Tropical-Extratropical and Inter-Hemispheric Climate Interaction

ABOT: Atmospheric Bridge – Oceanic Tunnel

热带–热带外及南北半球气候相互作用：大气桥梁与海洋通道

Haijun Yang (杨海军)
Laboratory for Climate and Ocean-Atmospheric Studies, Peking University (北京大学气候与海气实验室)
Department of Atmospheric and Oceanic Sciences, Fudan University (复旦大学大气与海洋科学系)
Email: yanghj@fudan.edu.cn

Concepts

Extratropical → Tropical

Tropical → Extratropical

Inter-hemispheric

Pacific VS. Atlantic

Conclusion

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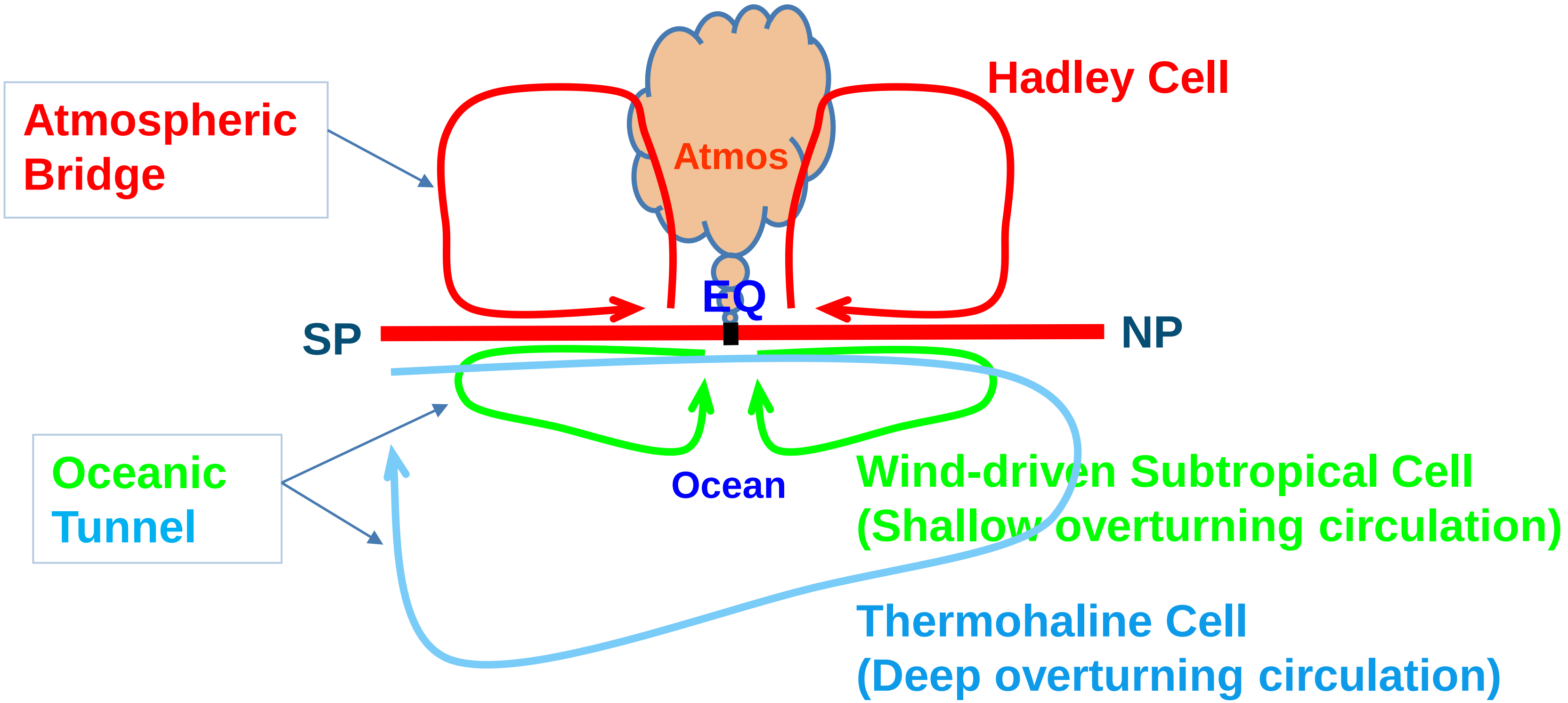
Tropics ⇔ Extratropics



Yang, H. and Z. Liu, 2005: Tropical-extratropical climate interaction as revealed in idealized coupled climate model experiments. *Climate Dynamics*, 24, 863-879.

Facts

- Many-many studies on Tropical ⇔ Extratropical
- Approach traditionally:
  - AGCM: Decoupled from full ocean dynamics (Lau 1997; Barnett et al. 1999)
  - OGCM: Decoupled from full atmosphere dynamics (Gu and Philander 1997; Liu 1998)

Problem: all Qualitative (定性) studies! (before 2000)

Motivation

To determine Quantitative (定量) impact

- Extratropics ➔ Tropics* (long timescale)
- Tropics ➔ Extratropics (short timescale)
- SH ➔ Tropics ➔ NH
- NH ➔ Tropics ➔ SH
- Pacific VS. Atlantic

in a Fully Coupled Earth System

Fundamentally Important !

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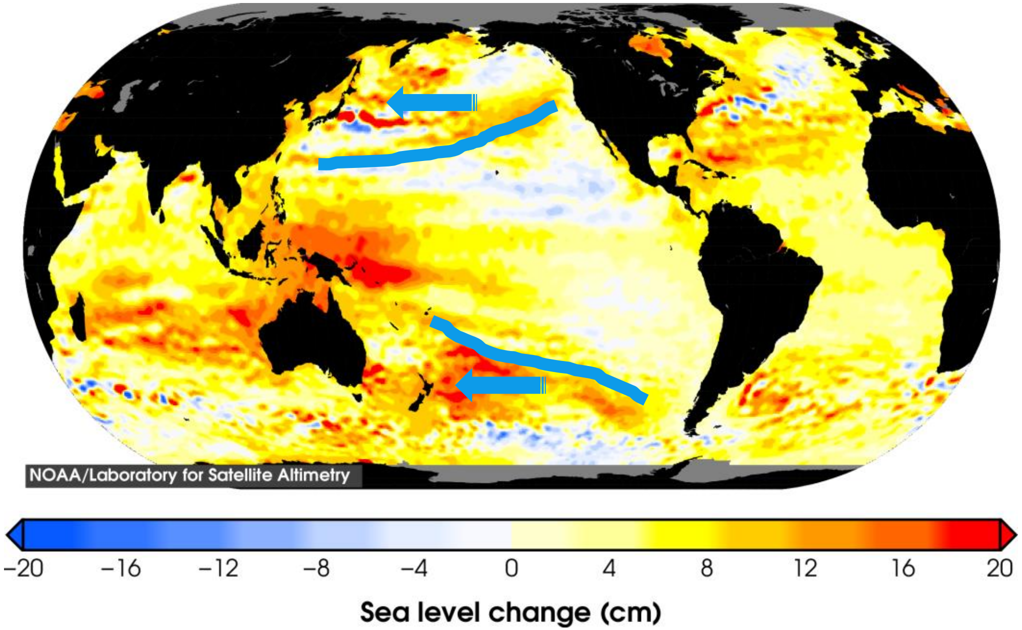
A Theoretical Model Study

Yang, H. and Z. Liu, 2003: Basin modes in a tropical-extratropical basin. *J. Phys. Oceanogr.*, 33(12), 2751-2763

Yang, H., Z. Liu and Q. Zhang, 2004: Tropical ocean decadal variability and resonance of planetary wave basin modes: II. Numerical study. *J. Climate*, 17, 1711-1721.

Qualitative(定性): Rossby Wave Dynamics

Topex/Poseidon SSHA: Large-scale ocean wave (1993-2014)



Basin Mode: Extratropics → Tropics

Theory: Linear shallow water model on Eq. Beta-plane

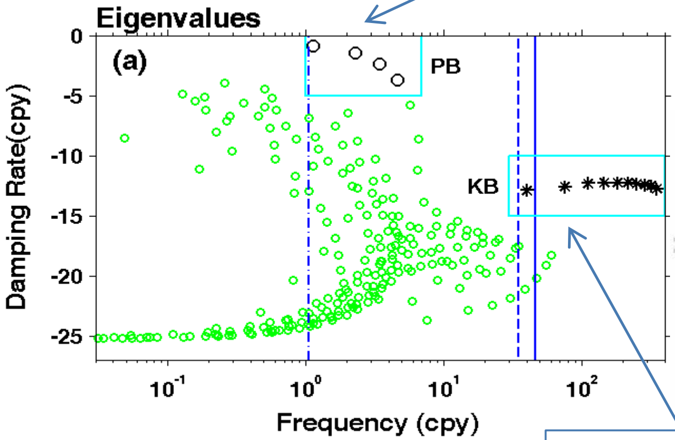
$$\begin{cases} u_t - yv + h_x + ru = 0 \\ v_t + yu + h_y + rv = 0 \\ h_t + u_x + v_y = 0 \end{cases} \Rightarrow \begin{pmatrix} u \\ v \\ h \end{pmatrix} = e^{-i\sigma t} \begin{pmatrix} \hat{u} \\ \hat{v} \\ \hat{h} \end{pmatrix} (x, y)$$

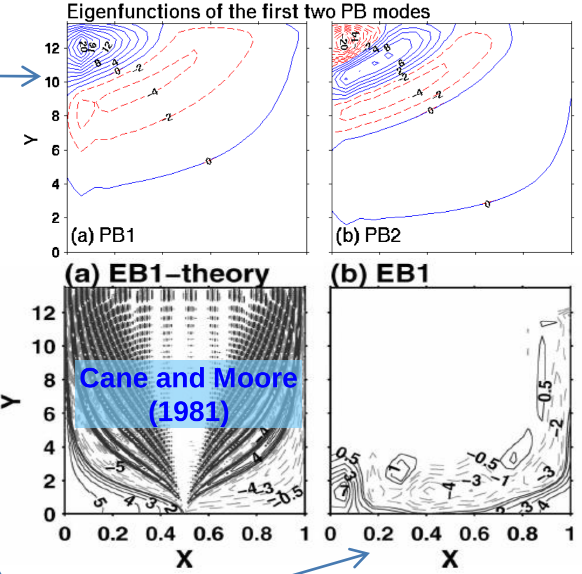
$$\Rightarrow i\sigma \begin{pmatrix} \hat{u} \\ \hat{v} \\ \hat{h} \end{pmatrix} = \begin{pmatrix} r & -y & \partial_x \\ y & r & \partial_y \\ \partial_x & \partial_y & 0 \end{pmatrix} \begin{pmatrix} \hat{u} \\ \hat{v} \\ \hat{h} \end{pmatrix} = L \begin{pmatrix} \hat{u} \\ \hat{v} \\ \hat{h} \end{pmatrix}$$

Basin Mode: Extratropics → Tropics

理论模式解出了年代际大尺度本征模

行星尺度
耗散最小

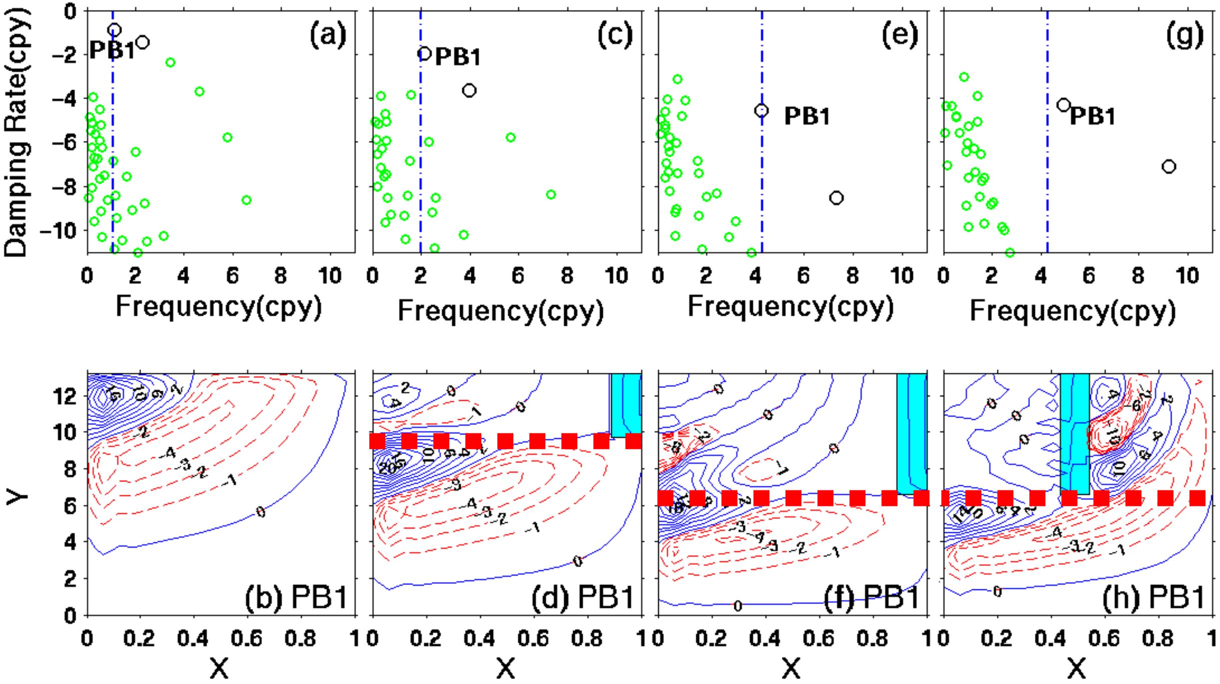




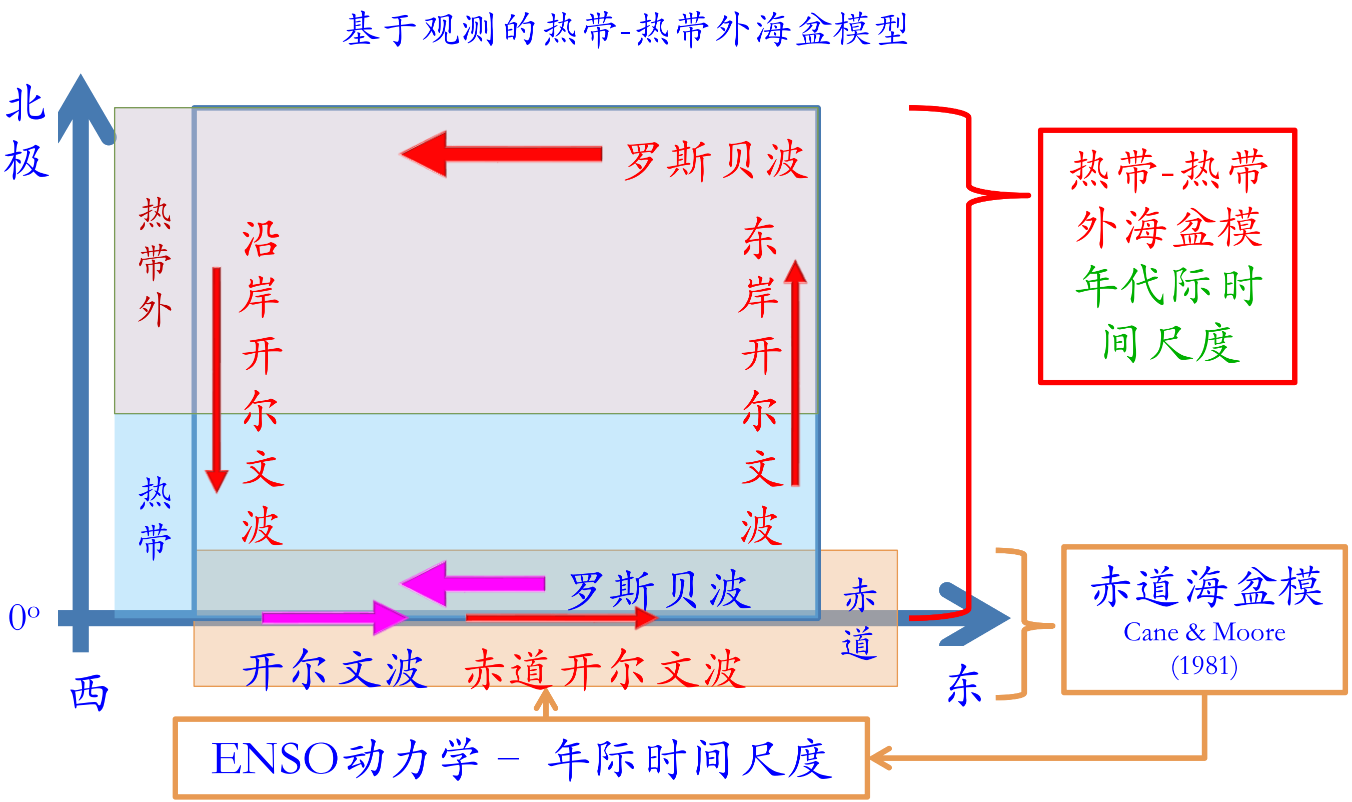
赤道海盆模

Planetary Wave Basin Mode（行星波海盆模）

Effective northern basin boundary



Planetary Wave Basin Mode



An Ocean GCM Study

Yang, H., Z. Liu and H. Wang, 2004: Influence of extratropical thermal and wind forcing on equatorial thermocline in an ocean GCM. *J. Phys. Oceanogr.*, 34(1), 174-187.

Model and Experiments

- GFDL MOM3

  Domain: the Pacific (40°S-80°N, 100°E-70°W)

  Resolution: 2° x 2°x 32-level. Maximum depth 5500 m

  Boundaries: Solid, restored to Levitus monthly climatology

  Initials: Levitus 95

  Forcing: COADS 1948-2000

  Experiments: CTRL; Only Wind; Only T&S

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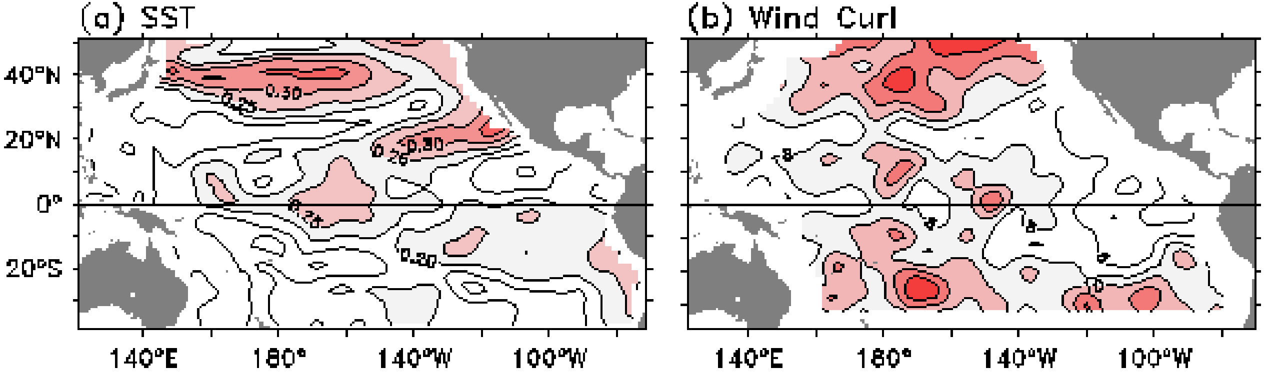
Observation: RMS of SST and Wind



Decadal-scale variability

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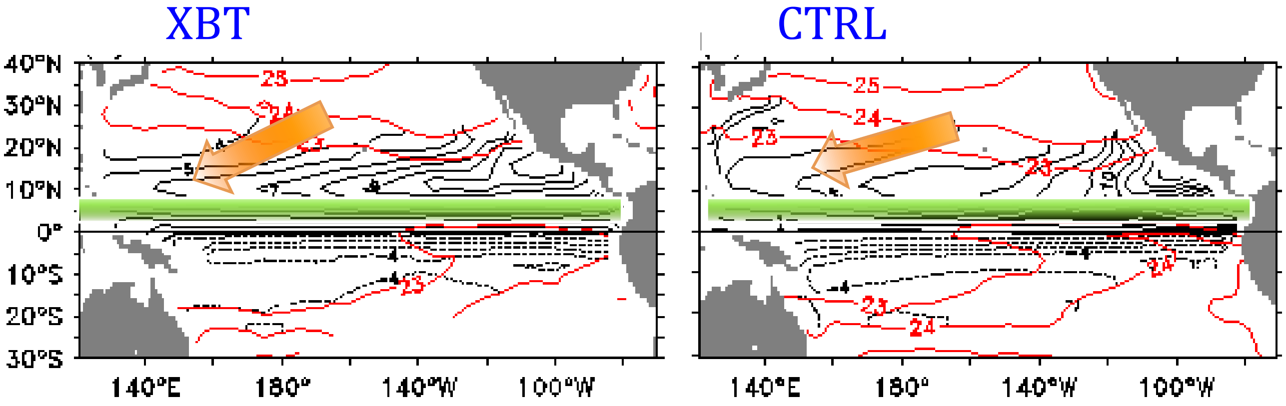
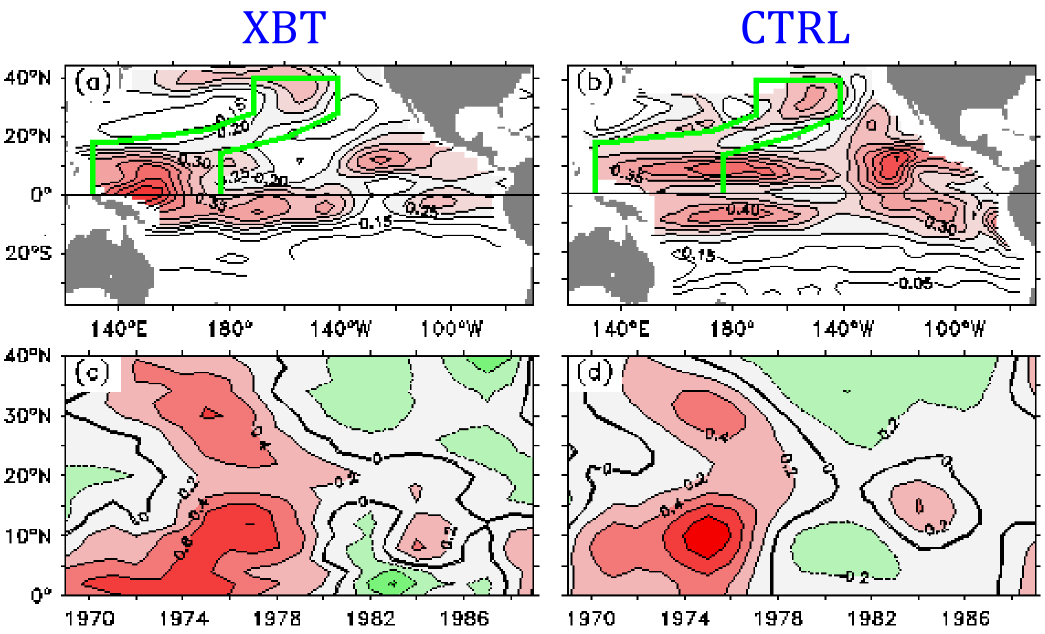
Mean Density & Potential Vorticity



Averaged between 24-26 σ_t

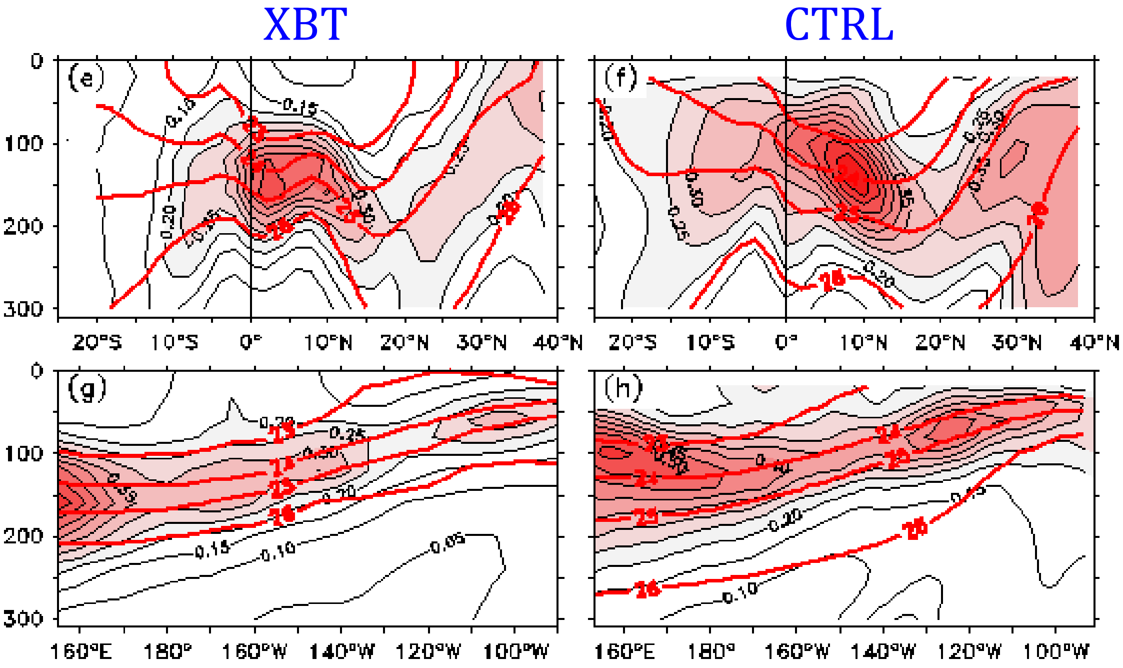
Observation VS. Model: 4-D structure



RMS(T) on 24-26 σ_t

T-evolution on 24-26 σ_t

Observation VS. Model: 4-D structure



Zonal mean RMS(T)

RMS(T) along equator

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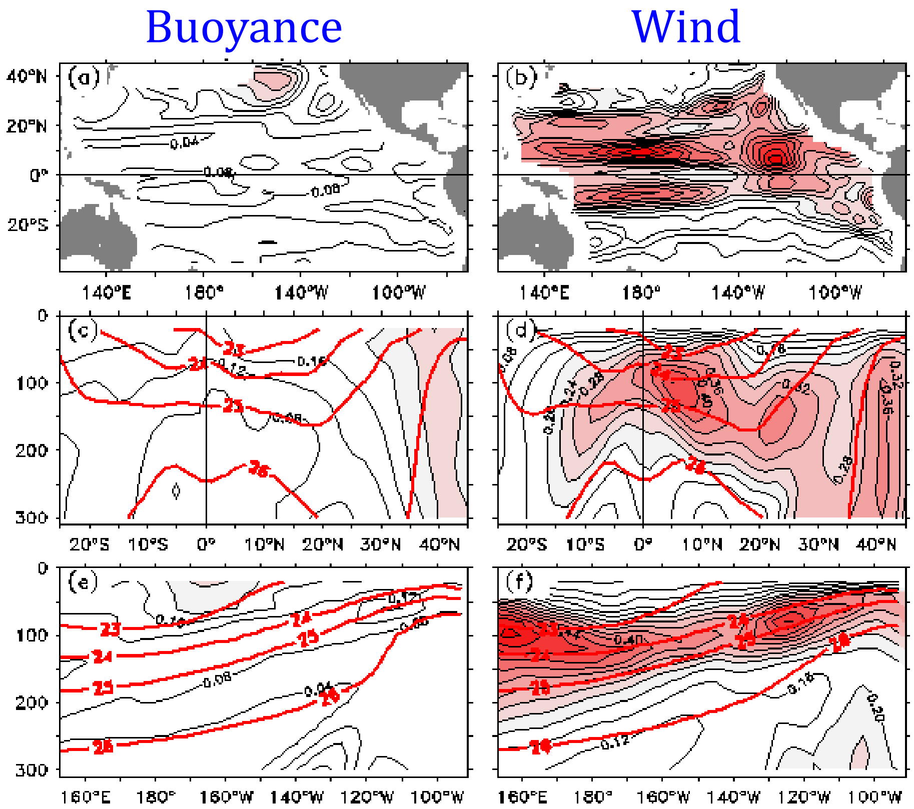
Buoyancy VS. Wind



Wind dominates!

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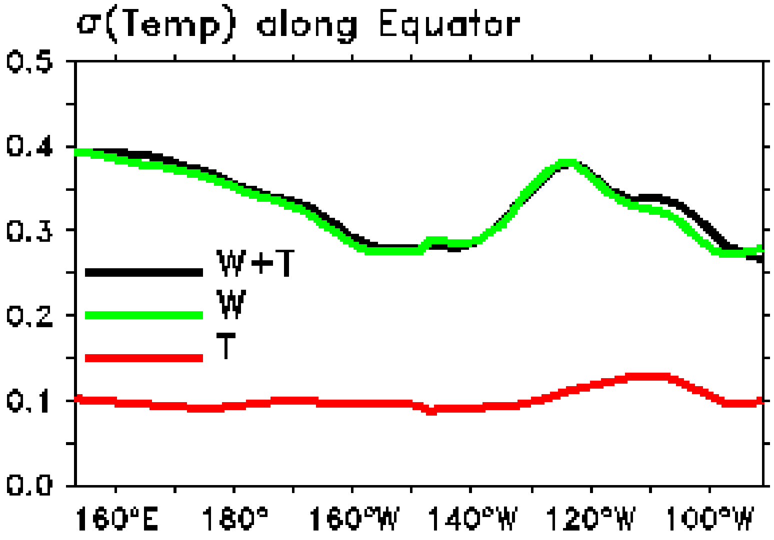
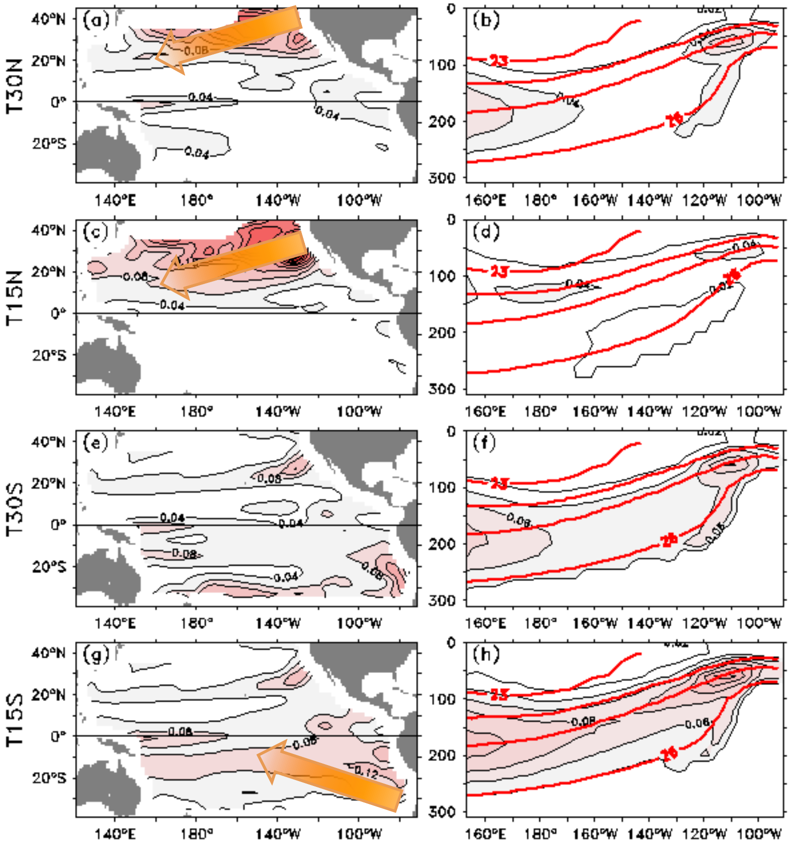
Buoyancy VS. Wind

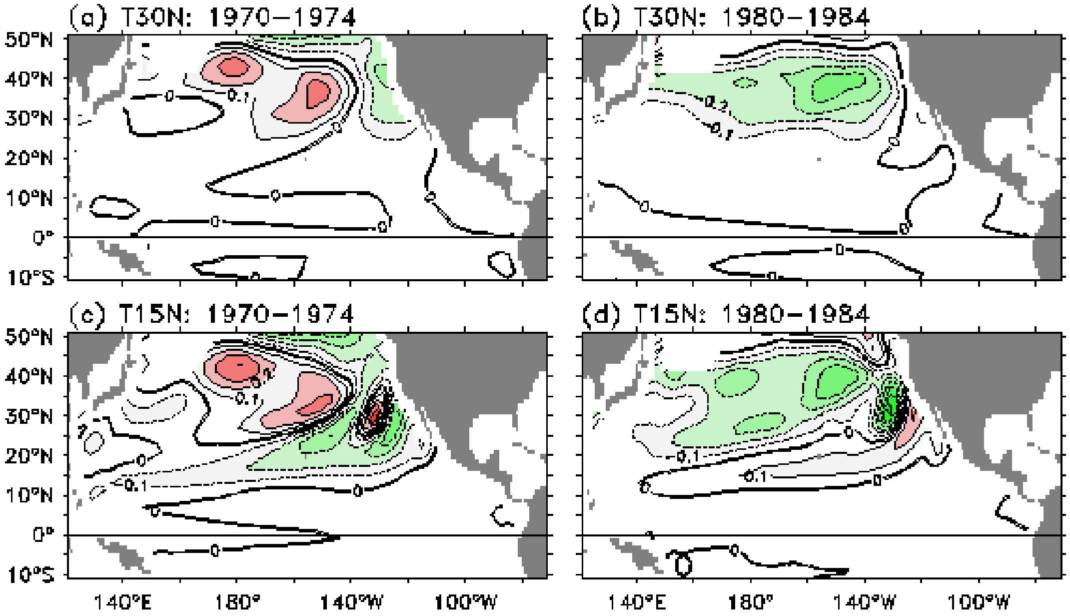


Wind dominates!

Buoyancy Forcing: Where Matters?



Buoyancy Forcing: Where Matters?



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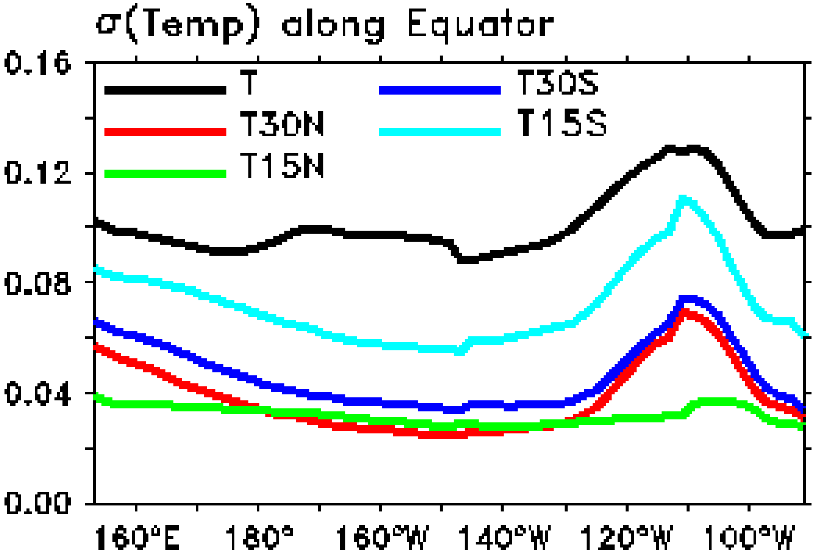
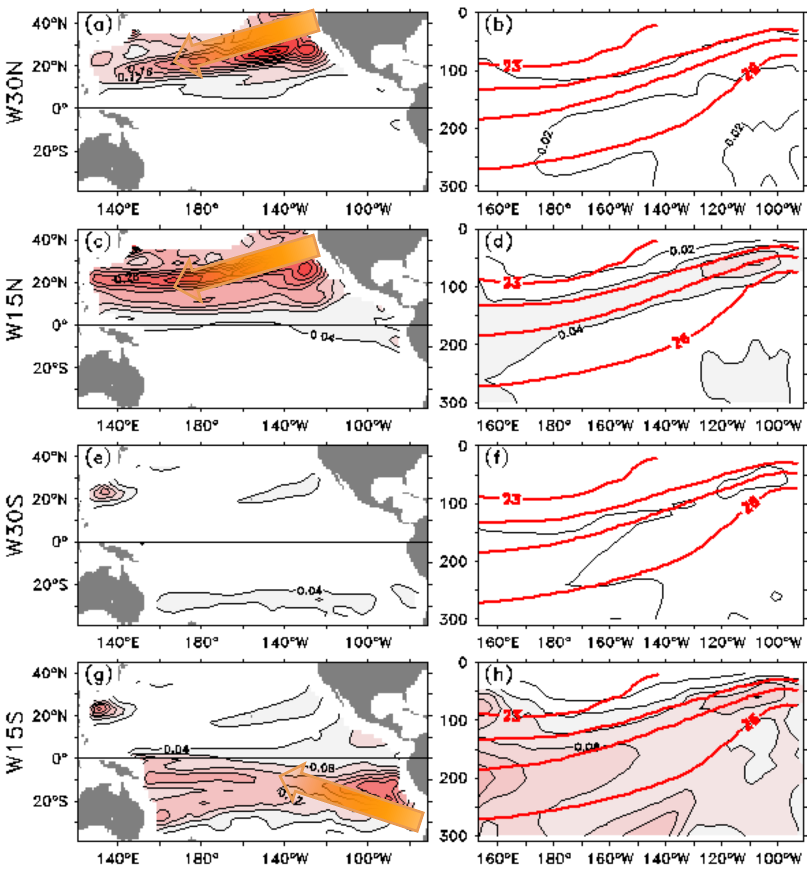
Buoyancy Forcing: Where Matters?



SH > NH

30N > 15N

Wind Forcing: Where Matters?



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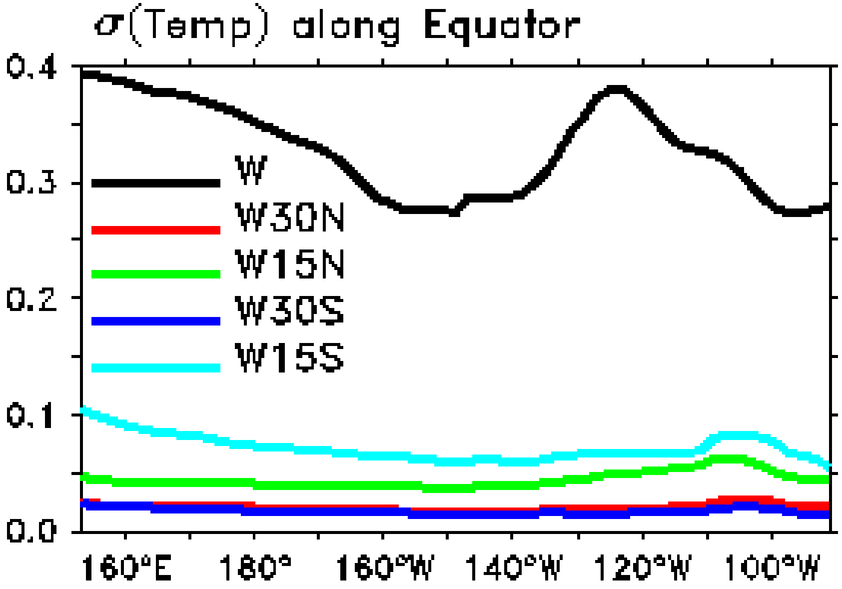
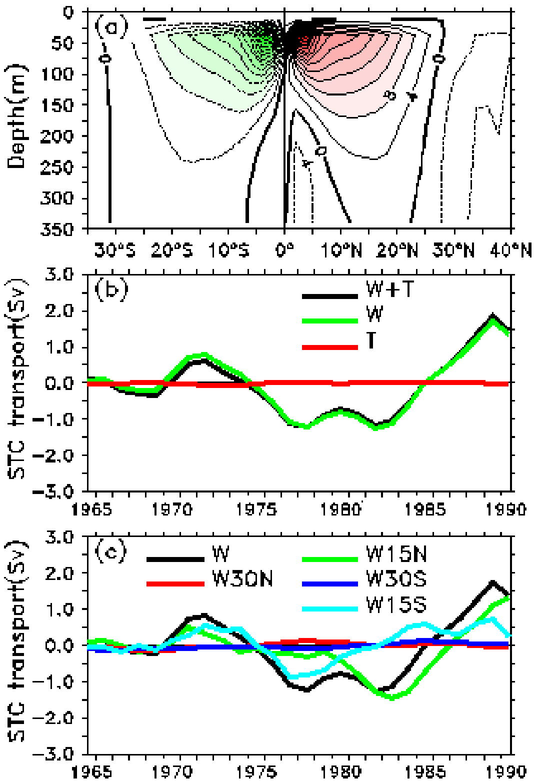
Wind Forcing: Where Matters?



SH ~ NH

Low > High

Summaries



- STC: critical passage
- Extratropics ➔ Tropics
  Wind perturbation dominates
- Buoyance forcing
  Mean advection
  Extratropical forcing
  Southern Hemisphere
- Wind forcing
  Tropical forcing
  Symmetric

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Motivation

To determine Quantitative (定量) impact

- Extratropics ➔ Tropics*
- Tropics ➔ Extratropics
- SH ➔ Tropics ➔ NH
- NH ➔ Tropics ➔ SH
- Pacific VS. Atlantic

in a Fully Coupled Earth System

Fundamentally Important !

Coupled Atmosphere-Ocean GCM Studies

Yang, H. and Z. Liu, 2005: Tropical-extratropical climate interaction as revealed in idealized coupled climate model experiments. *Climate Dynamics*, 24, 863-879.

Yang, H., H. Jiang, and B. Tan, 2005: Asymmetric impact of the North and South Pacific on the Equator in a coupled climate model. *Geophys. Res. Lett.*, 32(5), L05604

Model and Approach

- Fully coupled climate model (FOAM)

  Atmos. – R15, NCAR-CCM2

  Ocean – 1.4°×2.8°×32-level, GFDL-MOM

  Control Run: 1000 years

  Experiments: 200 years

- Partial coupling (PC) technique

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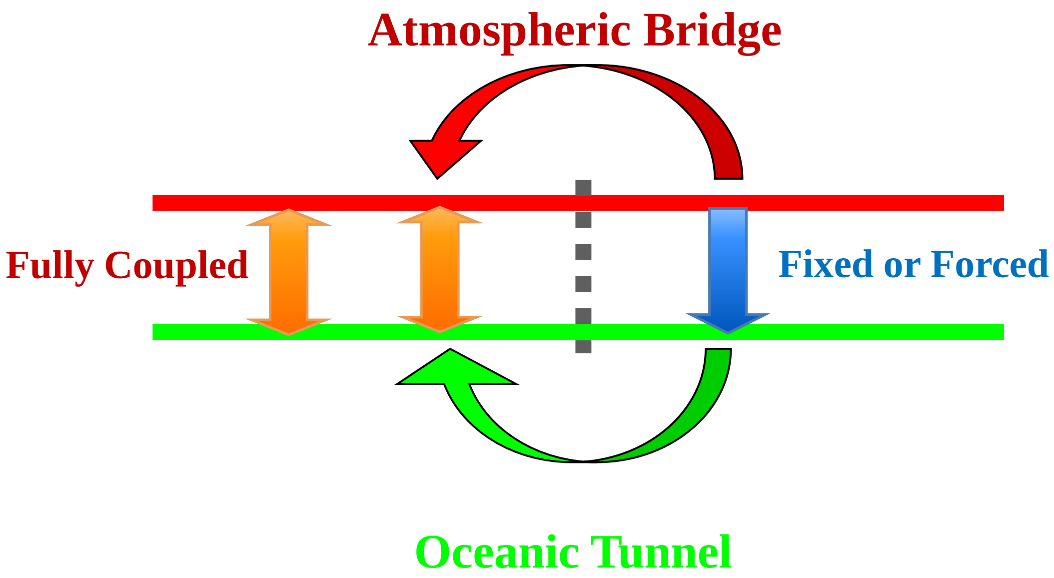
Partial Coupling



Extratropical → Tropical

Extratropical Control of tropical climate on decadal and longer timescales through both the Atmospheric Bridge and Oceanic Tunnel

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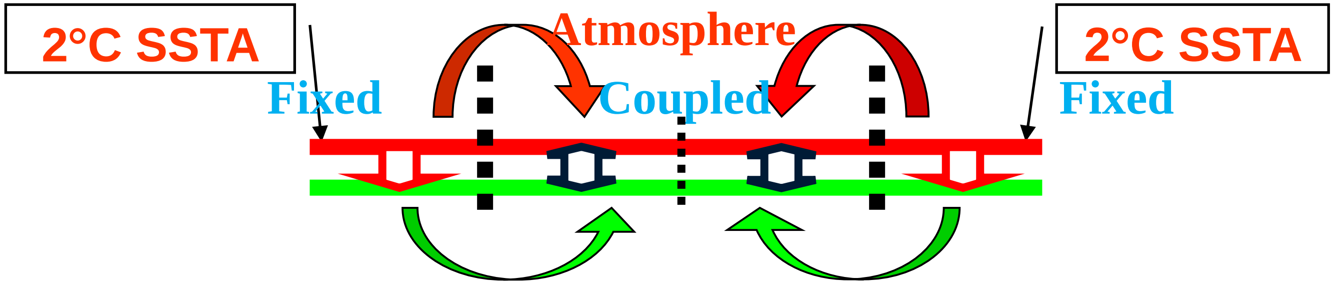
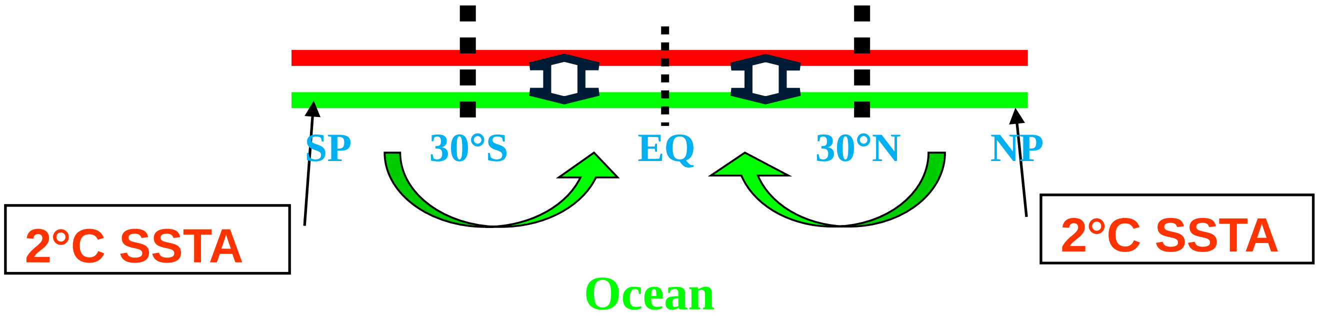
Partial Coupling Experiment

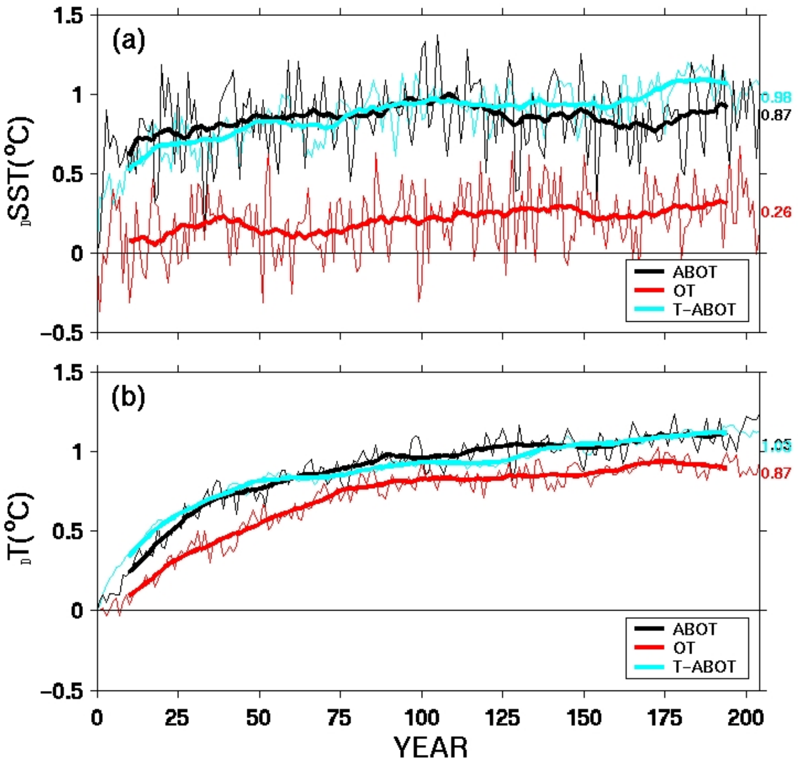
- ABOT: Atmospheric Bridge + Oceanic Tunnel



- OT: Ocean Tunnel only



Tropical Ocean Response



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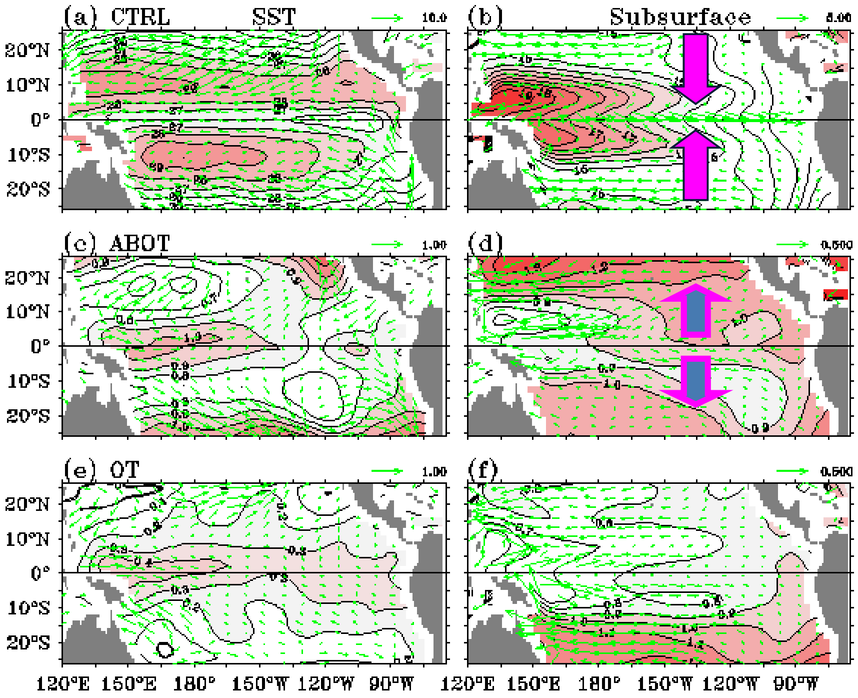
Tropical Response Pattern



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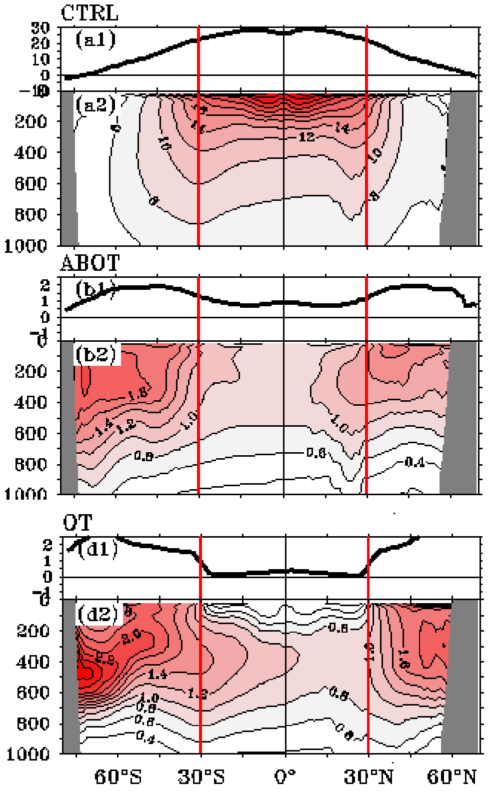
Tropical-Extratropical Connection



Summary

- Extratropics → Tropics

Atmos. Bridge: **70%**

Ocean Tunnel: **30%**

Mechanisms

- ABOT

Atmos. Bridge:

Ex-SST ↑ ⇒ ∇SST ↓ ⇒ HC ↓ ⇒ ITCZ ↓ ⇒ Wind ↓ ⇒ LH ↓ ⇒ EQ-SST ↑

***Ocean. Tunnel**:

HC ↓ ⇒ STCs ↓ ⇒ Cold Water Trans. ($V'T$) ↓ ⇒ EQ-SST ↑

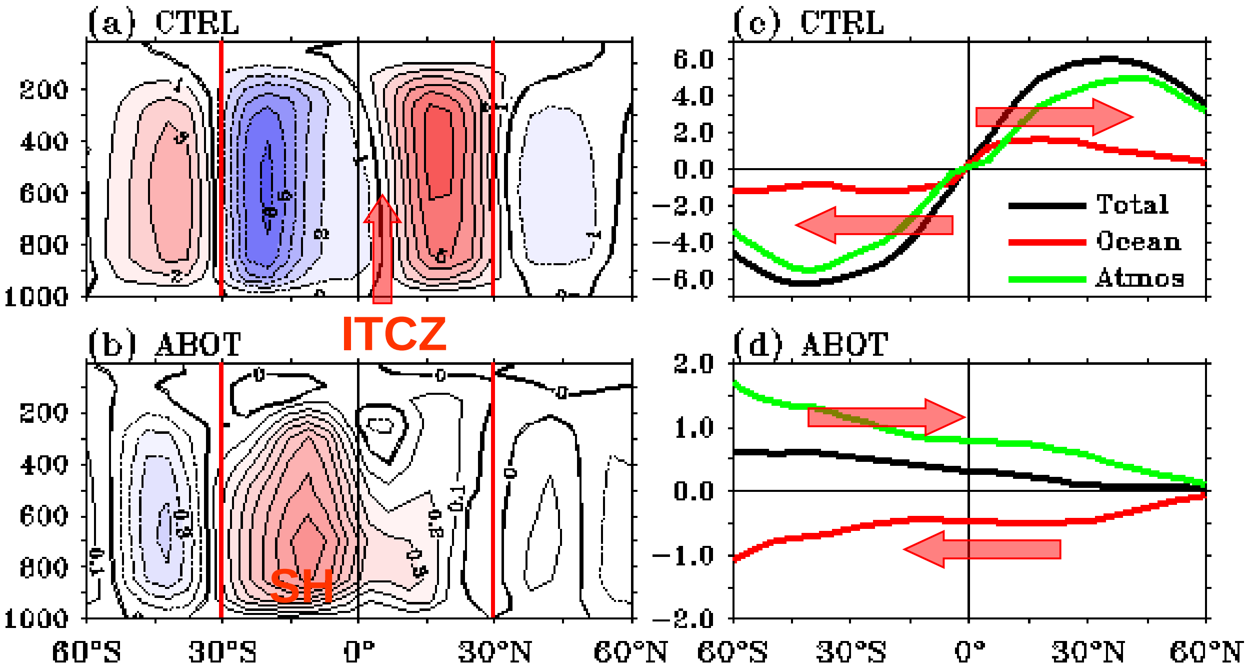
Warm Anomaly Subduction (VT', WT') ↑ ⇒ EQ-SST ↑

- OT

Ocean. Tunnel:

Warm Anomaly Subduction (VT', WT') ↑ ⇒ EQ-SST ↑

Hadley Cell and Heat Transport



Mechanisms of Atmospheric Bridge

- Ensemble experiments: 12-member, 12-year/exp
- Same as ABOT
- Ensemble mean: 1st year

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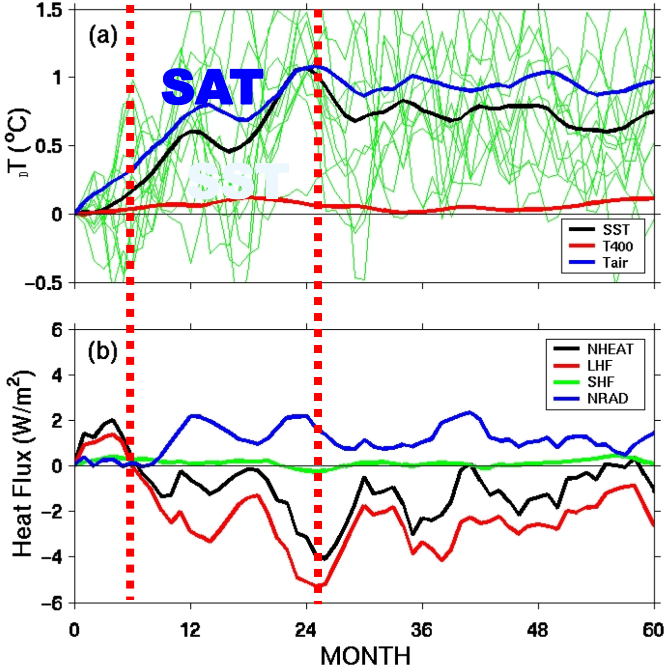
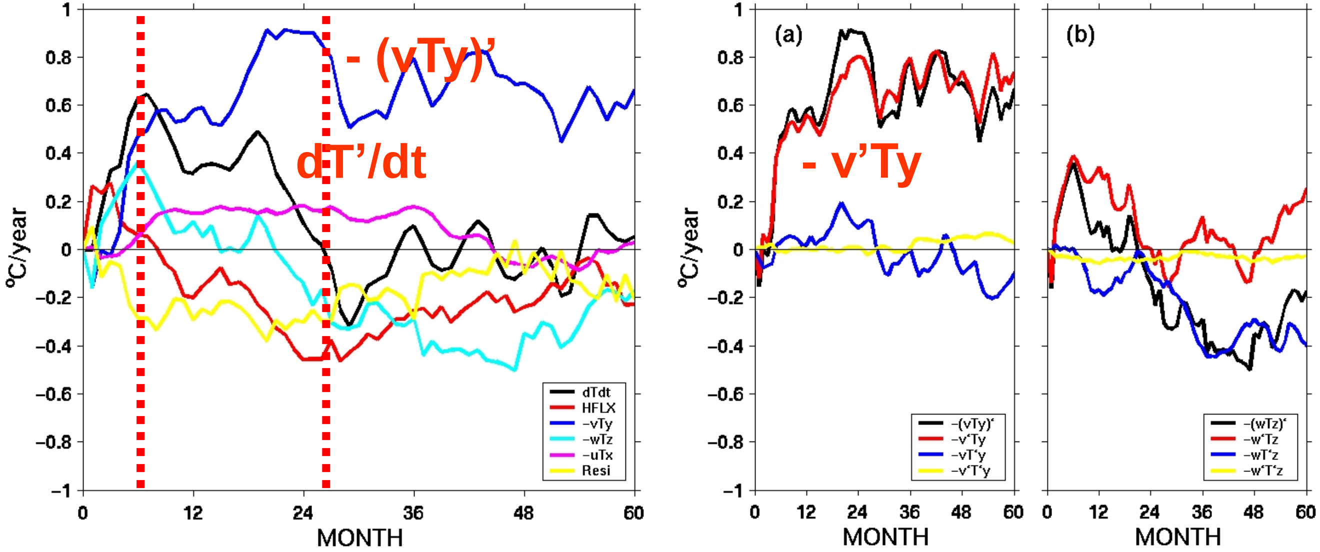
Thermodynamics: Surface Heat Budget



$$\frac{dT}{dt} = \mathrm{HFLX} + \left(-uT_x - vT_y - wT_z\right) + \left(A_h T_{xx} + A_h T_{yy}\right) + \mathrm{Residual}$$

$$\mathrm{HFLX} = F_{SW} + F_{LW} + F_{LH} + F_{SH}$$

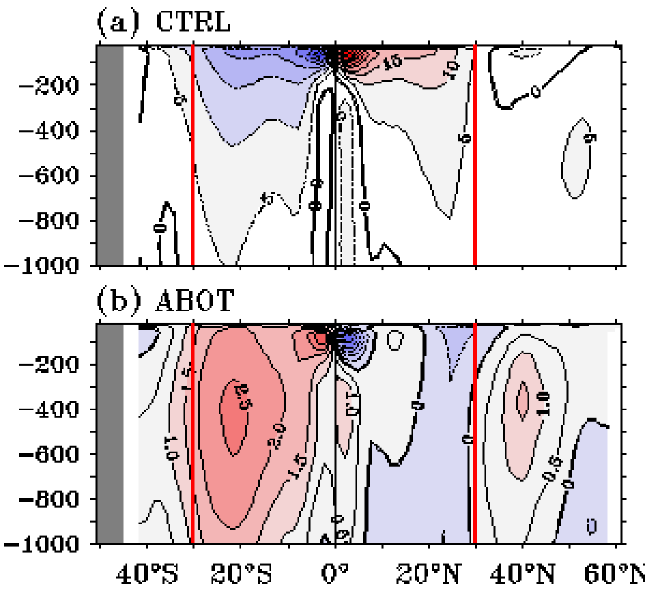
Ocean Dynamics: Term Balance



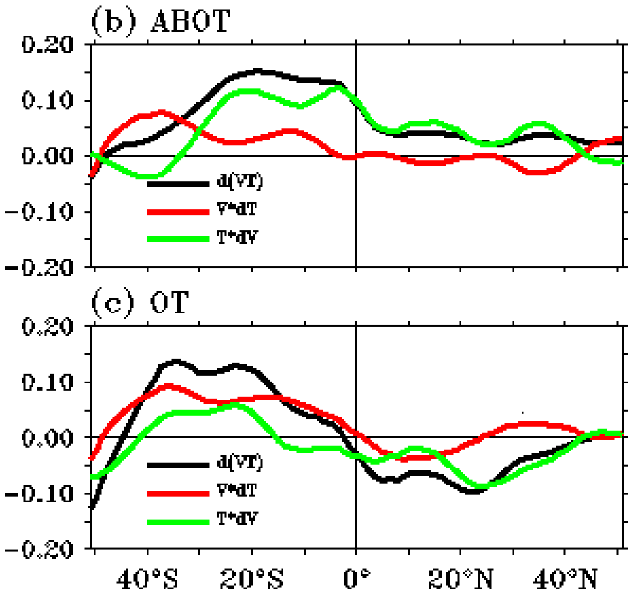
Before 6 months: Heat Flux ➔ T ↑

After 6 months: -(vTy)' ➔ T ↑ or -v'Ty (STC)

Ocean Dynamics: Difference in ABOT and OT



Overturning circulation (STC)

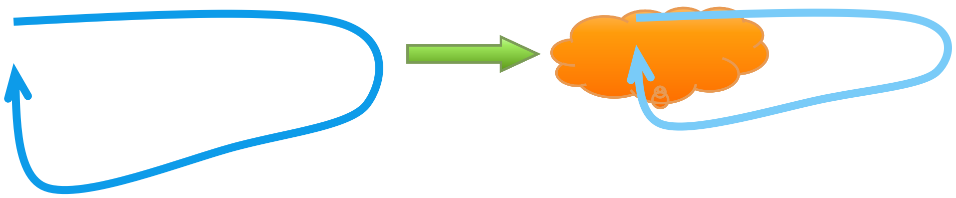


Oceanic Heat Transport

Ocean Dynamics: Difference in ABOT and OT

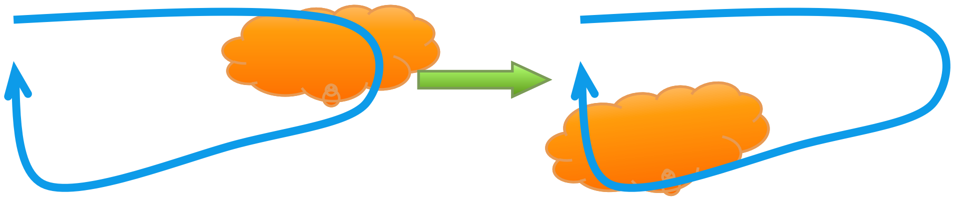
- ***Ocean. Tunnel in ABOT**

Perturbation advection ($V'T$) ↓ ⇒ EQ-SST ↑



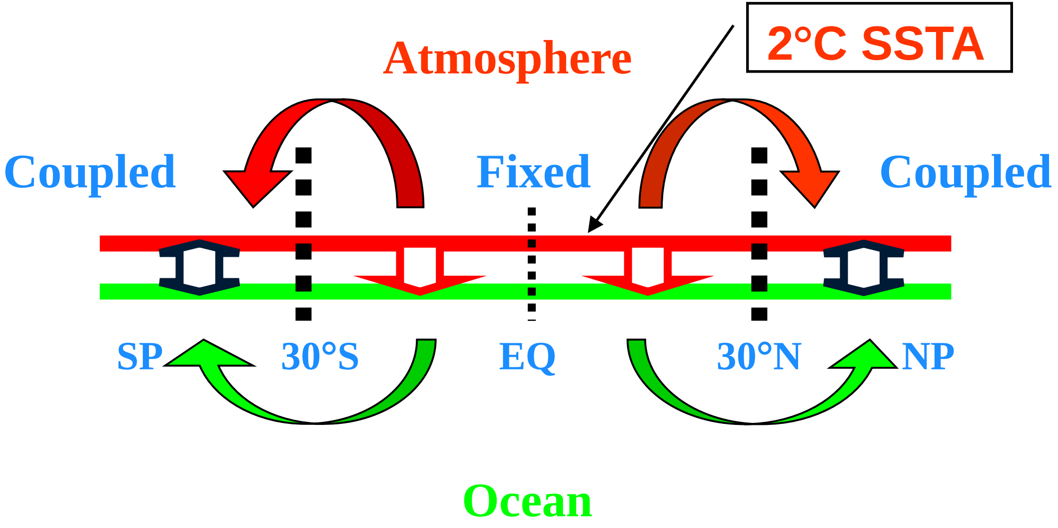
- **Ocean. Tunnel in OT**

Mean Subduction (VT', WT') ↑ ⇒ EQ-SST ↑

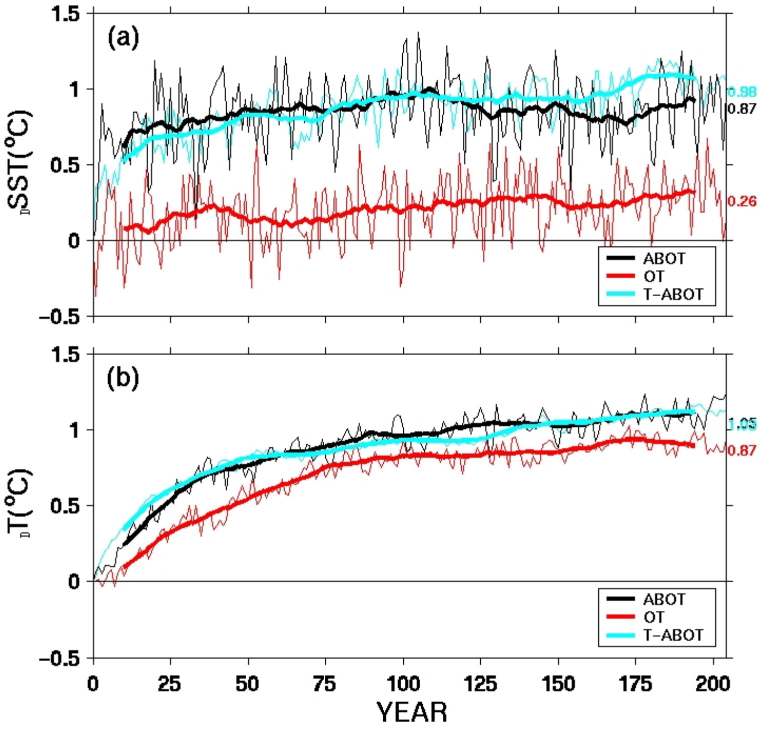


Tropical → Extratropical

- T-ABOT: Tropical Atmospheric Bridge + Ocean Tunnel



Extratropical Response



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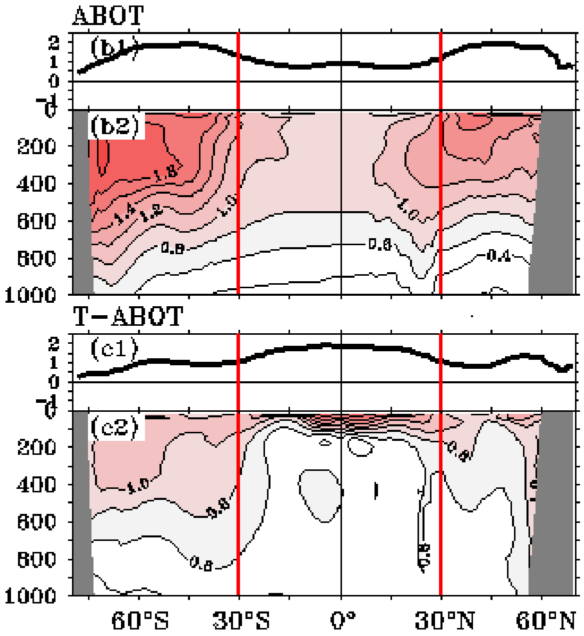
Extratropical Response



Mechanisms

- T-ABOT: Atmos. Bridge Only

EQ-SST ↑ ⇒ ∇SST ↑ ⇒ HC ↑ ⇒ Cloud ↓ ⇒ SW ↑

⇒ Ex-SST ↑↑ ⇐ sea ice – albedo feedback

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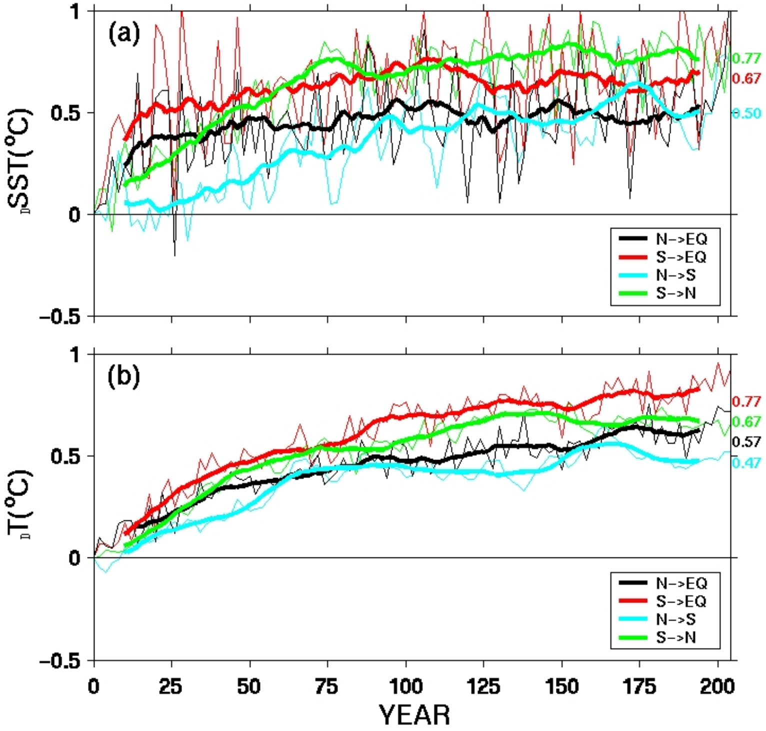
Inter-Hemispheric Interaction

SH ⇔ EQ ⇔ NH



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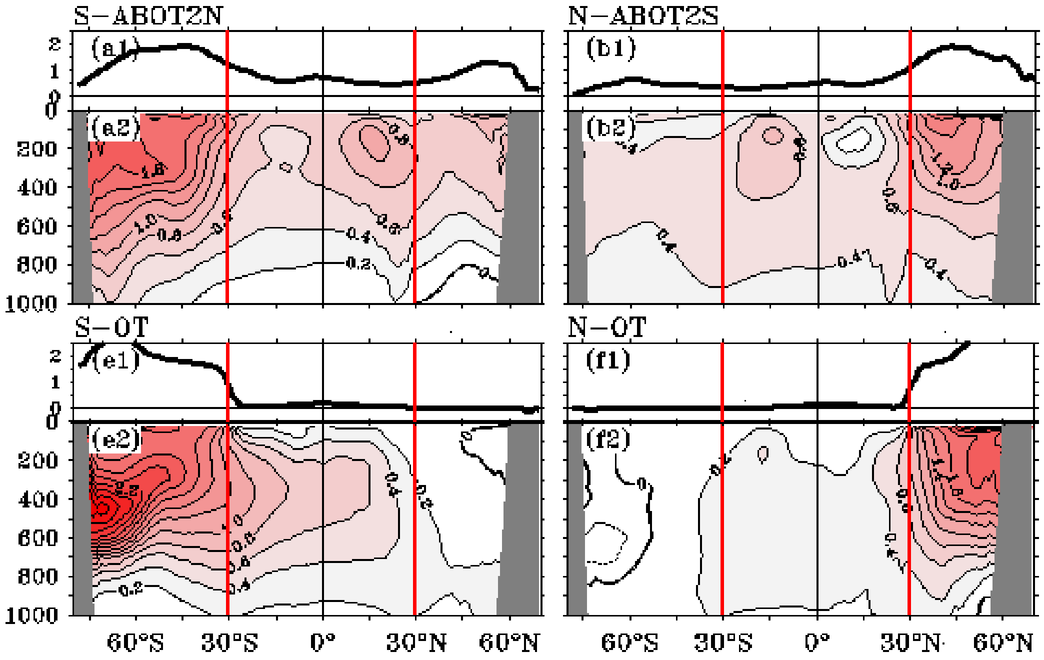
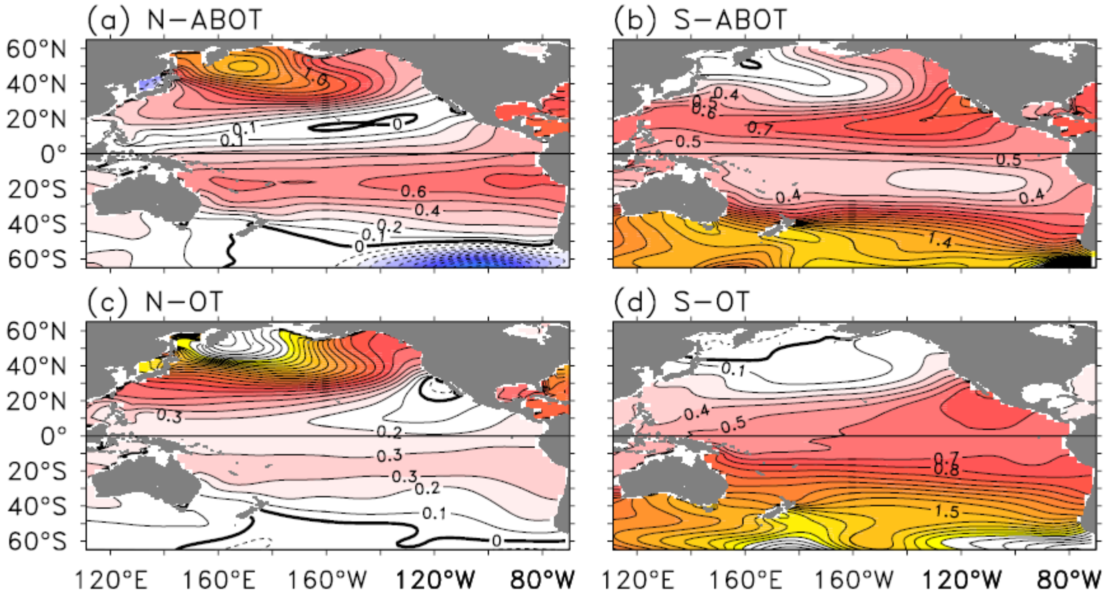
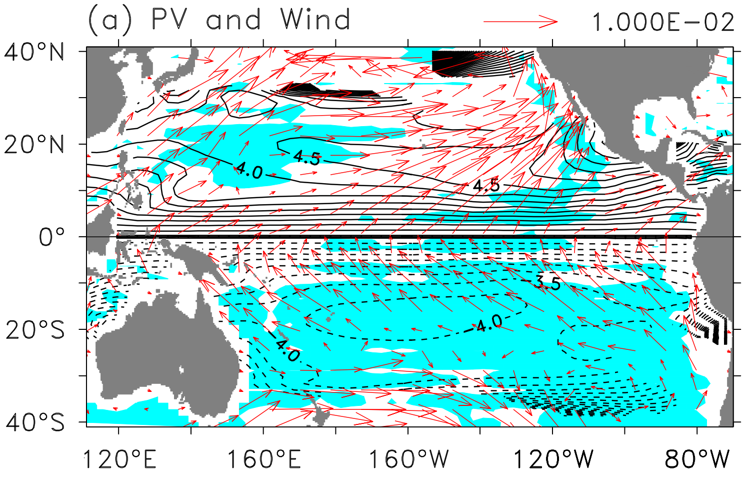
Inter-hemispheric Interaction



Inter-hemispheric Interaction



Mechanism: Potential Vorticity



PV at 24-26 σ_t , Surface wind and Ekman pumping

Yang, H., H. Jiang, and B. Tan, 2005: Asymmetric impact of the North and South Pacific on the Equator in a coupled climate model. *Geophys. Res. Lett.*, 32(5), L05604

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Summaries

- Equal impact: Tropics ⇔ Extratropics
- Extratropics ➔ Tropics

Atmos. Bridge: 70%; **Ocean Tunnel: 30%**

- Tropics ➔ Extratropics

Atmos. Bridge: 100%

- SH ➔ EQ **30%** more than NH ➔ EQ
- SH ➔ NH **60%** more than NH ➔ SH
- SH dominates in global climate change

Pacific VS. Atlantic

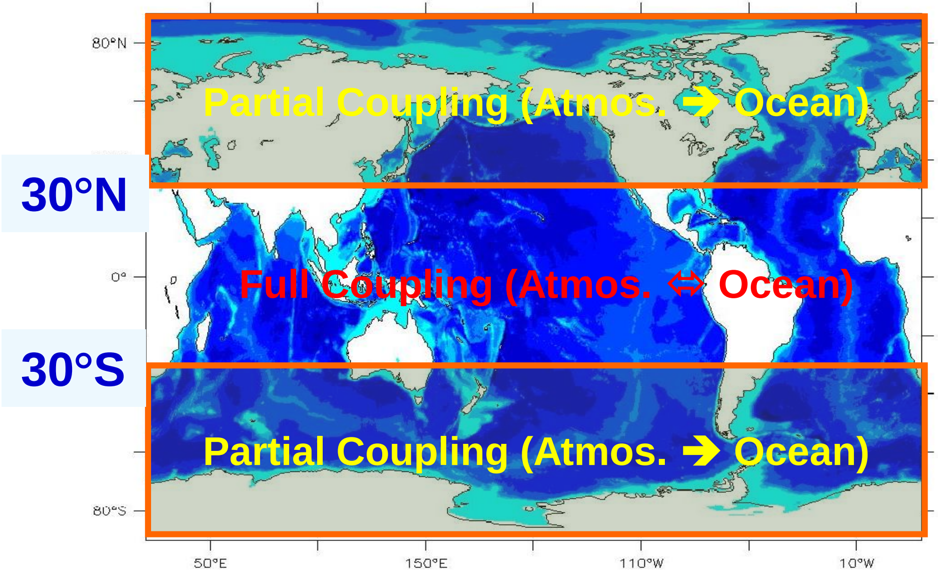
Yang, H., and L. Wang, 2008: Estimating the nonlinear response of tropical ocean to extratropical forcing in a coupled climate model. *Geophys. Res. Lett.*, 35, L15705, doi: 10.1029/2008GL034256.

Yang, H., and L. Wang, 2011: Tropical oceanic response to extratropical thermal forcing in a coupled climate model: A comparison between the Atlantic and Pacific Oceans. *J. Climate*, 24, 3850-3866

Pacific VS. Atlantic: A Summary

- Tropical SST
  - Same magnitude in Atlantic and Pacific
- Tropical thermocline
  - Much stronger in Atlantic than in Pacific
- Atlantic STC (wind-driven)
  - Asymmetric change and critical role

Experiments



- PC: Clim. + SSTA
- SSTA: ±2℃, ±4℃, ±8℃; 200 years
- P – Warming exp; M – Cooling exp.

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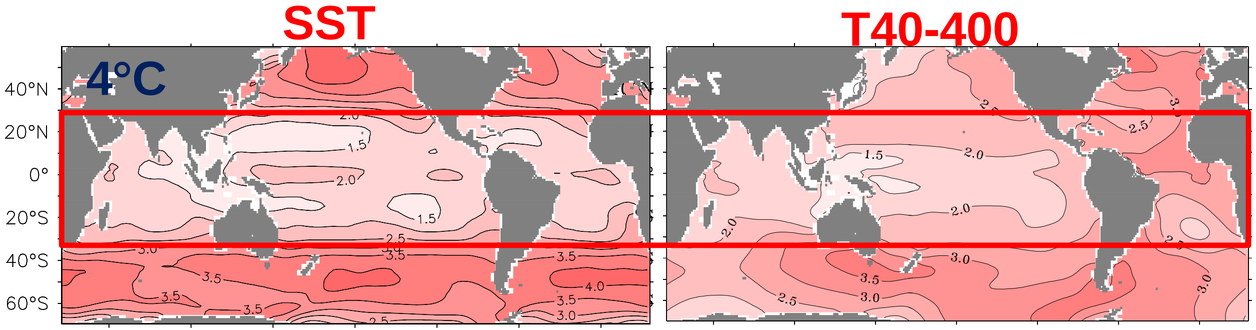
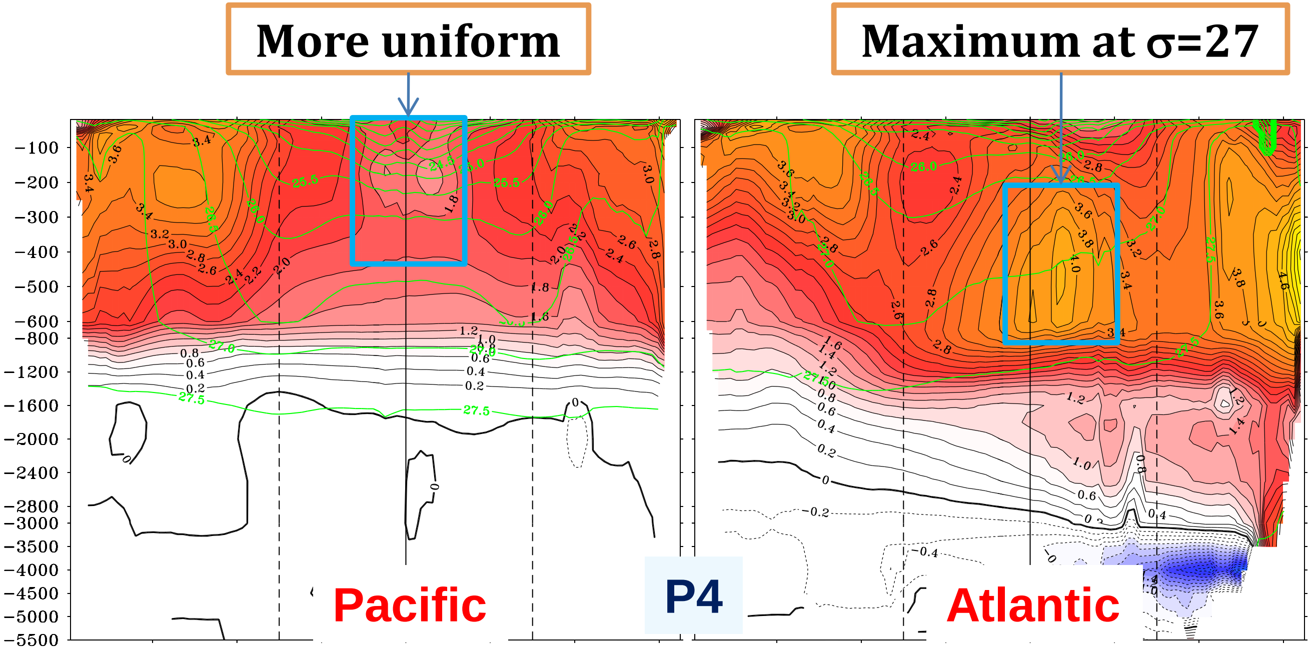
SST and Thermocline Changes



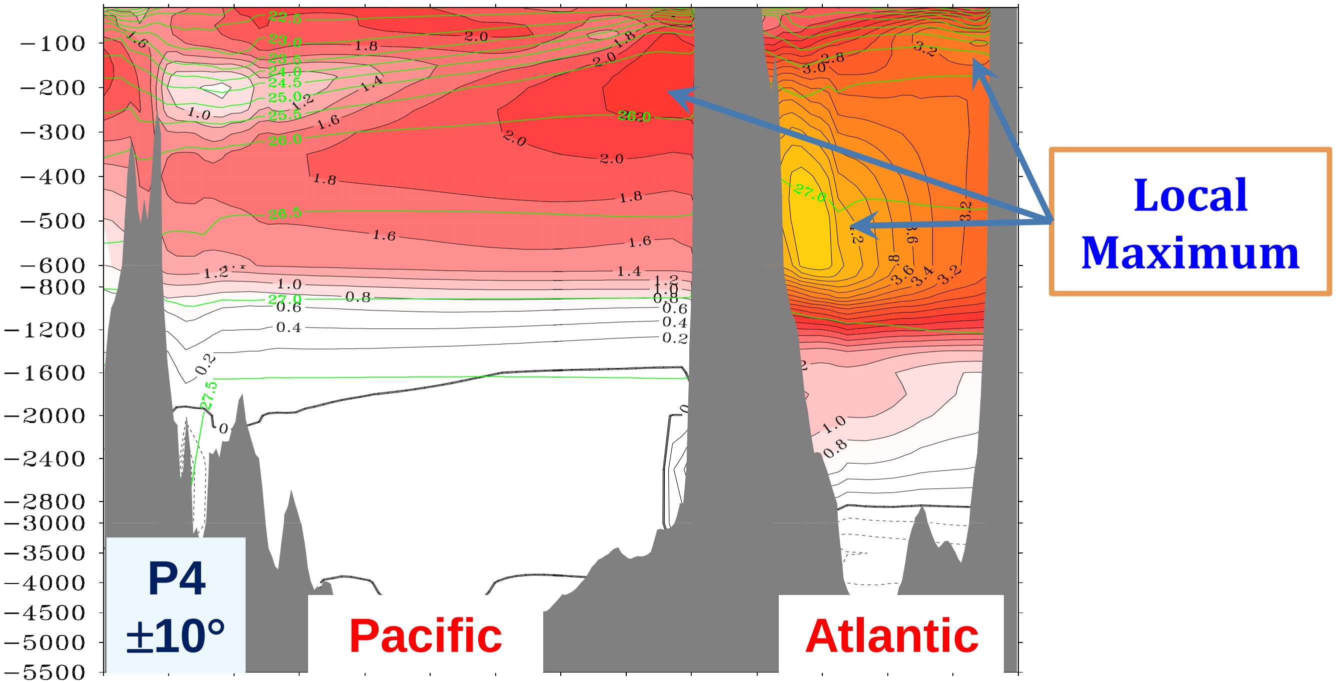
Meridional Section of Temperature Changes



Trop. Atlantic ≈ 2 x Pacific, different depth

Green line – Mean Density; Color – Temperature change

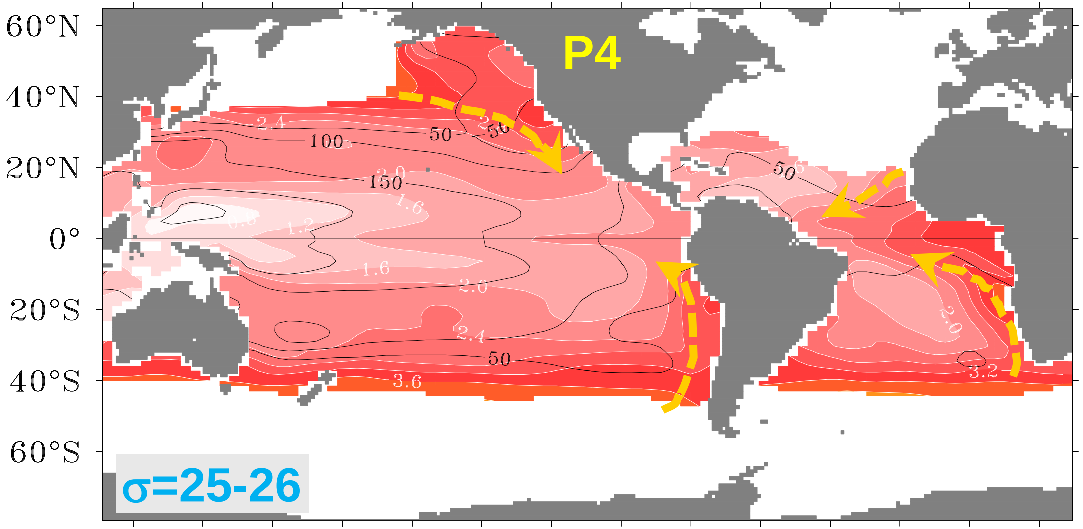
Zonal Section of Temperature Change



Trop. Atlantic ≈ 2 x Pacific, different depth

Green line – Mean Density; Color – Temperature change

Temperature Changes on Isopycnal Level



- Shallow subduction
- Pacific: Eastern boundary pathway from the SH
- Atlantic: Eastern boundary pathway from the SH
  Interior pathway from the NH

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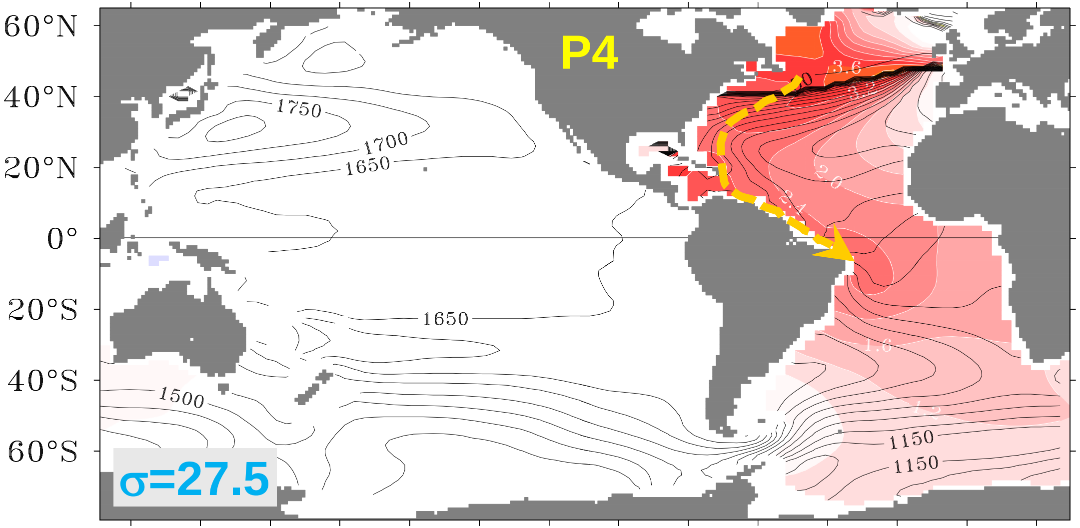
Temperature Changes on Isopycnal Level



- Intermediate water subduction
- Atlantic: Western boundary pathway from the NH

Black contour – depth of 27.5; color – T on 27.5

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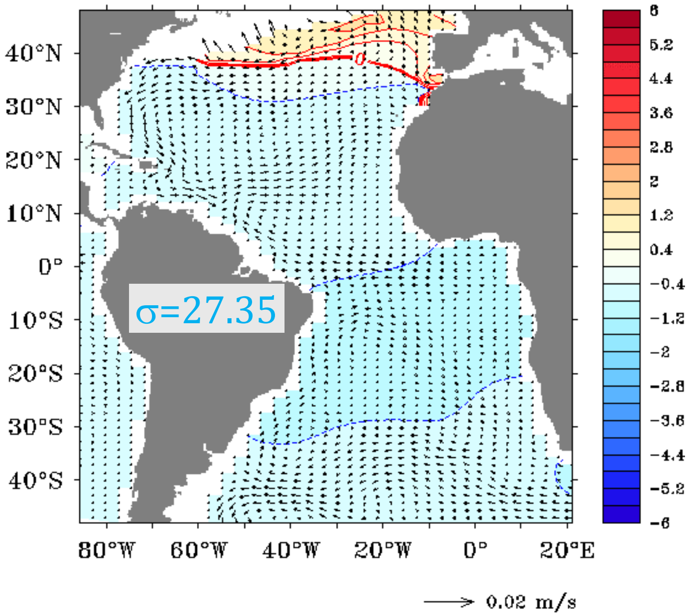
Basin Mode in CGCM

行星波海盆模，耦合模式验证了热带-热带外海盆模



中纬度大西洋影响热带的

路径

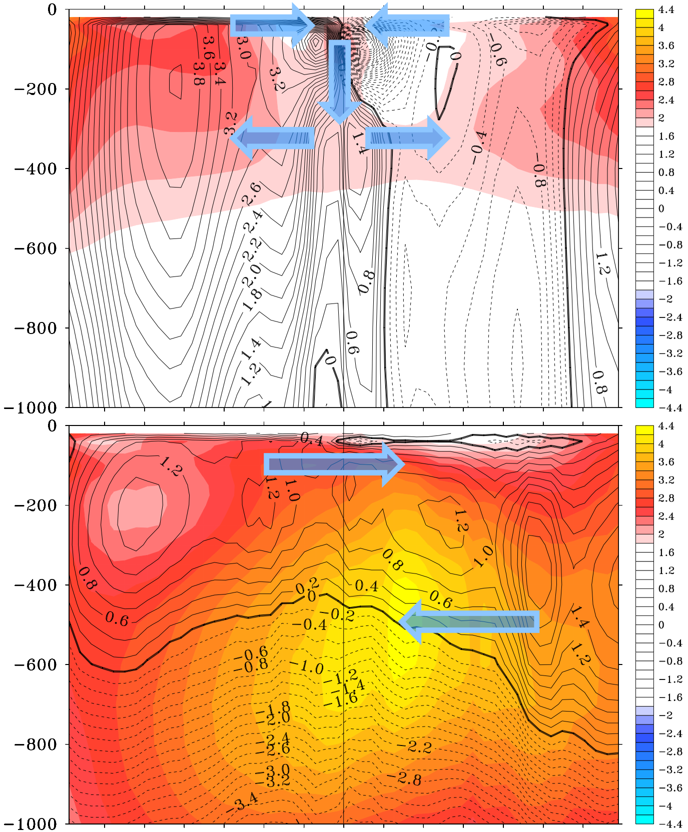
强度

时间尺度

Differences

- Differences (subsurface)
  - Much stronger in Atlantic
  - Deeper in Atlantic
  - Western Atlantic VS. Eastern Pacific

Changes in STC and Temperature



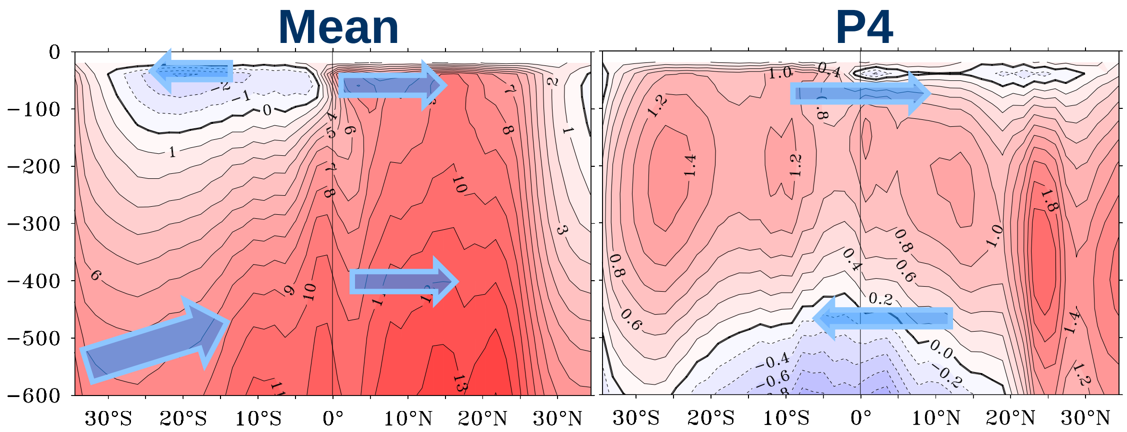
Pacific:

- Tropical temperature change ⬄ STCs change in both hemisphere, ***V*** & ***W***

Atlantic:

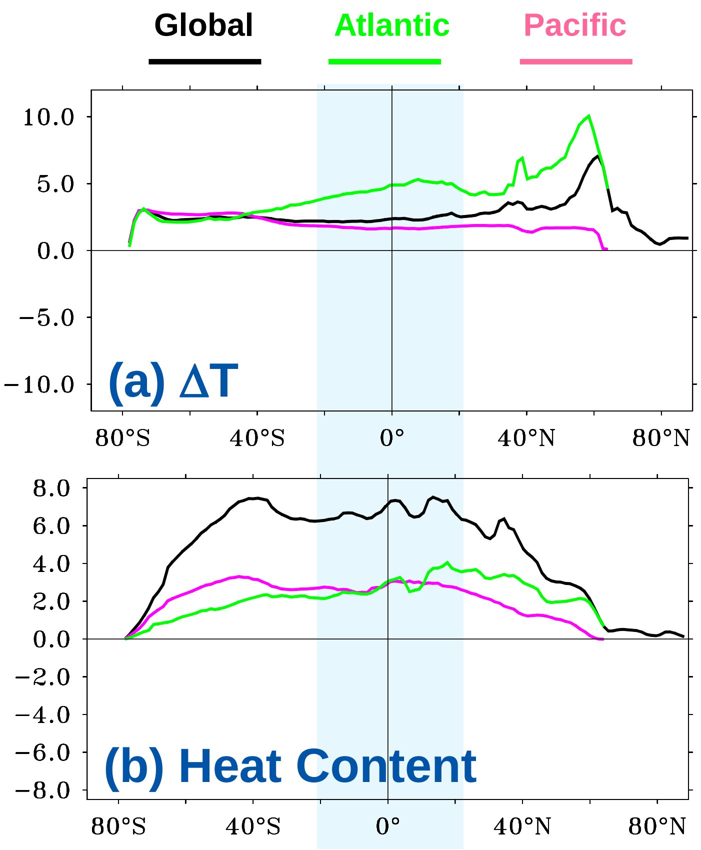
- Tropical subsurface maximum ⬄ Northern STC change, only ***V***

A Close Look at the Atlantic MOC



- MOC: thermohaline, weakened in P4
- STC: thermocline, wind-driven
  - Weakened in the southern branch
  - Strengthened in the northern branch

Atlantic VS Pacific: Relative Role



Zonal and vertical average (ΔT):

- Atlantic >> Pacific

Zonal and vertical integral (Heat content):

- Atlantic ≈ Pacific

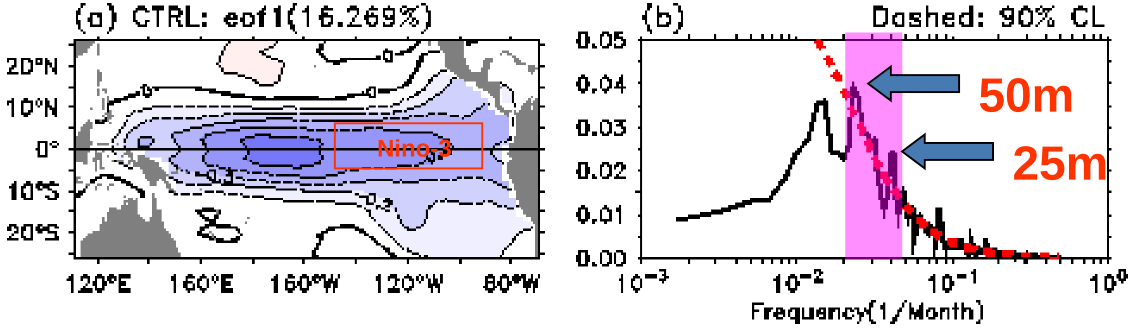
Comparable weighting in global ocean

Extratropics Warming → ENSO

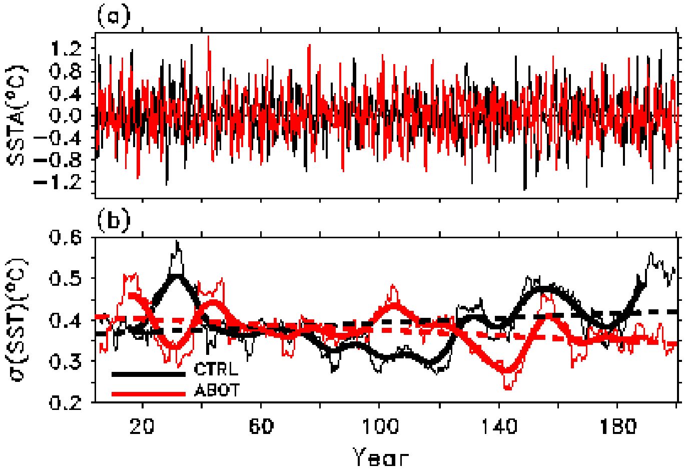
Zhang, Q., H. Yang, Y. Zhong, and D. Wang, 2005: An idealized study of the impact of extratropical climate change on ENSO. *Climate Dynamics*, 25, 869-880

Yang, H., Q. Zhang, Y. Zhong, S. Vavrus, and Z. Liu, 2005: How does extratropical warming affect ENSO? *Geophys. Res. Lett.*, 32(1), L01702

ENSO: 1st EOF mode



ENSO variability: Nino-3 SST



Nino-3: 150W-90W, 5N-5S

Remove:

Mean annual cycle

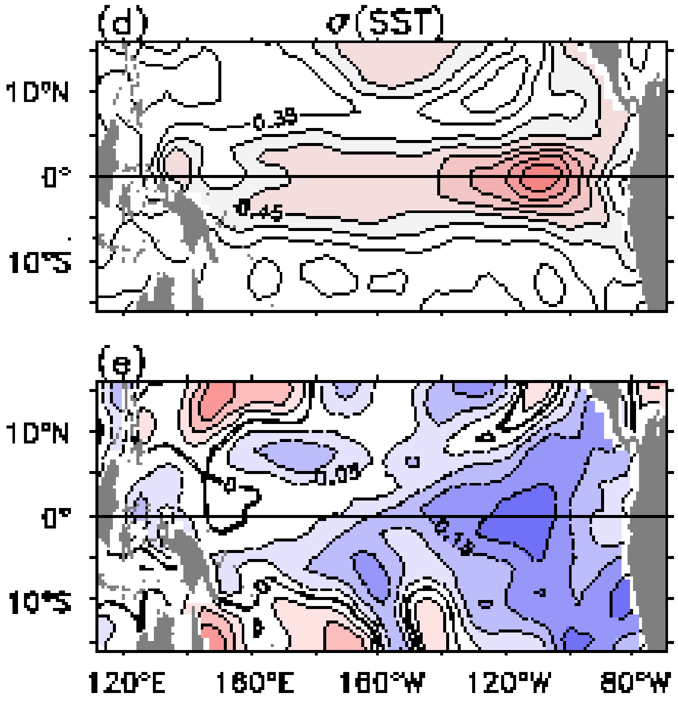
Secular linear trend

5-85 months band-pass filter

Standard Deviation:

10-year sliding window

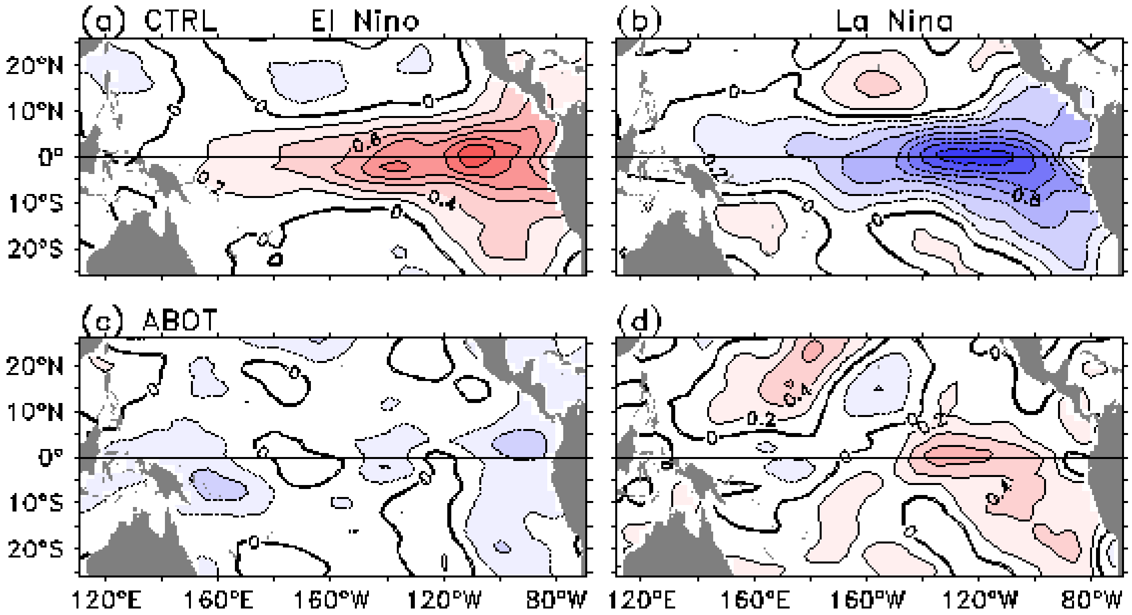
ENSO variability: σ(SST)



CTRL

ABOT

Skewed ENSO: El Nino vs. La Nina



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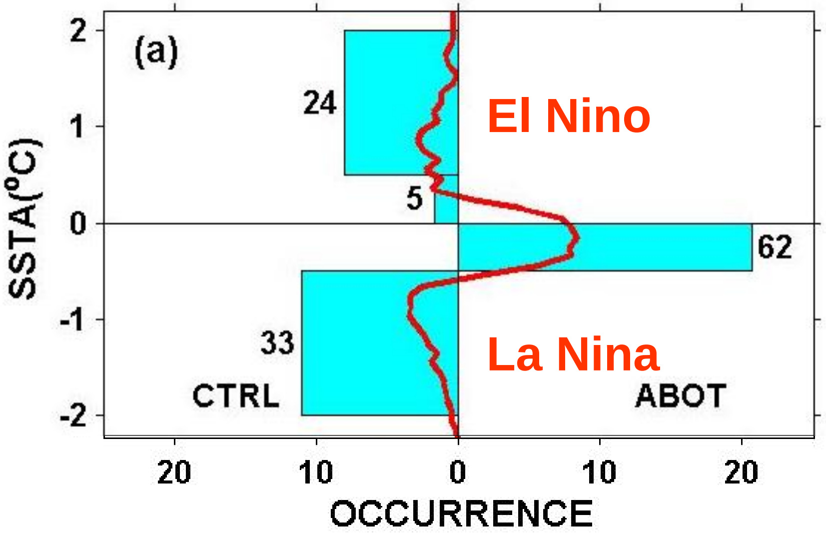
Skewed ENSO: Occurrence



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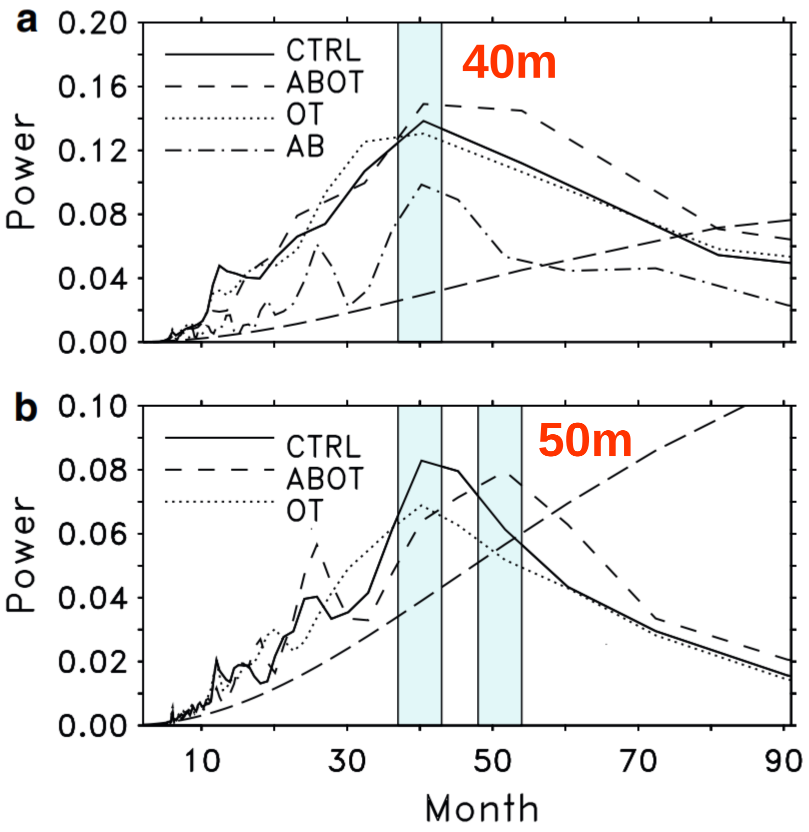
Slowed ENSO

ABOT



Extensive Change in ENSO!

- Intensity
- Pattern
- Frequency

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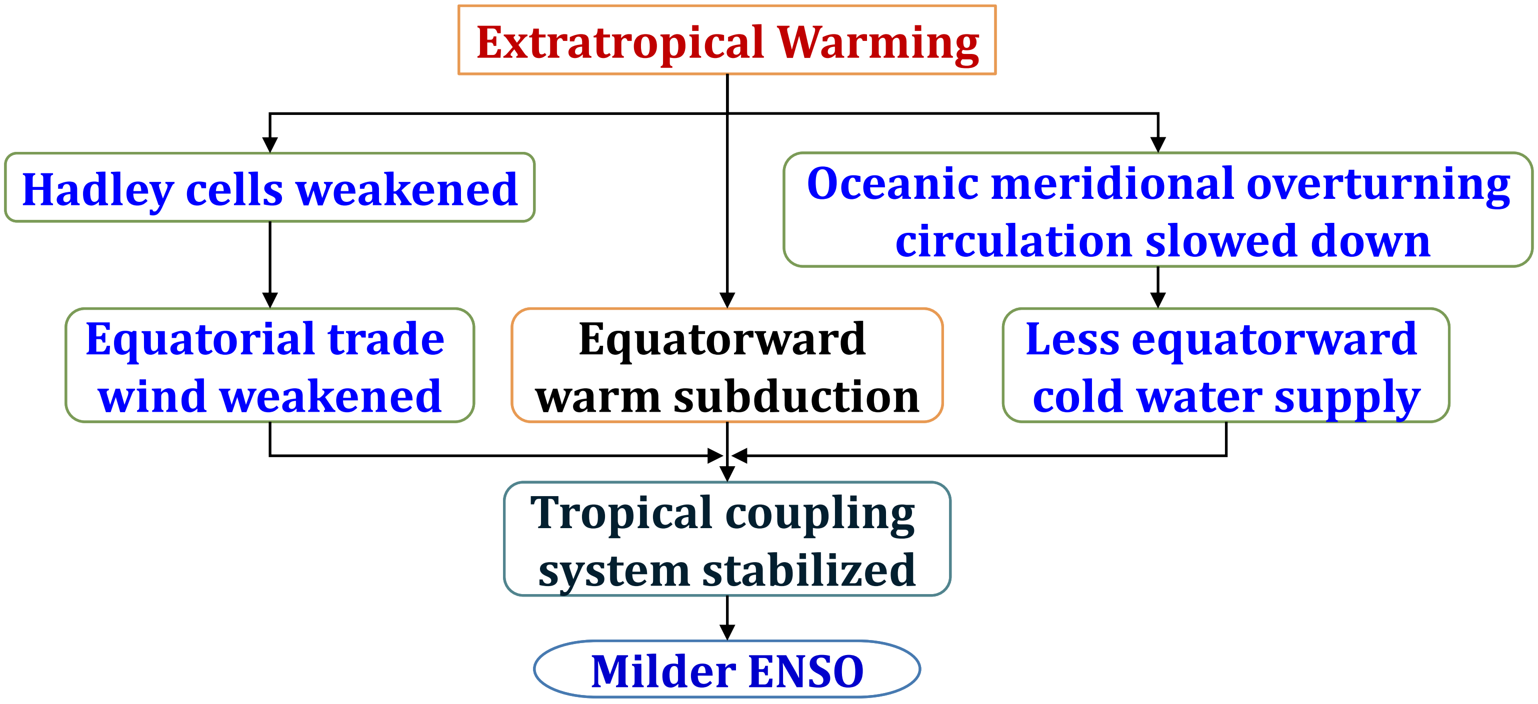
Conclusion Diagram



Implications

- Critical region in global climate change
- Regional contribution to global warming
- PDO: direct and indirect connection
- SH climate crucial for long-term climate prediction

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