Tropical Pacific Ocean in a Warming Climate

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with

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Outline

• Background
• Pacific subtropical cells (STCs)
• Ventilation of the Pacific equatorial thermocline
• Wind-driven tropical Pacific sea level change
• Conclusions
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Tropical Pacific Climate System

- STCs regulate the tropical Pacific upper ocean heat content.
- STCs regulate the watermass properties of the equatorial thermocline.

(Chang et al. 2006)
Subtropical Cells (STCs)

- STCs regulate the tropical Pacific upper ocean heat content.
- STCs regulate the watermass properties of the equatorial thermocline.
Observed STC Decadal Trend

(Zhang & McPhaden 2006)
Walker Circulation Weakens Under Global Warming

- Zonal SLP gradient reduced.
- Equatorial easterly trade winds weaken.
Oceanic Response

- Tropical thermocline shoals.
- Tropical thermocline flattens.
- Surface zonal currents weaken.
- STCs?
Recent Sea Level Rise (1993-2009)

- Fastest rise in the western tropical Pacific.
- La Nina-like spatial pattern.
- Already made significant social impact.

The Carteret Is.
Objectives

- How would the STCs change?
  - Meridional overturning
  - Surface divergence
  - Pycnocline convergence
  - ITF export

- How would the equatorial thermocline ventilation change?
  - Source region distribution
  - Transit time distribution

- How would the regional sea level change?
  - Winds
  - Stratification
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IPCC AR4/CMIP3 Models

<table>
<thead>
<tr>
<th>ID</th>
<th>Model name</th>
<th>Country</th>
<th>Ocean resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CGCM3.1 (T47)</td>
<td>Canada</td>
<td>1.9° × 1.9° L29</td>
</tr>
<tr>
<td>2</td>
<td>CGCM3.1 (T63)</td>
<td>Canada</td>
<td>1.4° × 0.9° L29</td>
</tr>
<tr>
<td>3</td>
<td>CSIRO-Mk3.0</td>
<td>Australia</td>
<td>1.9° × 0.8° L31</td>
</tr>
<tr>
<td>4</td>
<td>CSIRO-Mk3.5</td>
<td>Australia</td>
<td>1.9° × 0.8° L31</td>
</tr>
<tr>
<td>5</td>
<td>GFDL-CM2.0</td>
<td>U.S.</td>
<td>1° × 1°(0.3°) L50</td>
</tr>
<tr>
<td>6</td>
<td>GFDL-CM2.1</td>
<td>U.S.</td>
<td>1° × 1°(0.3°) L50</td>
</tr>
<tr>
<td>7</td>
<td>MRI-CGCM2.3.2</td>
<td>Japan</td>
<td>2.5° × 2°(0.5°) L23</td>
</tr>
</tbody>
</table>

- Model selecting criterion: ocean velocity archived on the original model grid.
- In other models, interpolation breaks mass conservation.
Meridional Overturning Streamfunction

- STCs tend to weaken in the NH
- STCs tend to strengthen in the SH
- STC trends tend to be stronger in the NH.
Upper Ocean Meridional Velocity

Ensemble–mean meridional velocity across 9°N

Ensemble–mean meridional velocity across 9°S
Surface Layer Transport (poleward)

Surface layer transport trends

Surface layer transport divergence trend

\[ r = -0.82 \]
Surface Layer Transport vs Ekman Transport

Multimodel ensemble-mean zonal surface wind stress (dPa)
Interior Pycnocline Transport (equatorward)
Interior vs Boundary Pycnocline Transport Convergence

![Graph showing pycnocline transport convergence trends and correlation between interior and boundary pycnocline transport convergence.](image-url)
Interior Pycnocline Transport Weakening Related to Pycnocline Flattening
ITF and Cross-pycnocline-base Transports

![Graph showing ITF and Cross-pycnocline-base transport trend.](image)
### Tropical Pacific Upper Ocean Mass Balance

<table>
<thead>
<tr>
<th></th>
<th>SFC</th>
<th>ITF</th>
<th>PYC-I</th>
<th>PYC-B</th>
<th>CPB</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001-2020 mean (Sv)</td>
<td>43.5</td>
<td>9.2</td>
<td>22.1</td>
<td>24.2</td>
<td>6.4</td>
</tr>
<tr>
<td>2001-2100 change (Sv)</td>
<td>-1.4±0.7</td>
<td>-1.5±0.2</td>
<td>-3.4±1.0</td>
<td>0.4±0.8</td>
<td>-0.1±0.9</td>
</tr>
</tbody>
</table>
Summary I

- STCs tend to show contrasting trends between the NH and SH.
- Robust weakening of ~3 Sv of the pycnocline transport convergence, mainly through interior pathways.
- ITF transport significantly weakens (~1.5 Sv), while the upward transport from below the pycnocline base changes little.
Outline

• Background
• Pacific subtropical cells (STCs)
• Ventilation of the Pacific equatorial thermocline
  • Source regions
  • Transit times
• Wind-driven tropical Pacific sea level change
• Conclusions
Water-mass Composition

- How to determine source water fraction $a_i$?
- How to characterize transit time scale?

\[ c = \sum_{i=1}^{N} a_i c_i \]
\[ \sum_{i=1}^{N} a_i = 1 \]
Transit Time Distribution (TTD) Theory

A-D tracer equation:

\[
\frac{\partial c}{\partial t} + u \cdot \nabla c - \nabla \cdot (\kappa \nabla c) = 0
\]

\[c = c_s(x, t) \text{ on } \Omega\]
Transit Time Distribution (TTD) Theory

A-D tracer equation:

\[ \frac{\partial c}{\partial t} + \mathbf{u} \cdot \nabla c - \nabla \cdot (\kappa \nabla c) = 0 \]

\[ c = c_s(x, t) \text{ on } \Omega \]

Solution:

\[ c(x, t) = \int_{-\infty}^{t} dt' \int_{\Omega} d^2x' c_s(x', t') G'(x, t; x', t') \]

\( G' \) is a (boundary) Green's function to the tracer eqn.
Transit Time Distribution (TTD)

Theory

A-D tracer equation:

\[
\frac{\partial c}{\partial t} + \mathbf{u} \cdot \nabla c - \nabla \cdot (\kappa \nabla c) = 0
\]

\[c = c_s(x, t) \text{ on } \Omega\]

Solution:

\[
c(x, t) = \int_{-\infty}^{t} dt' \int_{\Omega} d^2 x' c_s(x', t') G'(x, t; x', t')
\]

\[
c(x) = \int_{0}^{\infty} d\xi \int_{\Omega} d^2 x' c_s(x') G'(x, \xi; x')
\]

\[
= \sum_{i=1}^{N} A_i \int_{0}^{\infty} d\xi G'_i(x, \xi) c_i
\]

- \(G'\) is a (boundary) Green's function to the tracer eqn.

- \(G'\) is the transit time distribution over surface source location and transit time.
Transit Time Distribution (TTD) Theory

$G'$ satisfies:

$$\frac{\partial G'}{\partial t} + \mathbf{u} \cdot \nabla G' - \nabla \cdot (\kappa \nabla G') = 0$$

$$G' = \delta^2(\mathbf{x} - \mathbf{x}') \delta(t - t') \quad \text{on} \quad \Omega$$

- TTD is the response to an impulse BC.
- TTD is a complete diagnostics of surface-to-interior transport.
- $G'$ is a (boundary) Green's function to the tracer eqn.
- $G'$ is the transit time distribution over surface source location and transit time.
TTD in Forward and Adjoint Flows

- Interior response to a surface impulse in forward flow == surface flux response to an interior impulse source in adjoint flow.

- TTDs of multiple destinations for a single source: forward integration.

- TTDs of a single destination for multiple sources: adjoint integration.

(Holzer & Hall 2000)
OGCM Experiments

<table>
<thead>
<tr>
<th>Model specifications</th>
<th>CTRL</th>
<th>2 × CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain</td>
<td>near-global (80°E – 80°N)</td>
<td>same</td>
</tr>
<tr>
<td>Resolution</td>
<td>1° × 1°(0.3°) L46</td>
<td>same</td>
</tr>
<tr>
<td>Isopycnal mixing</td>
<td>Gent and McWilliams (1990)</td>
<td>same</td>
</tr>
<tr>
<td>Vertical mixing</td>
<td>KPP (Large et al. 1994)</td>
<td>same</td>
</tr>
<tr>
<td>Initialization</td>
<td>Levitus 1998 (at rest)</td>
<td>same</td>
</tr>
<tr>
<td>Mechanical forcing</td>
<td>NCEP semi-daily wind stresses</td>
<td>NCEP + perturbation</td>
</tr>
<tr>
<td>Buoyancy forcing</td>
<td>NCEP daily net heat/freshwater fluxes</td>
<td>NCEP + perturbation</td>
</tr>
<tr>
<td>SST/SSS relaxation</td>
<td>Levitus</td>
<td>Levitus + perturbation</td>
</tr>
<tr>
<td>Integration length</td>
<td>80 years</td>
<td>same</td>
</tr>
</tbody>
</table>

- MITgcm, climatological runs.
- Forcing perturbations taken from CMIP3 ensemble-mean differences between the pre-industrial and CO2 doubling simulations.
Passive Tracer (TTD) Runs

- Use the mean circulation and mixing coefficients for the last year of spin-up.
- Use transport matrix method (TMM; Khatiwala et al. 2005) for efficient tracer integration.
- Initialize tracer in the EUC (u>15 cm/s) between 170°-120°W.
- Integrate the adjoint tracer equation for 200 years.
- Results: TTDs of the equatorial thermocline water for all surface grid points.
Source Water Distribution (CTRL)

<table>
<thead>
<tr>
<th>Region</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQ (10°S-10°N)</td>
<td>21.4%</td>
</tr>
<tr>
<td>NH (10°N-80°N)</td>
<td>25.9%</td>
</tr>
<tr>
<td>SH (10°S-80°S)</td>
<td>43.6%</td>
</tr>
<tr>
<td>GLOBAL (80°S-80°N)</td>
<td>90.9%</td>
</tr>
</tbody>
</table>
Source Water Distribution (CTRL vs 2xCO2)

<table>
<thead>
<tr>
<th></th>
<th>EQ (10°S-10°N)</th>
<th>NH (10°N-80°N)</th>
<th>SH (10°S-80°S)</th>
<th>GLOBAL (80°S-80°N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td>21.4%</td>
<td>25.9%</td>
<td>43.6%</td>
<td>90.9%</td>
</tr>
<tr>
<td>2 x CO₂</td>
<td>21.5%</td>
<td>25.8%</td>
<td>45.7%</td>
<td>93.0%</td>
</tr>
</tbody>
</table>
Regional Transit Time Distributions

- No significant change except in the southern South Pacific (region e).
Attributing Equatorial Thermocline Warming

- EUC water

\[ \Delta T = 1.75^\circ C \]

- Source waters

\[ \Delta T = \sum_{i=1}^{N} a_i^{(2)} T_i^{(2)} - \sum_{i=1}^{N} a_i^{(1)} T_i^{(1)} \]

\[ \left. \begin{array}{l}
\left. \begin{array}{l}
\sum_{i=1}^{N} a_i^{(1)} \Delta T_i \\
\Delta a_i T_i^{(1)} \\
\Delta a_i \Delta T_i \\
\end{array} \right) \\
1.49^\circ C \\
0.24^\circ C \\
-0.03^\circ C \\
\end{array} \right. \]

\[ \sum_{i=1}^{N} \Delta a_i \Delta T_i = 1.71^\circ C \]
Source Water Distribution
(upper vs lower thermocline)

<table>
<thead>
<tr>
<th>Region</th>
<th>EQ (10°S-10°N)</th>
<th>NH (10°N-80°N)</th>
<th>SH (10°S-80°S)</th>
<th>GLOBAL (80°S-80°N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>59.7%</td>
<td>16.2%</td>
<td>19.7%</td>
<td>95.6%</td>
</tr>
<tr>
<td>Lower</td>
<td>3.9%</td>
<td>28.7%</td>
<td>49.8%</td>
<td>82.4%</td>
</tr>
</tbody>
</table>
Summary II

- The source regions of the equatorial thermocline water are broad and comprise several major sources.
- The large-scale distribution of source waters does not change in a warmer climate.
- The TTDs of the equatorial thermocline water show little change in a warmer climate, except in the southern South Pacific.
- Warming of the equatorial thermocline water is mainly caused by the source water warming.
- The upper thermocline ventilation is mainly associated with local detrainment, the lower thermocline ventilation the extratropical-tropical connections.
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Linear Wind-Driven Model (INC*)

- A multi-mode baroclinic equatorial wave model.
- Near-global configuration (65°S-65°N) with realistic coastlines.
- Spatial resolution is 2° zonally and 0.5° meridionally.
- Vertical mode decomposition allows spatially and temporally varying stratification ($N^2$ profiles).

Recent Sea Level Trend (1993-2008)

- 1993-2008 observed sea level trend well reproduced by the linear, wind-driven model.
- The effect of surface buoyancy forcing is secondary.
Projected Future Sea Level Trend (2001-2100)

- (a) IPCC AR4 multimodel ensemble
- (b) wind-only (r=0.29)
- (c) wind and spatially-varying stratification (r=0.38)
- (d) wind and spatiotemporally-varying stratification (r=0.50)
Summary III

- Recent sea level trend in the tropical Pacific can be well reproduced by a linear, wind-driven model that embodies only equatorial wave dynamics.

- Projected sea level trend in the tropical Pacific can also be reproduced by the linear model, particularly when both wind and stratification changes are taken into account.
Conclusions

- STC tends to weaken under global warming, in pycnocline transport convergence and ITF outflow.
- Source water and transit time distributions of the equatorial thermocline see no significant change under global warming.
- Both the observed and projected tropical Pacific sea level changes are likely wind-driven, and the effect of future stratification change also plays a role.
Thank You!