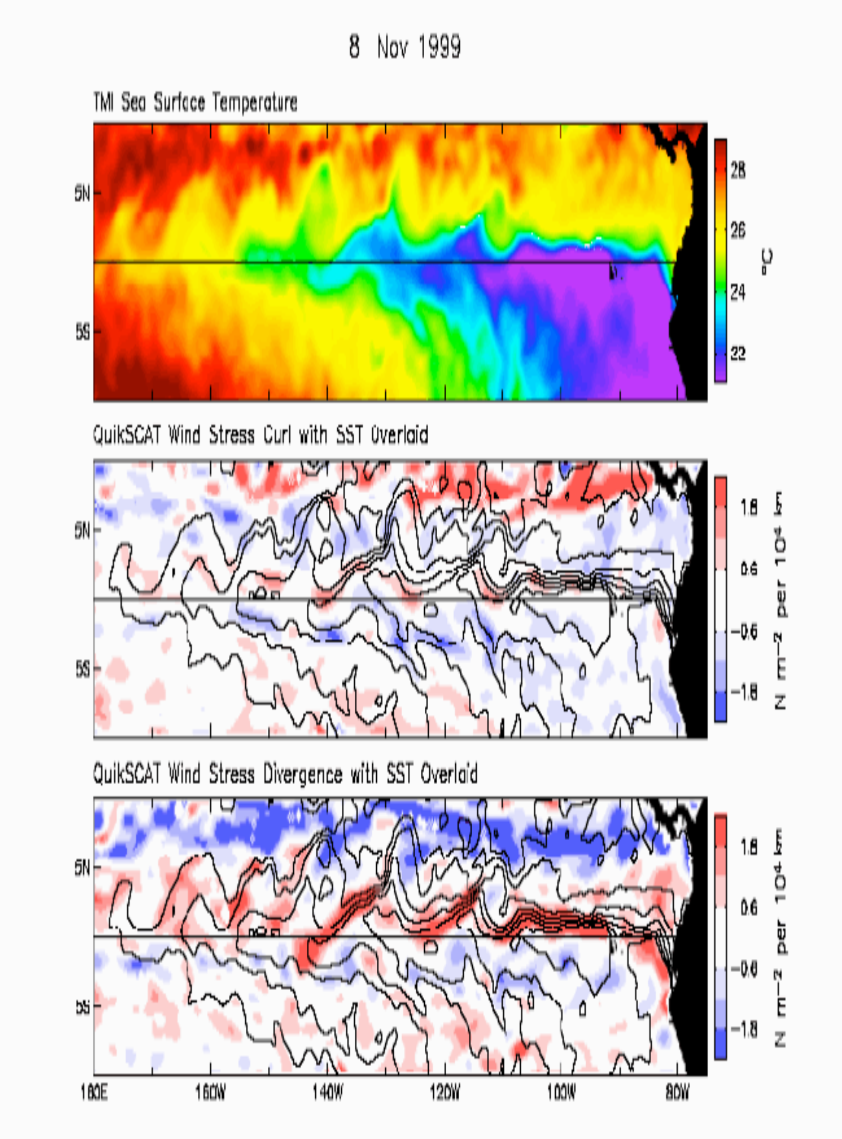
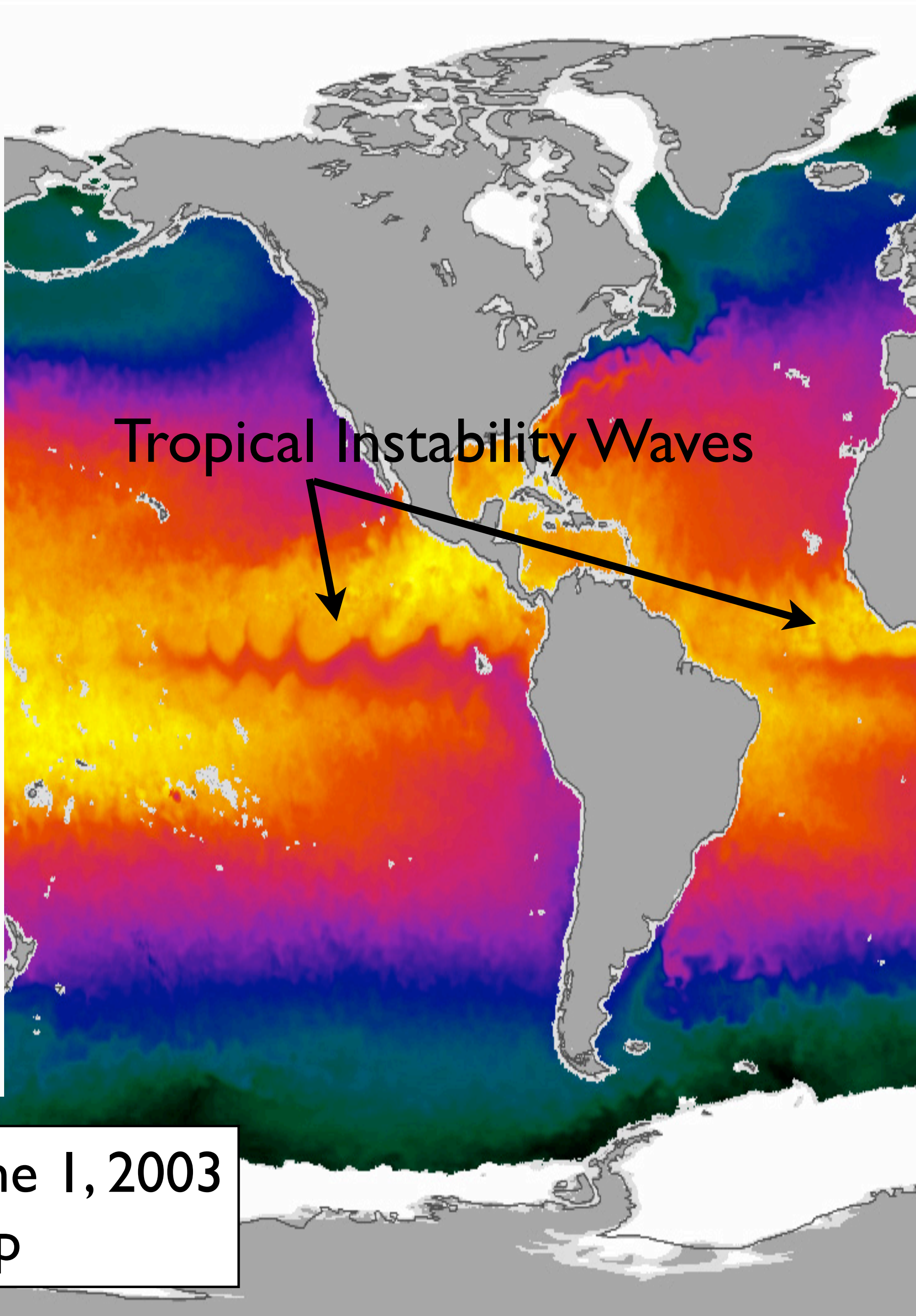
Mesoscale air-sea interactions and regional climate change: the Tropical Instability Waves example

Hyodae Seo, WHOI

KORDI, May 30, 2012





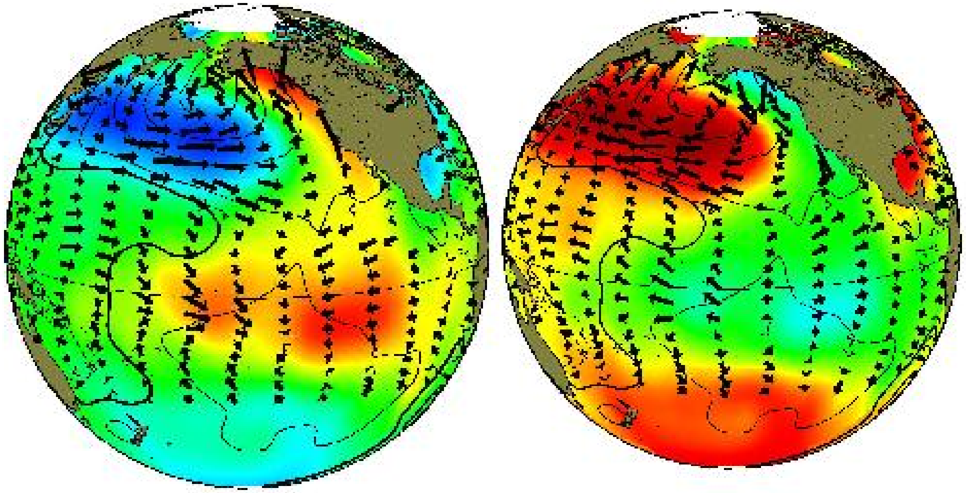
Tropical Instability Waves

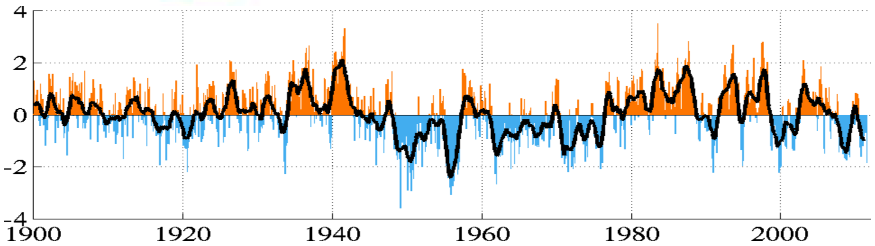
Global SST from AMSR-E on June 1, 2003
http://aqua.nasa.gov/highlight.php

Air-sea interactions on different spatial scales

Oceanic basin scale

Warm Phase PDO   Cold Phase PDO



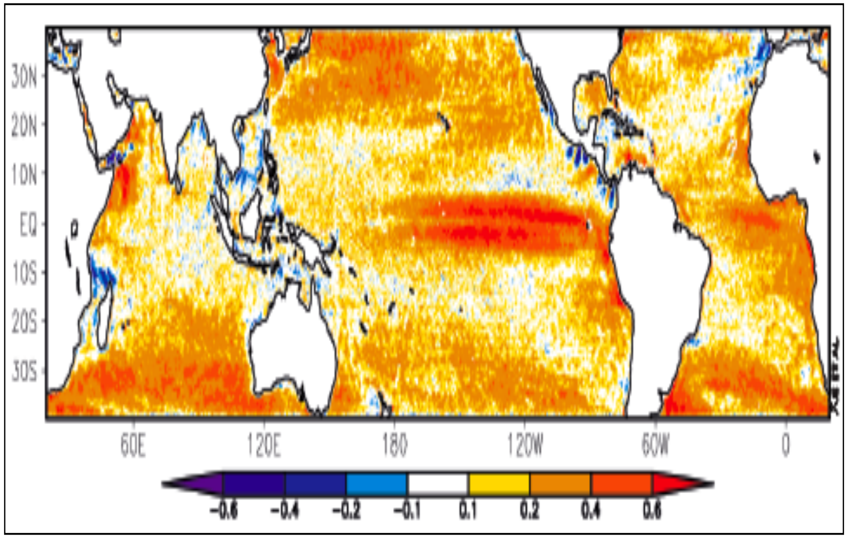


- Stronger wind ➔ colder SST (Negative correlation).

Matuna et al. 1997
http://jisao.washington.edu/pdo/

Oceanic mesoscale

Correlation: spatially *high-passed wind, SST*



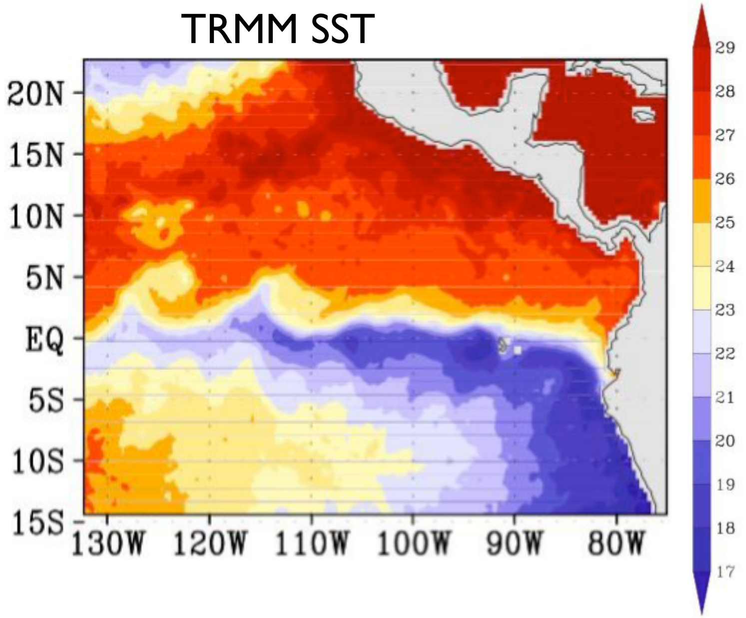
- 10-degree long. zonal high-pass filtered
- Positive correlation (Warm SST ➔ Stronger wind)

Xie et al. 2004

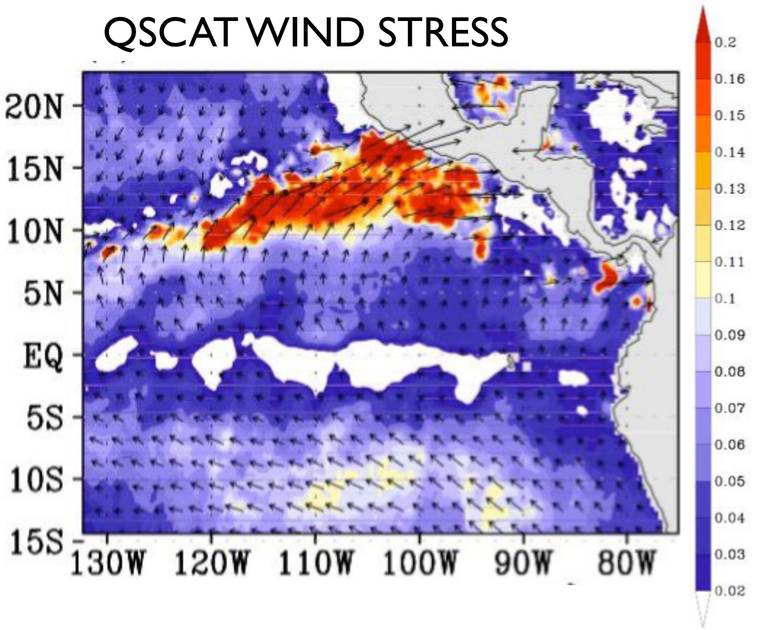
SST, wind and currents over TIWs

OBS

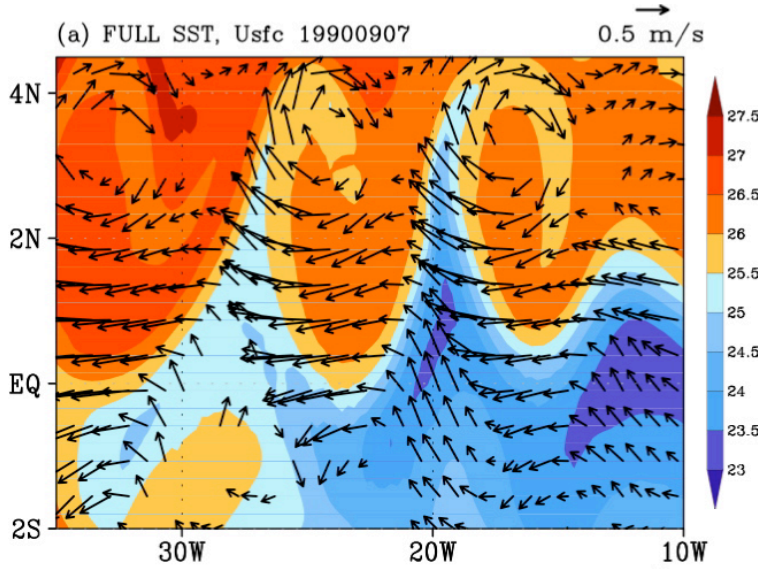
TRMM SST



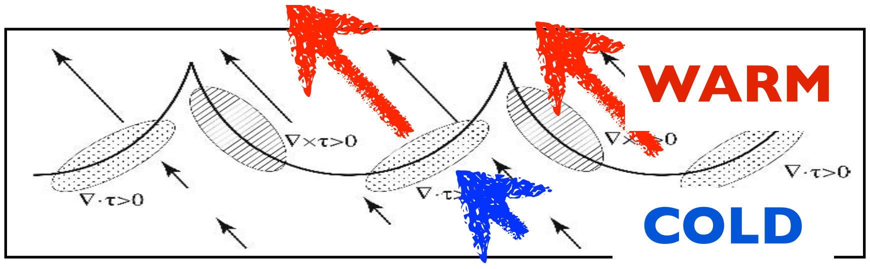
QSCAT WIND STRESS



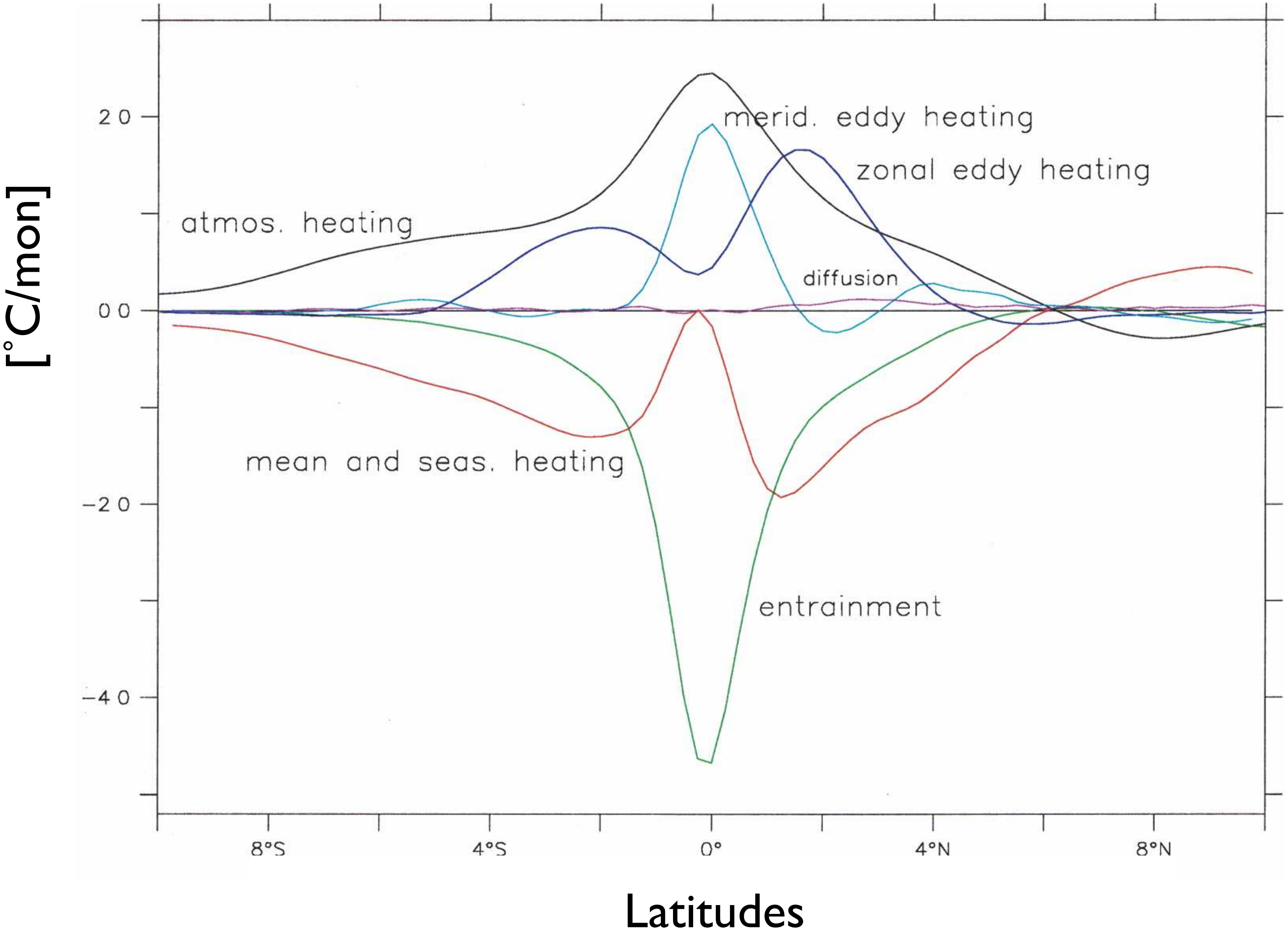
model



Chelton et al. 2001



Eddy temperature advection is the most important heating term in the equatorial cold tongue

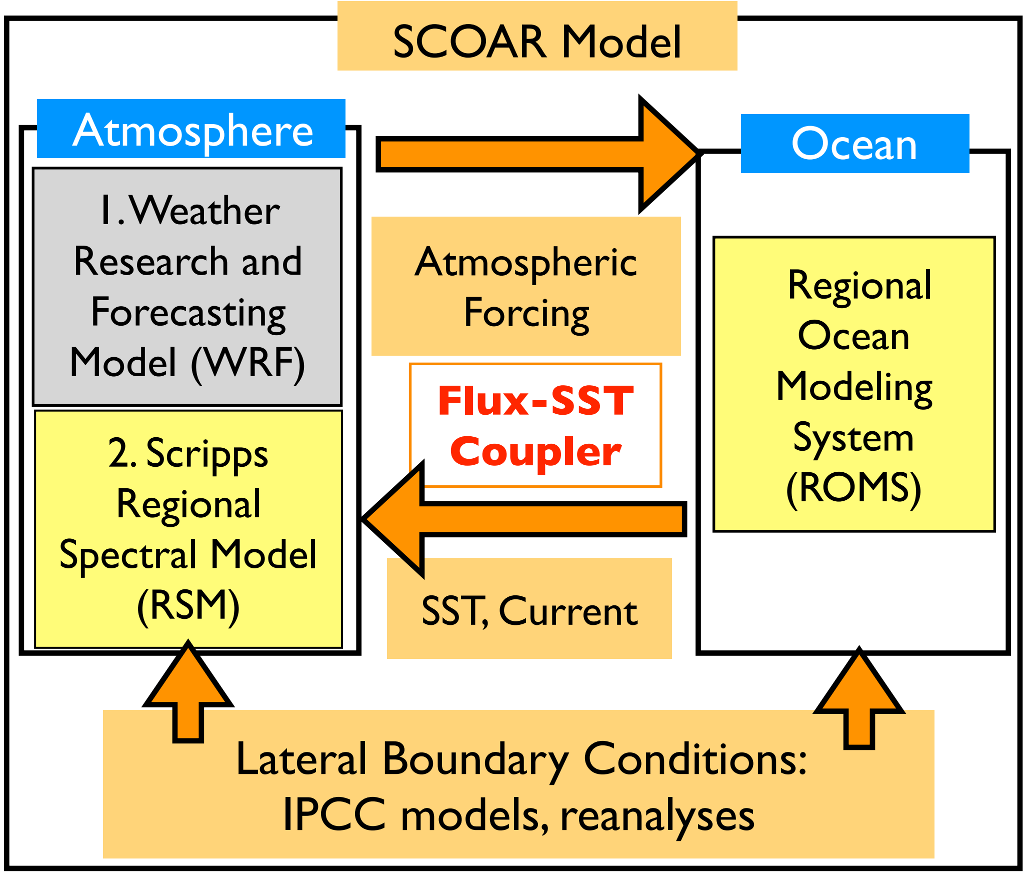


Jochum and Murtugudde 2005

Overview of my talk

- Regional coupled model
- Mesoscale ocean-atmosphere coupled feedback over TIWs:
  - Dynamic and thermodynamic coupled feedback
- Long-term effect of equatorial dynamic processes
  - on present-day and future climate in the tropical Atlantic sector
- Summary and discussion

Scripps Coupled Ocean-Atmosphere Regional (SCOAR) Model



SCOAR Model

Atmosphere

1. Weather Research and Forecasting Model (WRF)

2. Scripps Regional Spectral Model (RSM)

Atmospheric Forcing

Flux-SST Coupler

SST, Current

Ocean

Regional Ocean Modeling System (ROMS)

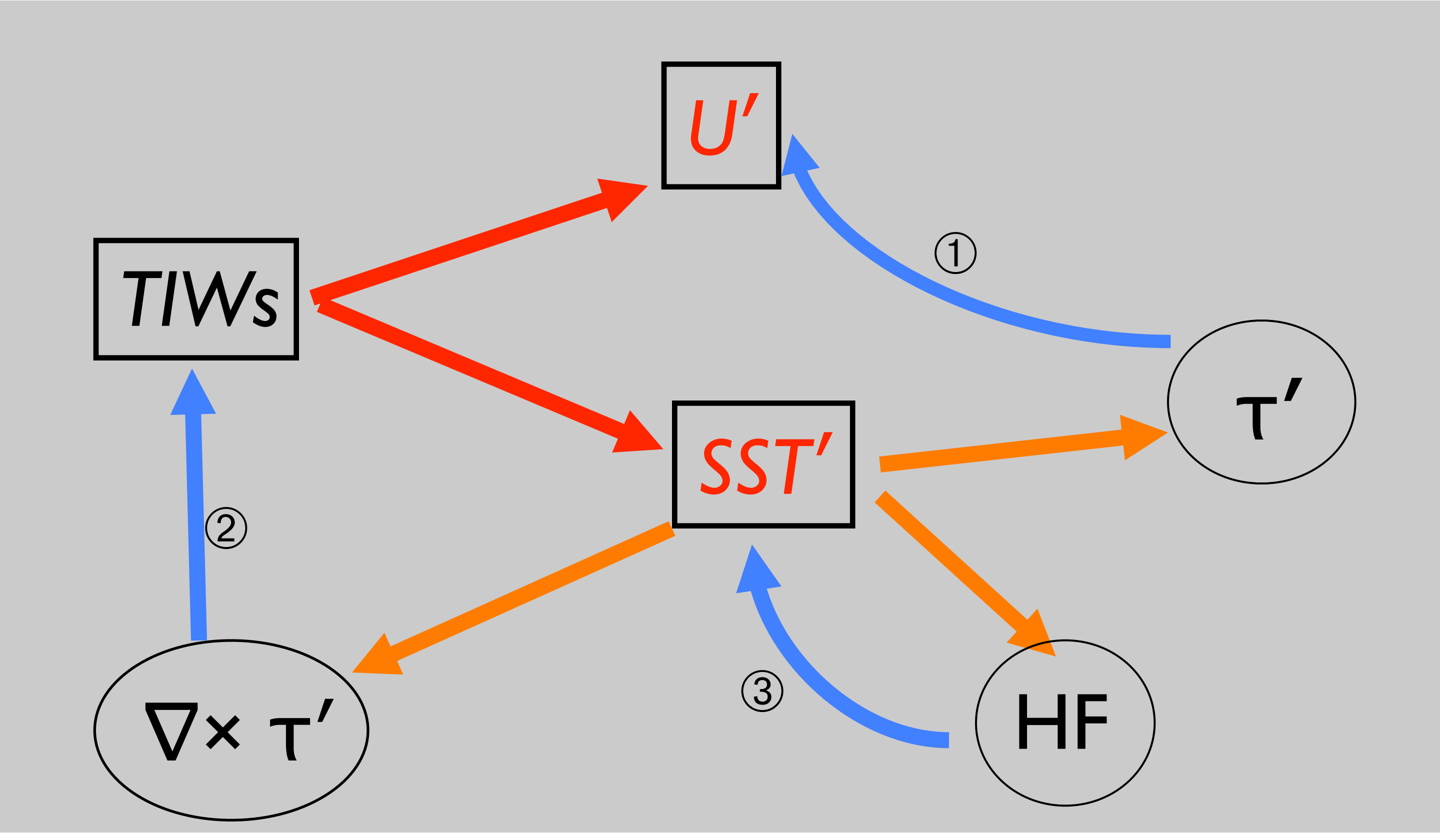
Lateral Boundary Conditions: IPCC models, reanalyses

- Higher model resolution BOTH in the ocean and atmosphere.
- An input-output-based coupler and sequential coupling
- Greater portability and applicability

Seo, Miller and Roads, 2007: The Scripps Coupled Ocean-Atmosphere Regional (SCOAR) model, with applications in the eastern Pacific sector. *Journal of Climate*

- Understanding the physical processes behind small-scale and large-scale climate dynamics
- Assess the regional aspects of global climate variability and change

High-frequency TIW-atmosphere coupling



① Coupling of wind and current?

② Feedback of wind stress curls to TIW energetics?

③ Atmospheric heat flux response to TIWs?

① Energetics of TIWs: Eddy kinetic energy budget

Feedback to TIW energetics

EKE Equation

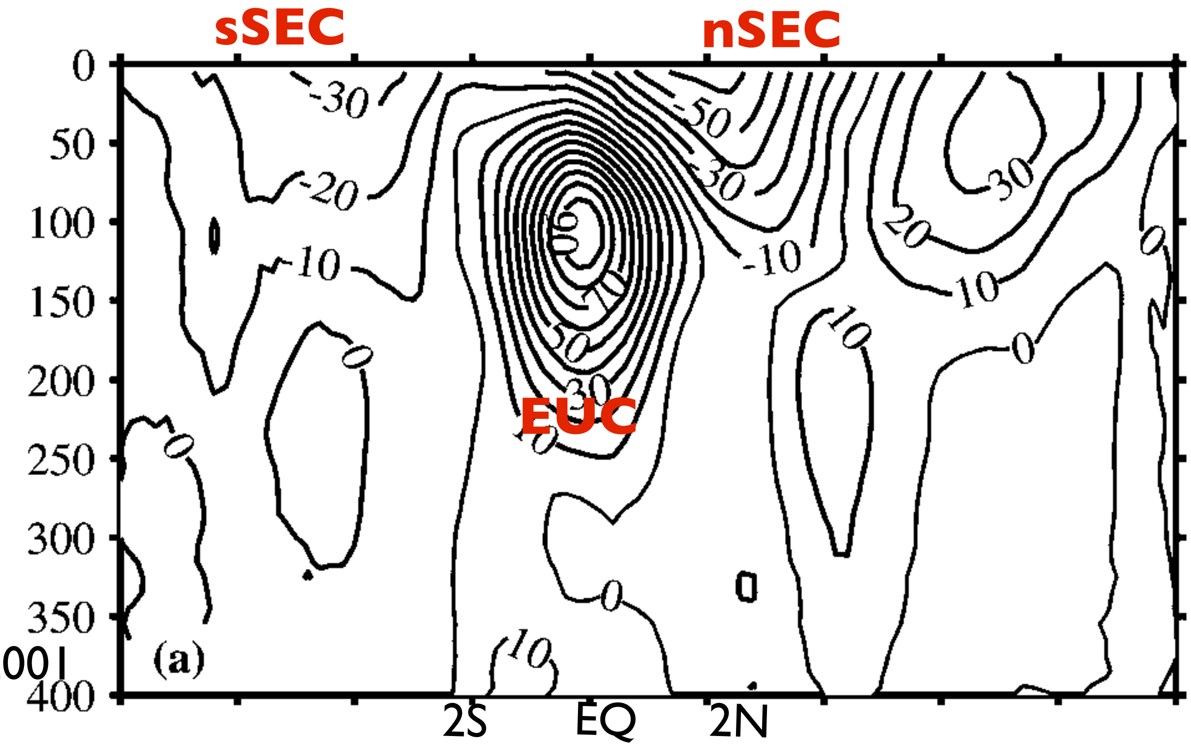
Baroclinic

Barotropic

$$\vec{U}\cdot\vec{\nabla}\vec{K}_e + \vec{u}'\cdot\vec{\nabla}\vec{K}_e = -\vec{\nabla}\cdot(\vec{u}'p') - g\rho'w' + \rho_o(-\vec{u}'\cdot(\vec{u}'\cdot\vec{\nabla}\vec{U}))$$

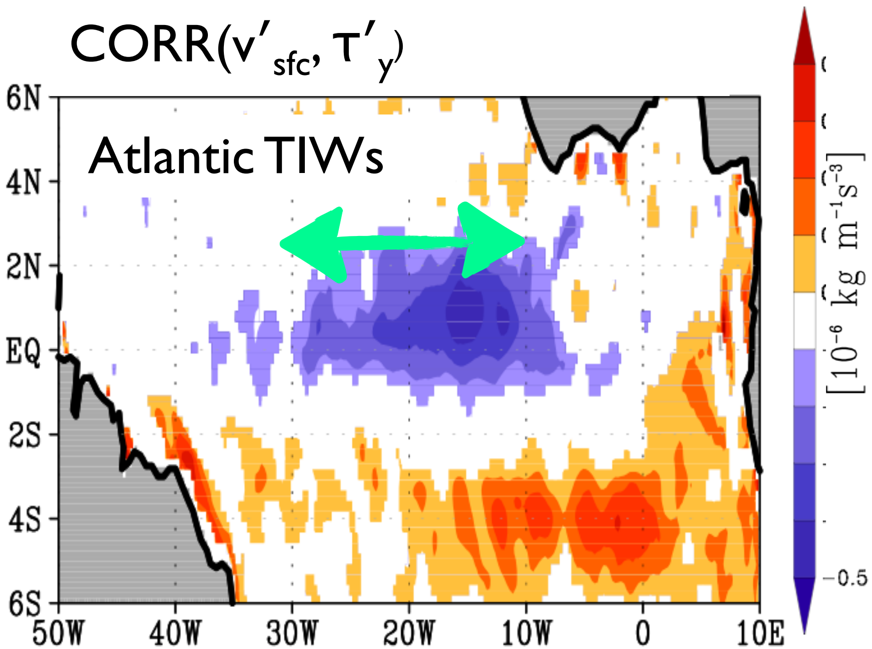
$$+\rho_o A_h \vec{u}'\cdot\nabla^2\vec{u}' + \rho_o\vec{u}'\cdot(A_v\vec{u}_z')_z + \vec{u}_{sfc}'\cdot\vec{\tau}_z'$$

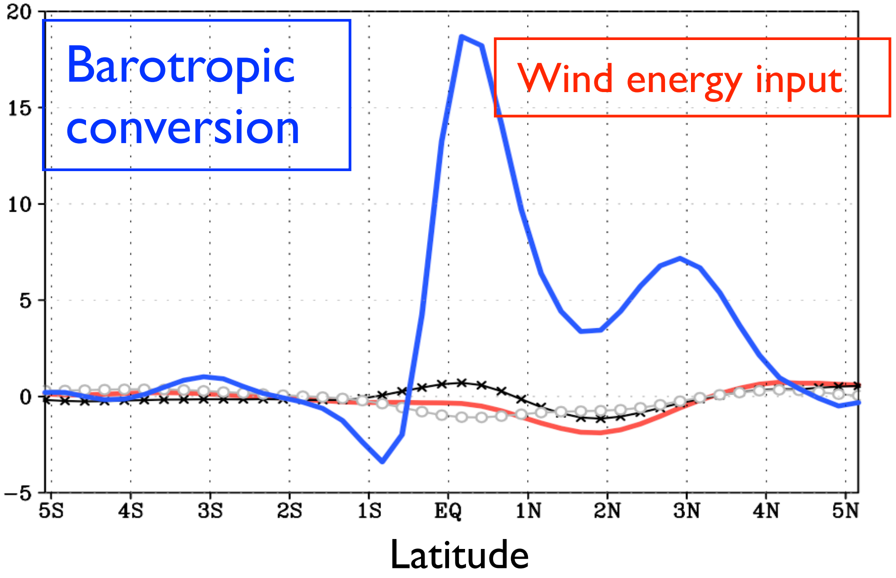
Correlation of wind stress and current

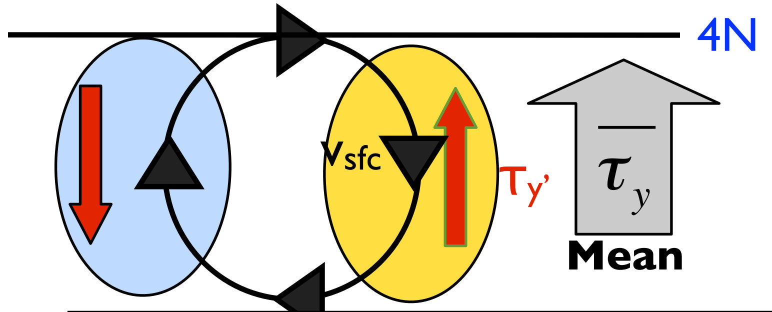


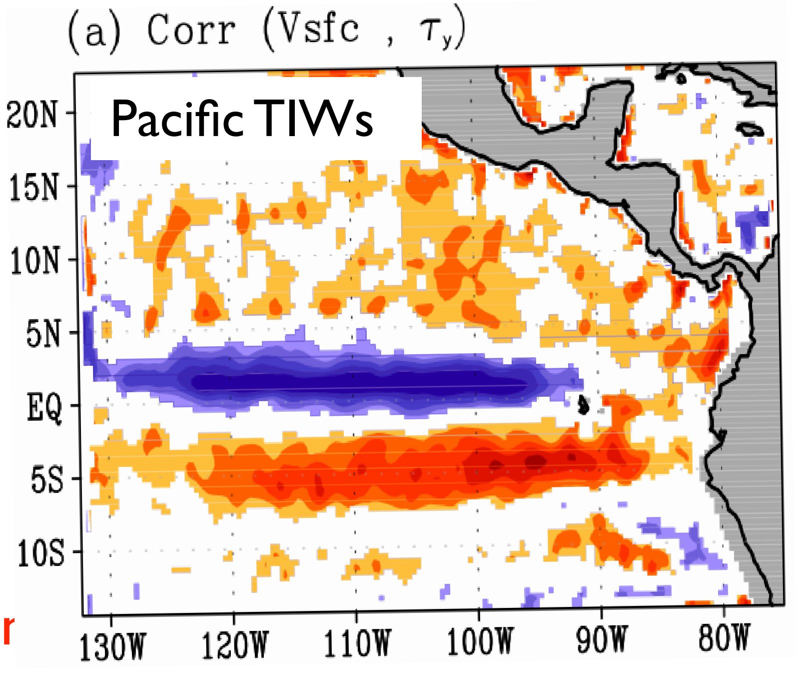
Johnson et al. 2001

Anomalies in current and wind stress are opposite in direction.







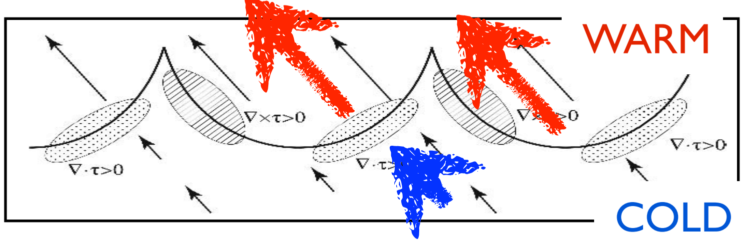


Small et al. (JGR, 2009) showed that this damping effect is even larger in the Pacific.

- Wi
  co
- Wind-current coupling ➔ energy si

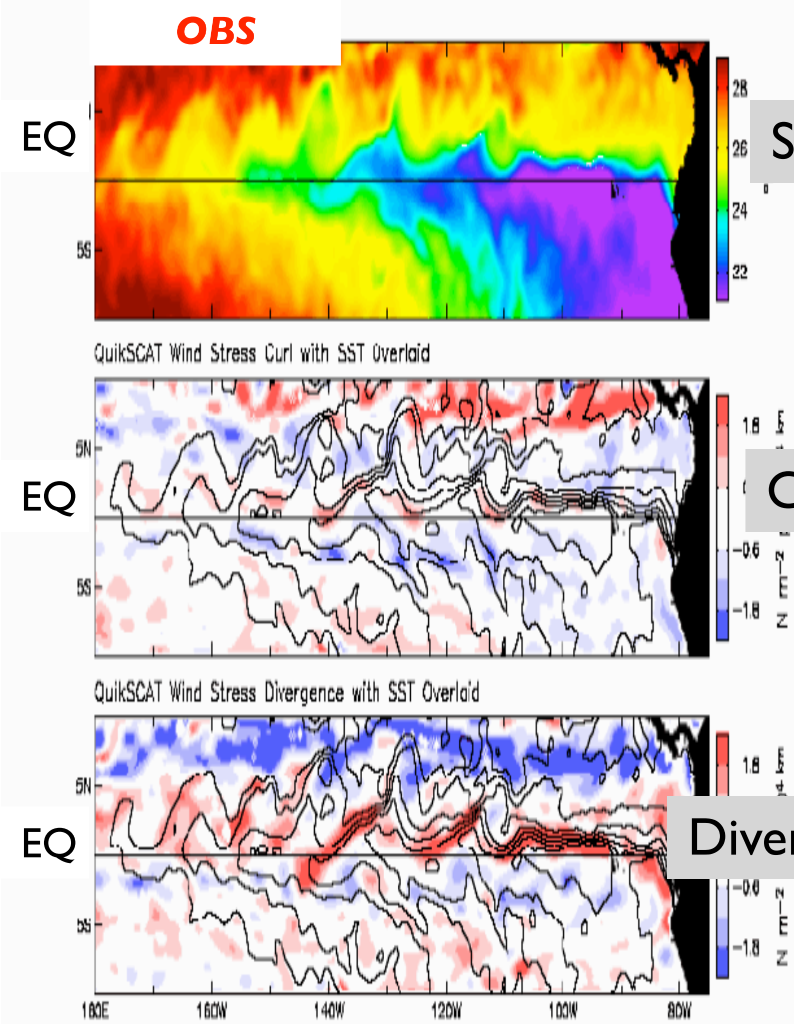
② Modification of wind stress curl by SST gradients:

SST gradients generate wind curl/div.



TRMM & QuikSCAT

OBS

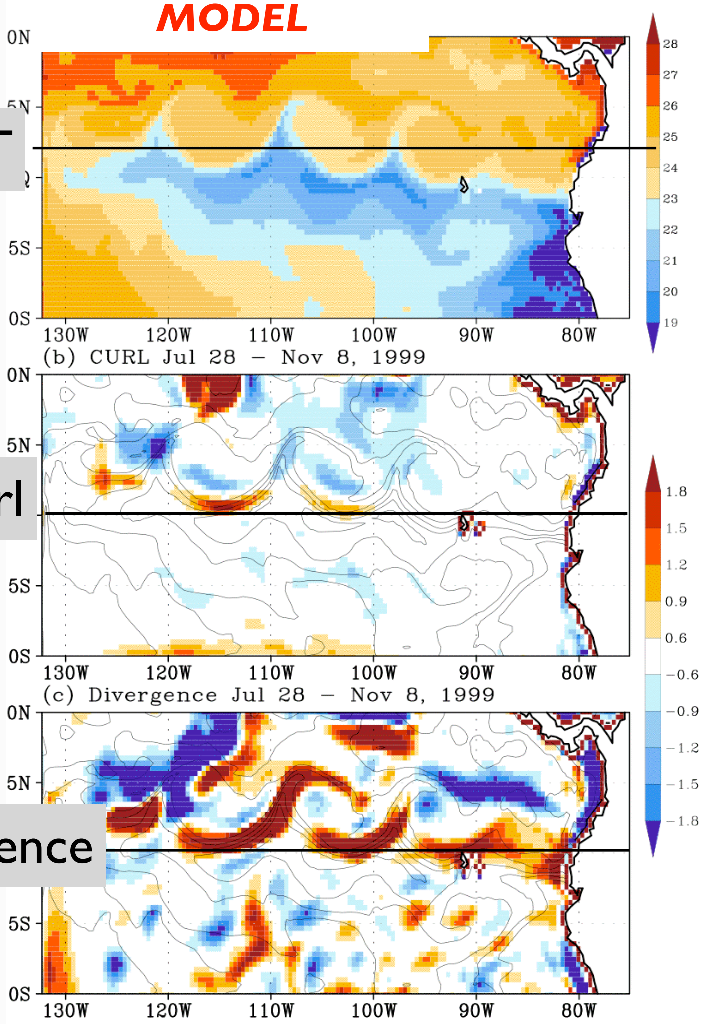


SST

Curl

Divergence

MODEL



A quasi-linear relationship between the derivatives of wind stress and SST.
Curls tend to be largest on the equator!

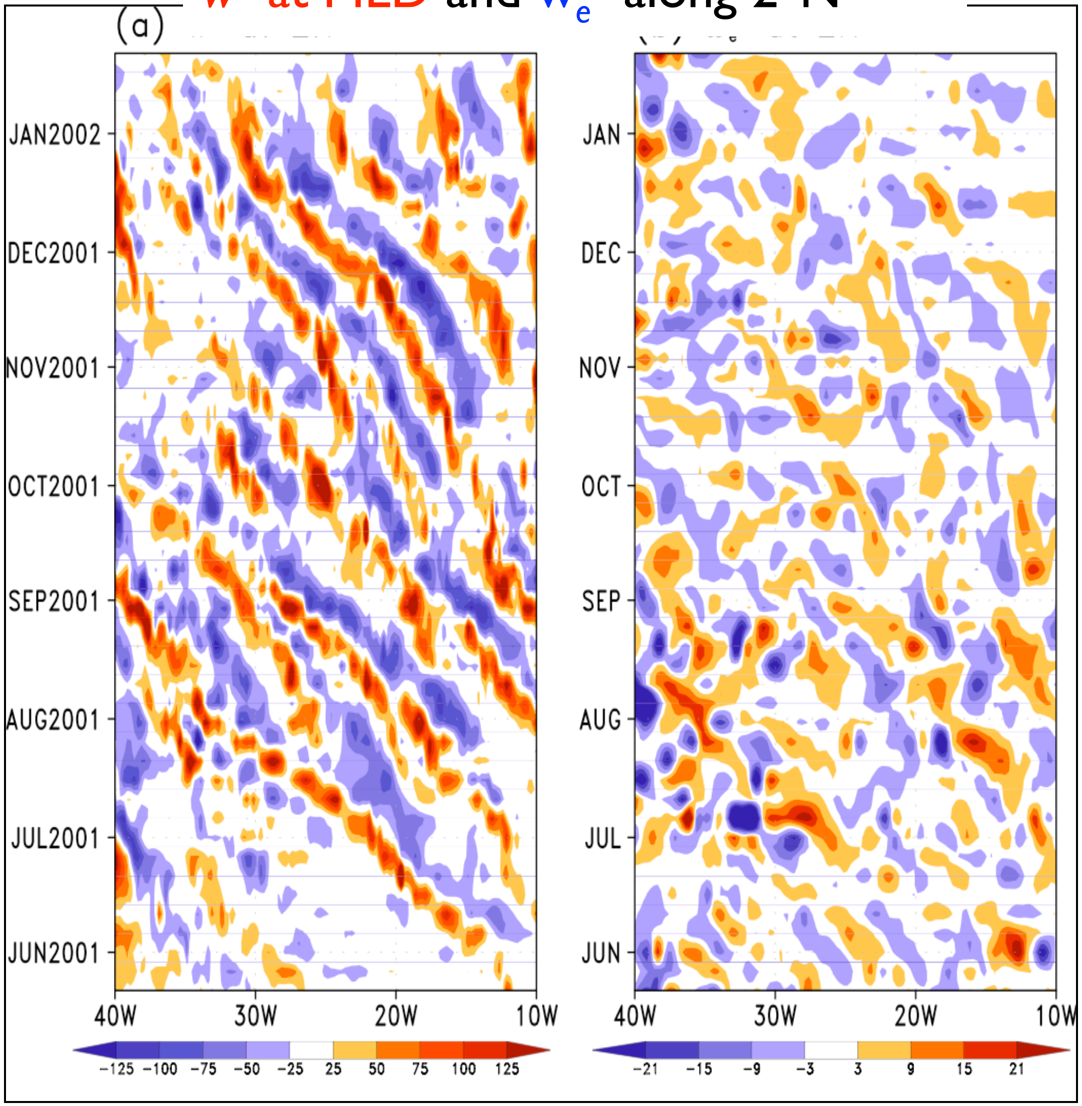
Feedback of perturbation Ekman pumping to TIWs

- Perturbation Ekman pumping velocity (w_e') and perturbation vertical velocity (w') of $\boldsymbol{-g\rho' w'}$.

- Overall, w_e' is much weaker than w'.

- Caveat: Difficult to estimate Ekman pumping near the equator.

- Away from the equator, this may affect the evolution of mesoscale eddies. (e.g., Chelton et al. 2007, Spall 2007, Seo et al. 2007, 2008 etc)



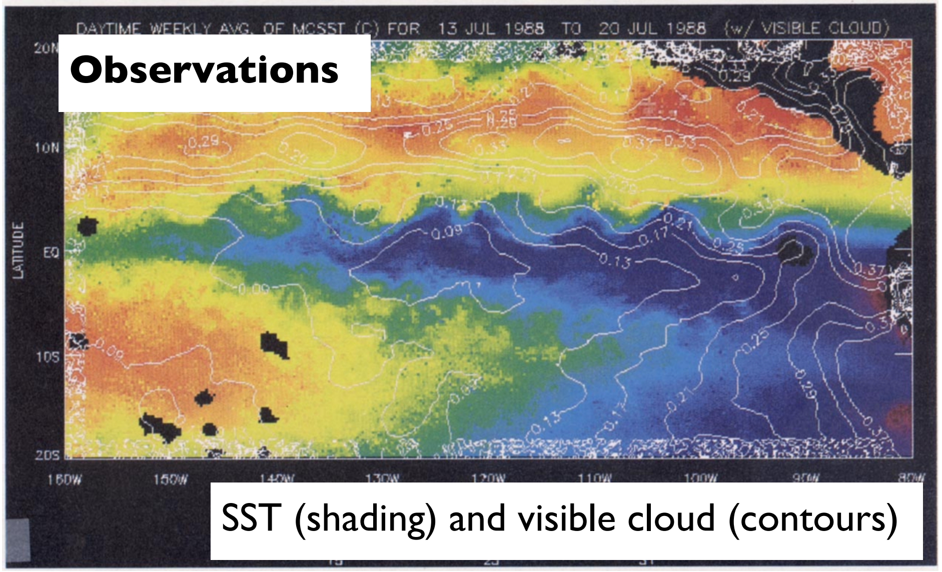
w' at MLD and w_e' along 2°N

Unit: 10^{-6}m/s, Zonally highpass filtered, and averaged over 30W-10W

③ Response and feedback of heat flux

3. Radiative and turbulent heat flux response to TIWs

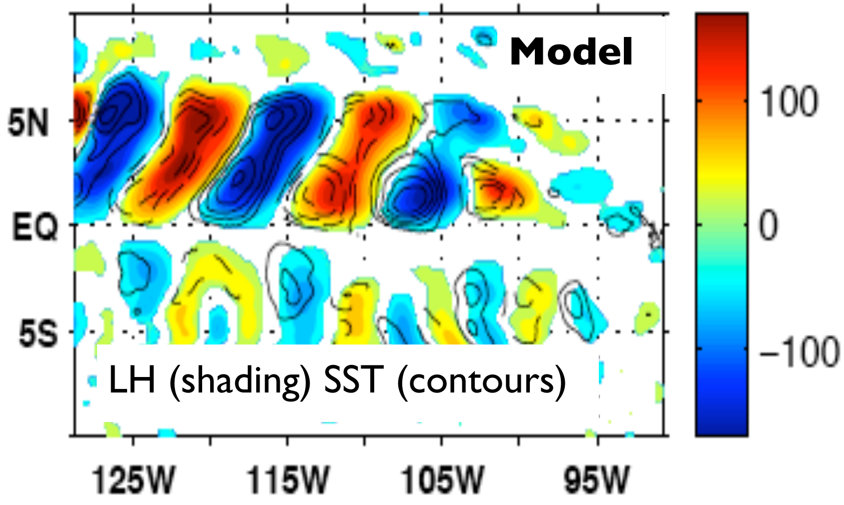
Downward shortwave radiation



SST (shading) and visible cloud (contours)

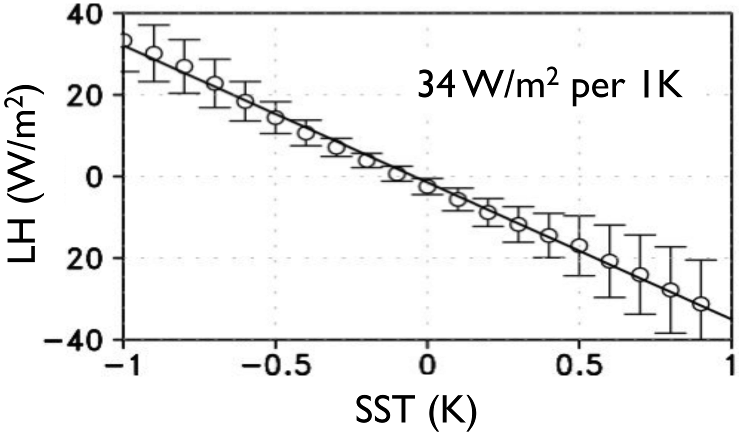
Deser et al. (1993): changes in SW of ~10 W/m² per 1K changes in SST
: -0.75°C / month (MLD=20m).

Latent heat flux and SST



LH (shading) SST (contours)

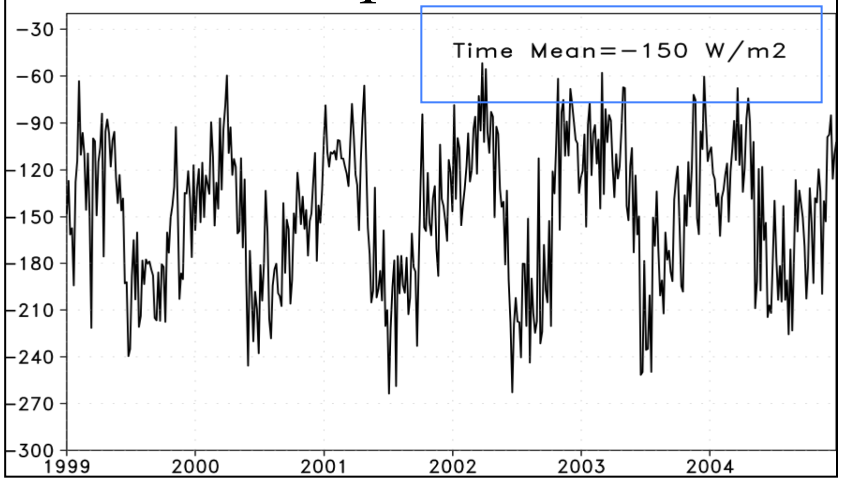
A quasi-linear relationship



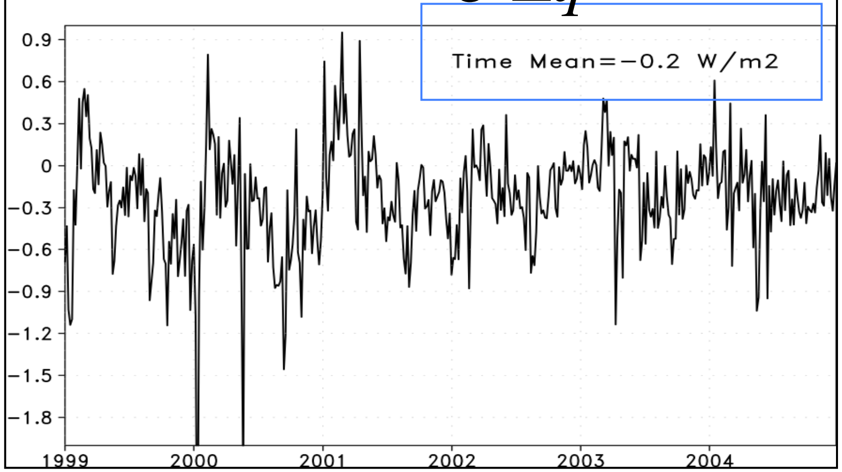
Instantaneous damping of local SST anomalies by perturbation heat flux

Are the TIW-induced LH anomalies important?

Mean: $\overline{U\Delta q}$



Perturbation: $U'\Delta q'$



Bulk aerodynamic forumla

$$LH = \rho L C_H U(\Delta q),$$

Reynolds averaging

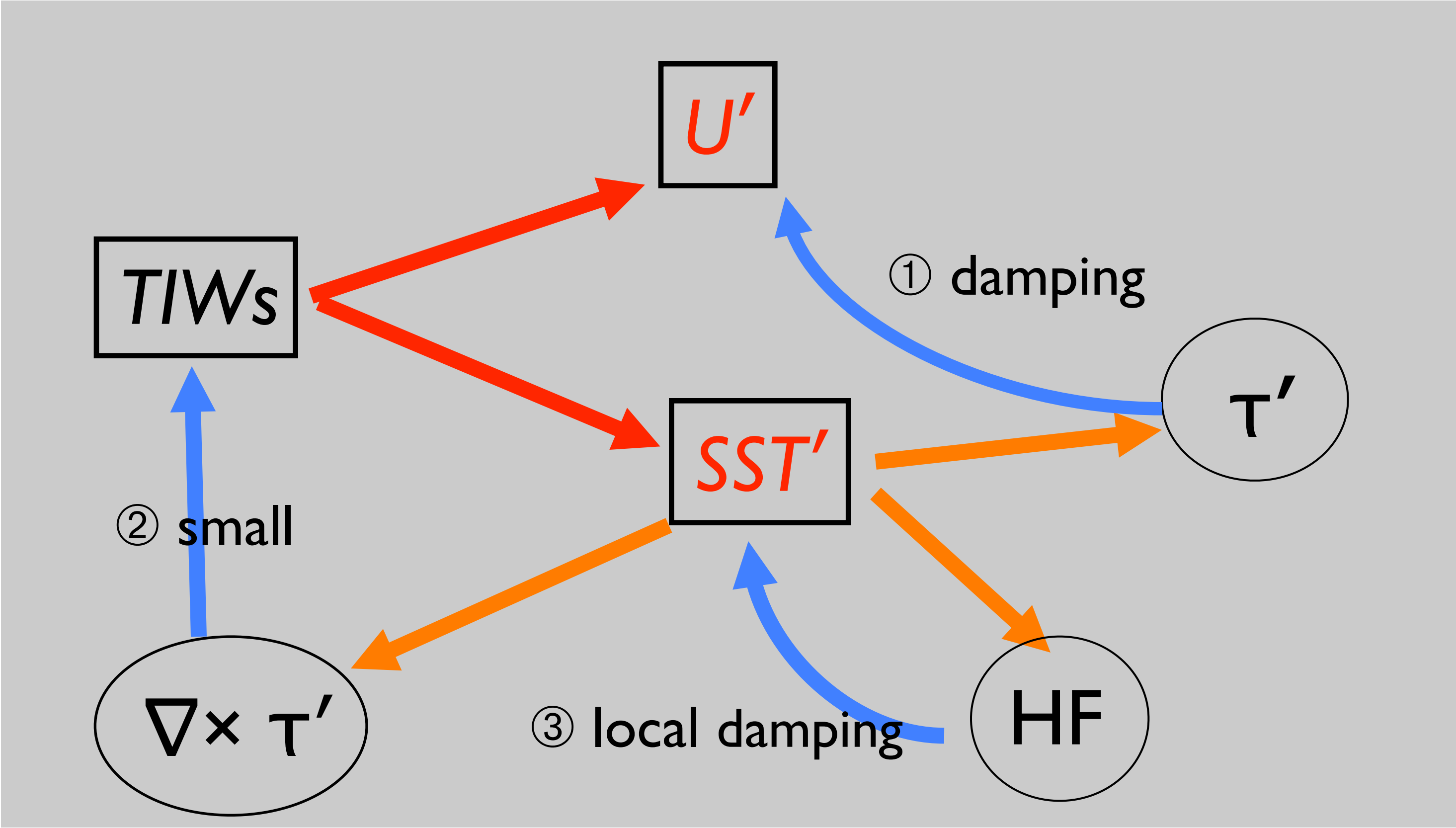
$$\overline{LH} = \rho L C_H (\overline{U\Delta q} + \overline{U'\Delta q'}),$$

- Rectification by high-frequency (TIW-induced) LH′ is small compared to the large-scale mean LH.

- TIWs still operate over the large-scale SST gradient and modulate the temperature advection

6-year time series at 2°N averaged over 30°W-10°W

A summary for high-frequency TIW-atmosphere coupling



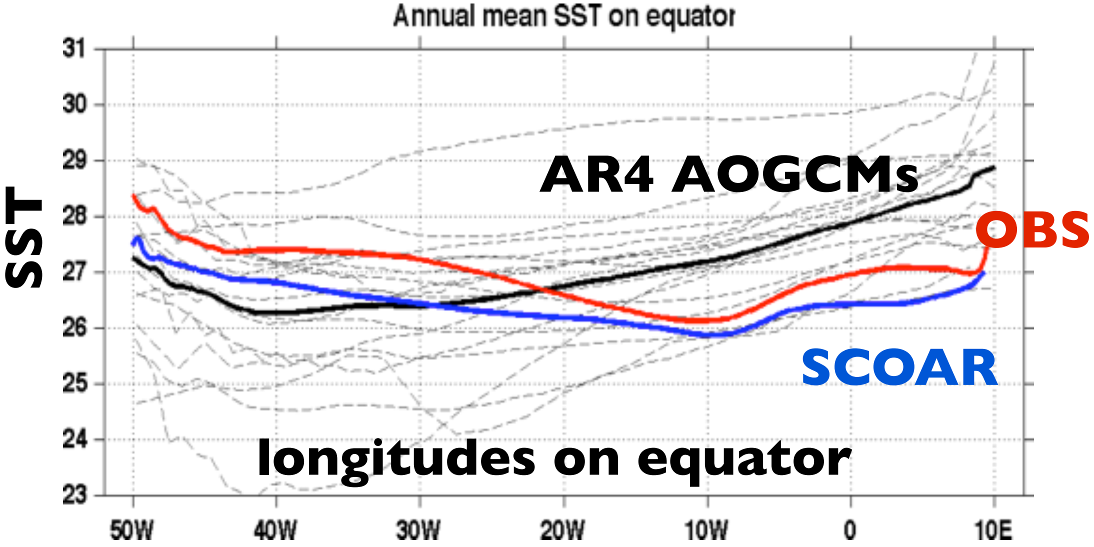
① Wind response damps TIW-current: Small but significant damping

② Negligible contribution at 2N (difficult to estimate near the equator)

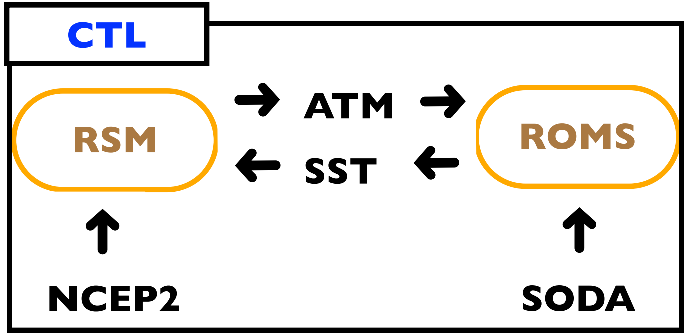
③ Damping of local SST (but small rectification to large-scale SST)

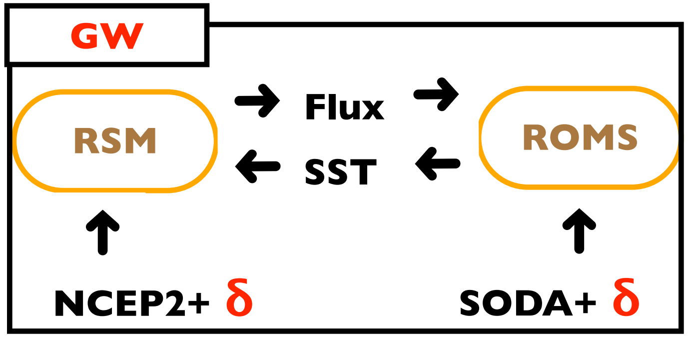
Part II:
Regional coupled downscaling of future climate projections
Equatorial Atlantic Ocean

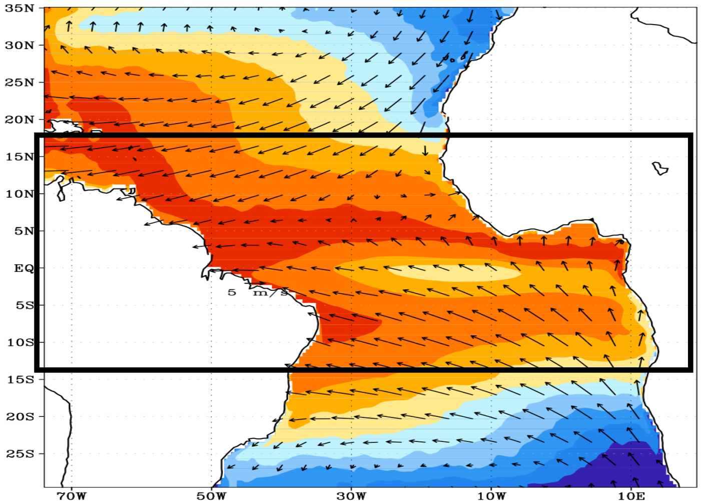
- IPCC AR4 models have large errors in simulation of equatorial climate.
  - Incorrect mean state: a reversed east-west gradient.
  - Underestimation of equatorial currents, upwelling and TIWs.
- The role in equatorial climate change is not well known.



Model and experiments







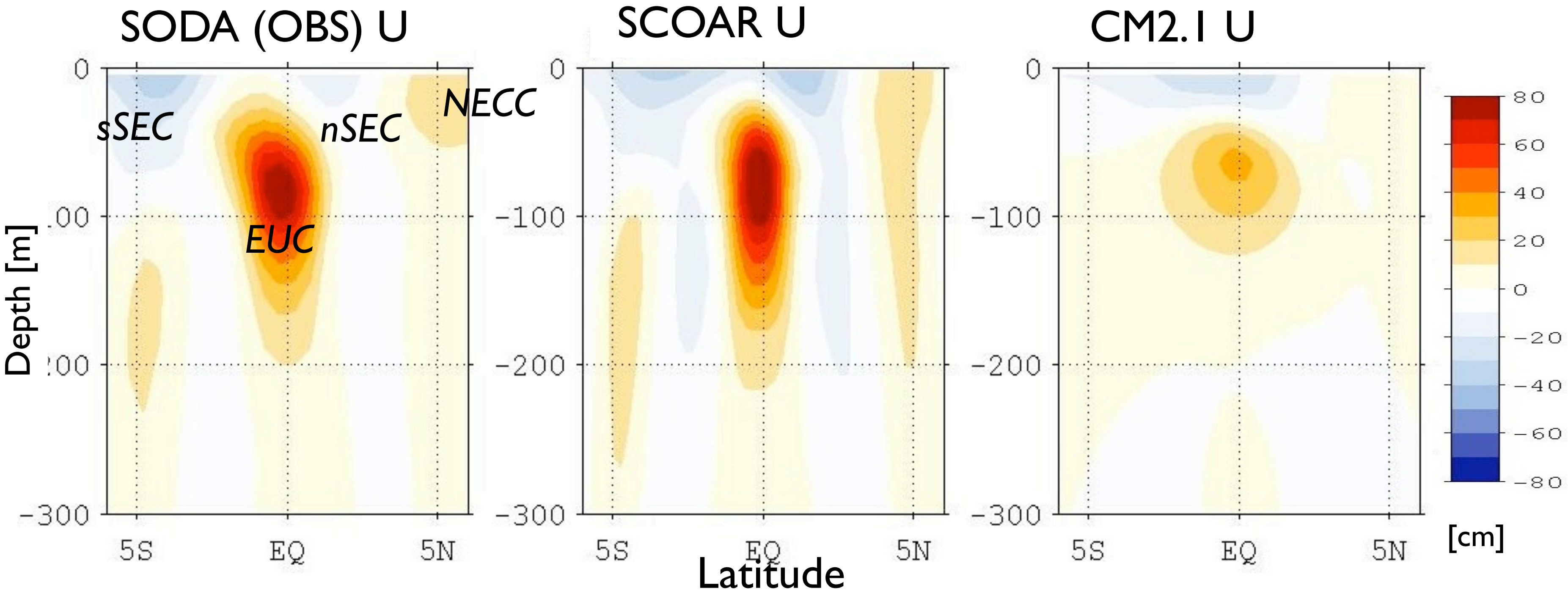
- **CTL**: RSM (NCEP2 6hrly) + ROMS (SODA monthly)
- 25 km ROMS + 50 km RSM
- 28-yr. integration: 1980-2007
- CO2=348 PPM

- δ=GFDL CM2.1 monthly difference: (2045-2050: A1B)-(1996-2000: 20C); 10-member ensemble mean
- **GW**: RSM (NCEP2 6-hrly+δ) + ROMS (SODA monthly+δ)
- CO2=521.75 PPM

pseudo-global warming simulations

CH4, 1730 PPB

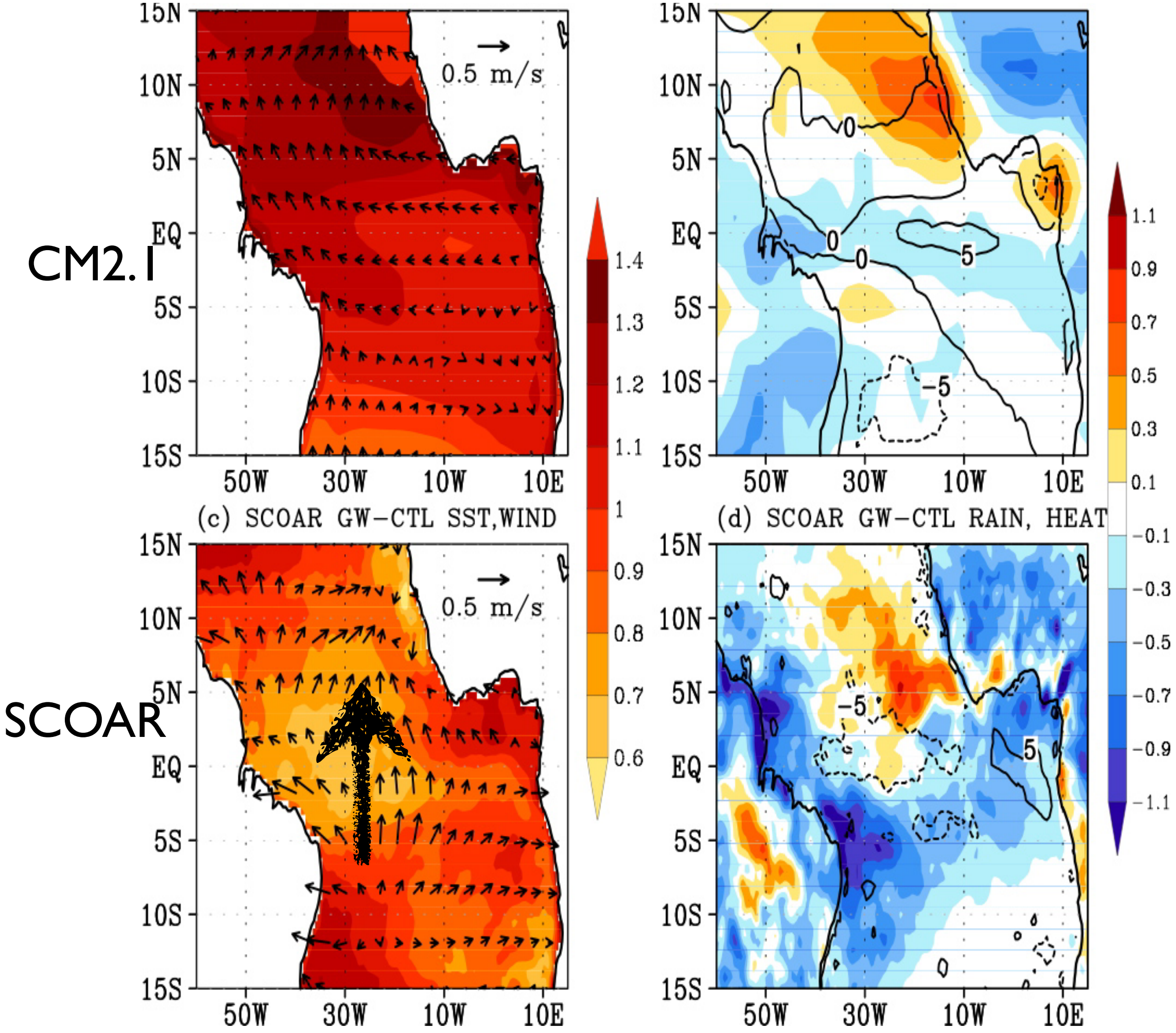
2. A stronger upwelling associated with the stronger Equatorial Undercurrent



- Weak EUC and weak upwelling in CM2.1.
- Strong EUC and strong upwelling in SCOAR.
- Stronger currents have an important implication for the dynamic instability.

30°W-10°W, 1998-2007

Change in annual mean state (GW-CTL)



SST, Wind

Precip, net heat flux

(c) SCOAR GW−CTL SST,WIND

(d) SCOAR GW−CTL RAIN, HEAT

- Distinct equatorial ocean response:
  - Reduced warming (more upwelling) in the equator.
  - Cross-equatorial southerly wind is stronger on equator.
- Similar large-scale atmospheric response:
  - Increased (decreased) rainfall in the tropical northeast (south) Atlantic.

Response of ocean to the *cross-equatorial southerly wind?*

1. Reduced warming on the equator?
2. Change in equatorial currents?

1. The reduced warming in the cold tongue is due to the increased upwelling.

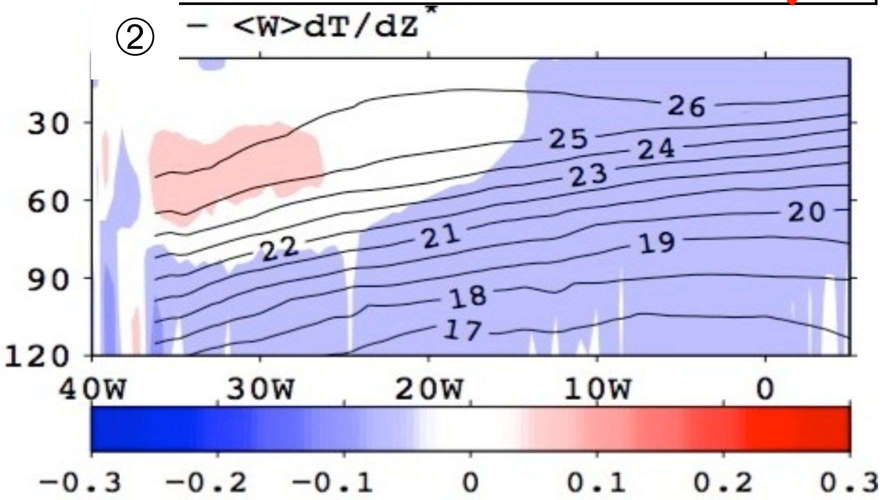
under global warming

$$-w\frac{\partial T}{\partial z} = \overset{①}{-\langle w\rangle\left\langle\frac{\partial T}{\partial z}\right\rangle} \overset{②}{- \langle w\rangle\frac{\partial T^*}{\partial z}} \overset{③}{- w^*\frac{\partial\langle T\rangle}{\partial z}} \overset{④}{\cancel{- w^*\frac{\partial T^*}{\partial z}}}$$

x=<x>+x*

<>: present-day mean (CTL)

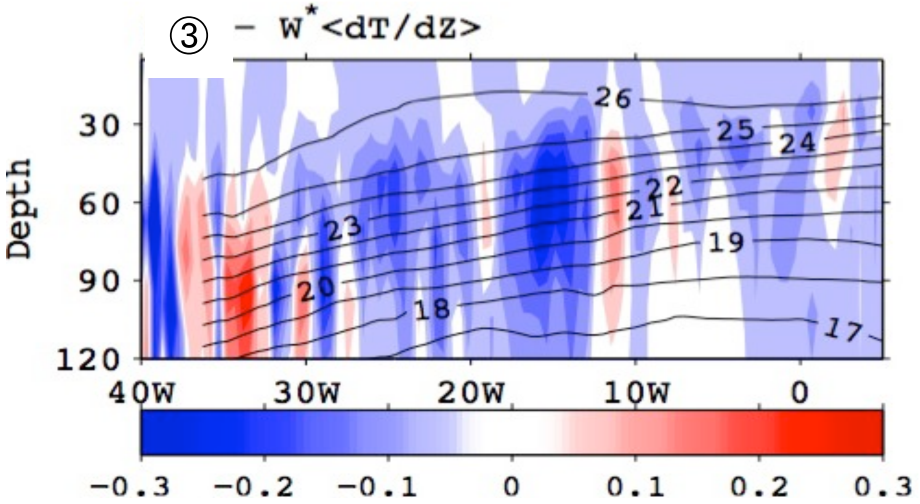
*: Perturbation (GW-CTL)



② *Radiative heating* ➜ *$dT^*/dZ > 0$:*

Ocean Dynamical Thermostat

(Clement et al. 1996, Cane et al. 1997)

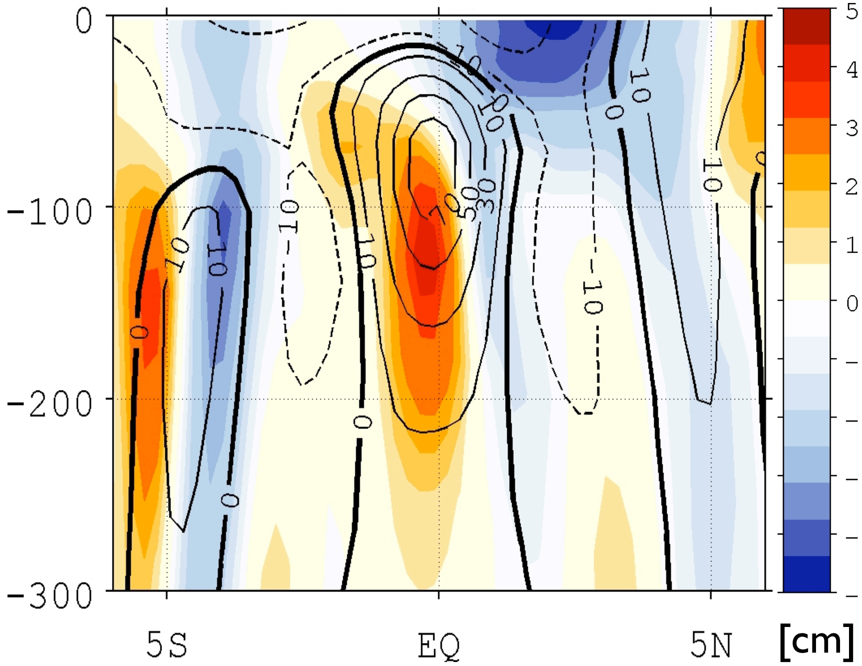


③ *Cross-equatorial wind* ➜ *$w^* > 0$.*

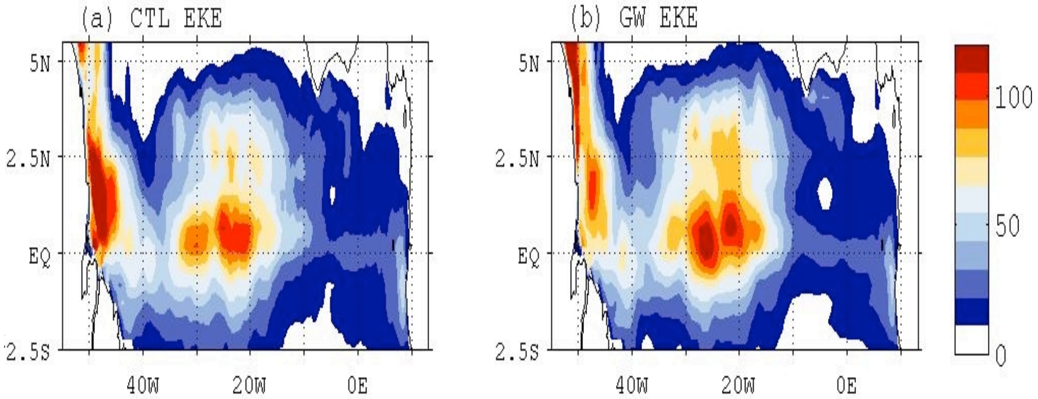
✔ Atlantic (w^*, ③) vs Pacific (dT^*/dZ, ②)

The enhanced current shears leads to the stronger instability and TIWs.

SCOAR δU



EKE becomes stronger by ~30%



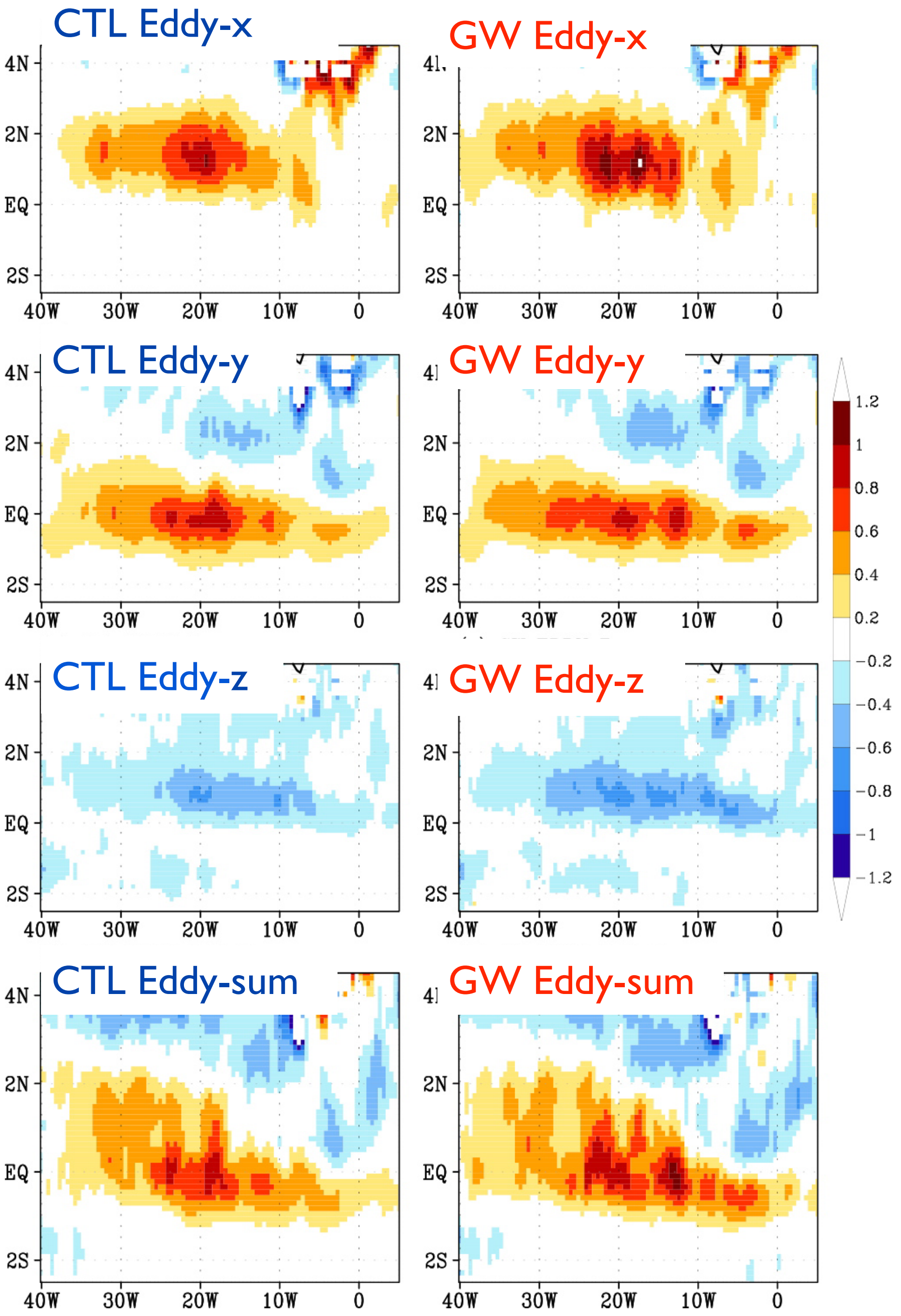
What is the implication for the equatorial heat budget?

- Cross-equatorial southerly wind ➜ Currents ↑ and w* ↑ ➜ Dynamic instability ↑
- Philander and Delecluse (1983), Yu et al., 1997

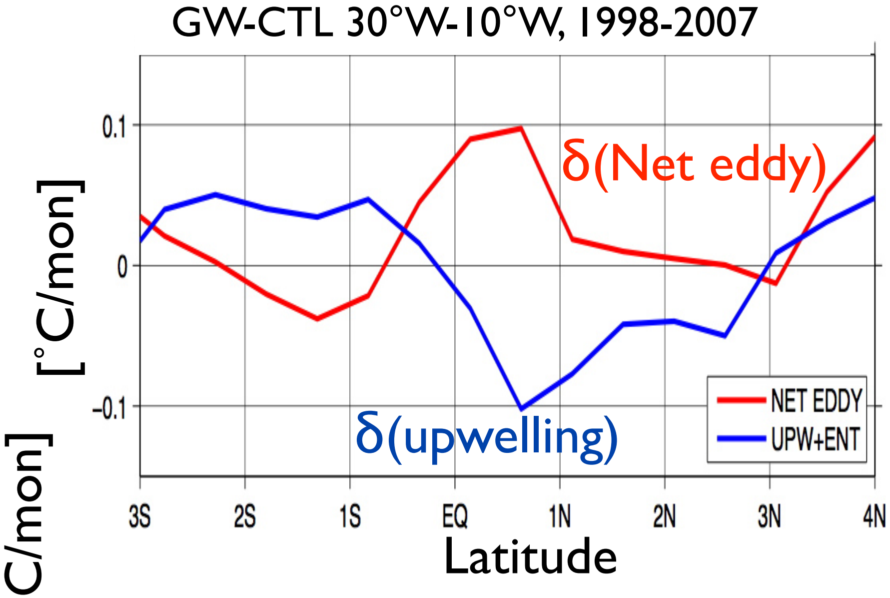
Ocean is more barotropically and baroclinically unstable.

30°W-10°W, 1998-2007

Eddy temperature advection is intensified!



GW-CTL 30°W-10°W, 1998-2007



- TIW-heat flux significantly compensates for the cooling by enhanced upwelling.

Summary and discussion

1. Ocean fronts and eddies cause coherent perturbations in the atmosphere
   - Feedback to larger-scale climate system is an active area of research.
   - *Coupled downscaling* is a useful method to capture the two-way feedback.
2. TIWs impact the mean state through eddy heat flux.
   - Both in the present-day and in a changing climate.
   - Global models need to include the effect of TIWs.
   - Need an accurate representation of ocean dynamical processes.

Coupled downscaled modeling is a useful approach for studying multi-scale processes and their influence on regional climate variability and change.

Thanks