The annual cycle of circulation in the southwest subtropical Pacific

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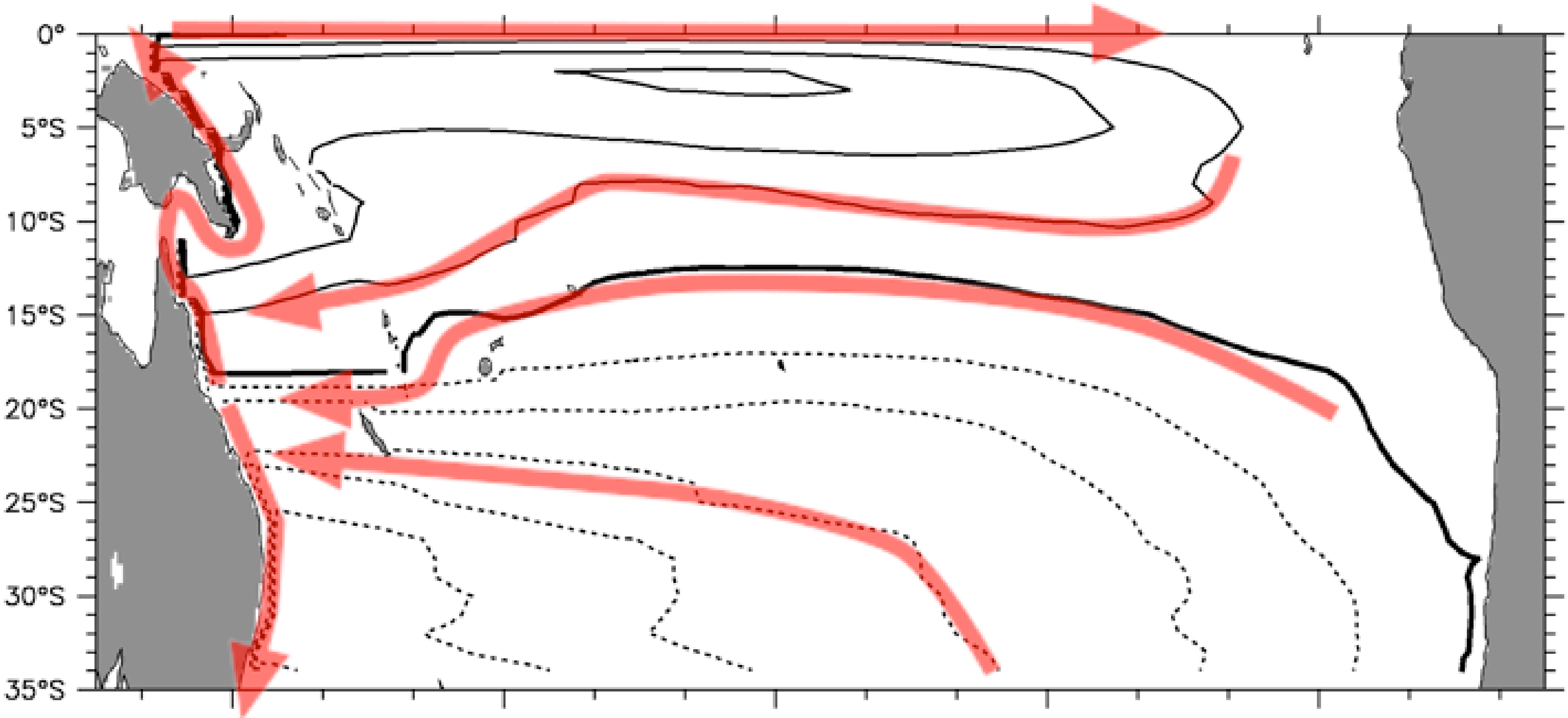
(Manuscript accepted by JPO)

- We are interested in the southwestern Pacific because of its position athwart a major pathway from the subtropics to the equator:
  How are water masses redistributed at the western boundary?
- It is likely that interannual and decadal variability is most climatically important, but here we take a first step by looking at the annual cycle.
- In the absence of observations sufficient to diagnose the variability, we analyze an ocean GCM (OPA/ORCA).

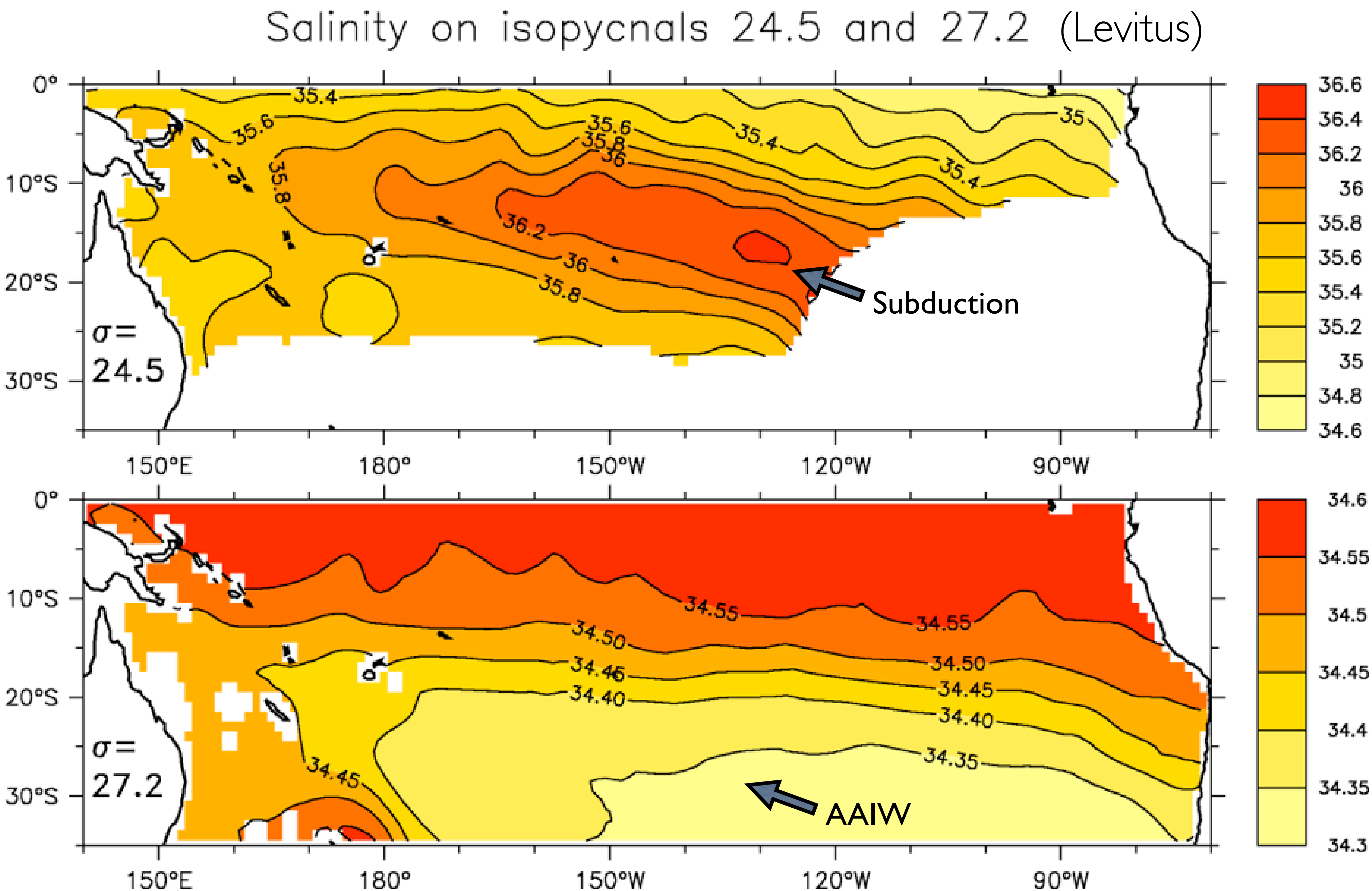
The big picture:
Redistribution of mass at the western boundary

Island Rule (Sverdrup) streamfunction (ERS winds)

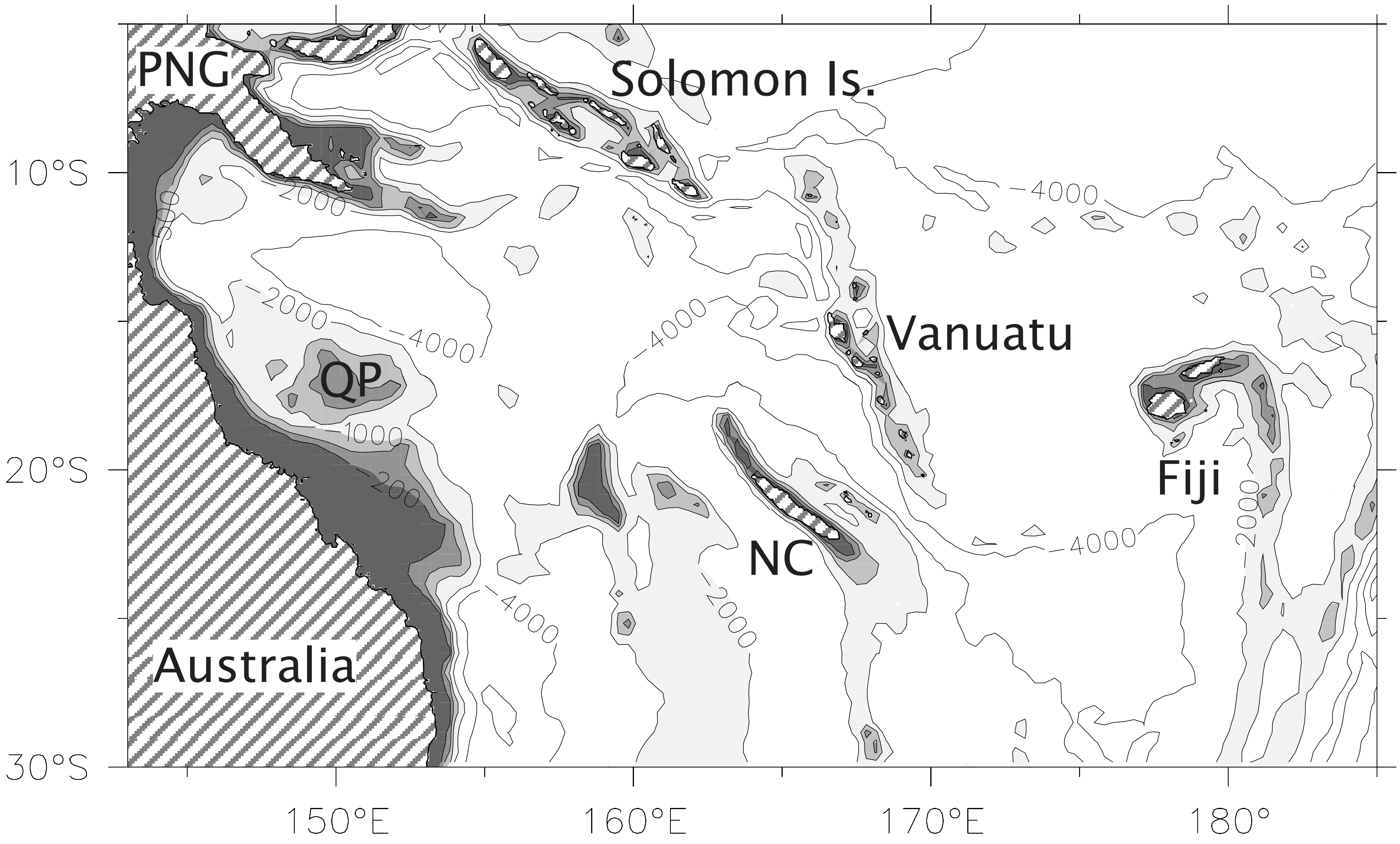


If the bifurcation moves, does it change the mass transport to the equator?

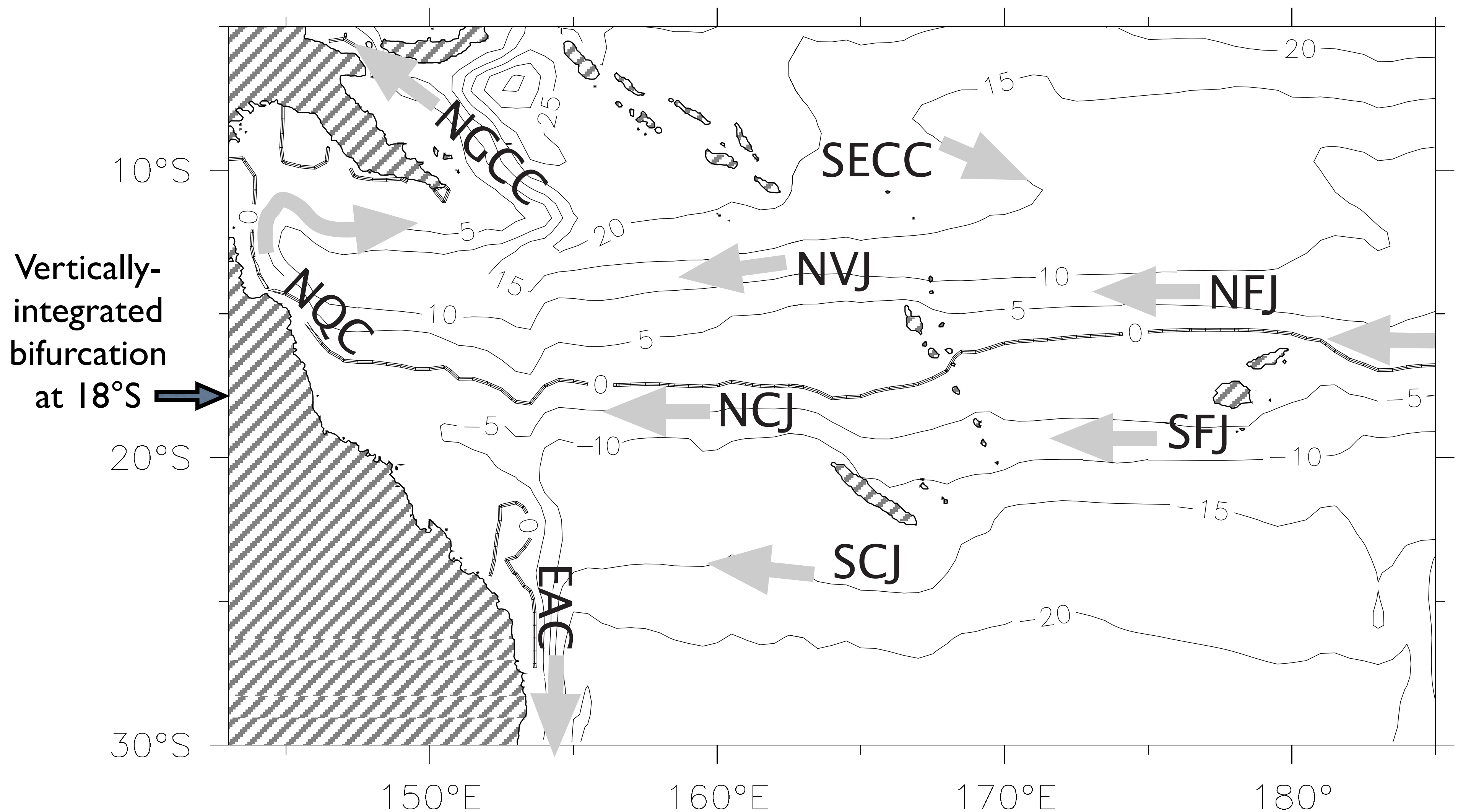
Water mass redistribution in the SW subtropical Pacific



Bathymetry of the SW subtropical Pacific



ORCA model streamfunction



Western Boundary Currents

EAC = East Australian Current

NQC = North Queensland Current

NGCC = New Guinea Coastal Current

SECC = South Equatorial Countercurrent

N, SFJ = North, South Fiji Jet

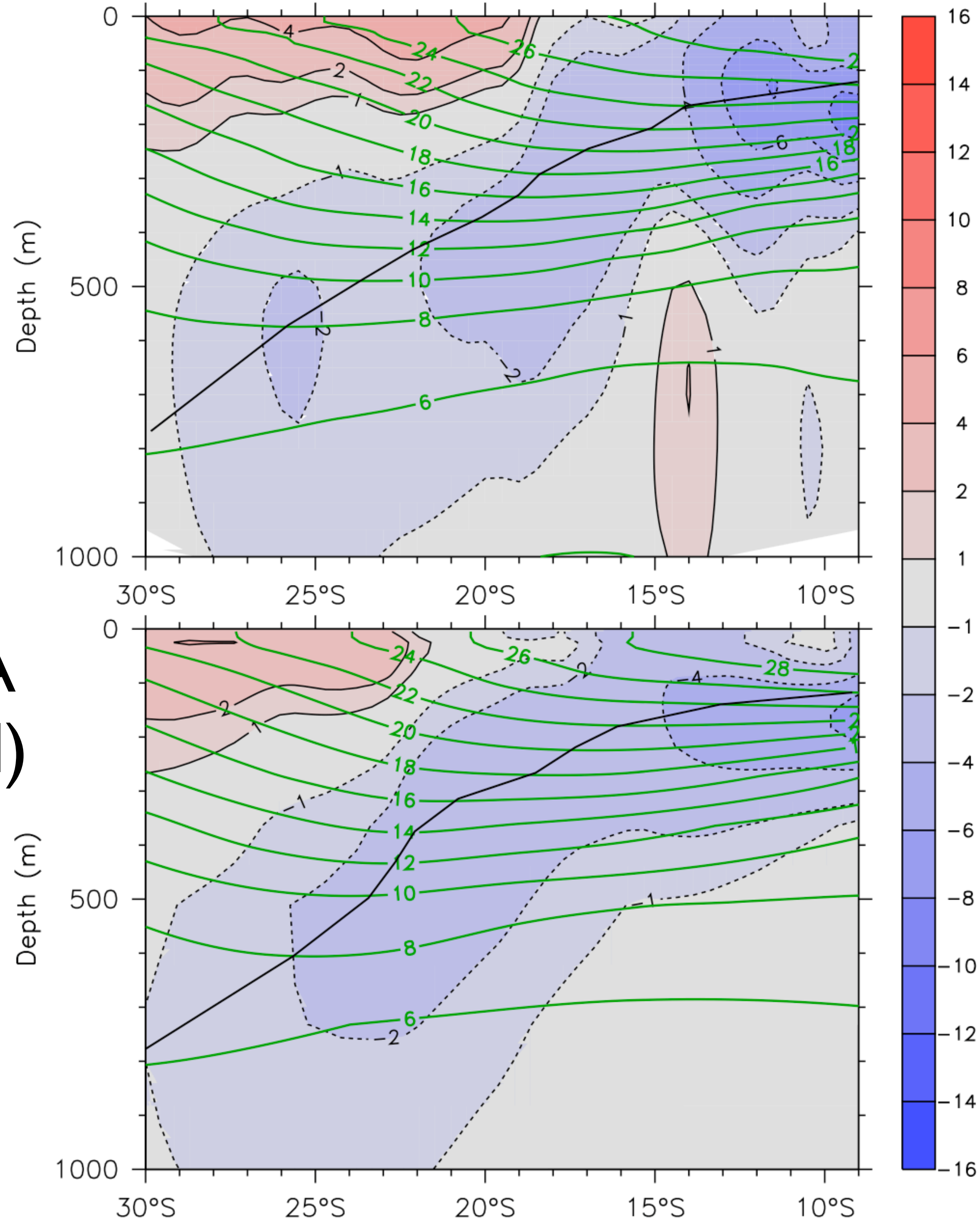
NVJ = North Vanuatu Jet

N, SCJ = North, South Caledonian Jet

Zonal current and temperature at 175°W (east of islands)

CARS (obs)

ORCA (model)

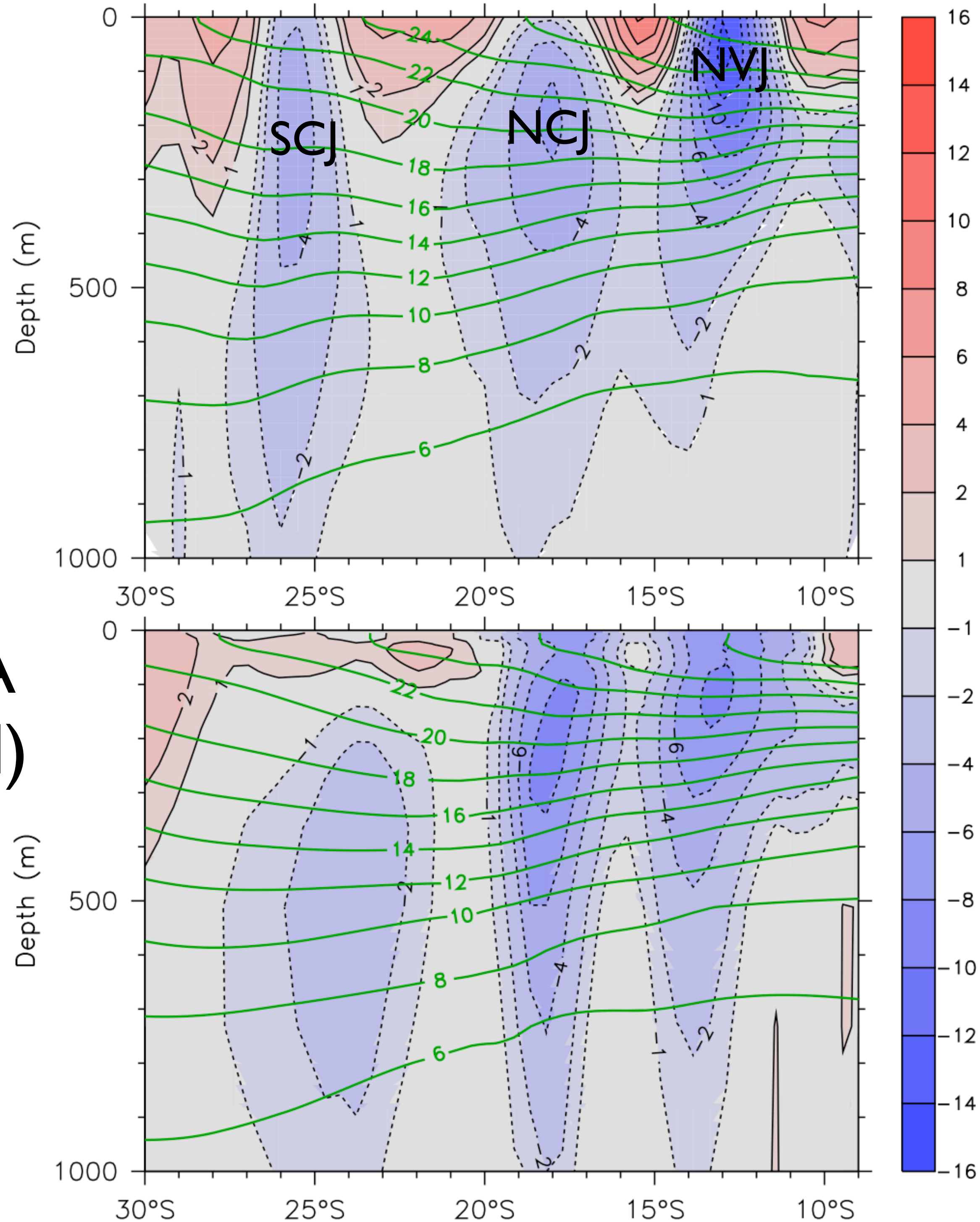


CARS is a new CSIRO CTD compilation for the S Pacific and S Indian Oceans

Ridgway & Dunn (2003)

CARS
(obs)

ORCA
(model)



Zonal current and temperature at 162.5°E (west of N.C.)

The SEC is broken into distinct jets behind the islands.

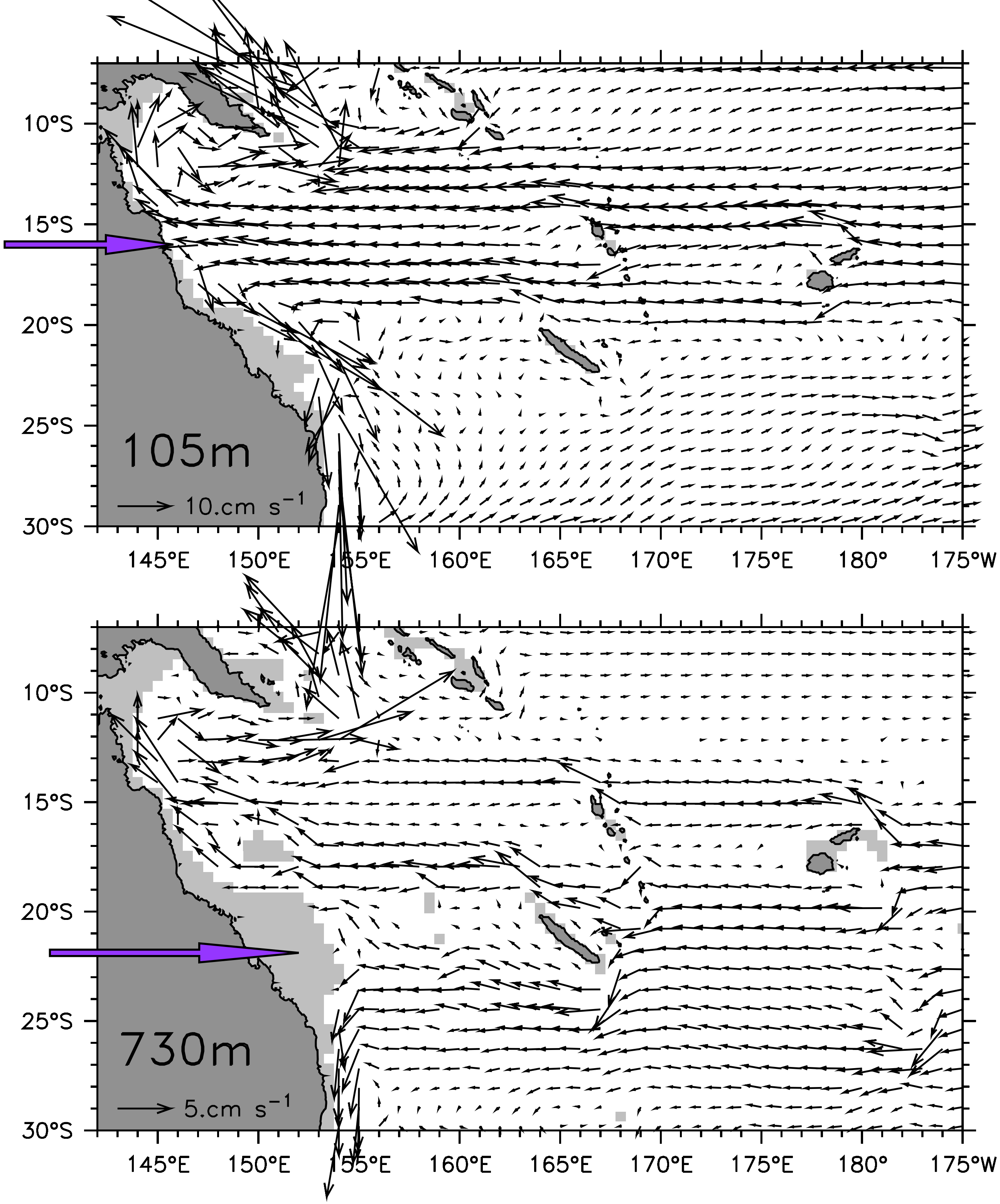
The jets have subsurface maxima.

(The NCJ extends very deep).

Tilted gyre, tilted bifurcation

105m

Bifurcation at 16°S



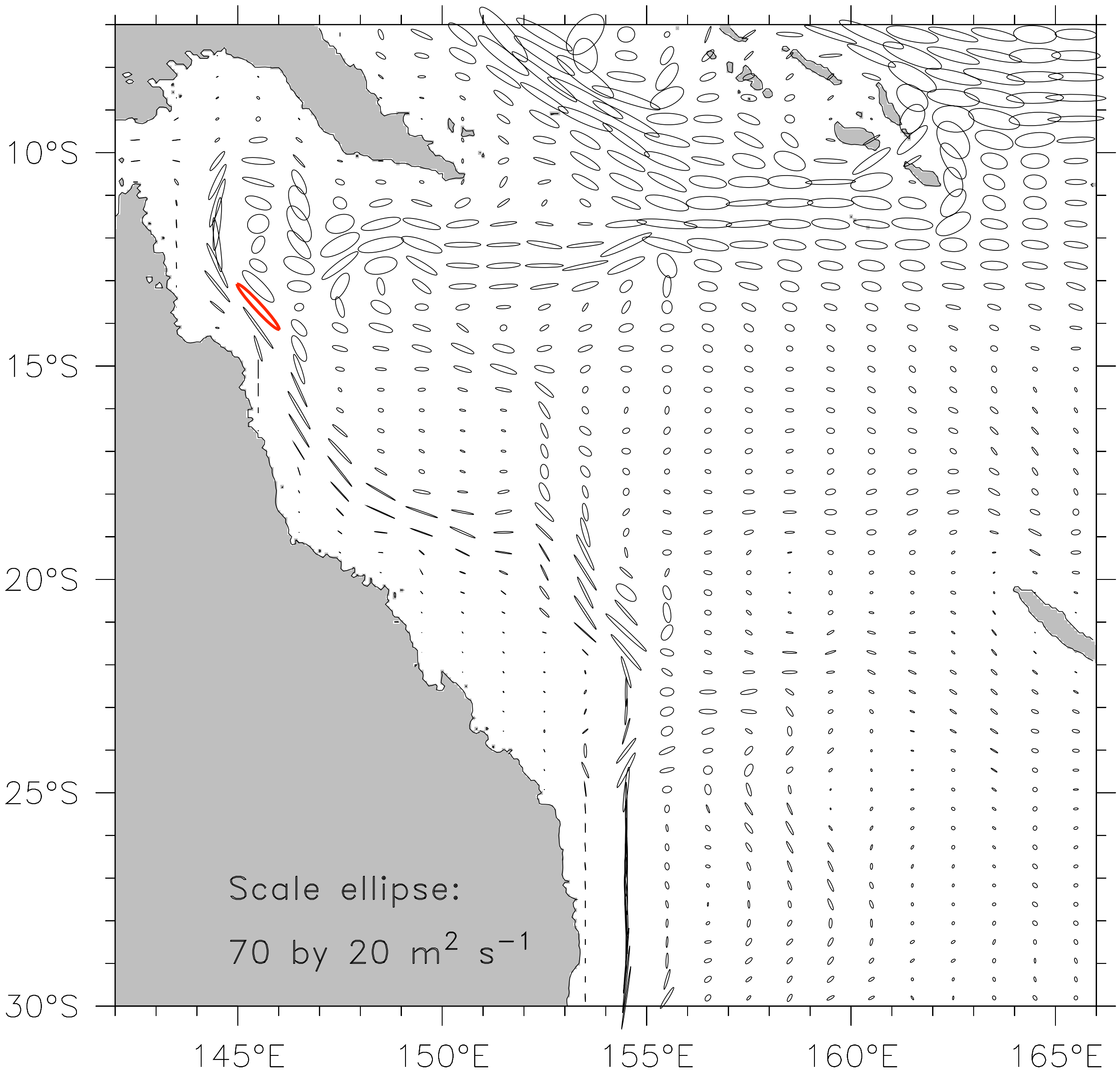
730m

Bifurcation at 22°S

Summary of brief look at mean circulation

- Complex regional geometry/topography
- SEC divided into jets
- Tilted gyre (hence tilted bifurcation)
- Bifurcation/redistribution of SEC inflow
  - ⇨ Climate consequences?
  - ⇨ Implication that variations of the bifurcation produce transport anomalies to the equator

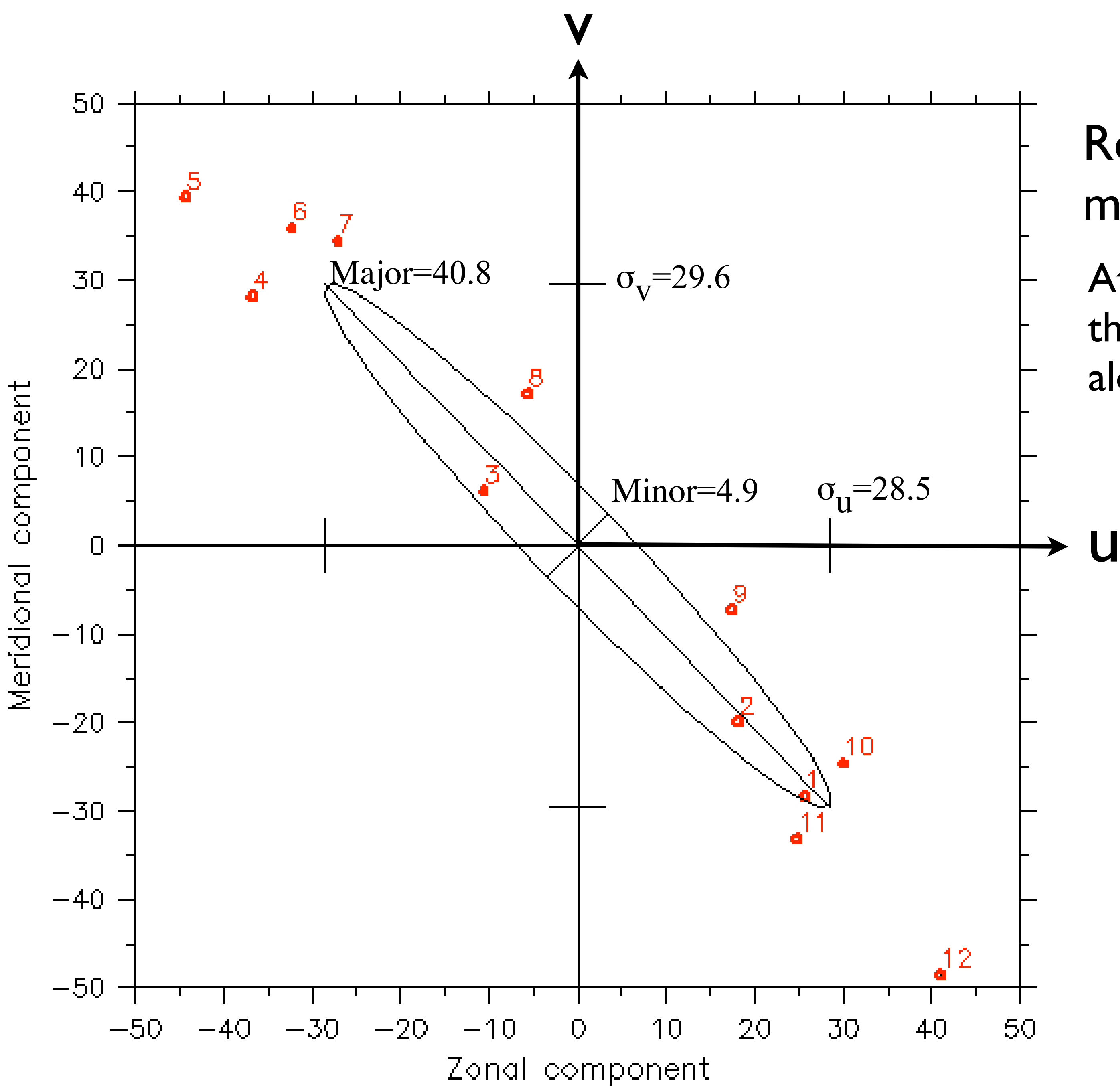
OGCM annual cycle transport variance ellipses



0-2060m transport

The major and minor axes of a variance ellipse are the standard deviations of the velocity components, *after the ellipse has been rotated to express the maximum possible variance in the major axis direction.*

Variance ellipse at 13.6°S, 145.5°E

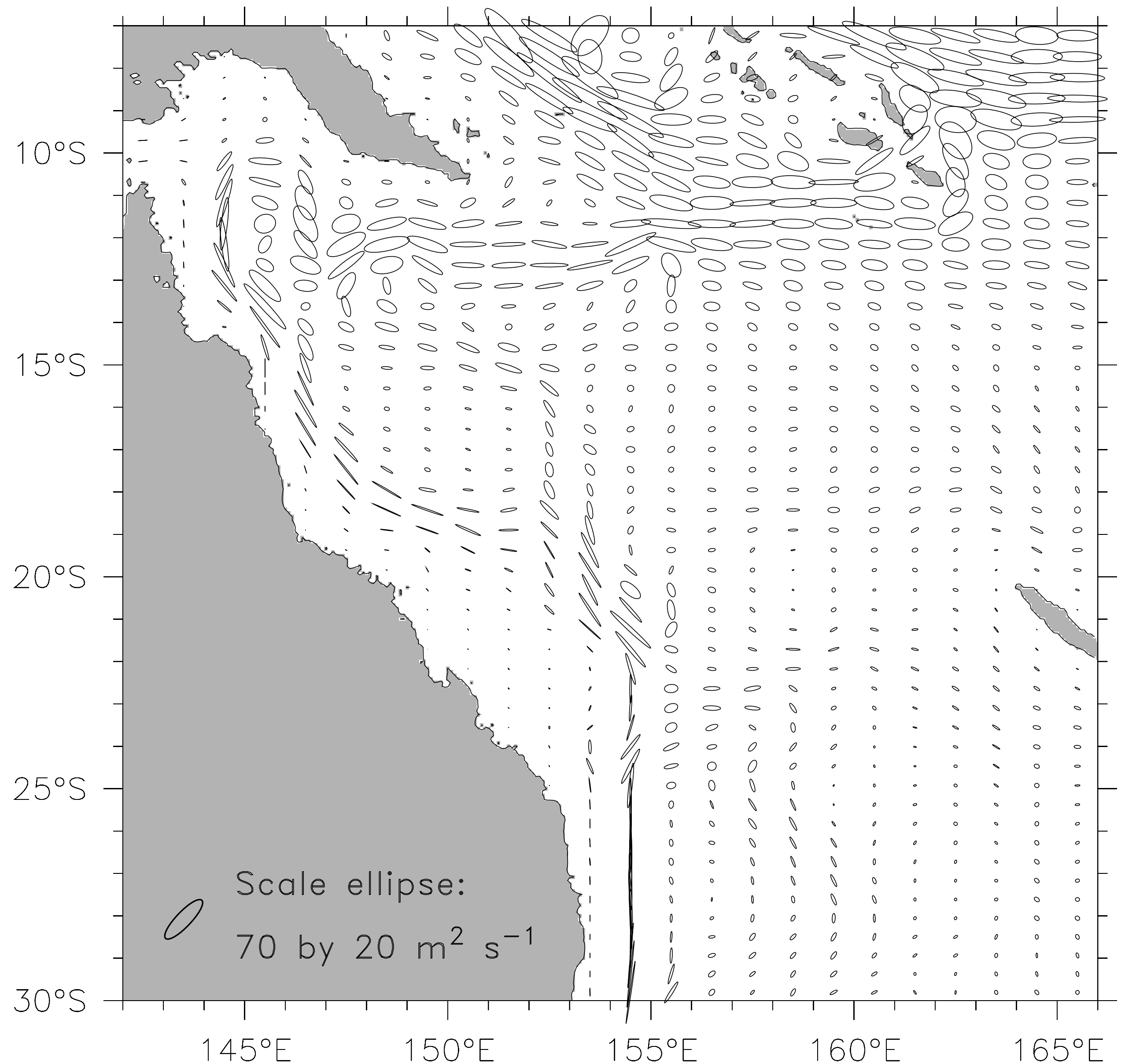


Red dots show monthly anomalies

At this location, 98% of the variance is expressed along the major axis.

(Units $m^2\ s^{-1}$)

OGCM annual cycle transport variance ellipses



0-2060m transport

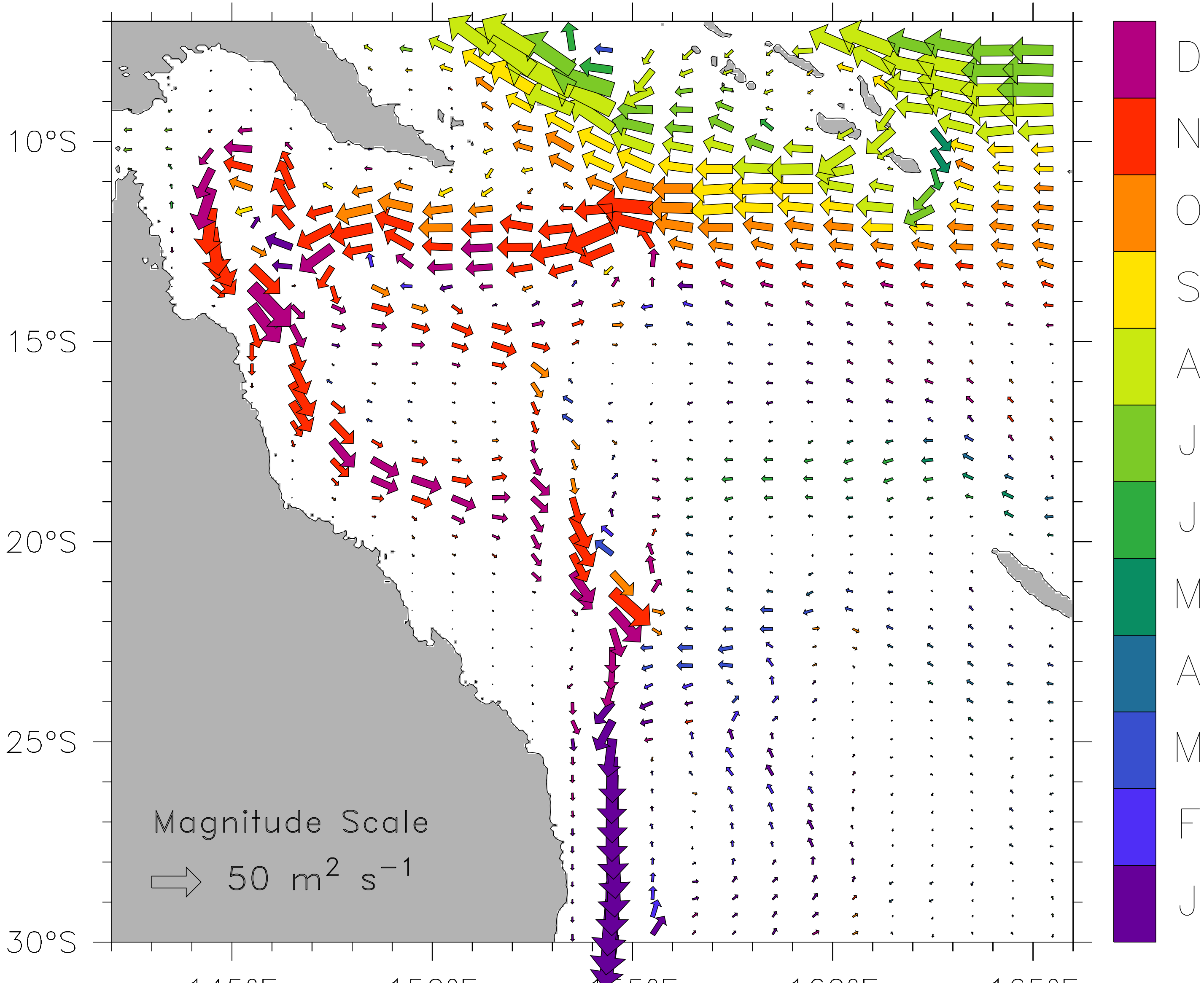
Small variability in the interior gyre.

Large-amplitude currents in the tropics and along the western boundary.

Elongated ellipses show 80-90+% of variance on the major axes, which are mostly aligned along the mean currents.

➡ Use the major axes to define a current-anomaly-following coordinate.

OGCM 1 cpy transport harmonic from variance ellipses



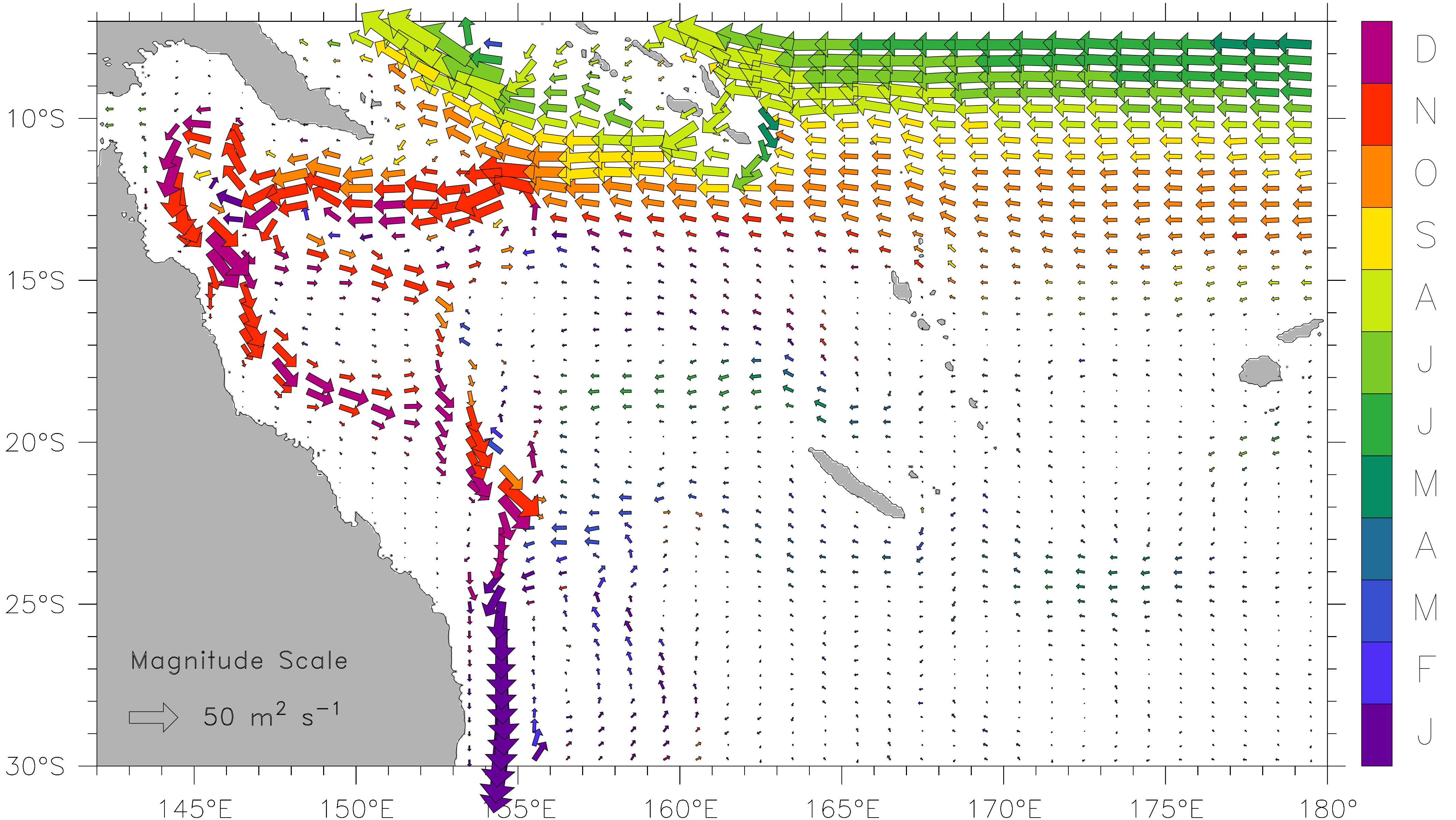
Vector size = amplitude (scale lower left)

Direction = major axis of variance ellipse (not mean current)

Color = month of maximum transport

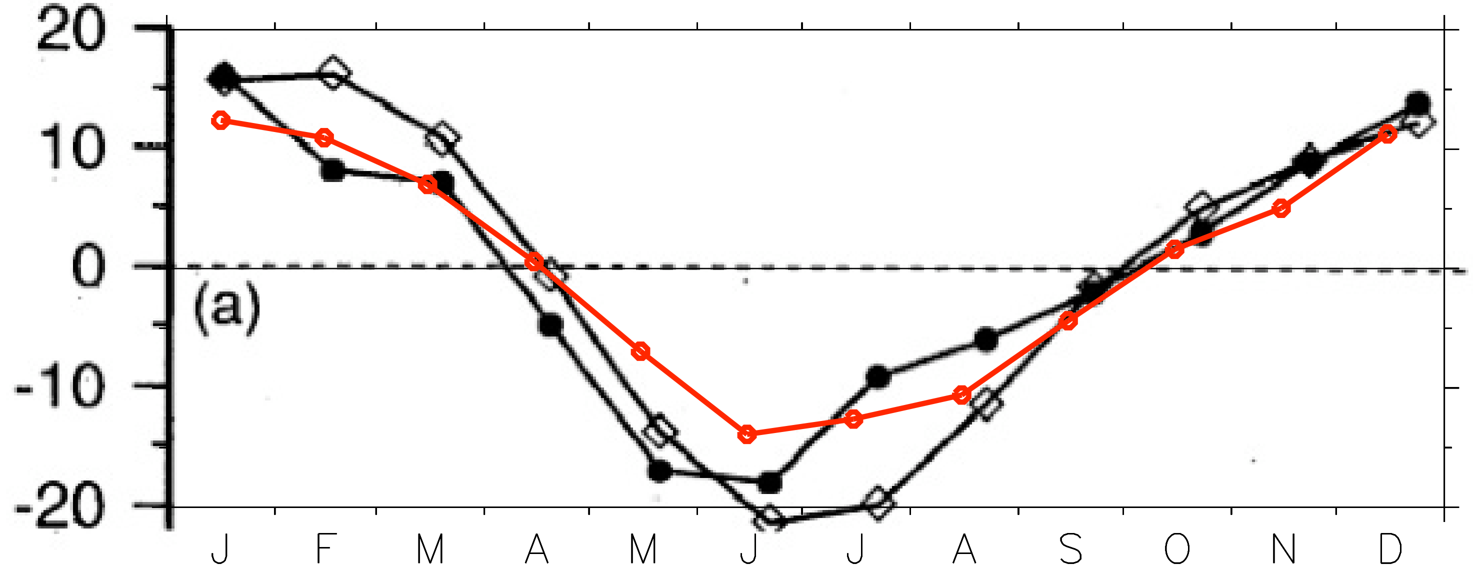
The same pattern extends to the east

Little transport variance in the gyre center



Annual cycle surface speed in the EAC at 29°S

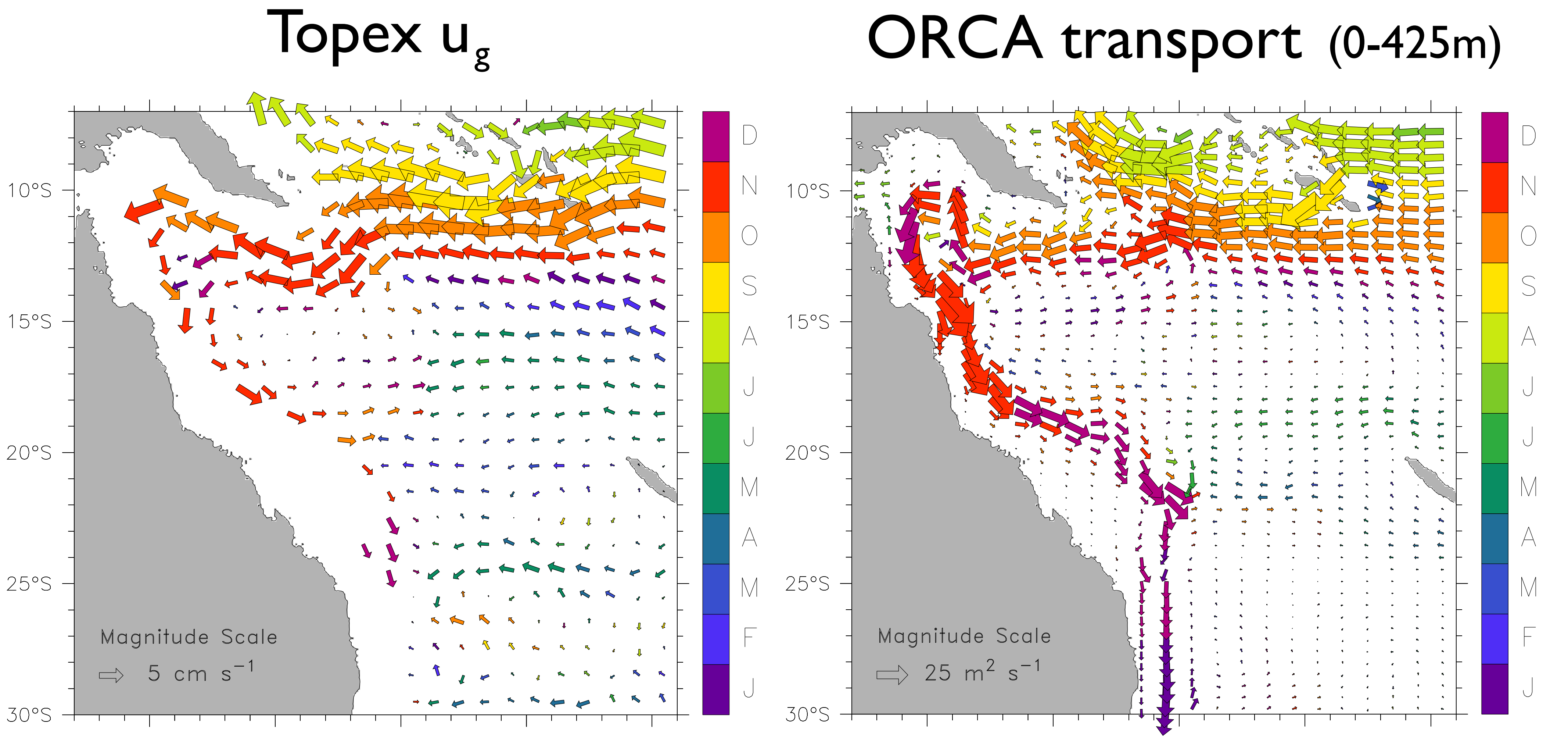
(Positive southward)



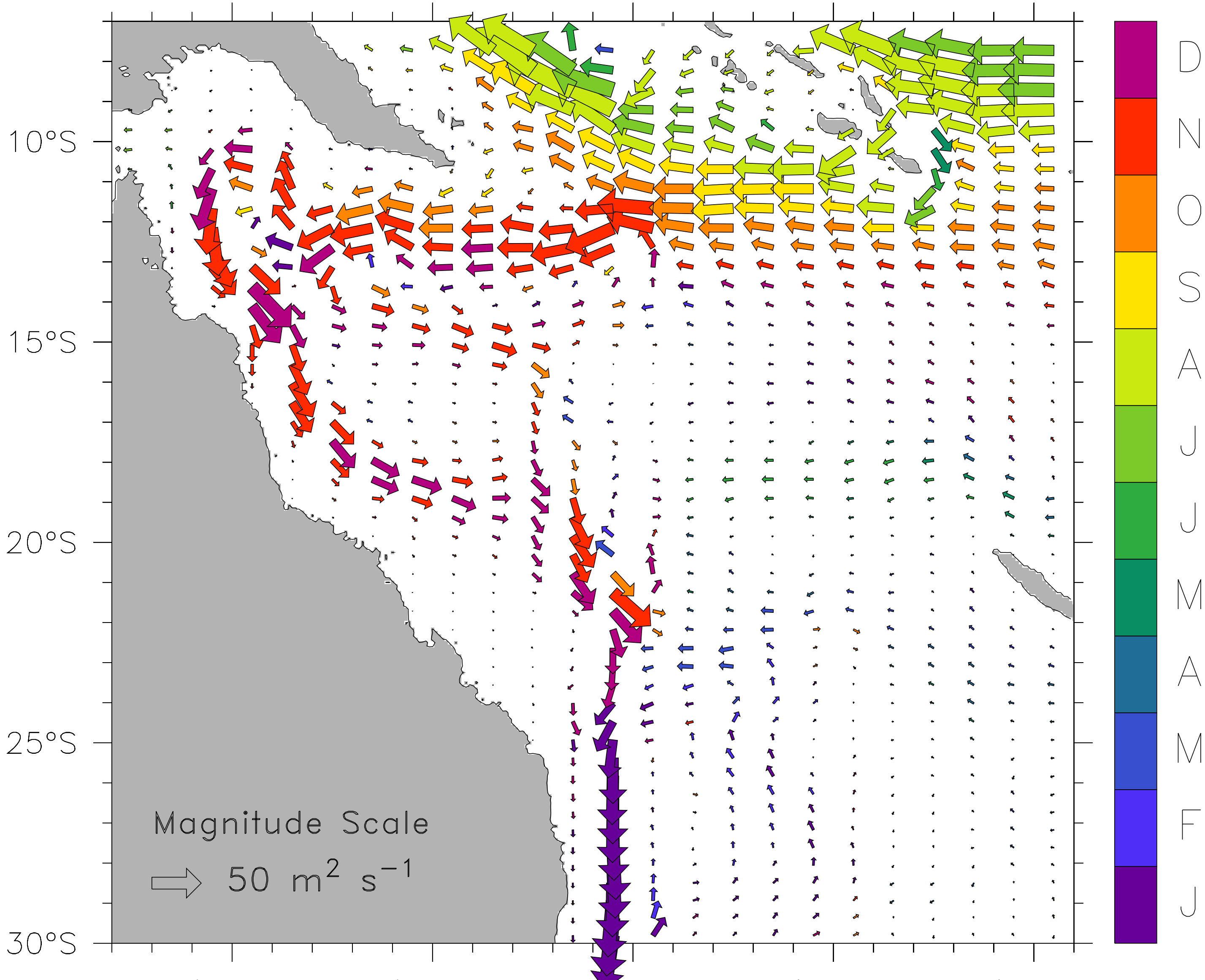
Black: Ridgway & Godfrey (1997) Fig.4a (extracted).
Diamonds = ship drift, Circles = v_g from sea level/DH

Red: ORCA OGCM surface speed

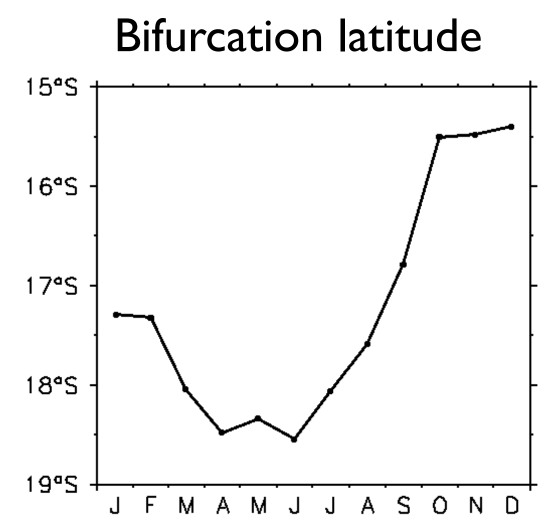
Annual cycle harmonic vectors



Do subtropical WBC anomalies connect to the equator?

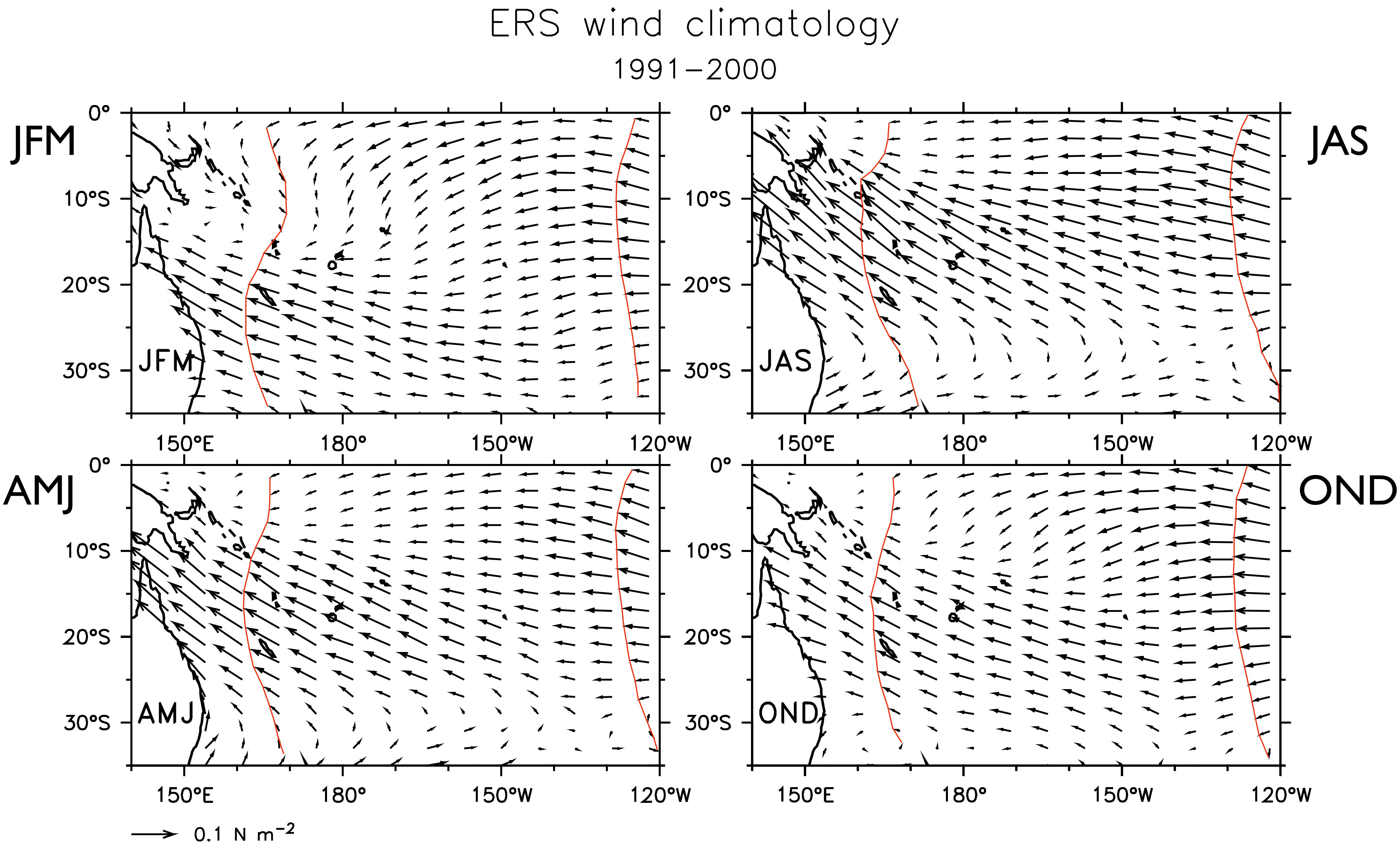


The WBC along the entire coast of Australia fluctuates coherently, while anomalies of the NGCC are nearly of the opposite phase.



Annual Australia WBC anomalies *do not* represent corresponding transport anomalies to the equator.

Curl variations are much larger in the west



The familiar reduced-gravity long Rossby wave model

$$\frac{\partial h}{\partial t} + c_r \frac{\partial h}{\partial x} + Rh = -Curl\left(\frac{\tau}{f\rho}\right), \qquad c_r = -\beta \frac{c^2}{f^2}$$

h is the ULT anomaly, c is the Kelvin speed, R is a damping timescale, $(2\ \mathrm{yr})^{-1}$.

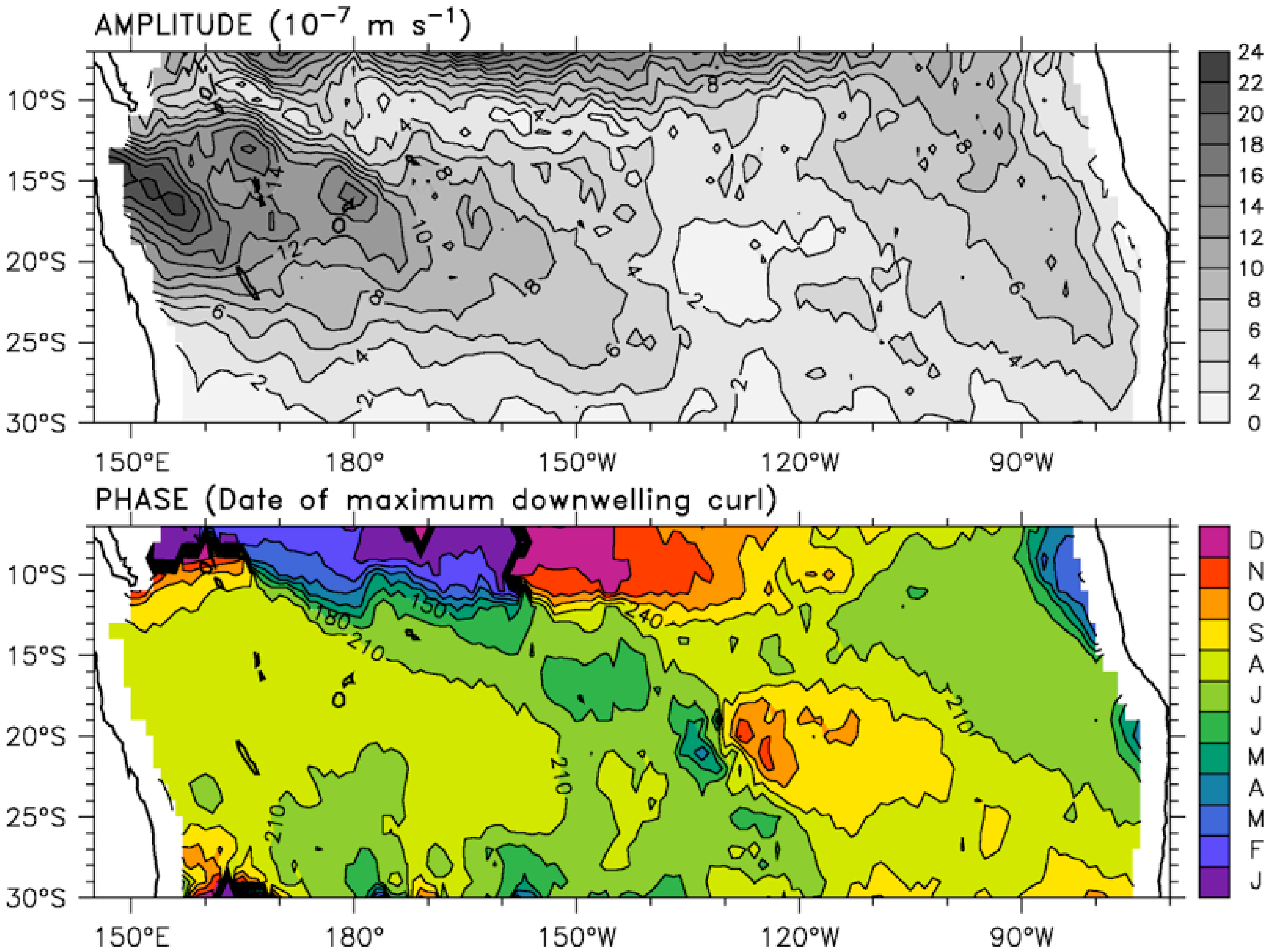
The solution is found at each latitude independently:

$$h(x,t) = -\frac{1}{c_r}\int_{x_E}^{x} e^{-\frac{R}{c_r}(x-x')} Curl\left(\frac{\tau(x', t - \frac{x-x'}{c_r})}{f\rho}\right) dx'$$

The model is forced with an annual cycle of ERS winds (1991-2000), assuming no eastern boundary influence.

1 cpy harmonic of $Curl(\tau/f\rho)$

$$w_e = \frac{1}{f\rho}Curl(\tau) + \frac{\beta}{f^2\rho}\tau^x$$



Equatorial-subtropical divide along 11°S

ERS winds 1991-2000

Because the winds have a simple form ....

Chen and Qiu (2004) showed that for winds of the form:

$$Curl\left(\frac{\tau}{\rho f}\right) = Be^{i\omega t}e^{-(x-x_w)/L}$$

(standing oscillation with uniform phase, decaying eastward)

The Rossby solution is also a standing oscillation:

$$h(x,t) = \left(\frac{1}{i\omega - \frac{c_r}{L}}\right) Curl\left(\frac{\tau}{\rho f}\right)$$

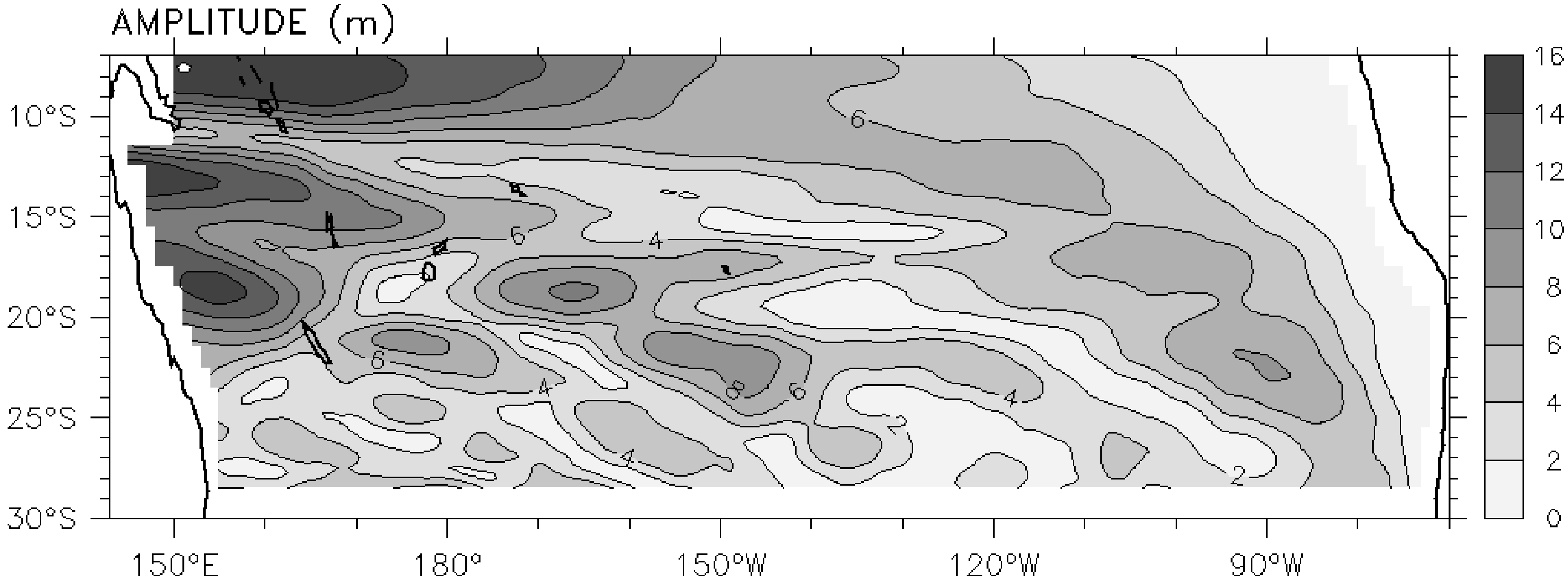
which lags the Curl by $tan^{-1}(\omega L/c_r)$ = 2.5-3 months:

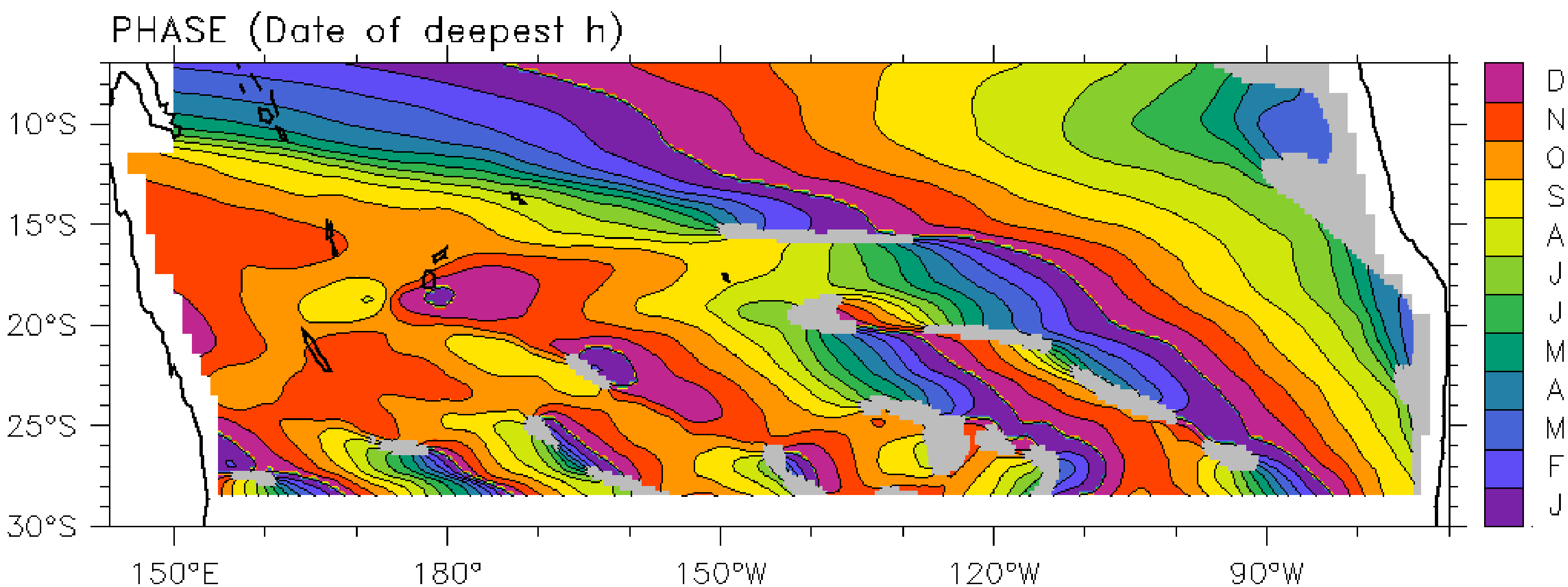
$$= -\left(1 + i\frac{\omega L}{c_r}\right)\left(\frac{1}{\frac{\omega^2 L}{c_r} + \frac{c_r}{L}}\right) Curl\left(\frac{\tau}{\rho f}\right)$$

Phase lag — Amplitude

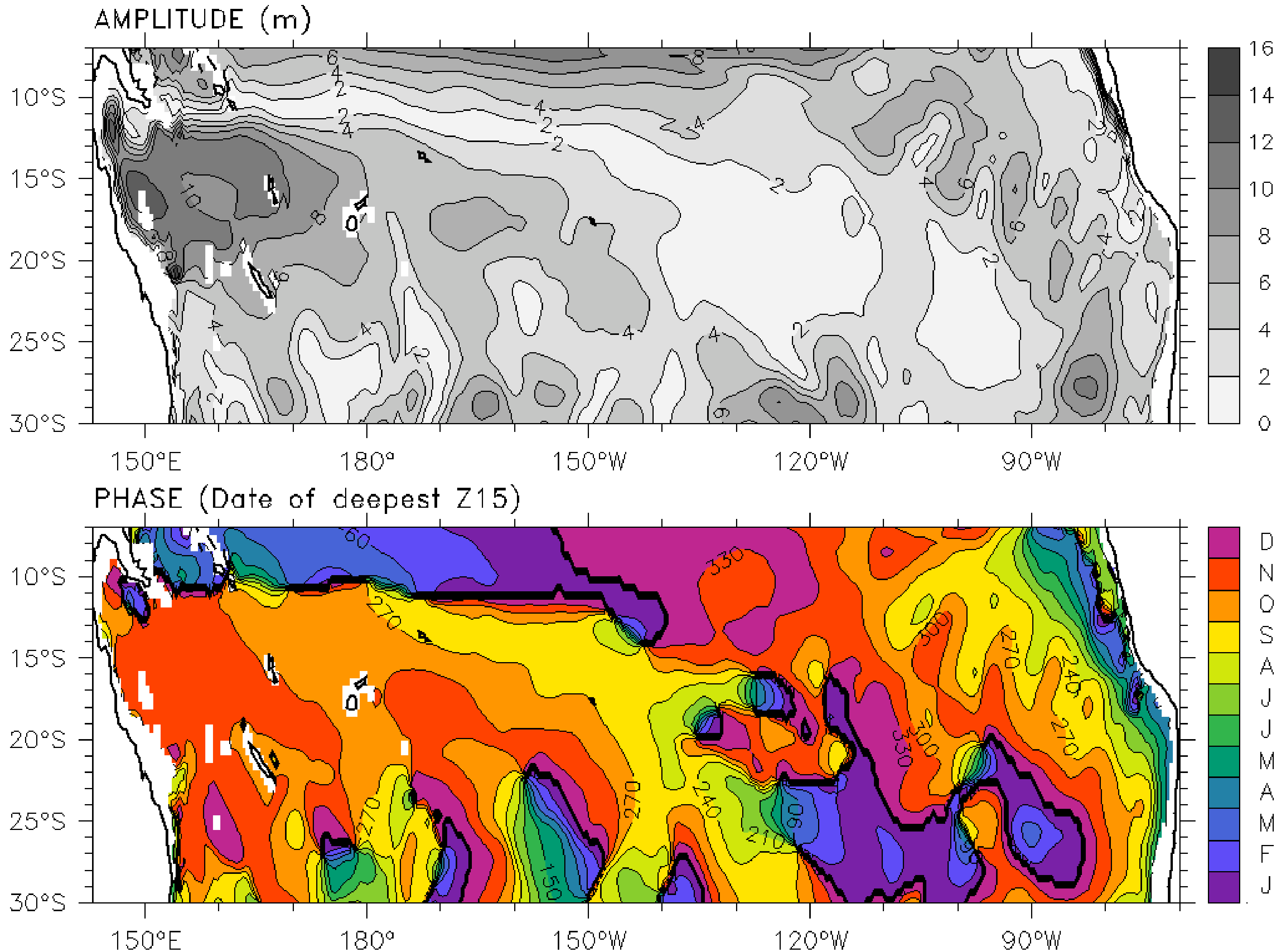
- Propagating Rossby waves will not be apparent in this solution (will look a lot like Ekman pumping)
- Expect uniform phase (max h in Nov) and growing amplitude in the west

1 cpy harmonic of Rossby model h (real winds)

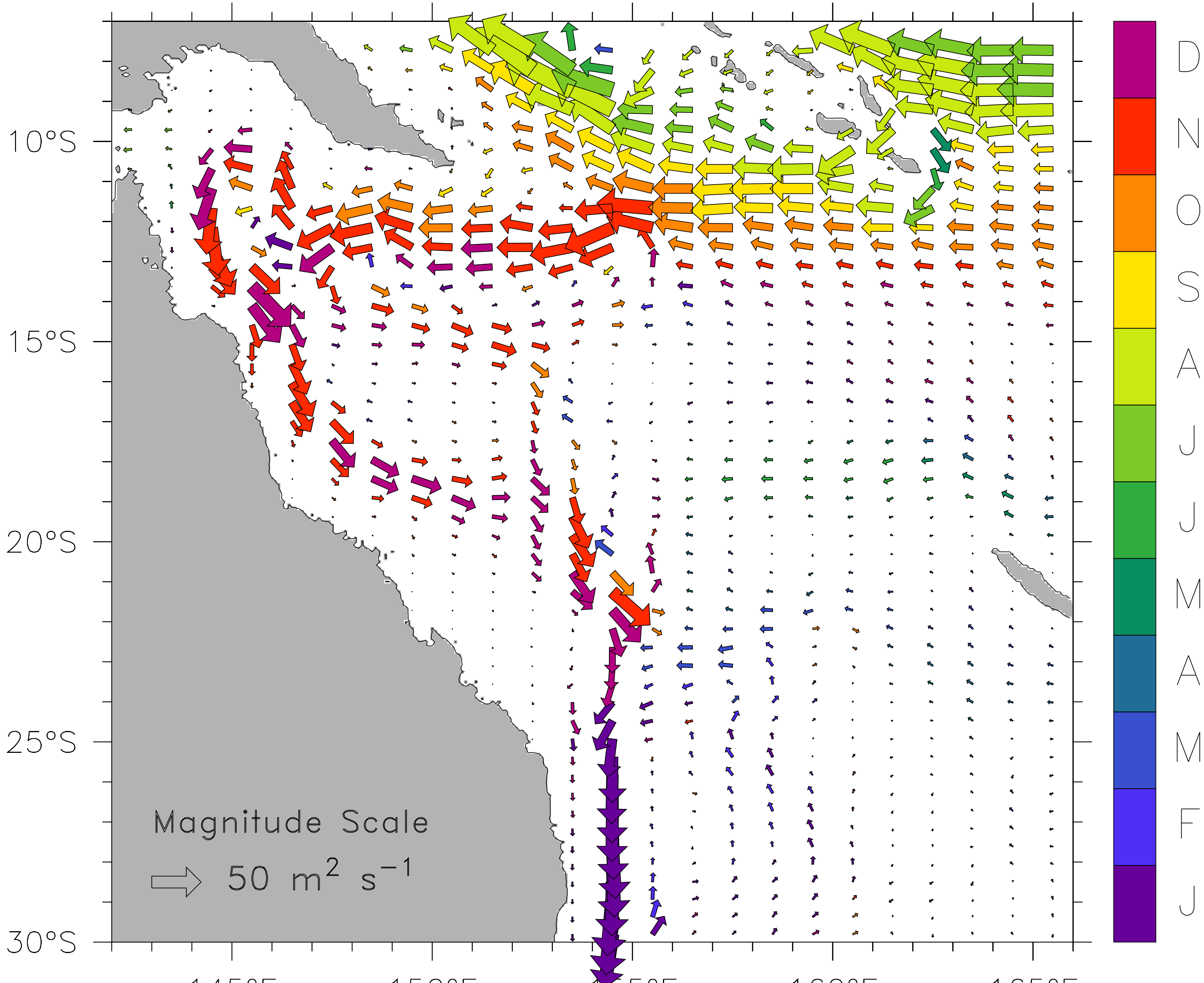




1 cpy harmonic of OGCM 15°C depth



The annual cycle is a spinup and spindown of the gyre



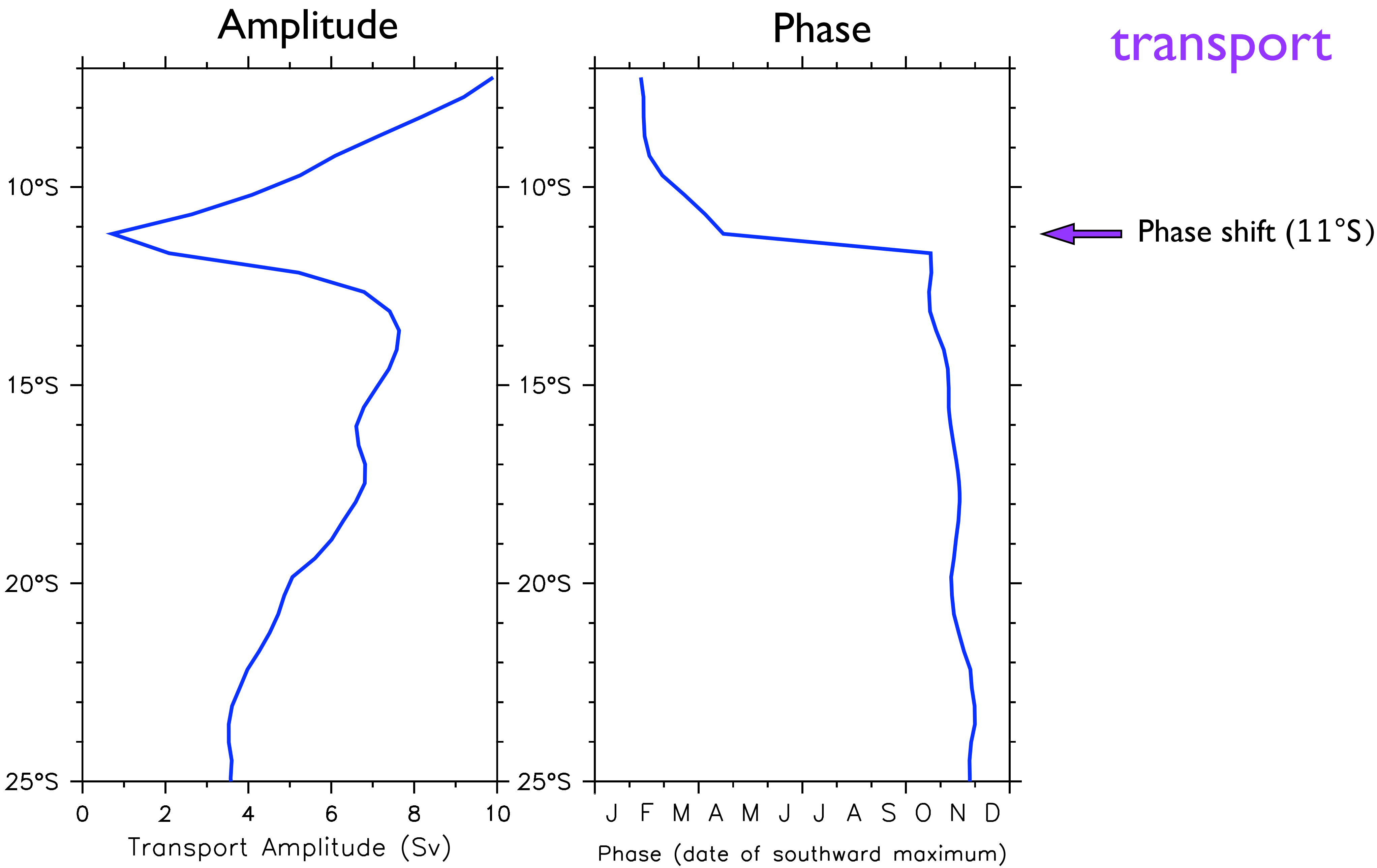
The wind-driven changes are a shoaling of the gyre in the 1st half of the year, and a deepening in the 2nd.

The resulting transport anomalies are alternately clockwise (spindown) and anticlockwise, but the tropical side is much stronger.

The OGCM solution shows that this also describes the western boundary changes.

ORCA model

1 cpy harmonic of WBC transport



Deducing western boundary current anomalies from the interior Rossby solution

- By its neglect of velocity acceleration terms, friction and nonlinearity, the long Rossby model explicitly excludes western boundary dynamics.
- But, the WBC can be deduced as an equatorward accumulation of the incoming zonal transport due to Rossby waves (Godfrey 1975, Appendix B.2).

In the reduced gravity system, the WBC transport anomaly is:

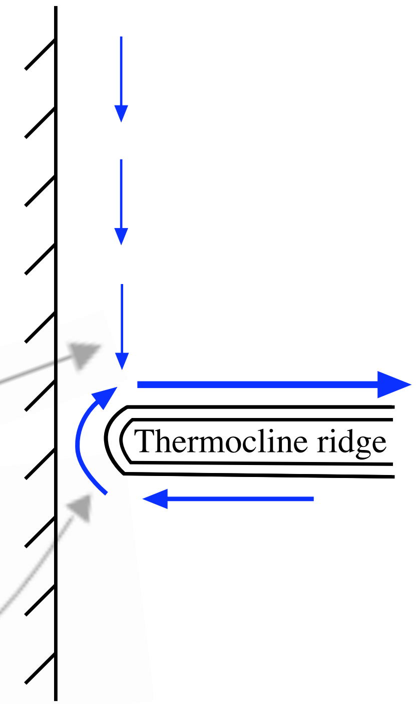
$$V(y) = V_S - \int_{y_S}^{y} u_{RW}\, dy' = V_S + \int_{y_S}^{y} \frac{c^2}{f} \frac{\partial h_{RW}}{\partial y'} dy'$$

$$= V_S + c^2 \left(\frac{h_{RW}(y)}{f} - \frac{h_{RW}(y_s)}{f_S} + \int_{y_S}^{y} \frac{\beta}{f^2} h_{RW}\, dy' \right)$$

Direct effect of Rossby h-field

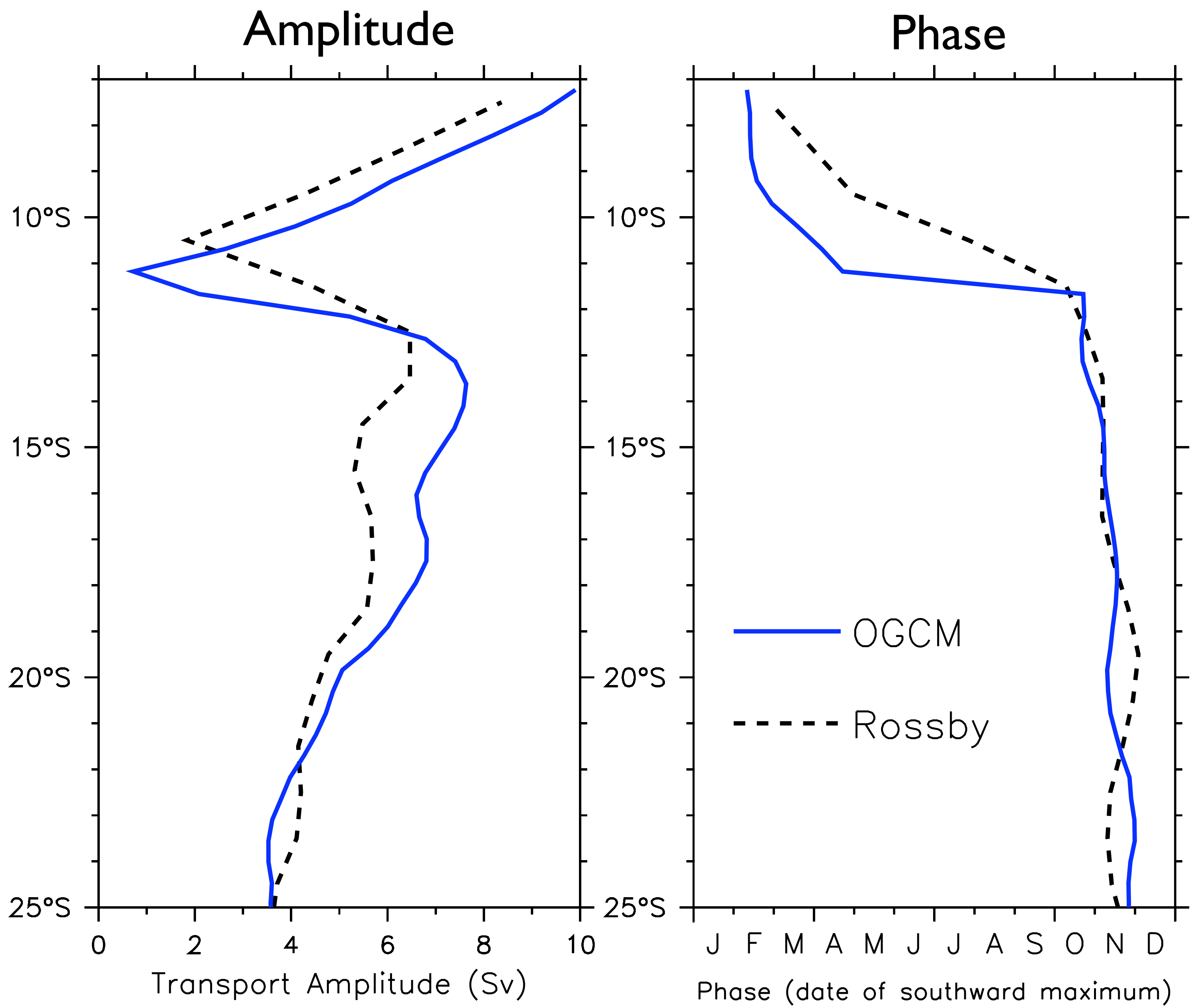
Constant term. Cancels at y_S

β-term. Mismatch of u_{RW}



Compare Rossby model

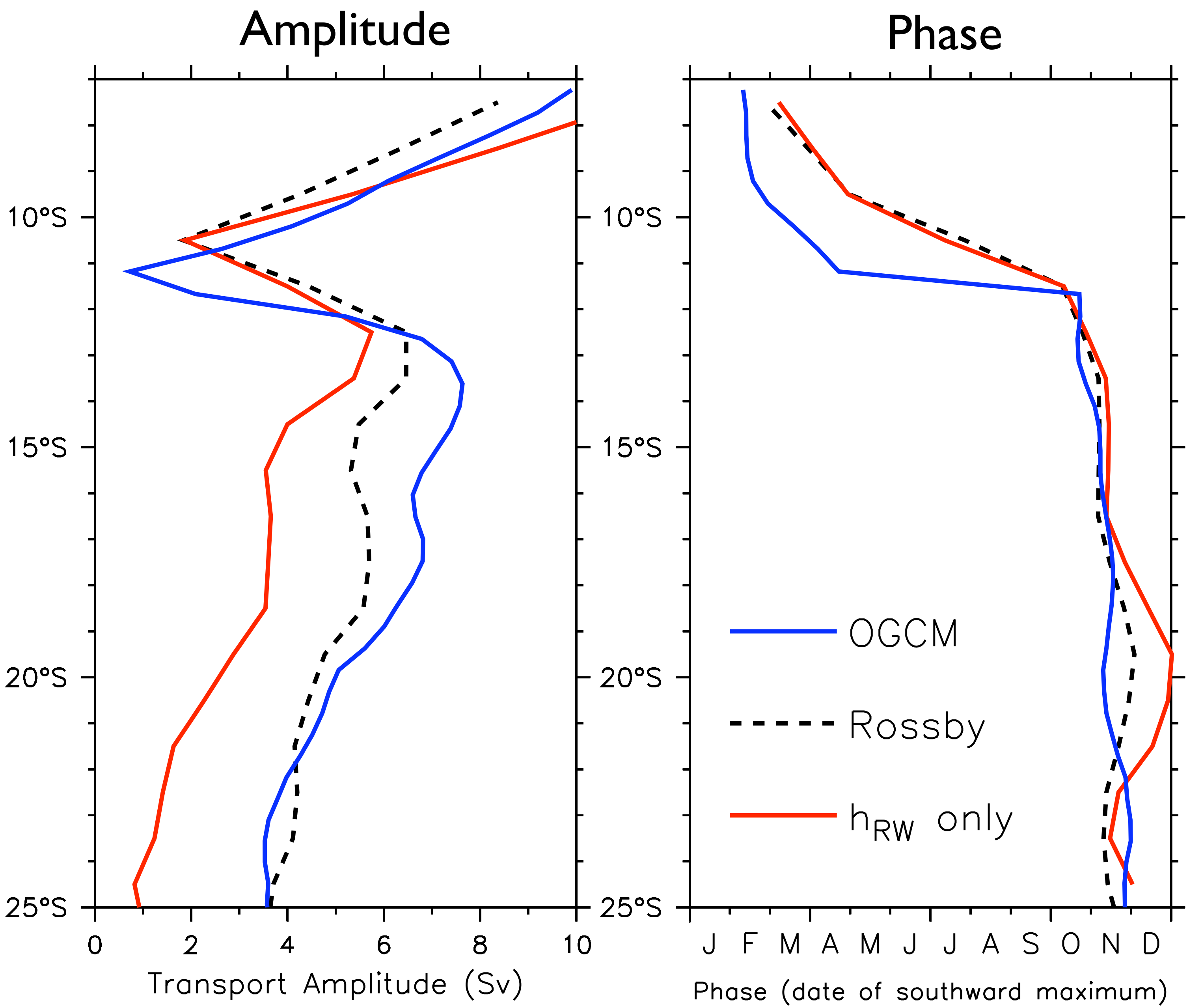
1 cpy harmonic of WBC transport



The 11°S phase shift is found in the Rossby solution, though it excludes western boundary dynamics and "knows" about the continent only from the 25°S boundary condition.

Compare Rossby model: direct effect only

1 cpy harmonic of WBC transport

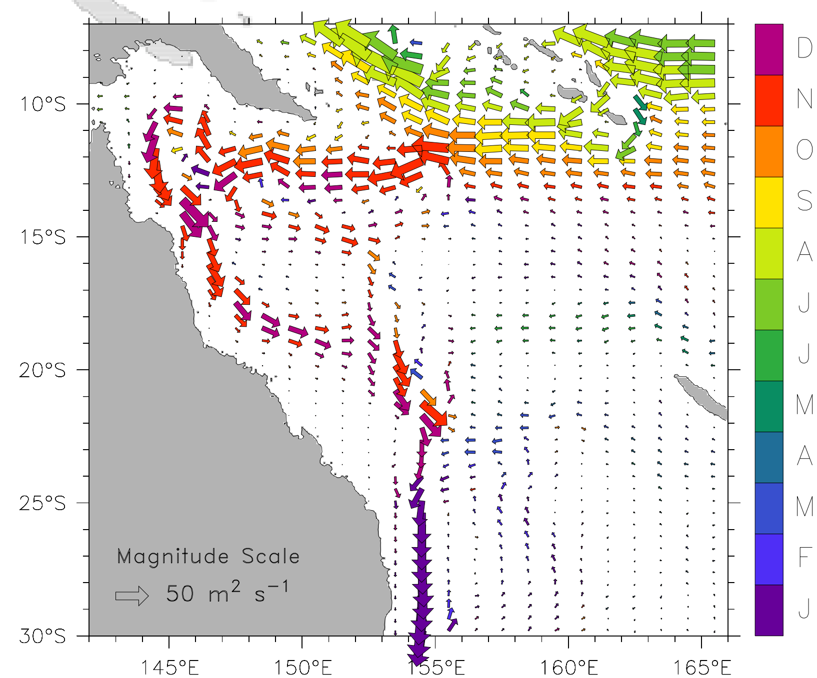


The structure of the solution is primarily in the direct effect of the interior Rossby height field.

The remainder:
1) 25°S B.C.
2) β-term (Godfrey)

Conclude:

- A linear Rossby model represents much of the annual variability in the subtropical South Pacific. The interior of the gyre heaves in a standing oscillation, driven by strong wind variations in the west.
- Model WBCs along the east coast of Australia vary coherently. A linear model is useful for interpreting WBC variability. (But ...)
- The out of phase WBC across 11°S is due to interior winds, not to boundary dynamics or the shape of the coast.
- The bifurcation latitude is meaningless with respect to annual transport from the South Pacific subtropical gyre to the equator. What about the North Pacific?
- The OGCM predicts the occurrence of annual WBCs on the deep east flanks of the Queensland Plateau and the Solomon Islands.

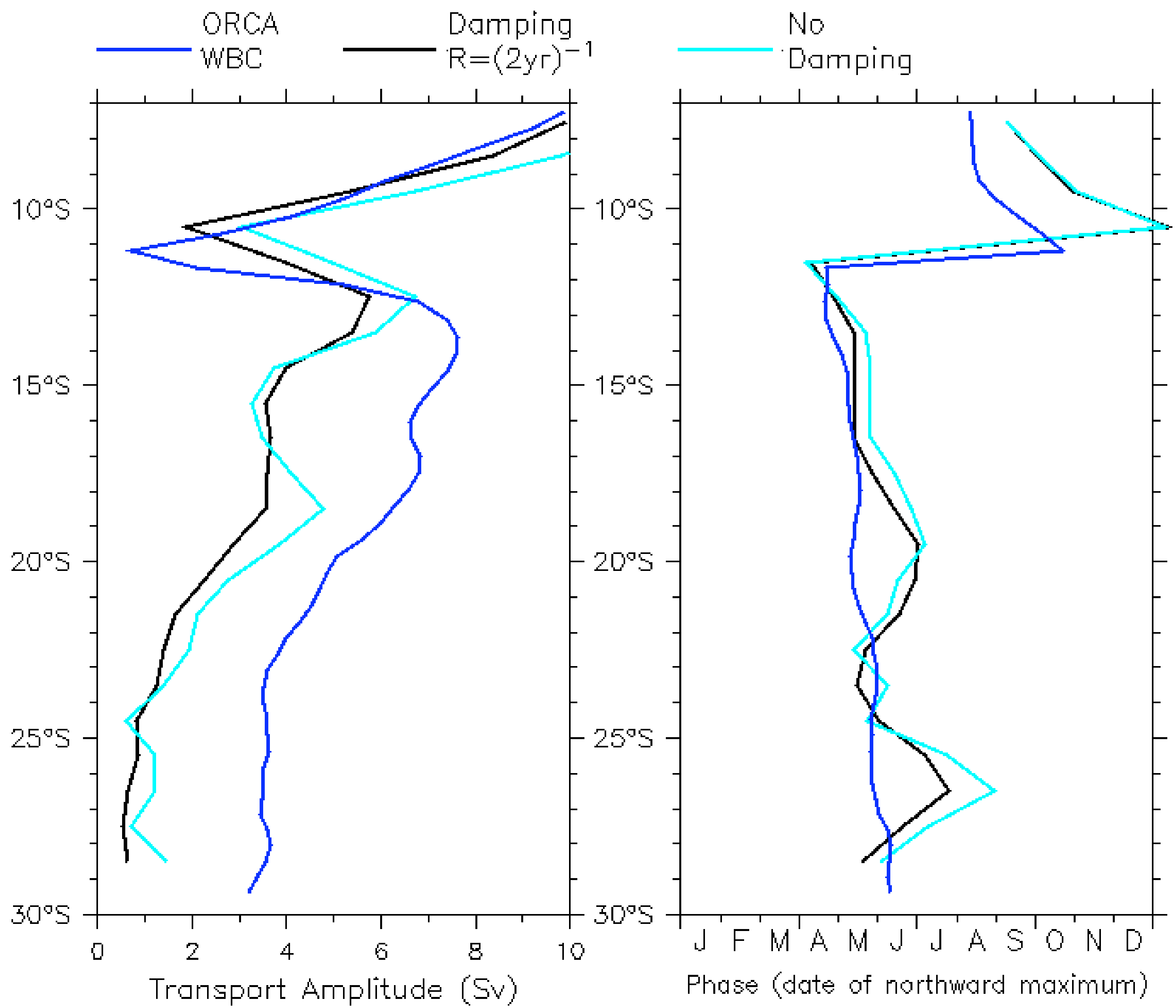


Extra

Figures

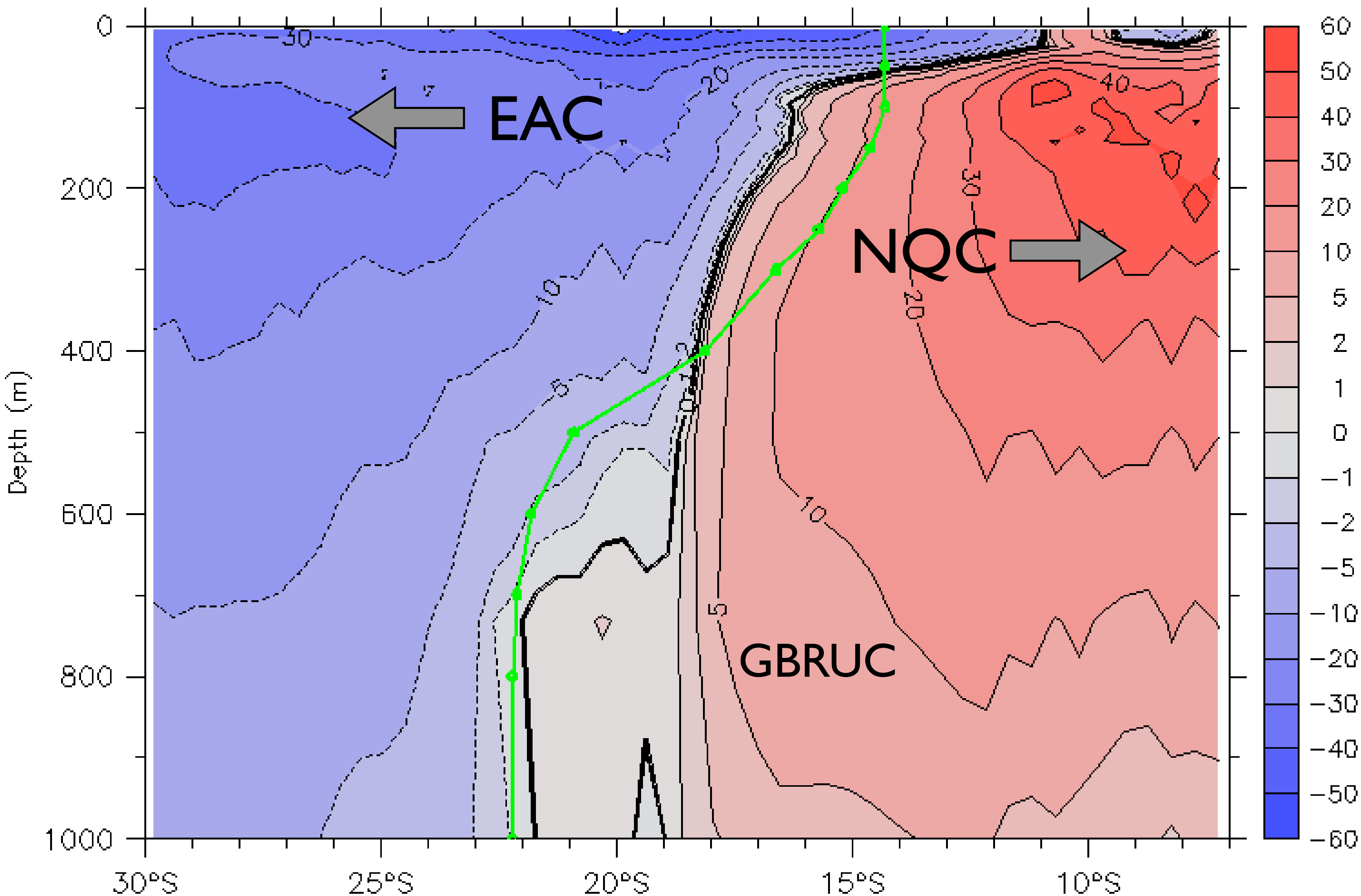
Follow

Rossby solution: effect of damping term

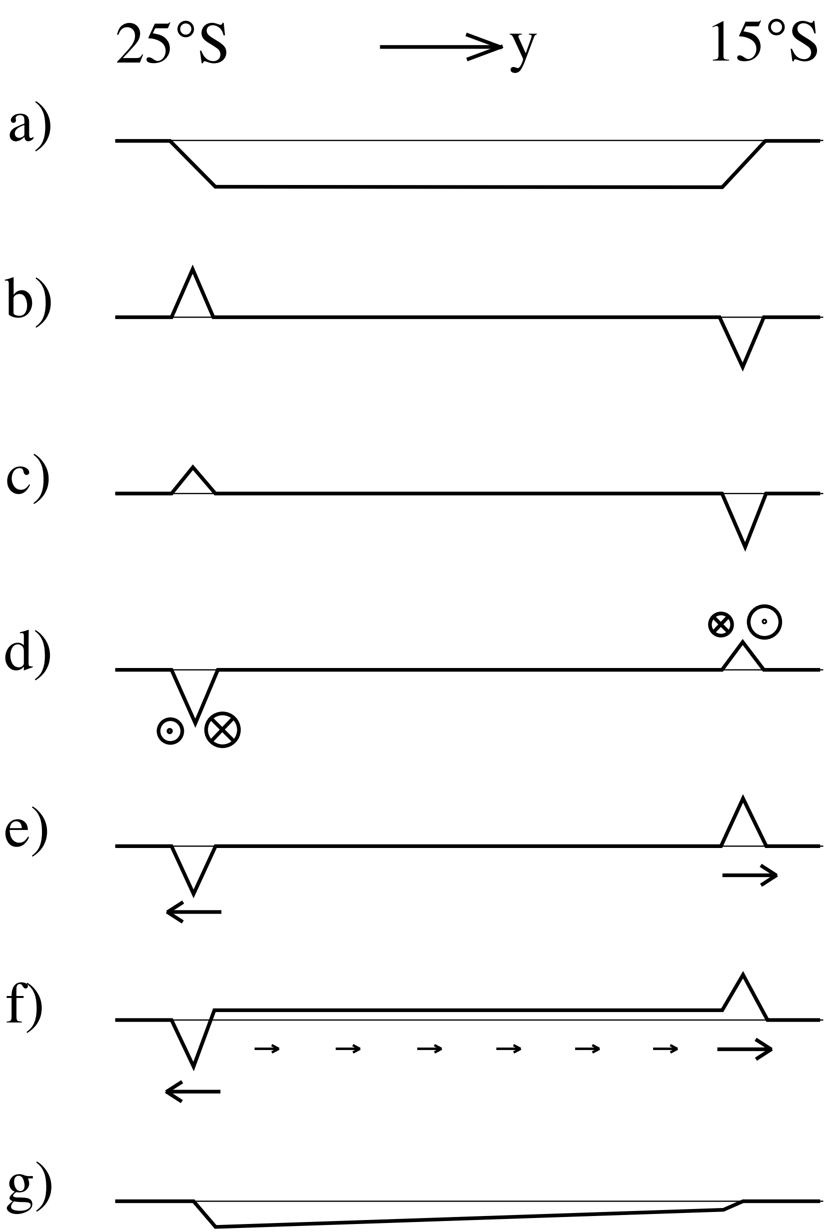


Mean model western boundary current

Green line is bifurcation from CARS data



Godfrey WBC due to incoming Rossby waves. Longshore pressure gradient within the western BL balances boundary friction.



a) τ^x *(Patch of trade winds)*

b) $Curl(\tau) = -\frac{\partial \tau^x}{\partial y}$

c) $Curl(\frac{\tau}{f}) \approx \frac{1}{f} Curl(\tau)$

d) $h_{RW}(y,t)$

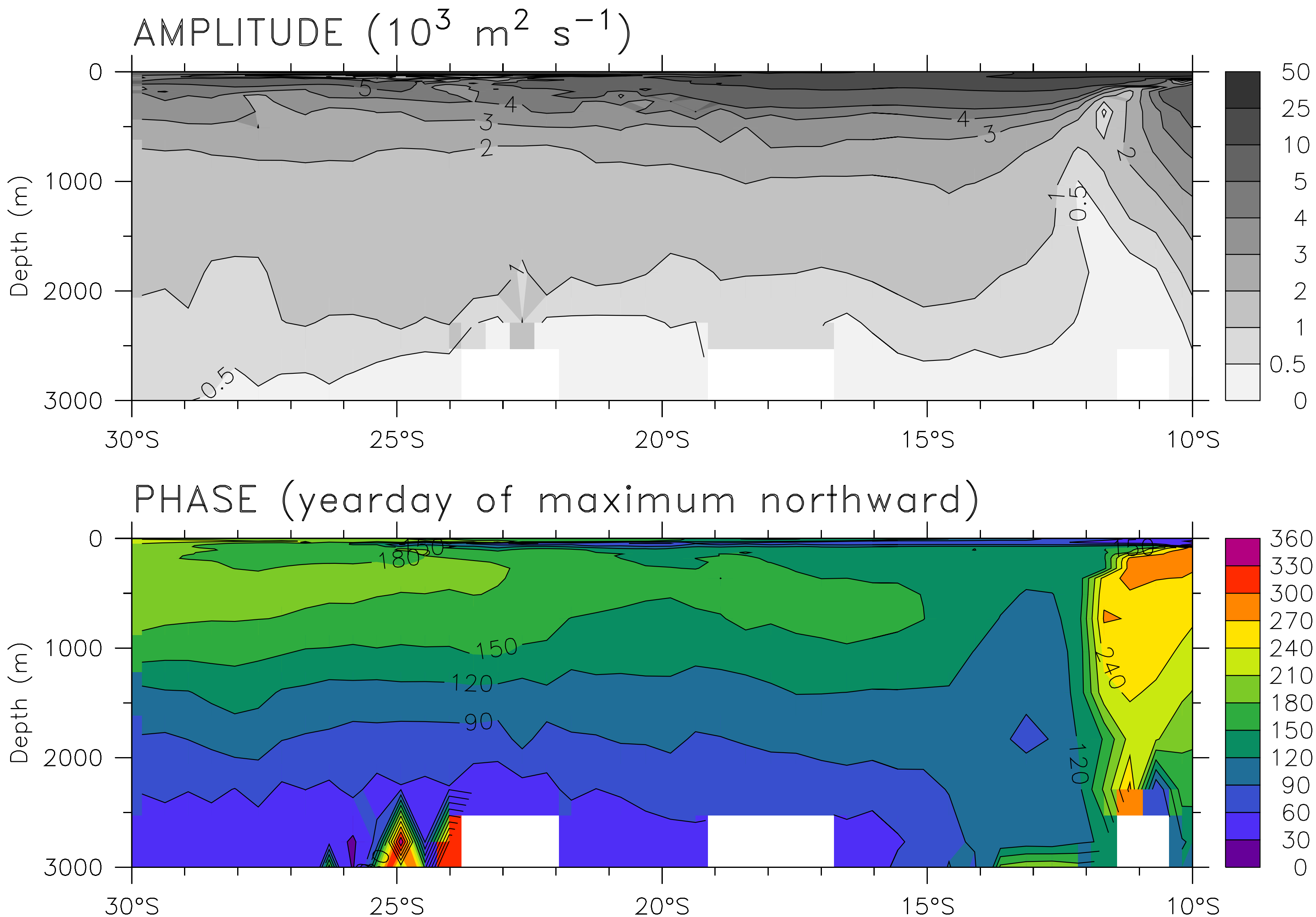
e) $V_{WBC}(direct) = \frac{c^2}{f} h_{RW}$

f) $V_{WBC}(actual)$

$= \frac{c^2}{f}(h_{RW} - h_{WB})$

g) h_{WB}

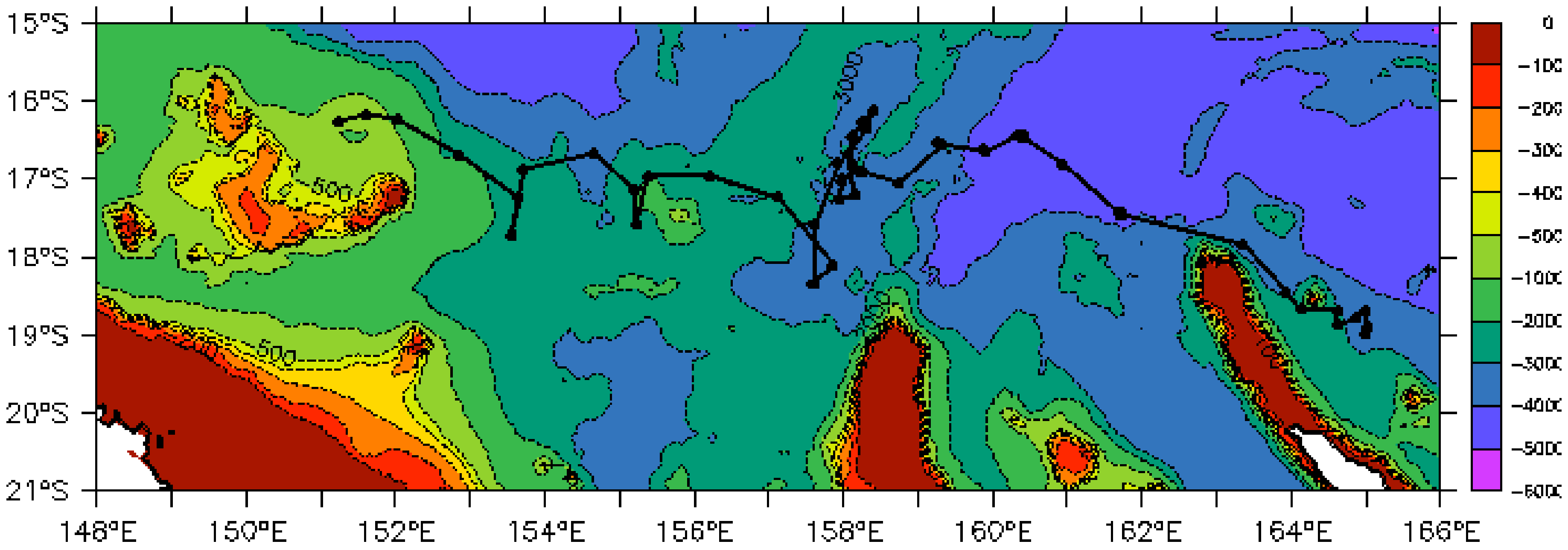
1 cpy harmonic of ORCA WBC transport/depth



Zonal integral of ORCA v from coast to 160°E (S of 20°S) or 156°E (Sv)

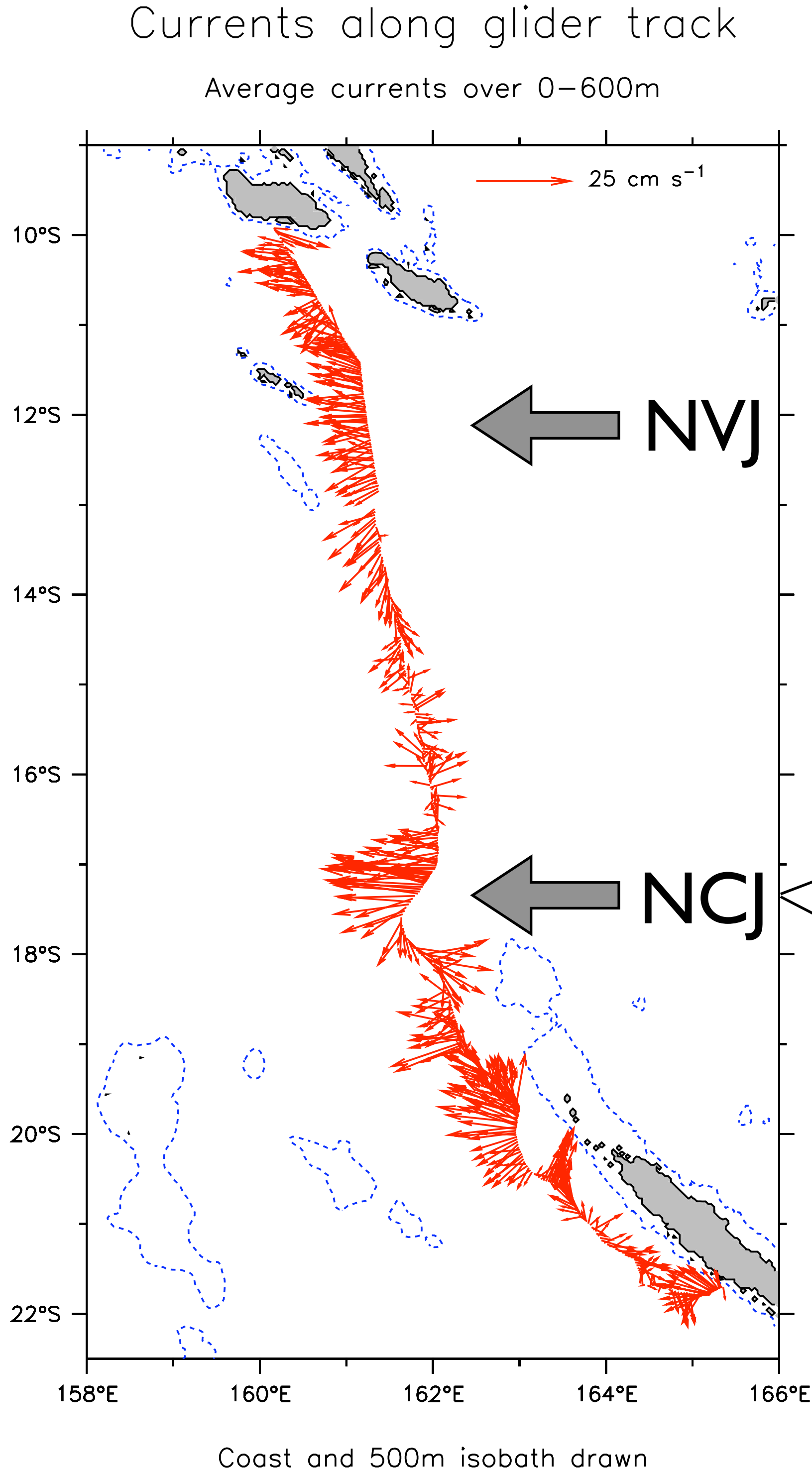
Trajectory of Argo float 5900911

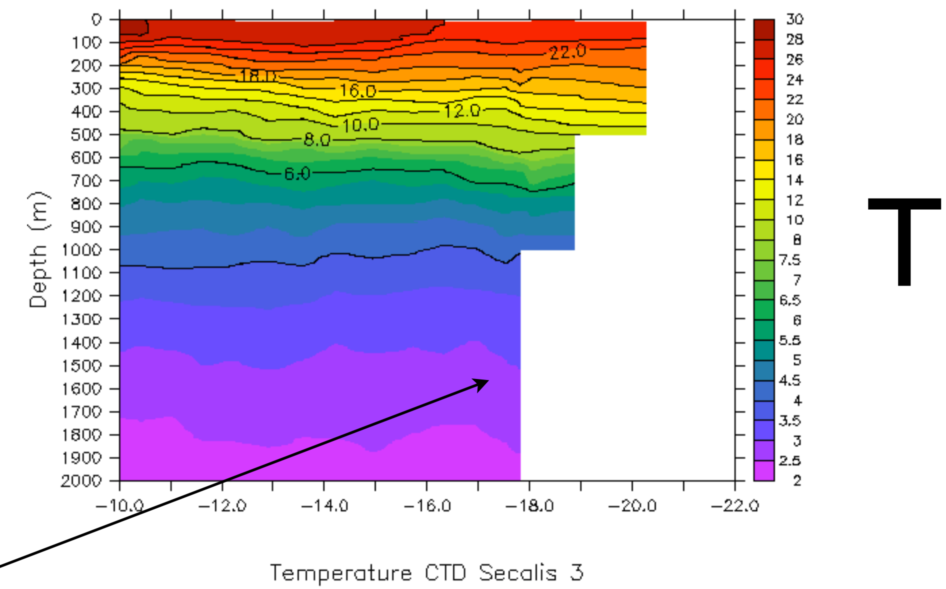
Launched during Frontalis3 on 23 Apr 2005. Through 30 Jun 2006

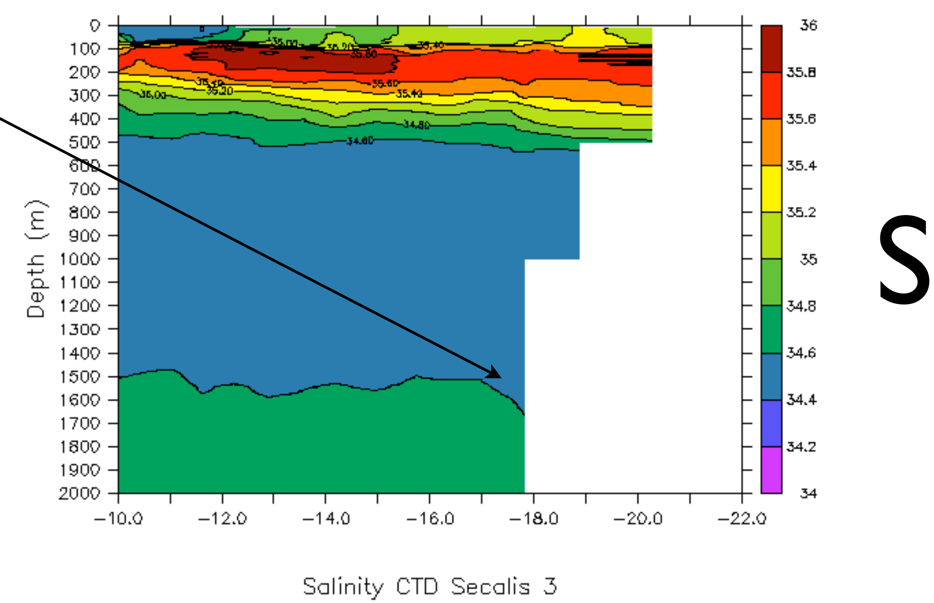


Net motion = 1496 km in 433 days = 4.0 cm s^{-1}

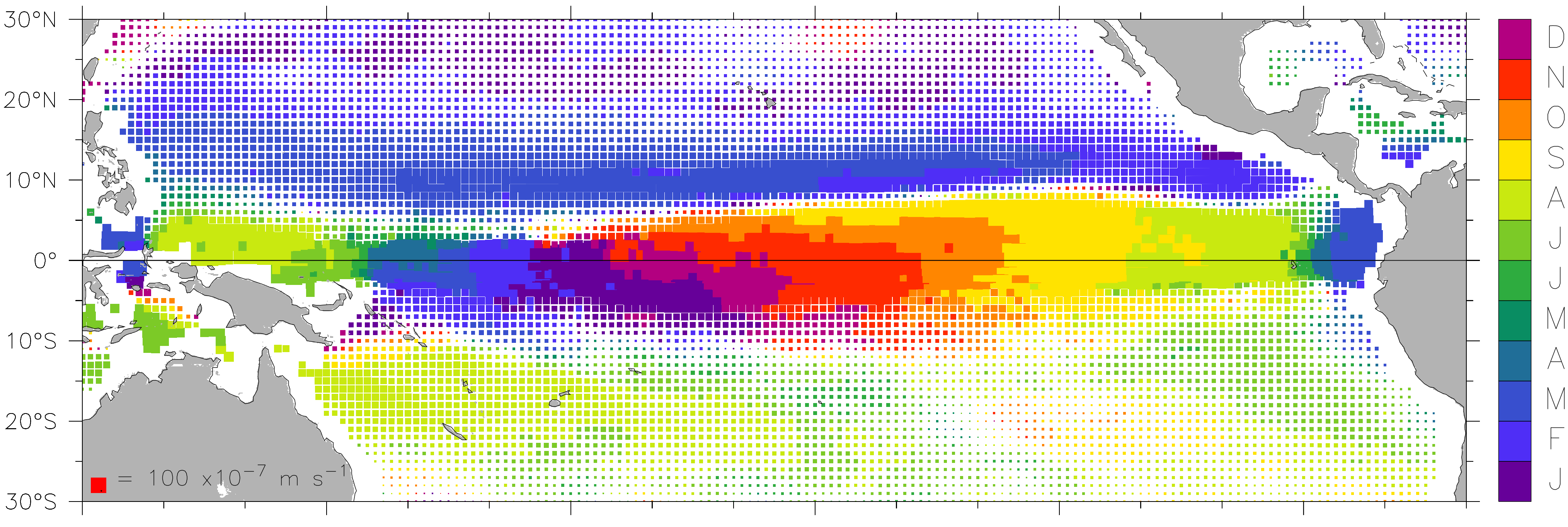
The NCJ extends very deep!
Sections during July-Oct 2005





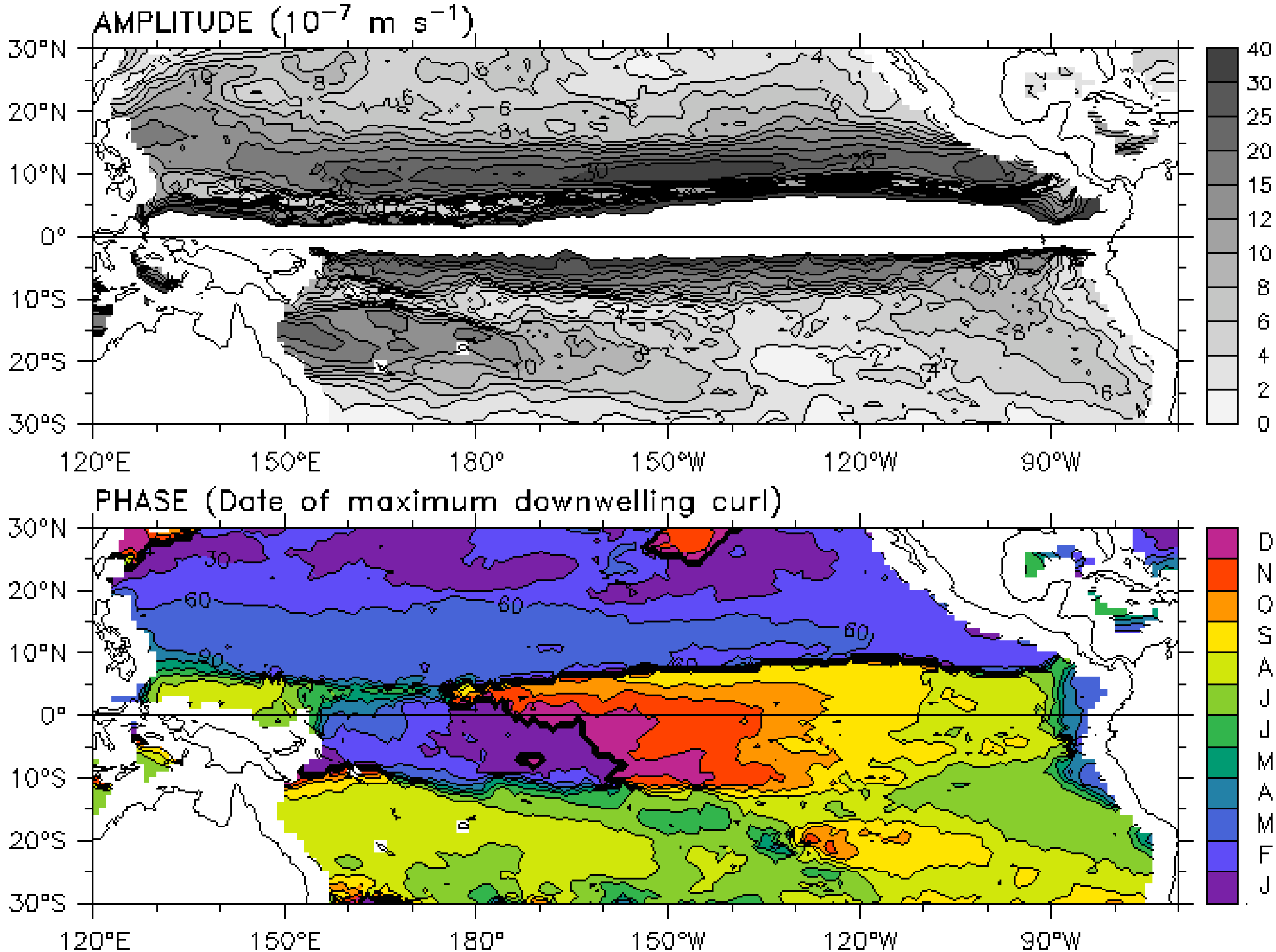


1 cpy harmonic of $Curl(\tau/f\rho)$

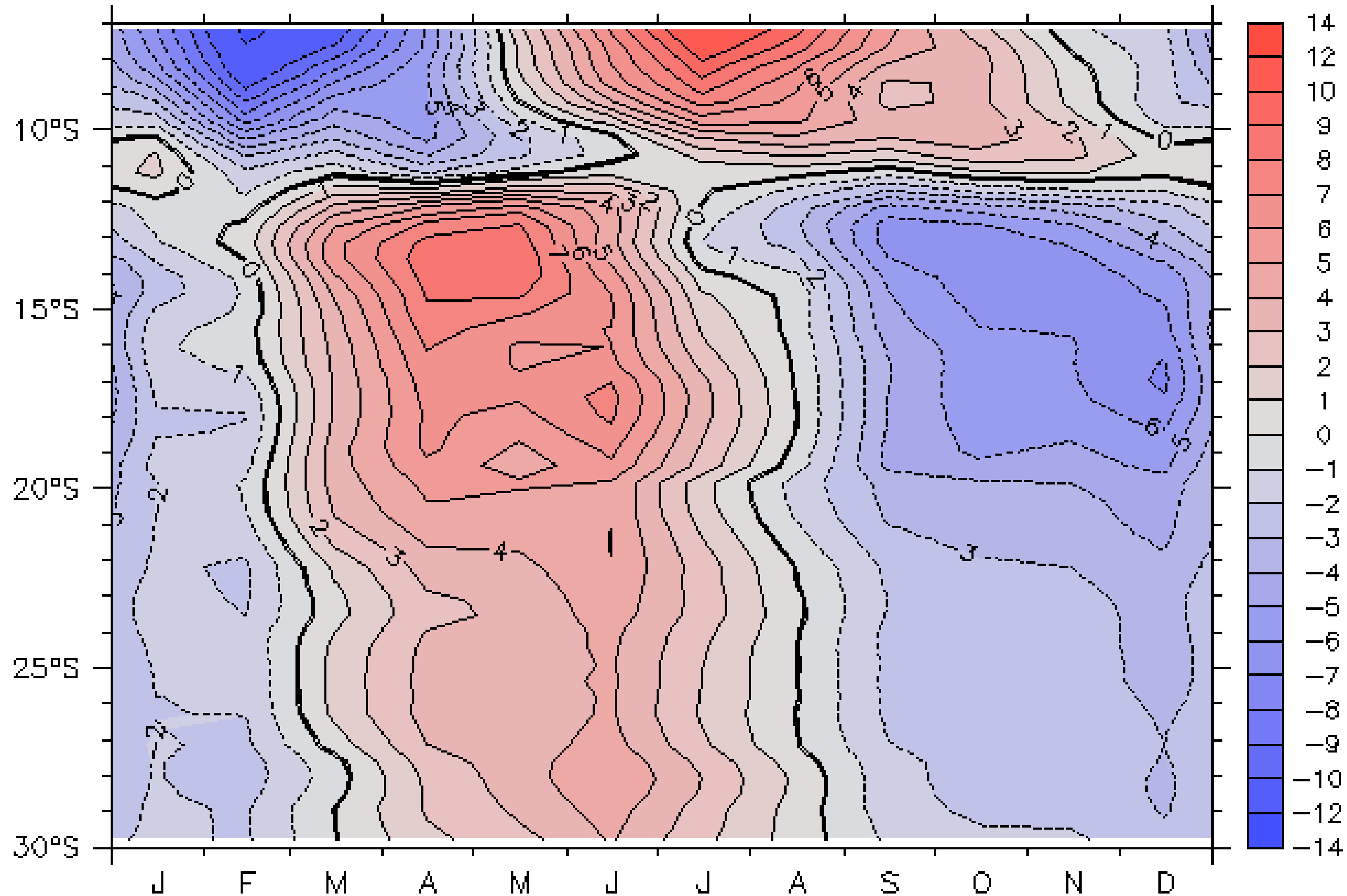


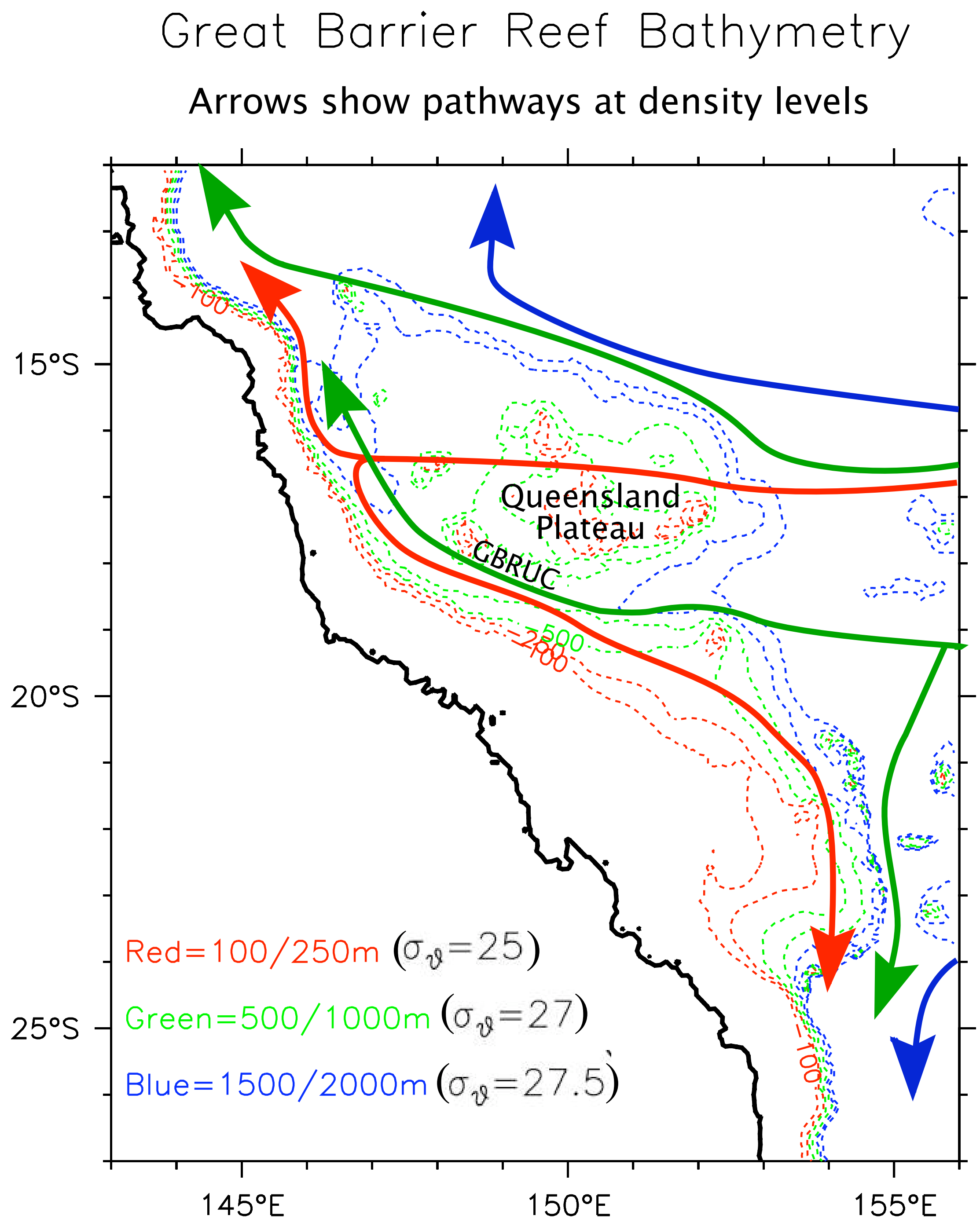
Area of square indicates amplitude (scale at lower left)
Color of square indicates phase (month of maximum downwelling)

1 cpy harmonic of $Curl(\tau/f\rho)$



ORCA seasonal WBC transport anomalies (Sv)

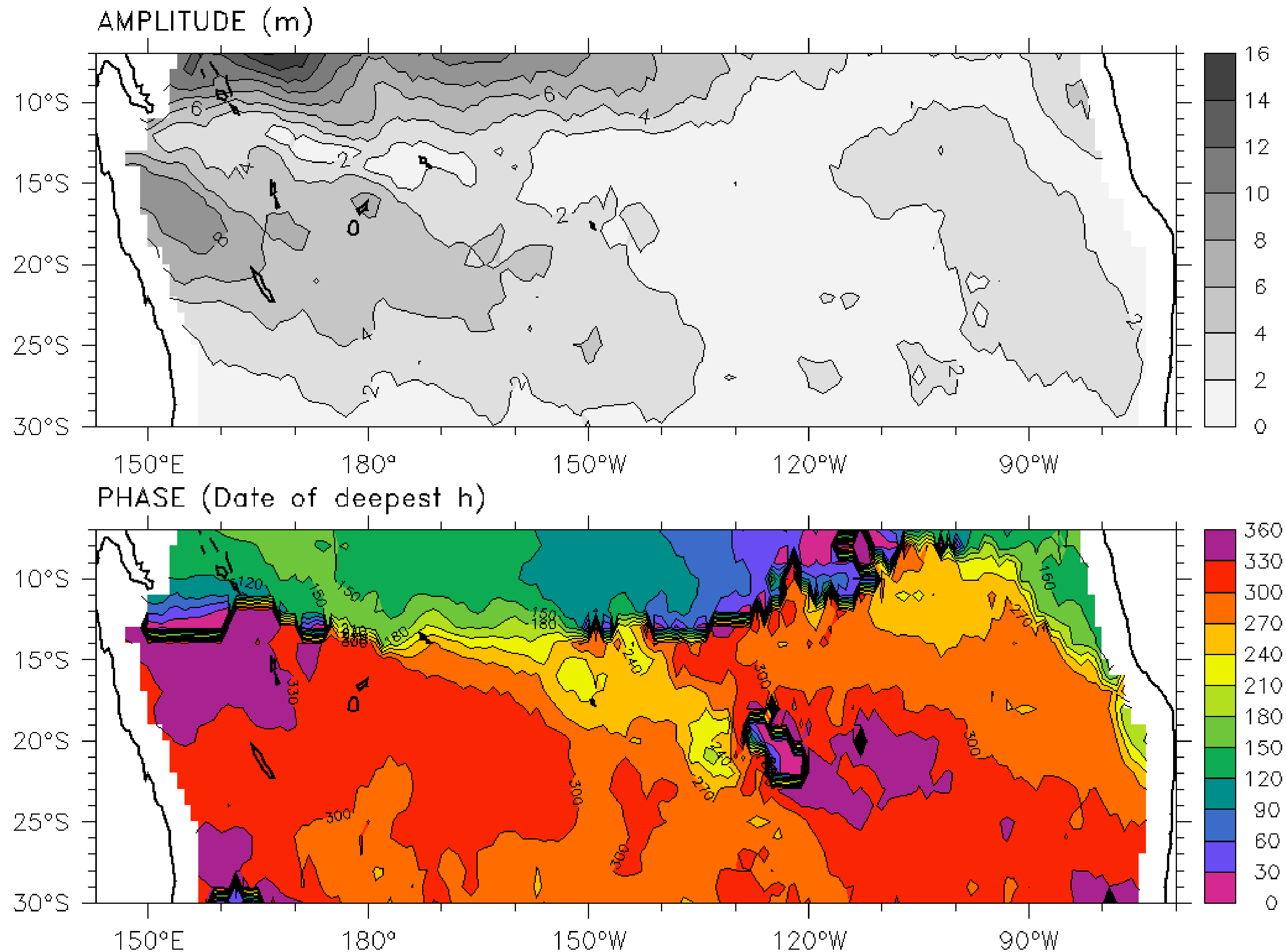




The Queensland Plateau greatly complicates description or diagnosis of the bifurcation!

Rossby solution h implied by Chen/Qiu 04 form of wind forcing

$h = \mathrm{Curl}(\tau/f\rho)/(i\omega - c_r/L)$. ERS winds 1 cpy. $c_k = 3.5\ \mathrm{m\ s^{-1}}$, $L = 9000\mathrm{km}$

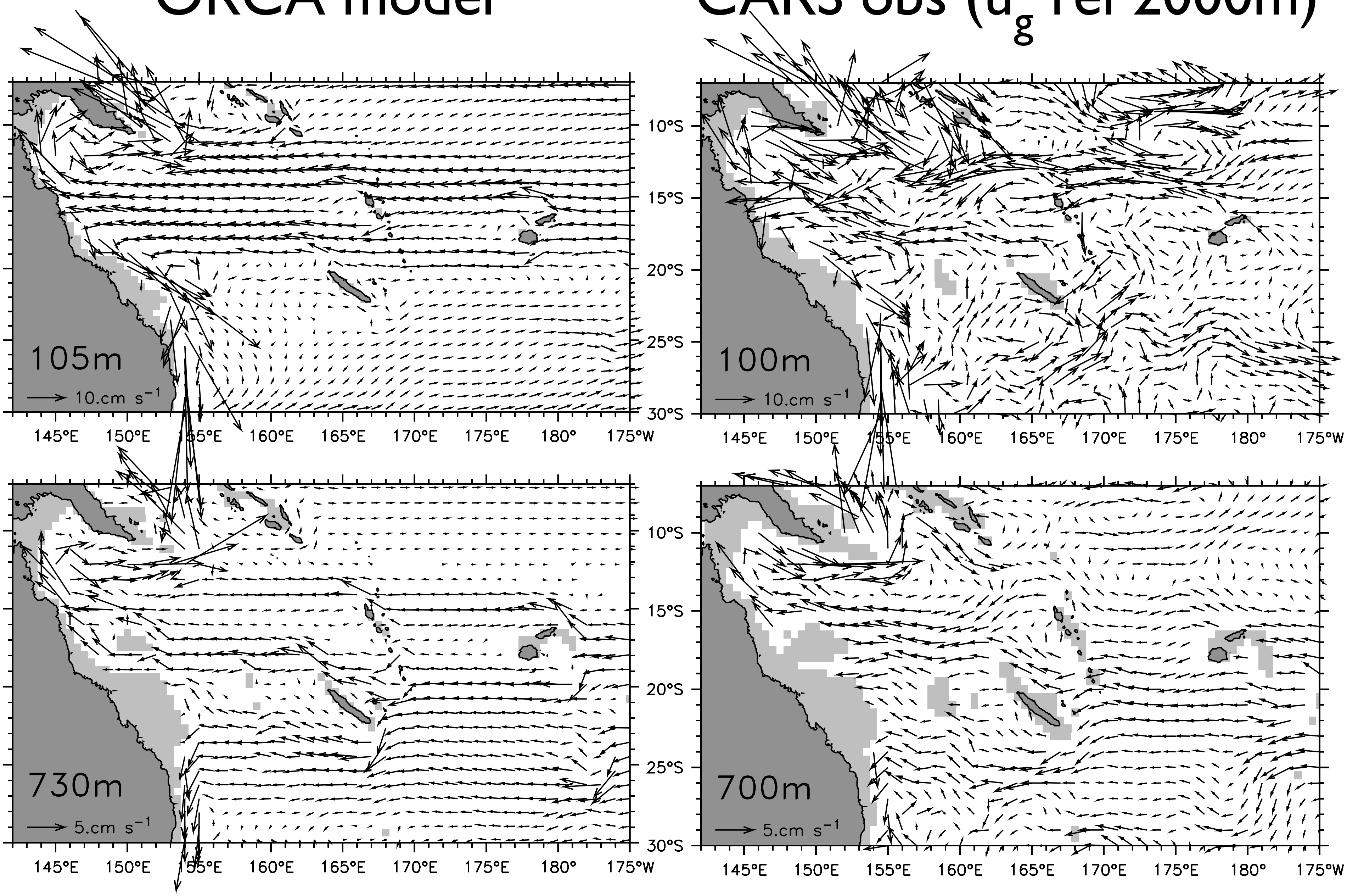


$\alpha = \omega L/c_r$. $1/(i\omega - c_r/L) = -(1+i\alpha)/(\omega(\alpha+1/\alpha))$

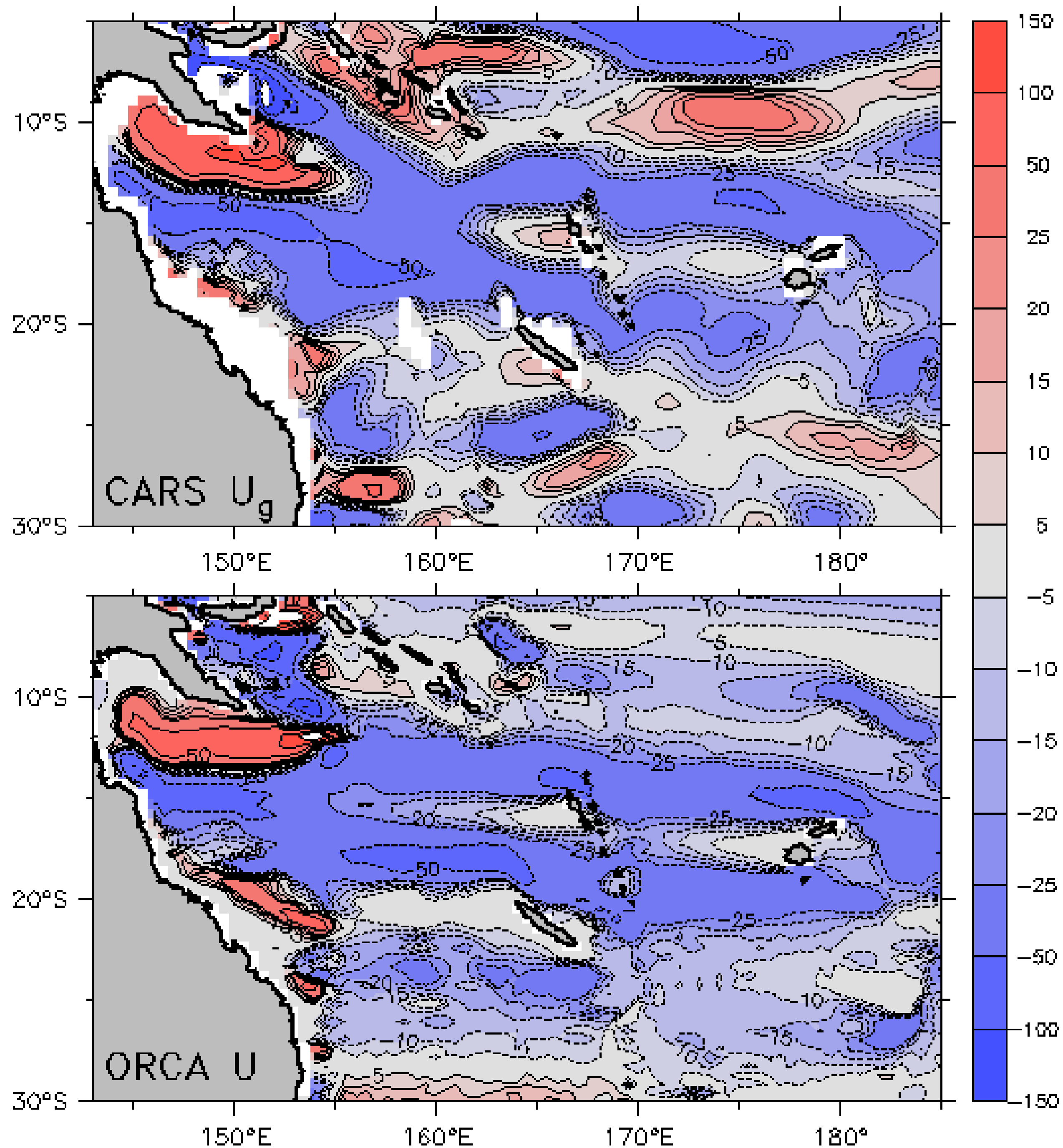
$\mathrm{Lag} = \tan^{-1}(\alpha)$. $\mathrm{Magnitude} = \mathrm{Curl}(\tau/f\rho)[(1+\alpha)^{1/2}/\omega(\alpha+1/\alpha)]$

Compare ORCA and CARS currents

ORCA model | CARS obs (u_g rel 2000m)



ORCA and CARS zonal transport



<u>0-2000m transport</u>

CARS = u_g rel 2000m

ORCA = total u > 2000m

($m^2\ s^{-1}$)

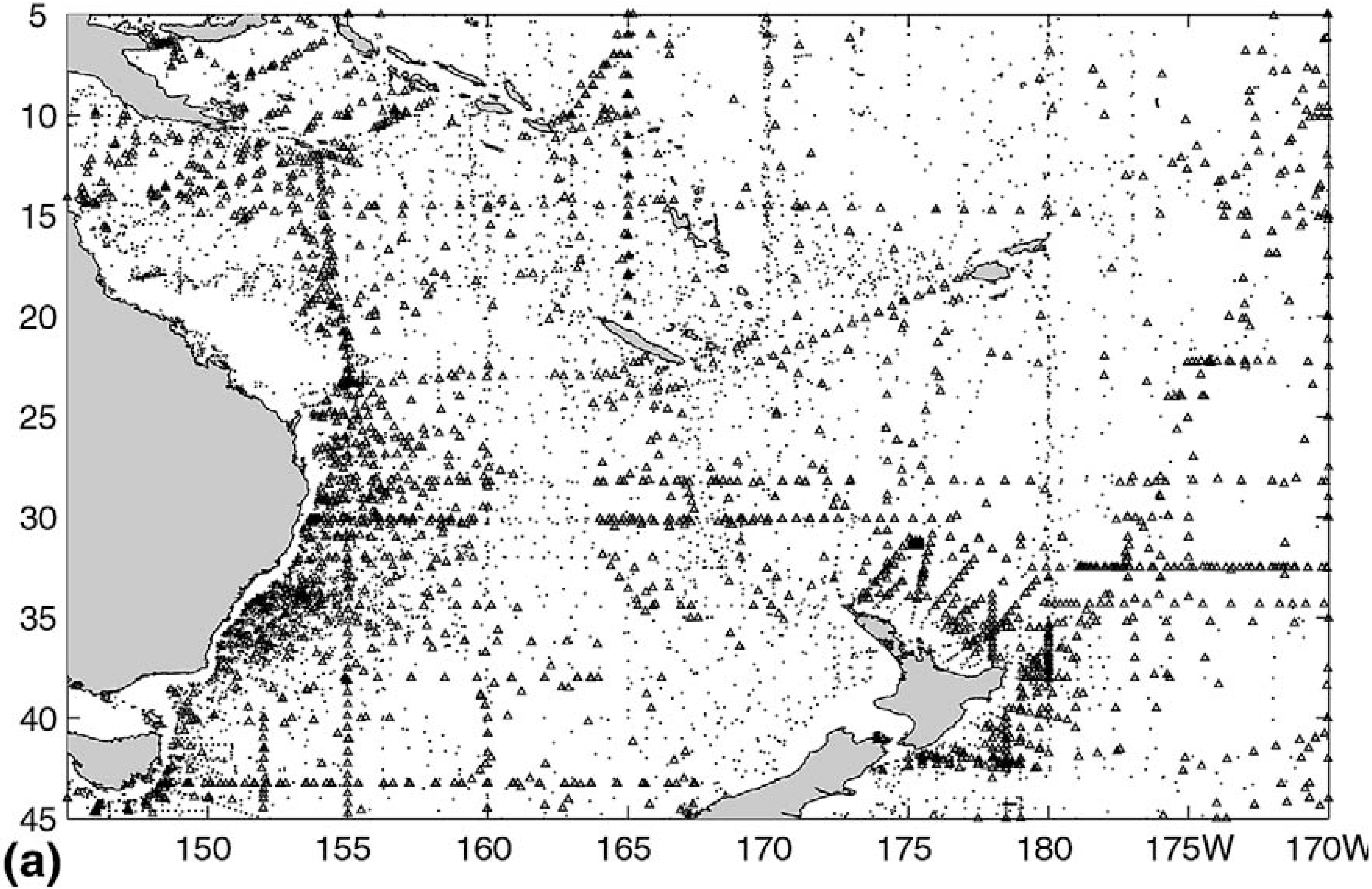
CARS is a new CSIRO CTD compilation for the S Pacific and S Indian Oceans

Ridgway & Dunn (2003)

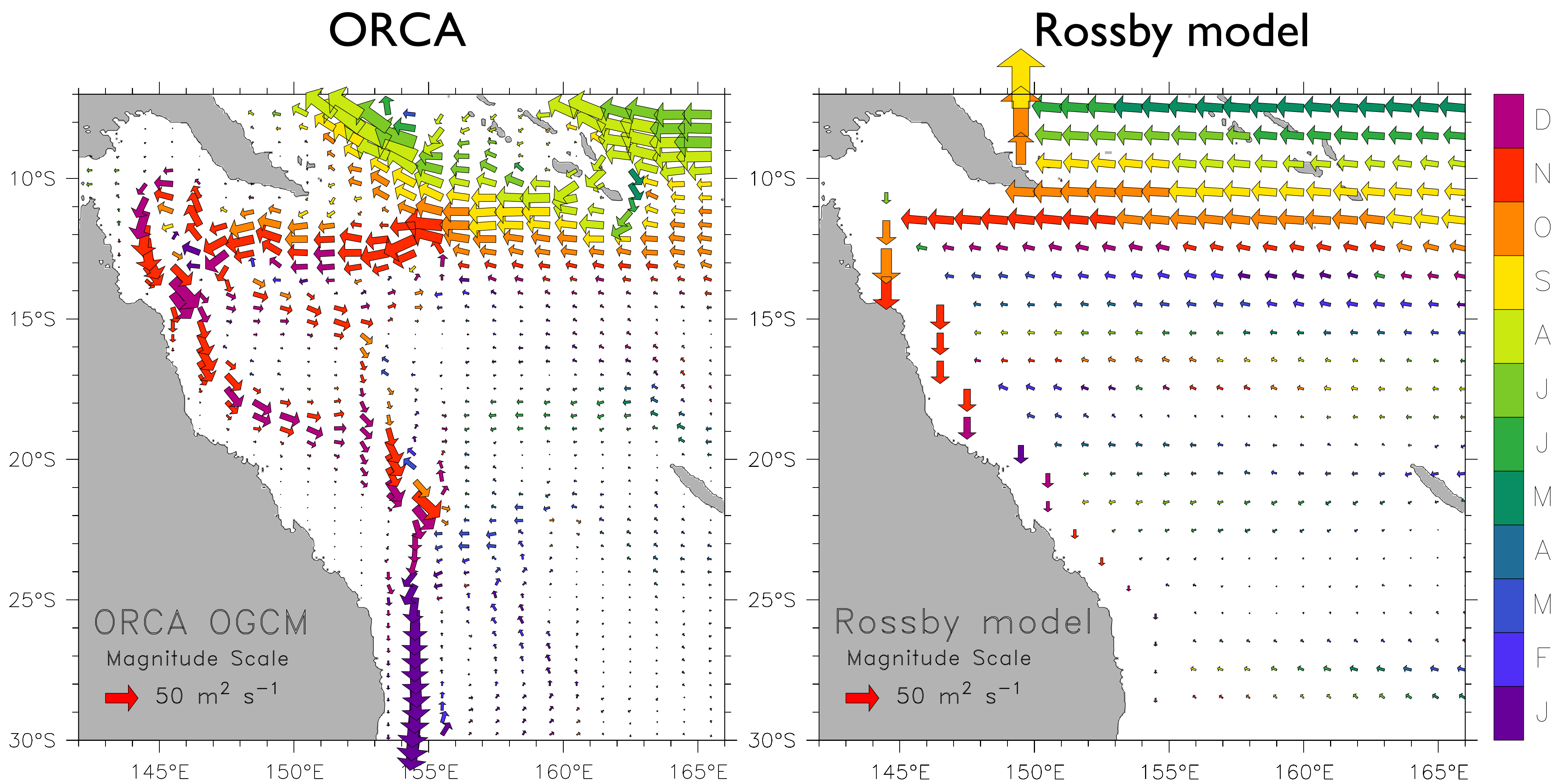
Available T/S profiles (CARS climatology)

K.R. Ridgway, J.R. Dunn / Progress in Oceanography 56 (2003) 189–222

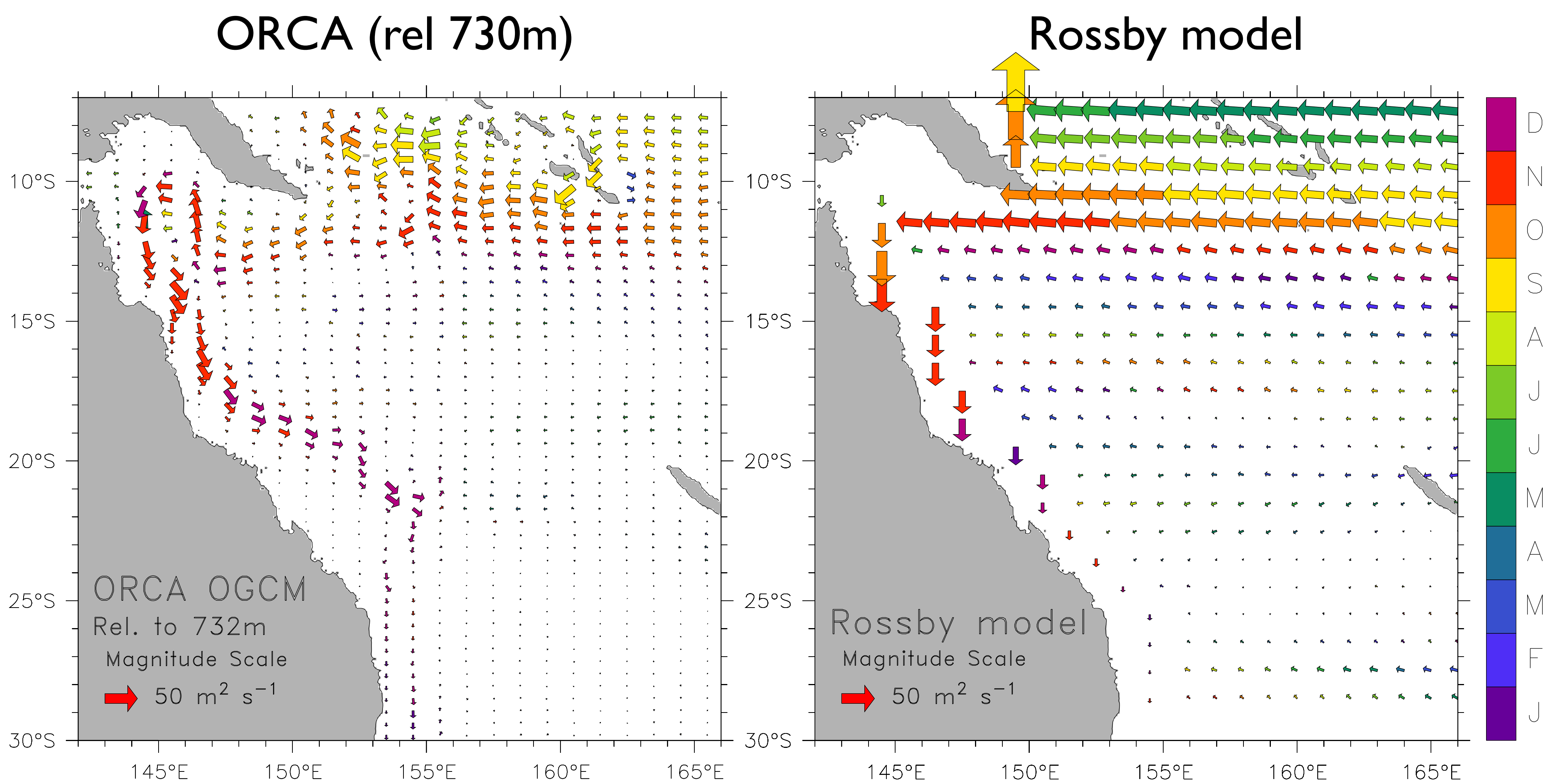
Dots > 500m;   Triangles > 2000m

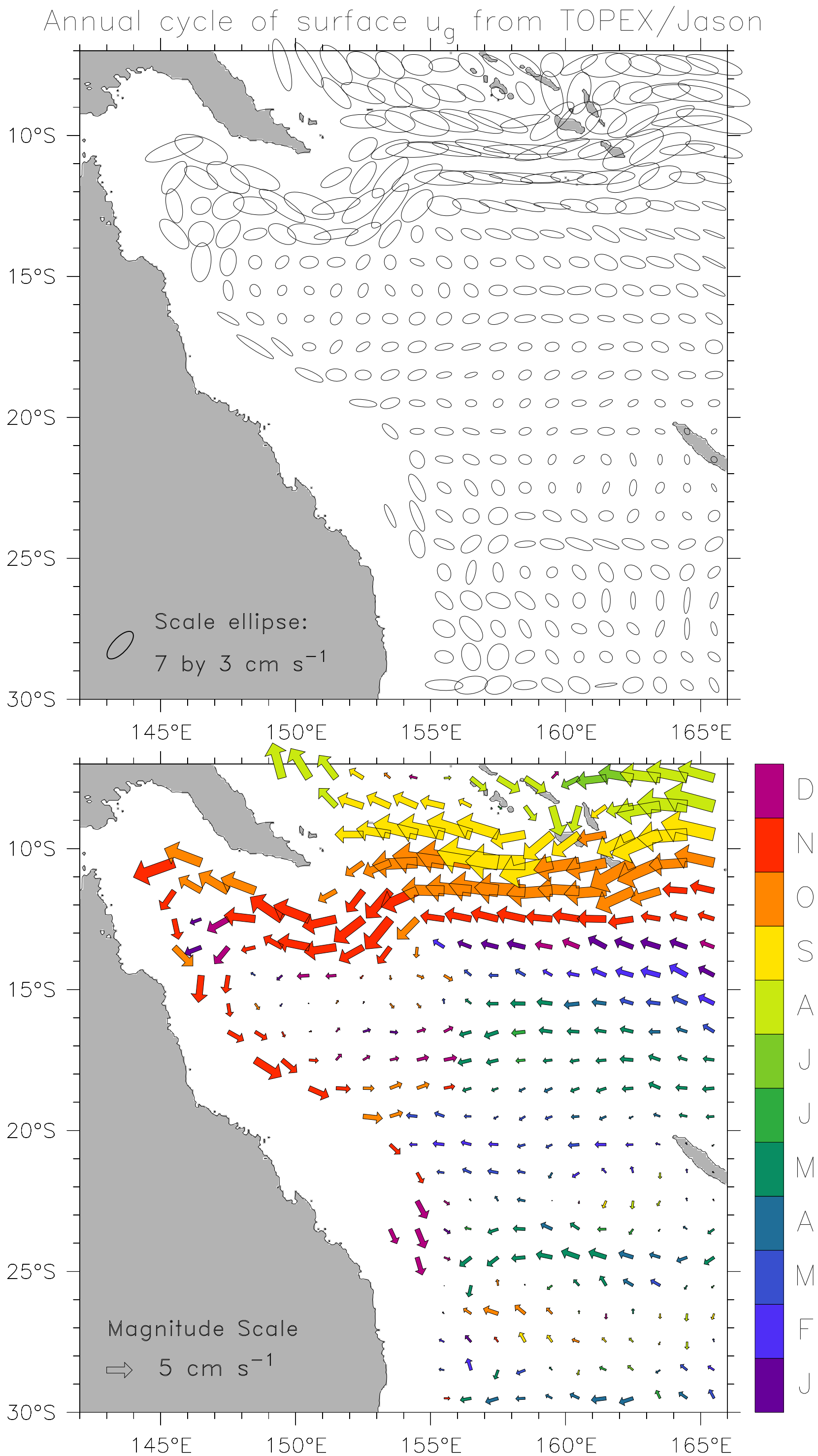


1 cpy harmonic of transport



1 cpy harmonic of transport





Topex/Jason surface velocity: Variance ellipses and harmonic vectors