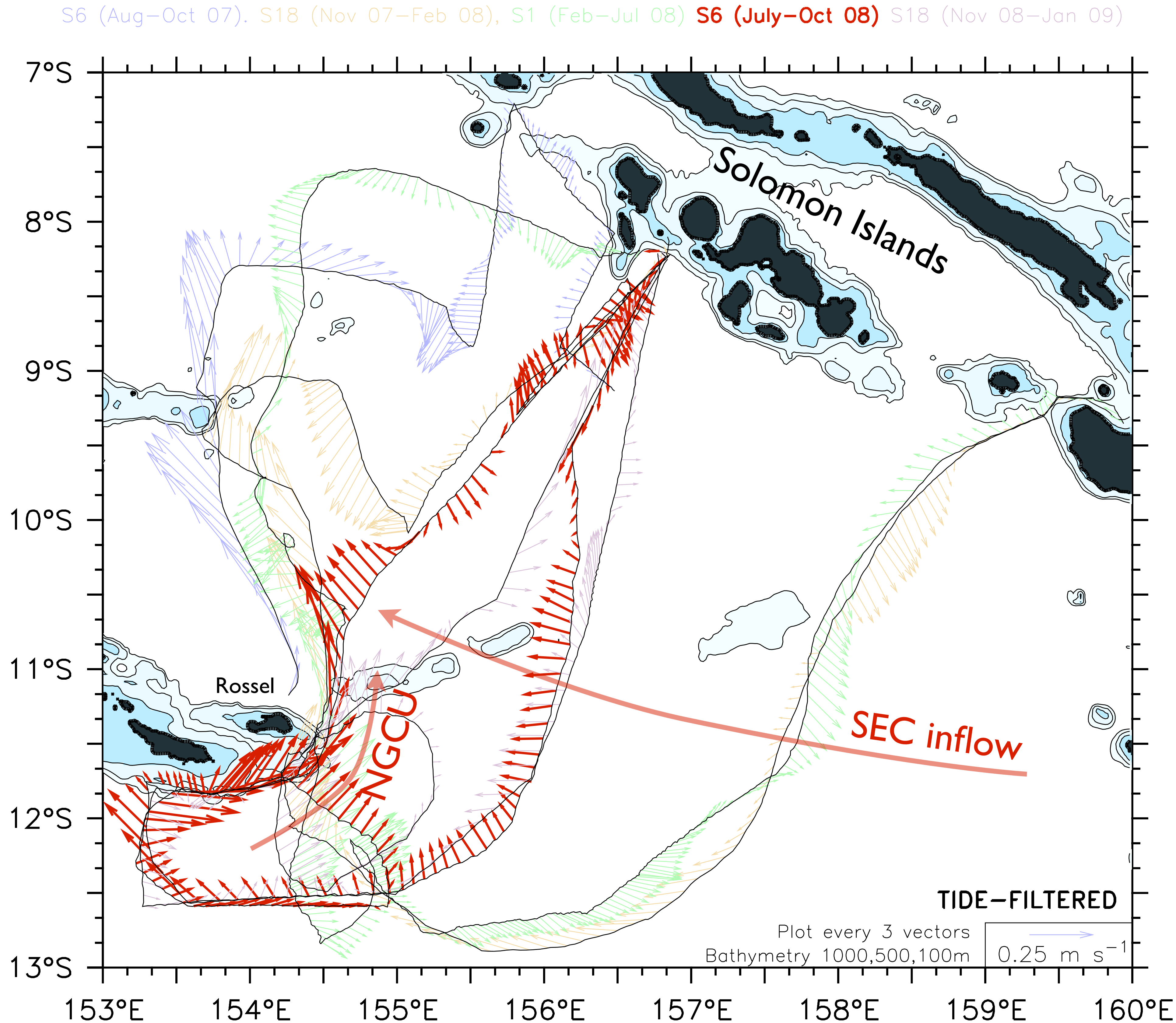


Jul-Oct 08: Post-La Niña restoration (normal?)

<u>Fourth mission:</u>

"Normal" SEC.

NGCU = 15-20 Sv

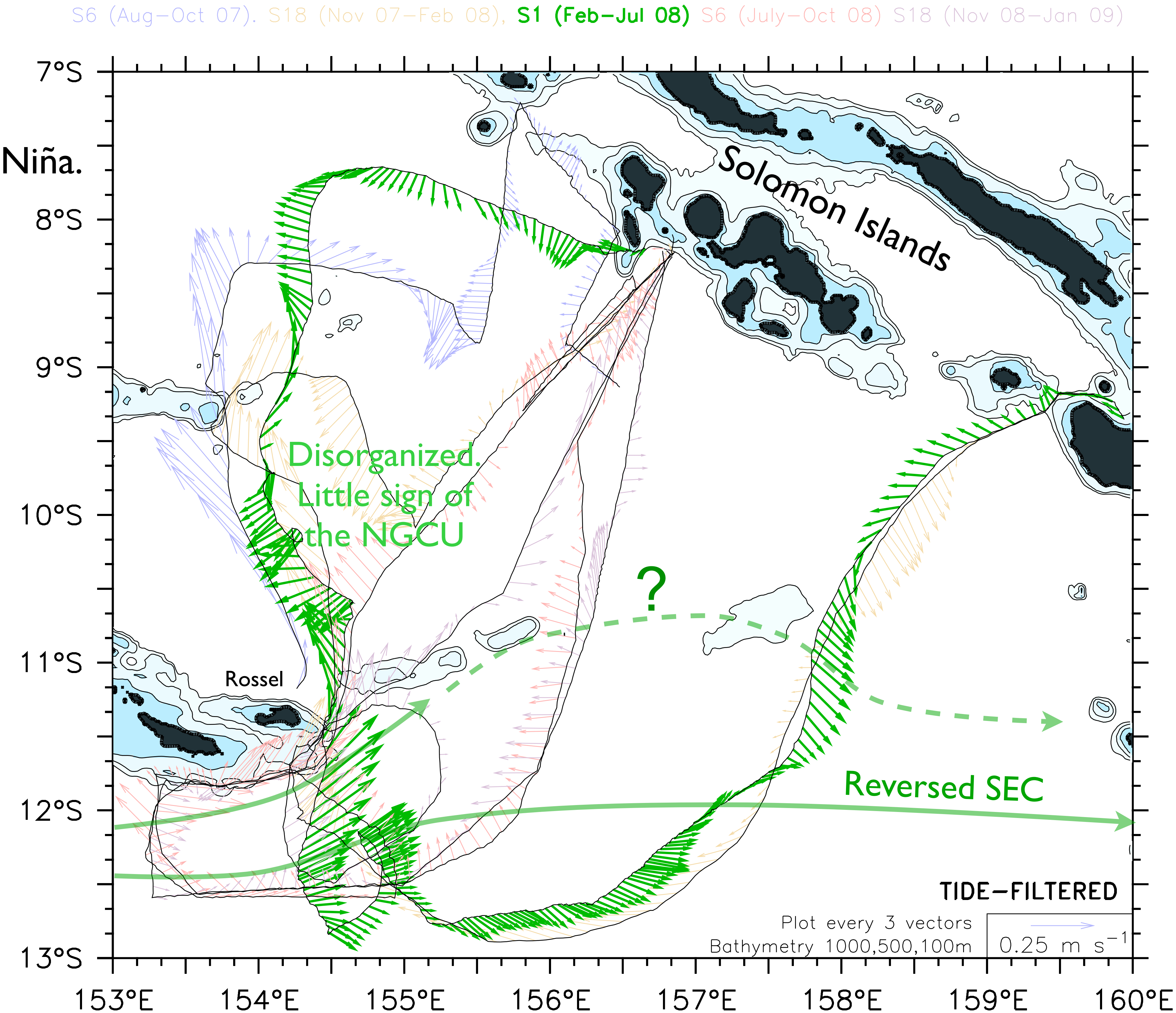


Feb-Jun 08: Strong La Niña anomalies

<u>Third mission:</u>

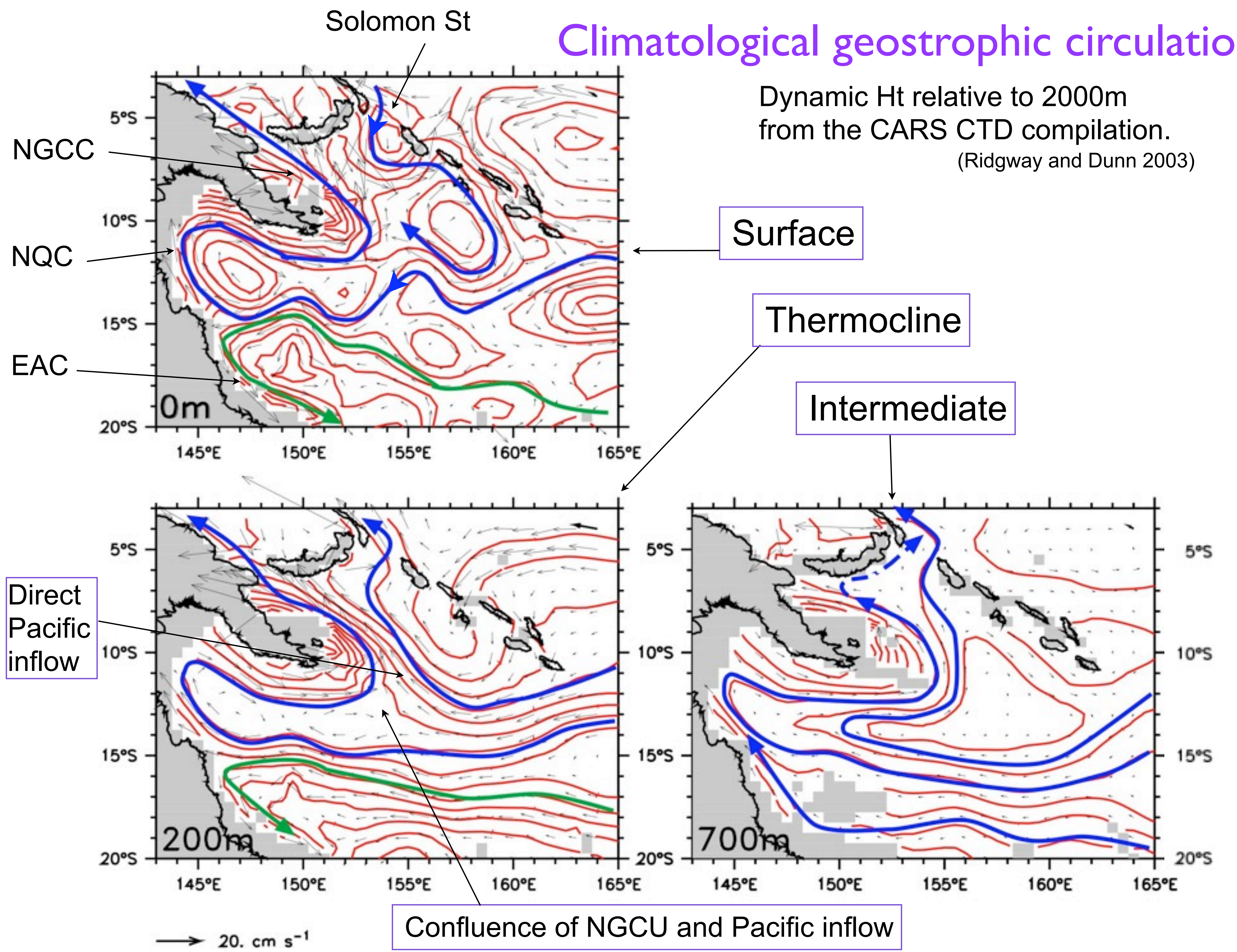
Reversed SEC during La Niña.

Erratic, disorganized flow inside the Solomon Sea.



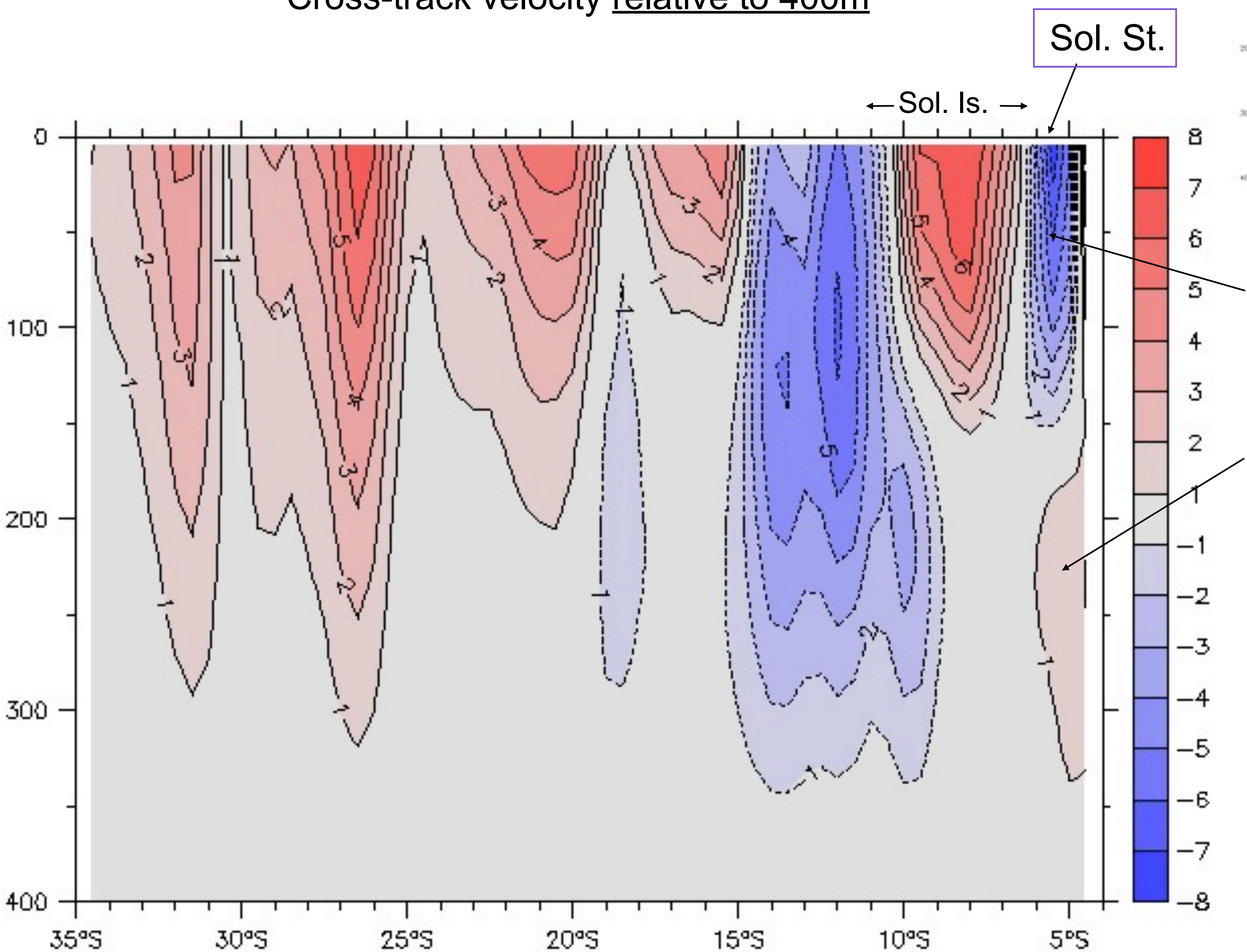
Climatological geostrophic circulation

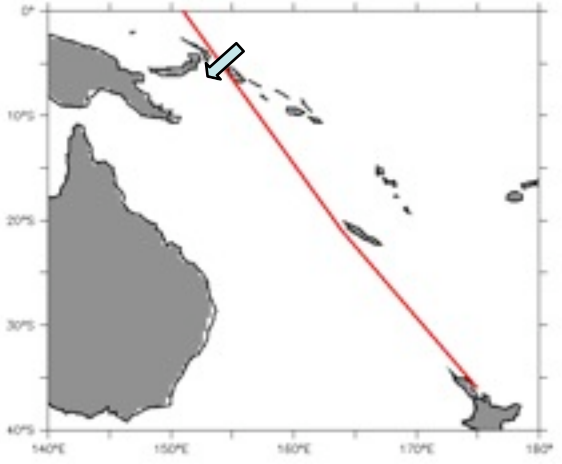
Dynamic Ht relative to 2000m
from the CARS CTD compilation.
(Ridgway and Dunn 2003)



Mean u_g on the Auckland-Solomon St XBT track

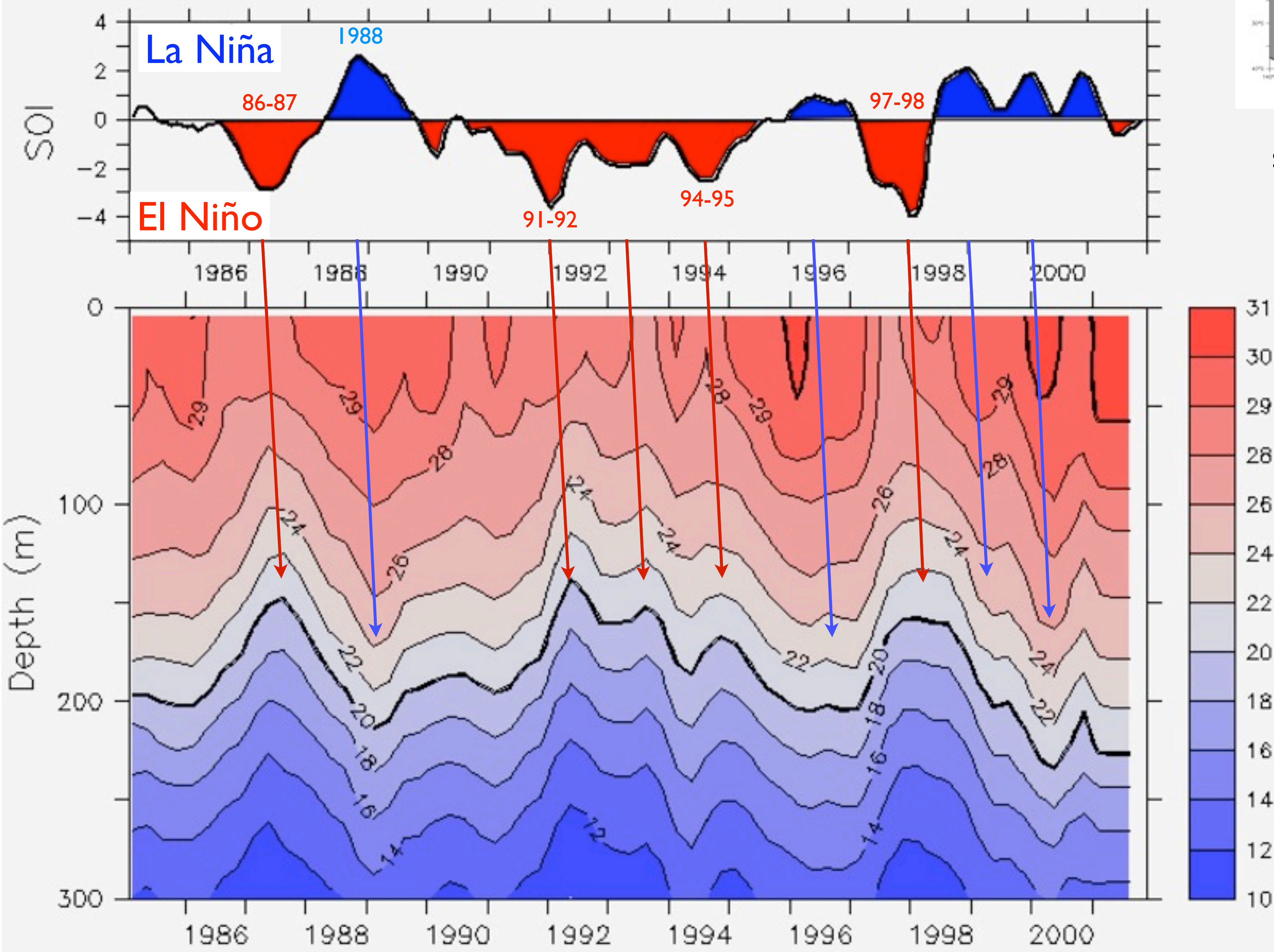
Cross-track velocity relative to 400m

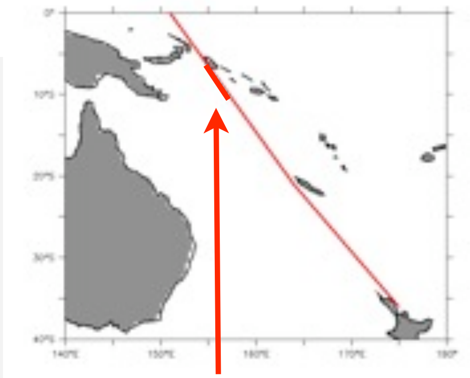




An oblique XBT crossing of the Solomon Strait confirms ORCA model current reversal above the thermocline.

Solomon Sea temperatures and El Niño

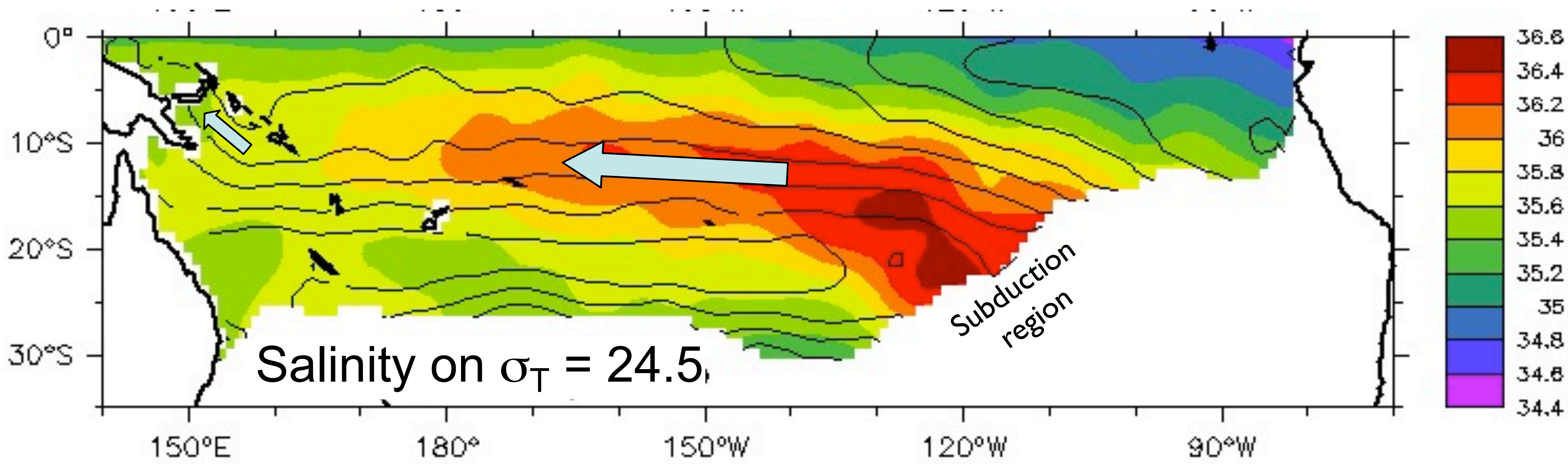




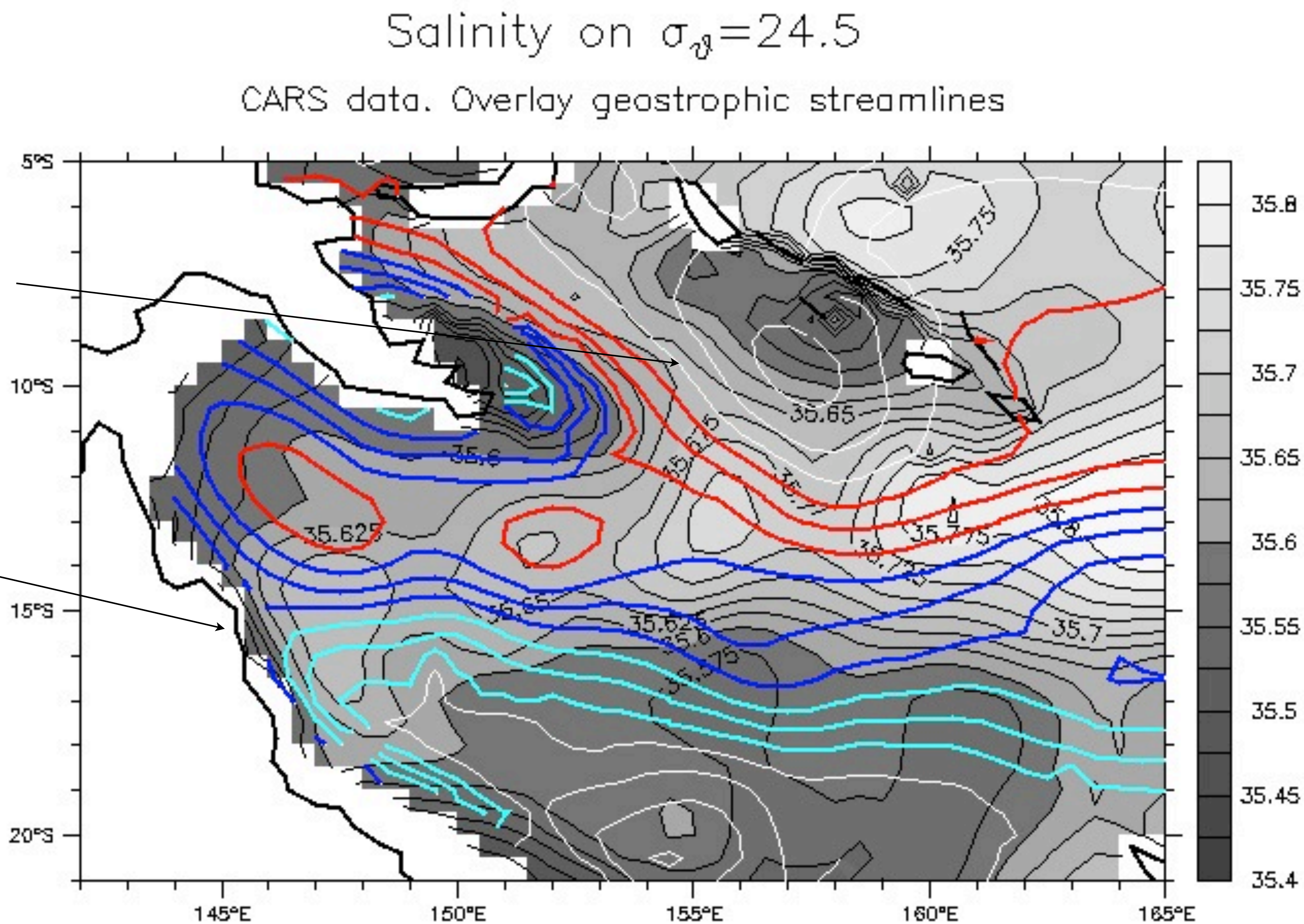
XBT track
(Merchant ship)
Sampled from 6-10°S

High salinity water flows from the SE subtropics to the Solomon Sea

(Contours show geostrophic flow on the isopycnal)



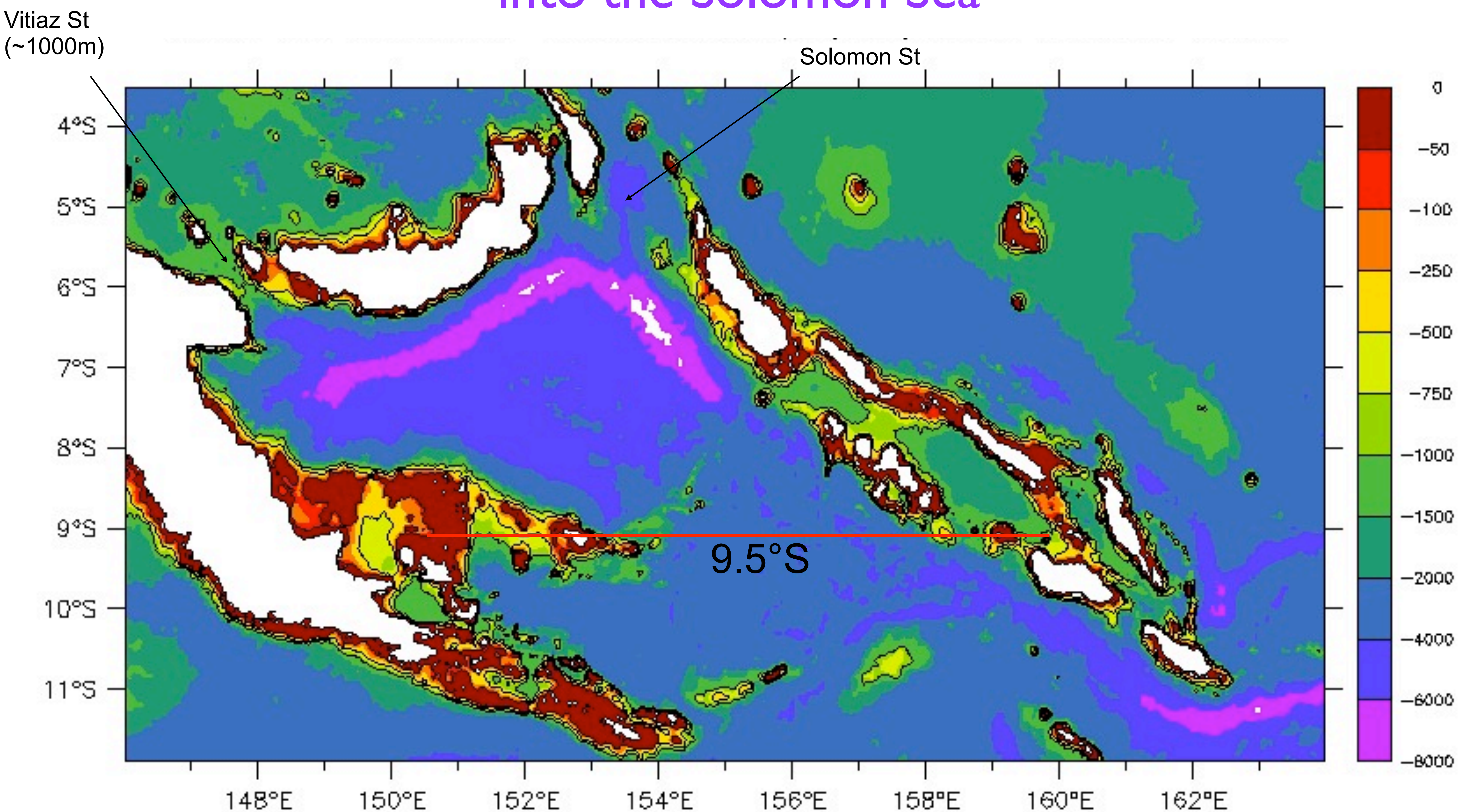
The high-S tongue enters the Solomon Sea from the open Pacific



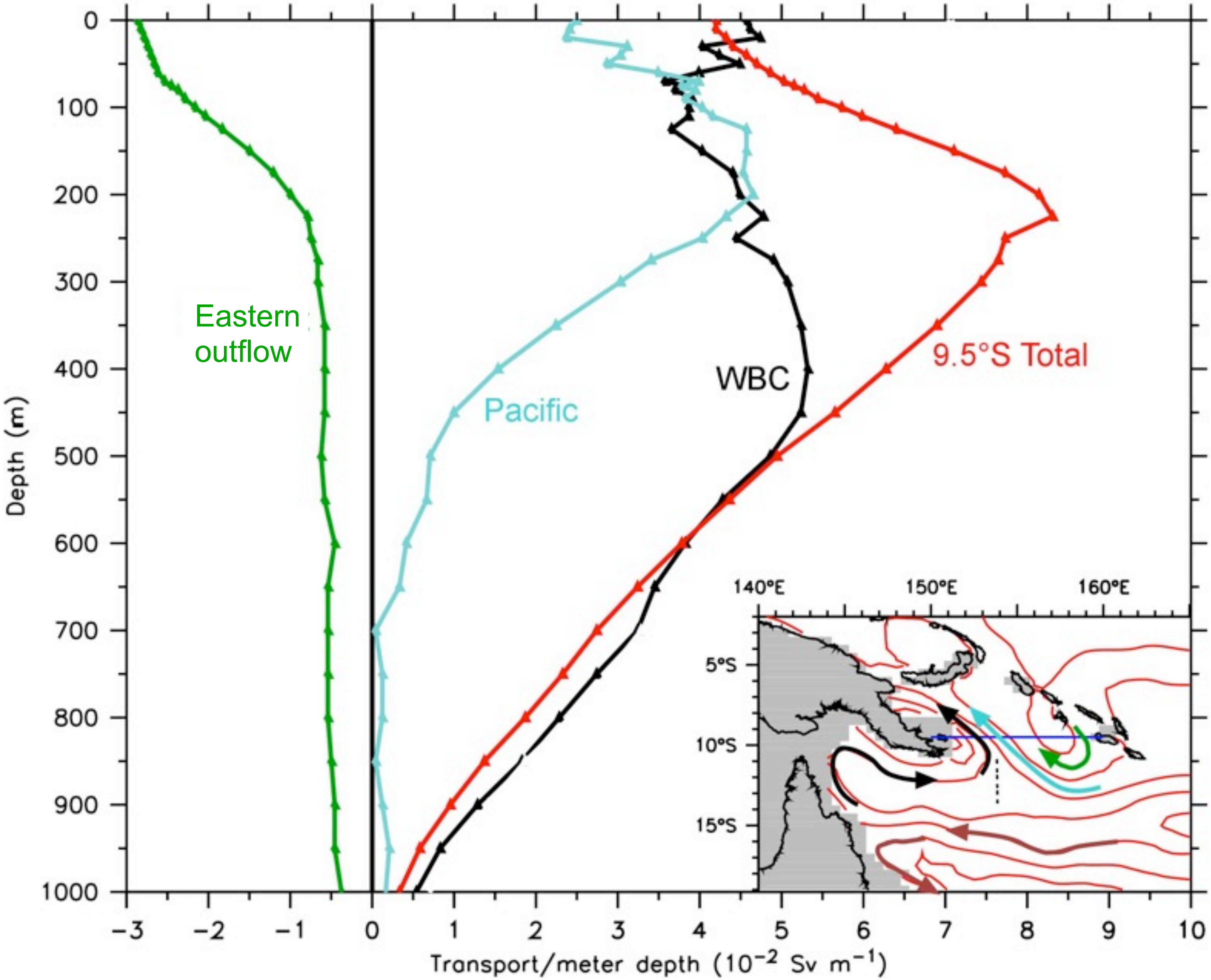
High-S tongue

Bifurcation of NQC/EAC

Climatological picture of flow across 9.5°S into the Solomon Sea



Climatological mean flow across 9.5°S into the Solomon Sea

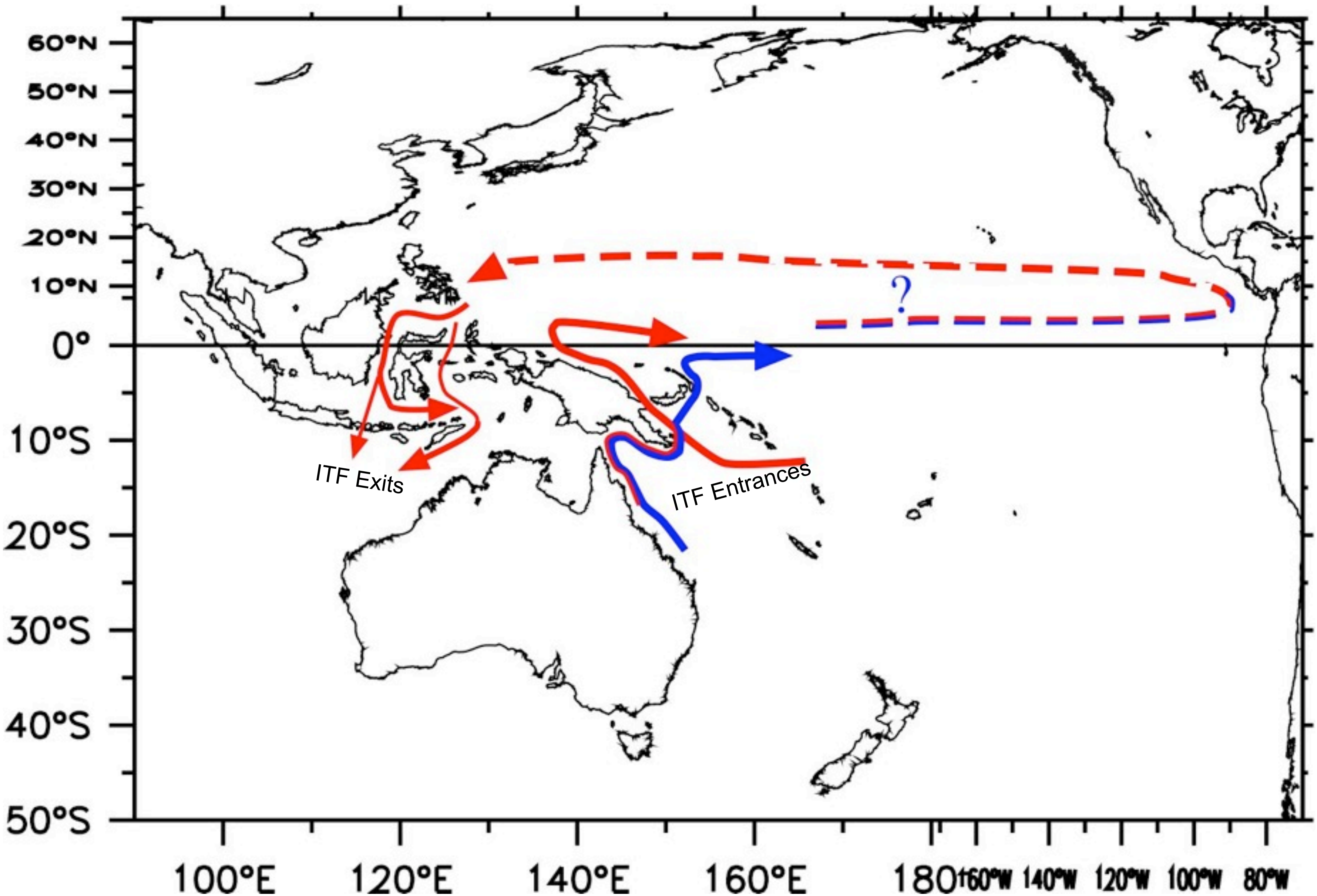


CARS data:

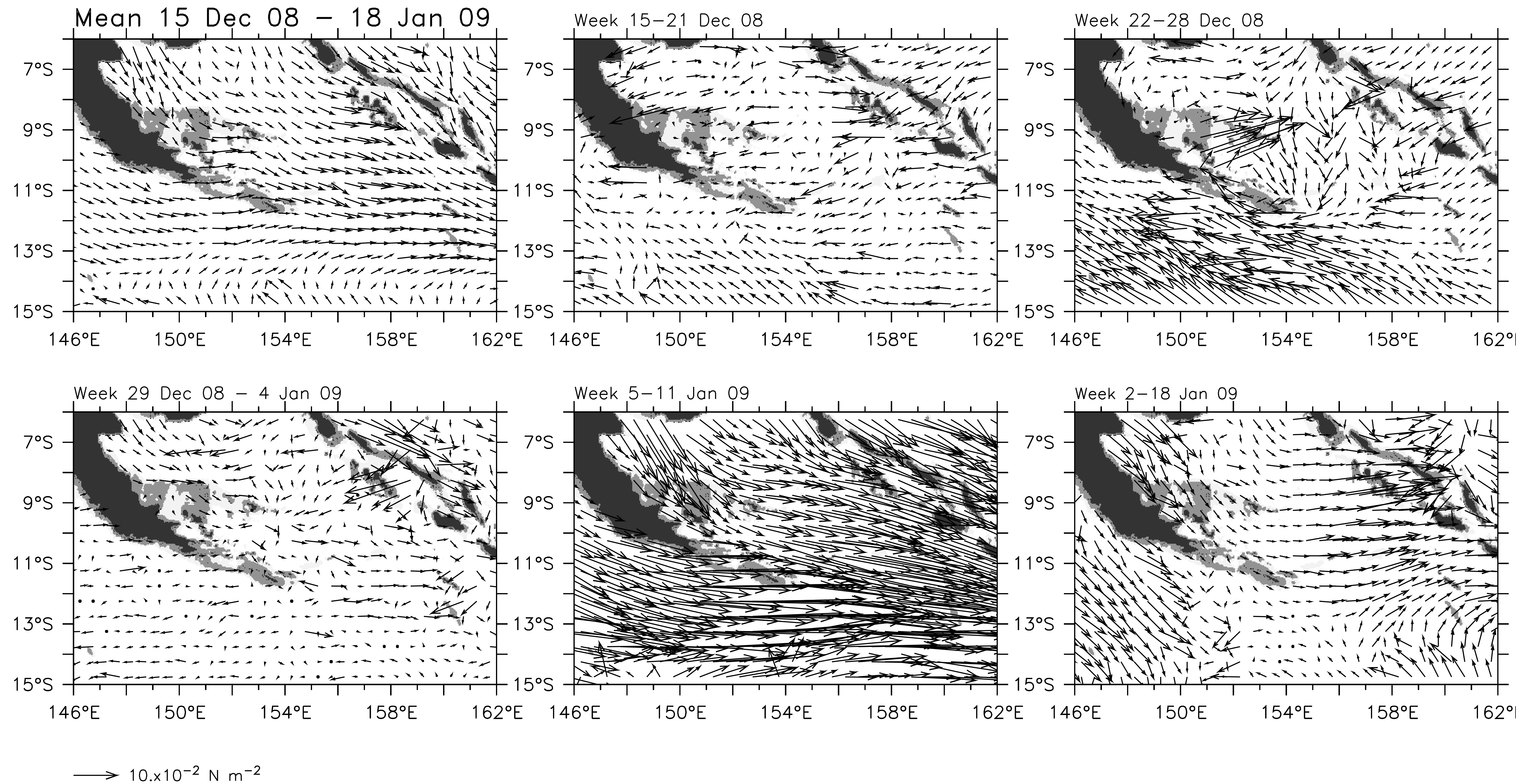
Thermocline flow enters from both the NGCU and the Pacific, but **intermediate water all arrives via the WBC**.

The ITF consists of a series of mixing basins starting with the Solomon Sea,

that transform SW Pacific intermediate water to the shallower, warmer water that exits into the Indian Ocean.



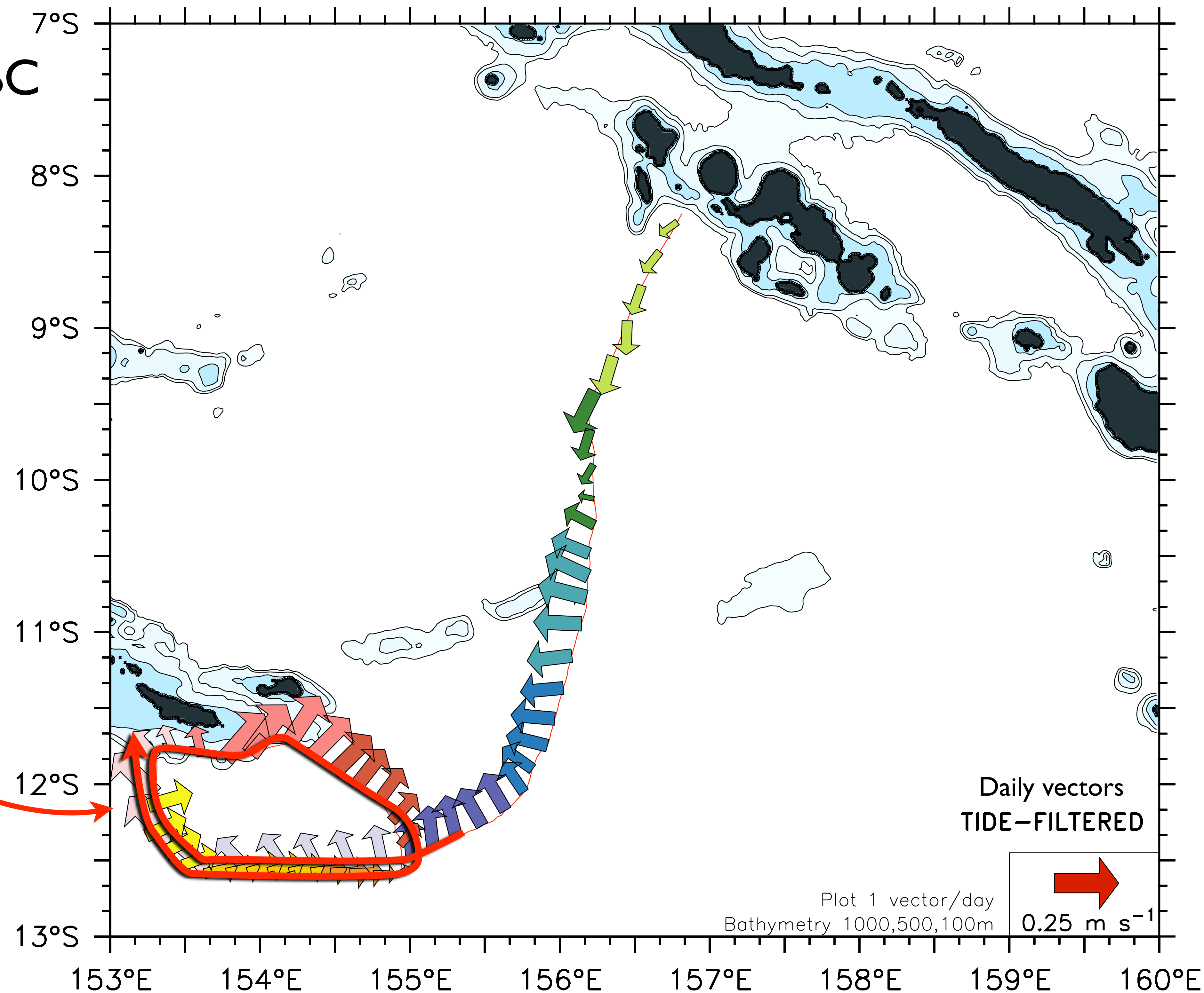
Quikscat weekly wind stress during NGCC sections (CERSAT)



Non-synoptic sampling ....

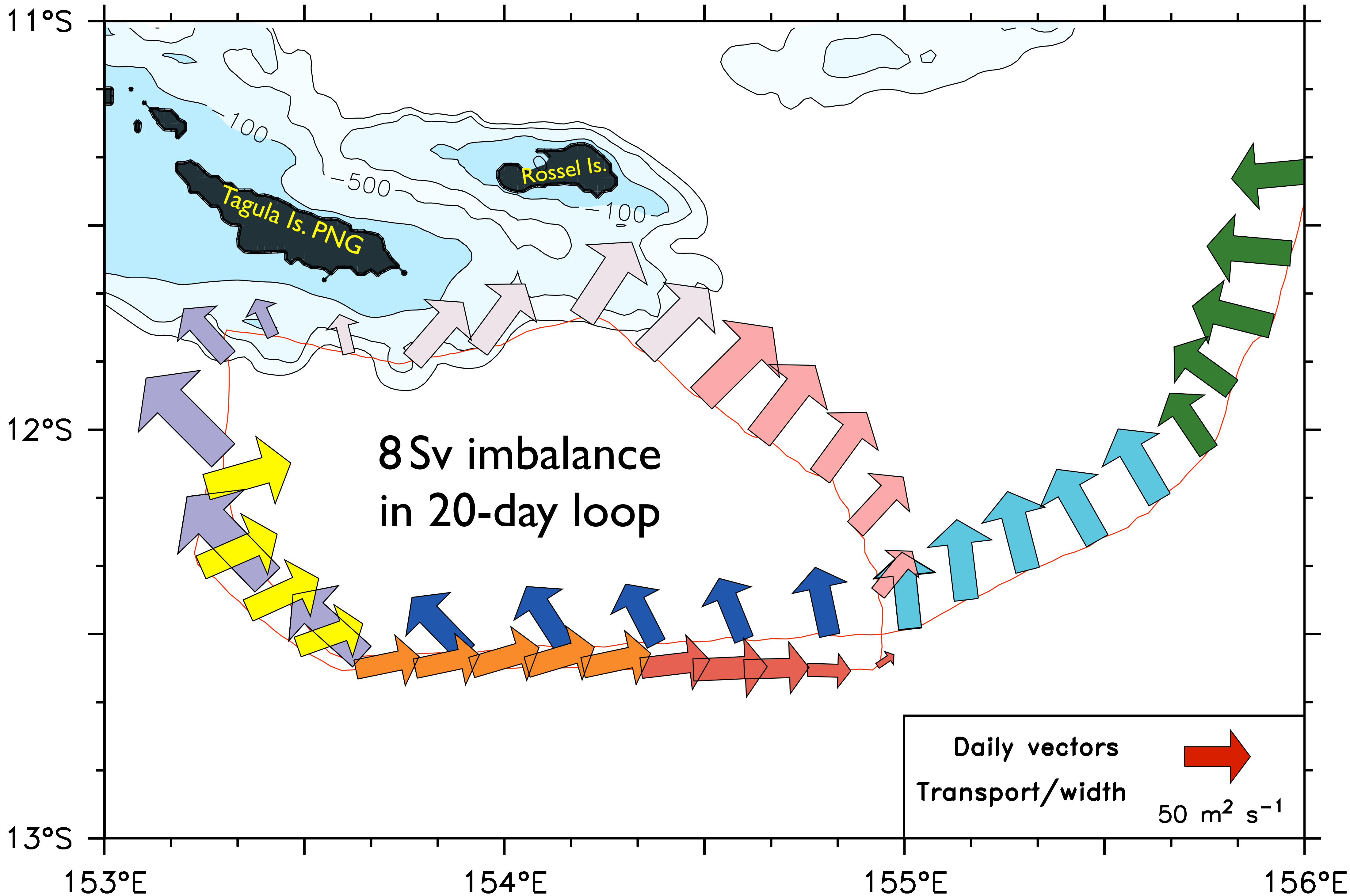
Glider velocity: 4th mission

Loop with multiple crossings of the WBC to test sampling



Glider transport: 3 crossings of the WBC in ~25 days

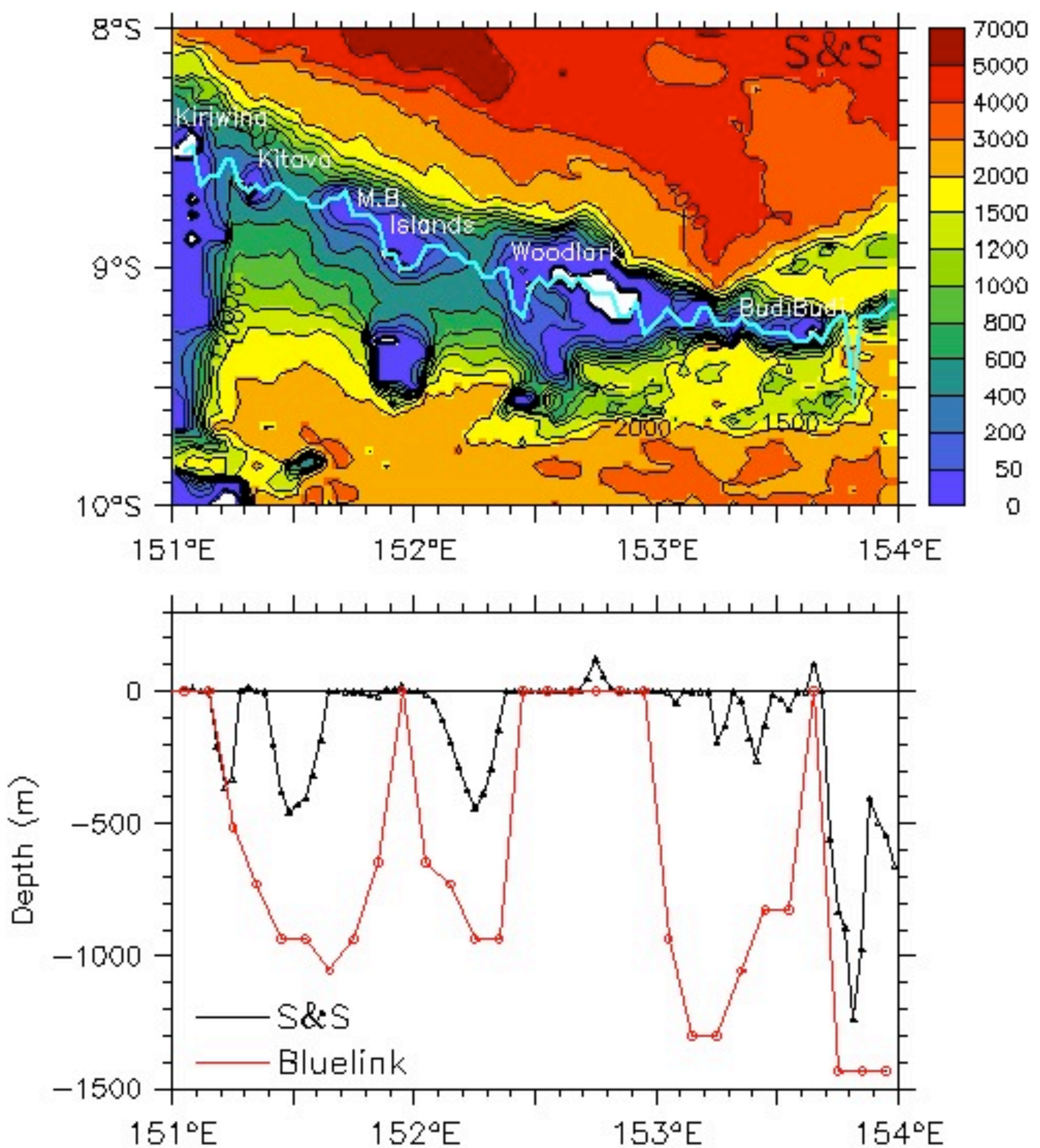
⇒ Non-synoptic sampling: Need additional information!



Solomon Sea bathymetry maps ....

Sill depths along the Woodlark Archipelago

Compare Smith & Sandwell 2–minute data with Bluelink (T–grid)



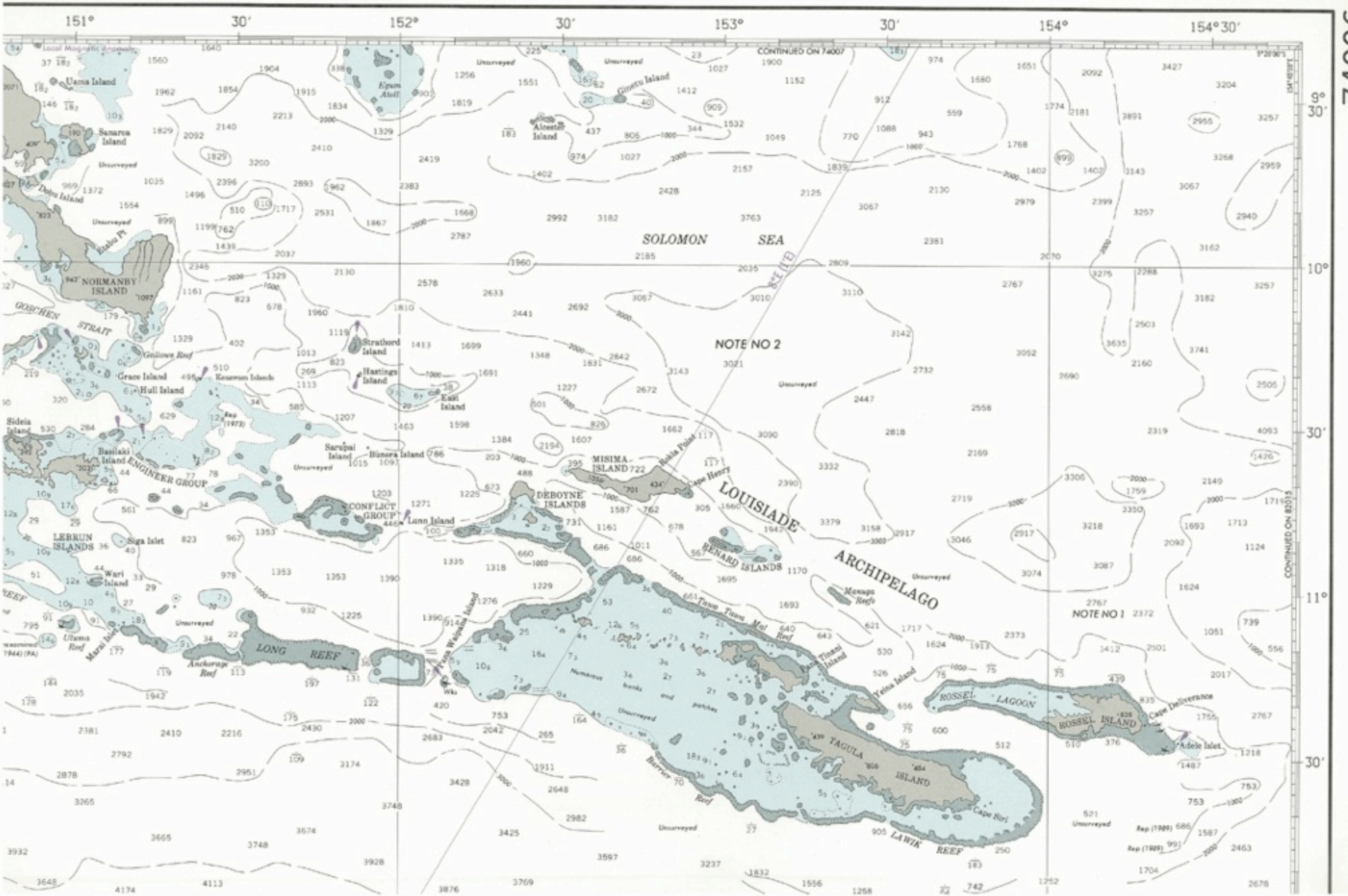
AGO

SOUNDINGS IN METERS
(meters and decimeters to 20)
reduced to the approximate level of Indian Springs Low Water

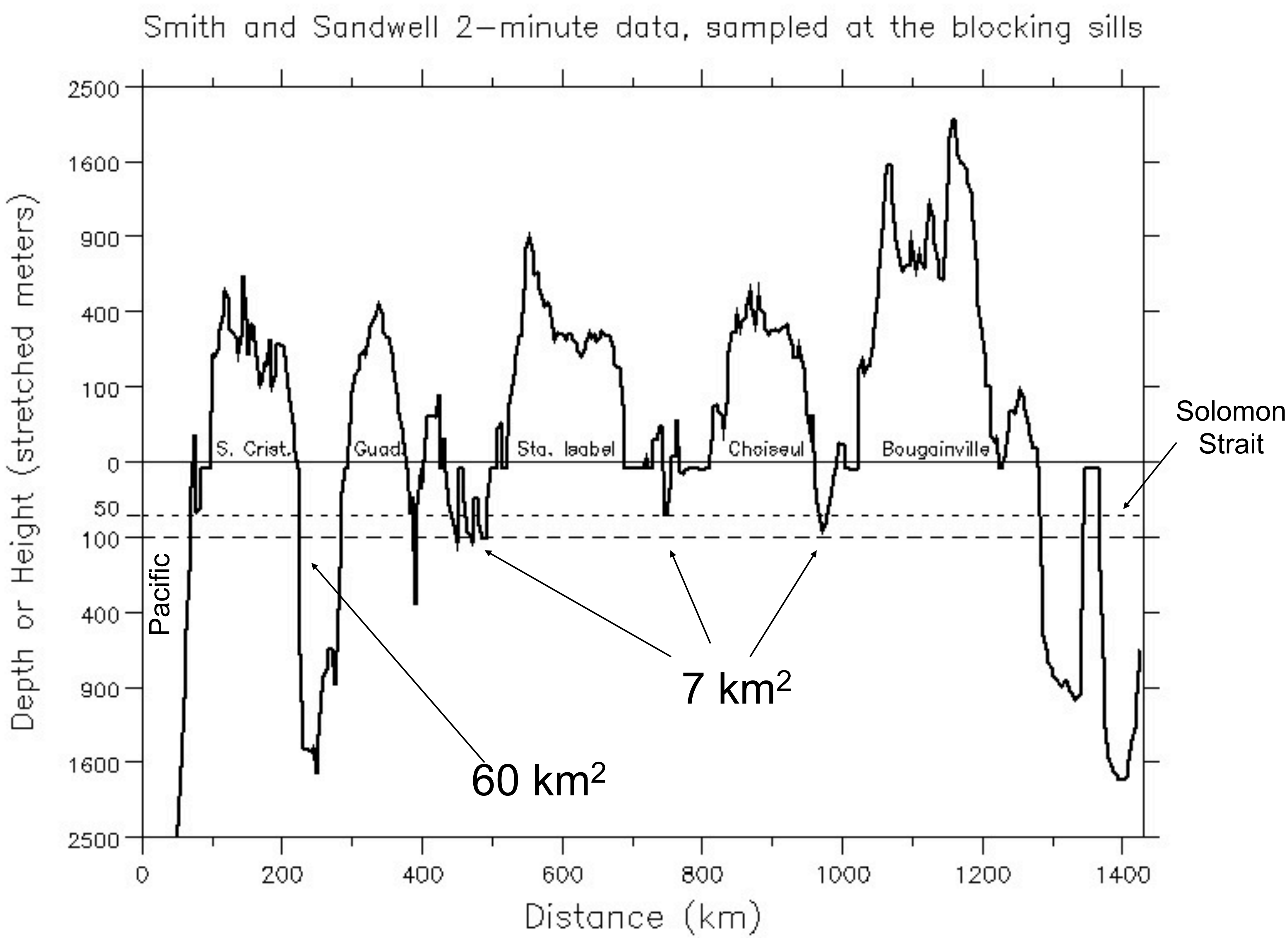
HEIGHTS IN METERS ABOVE MEAN SEA LEVEL

direction to variation, it is to be subtracted and the variation is decreasing.

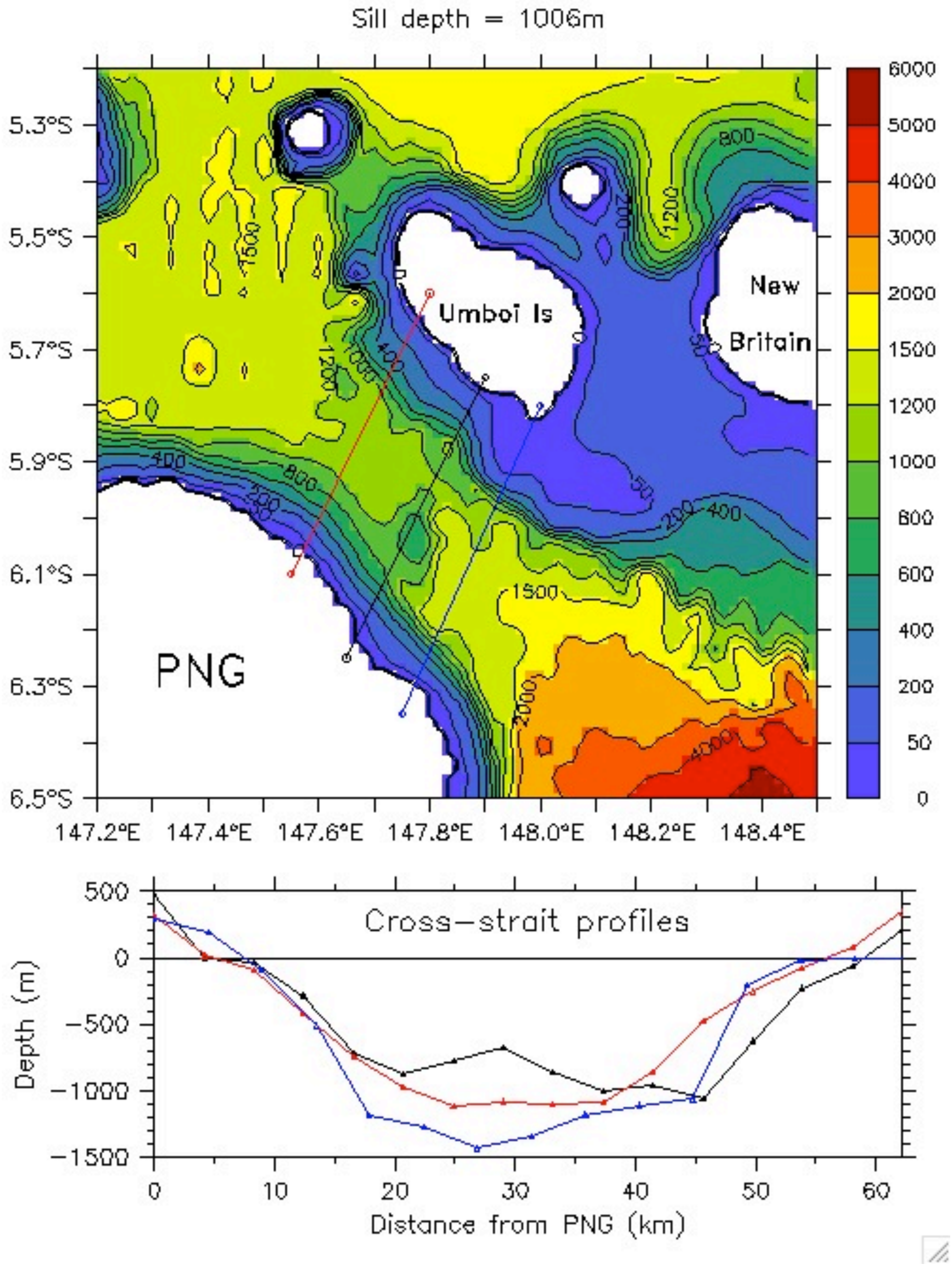
SOUNDINGS IN METERS



Solomon Island sills



Vitiaz St. bathymetry (Smith & Sandwell 1′)

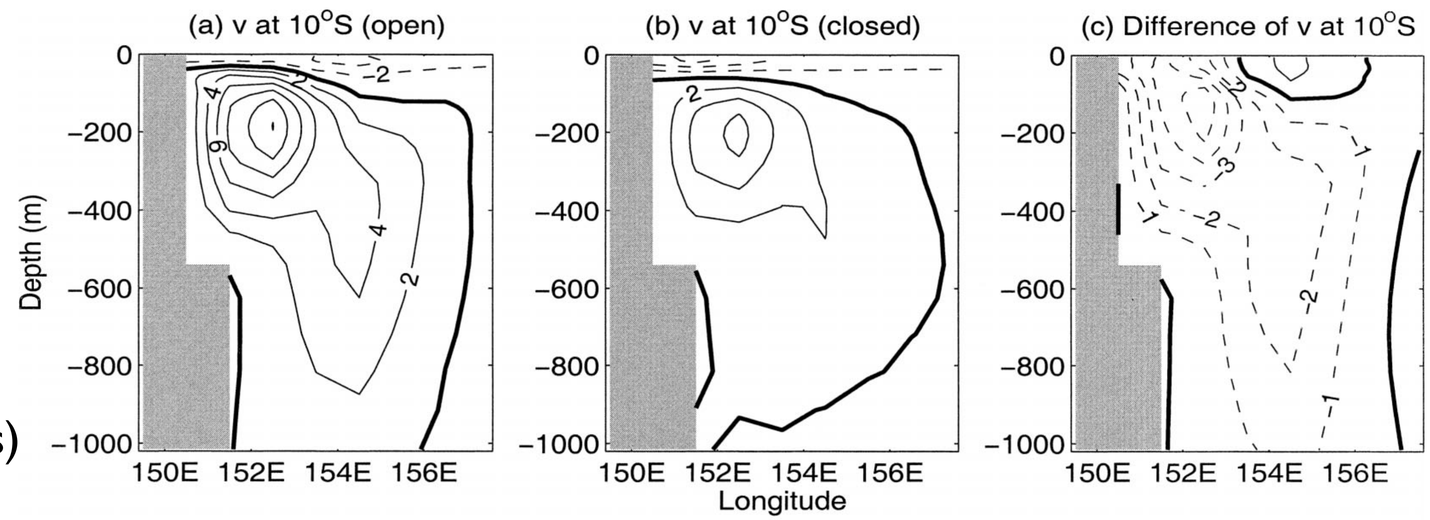


Why is the NGCU an undercurrent?

Always observed, commonly modeled:

Lee et al (JPO 2002)

MITGCM (⅓°x1° in tropics)

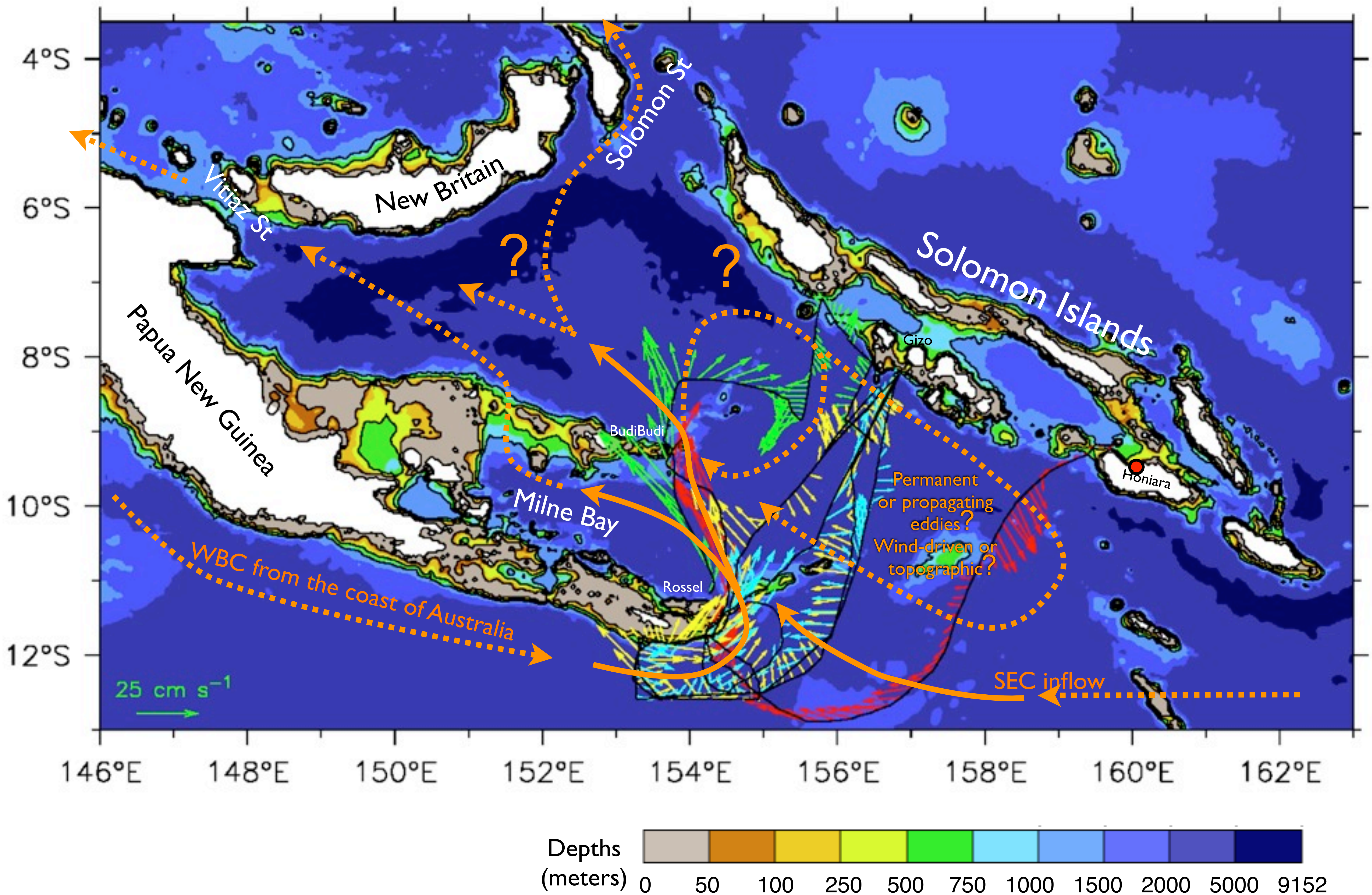


Two separate questions:

1. Why is there poleward shear above 400m?
2. Why does the NGCU extend so deep?

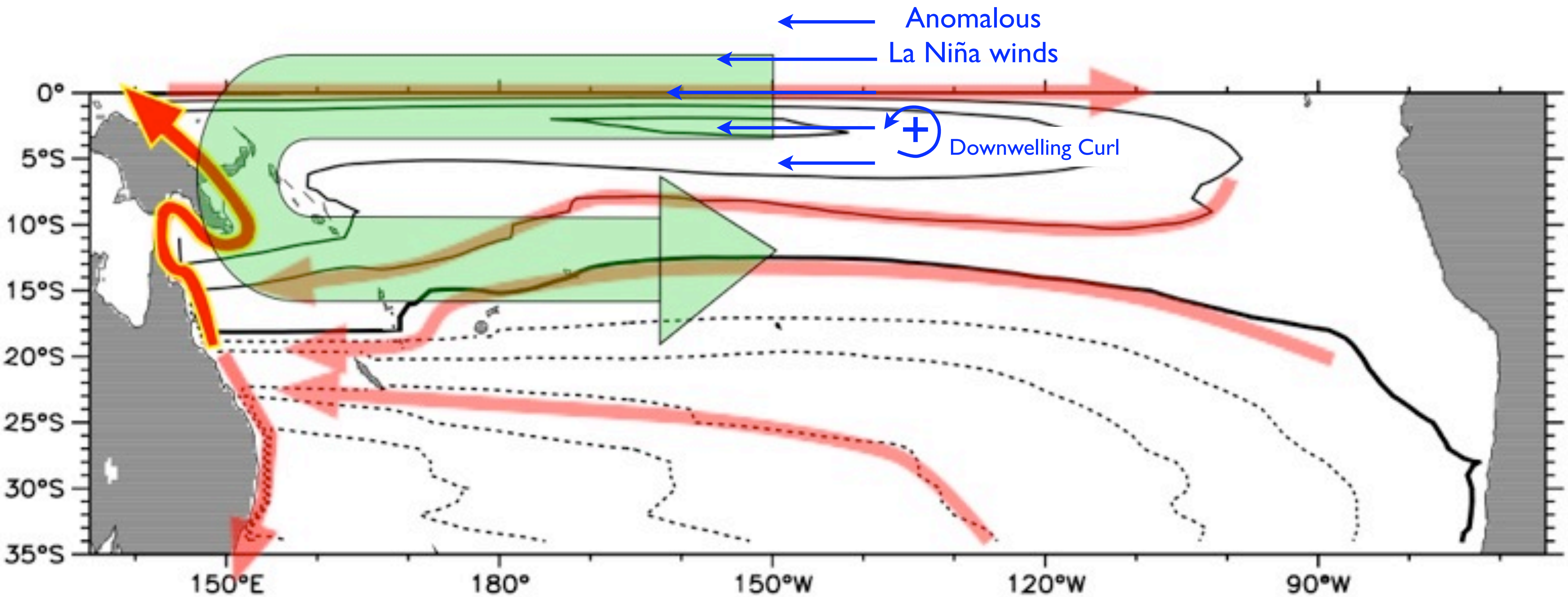
And note that the NGCU is a Sverdrup (Island Rule) western boundary current, completing the cyclonic gyre south of the equator.

What can be said about the pattern of circulation?



La Niña transport anomalies

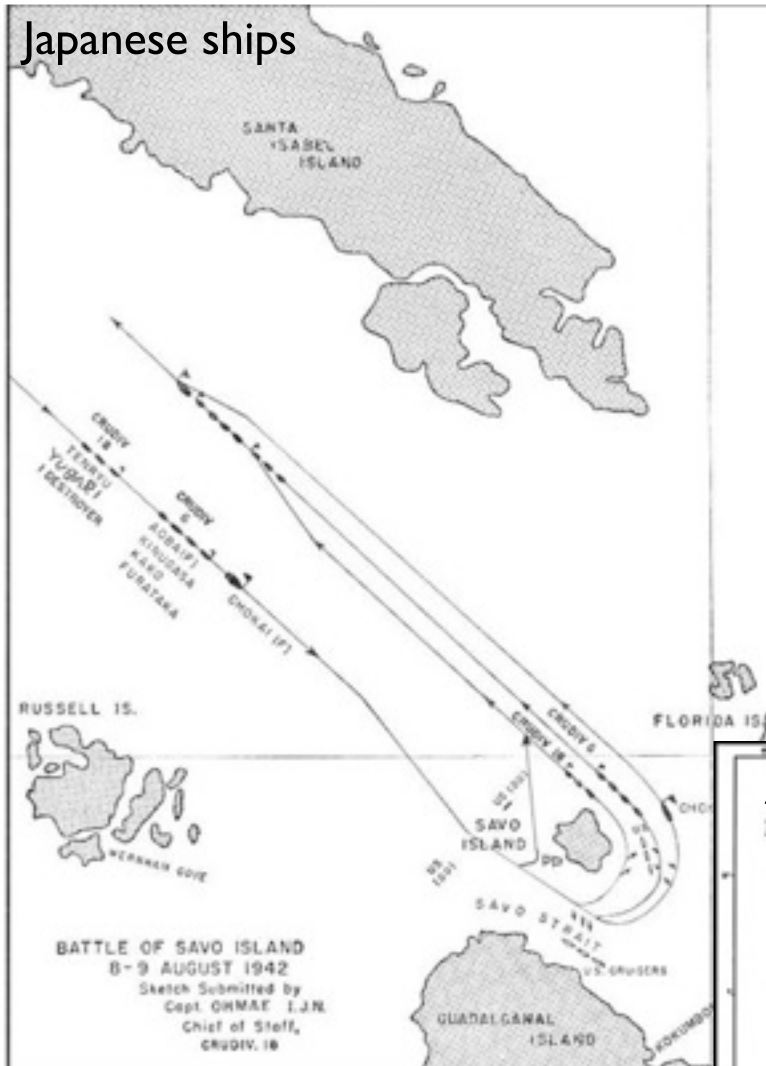
ENSO modifies western boundary transports: La Niña tends to weaken the circulation in the west

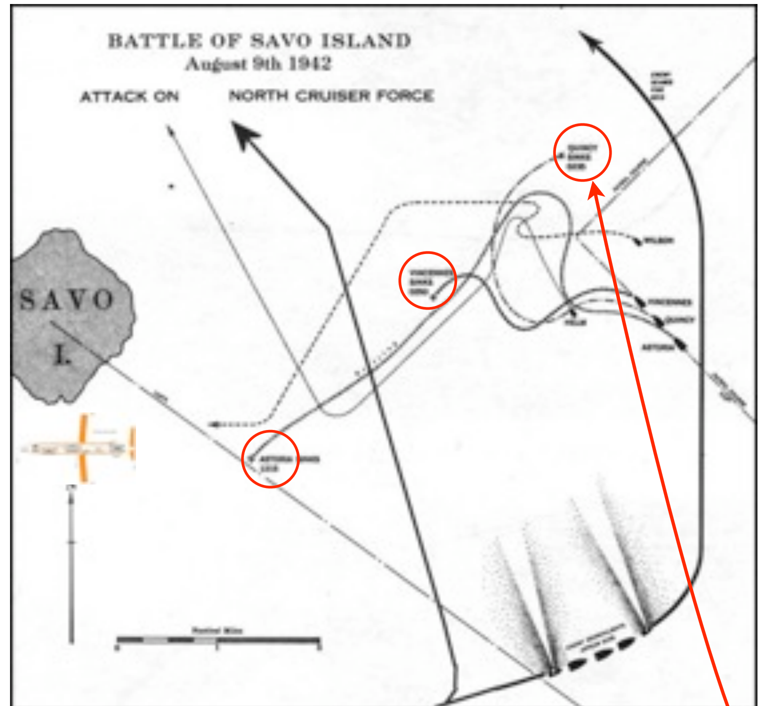


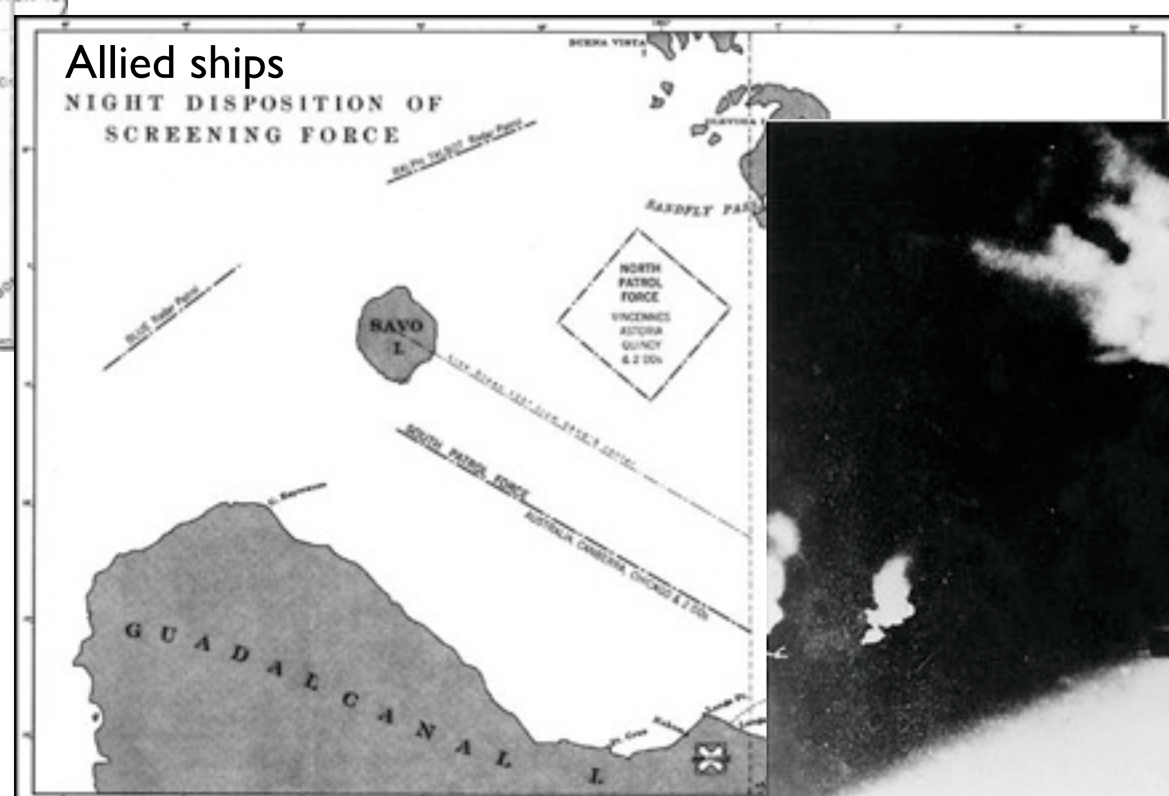
The LLWBCs likely play a key role in ENSO:
filling and draining the West Pacific warm pool.

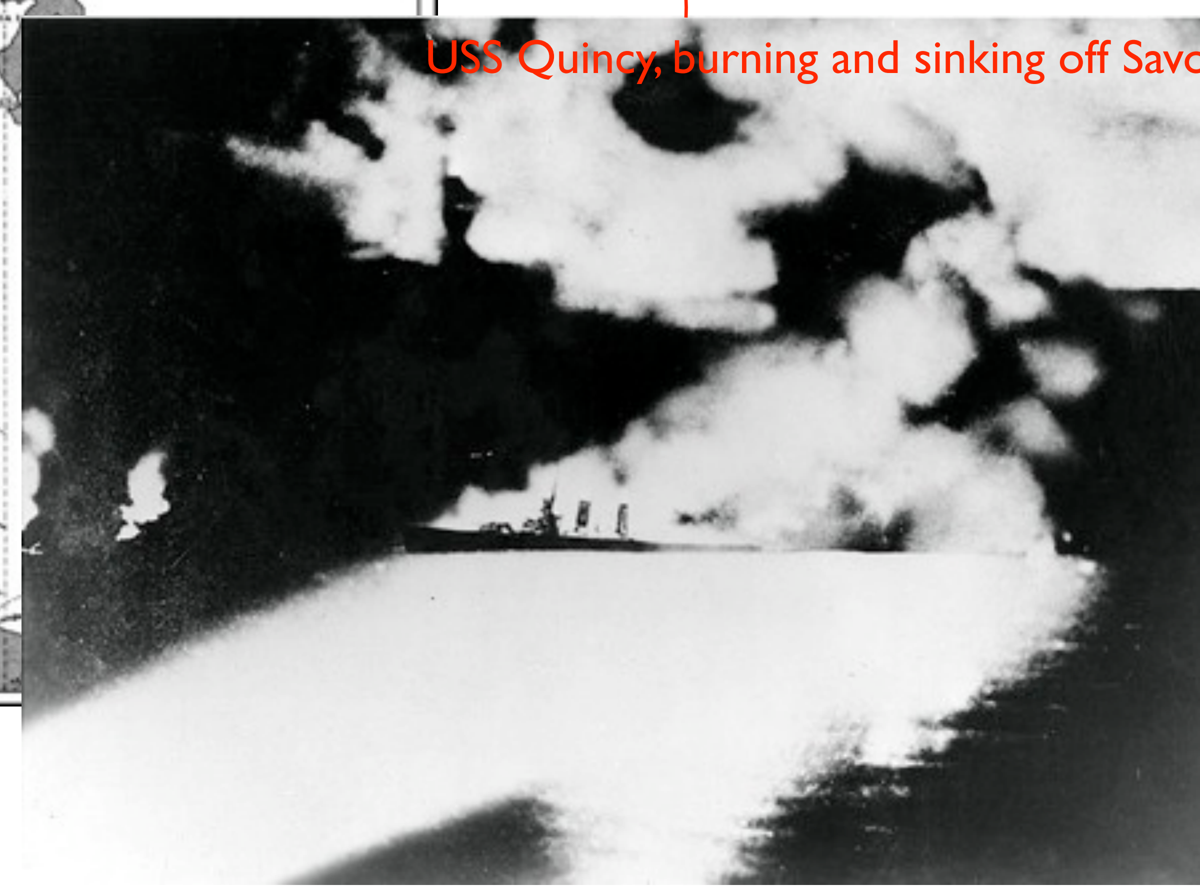
LLWBC anomalies oppose interior meridional transports,
with a lag of a few months.

Battle of Savo Island, Aug 9-11 1942









The U.S. Navy was still obsessed with a strong feeling of technical and mental superiority over the enemy. In spite of ample evidence as to enemy capabilities, most of our officers and men despised the enemy and felt themselves sure victors in all encounters under any circumstances. The net result of all this was a fatal lethargy of mind which induced a confidence without readiness, and a routine acceptance of outworn peacetime standards of conduct. I believe that this psychological factor, as a cause of our defeat, was even more important than the element of surprise.

Admiral Richmond Turner

http://en.wikipedia.org/wiki/Battle_of_Savo_Island