Ocean mesoscale eddies, air-sea interactions and regional climate: regional coupled climate modeling

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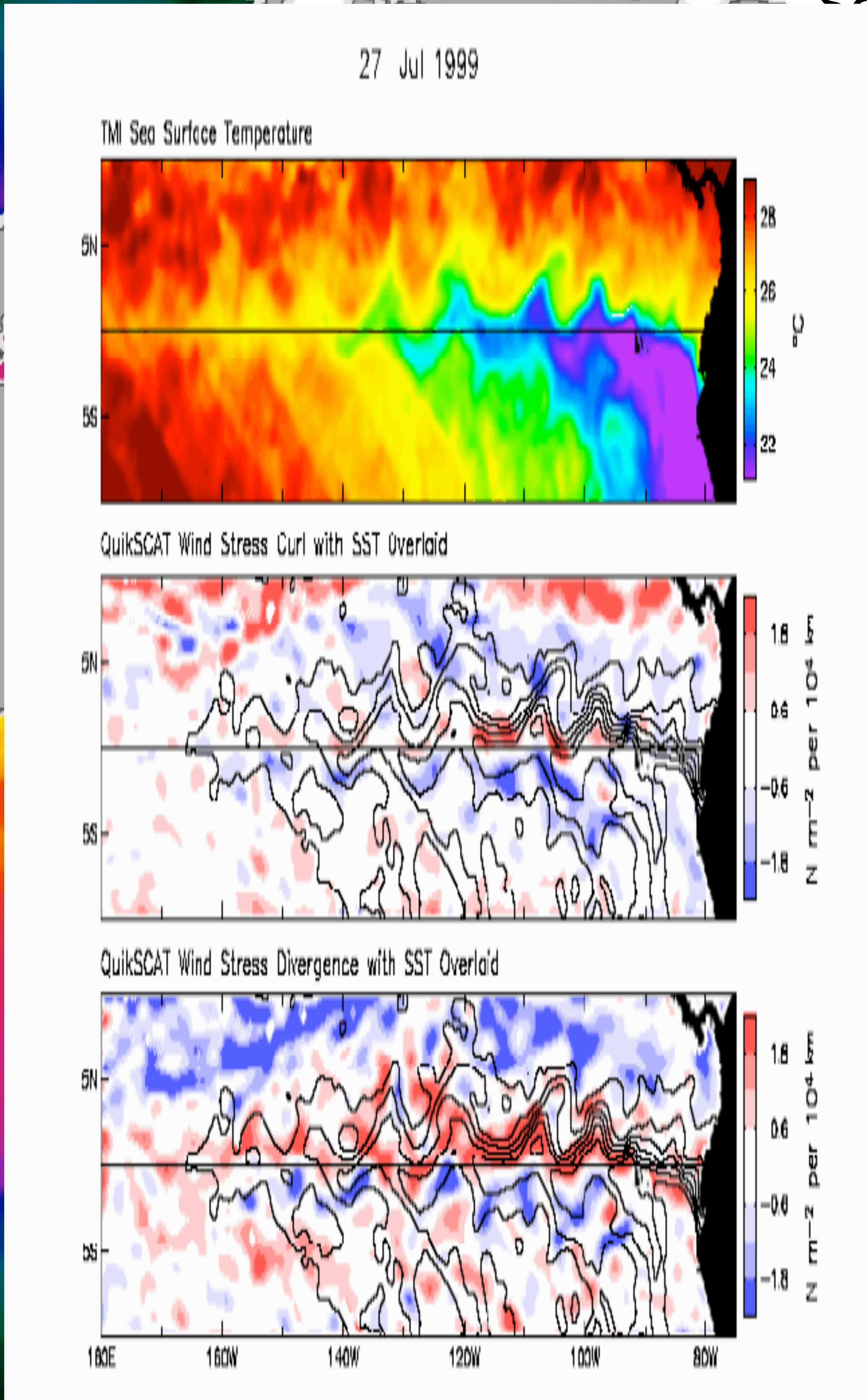
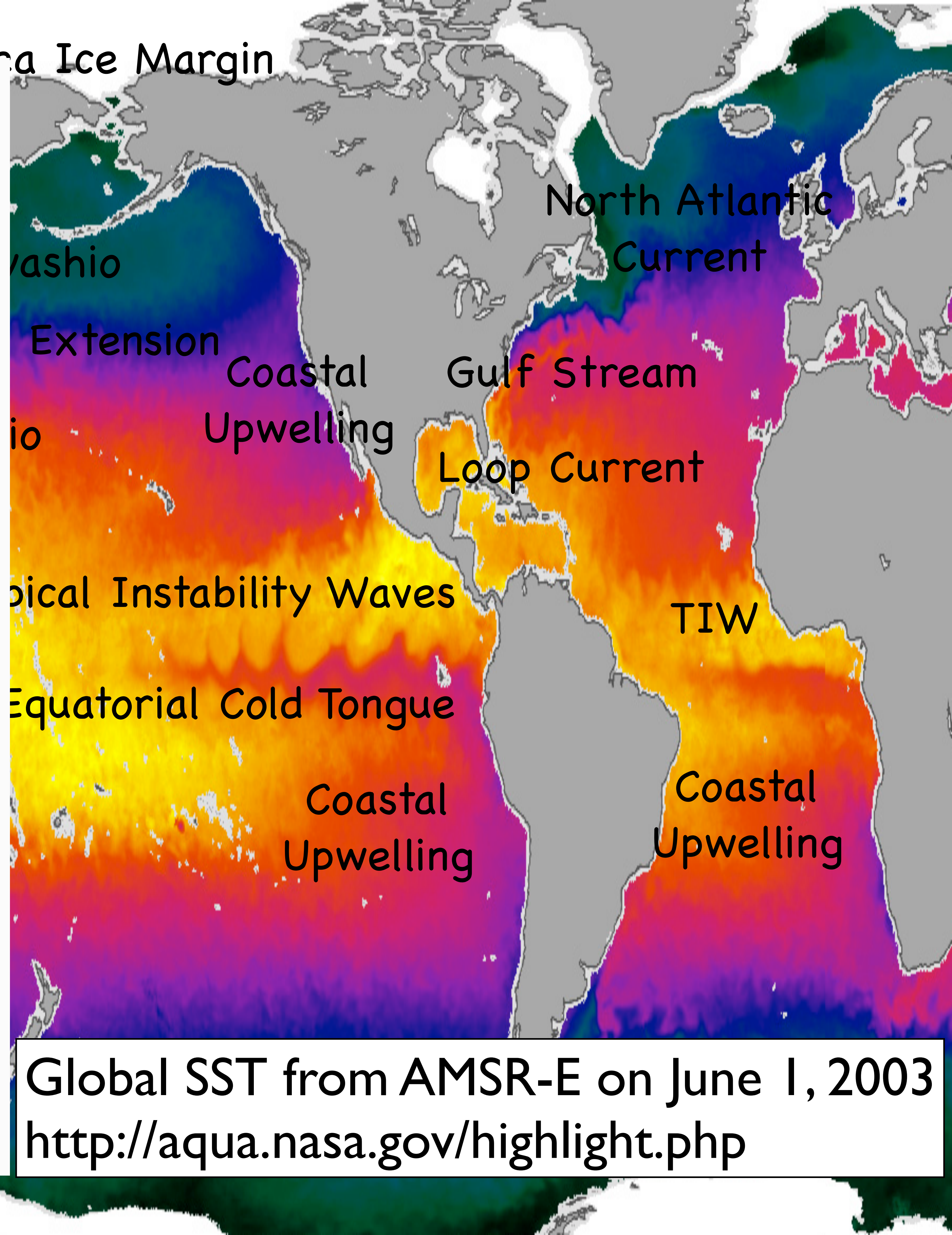
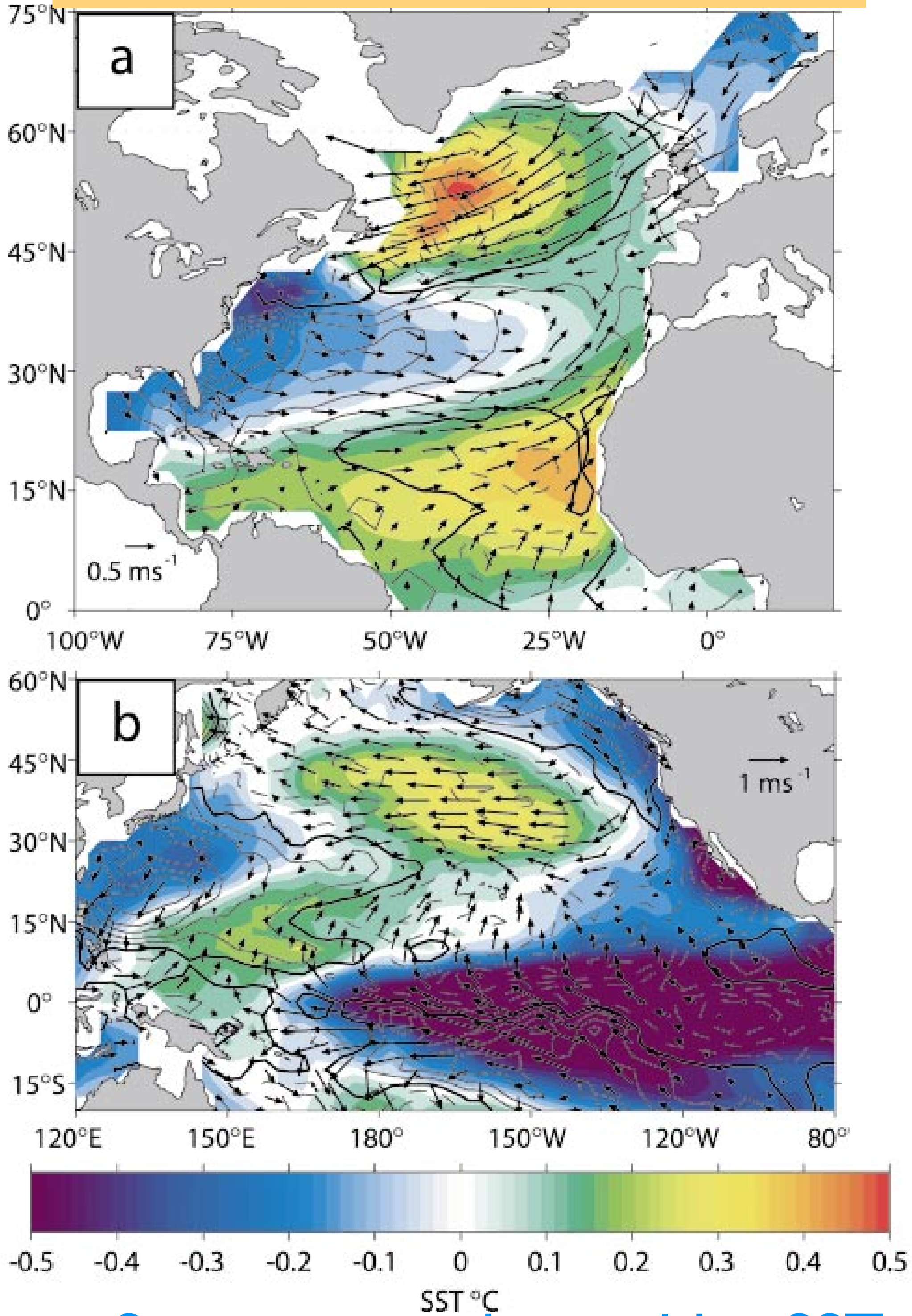




Global SST from AMSR-E on June 1, 2003
http://aqua.nasa.gov/highlight.php

Air-sea interactions on different oceanic scales

Oceanic basin-scale: NAO

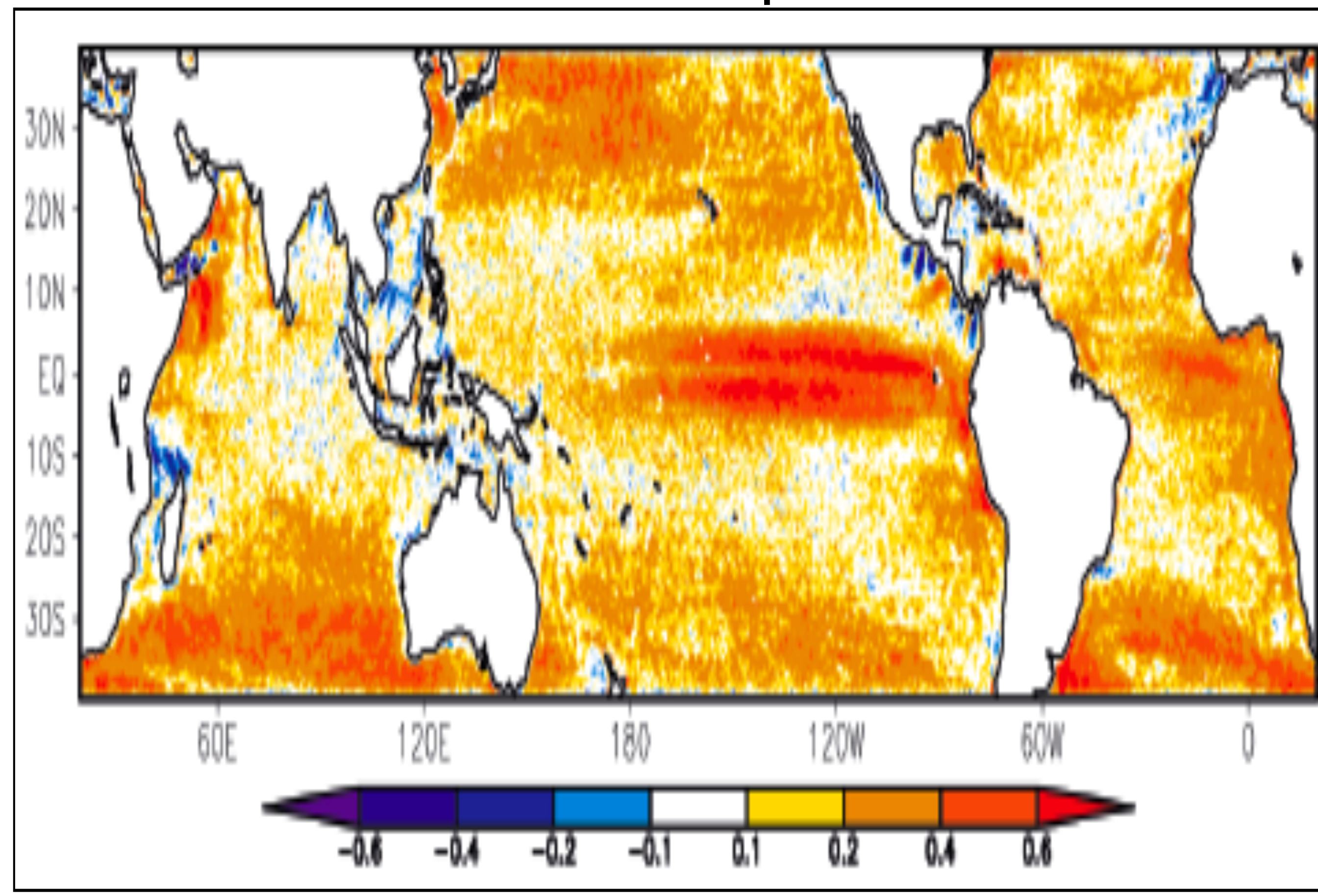


Stronger wind ➔ colder SST
(Negative correlation).

Kushnir et al. 2002

Oceanic mesoscale: eddies

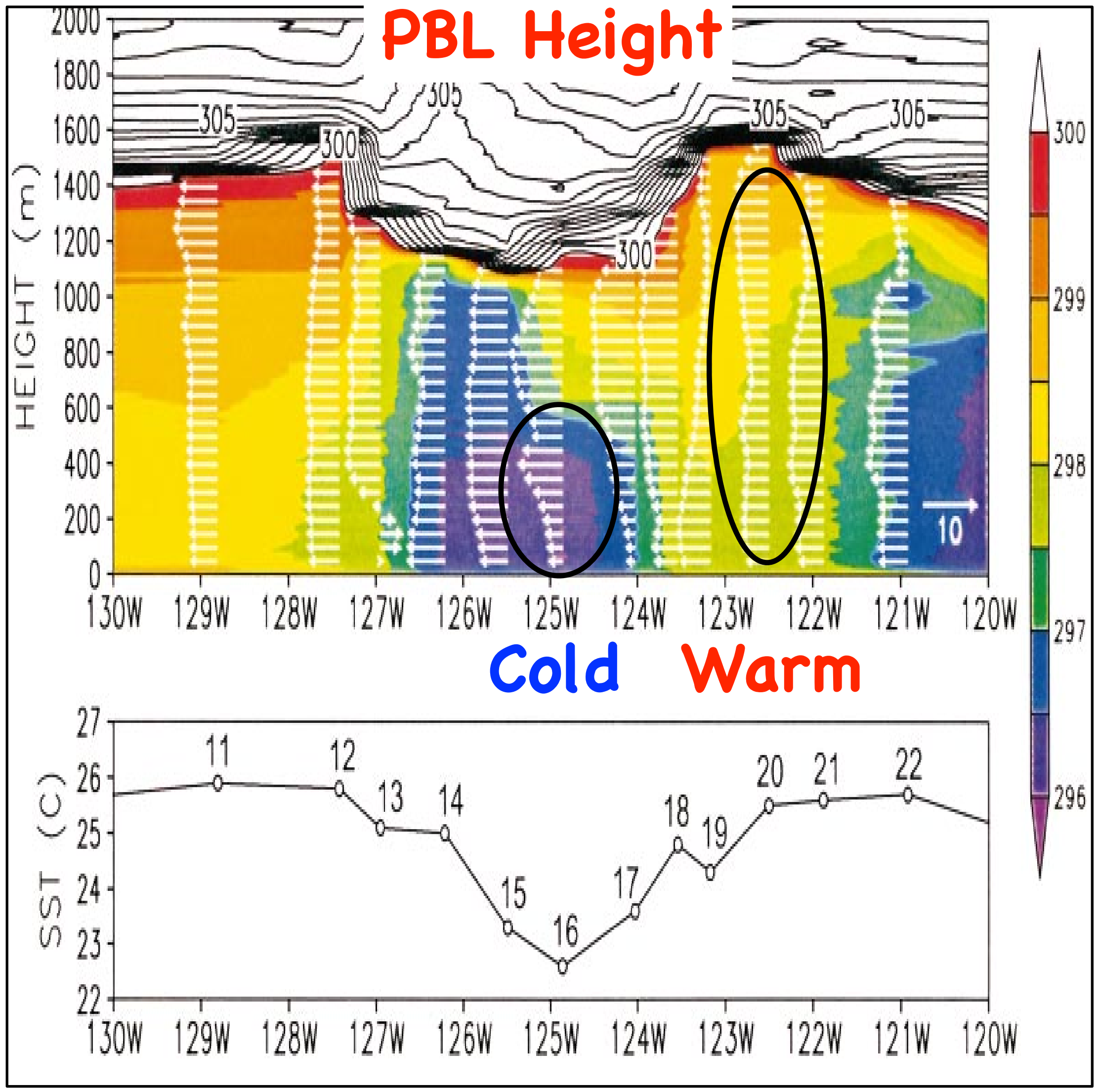
Correlation in wind speed and SST



Spatially high-passed wind, SST
Positive correlation
(Warm SST ➔ Stronger wind)

Xie et al. 2004

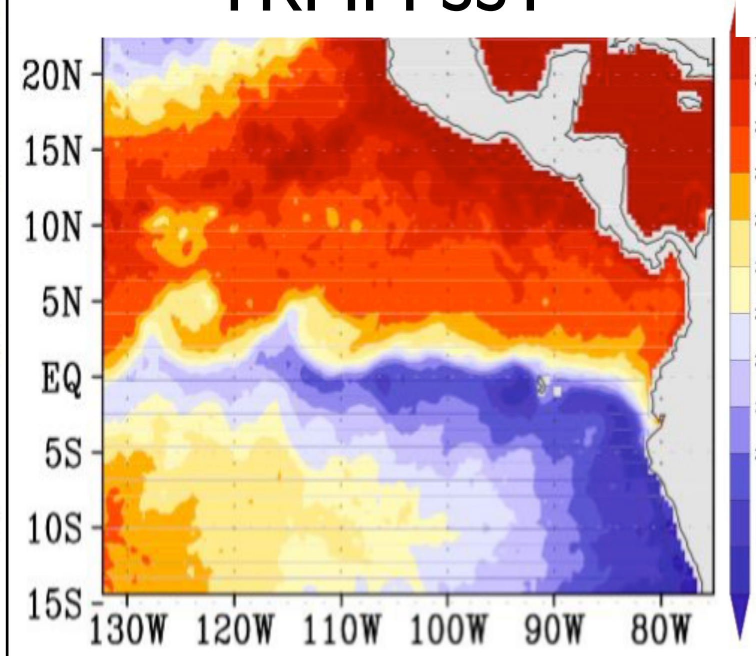
Mechanisms for positive correlation between SST and wind speed



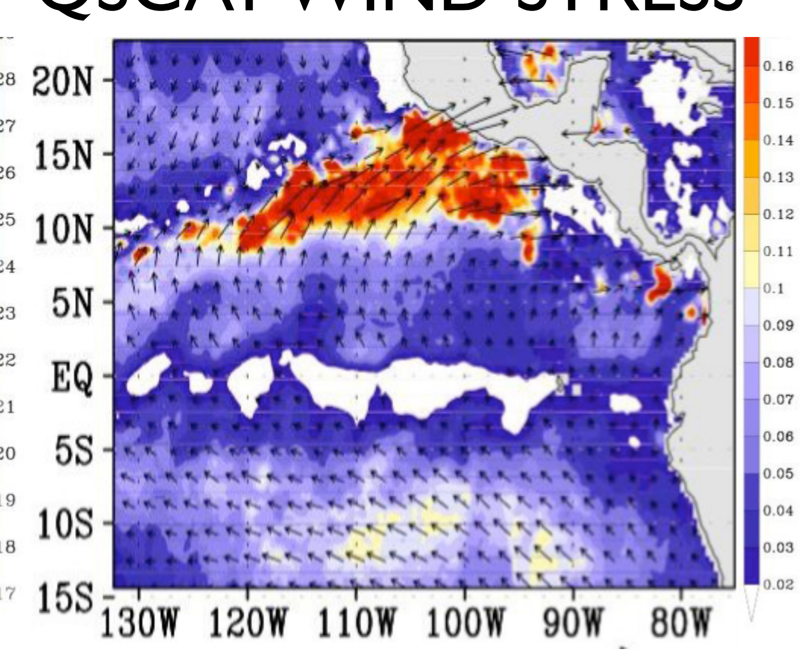
Hashizume et al. 2002

Destabilized ABL over warm SST
➔ Downward momentum mixing
➔ Accelerating surface winds
(Wallace et al. 1998)

TRMM SST



QSCAT WIND STRESS

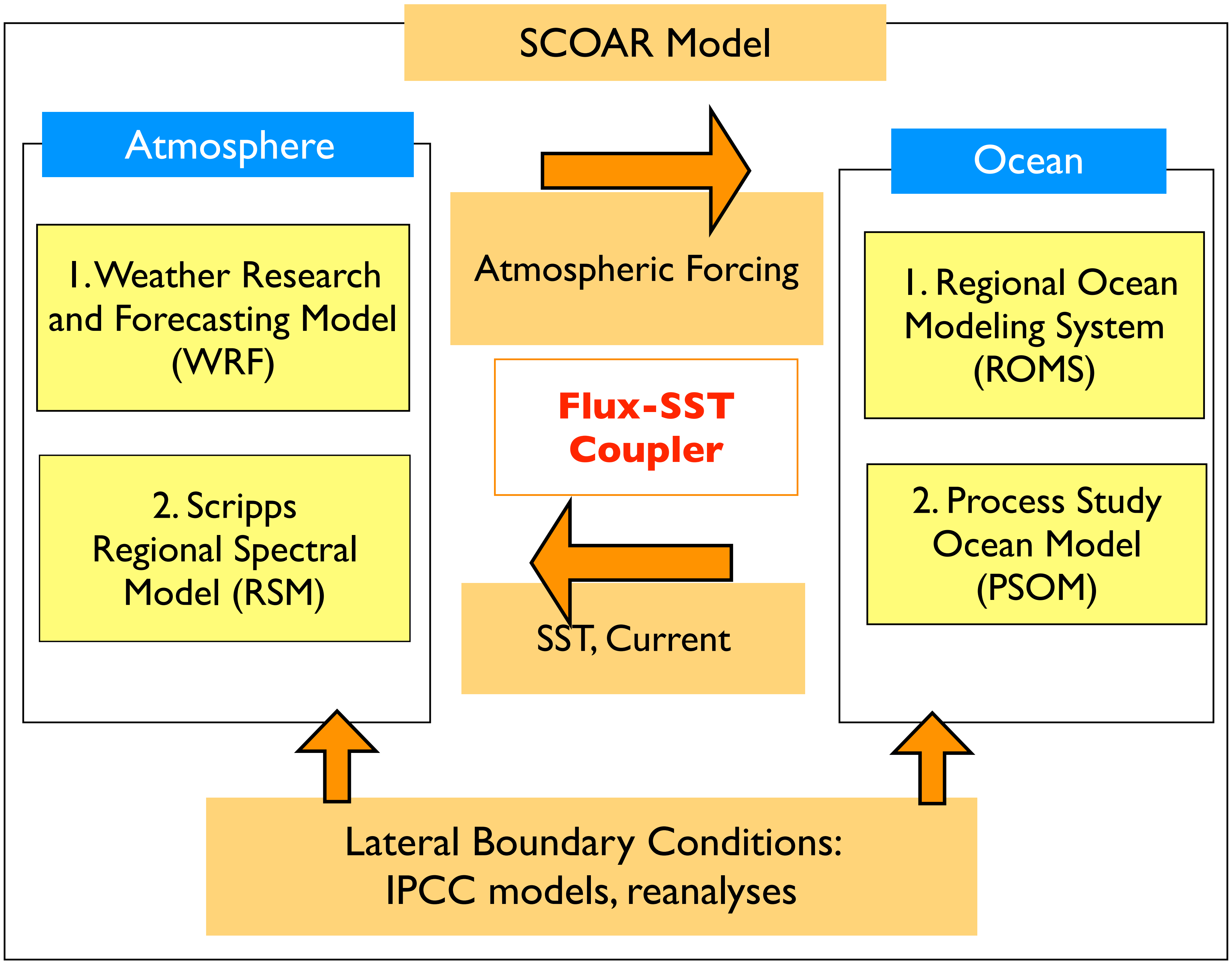


TIWs trigger mesoscale response in the atmospheric boundary layer.

Limited information from satellite and in situ data makes fuller understanding of dynamics of fine-scale interactions difficult.

➔ Need a coupled model with improved representation of oceanic eddies AND their influence on the atmosphere.

Scripps Coupled Ocean-Atmosphere Regional (SCOAR) Model



- Study mesoscale ocean-atmosphere interactions and large-scale climate.
- An input-output-based coupler and sequential coupling.
- Great portability and applicability

Seo, Miller and Roads, J. Climate 2007

Overview of my talk

- Regional Coupled Model

1. Dynamics of coherent variations in the atmosphere to SST
   (1) TIWs in the equatorial Pacific and Atlantic
   (2) Sea ice in the Arctic Ocean

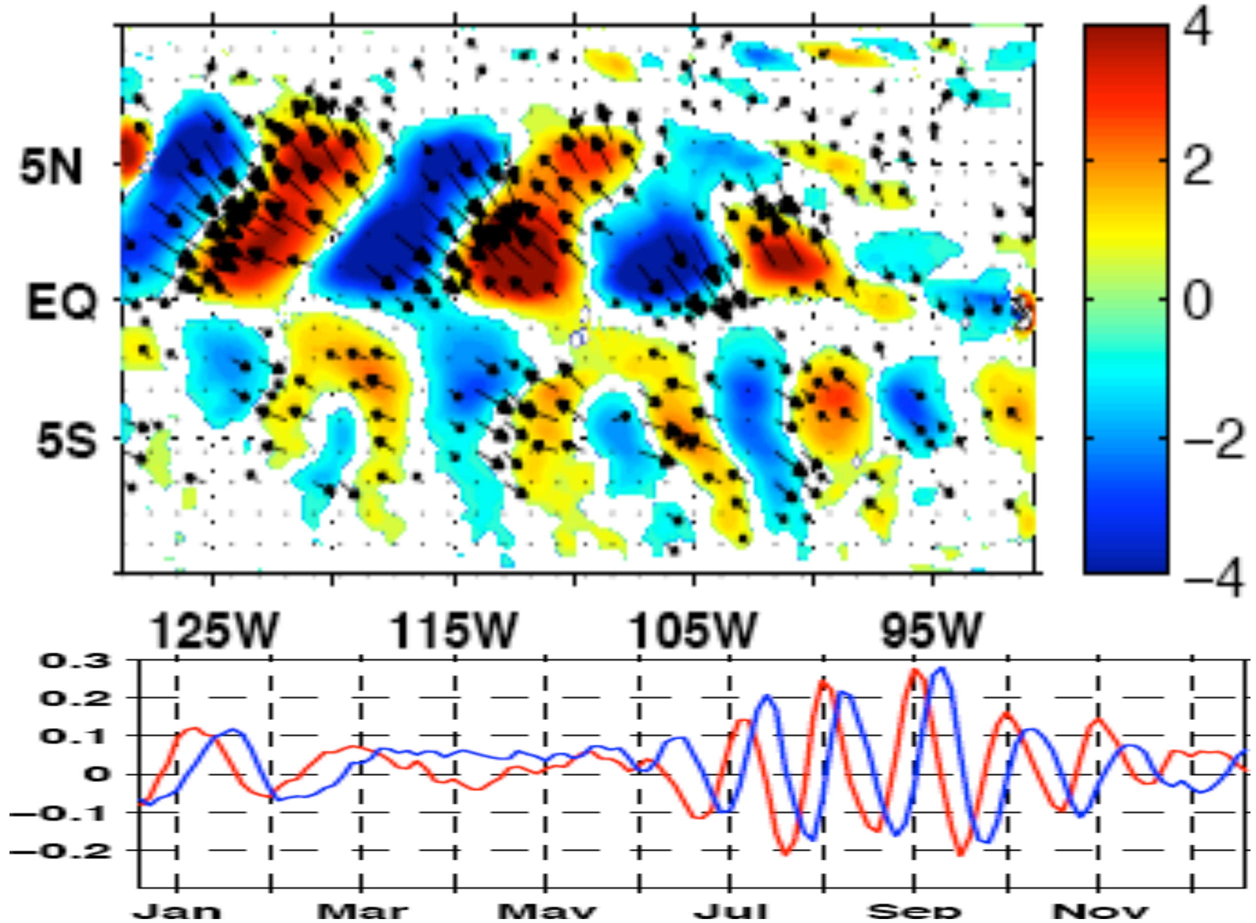
2. Role of ocean dynamics in shaping SST warming in a changing climate in the equatorial Atlantic

- Summary and discussion

Mesoscale Air-Sea Interactions over tropical instability waves

How do these wind responses feedback to ocean mesoscale variability?

Combined EOF 1 of SST & Wind vectors



① Direct influence from SST:

SST ➜ $\boldsymbol{\tau}'$

② Modification of wind stress curl/div

$\nabla_d SST$ ➜ $\nabla \cdot \boldsymbol{\tau}'$

$\nabla_c SST$ ➜ $\nabla \times \boldsymbol{\tau}'$

Feedback to TIWs through ①

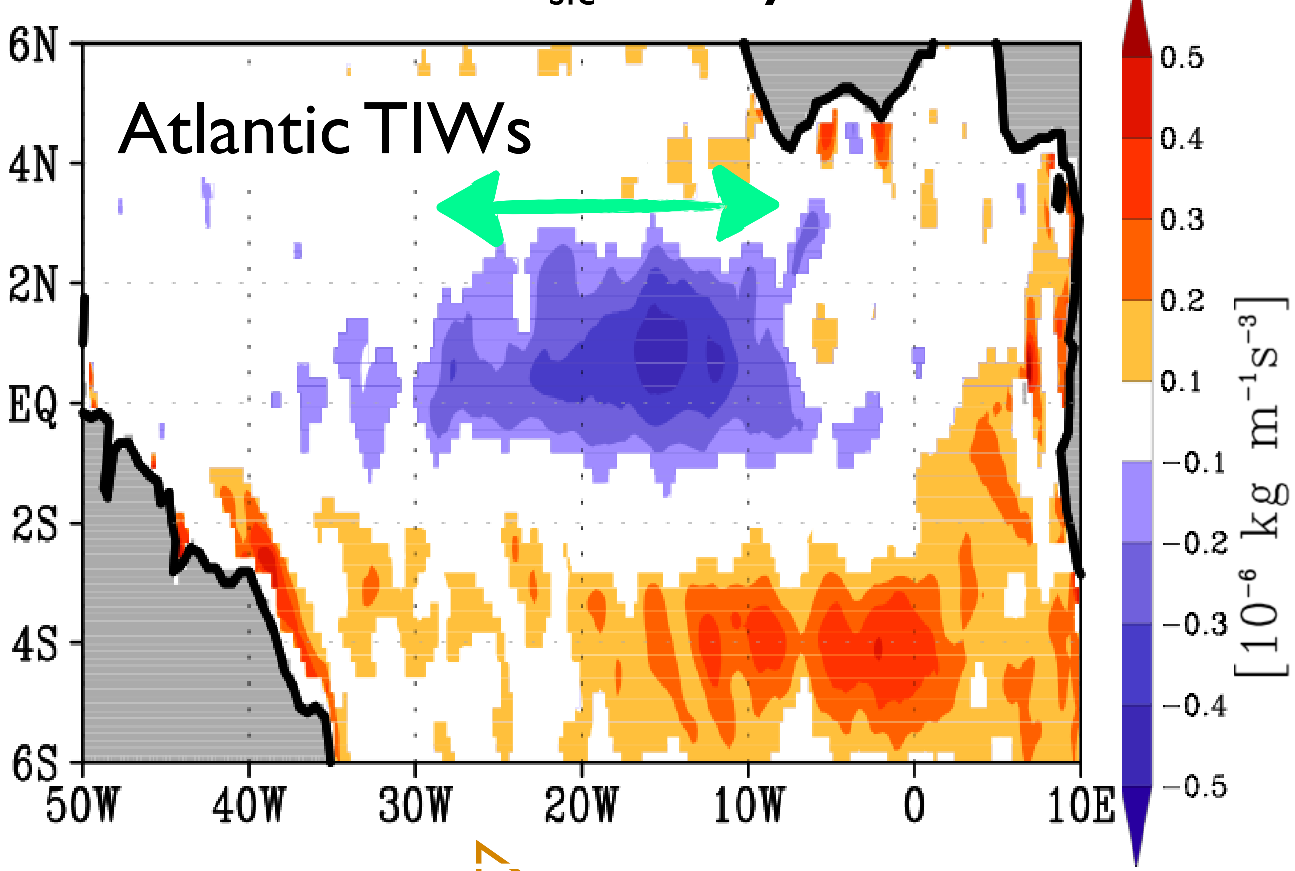
BC BT

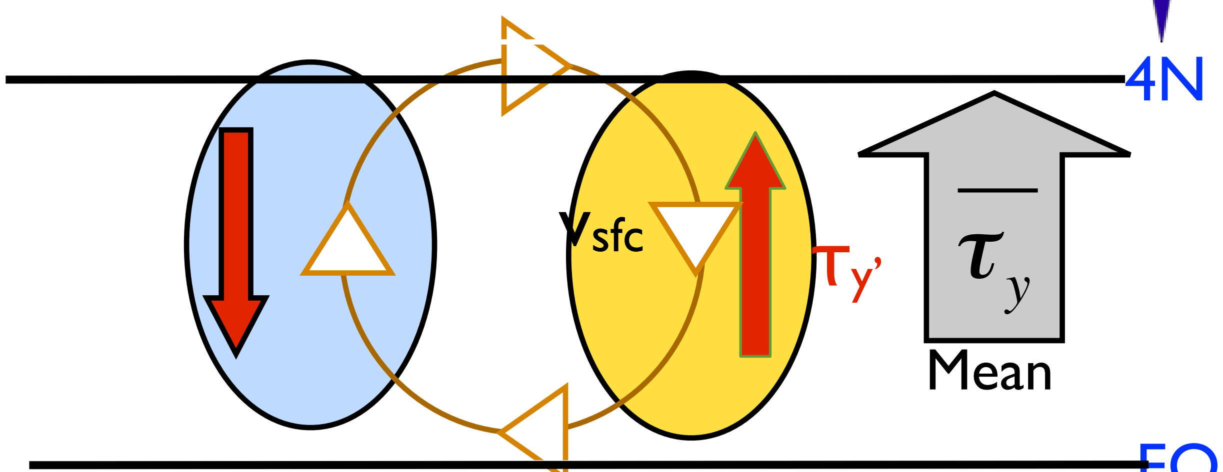
$$\vec{U}\cdot\vec{\nabla}\vec{K}_e + \vec{u}'\cdot\vec{\nabla}\vec{K}_e = -\vec{\nabla}\cdot(\vec{u}'p') - g\rho'w' + \rho_o(-\vec{u}'\cdot(\vec{u}'\cdot\vec{\nabla}\vec{U}))$$

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

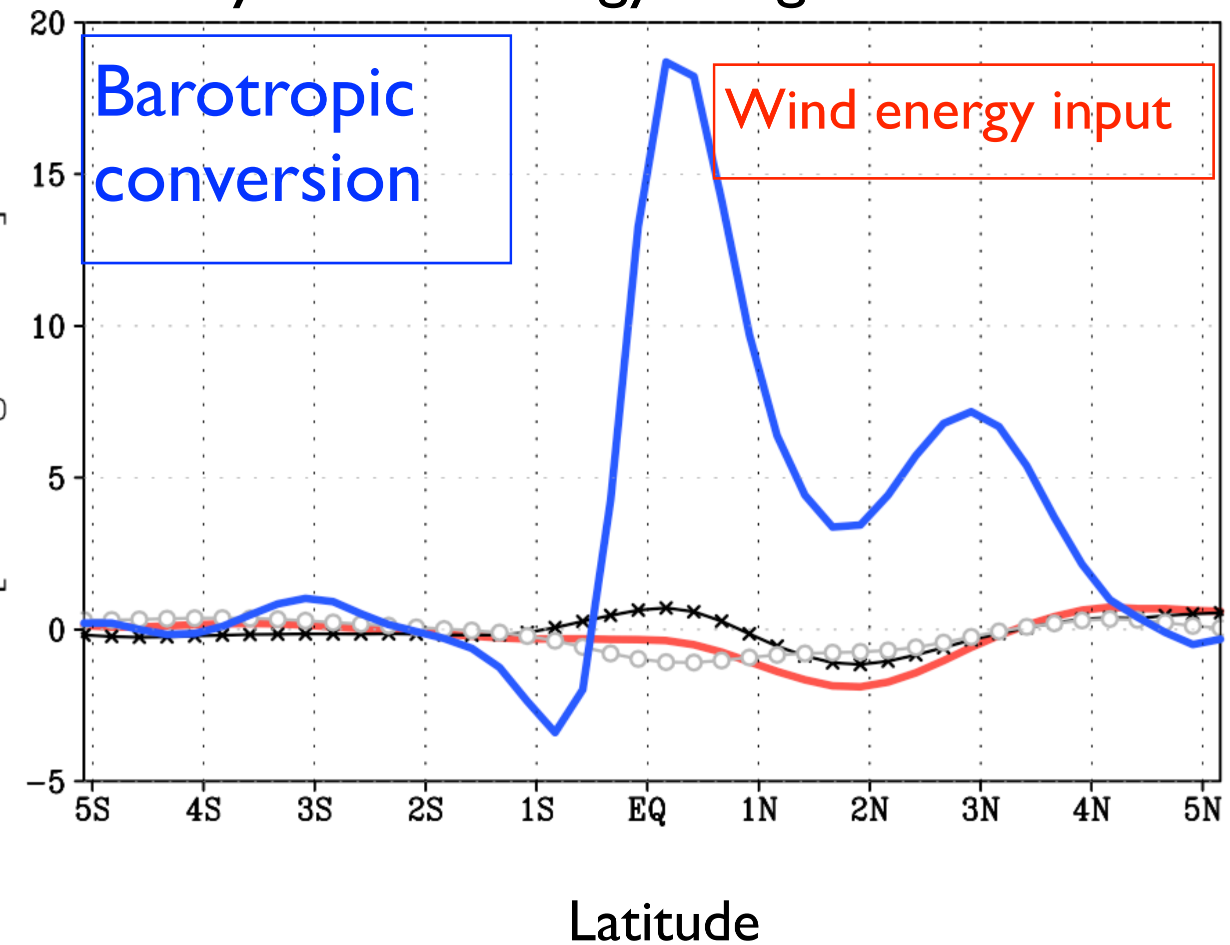
Anomalies in current and wind stress are opposite in direction, meaning wind response damping the ocean!

Correlation of v'_{sfc} and $\boldsymbol{\tau_y}'$





Eddy kinetic energy budget

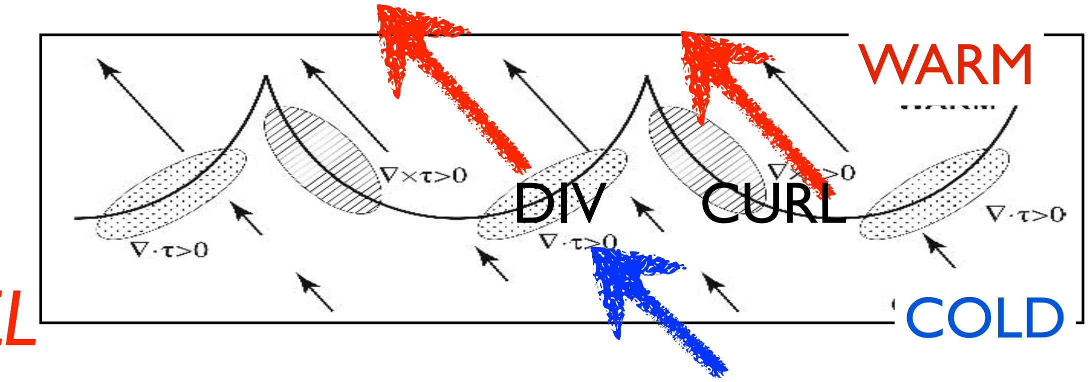


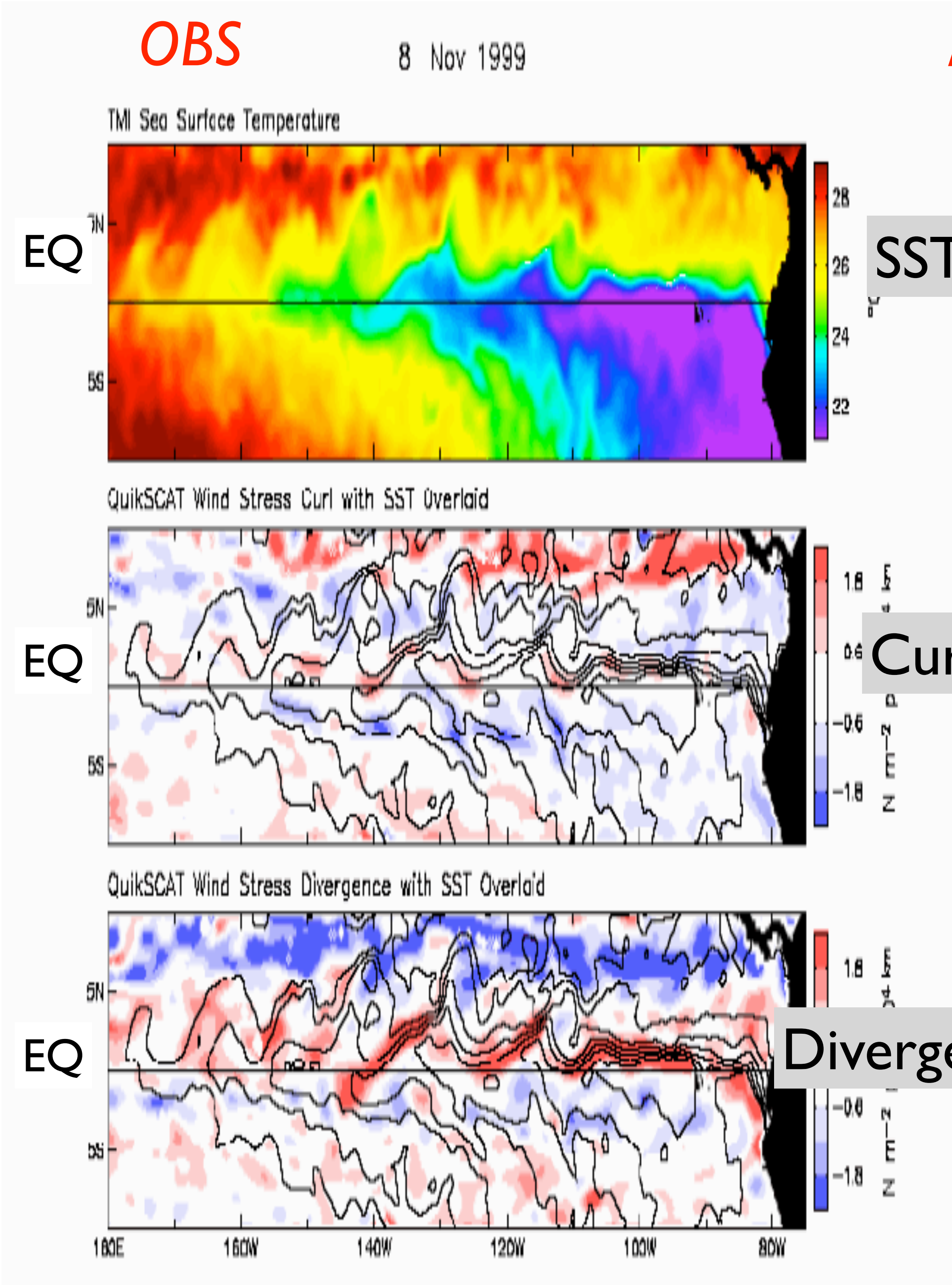
- Wind contribution to TIWs is ~10% of BT conversion rate.
- A small but significant damping of TIW.

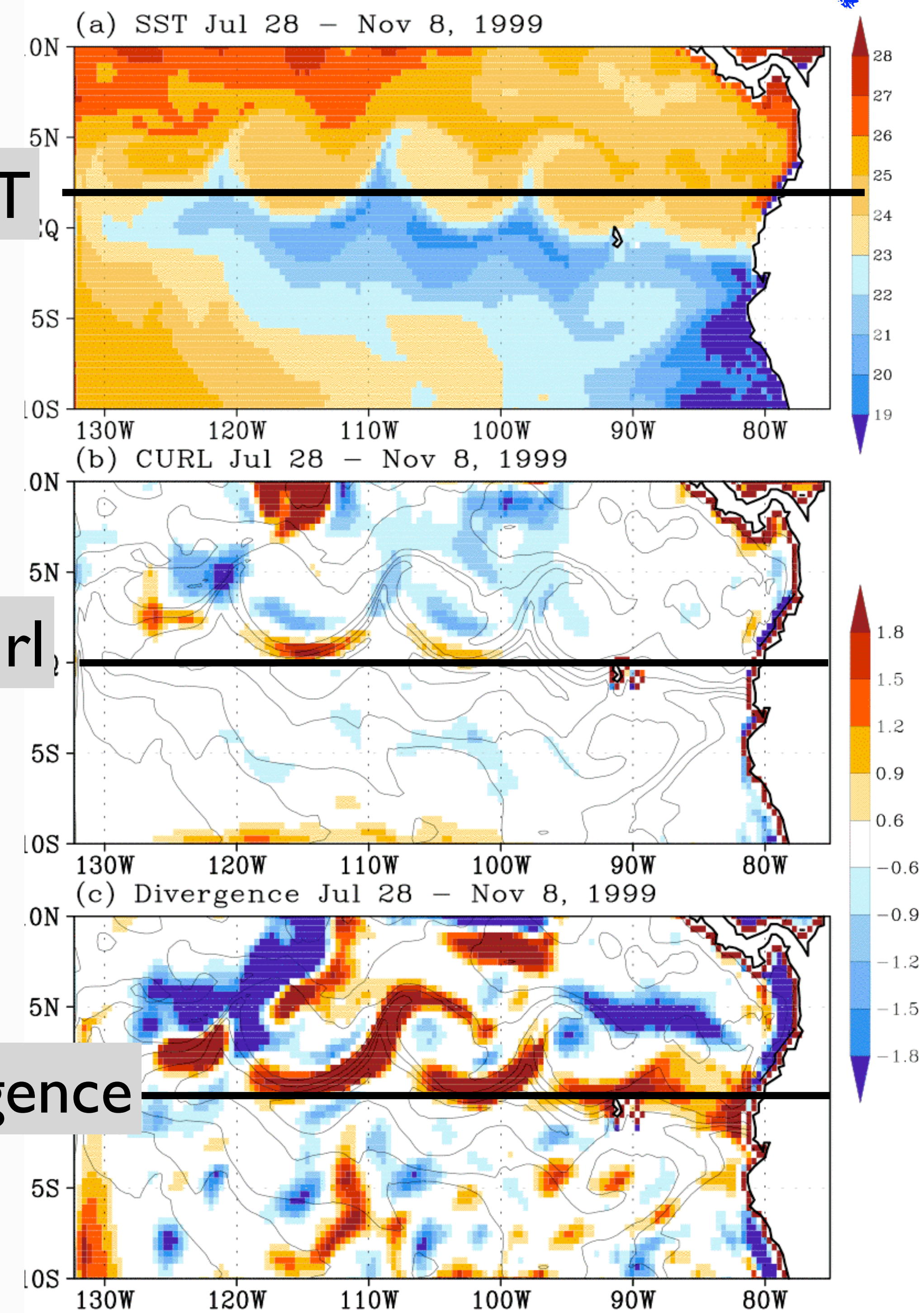
- Wind and current are negatively correlated.
- Wind-current coupling ➔ energy sink

② Modification of wind stress curl by SST gradients:

Coherent variability of wind stress curl and divergence to SST gradients!



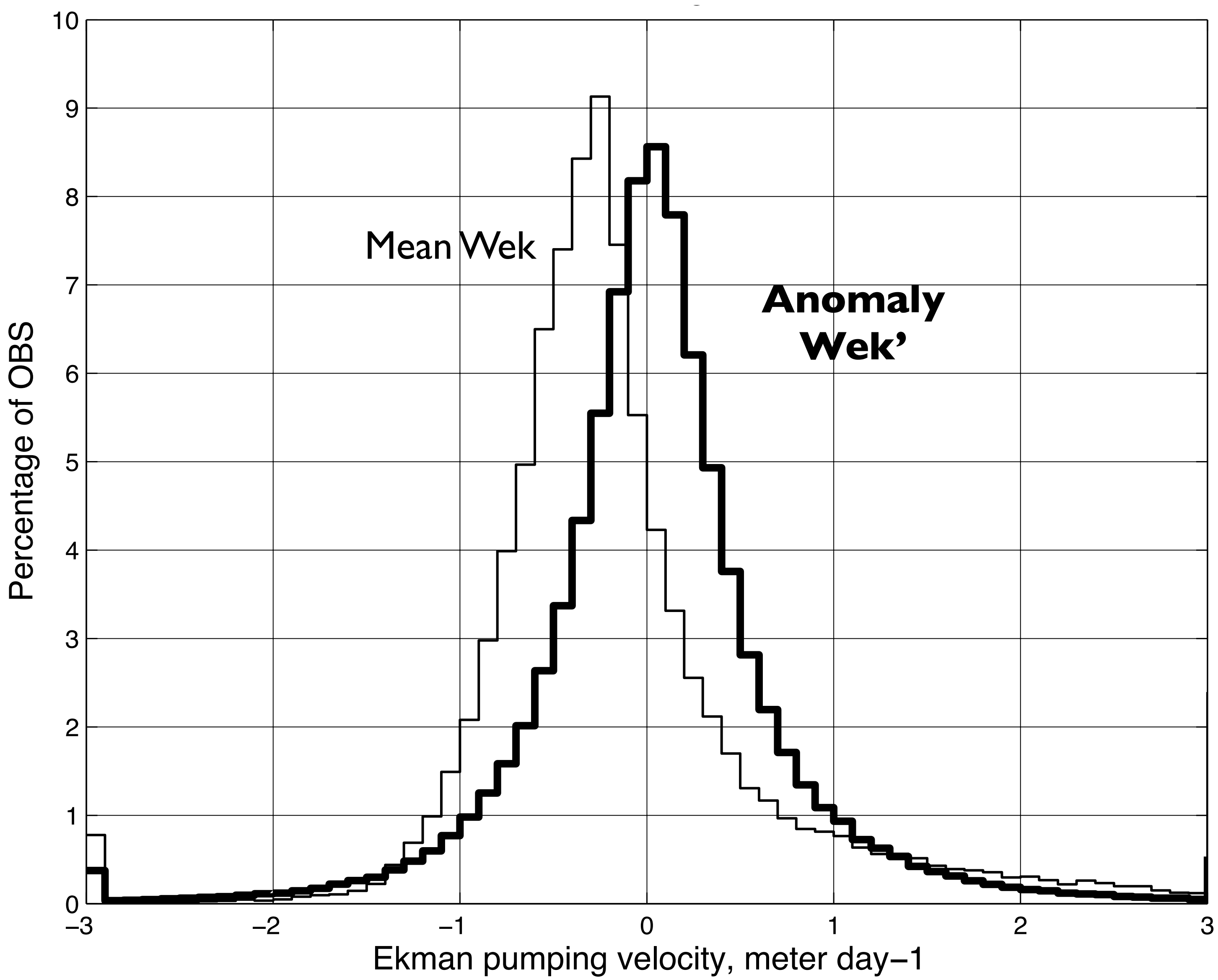




Is this eddy-mediated Ekman pumping important for ocean circulation? Yes!

$$w_{EK} = \frac{1}{\rho_w f} \nabla \times \boldsymbol{\tau}$$

PDF of W_{EK} by mean and perturbation



- Eddy-induced Ekman pumping vertical velocity exhibit a comparable dynamic range to that by mean Ekman pumping.
- This W_{EK}' is **additional** wind stress curl forcing of the ocean.
- This effect will influence the mean state through low-frequency rectification.

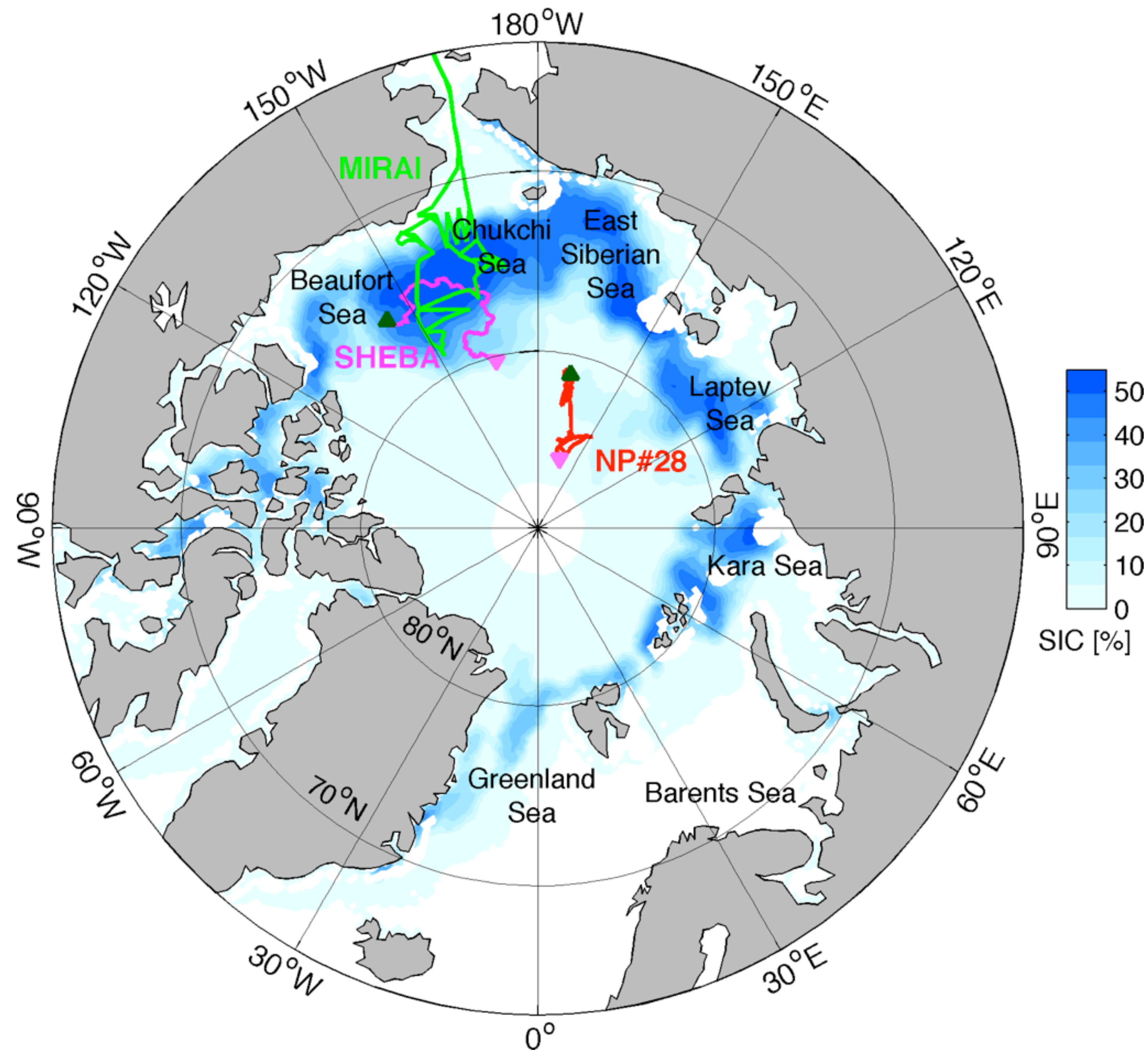
A similar story is applied to the ABL fields in the Arctic over sea ice:
Separation of spatial scale of wind response

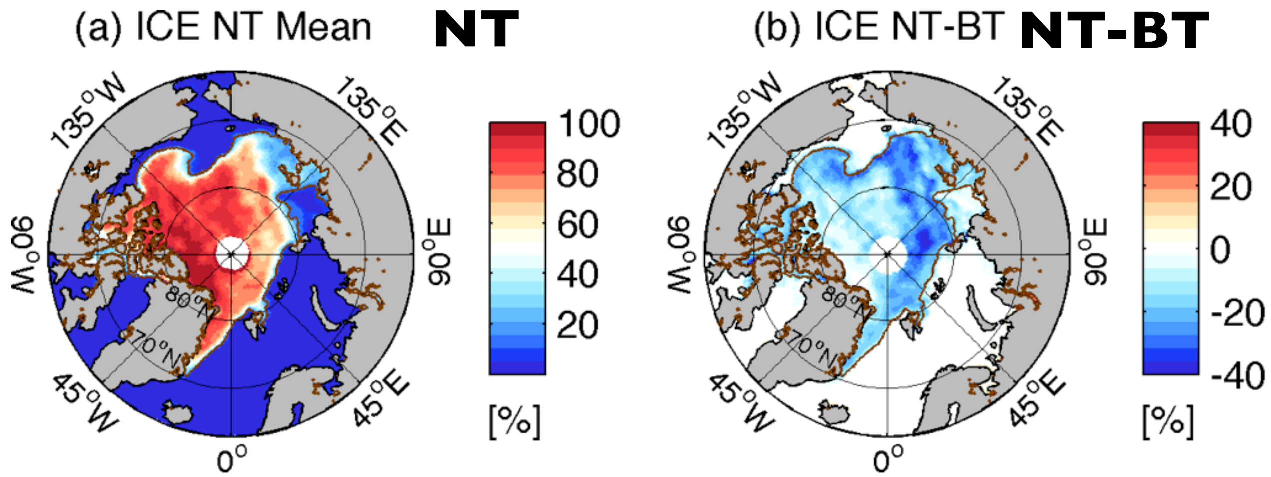
Polar WRF simulation

- Polar WRF: Hines and Bromwich (2008)
  - WRF optimized for polar regions
  - Modified surface layer model for improved surface energy balance

- Experiments
- November 2008 - October 2009
  - Sea ice forcing:
  - NT: NASA Team Algorithm
  - BT: NASA Bootstrap Algorithm

Polar WRF domain, in situ datasets overlaid with STD of SON SIC





Pan-Arctic response pattern

Focusing on NT - BT in September 2009

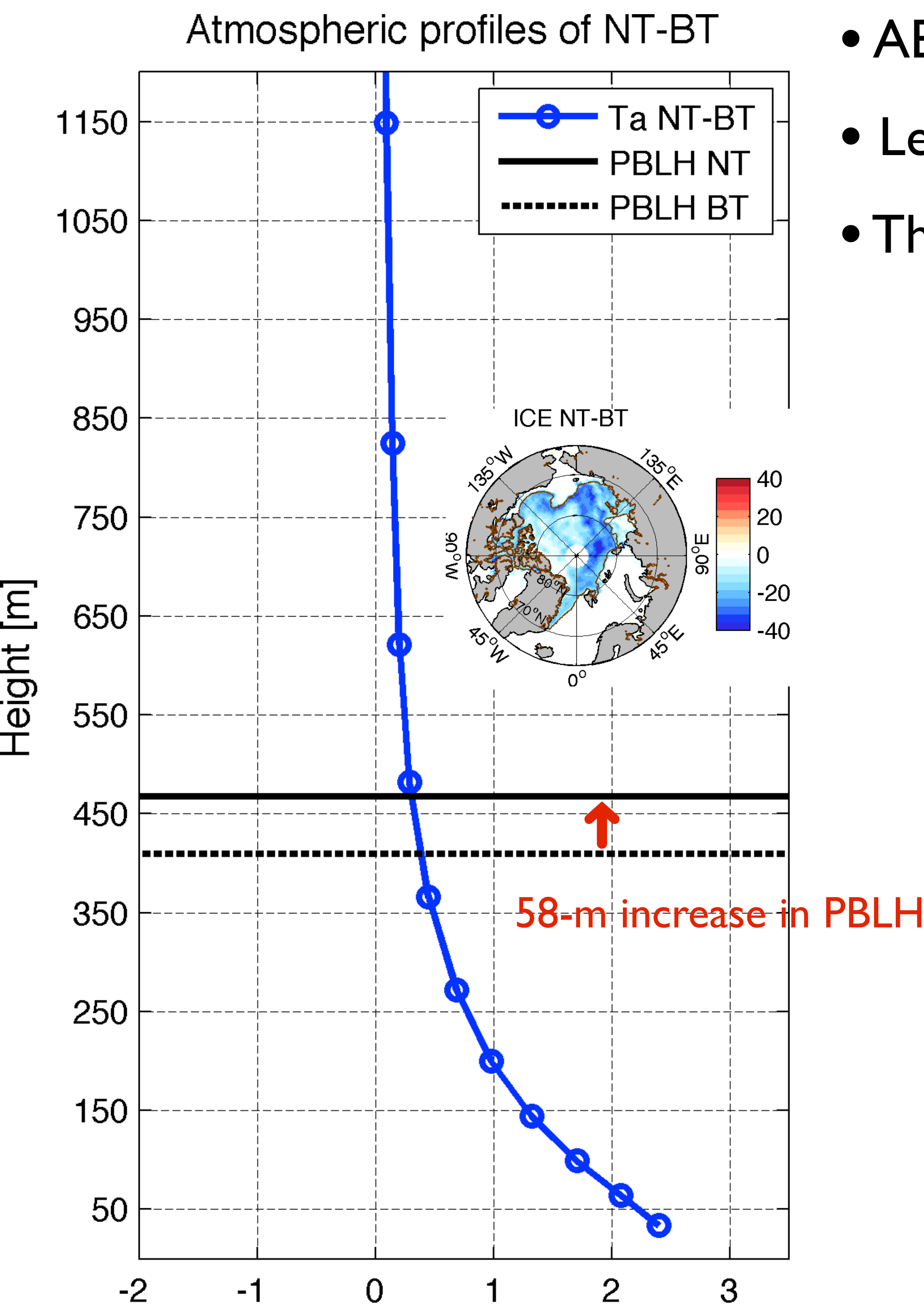
Large change in ABL compared to the mean values

East Siberian Sea	Mean	Difference
T2	-5 °C	+5 °C
PBLH	450 m	100 m
TCWP	60 gm^{-2}	10 gm^{-2}

SIC uncertainty is a decisive factor for hindcast skill!

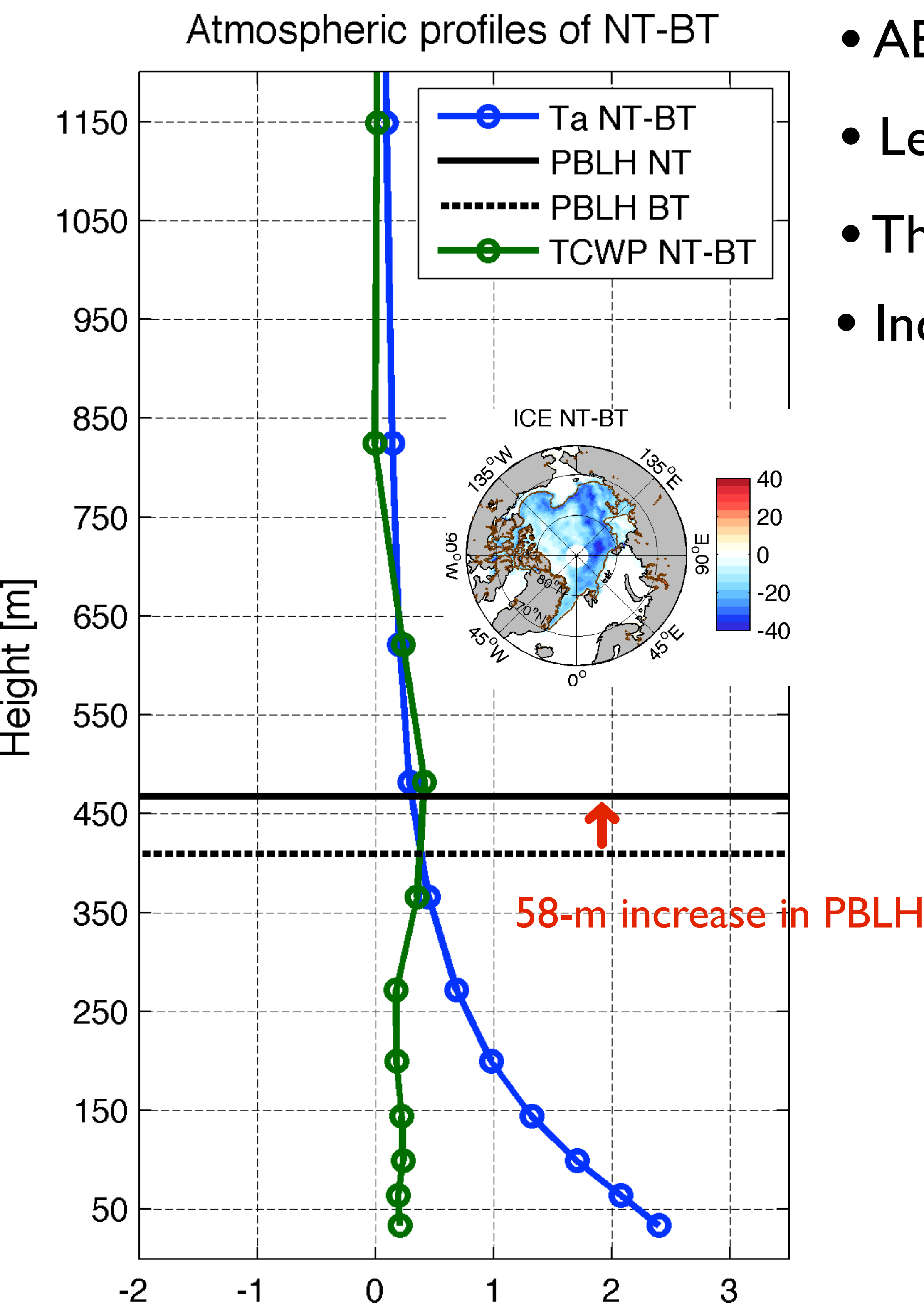
- SIC difference and ABL sensitivity on the comparable basin-scales

Arctic-basin averaged vertical profiles difference (NT-BT)



- ABL stability adjustment to SST: Wallace et al., (1989).
- Less SIC ➔ Higher PBL
- The basin-wide increase in air temperatures below PBL.

Arctic-basin averaged vertical profiles difference (NT-BT)



- ABL stability adjustment to SST: Wallace et al., (1989).
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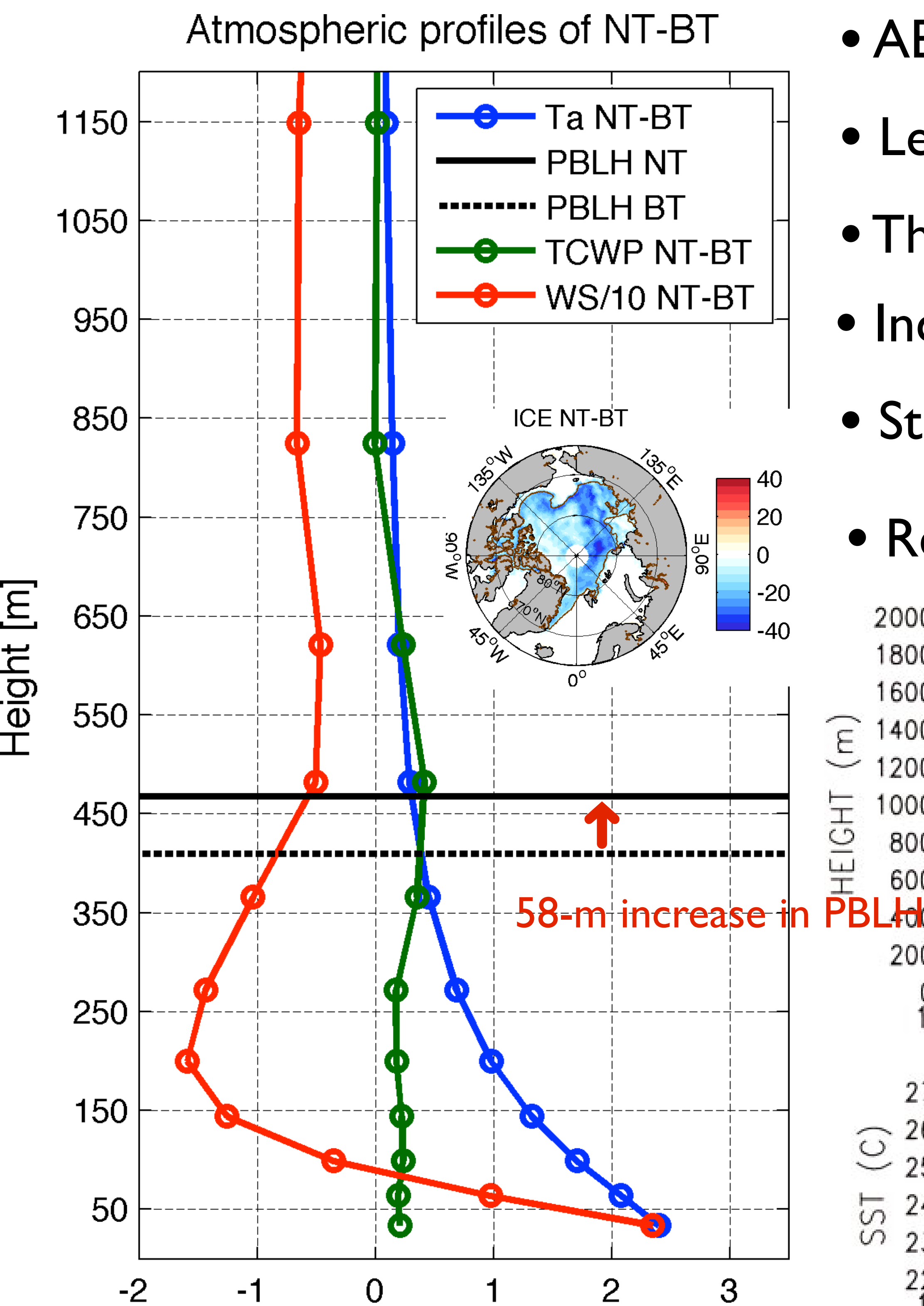
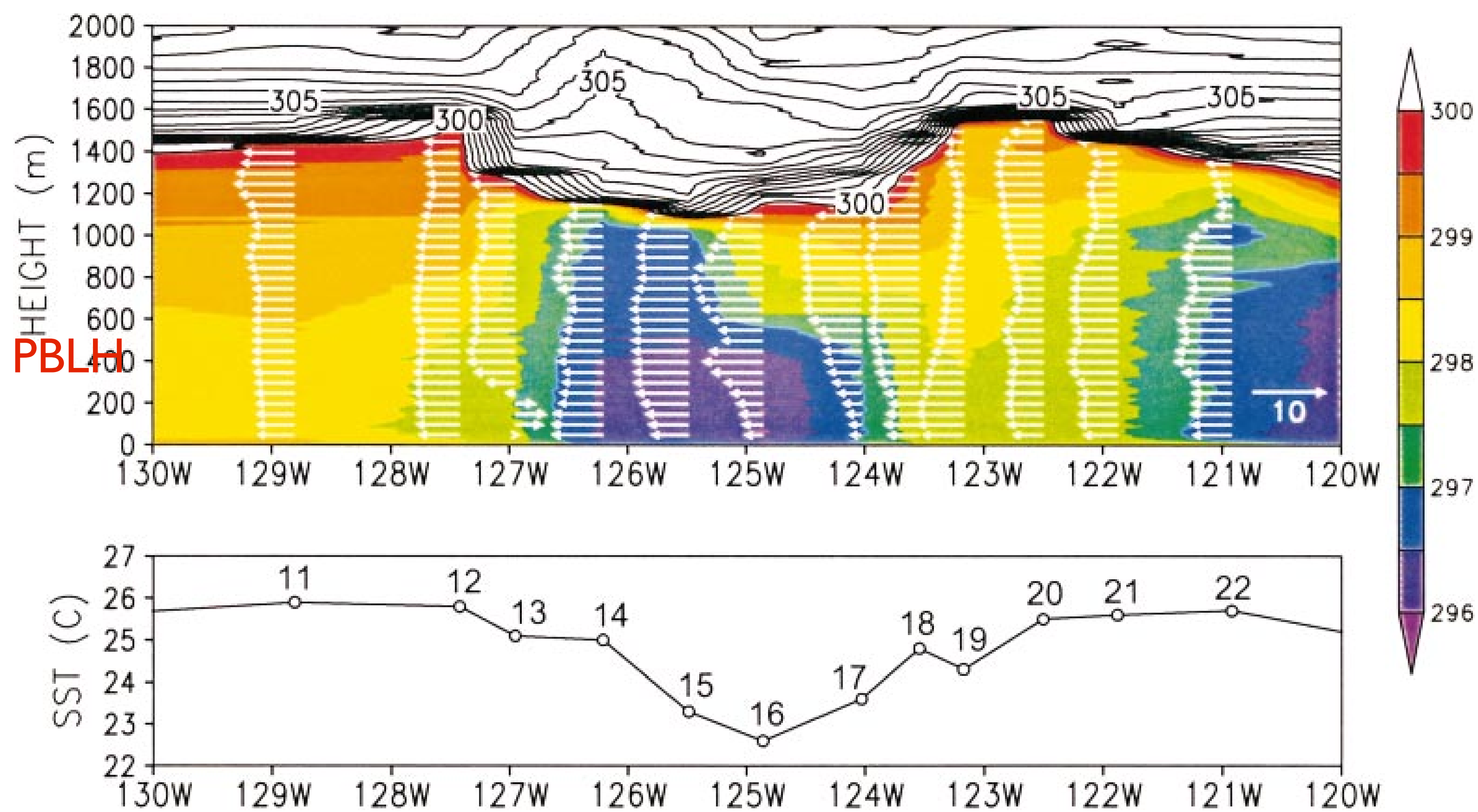


- ABL stability adjustment to SST: Wallace et al., (1989).
- Less SIC ➔ Higher PBL
- The basin-wide increase in air temperatures below PBL.
- Increased cloud water path near the top of PBL.
- Stronger wind below 100 meter but weaker wind aloft
- Reminiscent of what is happening in mid to low latitudes!

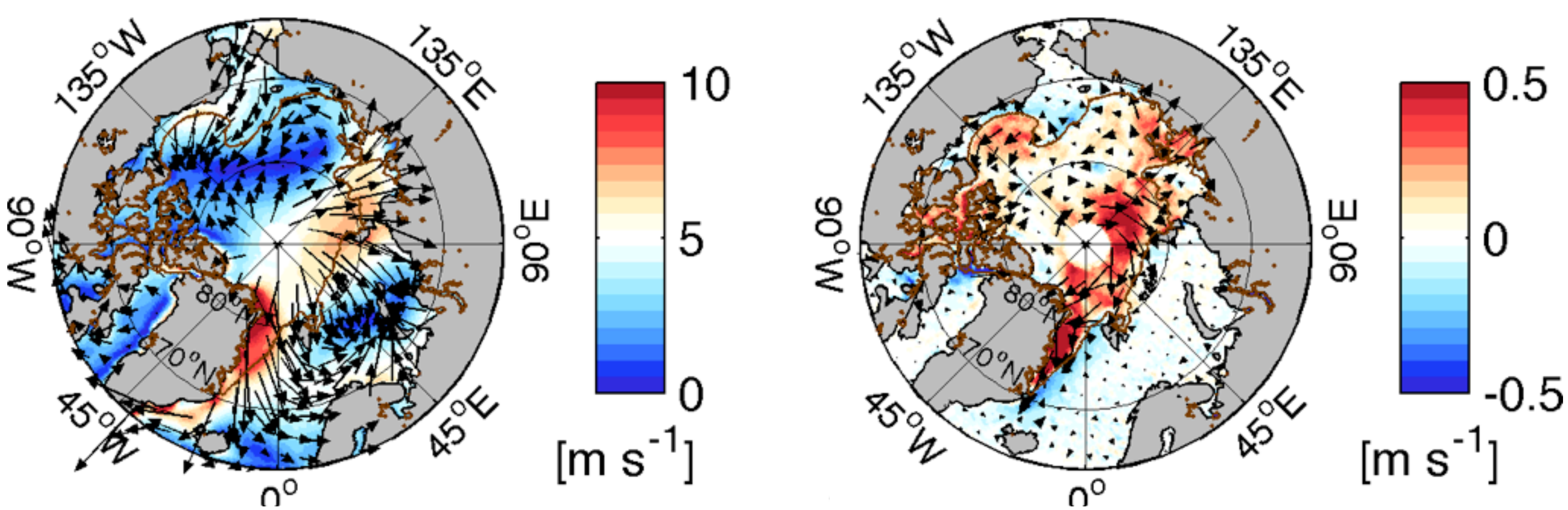


Observations of ABL evolution in the eastern tropical Pacific
Hashizume et al. (2002)

Contrasting responses in two near-surface wind fields: W10 and Wg (≈∇SLP)

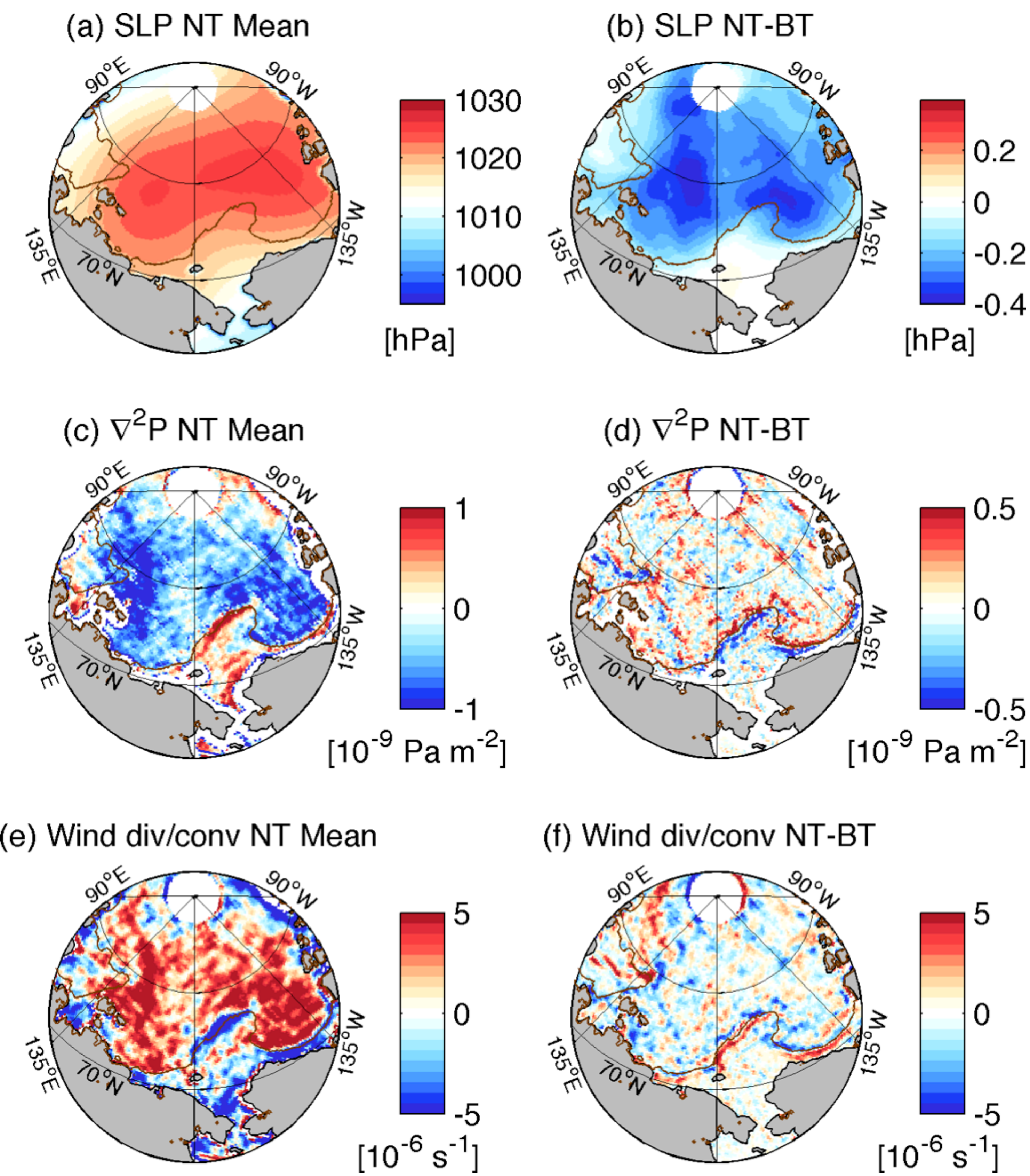
NT - BT in September 2009

W10 NT Mean — W10 NT-BT



- Stronger W10 with reduced SIC
  - Most dramatic changes in the interior Arctic
  - >10% change of the mean.

Wg response is more pronounced on the smaller scale than W10



- A simple marine boundary layer model of *Lindzen and Nigam (1987):*
- *Assuming* steady flow, no advection, linear friction,

$$\rho_o\left(\nabla\cdot\vec{u}\right)=-\left(\nabla^2 P\right)\varepsilon/\left(\varepsilon^2+f^2\right)$$

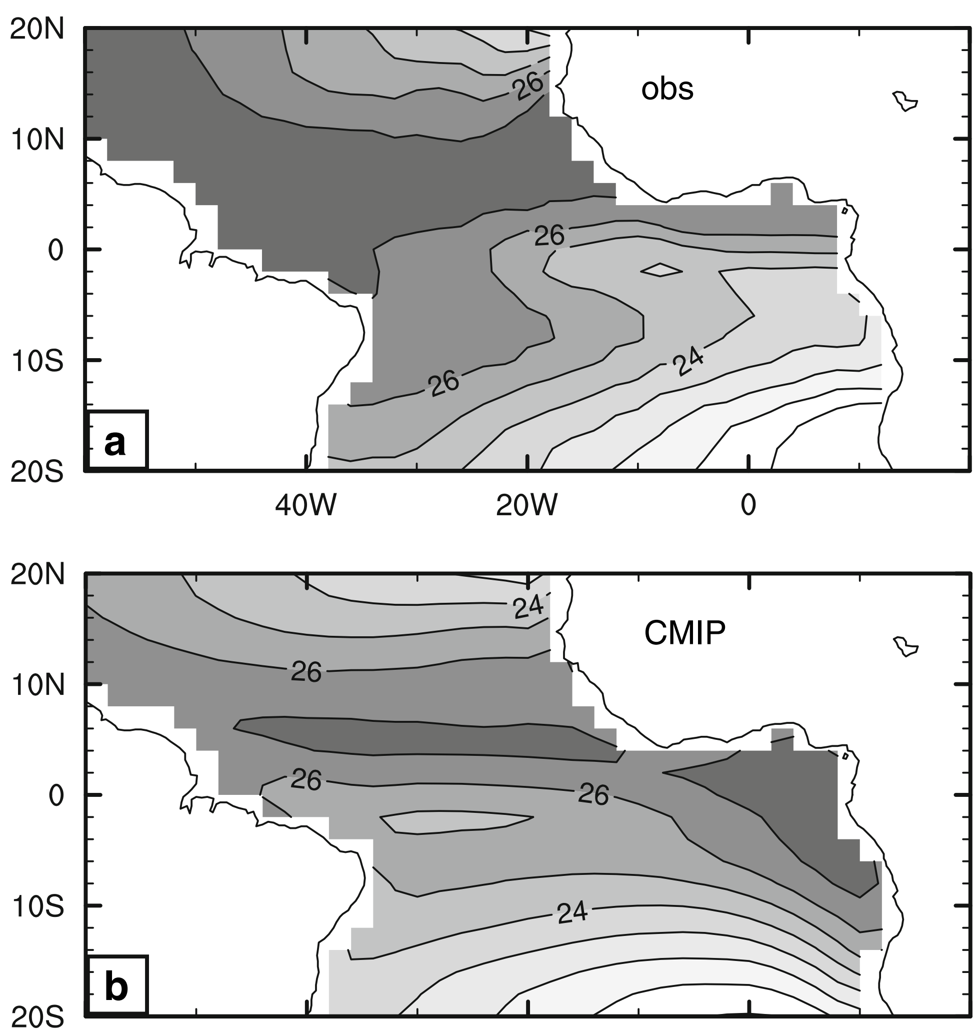
- Div. /Conv. of surface wind is linearly proportional to SIC-induced Laplacian of SLP

- ∇^2 would be effective in highlighting small-scale response,

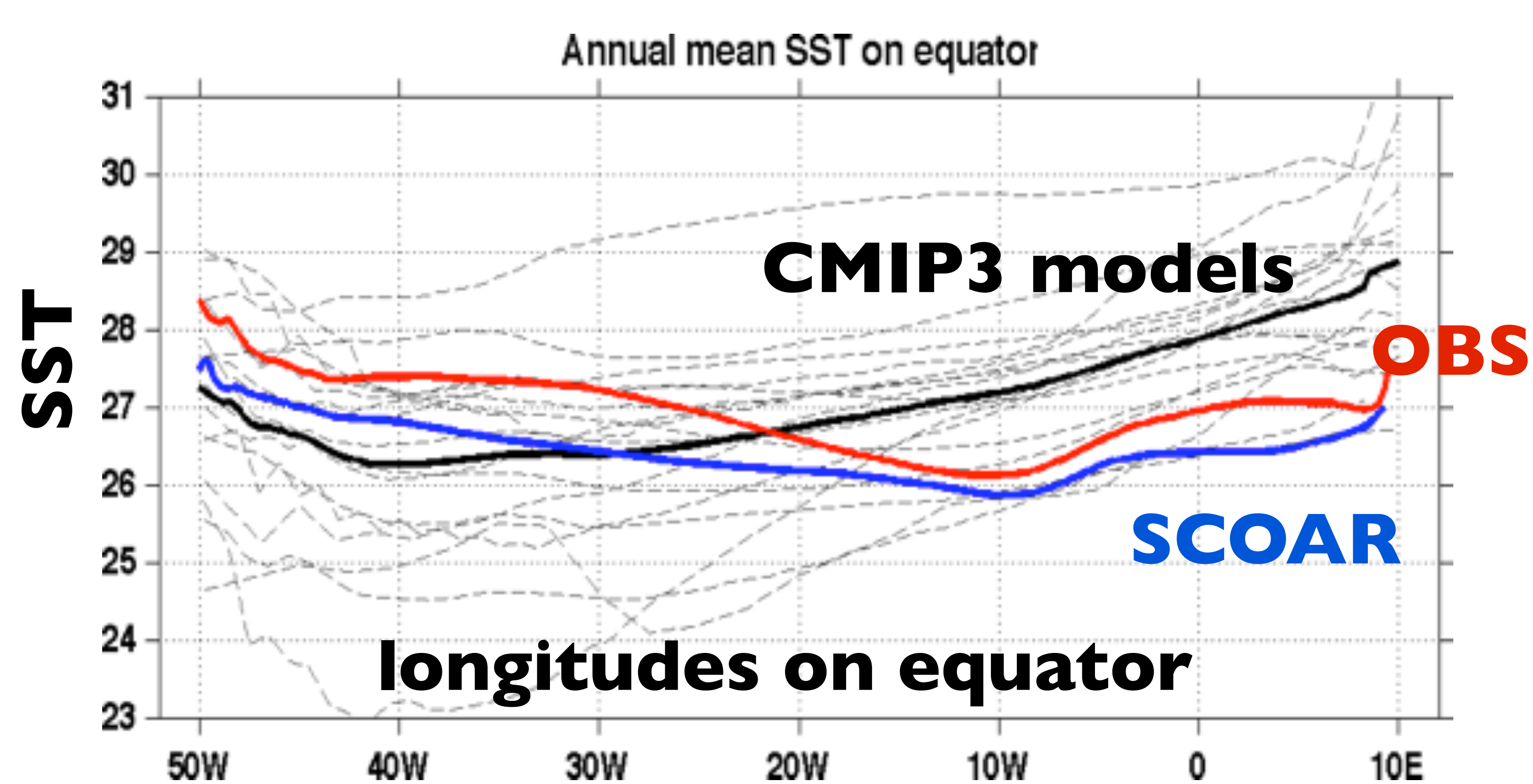
  e.g., along the sea ice margins.

What is the role of ocean dynamics in shaping regional SST pattern in a warming climate? The Equatorial Atlantic Ocean..

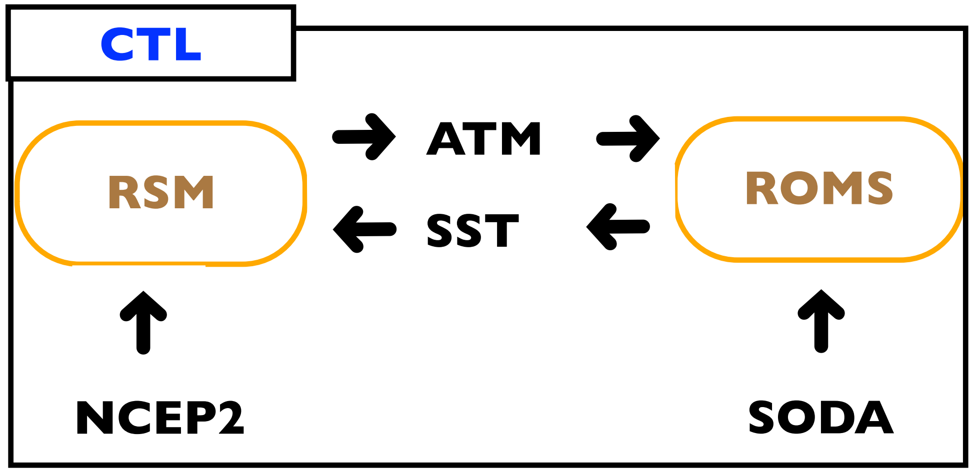
- IPCC-class models have large biases in simulation of the equatorial climate
    - Especially in the Atlantic.
    - A reversed east-west gradient.
    - Underestimation of equatorial currents, upwelling and TIWs.

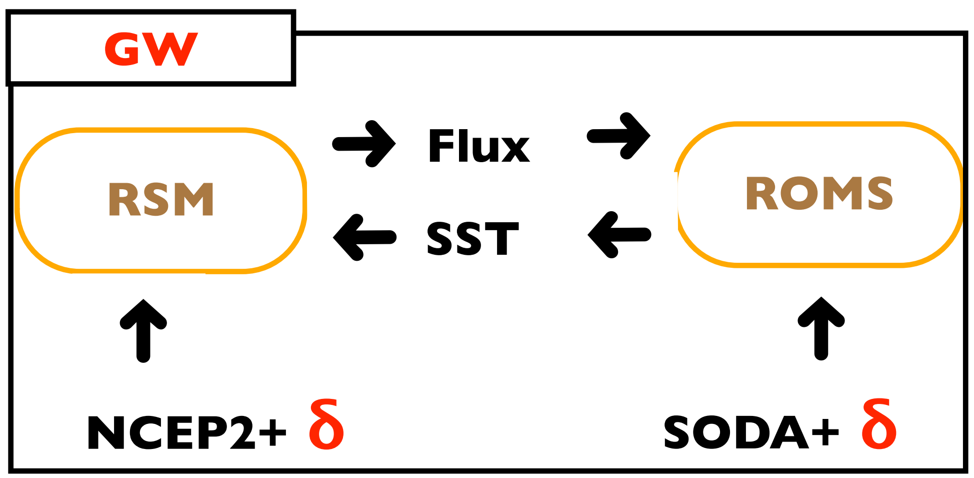


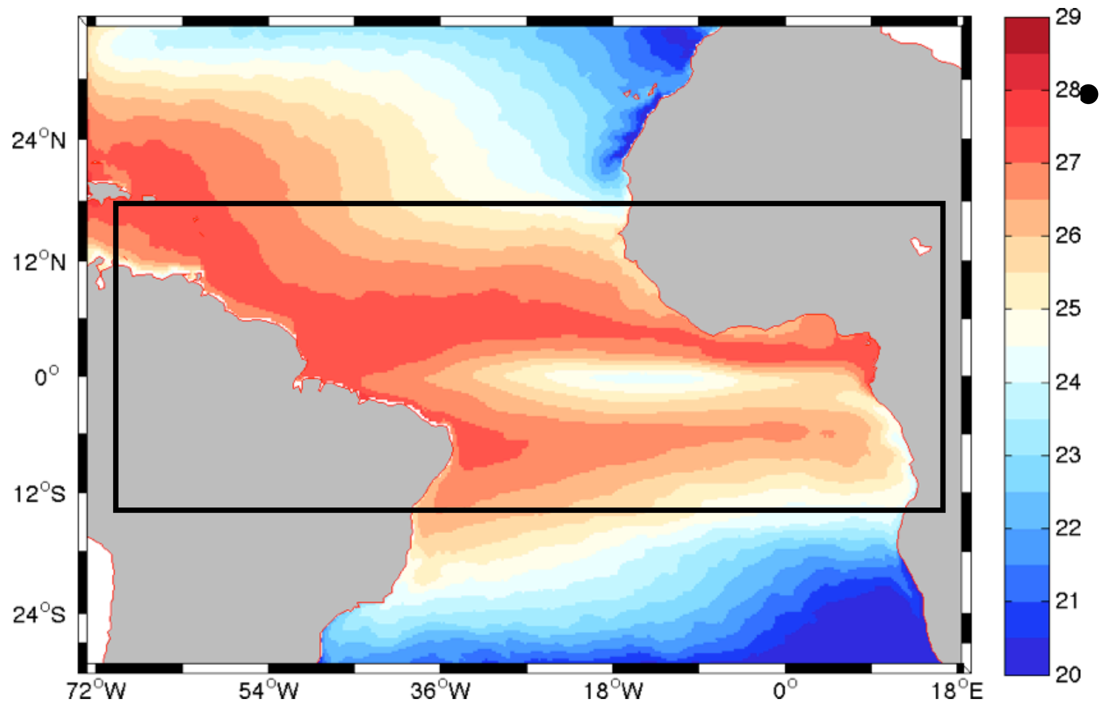
Richter and Xie 2008



Model and experiments



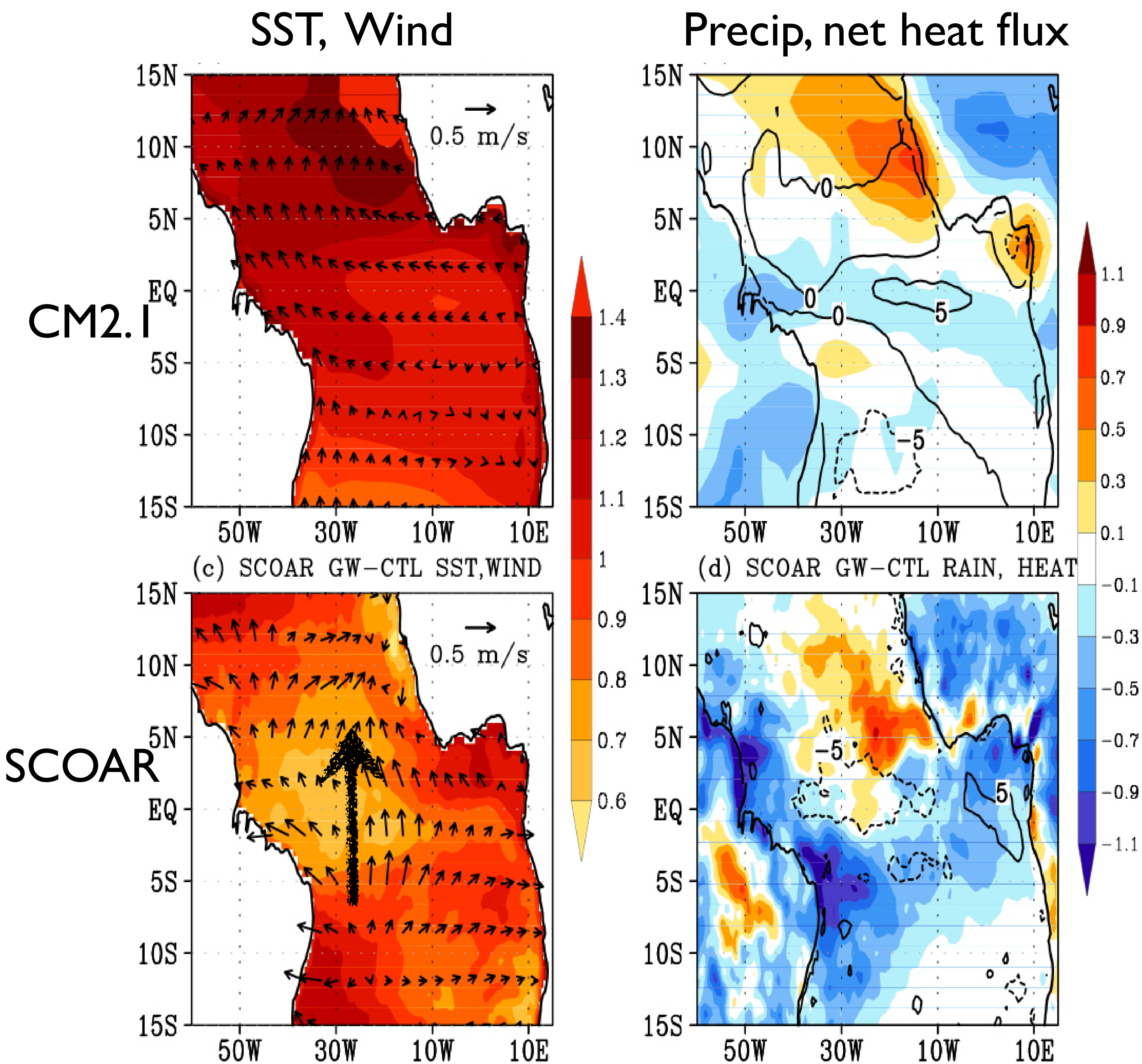




- **CTL**: RSM (NCEP2 6hrly) + ROMS (SODA monthly)
- 25 km ROMS + 50 km RSM
- 28-yr. integration: 1980-2007
- CO_2=348 PPM
- δ=GFDL CM2.1 monthly difference: (2045-2050: A1B)-(1996-2000: 20C); 10-member ensemble mean
- **GW**: RSM (NCEP2 6-hrly+δ) + ROMS (SODA monthly+δ)
- CO_2=521.75 PPM

pseudo-global warming method in a regional coupled model (Seo and Xie 2011)

Change in annual mean state (GW-CTL)

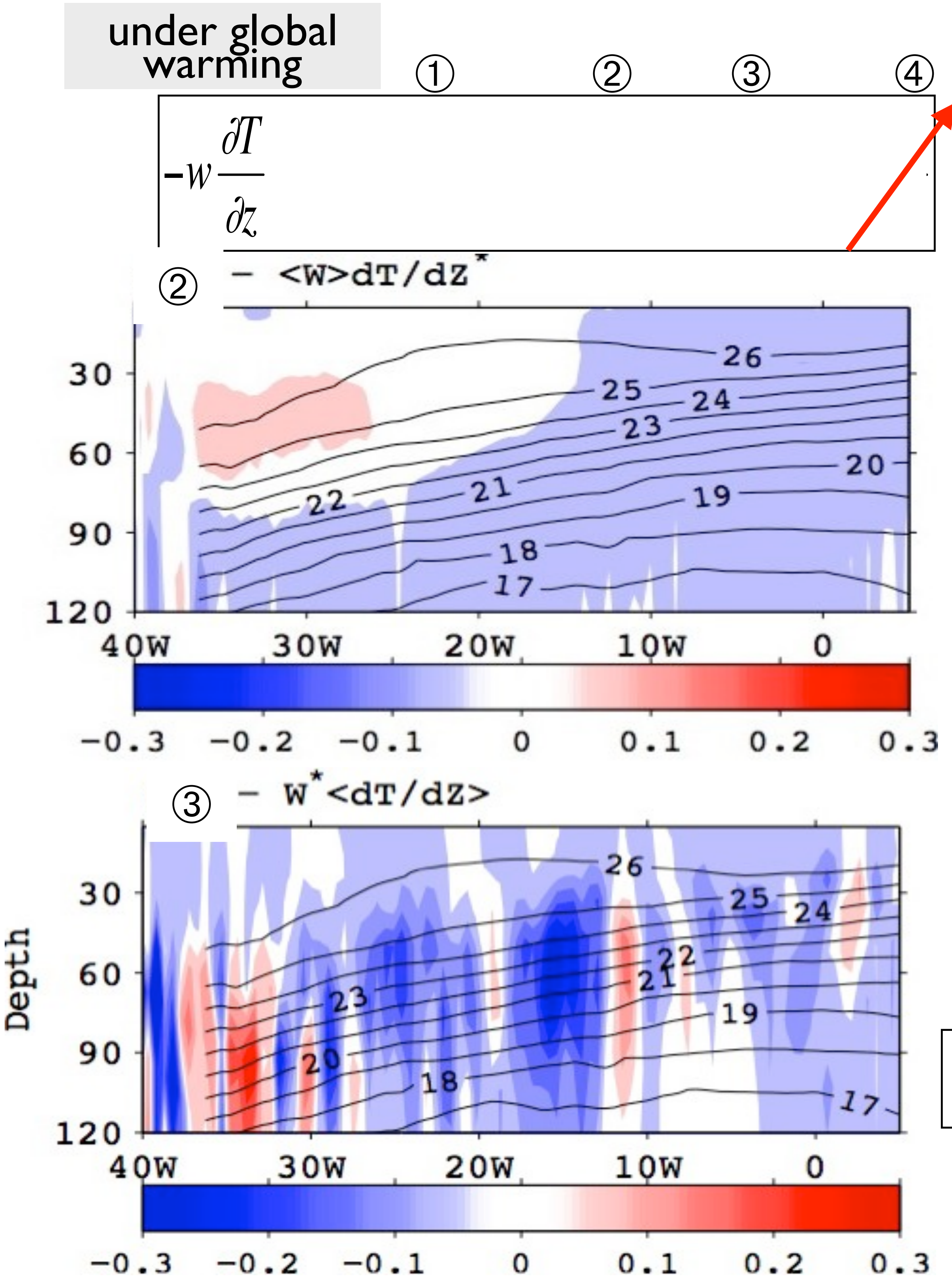


- Different equatorial ocean response:
  - Reduced warming (more upwelling) in the equator.
  - Cross-equatorial southerly wind is stronger on equator.
- Similar large-scale atmospheric response
  - Increased (decreased) rainfall in the tropical northeast (south) Atlantic.

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

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

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



$x = \langle x \rangle + x^*$

<>: present-day mean (CTL)

*: Perturbation (GW-CTL)

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

Ocean Dynamical Thermostat

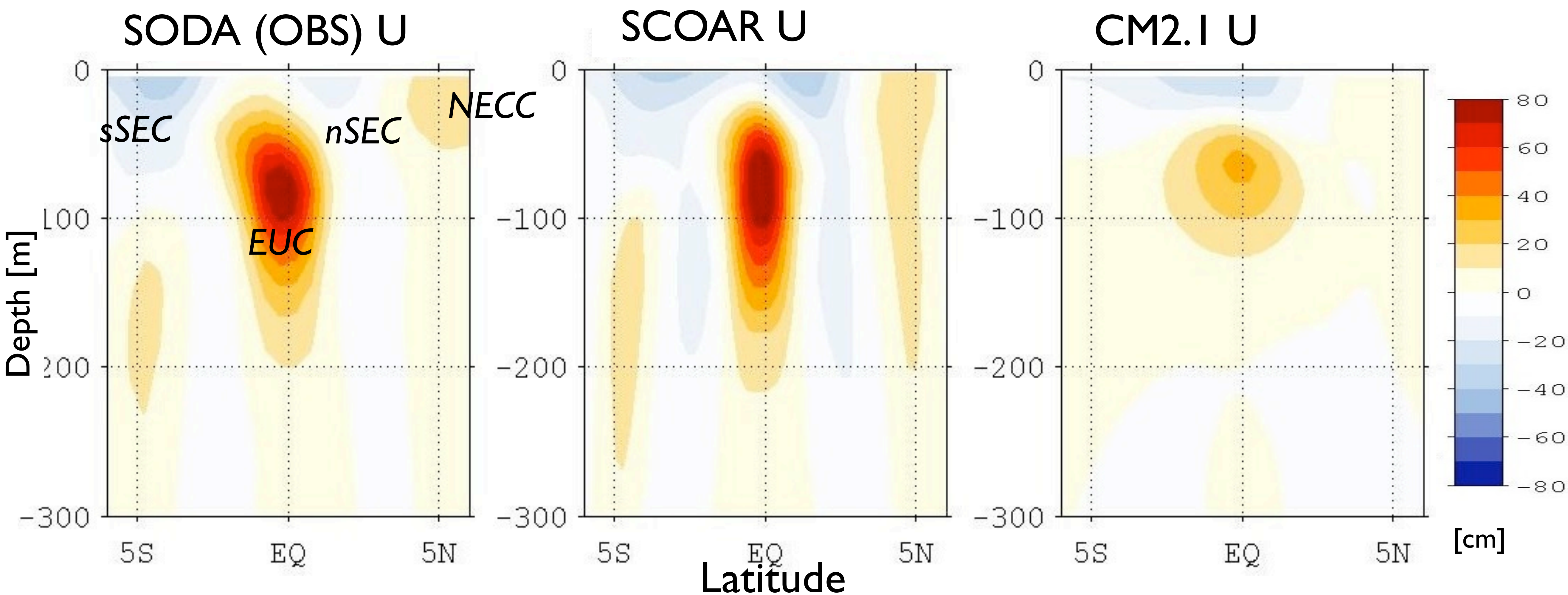
(in the Pacific:

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

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

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

2. Stronger upwelling associated with stronger Equatorial Undercurrent

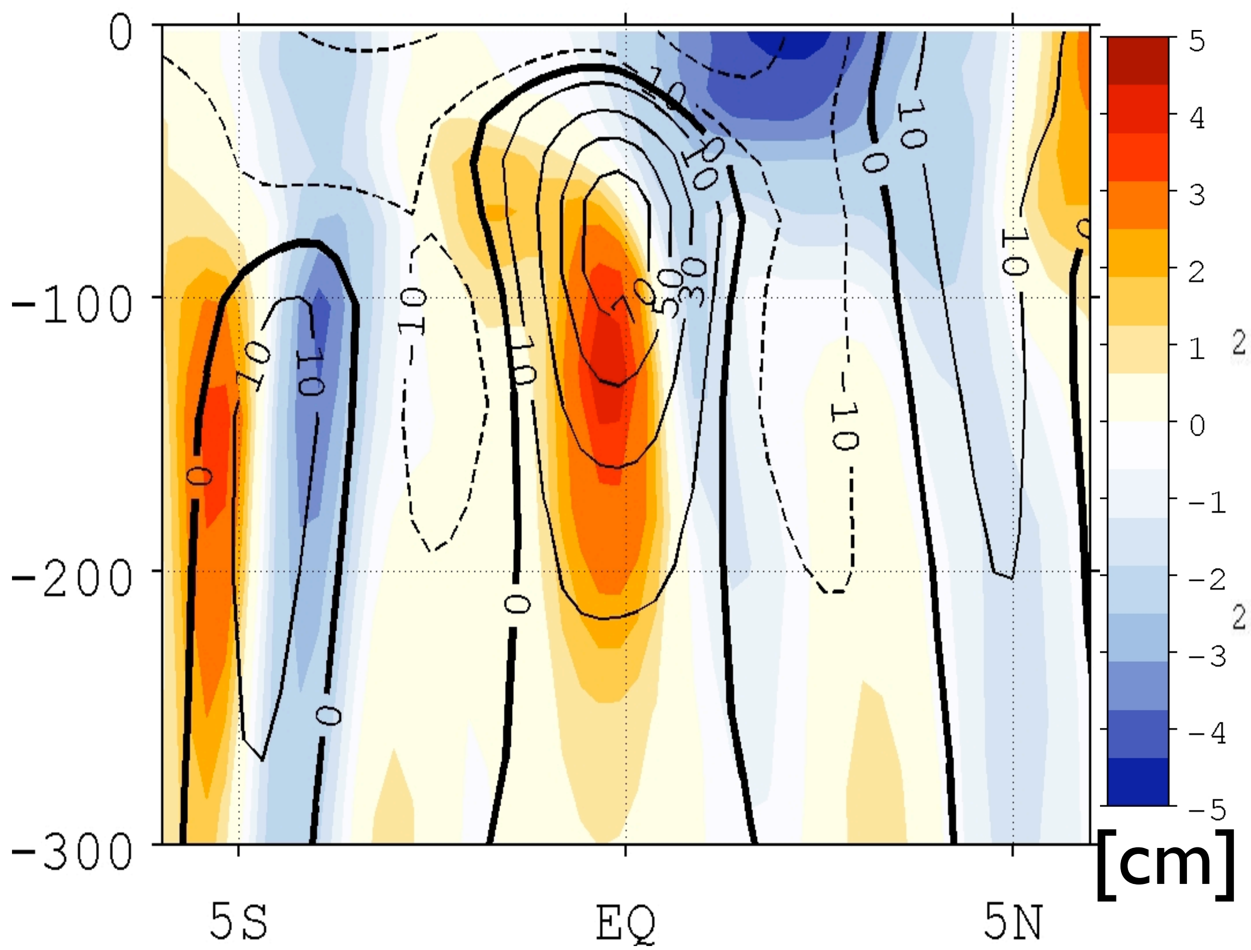


- Weak EUC and weak upwelling in CM2.1.
- Strong EUC and strong upwelling in SCOAR.
- Stronger currents have an important implication for the dynamic instability.

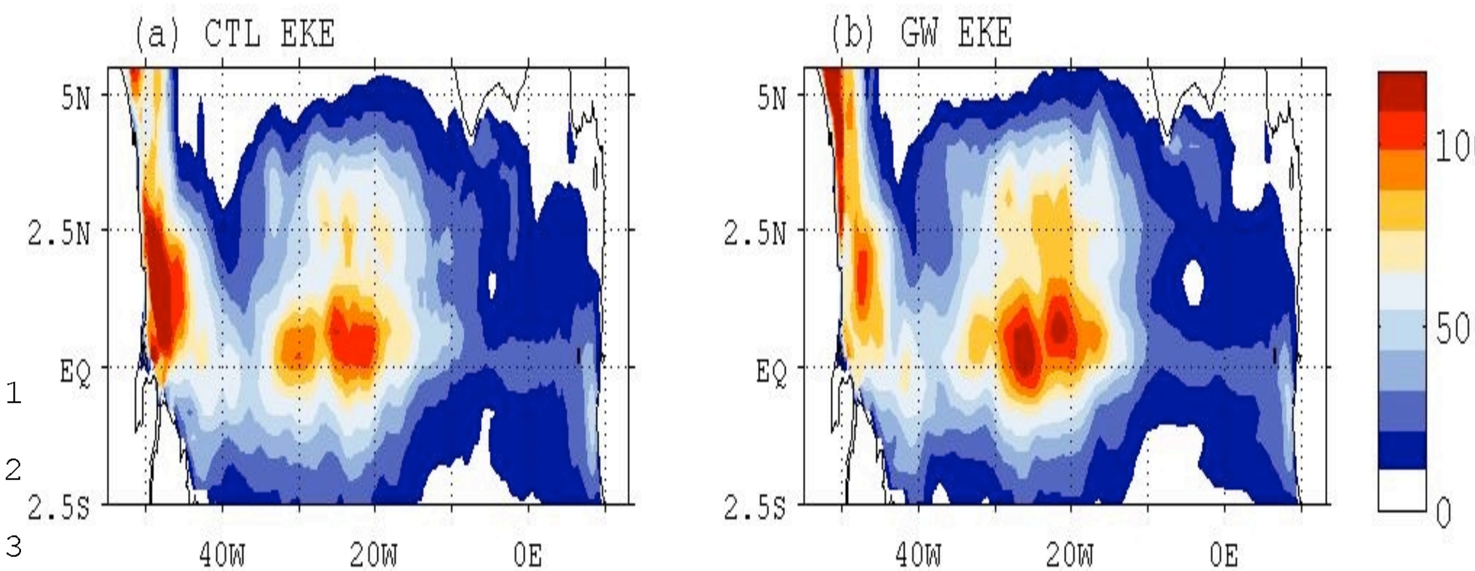
30°W-10°W, 1998-2007

Enhanced current shears lead to dynamic instability and TIWs.

SCOAR δU



EKE becomes stronger by ~30%



What is the implication for the equatorial heat budget?

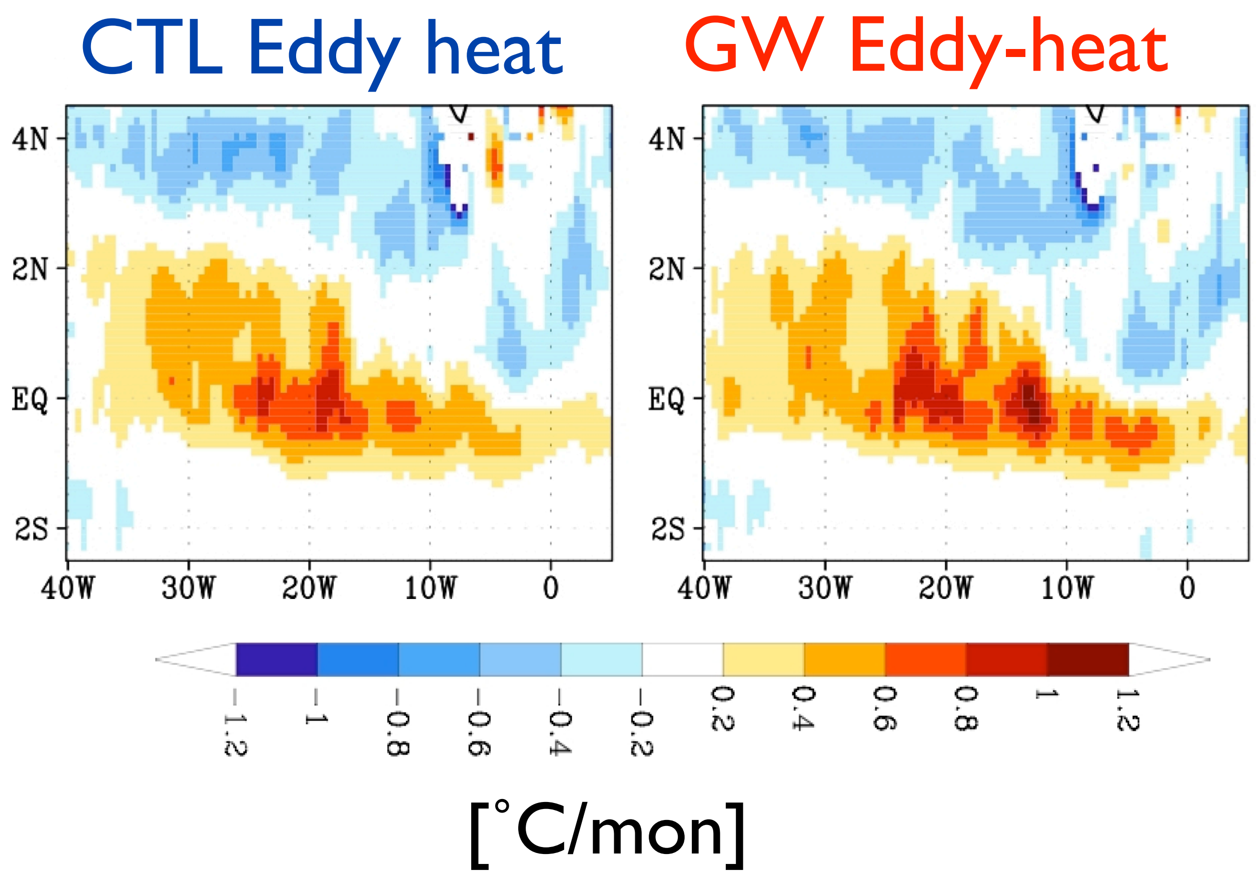
- Cross-equatorial southerly wind ➜ Currents ↑ and w* ↑ ➜ Dynamic instability ↑

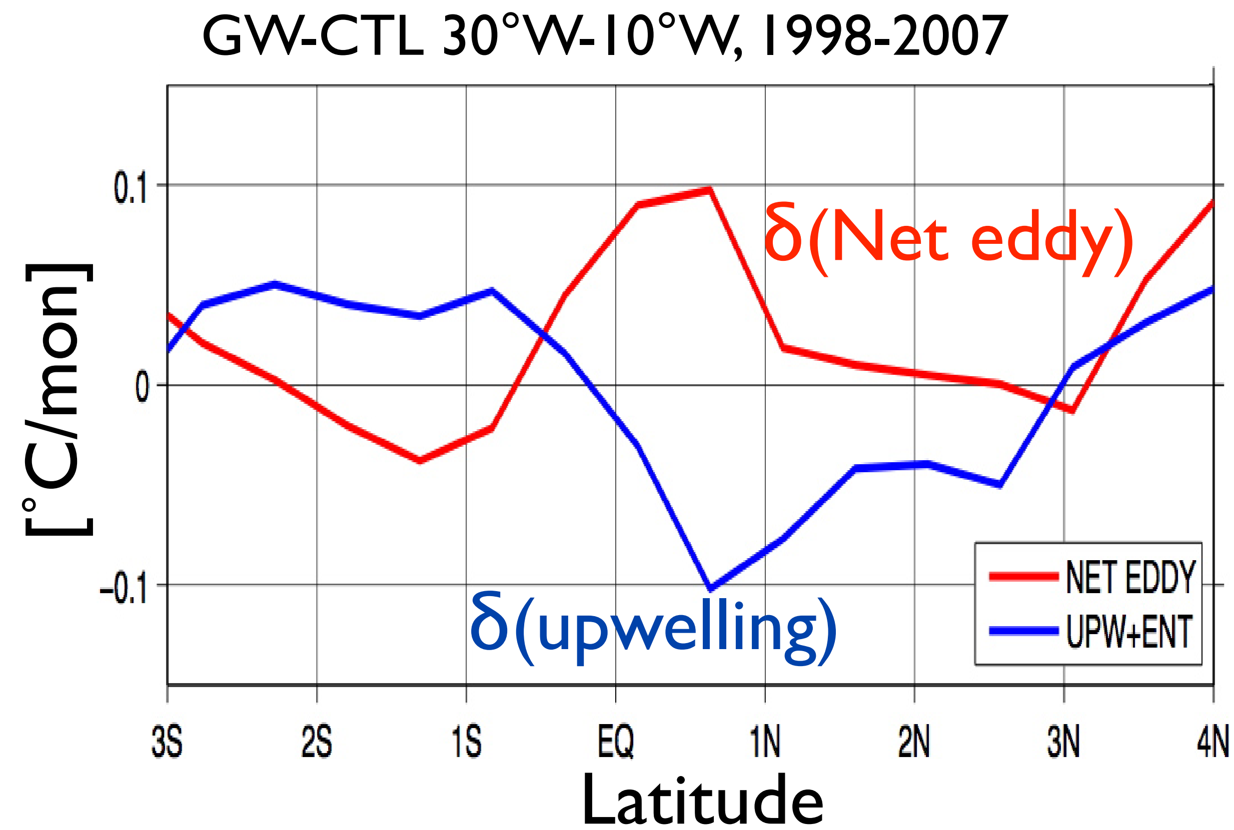
- Philander and Delecluse (1983), Yu et al., 1997

The equatorial ocean is more dynamicall unstable.

30°W-10°W, 1998-2007

Eddy temperature advection is intensified





- <u>GW-CTL</u>: All components of eddy temperature advection strengthen.
- TIW-heat flux significantly compensates for cooling due to enhanced upwelling.

Summary and discussion

1. Ocean fronts and eddies cause coherent perturbations in the atmosphere
   - Ubiquitous features observed throughout the World Oceans
   - Limited understanding on the feedback to larger-scale climate system
   - Process-modeling using regional coupled model helps alleviate the problem in GCMs

2. TIWs impact the mean state through eddy heat flux.

- Need an accurate representation of ocean dynamical processes.
- Improved parameterizations based on information from regional coupled model.

Regional modeling as a critical way to obtain a glimpse into what improvements we can expect and what deficiencies may remain in the current and next generation climate model experiments.

Thanks!

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