# 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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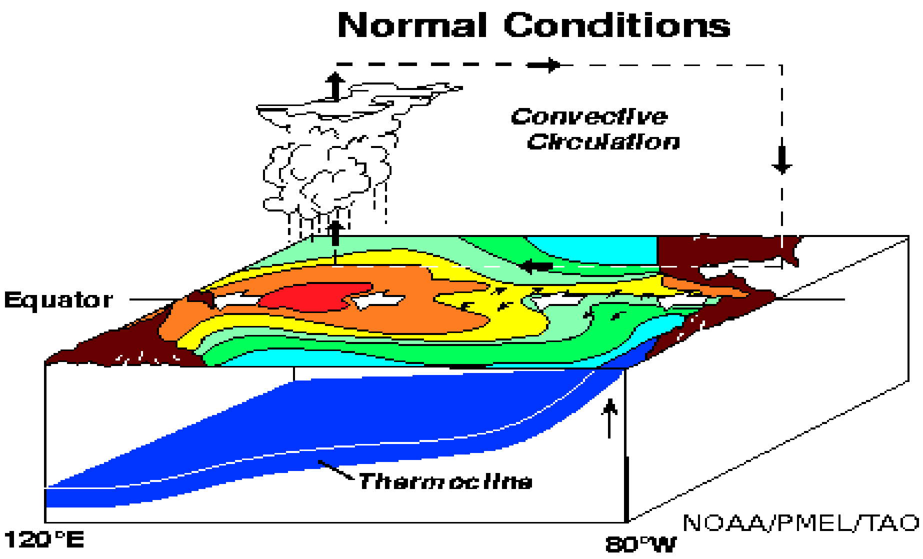
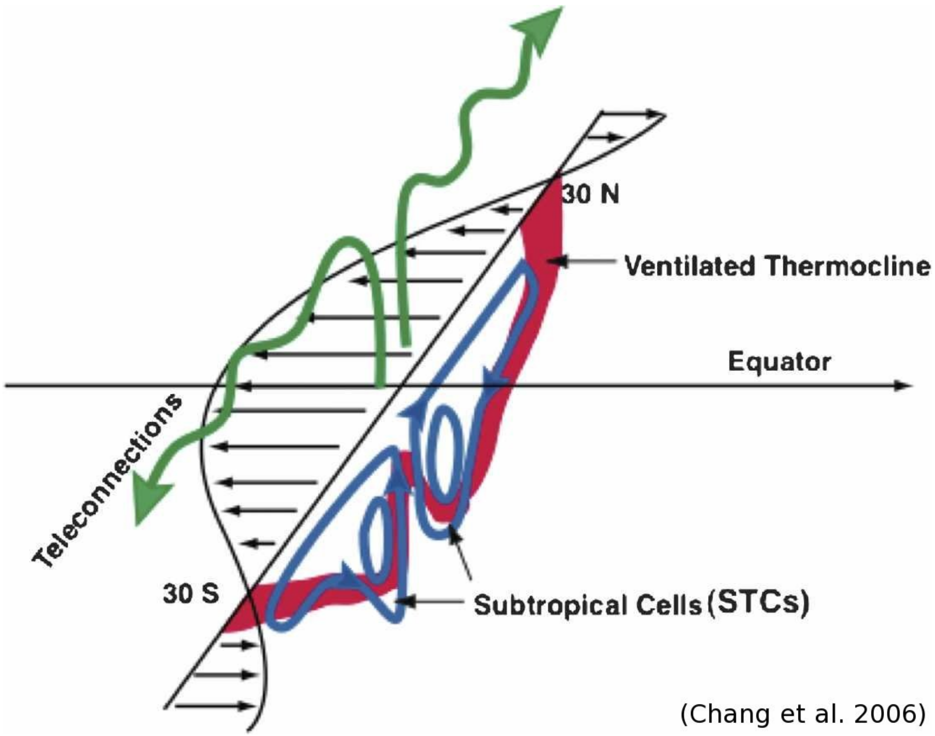
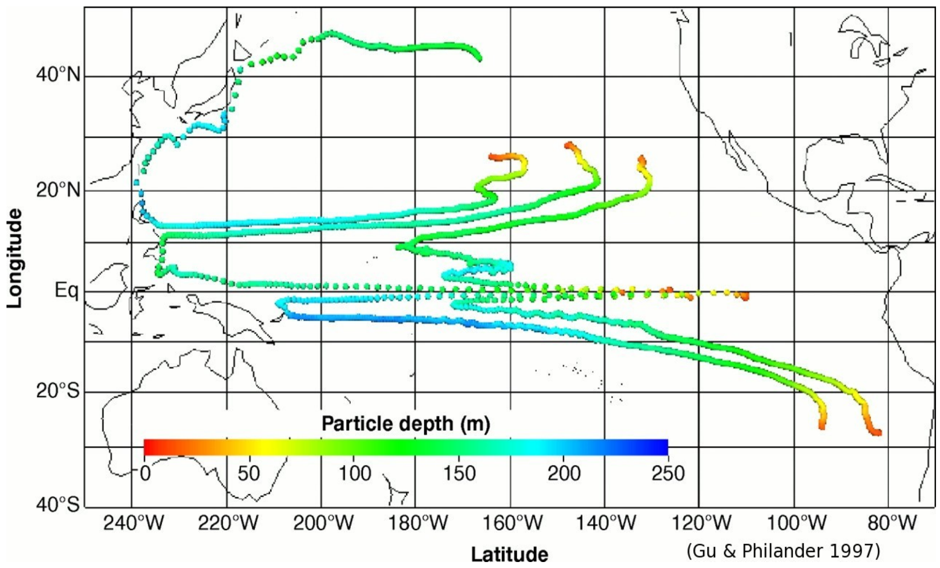
# Tropical Pacific Climate System

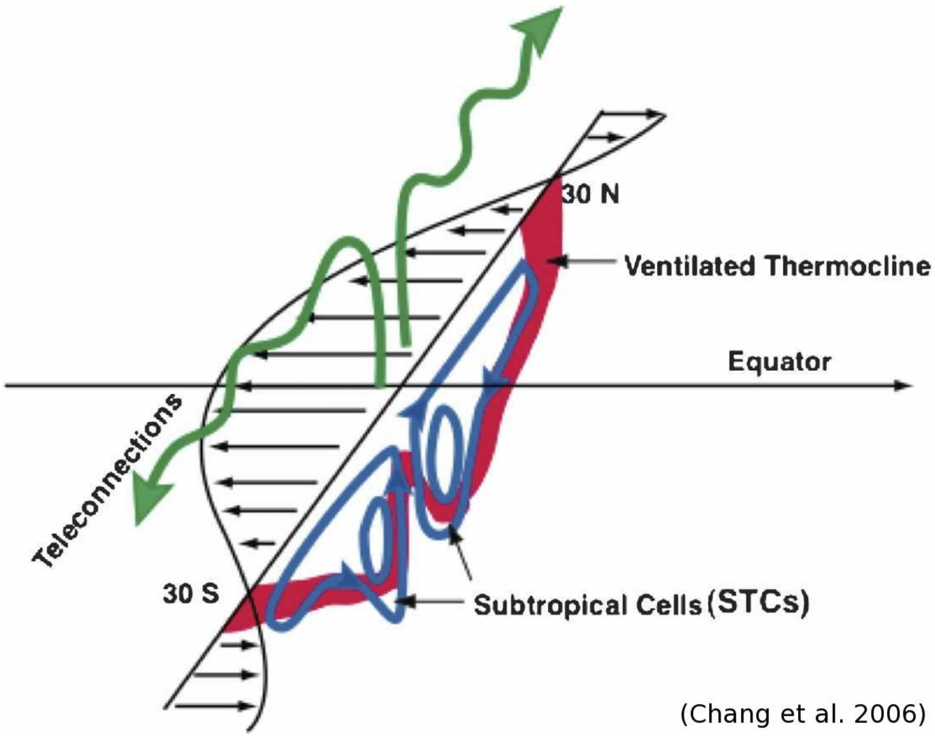



(Chang et al. 2006)

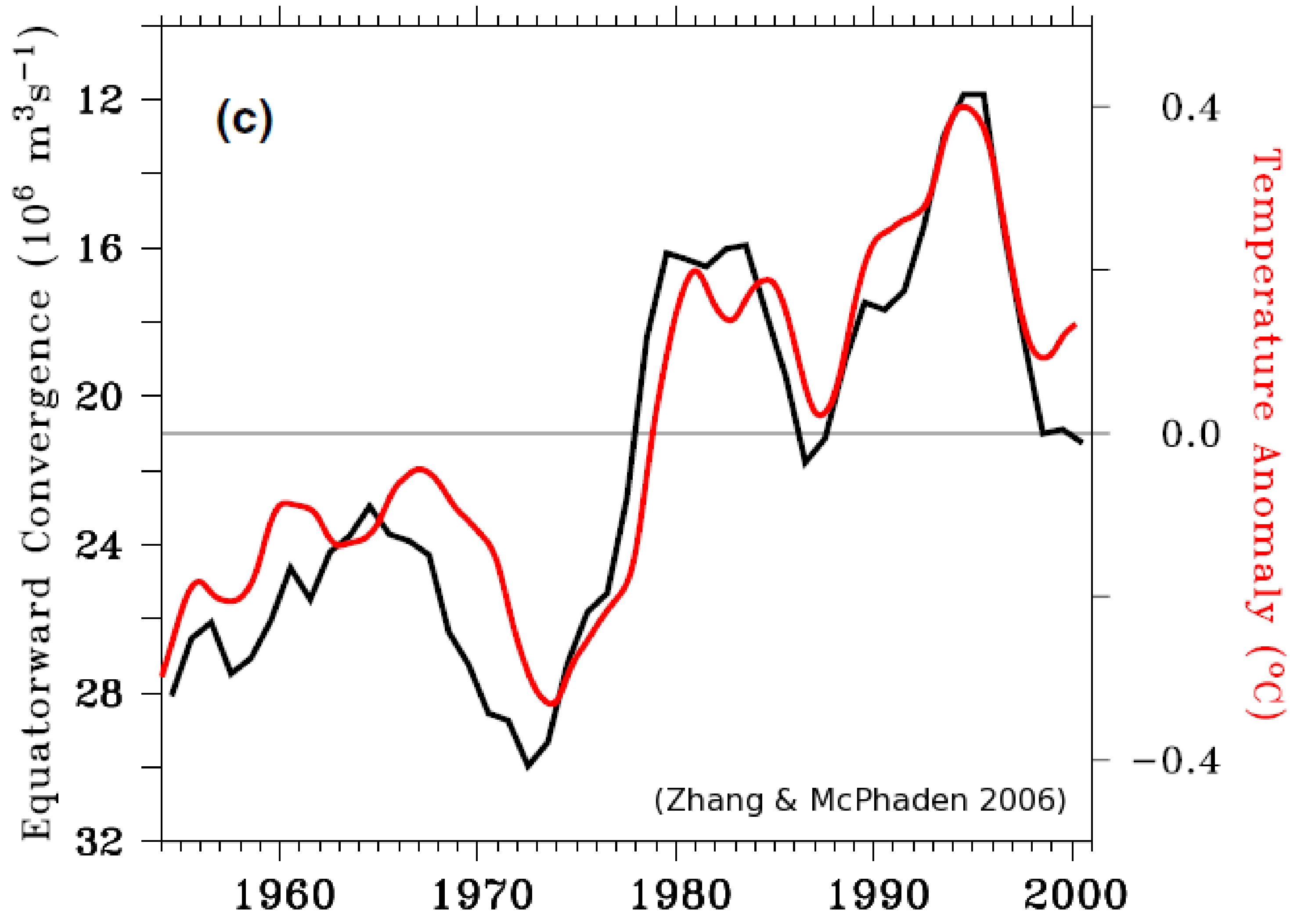
# Subtropical Cells (STCs)



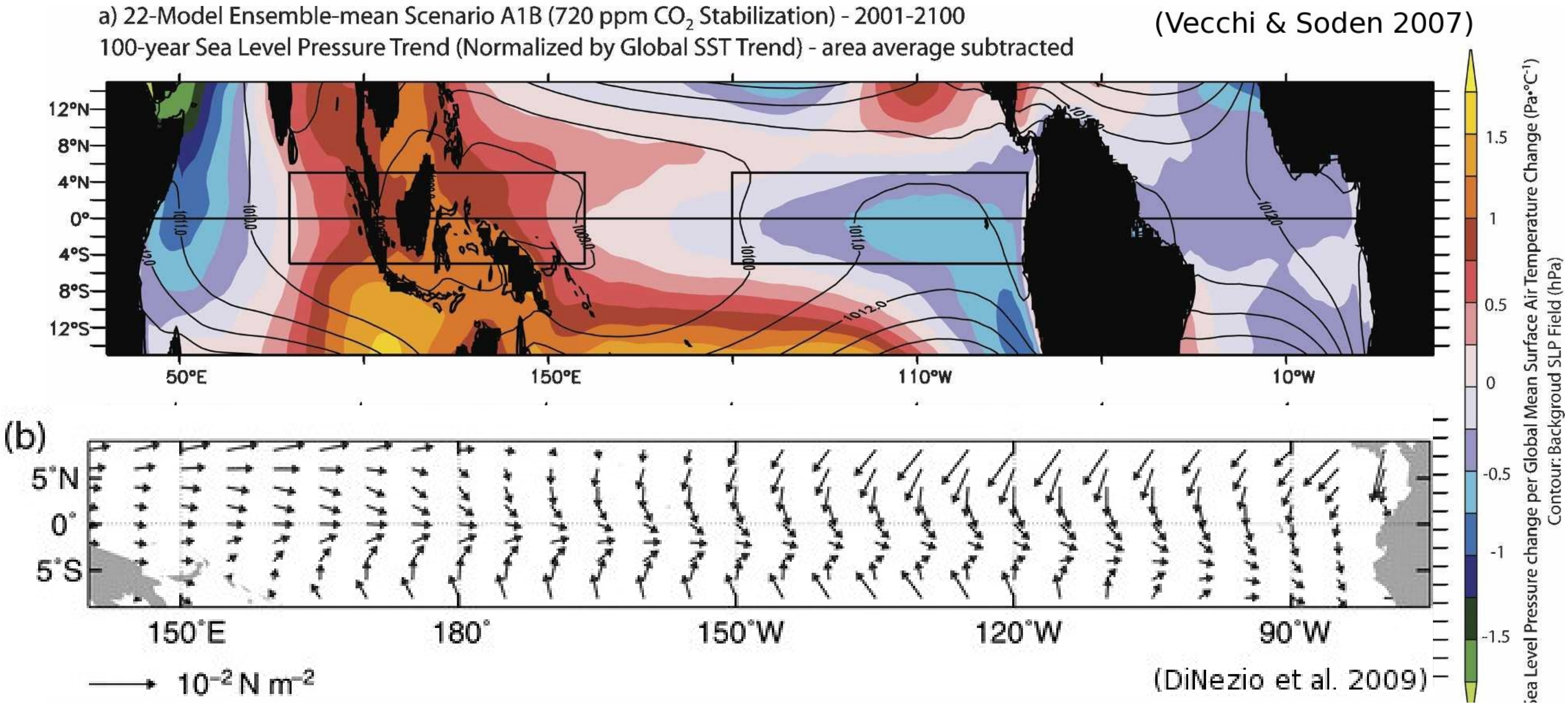




- STCs regulate the tropical Pacific upper ocean heat content.
- STCs regulate the watermass properties of the equatorial thermocline.

# Observed STC Decadal Trend

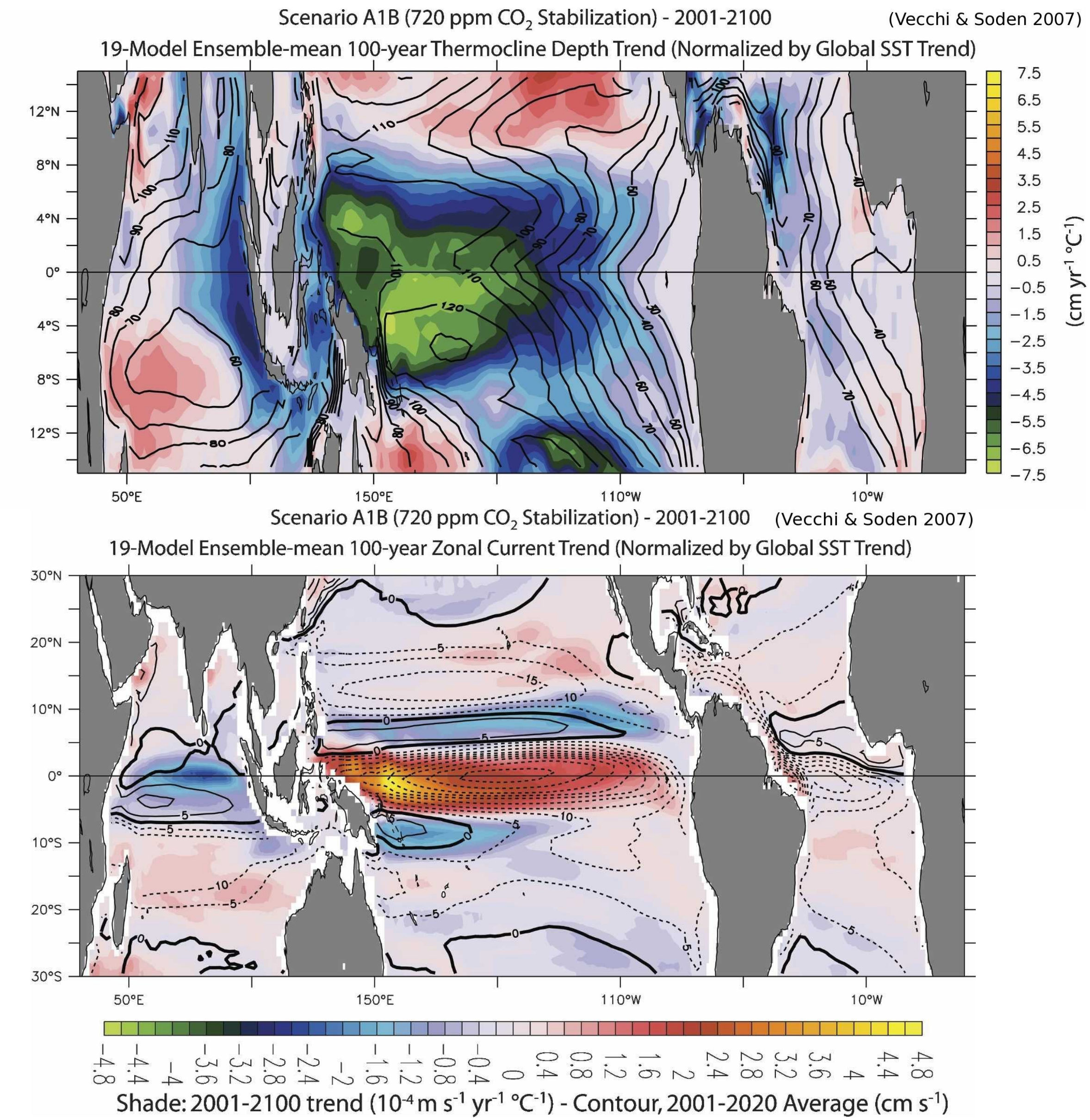


# Walker Circulation Weakens Under Global Warming



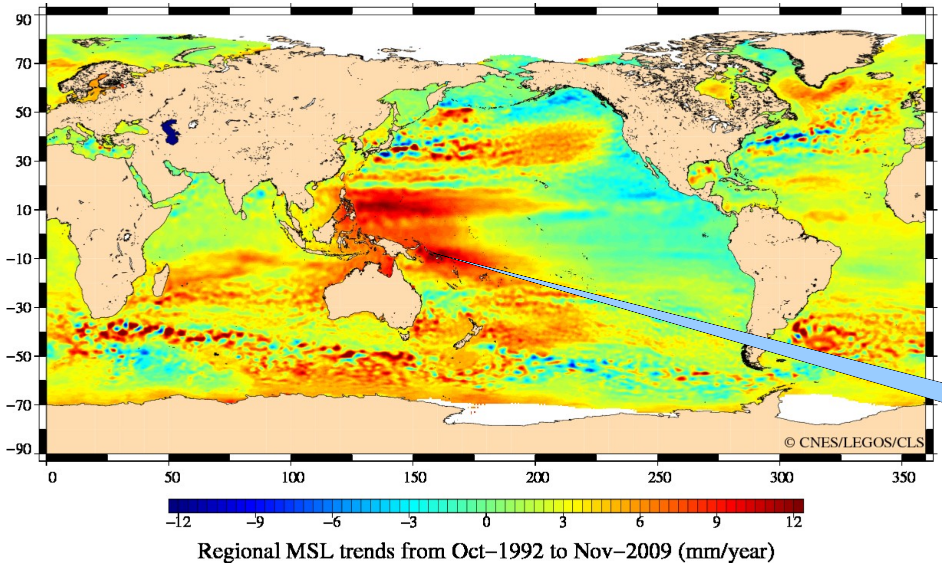

- Zonal SLP gradient reduced.
- Equatorial easterly trade winds weaken.

# Oceanic Response




- Tropical thermocline shoals.
- Tropical thermocline flattens.
- Surface zonal currents weaken.
- STCs?

# Recent Sea Level Rise (1993-2009)




The Carteret Is.

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

# 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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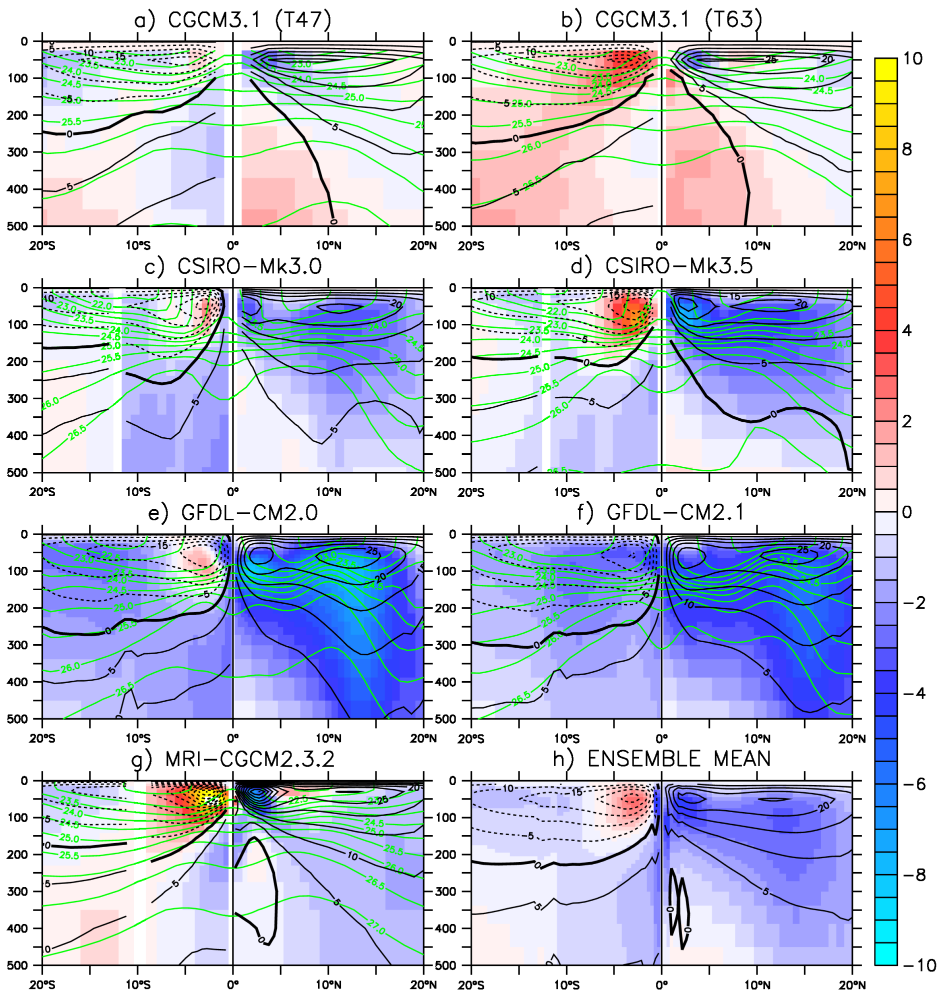
# IPCC AR4/CMIP3 Models

| ID | Model name | Country | Ocean resolution |
|---|---|---|---|
| 1 | CGCM3.1 (T47) | Canada | $1.9^\circ \times 1.9^\circ$ L29 |
| 2 | CGCM3.1 (T63) | Canada | $1.4^\circ \times 0.9^\circ$ L29 |
| 3 | CSIRO-Mk3.0 | Australia | $1.9^\circ \times 0.8^\circ$ L31 |
| 4 | CSIRO-Mk3.5 | Australia | $1.9^\circ \times 0.8^\circ$ L31 |
| 5 | GFDL-CM2.0 | U.S. | $1^\circ \times 1^\circ (0.3^\circ)$ L50 |
| 6 | GFDL-CM2.1 | U.S. | $1^\circ \times 1^\circ (0.3^\circ)$ L50 |
| 7 | MRI-CGCM2.3.2 | Japan | $2.5^\circ \times 2^\circ (0.5^\circ)$ L23 |

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

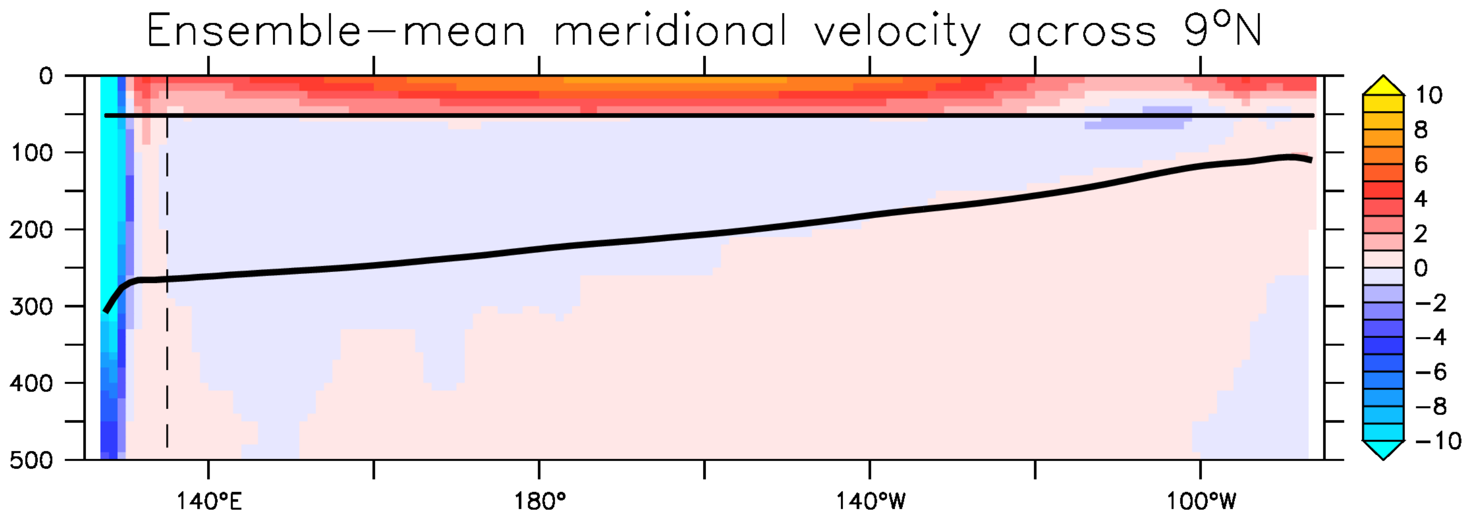
# Meridional Overturning Streamfunction

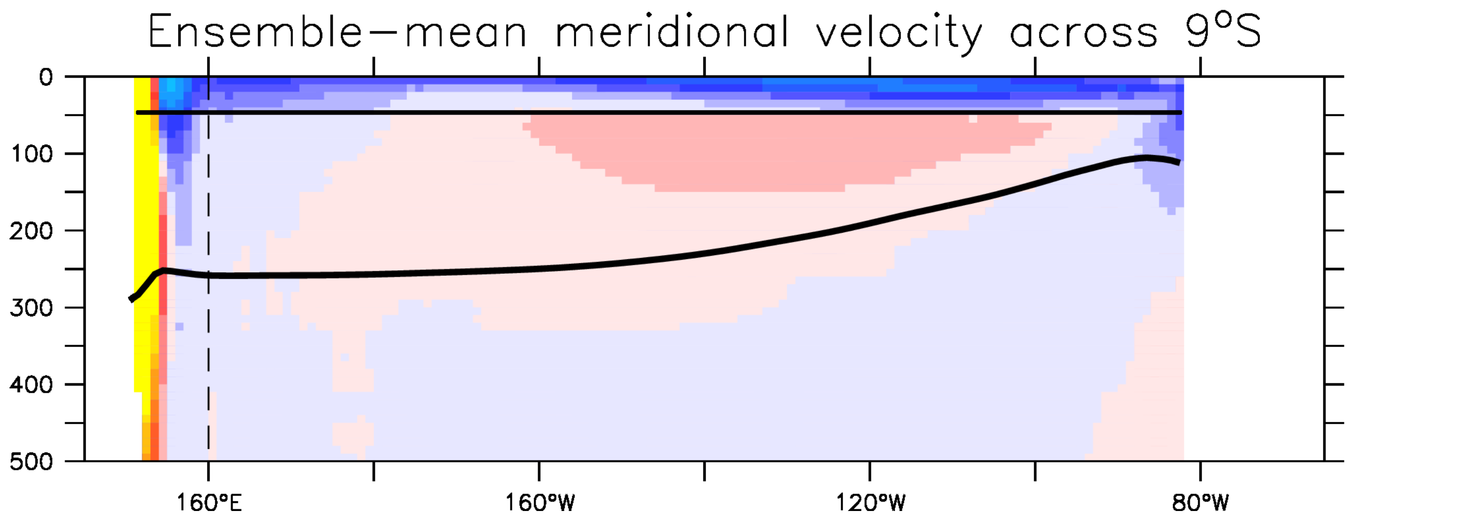



20°S 20°N

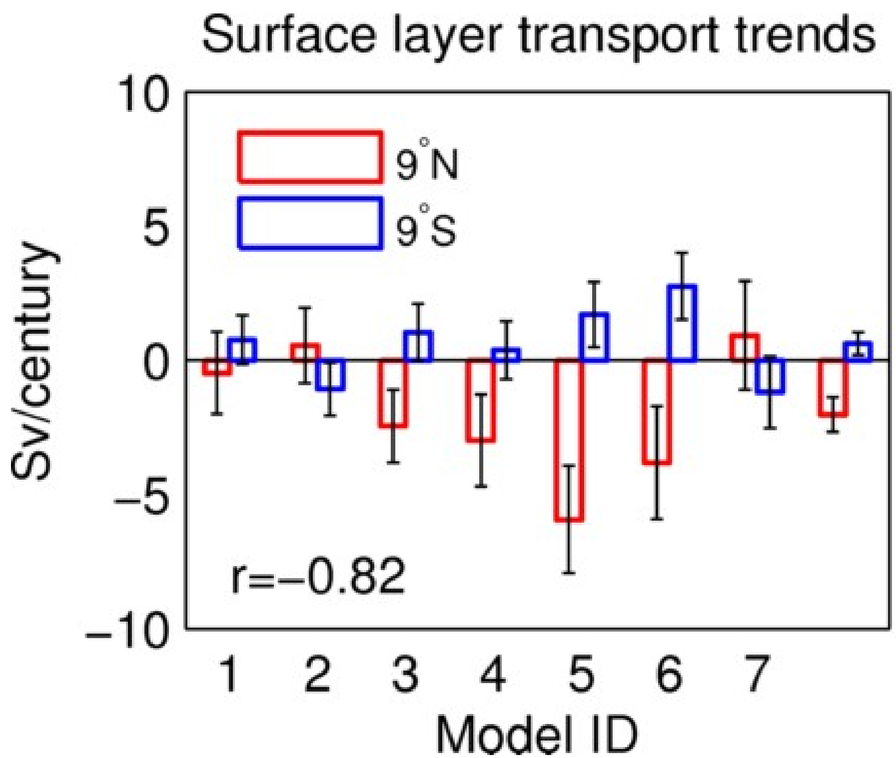
- STCs tend to
  - weaken in the NH
  - strengthen in the SH
- STC trends tend to be stronger in the NH.

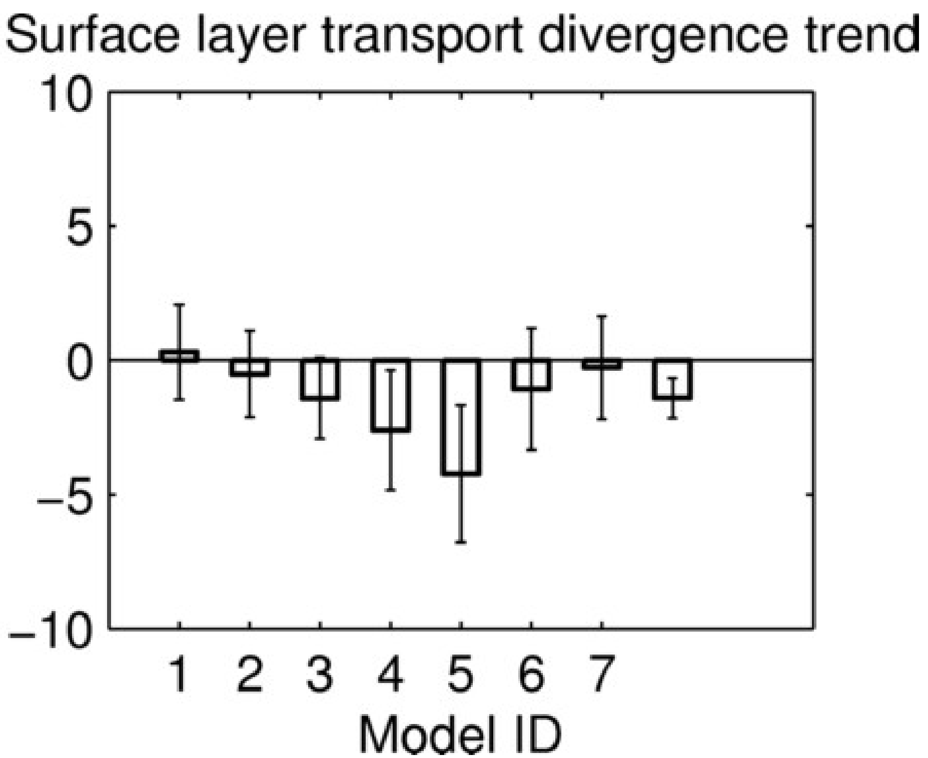
# Upper Ocean Meridional Velocity



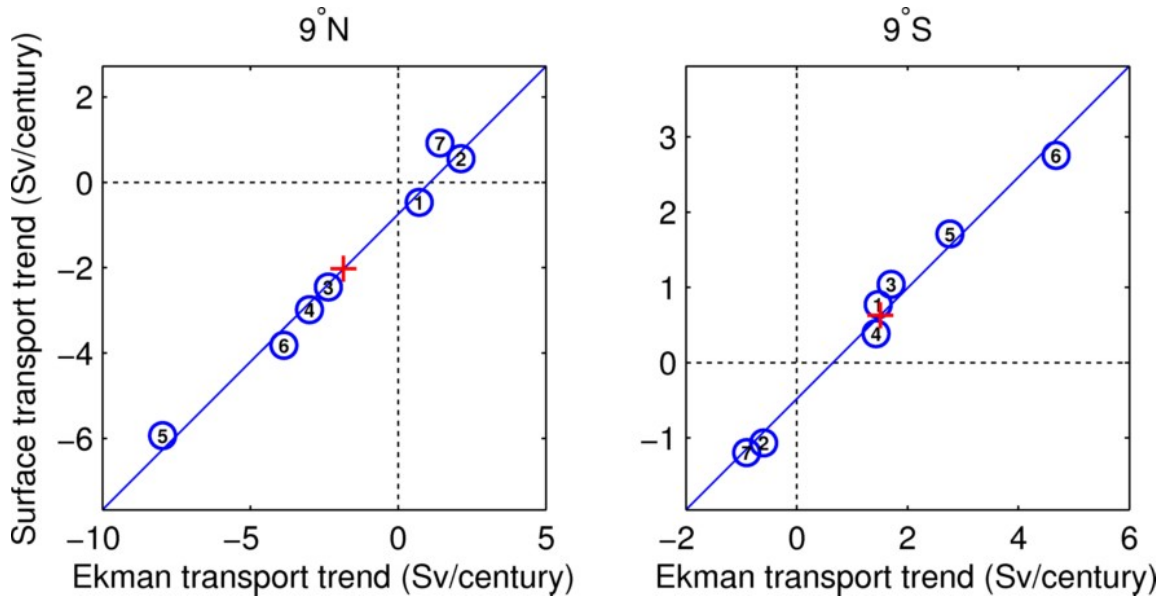



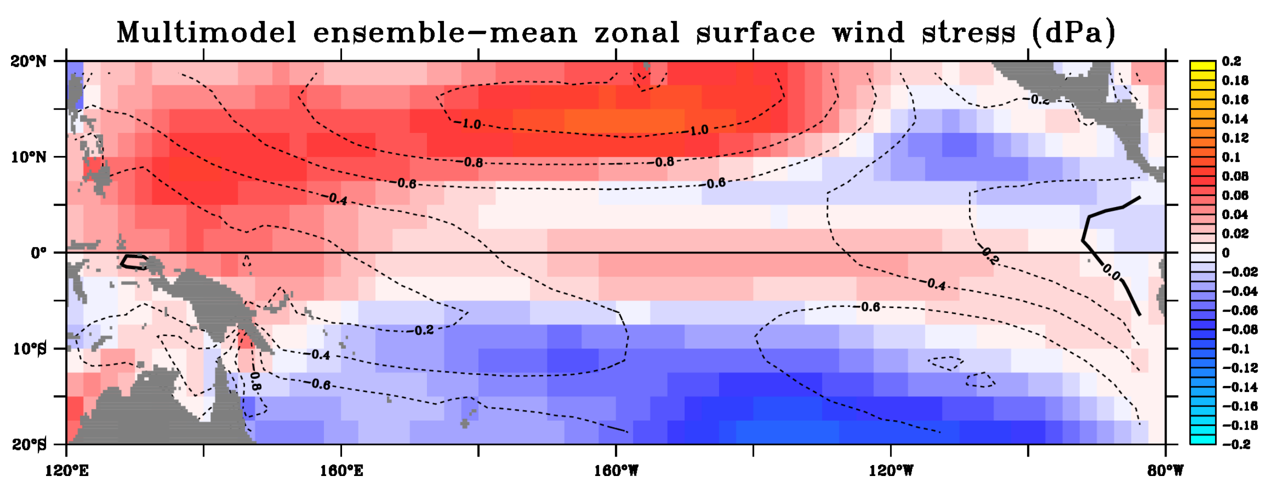
# Surface Layer Transport (poleward)



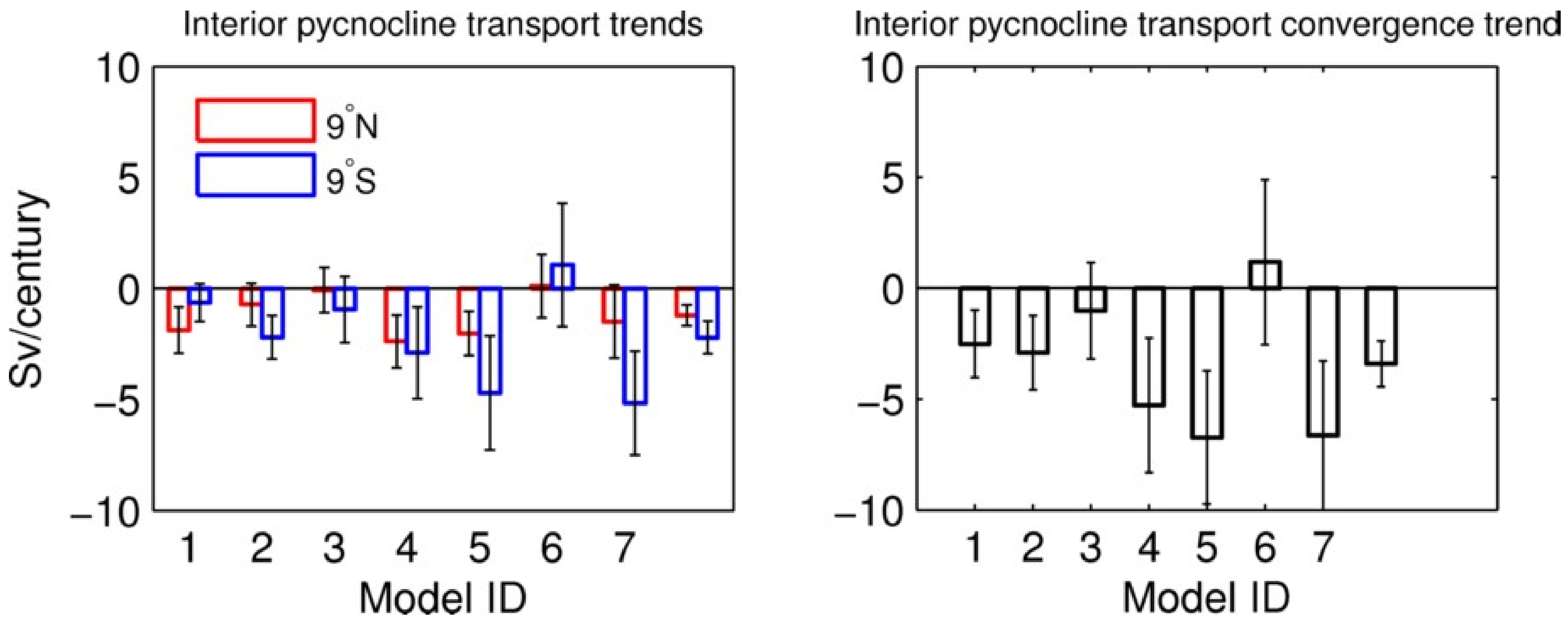



# Surface Layer Transport vs Ekman Transport

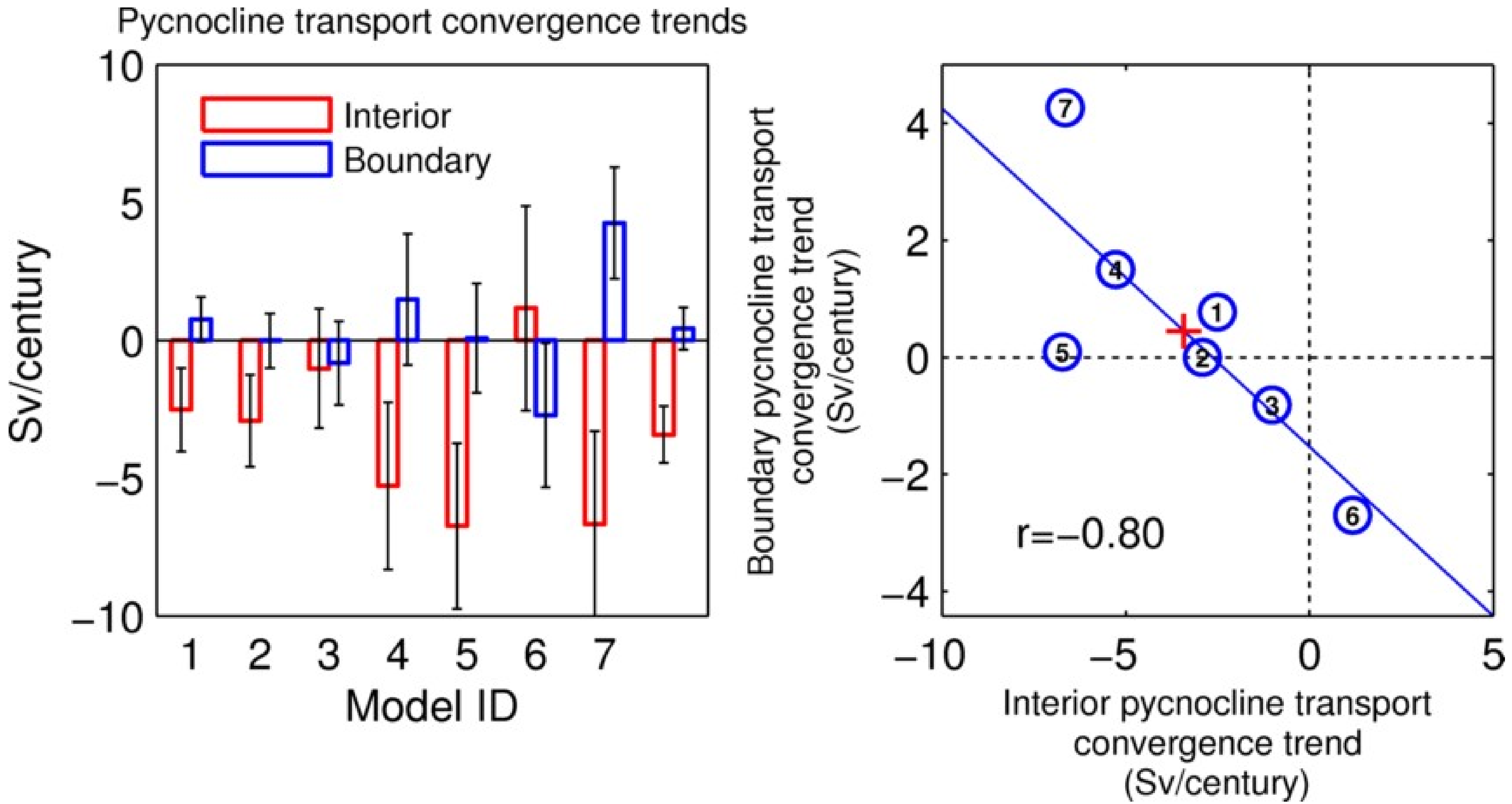


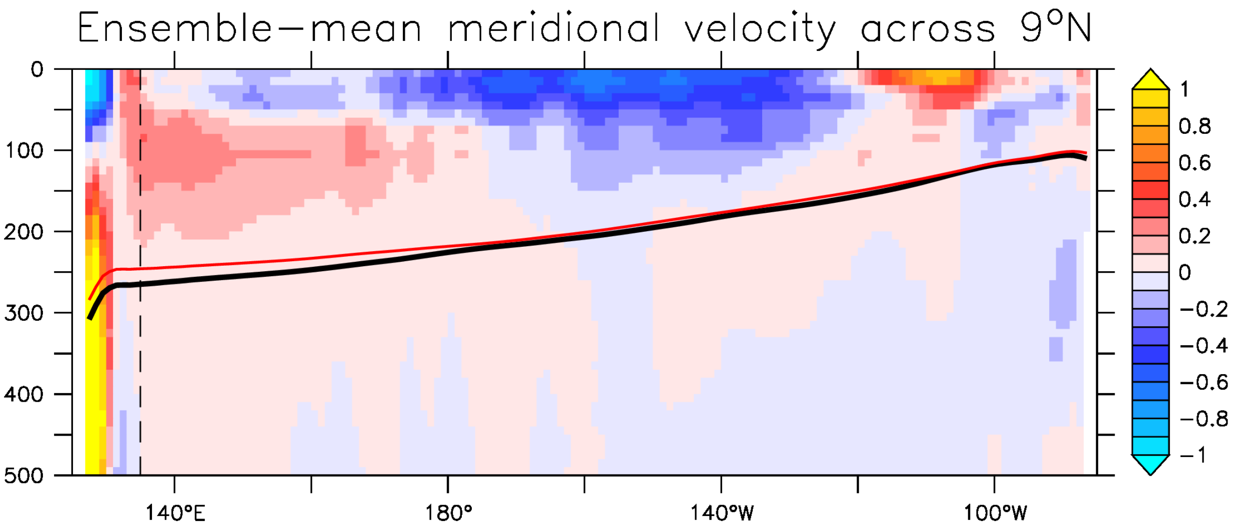
# Interior Pycnocline Transport (equatorward)

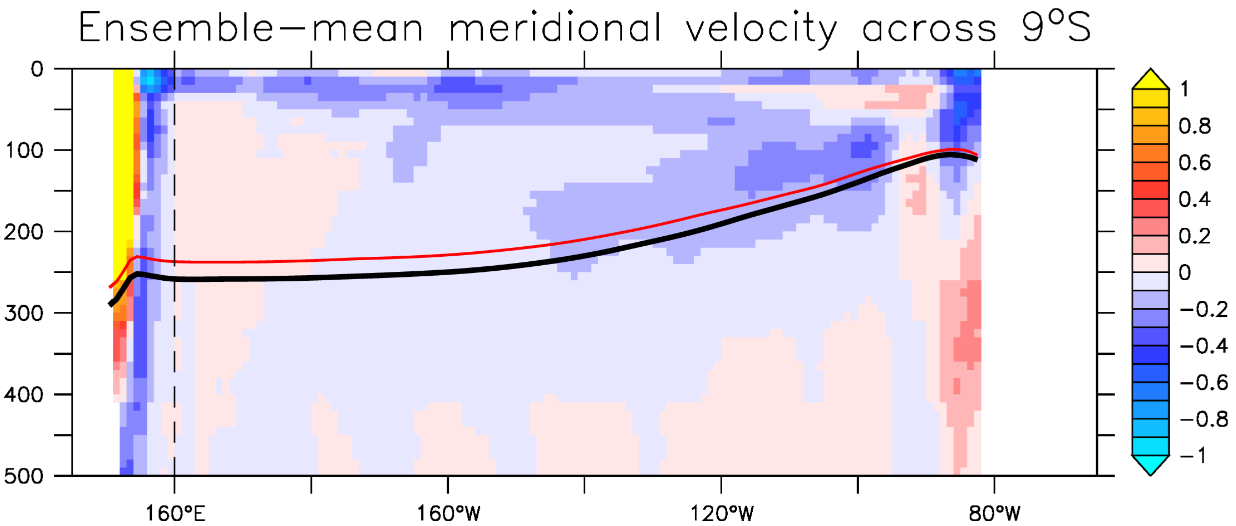


# Interior vs Boundary Pycnocline Transport Convergence

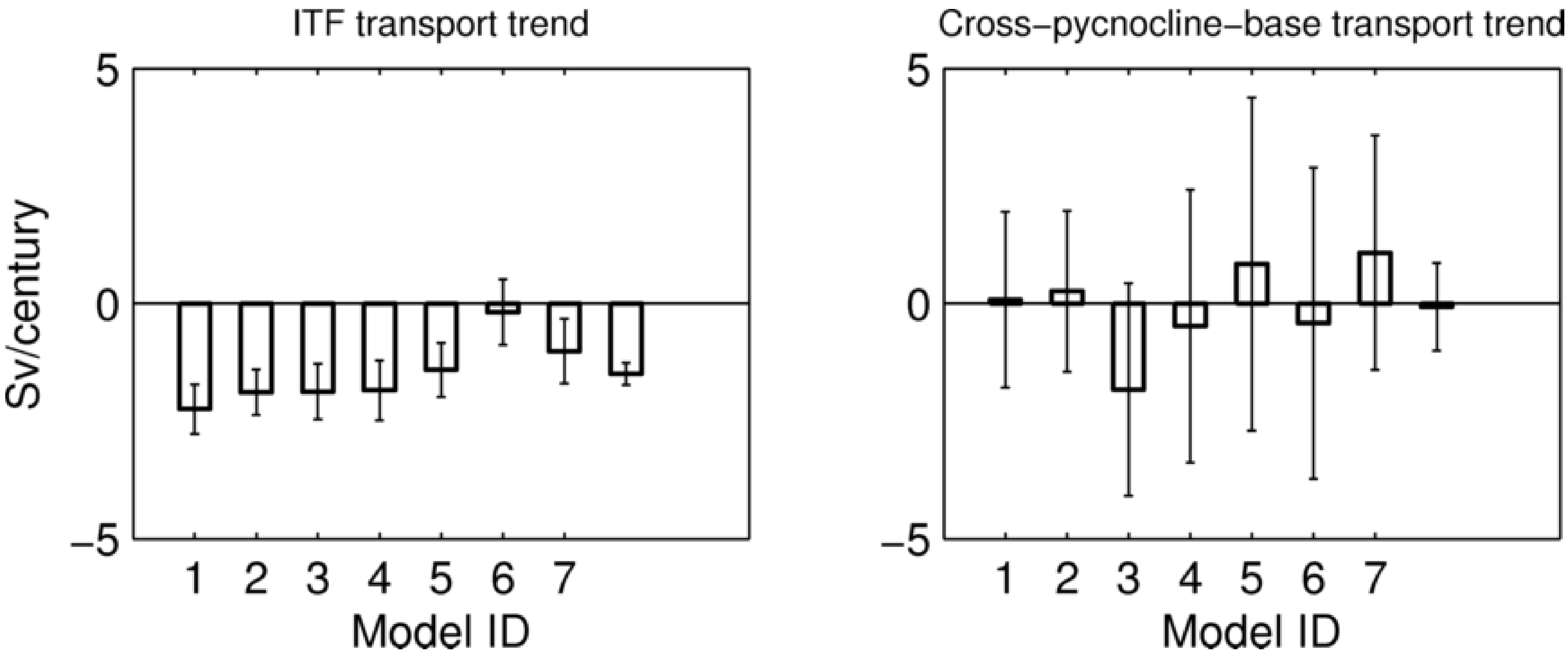


# Interior Pycnocline Transport Weakening Related to Pycnocline Flattening



# ITF and Cross-pycnocline-base Transports



# Tropical Pacific Upper Ocean Mass Balance

| | SFC | ITF | PYC-I | PYC-B | CPB |
|---|---|---|---|---|---|
| 2001-2020 mean (Sv) | 43.5 | 9.2 | 22.1 | 24.2 | 6.4 |
| 2001-2100 change (Sv) | -1.4±0.7 | -1.5±0.2 | -3.4±1.0 | 0.4±0.8 | -0.1±0.9 |

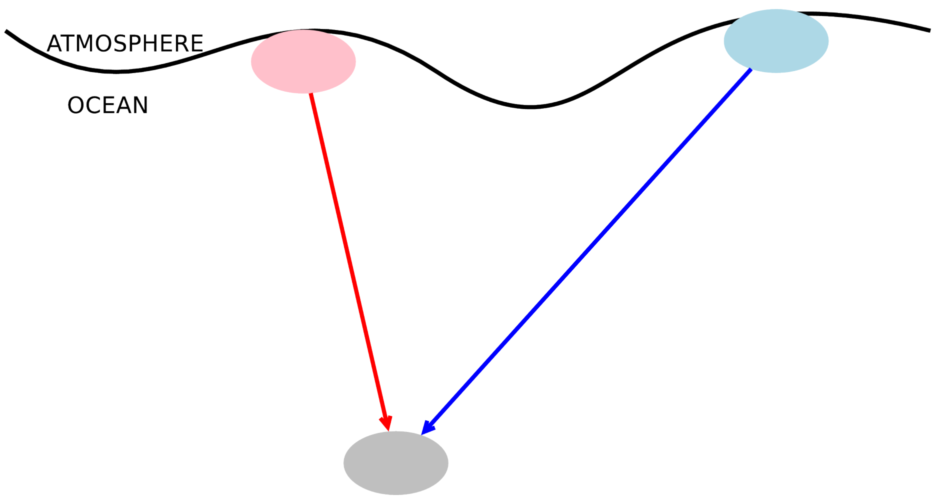
# Summary I

- 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




$$c = \sum_{i=1}^{N} a_i c_i$$

$$\sum_{i=1}^{N} a_i = 1$$

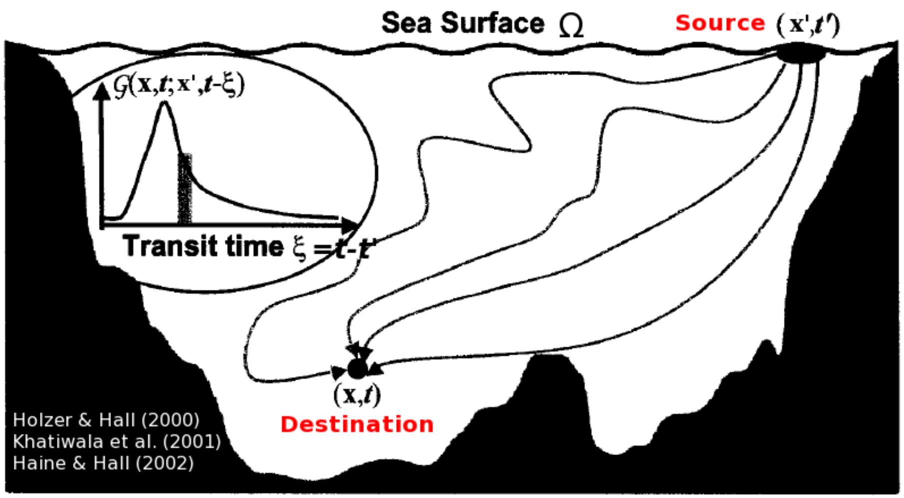
- How to determine source water fraction $a_i$?
- How to characterize transit time scale?

# Transit Time Distribution (TTD) Theory

A-D tracer equation:

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

$$c = c_s(\mathbf{x}, t) \text{ on } \Omega$$



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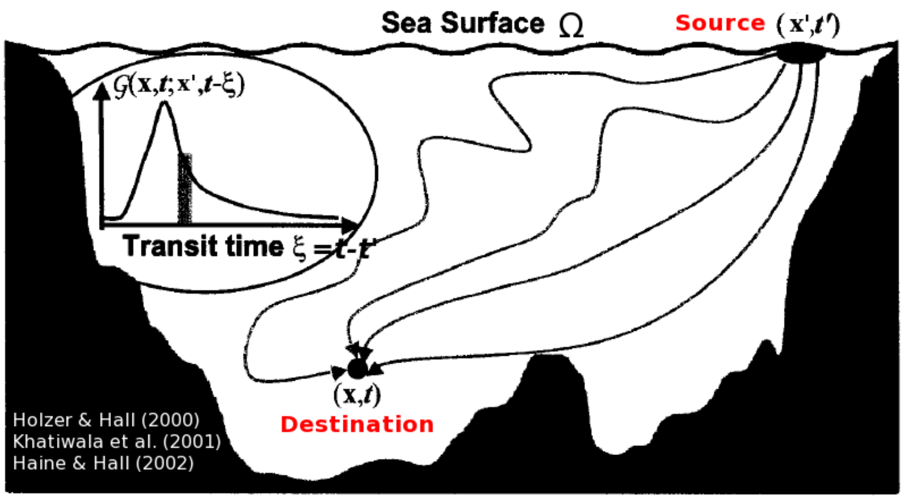


Solution:

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

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

# Transit Time Distribution (TTD) Theory

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

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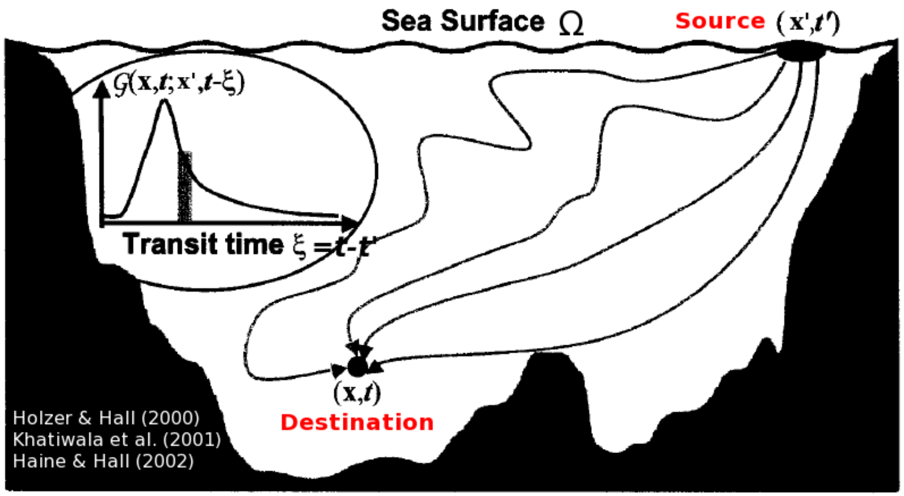



Solution:

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

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

$$= \sum_{i=1}^{N} \underbrace{A_i \int_{0}^{\infty} d\xi G'_i(\mathbf{x}, \xi)}_{a_i} c_i$$

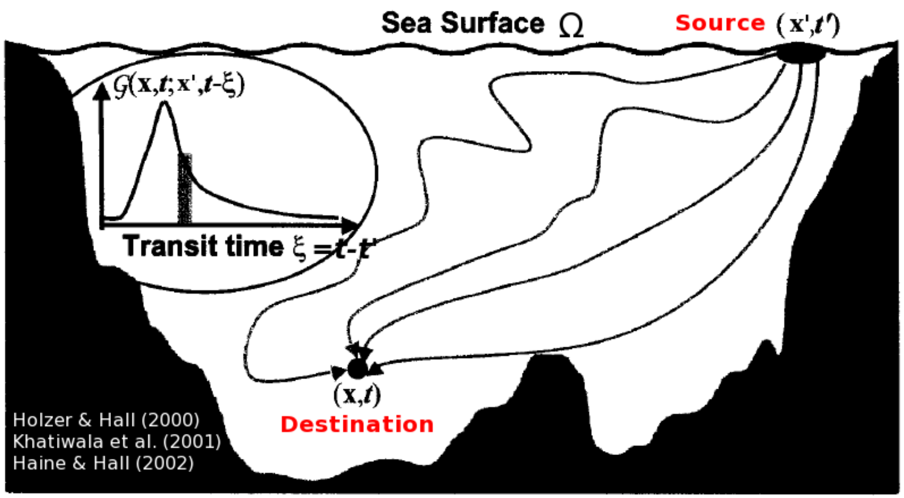
- *G′* is a (boundary) Green's function to the tracer eqn.
- *G′* is the **transit time distribution** over surface source location and transit time.

# Transit Time Distribution (TTD) Theory

*G*' satisfies:

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

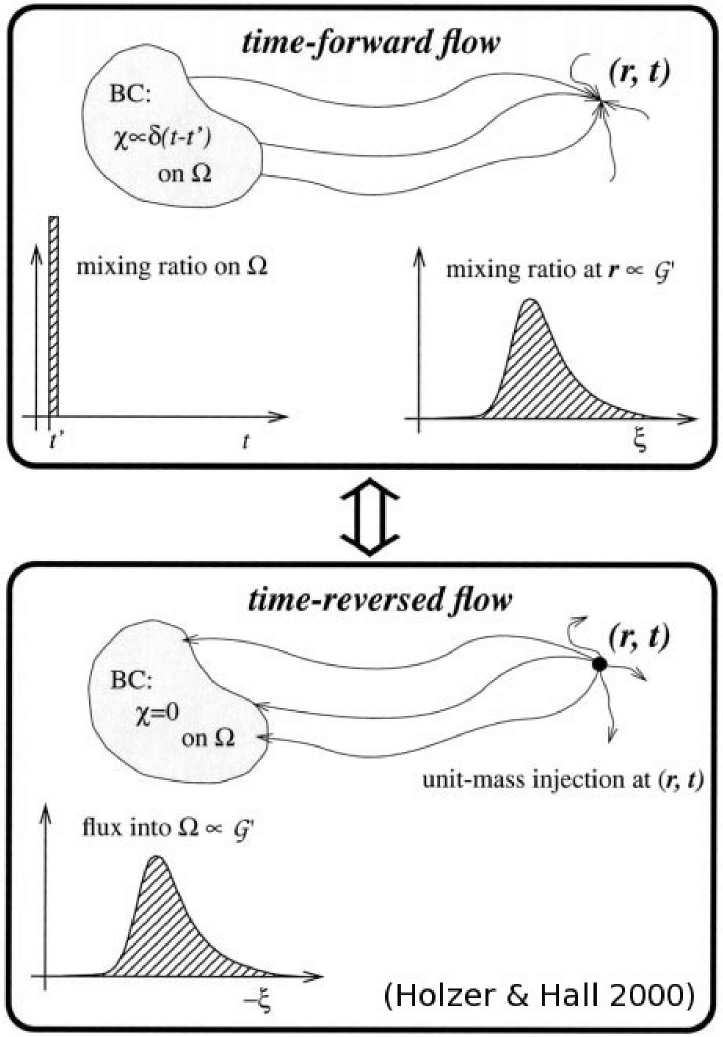
$$G' = \delta^2(\mathbf{x} - \mathbf{x}')\delta(t - t') \quad \text{on} \quad \Omega$$




- 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.



# OGCM Experiments

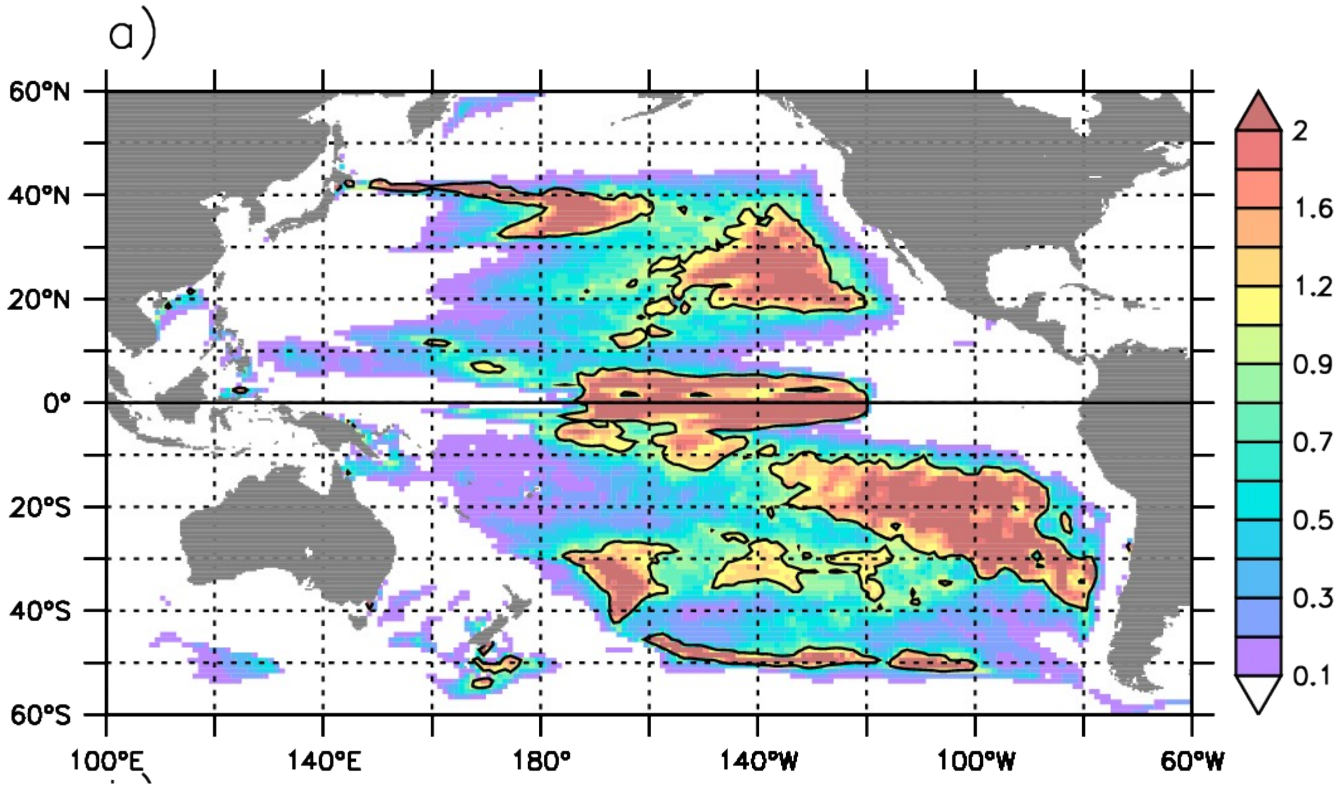
| Model specifications | CTRL | $2 \times CO_2$ |
|---|---|---|
| Domain | near-global (80°E – 80°N) | same |
| Resolution | $1° \times 1°(0.3°)$ L46 | same |
| Isopycnal mixing | Gent and McWillams (1990) | same |
| Vertical mixing | KPP (Large et al. 1994) | same |
| Initialization | Levitus 1998 (at rest) | same |
| Mechanical forcing | NCEP semi-daily wind stresses | NCEP + perturbation |
| Buoyancy forcing | NCEP daily net heat/freshwater fluxes | NCEP + perturbation |
| SST/SSS relaxation | Levitus | Levitus + perturbation |
| Integration length | 80 years | same |

- MITgcm, climatological runs.
- Forcing perturbations taken from CMIP3 ensemble-mean differences between the pre-industrial and CO2 doubling simulations.

# Passive Tracer (TTD) Runs

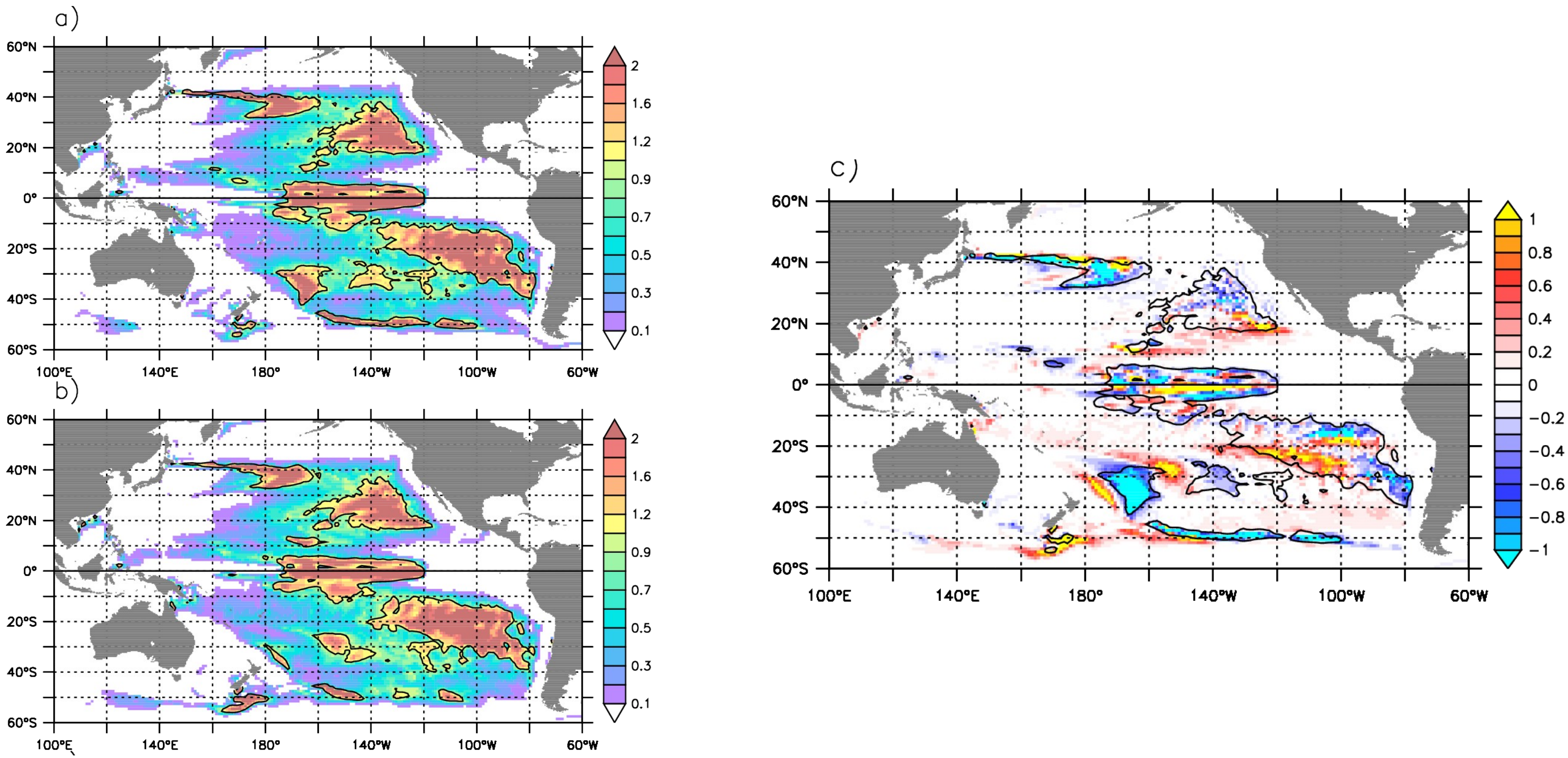
- Use the mean circulation and mixing coefficients for the last year of spin-up.
- Use transport matrix method (TMM; Khatiwala et al. 2005) for efficient tracer integration.
- Initialize tracer in the EUC (u>15 cm/s) between 170°-120°W.
- Integrate the adjoint tracer equation for 200 years.
- Results: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

# Source Water Distribution (CTRL)



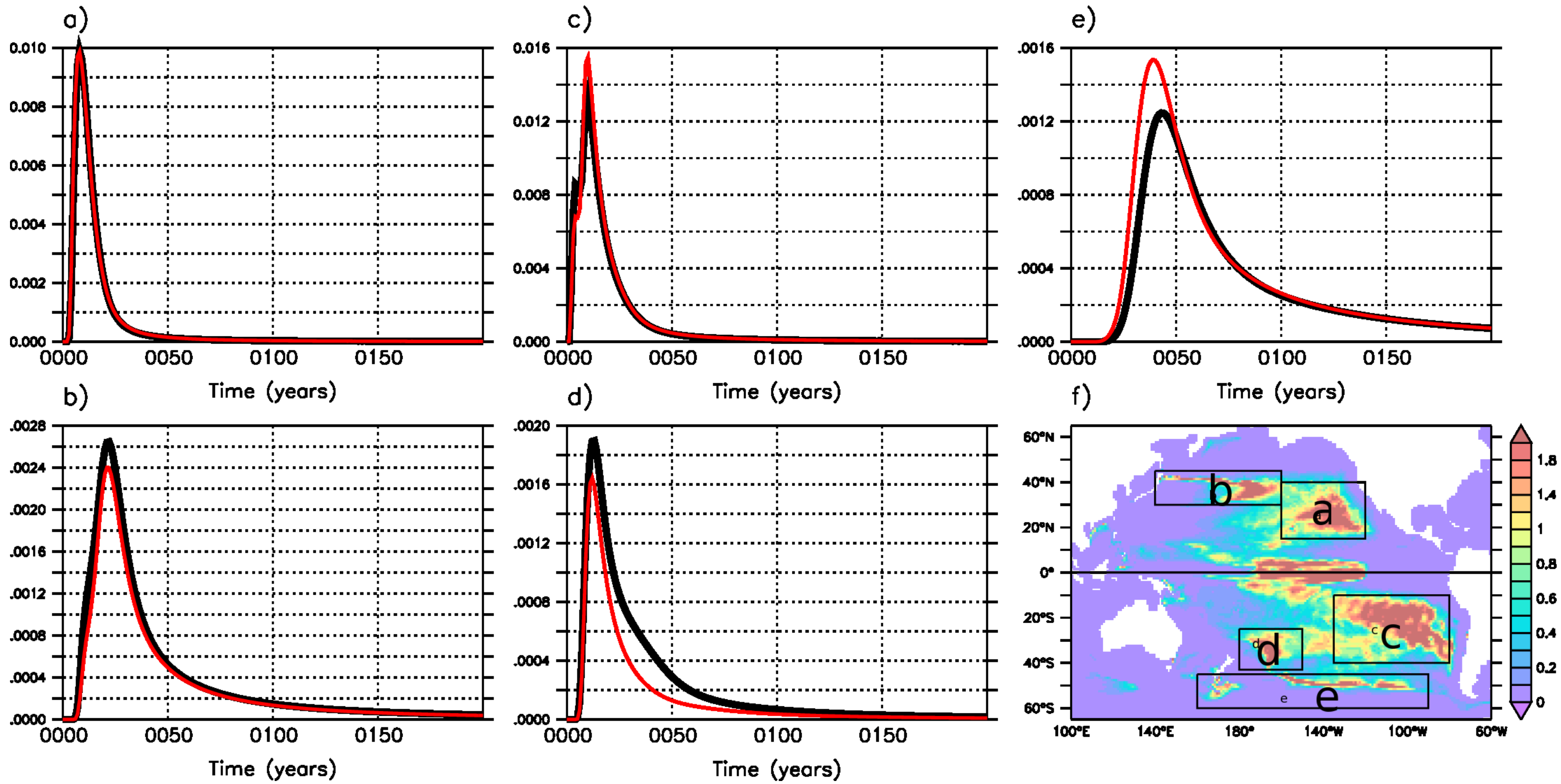

| EQ (10°S-10°N) | NH (10°N-80°N) | SH (10°S-80°S) | GLOBAL (80°S-80°N) |
|---|---|---|---|
| 21.4% | 25.9% | 43.6% | 90.9% |

# Source Water Distribution (CTRL vs 2xCO2)




| | EQ (10°S-10°N) | NH (10°N-80°N) | SH (10°S-80°S) | GLOBAL (80°S-80°N) |
|---|---|---|---|---|
| CTRL | 21.4% | 25.9% | 43.6% | 90.9% |
| $2 \times CO_2$ | 21.5% | 25.8% | 45.7% | 93.0% |

# Regional Transit Time Distributions




- No significant change except in the southern South Pacific (region e).

# Attributing Equatorial Thermocline Warming

- EUC water

$$\Delta T = 1.75°\mathrm{C}$$

- Source waters

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

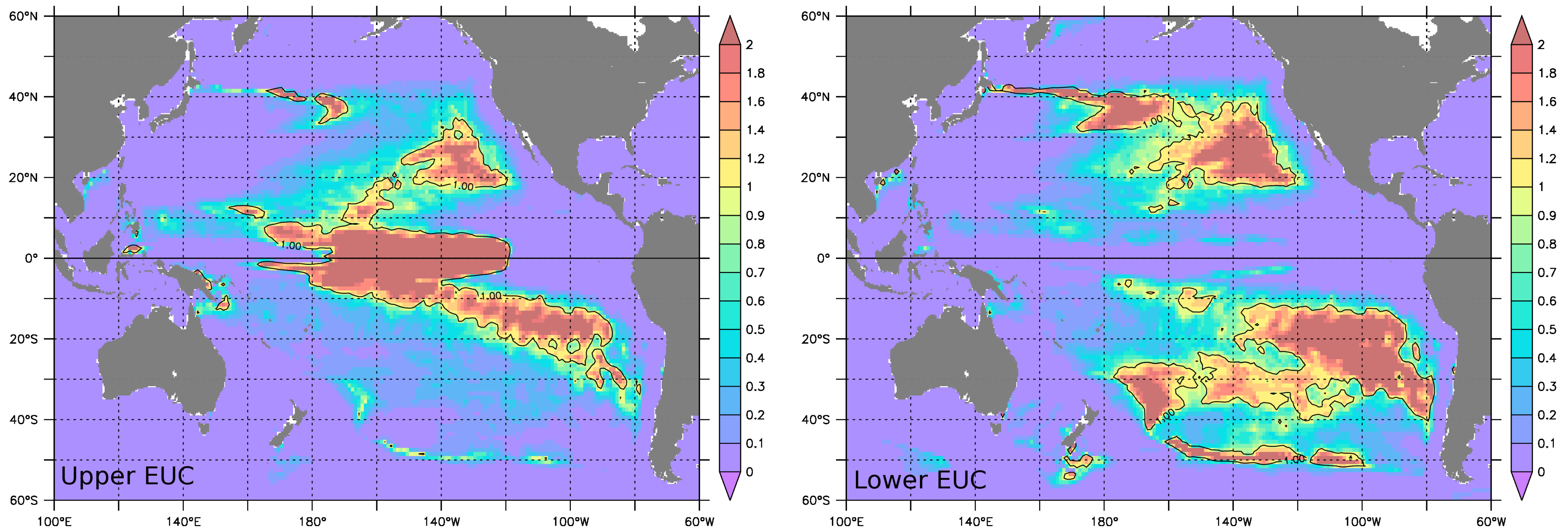
$$' = \sum_{i=1}^{N} a_i^{(1)} \Delta T_i \qquad 1.49°\mathrm{C}$$

$$+ \sum_{i=1}^{N} \Delta a_i T_i^{(1)} \qquad 0.24°\mathrm{C}$$

$$' + \sum_{i=1}^{N} \Delta a_i \Delta T_i \qquad -0.03°\mathrm{C}$$

$$' = 1.71°\mathrm{C}$$

# Source Water Distribution (upper vs lower thermocline)




| | EQ (10°S-10°N) | NH (10°N-80°N) | SH (10°S-80°S) | GLOBAL (80°S-80°N) |
|---|---|---|---|---|
| Upper | 59.7% | 16.2% | 19.7% | 95.6% |
| Lower | 3.9% | 28.7% | 49.8% | 82.4% |

# 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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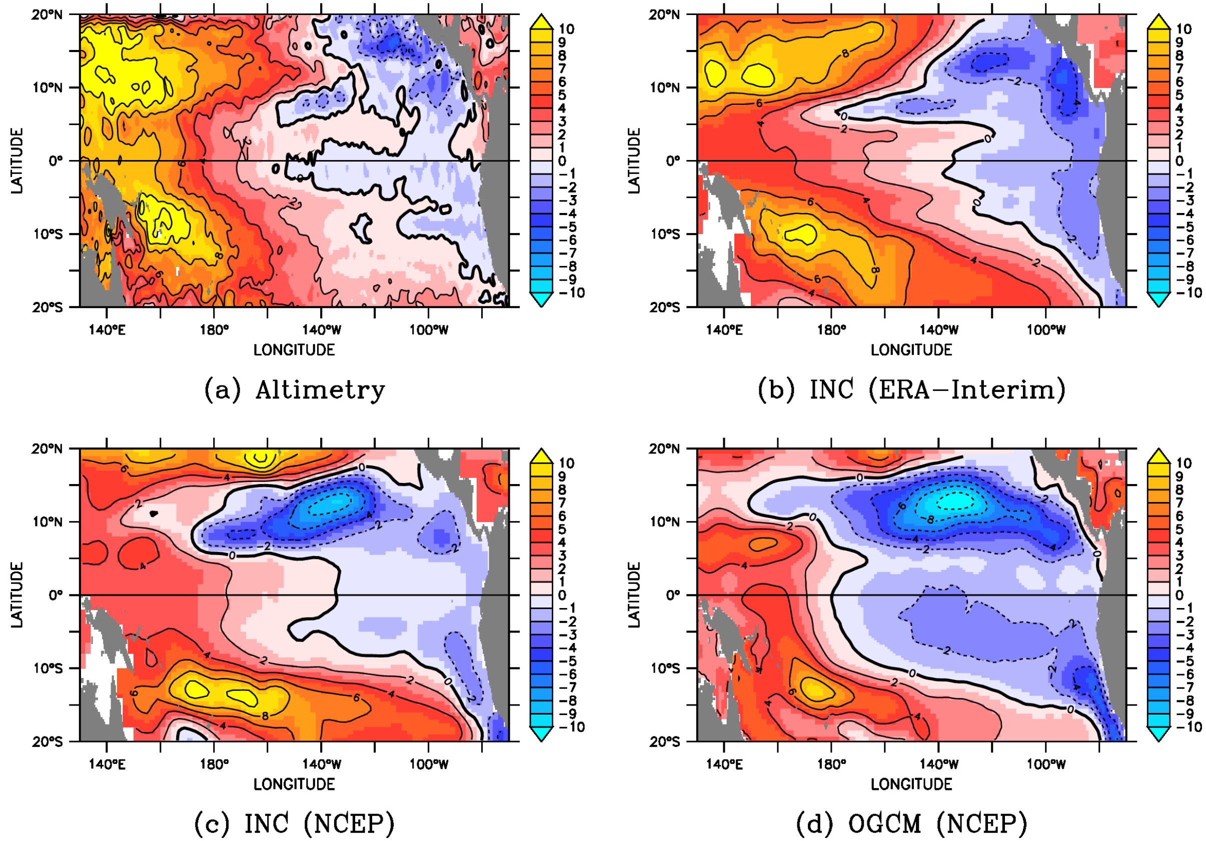
# Linear Wind-Driven Model (INC*)

- 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).

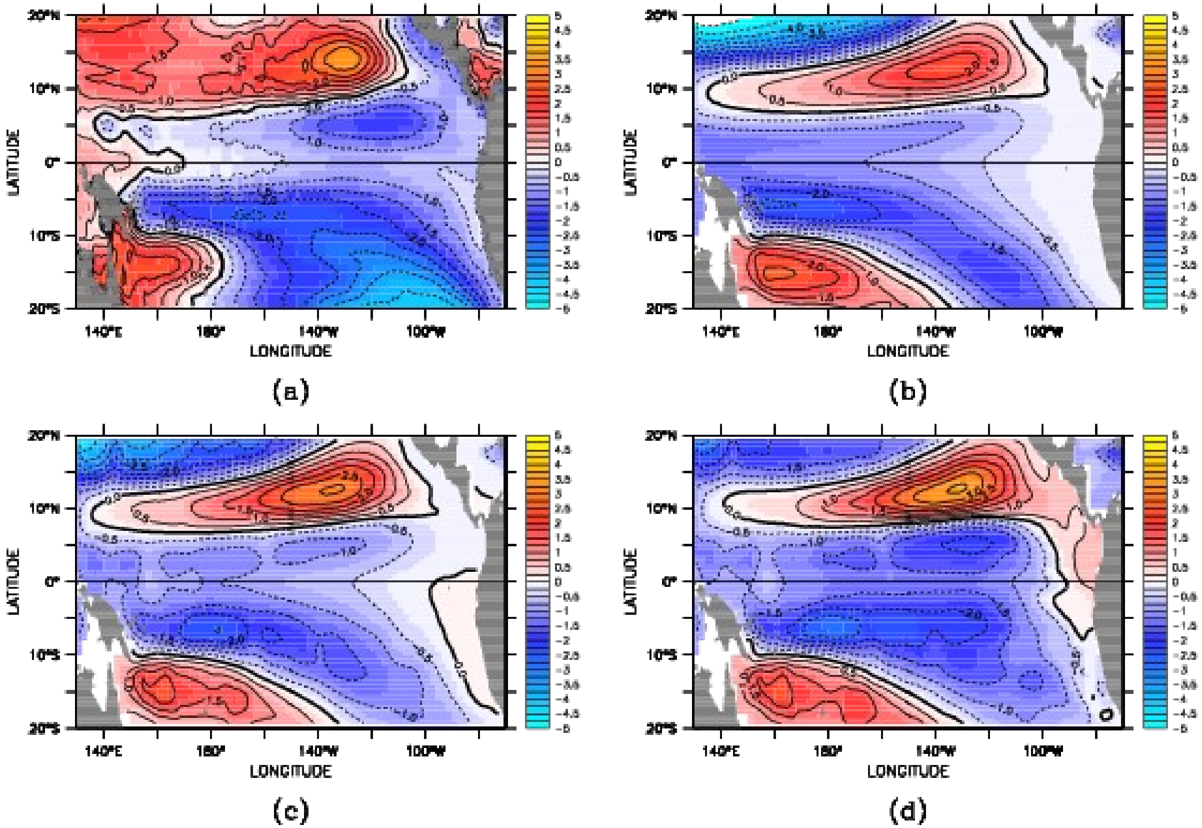
* Israeli, Naik & Cane 2000: An unconditionally stable scheme for the shallow water equations. *M.W.R.*

# 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!