The annual cycle of circulation in the southwest subtropical Pacific

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• 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

Salinity on isopycnals 24.5 and 27.2 (Levitus)

Subduction

AAIW

σ = 24.5

σ = 27.2
Bathymetry of the SW subtropical Pacific

PNG  Solomon Is.  Vanuatu  Fiji  Australia

Australia

10°S  20°S  30°S  150°E  160°E  170°E  180°
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
CARS (obs)

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

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

ORCA (model)

Ridgway & Dunn (2003)
CARS (obs)

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).

ORCA (model)
Bifurcation at 16°S

Bifurcation at 22°S

Tilted gyre, tilted bifurcation
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
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.

\[ \sigma_u = 28.5 \quad \sigma_v = 29.6 \]

Minor = 4.9

Major = 40.8

(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

Magnitude Scale

$\rightarrow 50 \text{ m}^2 \text{ s}^{-1}$
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

Topex $u_g$

ORCA transport (0-425m)
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

ERS wind climatology
1991–2000

0° 10°S 20°S 30°S

0° 10°S 20°S 30°S

0° 10°S 20°S 30°S

0° 10°S 20°S 30°S

150°E 180° 150°W 120°W

150°E 180° 150°W 120°W

150°E 180° 150°W 120°W

150°E 180° 150°W 120°W

→ 0.1 N m^{-2}
The familiar reduced-gravity long Rossby wave model

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

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

The solution is found at each latitude independently:

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

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:

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

(standing oscillation with uniform phase, decaying eastward)

The Rossby solution is also a standing oscillation:

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

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

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

- 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

Amplitude

Phase

Phase shift (11°S)
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 \( y_S \)
- \( \beta \)-term. Mismatch of \( u_{RW} \)
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

![Graph showing Amplitude and Phase](image)

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) $\beta$-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 $11^\circ$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.
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


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 $\text{Curl}(\tau/\rho)$

Area of square indicates amplitude (scale at lower left)
Color of square indicates phase (month of maximum downwelling)
1 cpy harmonic of $\text{Curl}(\tau/\rho)$
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

\[
h = \frac{\text{Curl}(\tau/\rho)}{(i \omega - c_r/L)}. \text{ERS winds 1 cpy. } c_r = 3.5 \text{ m s}^{-1}, L = 9000 \text{km}
\]

**AMPLITUDE (m)**

**PHASE (Date of deepest \( h \))**

\[
\alpha = \frac{\omega L}{c_r}, \quad \frac{1}{(i \omega - c_r/L)} = \frac{1}{-i} = -\frac{1}{\omega(\alpha + 1/\alpha)}
\]

\[\text{Lag} = \tan^{-1}(\alpha). \quad \text{Magnitude} = \text{Curl}(\tau/\rho)\left((1+\alpha)^{1/2}/\omega(\alpha+1/\alpha)\right)\]
Compare ORCA and CARS currents

ORCA model

CARS obs (u\textsubscript{g} \text{rel 2000m})

105m

100m

730m

700m
ORCA and CARS zonal transport

0-2000m transport
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)
Fig. 2. The distribution of (a) the (T, S) casts as a function of position, small dots represent casts of 500 m depth or greater and triangles indicate those with 2000 m or greater, (b) the (T, S) casts as a function of year at the two depth ranges.

Methods

Our interpolation tool is locally weighted least squares (Cleveland & Devlin, 1988). The data are smoothed in space by projecting onto spatial quadratic functions, simultaneously fitted by annual and semi-annual harmonic components and the influence of both variable bathymetry and coastal barriers is included. The major reason for choosing this interpolation scheme is that it is both computationally inexpensive and very easy to make allowance for the spatial and temporal complexity of the data. For example, it is capable of fitting seasonal components in a single step with the mean, thus minimizing any temporal bias in the available T/S profiles (CARS climatology).

Available T/S profiles (CARS climatology)
1 cpy harmonic of transport

ORCA

Rossby model

ORCA OGCM
Magnitude Scale
$50 \text{ m}^2 \text{ s}^{-1}$

Rossby model
Magnitude Scale
$50 \text{ m}^2 \text{ s}^{-1}$
1 cpy harmonic of transport

ORCA (rel 730m)

Rossby model

ORCA OGCM
Rel. to 732m
Magnitude Scale
50 m² s⁻¹

Rossby model
Magnitude Scale
50 m² s⁻¹
Topex/Jason surface velocity: Variance ellipses and harmonic vectors