Dynamics of near-surface winds over ocean eddies and sea ice: Regional modeling studies of tropical and arctic atmospheres

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GSO Seminar, URI
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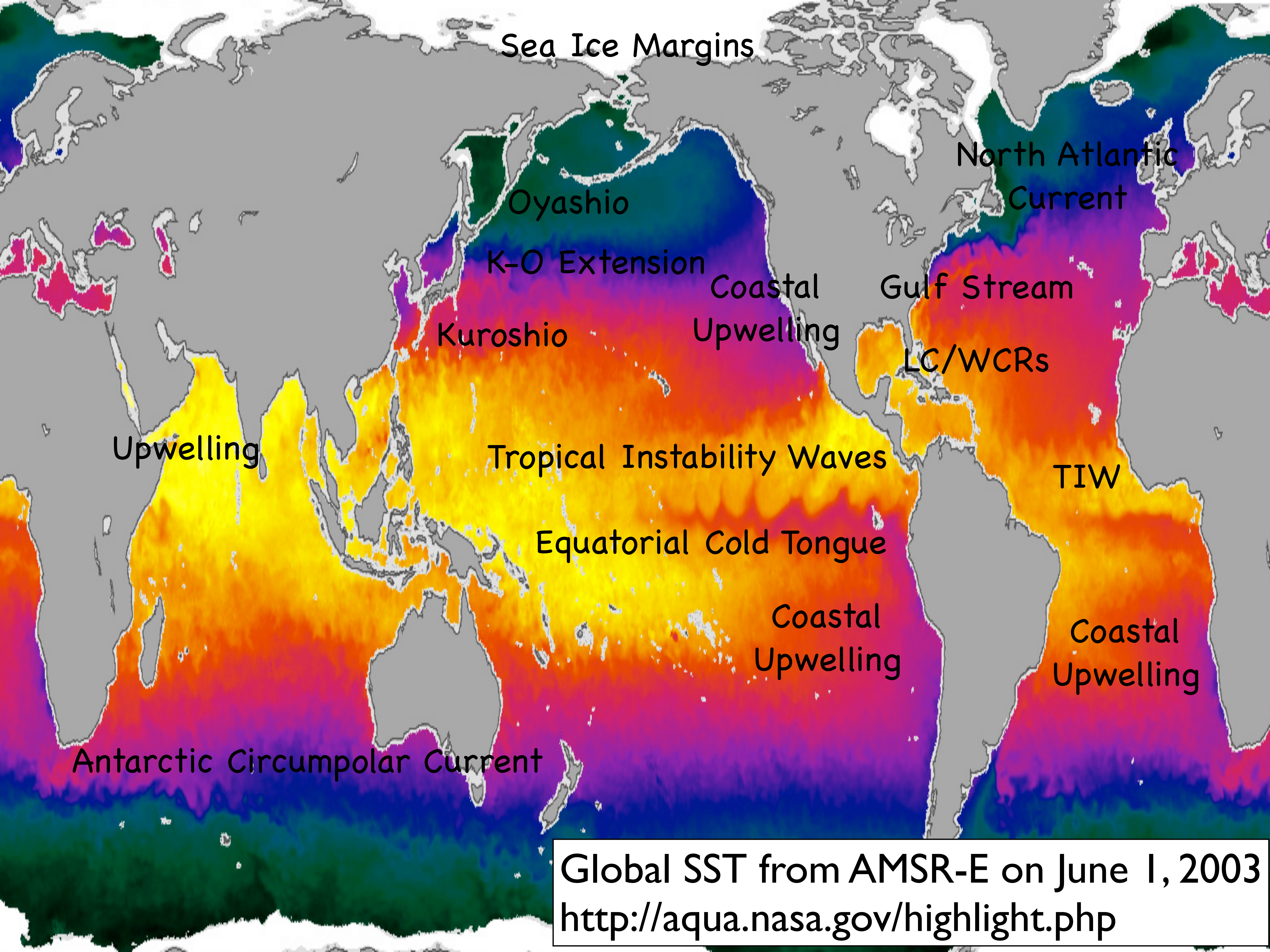
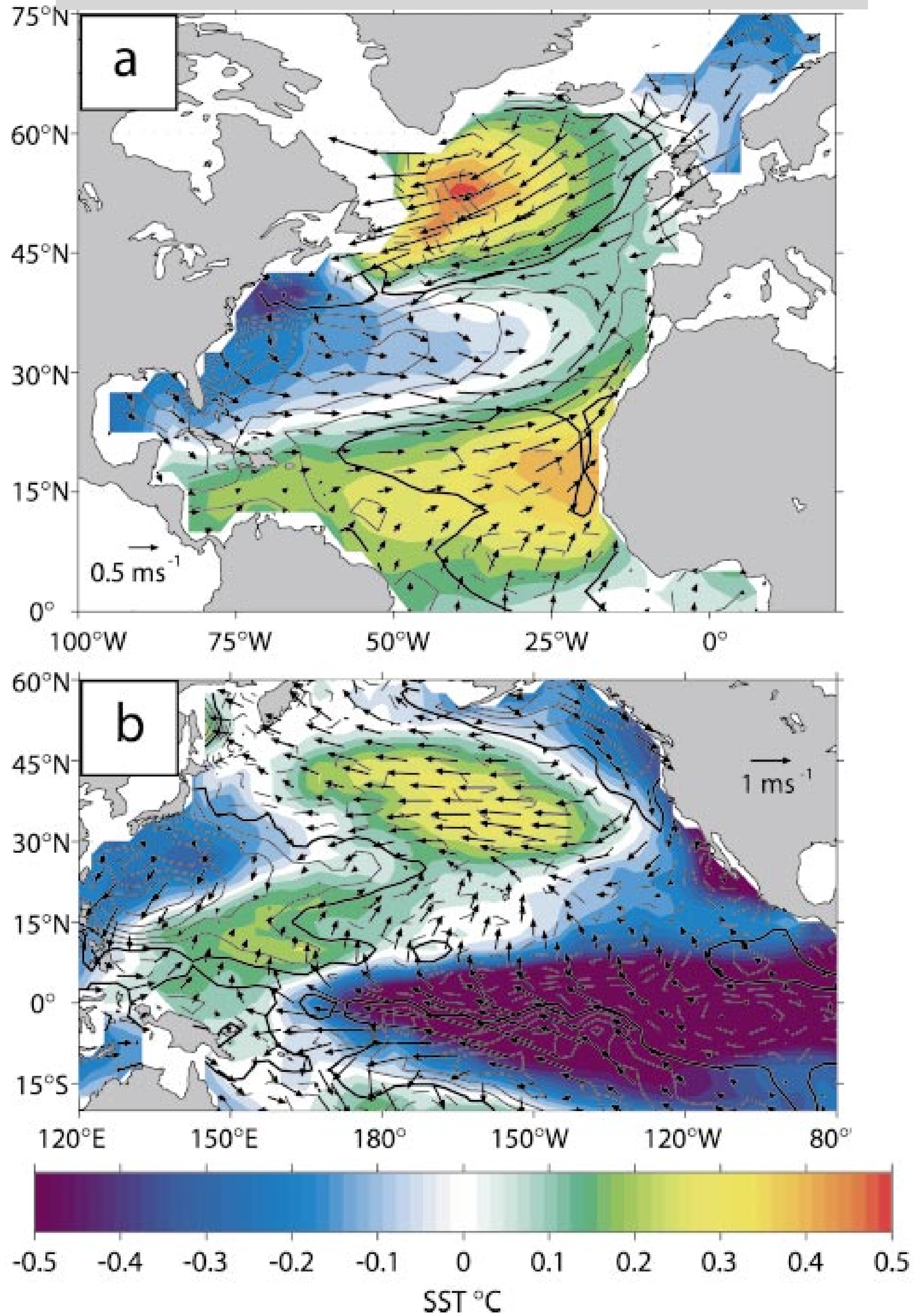

Sea Ice Margins
Oyashio
K-O Extension
Kuroshio
Coastal
Upwelling
North Atlantic
Current
Gulf Stream
LC/WCRs
Upwelling
Tropical Instability Waves
TIW
Equatorial Cold Tongue
Coastal
Upwelling
Coastal
Upwelling
Antarctic Circumpolar Current
Global SST from AMSR-E on June 1, 2003
http://aqua.nasa.gov/highlight.php

Air-sea interactions on different oceanic scales

Oceanic basin-scale

NAO

PDO/ENSO

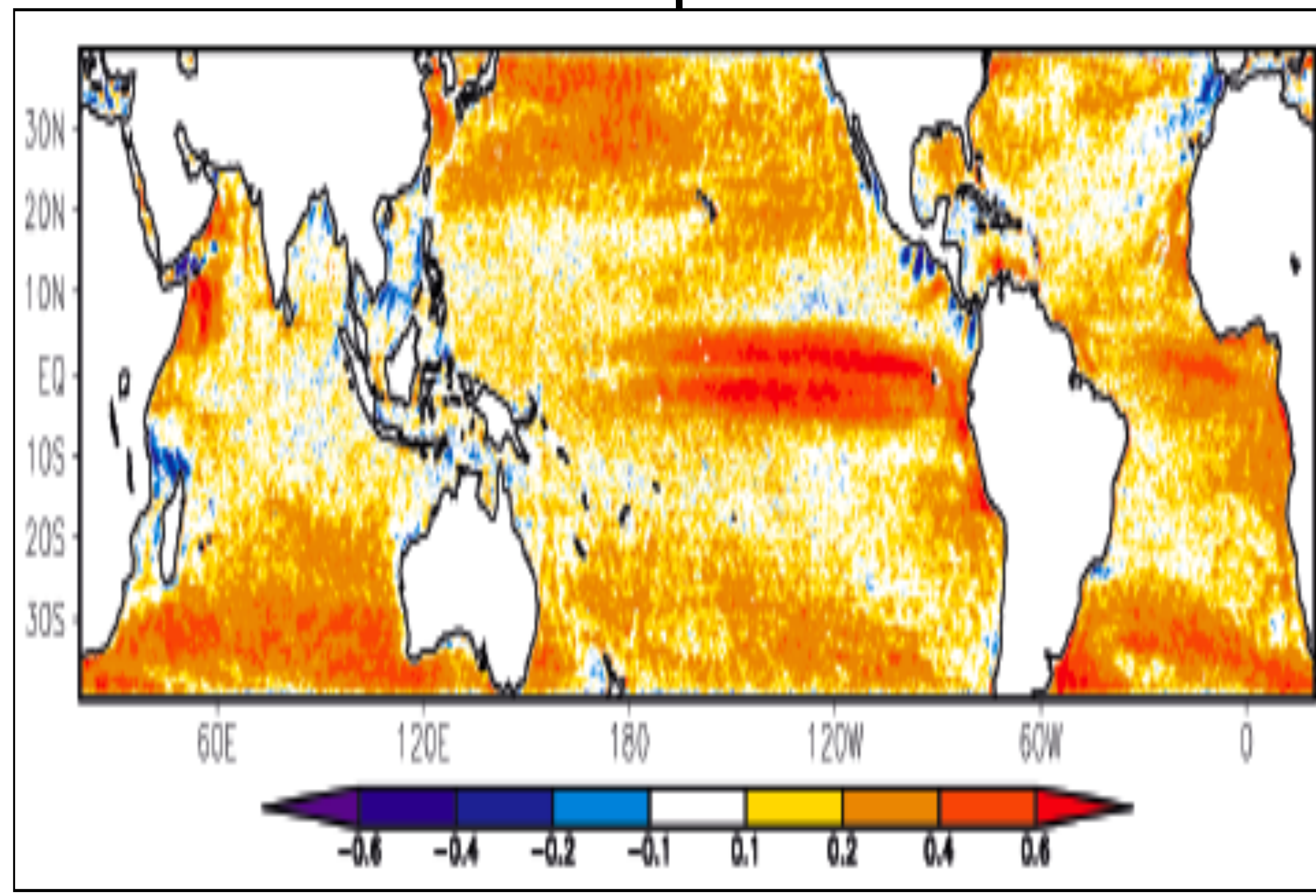


Stronger wind ➔ colder SST (Negative correlation).

Kushnir et al. 2002

Oceanic mesoscale

Correlation: zonally (10°) high-pass filtered wind speed and SST

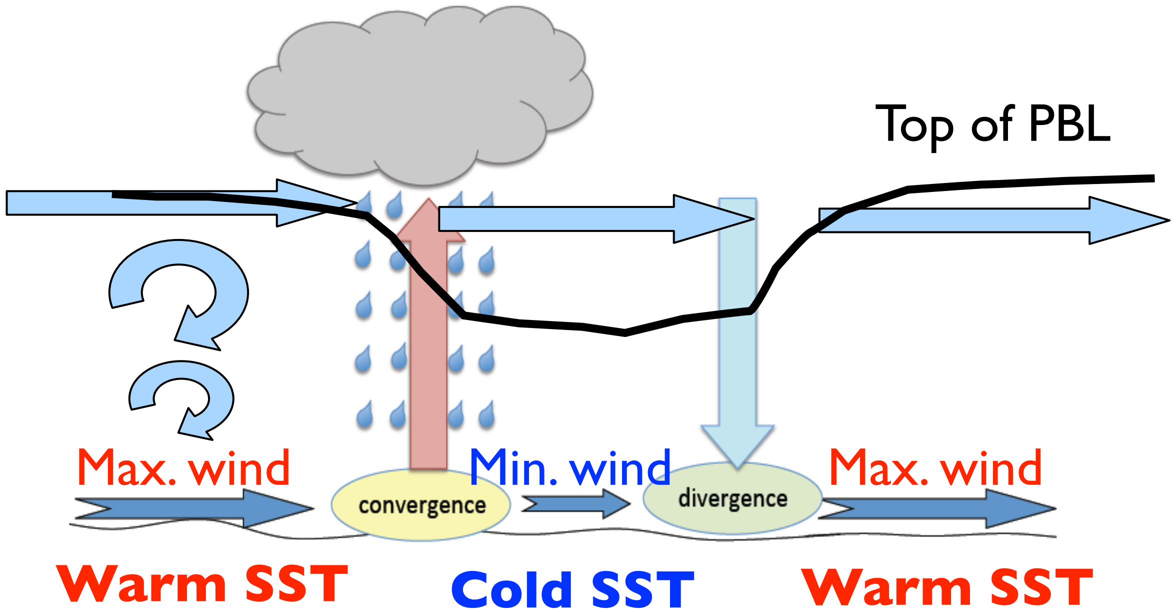


Positive correlation (Warm SST ➔ Stronger wind)

Xie, 2004

How do mesoscale SSTs influence the surface wind?

Vertical Mixing Mechanism: Wallace et al. 1989

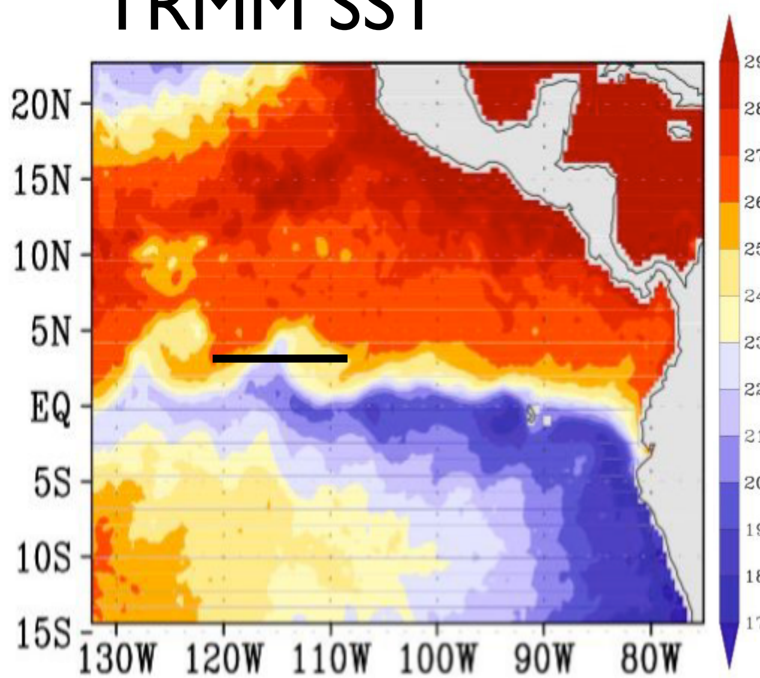


Warm SST anomalies decreases the stability of the ABL ➔ Increased downward momentum mixing ➔ higher surface winds

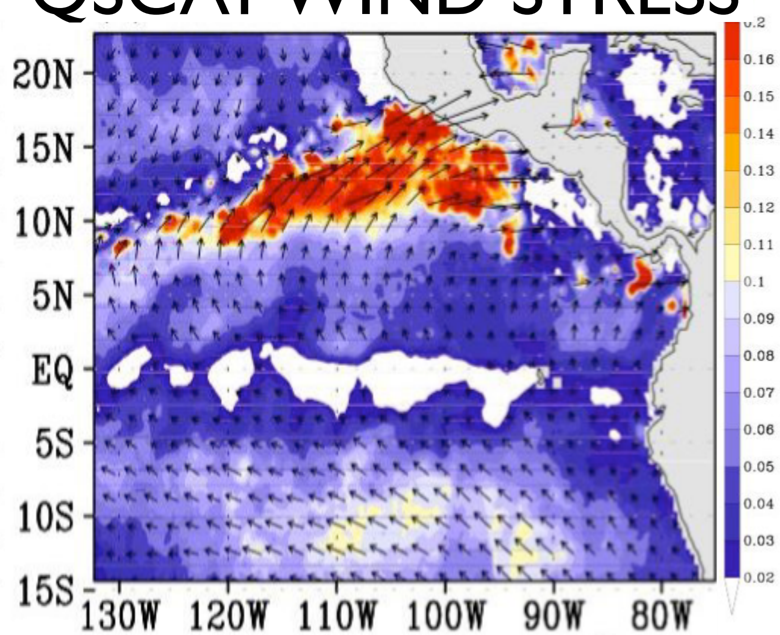
SST′➔Stability➔τ′

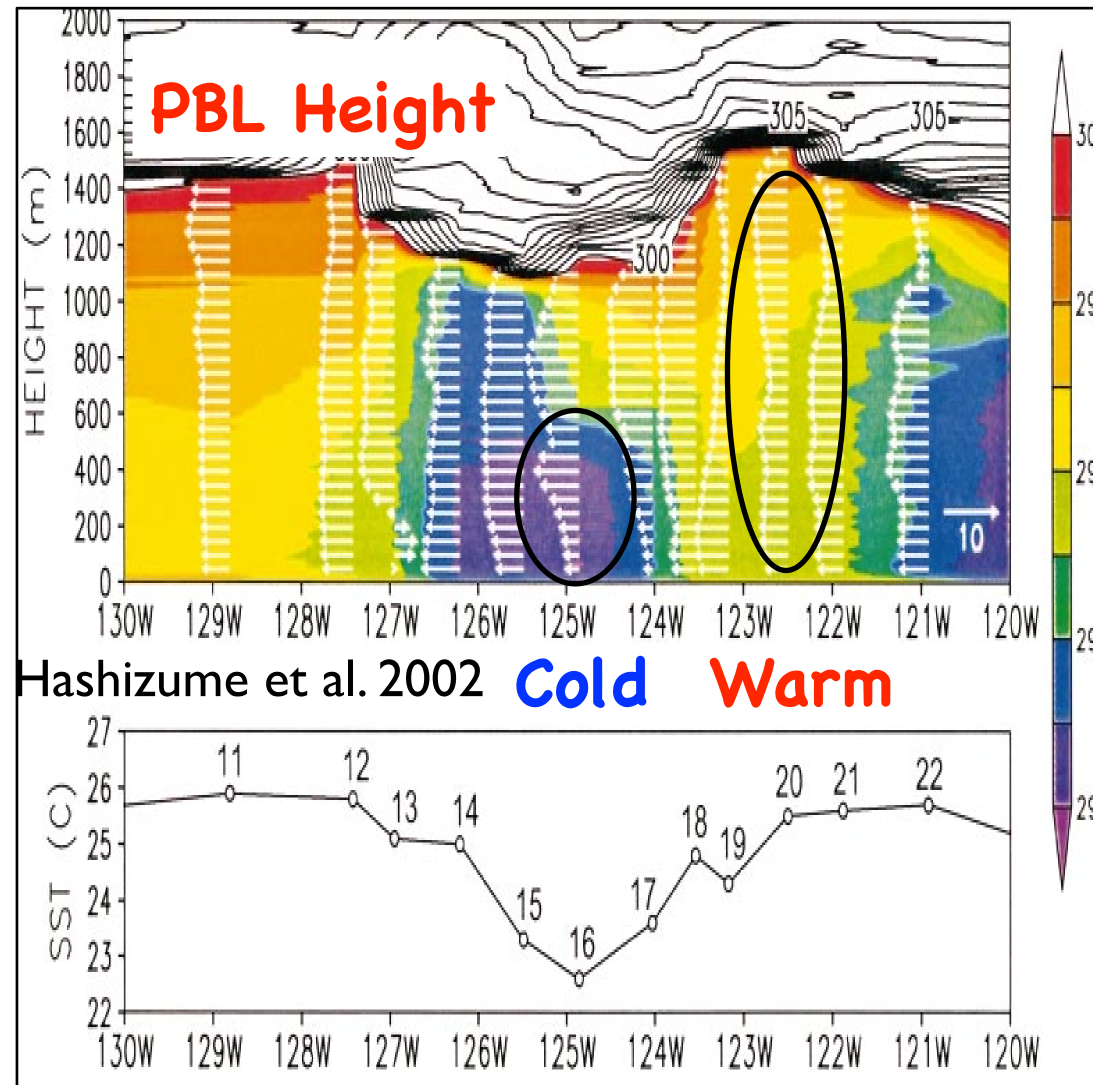
Wind speed and SST are in phase.

TRMM SST



QSCAT WIND STRESS

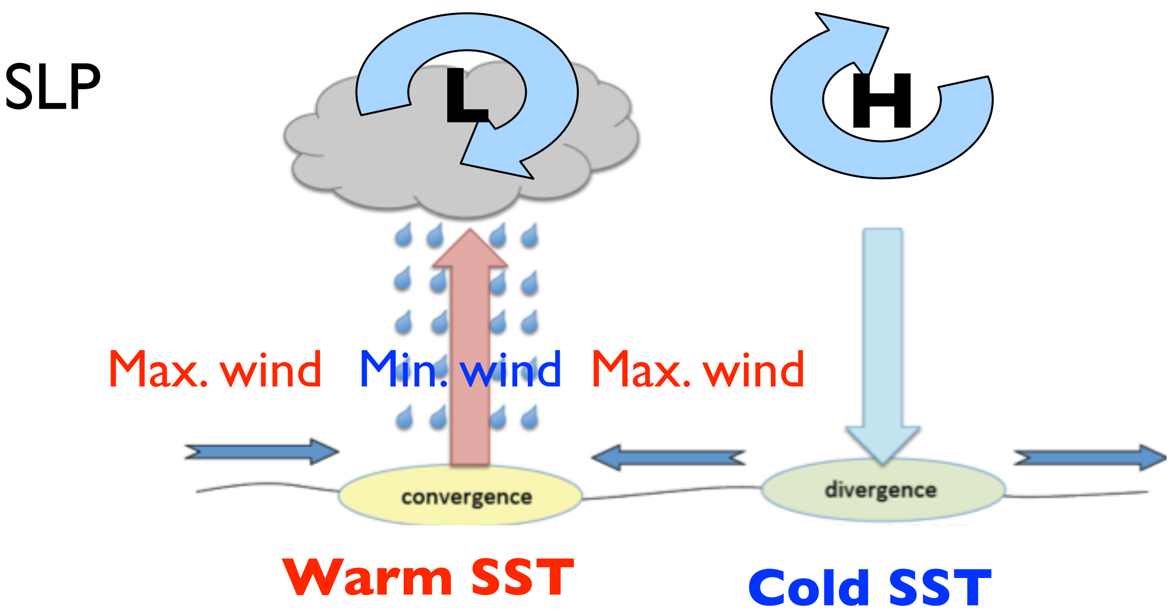




Imprints of TIW-SSTs in the surface wind stress via local ABL coupling: SST ➔ τ'

Seo et al., 2007a

Pressure Adjustment Mechanism: Lindzen and Nigam (1987)



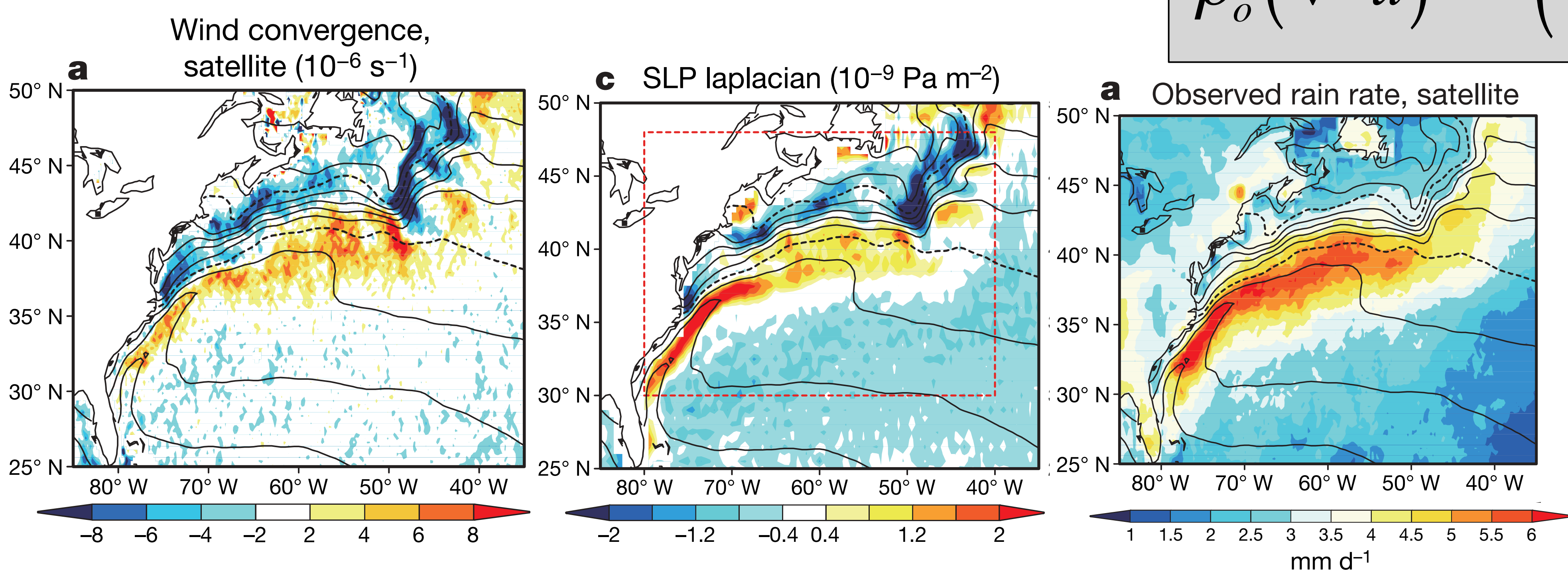
SST anomalies ➔ air density (hence SLP) anomalies ➔ Pressure gradient leads to cross-frontal flow ➔ convergence (divergence) over warm (cold SSTs)

SST′➔P′➔τ′

Wind speed and SST are in quadrature.

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

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



SST-induced ∇^2P leads to ∇·u and convection (vertical motions)

Minobe et al. 2008

Goal of my talk

- Use regional coupled ocean-atmosphere model

- To understand the variations of surface winds associated with small-scale SST variations,
  - Tropical Instability Waves in the tropics
  - Sea ice in the Arctic Ocean
- To assess their feedback effect on the ocean

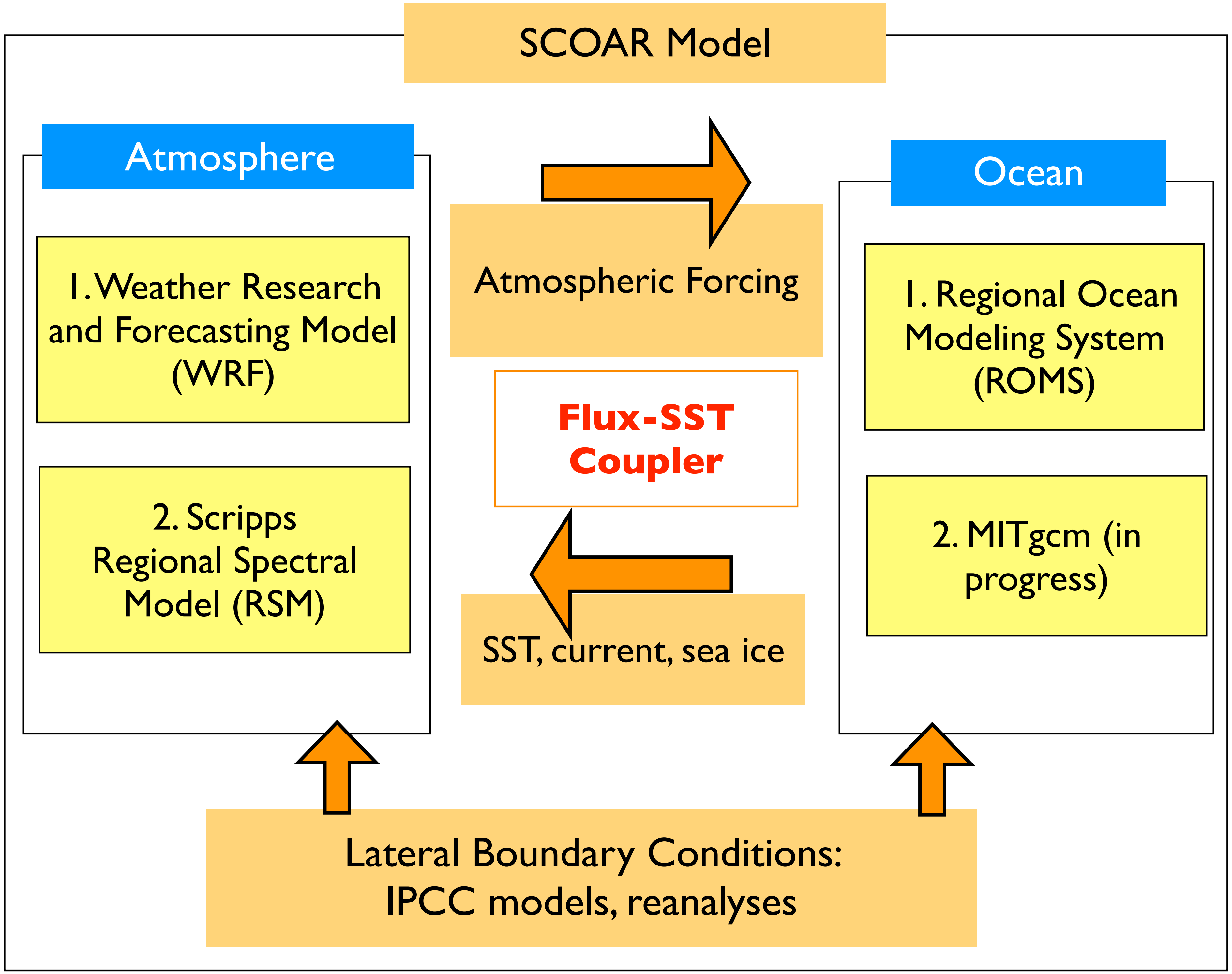
Some similarities in process

Stable ABL with a capping inversion cold surface by upwelling (sea ice)
Unstable ABL due to warm phase of TIWs (drift of sea ice)
Strong lateral gradient of SST near TIWs (marginal ice zones)

- Summary and discussion

Scripps Coupled Ocean-Atmosphere Regional (SCOAR) Model

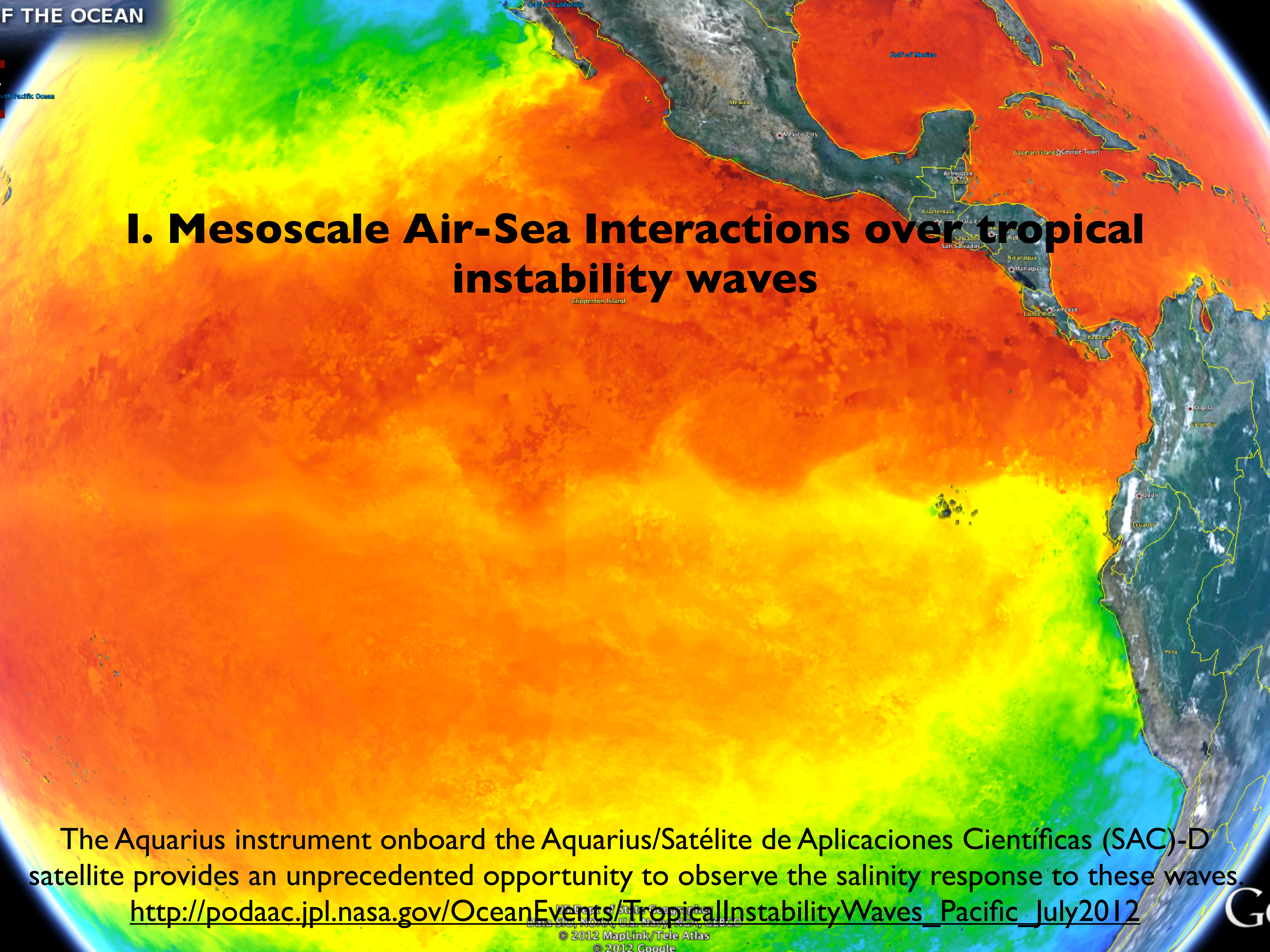
(Seo et al., 2007)



- An I/O-based file coupler. Easy to add model.
- Great portability and applicability
- Matching resolution in the ocean and weather models.

Improved representation of the influence of oceanic eddies on the atmosphere.

Study the dynamics of mesoscale O-A coupling and its influence on the large-scale dynamics



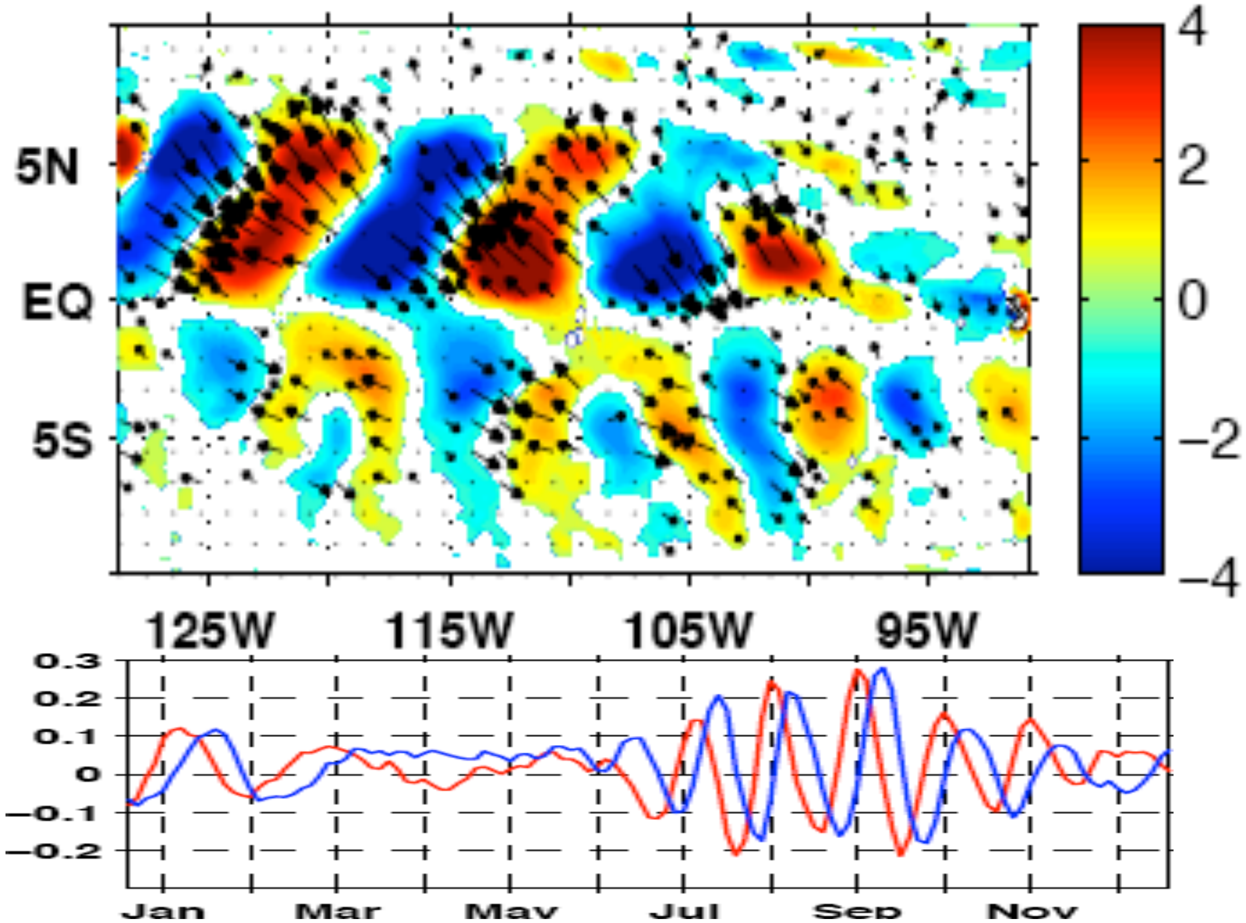
I. Mesoscale Air-Sea Interactions over tropical instability waves

The Aquarius instrument onboard the Aquarius/Satélite de Aplicaciones Científicas (SAC)-D satellite provides an unprecedented opportunity to observe the salinity response to these waves.

http://podaac.jpl.nasa.gov/OceanEvents/TropicalInstabilityWaves_Pacific_July2012

Vertical mixing mechanism appears the dominant mechanism over TIWs

Combined EOF 1 of SST & Wind vectors



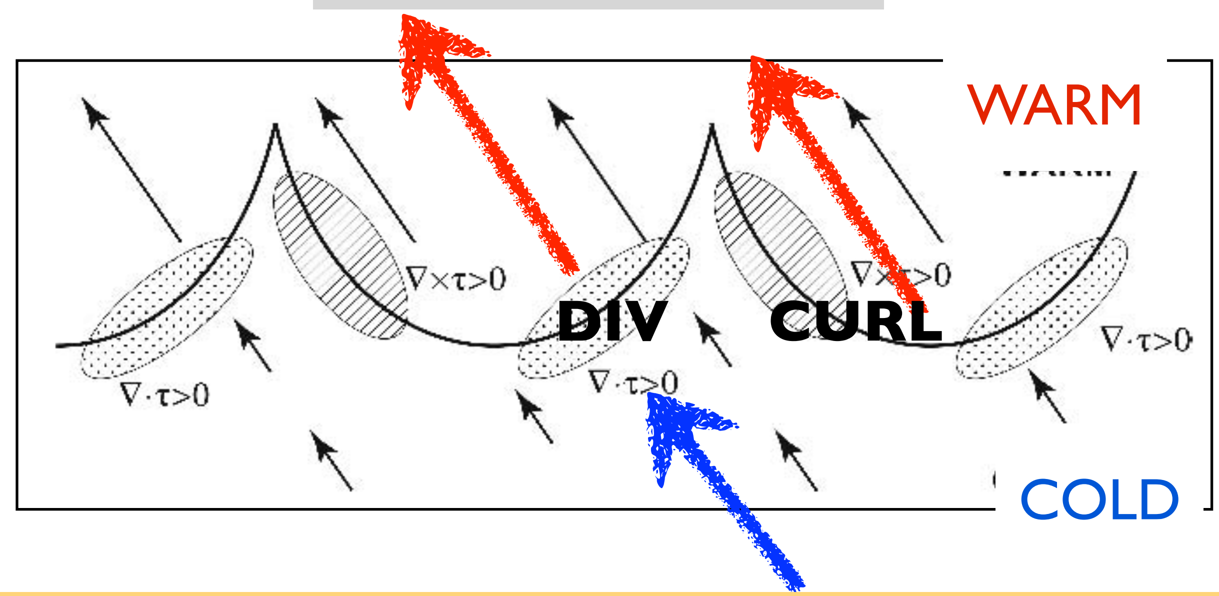
① Direct influence from SST
(Wallace et al. 1989; Hayes et al. 1989)

$SST' \rightarrow \tau'$

② Modification of wind stress curl/div
(Chelton et al. 2001)

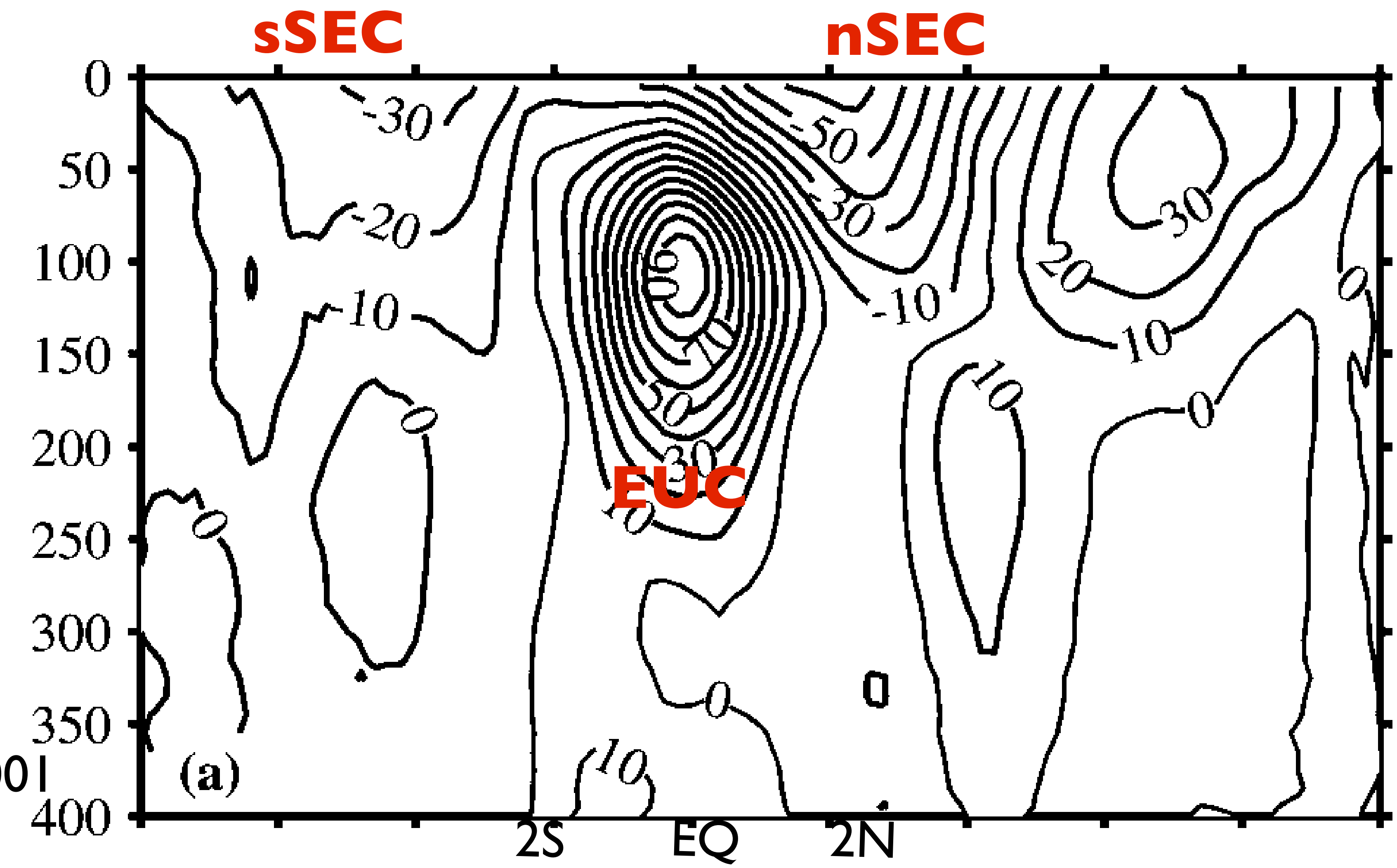
$\nabla_d SST' \rightarrow \nabla \cdot \tau'$

$\nabla_c SST' \rightarrow \nabla \times \tau'$



How do these wind responses feed back on to the ocean mesoscale variability?

① Feedback from $\boldsymbol{\tau}'$ (←SST′) to energetics of TIWs



Johnson et al. 2001

Eddy kinetic energy budget

Baroclinic

Barotropic

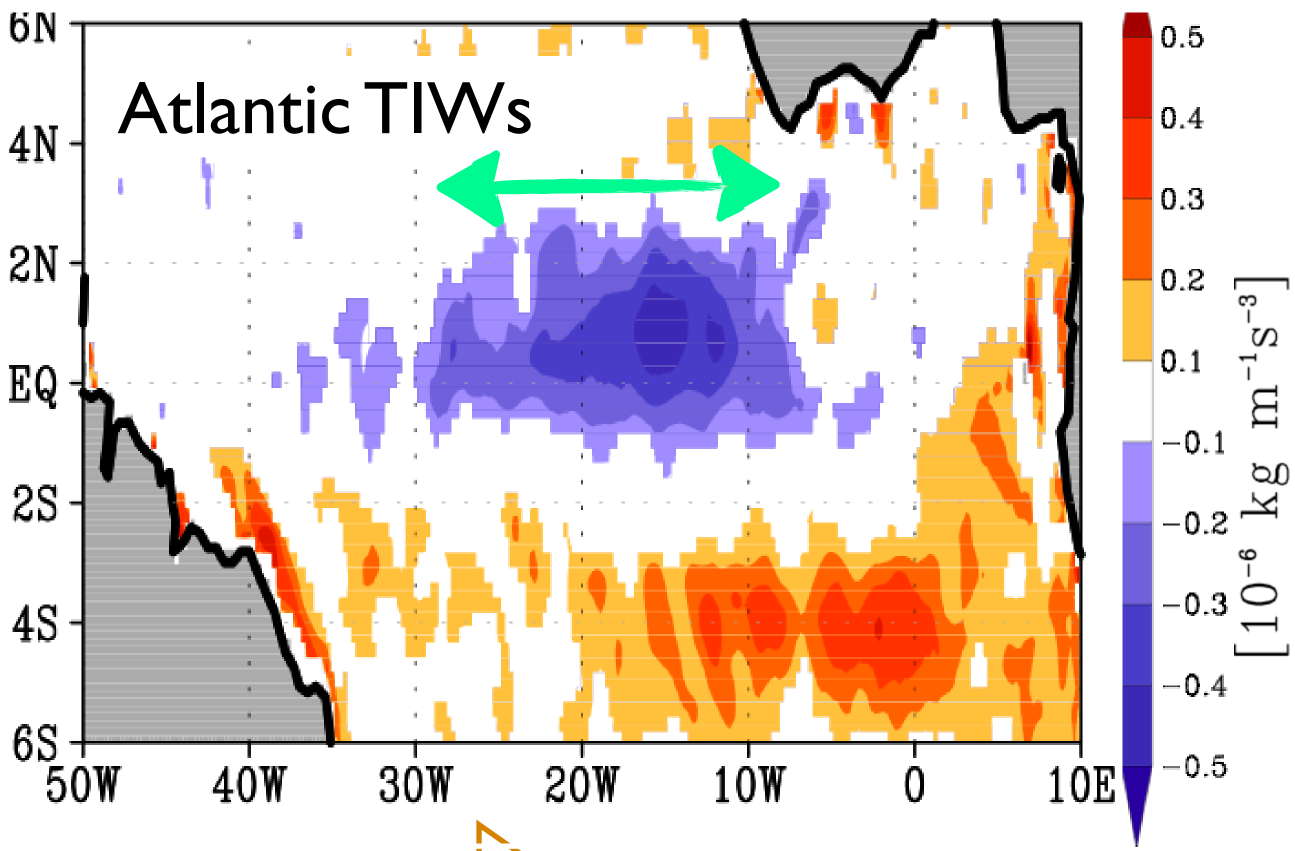
$$\vec{U}\cdot\vec{\nabla}K_e + \vec{u}'\cdot\vec{\nabla}K_e = -\vec{\nabla}\cdot(\vec{u}'p') - g\rho'w' + \rho_o(-\vec{u}'\cdot(\vec{u}'\cdot\vec{\nabla}\vec{U}))$$

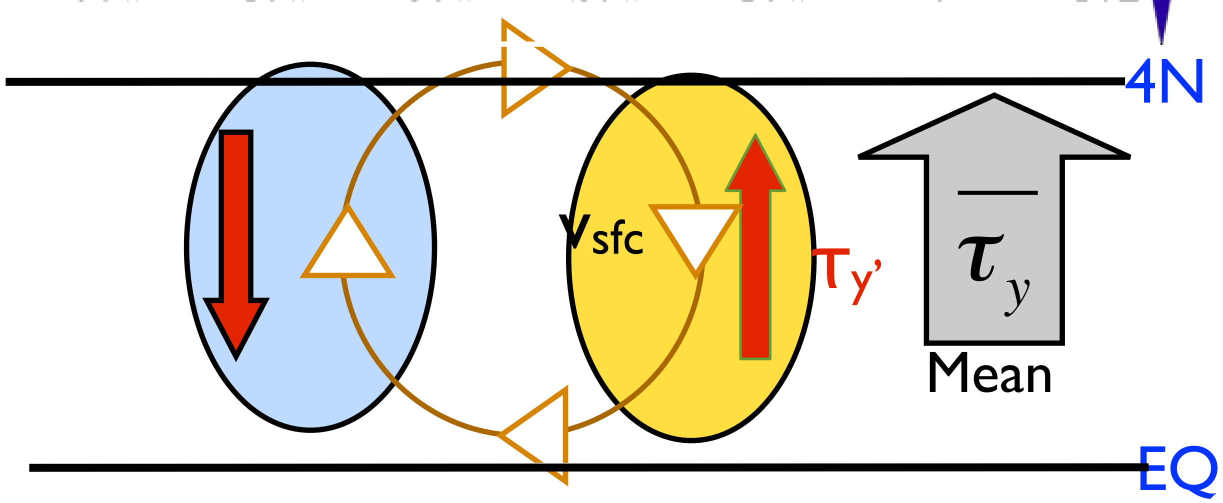
$$+\rho_o A_h \vec{u}'\cdot\nabla^2\vec{u}' + \rho_o\vec{u}'\cdot(A_v\vec{u}_z')_z + \vec{u}_{sfc}'\cdot\vec{\tau}_z'$$

Correlation of wind stress and current

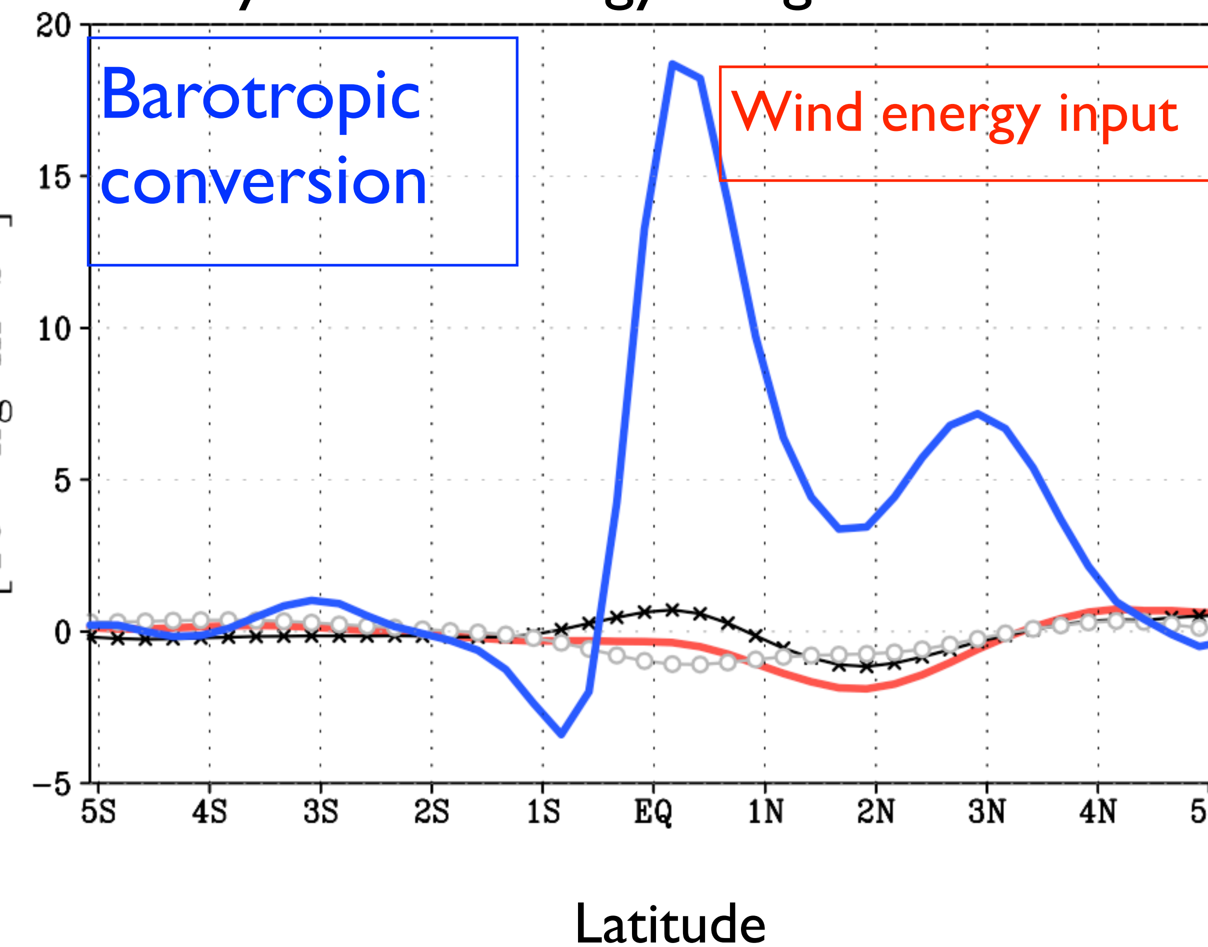
τ' are in the opposite direction to the current: *wind response damps the waves!*

Correlation of highpass filtered v'_{sfc} and τ_y'





Eddy kinetic energy budget



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

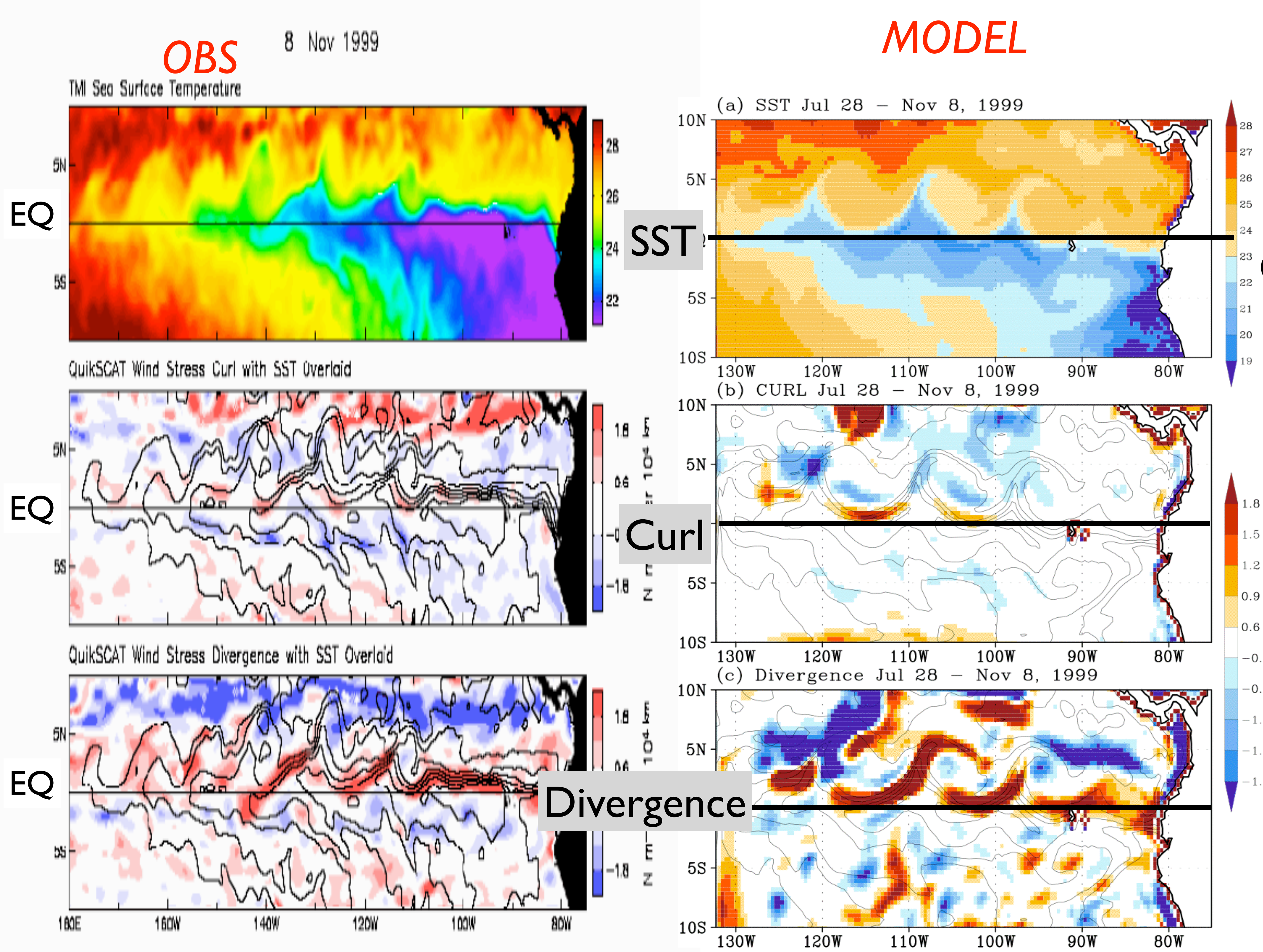
- Wind and current are negatively correlated.
- Wind-current coupling ➔ energy sink

② Modification of wind stress curl and divergence by SST gradients:

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

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

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



Coupling coeff. (s) is a commonly used *metric* for this relationship

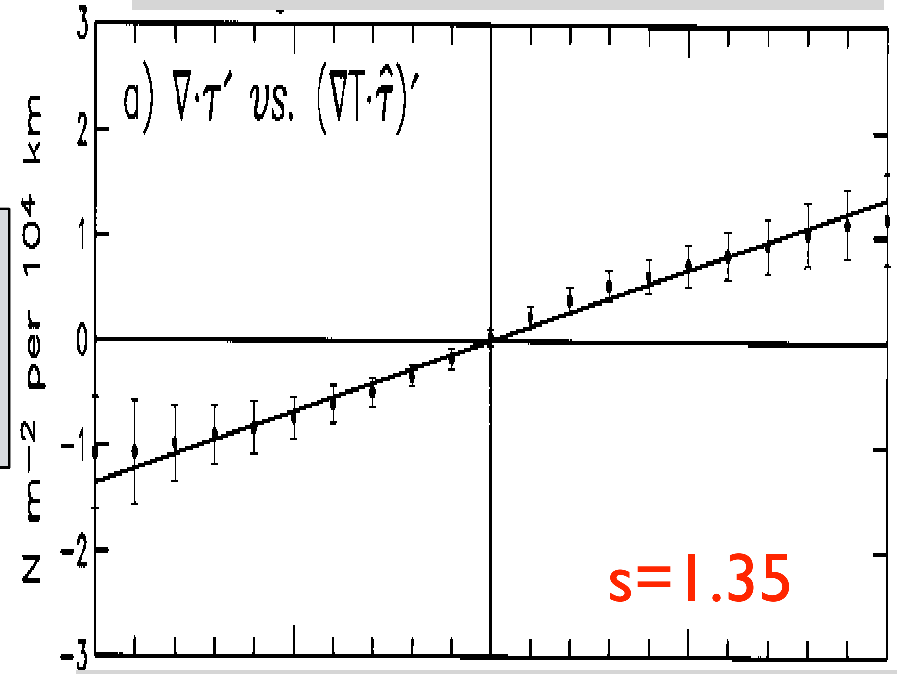
$$\nabla \times \tau' = s \nabla_c SST'$$

$$\nabla \cdot \tau' = s \nabla_d SST'$$

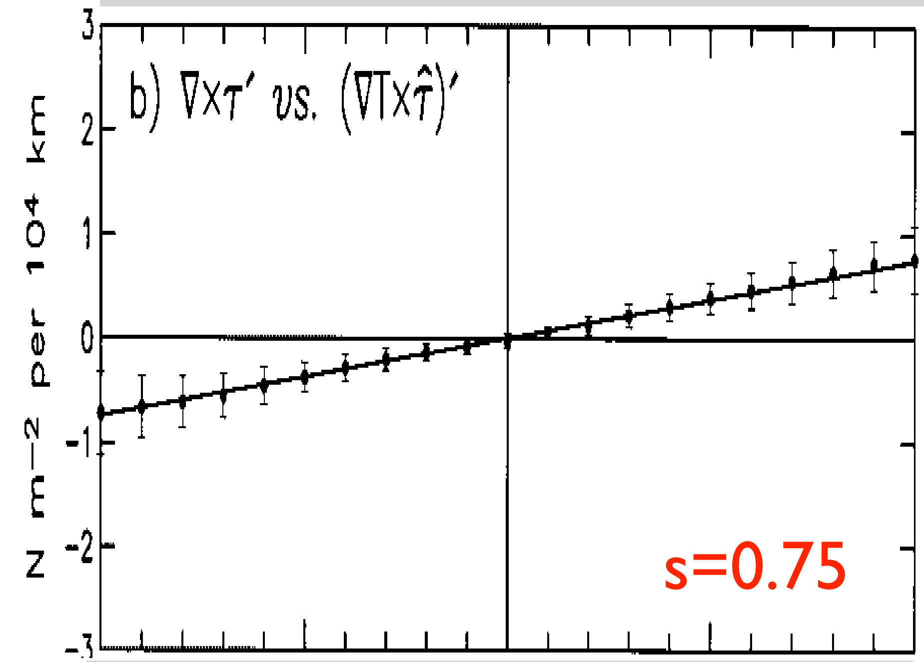
Observed s and evaluate the SCOAR model

OBS: Chelton et al. 2001

$\nabla \cdot \boldsymbol{\tau}' = s \nabla_d SST'$

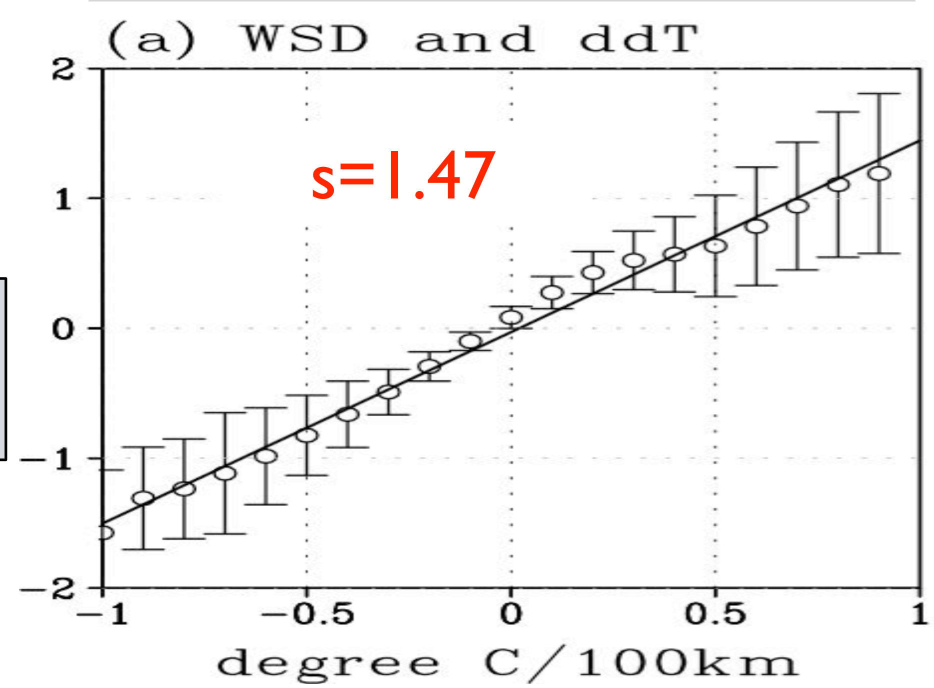


$\nabla \times \boldsymbol{\tau}' = s \nabla_c SST'$

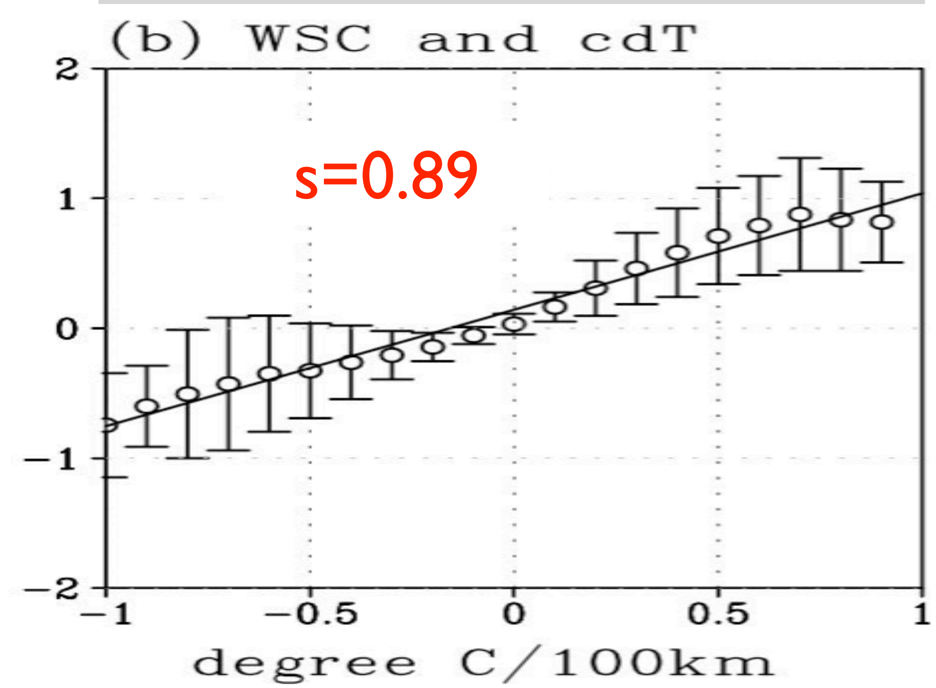


Model: Seo et al. 2007

$\nabla \cdot \boldsymbol{\tau}' = s \nabla_d SST'$



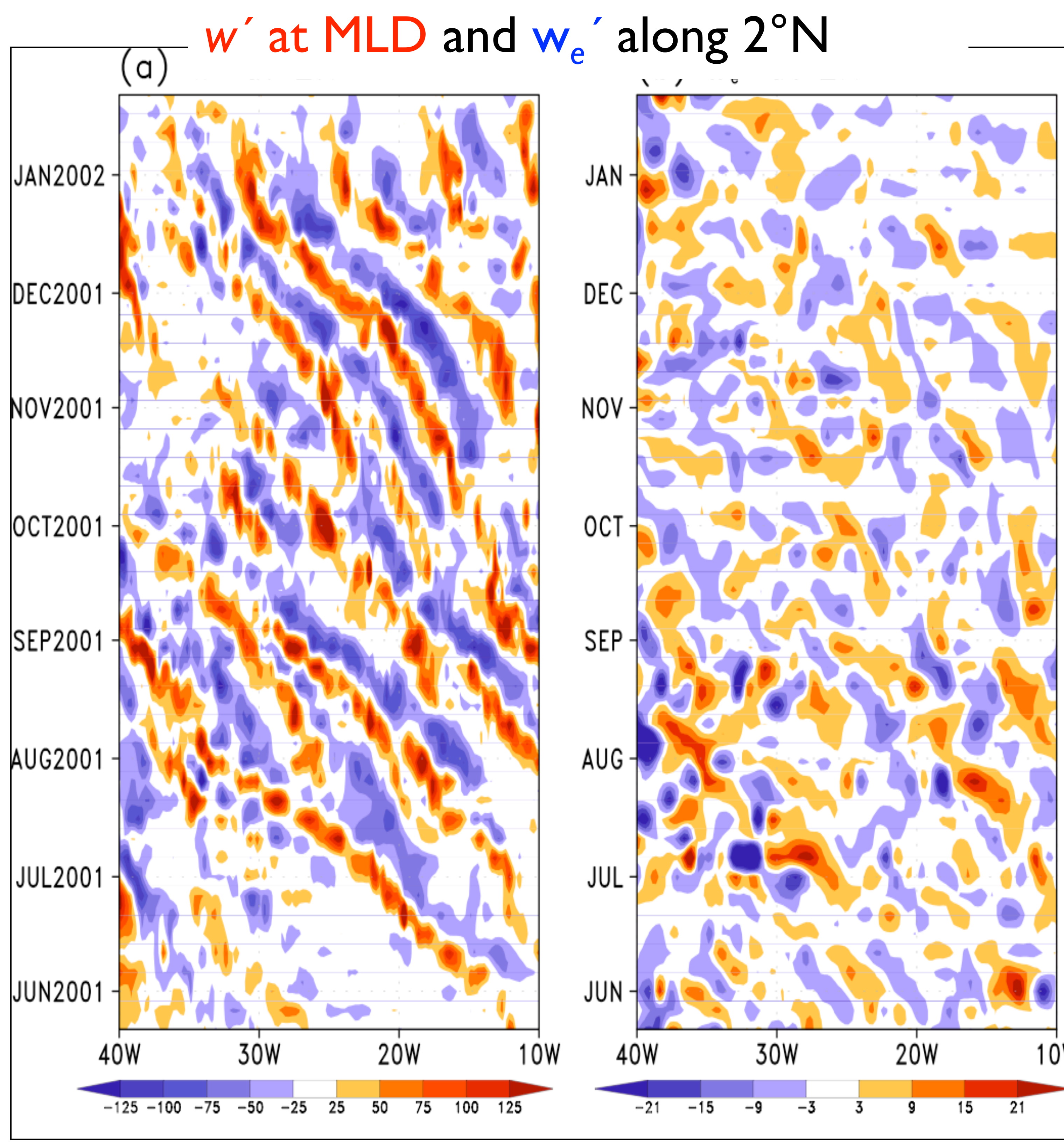
$\nabla \times \boldsymbol{\tau}' = s \nabla_c SST'$



1S-3N, 125-100W, Jul-Dec, 1999-2003

Do perturbation wind stress curls feed back to TIWs via Ekman pumping?

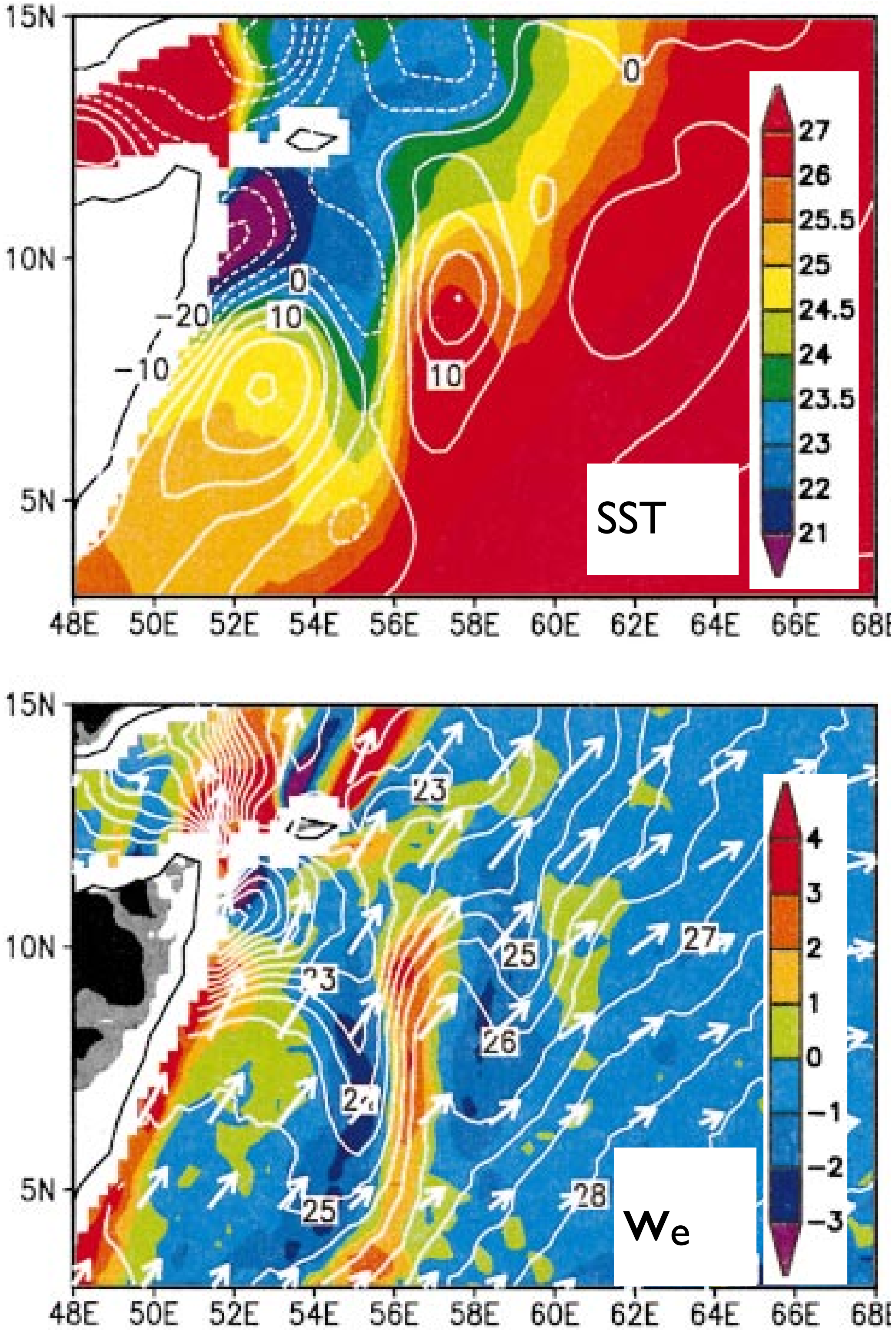
- Perturbation Ekman pumping velocity (w_e') and perturbation vertical velocity (w') of $\boldsymbol{-g\rho' w'}$.
- Overall, w_e' is much weaker than w'.
- Caveat: Difficult to estimate Ekman pumping near the equator.
- Away from the equator, this may affect the evolution of mesoscale eddies. (e.g., Chelton et al. 2007, Spall 2007, Seo et al. 2007, 2008 etc)



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

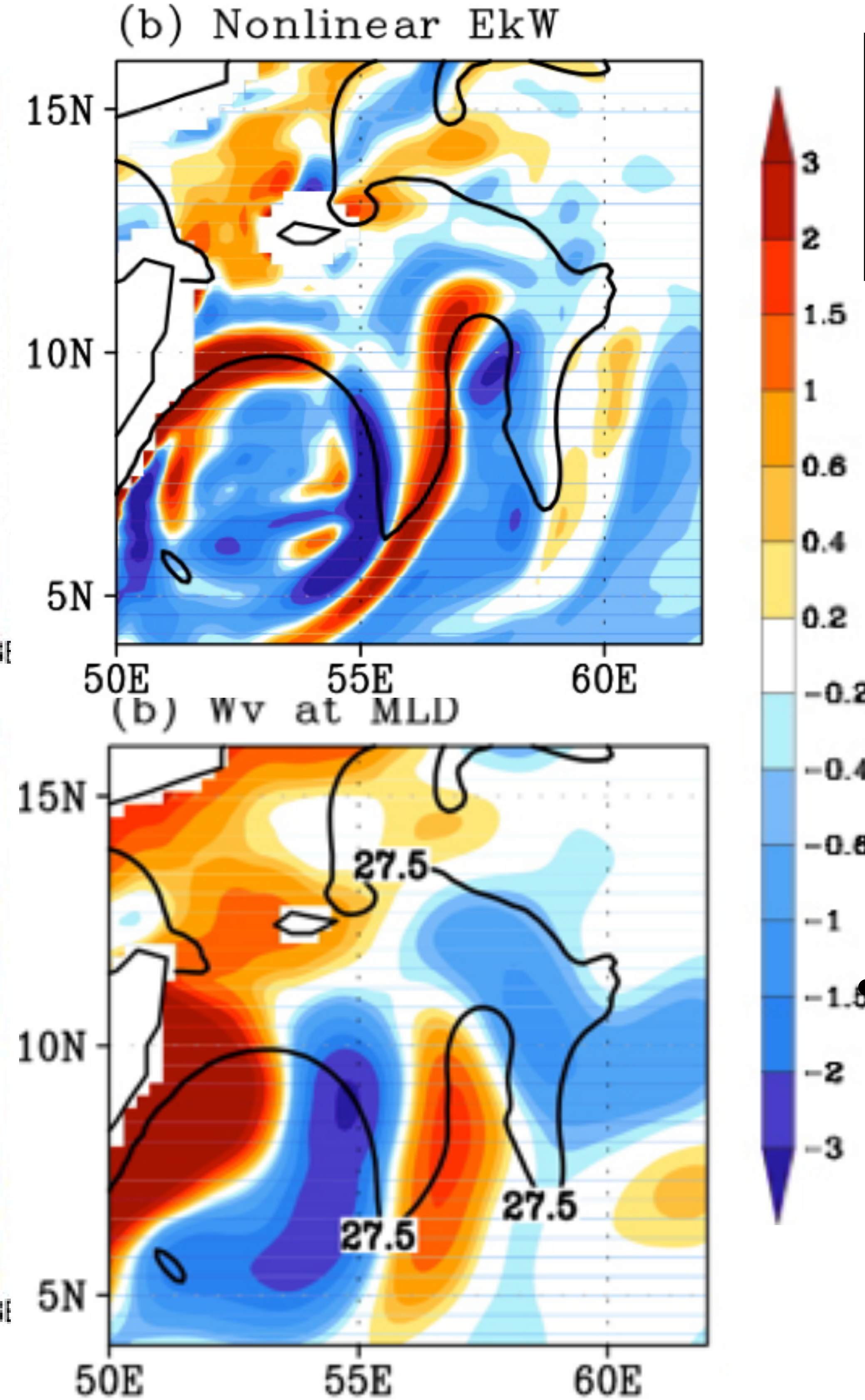
Summertime Ekman pumping velocity in the western Arabian Sea

Satellite observations



Vecchi et al . 2004

SCOAR Model

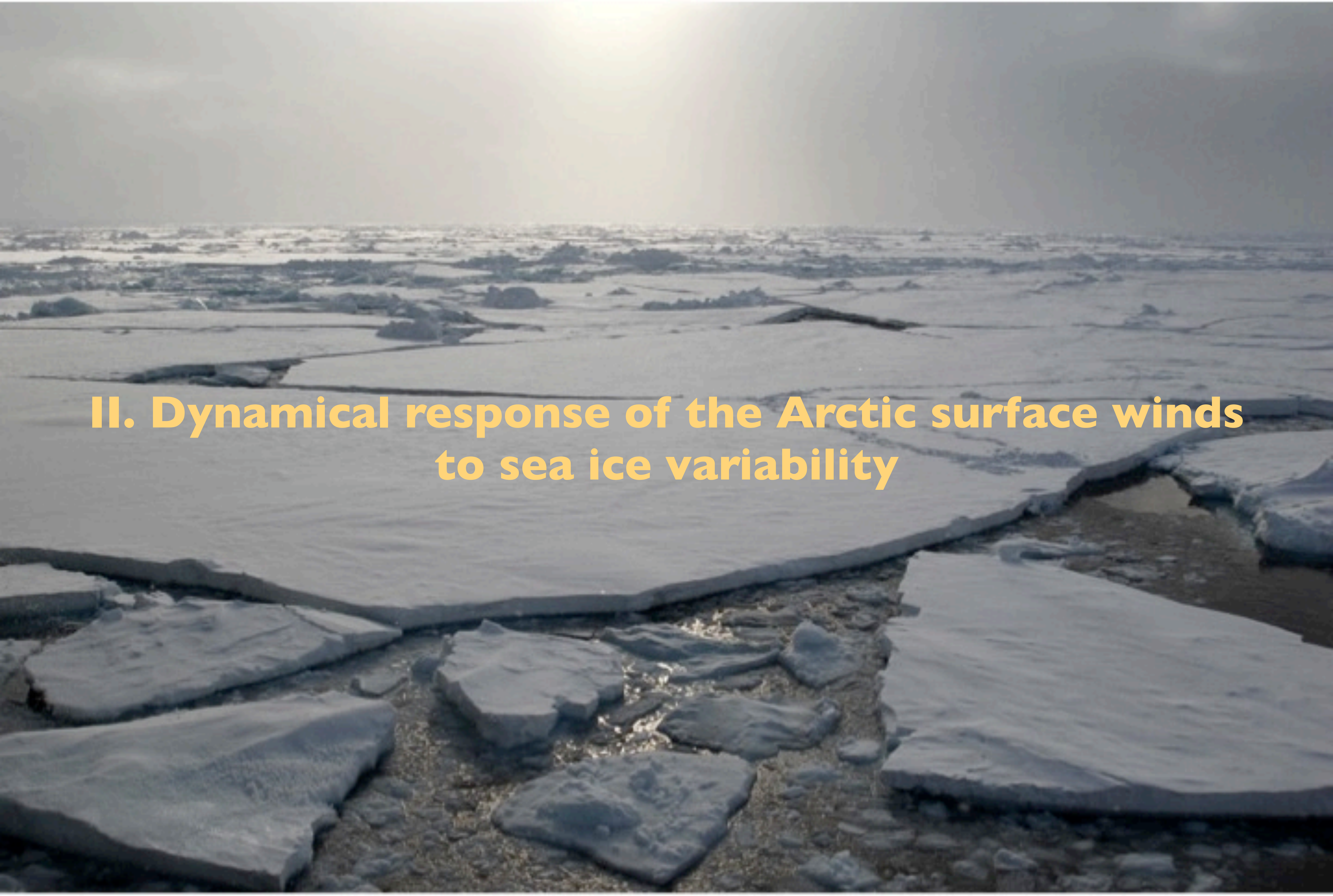


Seo et al. 2008

- Ro≈1

$$Wek = \frac{1}{\rho(f+\zeta)}(\nabla \times \vec{\tau})$$

- The feedback to ocean likely important but mechanism is not clear (likely involve submeso-scale process)
- This additional eddy-induced Wek can potentially affect the evolution of eddies

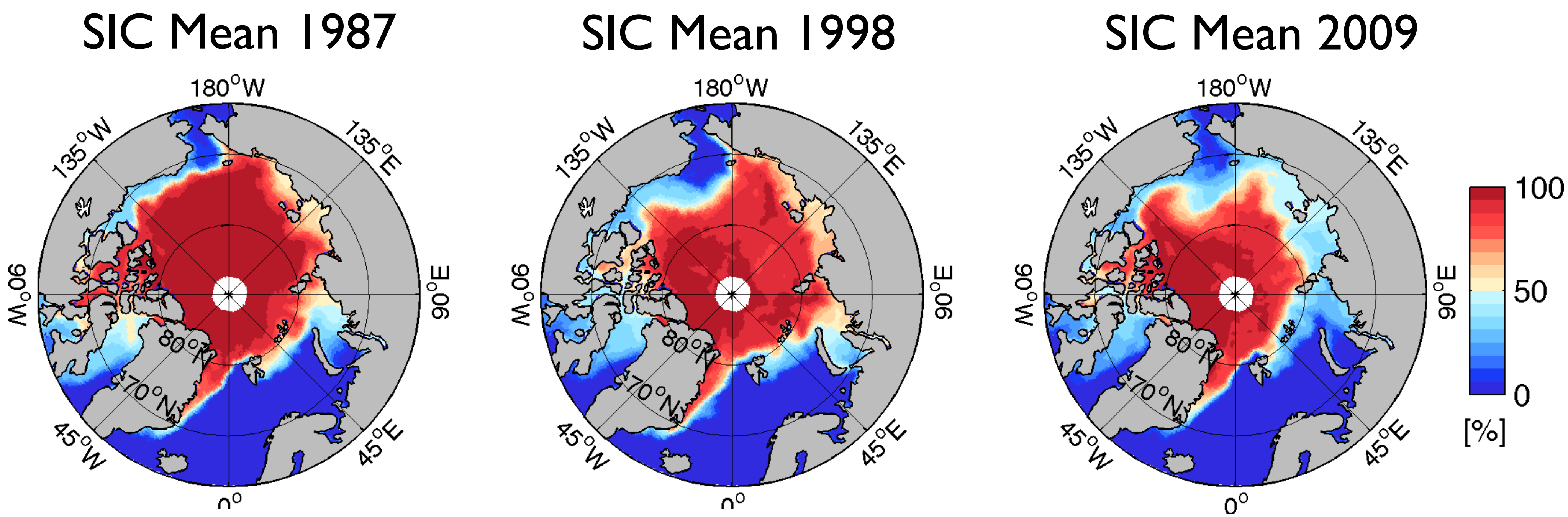

II. Dynamical response of the Arctic surface winds
to sea ice variability

Sea ice concentration (SIC) from the passive microwave radiometers

The most extensively and continuously observed climate variable; yet different retrieval algorithms yield diversity in SIC estimates.

1) **NT**: NASA-TEAM, 2) **BT**: NASA Bootstrap, 3) **EU**: EUMET-SAT hybrid

MEAN of SIC datasets

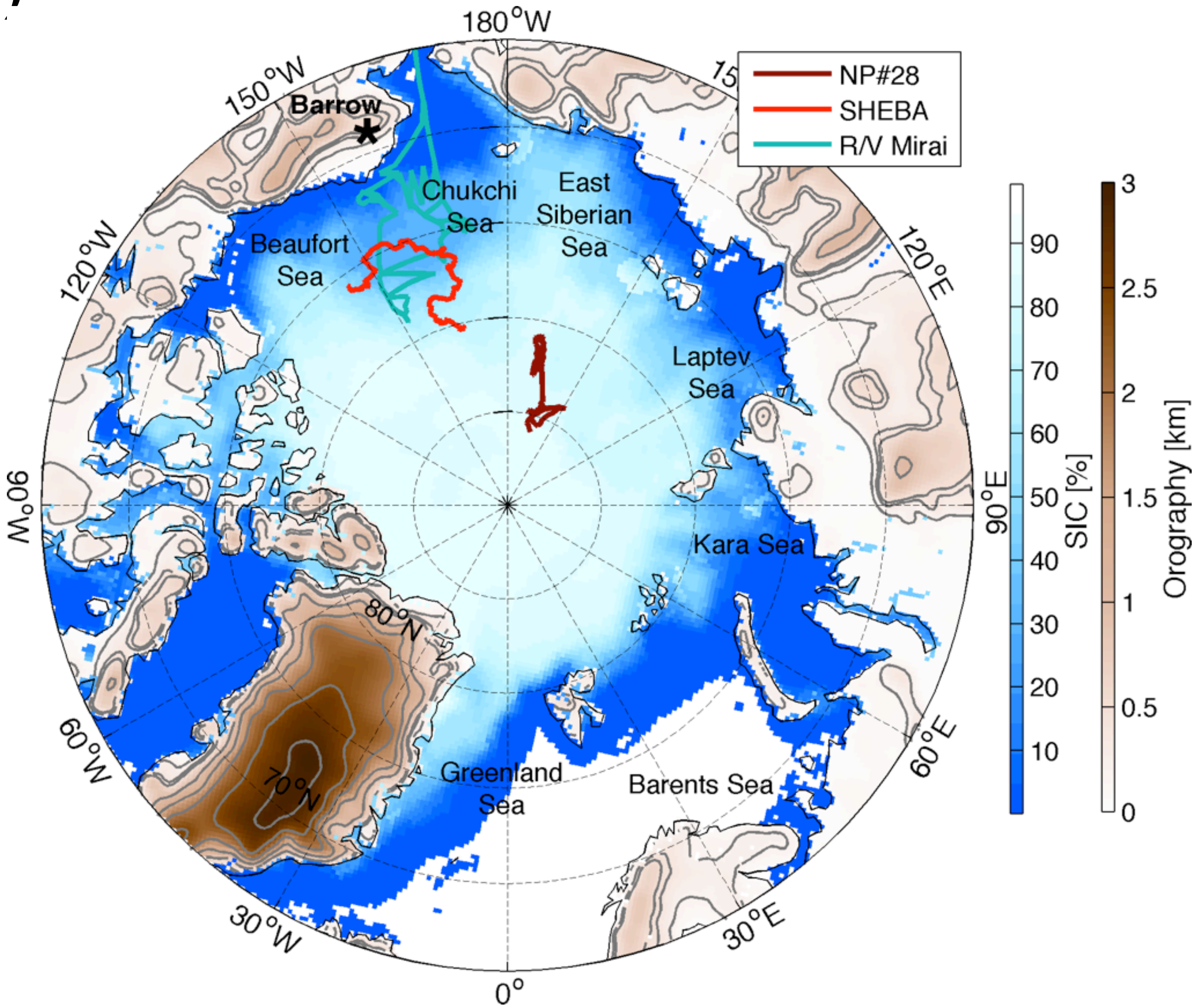


Goal:
Interpret the surface wind variations over various SICs
using two ABL mechanisms

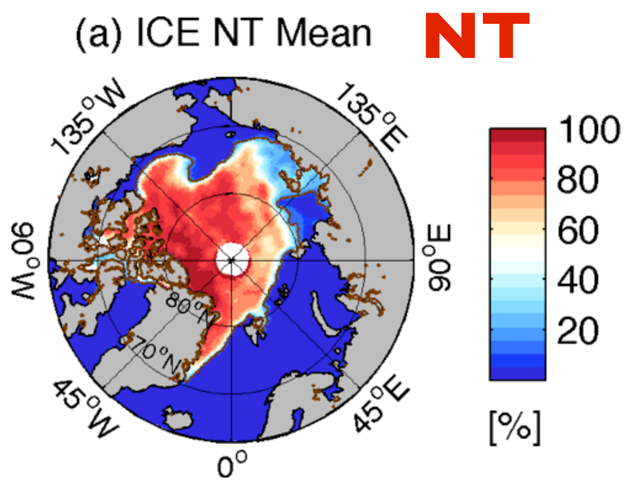
Polar WRF simulation

- Polar WRF: Hines and Bromwich (2008)
  - WRF optimized for polar regions
  - Modified surface layer model for improved surface energy balance
- Experiments
  - Three one-year (Nov-Oct) runs separated by 11 years
  - 1986-1987 : North Pole Station #28
  - 1997-1998 : SHEBA
  - 2008-2009 : R/V Mirai
  - Each period forced with NT, BT, EU

Model domain, in situ datasets overlaid with STD of SON SIC



- Polar WRF produces reasonable skill in ABL thermodynamics and surface winds against these in situ datasets various ice conditions (Seo and Yang, 2013)



Atmospheric sensitivity to SIC

Focusing on NT - BT in September 2009

Large change in ABL compared to the mean values

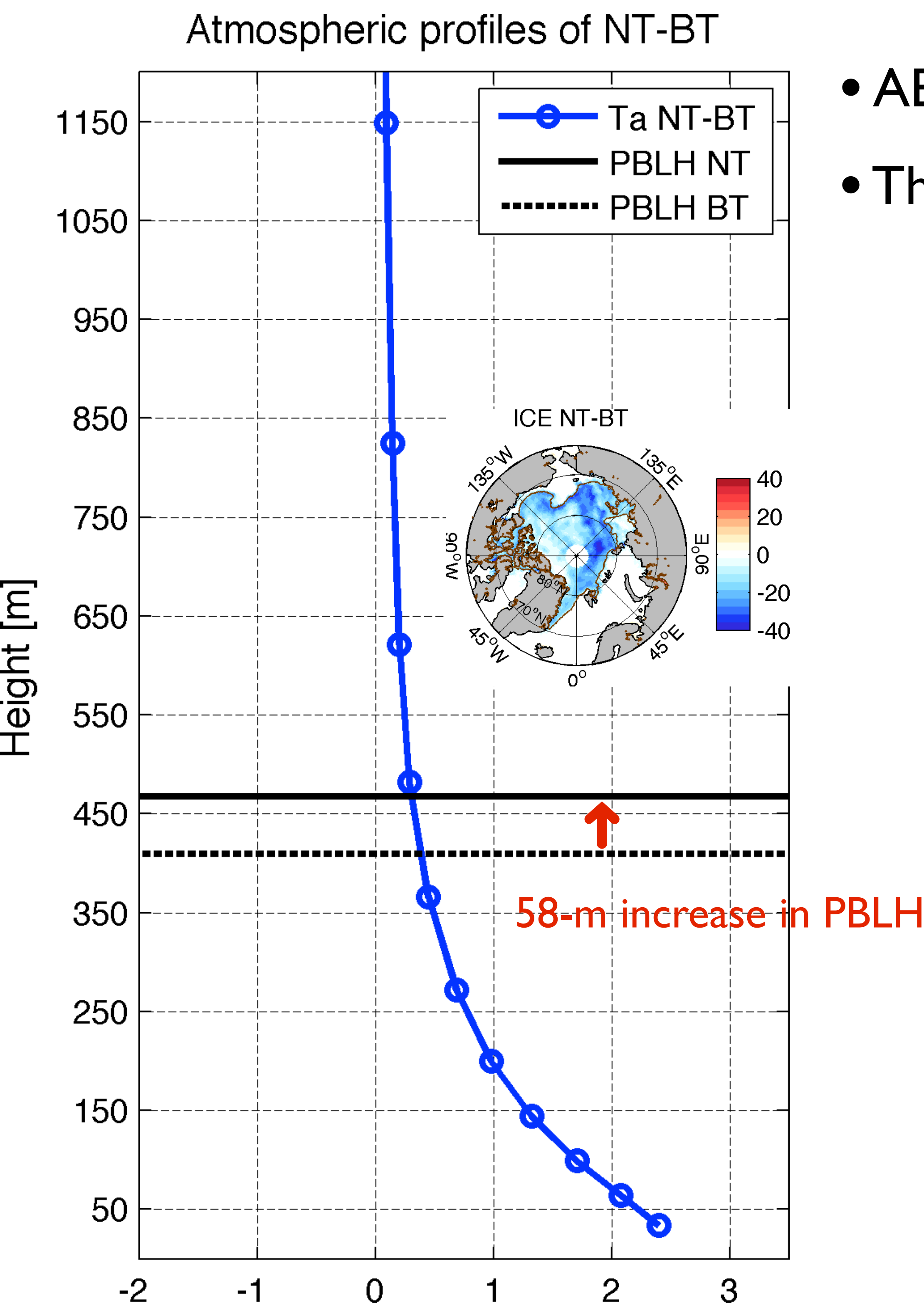
East Siberian Sea	Mean	Difference
T2	-5 °C	+5 °C
PBLH	450 m	100 m
TCWP	60 gm^{-2}	10 gm^{-2}

SIC uncertainty is a decisive factor for hindcast skill!

- SIC difference and ABL sensitivity on comparable spatial-scales

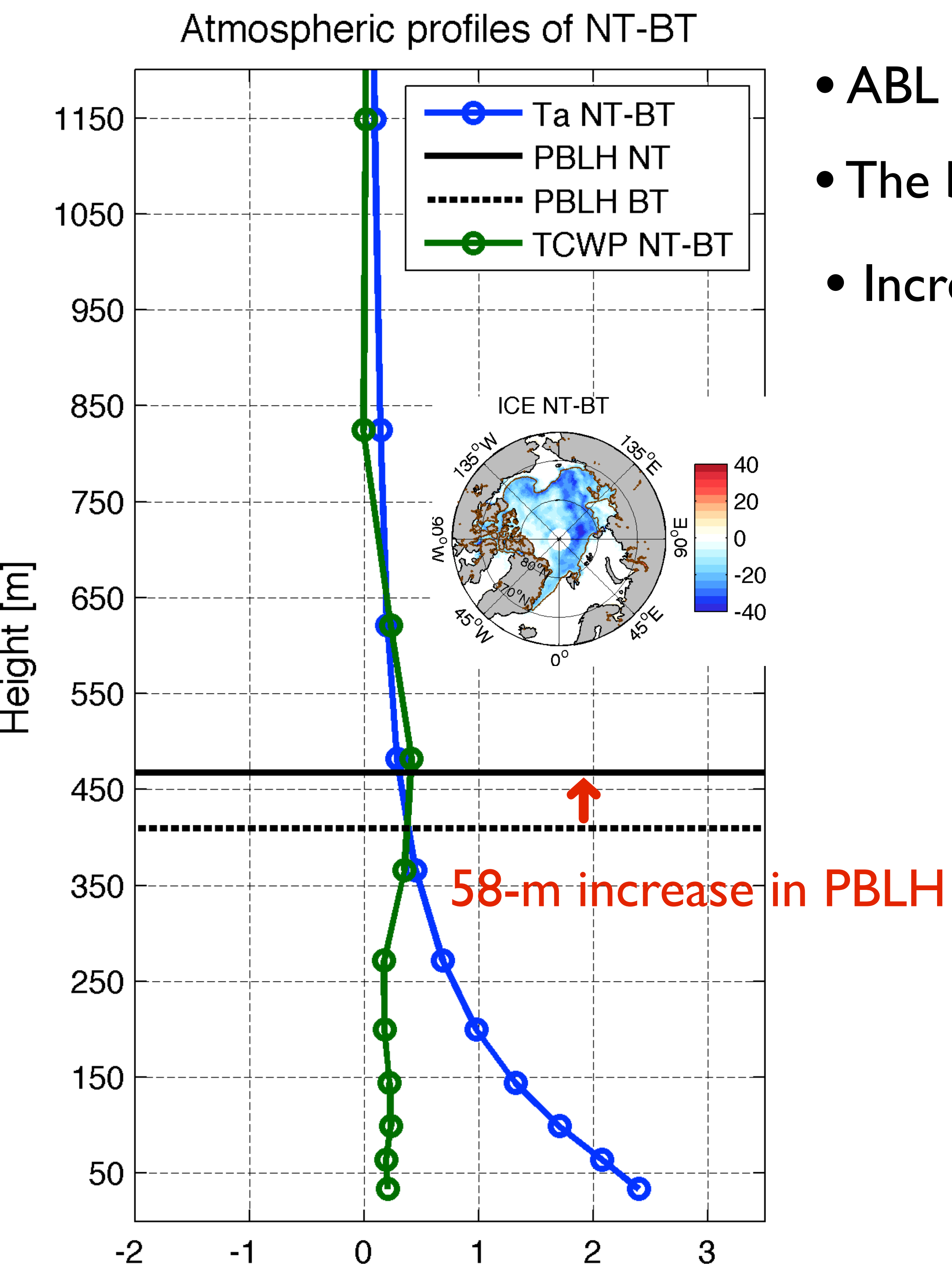
SST′ ➜ ABL stability

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



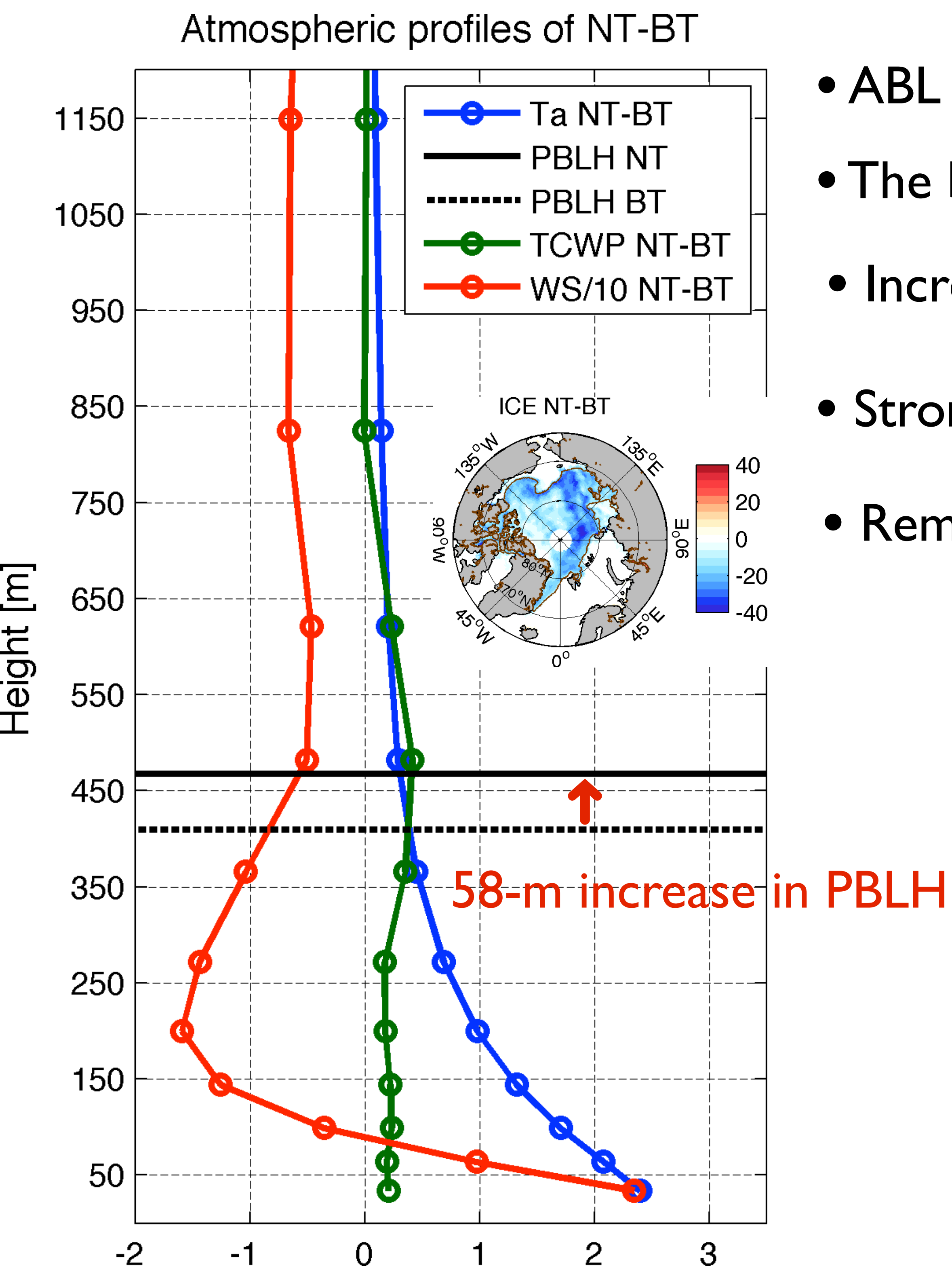
- ABL stability adjustment to SST: Less SIC ➔ Higher PBL
- The basin-wide increase in air temperatures below PBL.

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

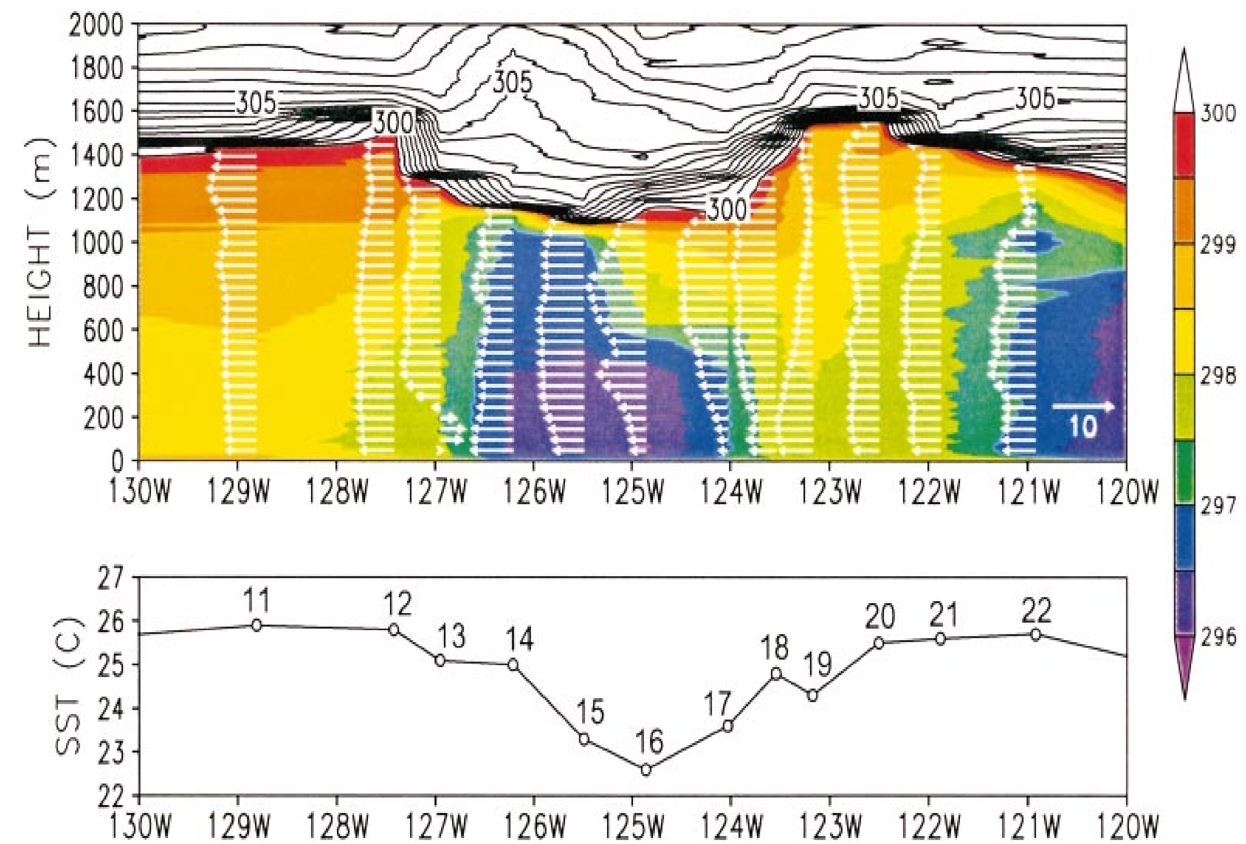


- ABL stability adjustment to SST: Less SIC ➔ Higher PBL
- The basin-wide increase in air temperatures below PBL.
- Increased cloud water path near the top of PBL.

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



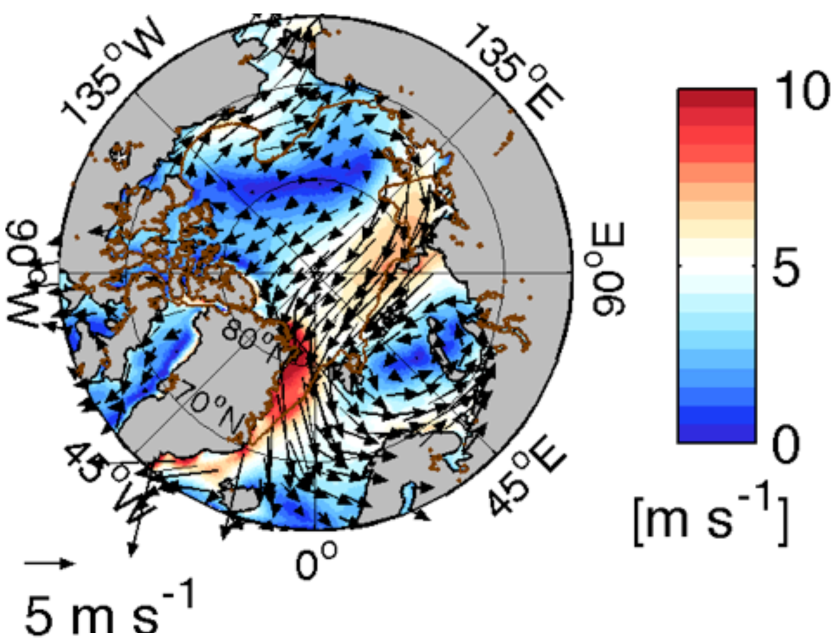
- ABL stability adjustment to SST: Less SIC ➔ Higher PBL
- The basin-wide increase in air temperatures below PBL.
- Increased cloud water path near the top of PBL.
- Stronger wind below 100 meter but weaker wind aloft
- Reminiscent of what is happening in mid to low latitudes!



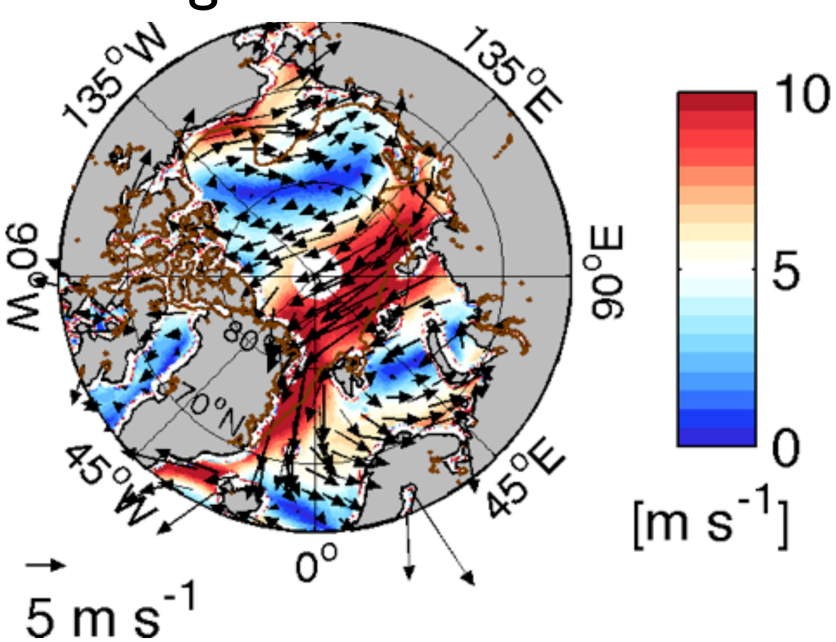
Very different responses in two near-surface winds to the same SIC difference: W10 and Wg ($\approx \nabla$SLP)

September 2009

W10 NT Mean



Wg NT Mean



- Increased W10 with reduced SIC
  - Most dramatic changes in the interior Arctic

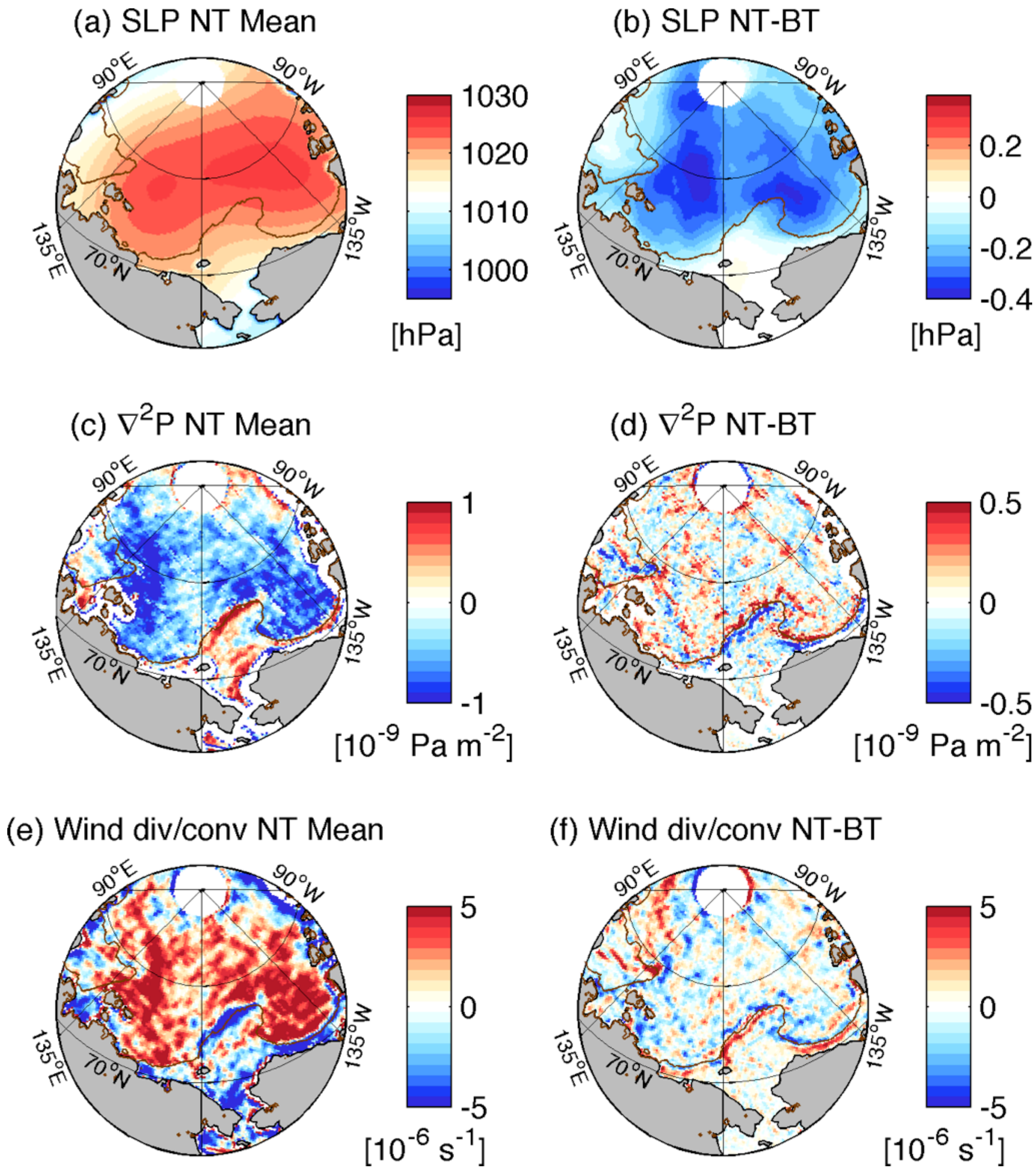
$SST' \rightarrow \tau'$ (Chelton et al. 2001)

- Reduced Wg along the ice margins!
  - No significant changes in the interior Arctic.

➜ The spatial scale of Wg response is smaller than that of W10.

$\nabla^2 T \rightarrow \nabla^2 P \rightarrow \nabla \cdot \tau'$ (Lindzen and Nigam, 1987)

Wg response should be interpreted as due to the pressure adjustment mechanism



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MABL model of

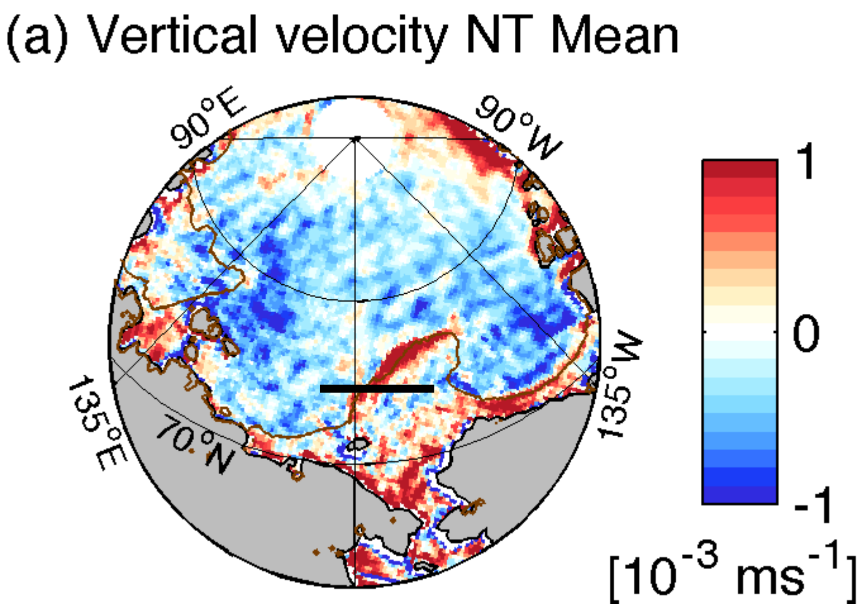
Lindzen and Nigam (1987):

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

$\nabla\cdot$u is linearly proportional to SIC-induced $\nabla^2 P$.

Wind response more pronounced on the smaller scale than W10; e.g., along the ice edges

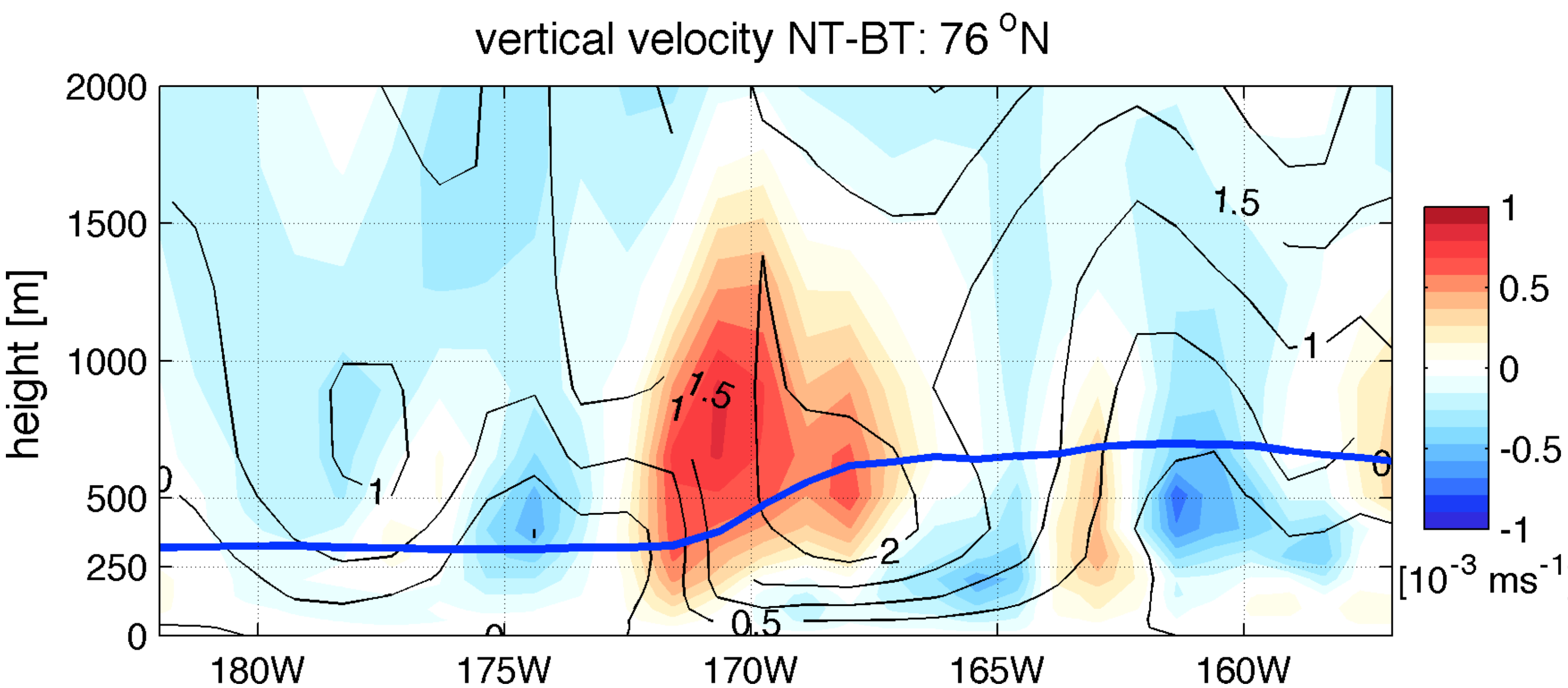
Large vertical motion induced by pressure gradient mechanism



Vertical integration yields

$$w(z) = \frac{1}{\rho_o}\left(\frac{\varepsilon z}{\varepsilon^2 + f^2}\right)\nabla^2 P$$

- SIC-induced vertical velocity (*w*) is proportional to $\nabla^2 P$.



- Large w anomaly extends beyond the top of the ABL;
- This "deep" response may influence the larger-scale circulation (as in the Gulf Stream).

September 2009

Summary

- SST variations associated with ocean mesoscale eddies cause coherent perturbations in the ABL
  - a ubiquitous feature observed throughout the World Oceans
  - atmospheric feedback (wind stress, curls and heat flux) important for mesoscale ocean dynamics
  - including the arctic: sea ice variability acting like SST fronts

- Eddies and sea ice produce large **anomalies and gradient in SSTs**.
  - *Vertical mixing mechanism*: Overland (1985), Wallace et al. (1989)
    - Surface wind increases (decreases) over the warm (cold) surface
    - Comparable spatial scale of response to the SST:

$$\nabla_d SST' \rightarrow \nabla \cdot \boldsymbol{\tau}' \quad \nabla_c SST' \rightarrow \nabla \times \boldsymbol{\tau}'$$

- *Pressure adjustment mechanism*: Lindzen and Nigam (1987), Minobe et al. (2008)
  - ∇^2 would be effective in highlighting small-scale response,
  - e.g., along the sea ice margins.

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

Discussion

W10 and Wg reflect different spatial information of sea ice changes!

- The ocean-ice modelers often use wind stress from
  (1) in situ SLP-based Wg:
    - underestimates the effect of large-scale SIC changes on wind.
  (2) coarse resolution atmospheric reanalyses:
    - underestimate the wind variations across the ice margins.

Both effects should be taken into account for improved simulation of the circulation of ocean and sea ice.

Thanks!

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