Mesoscale air-sea interaction and feedback in the western Arabian Sea

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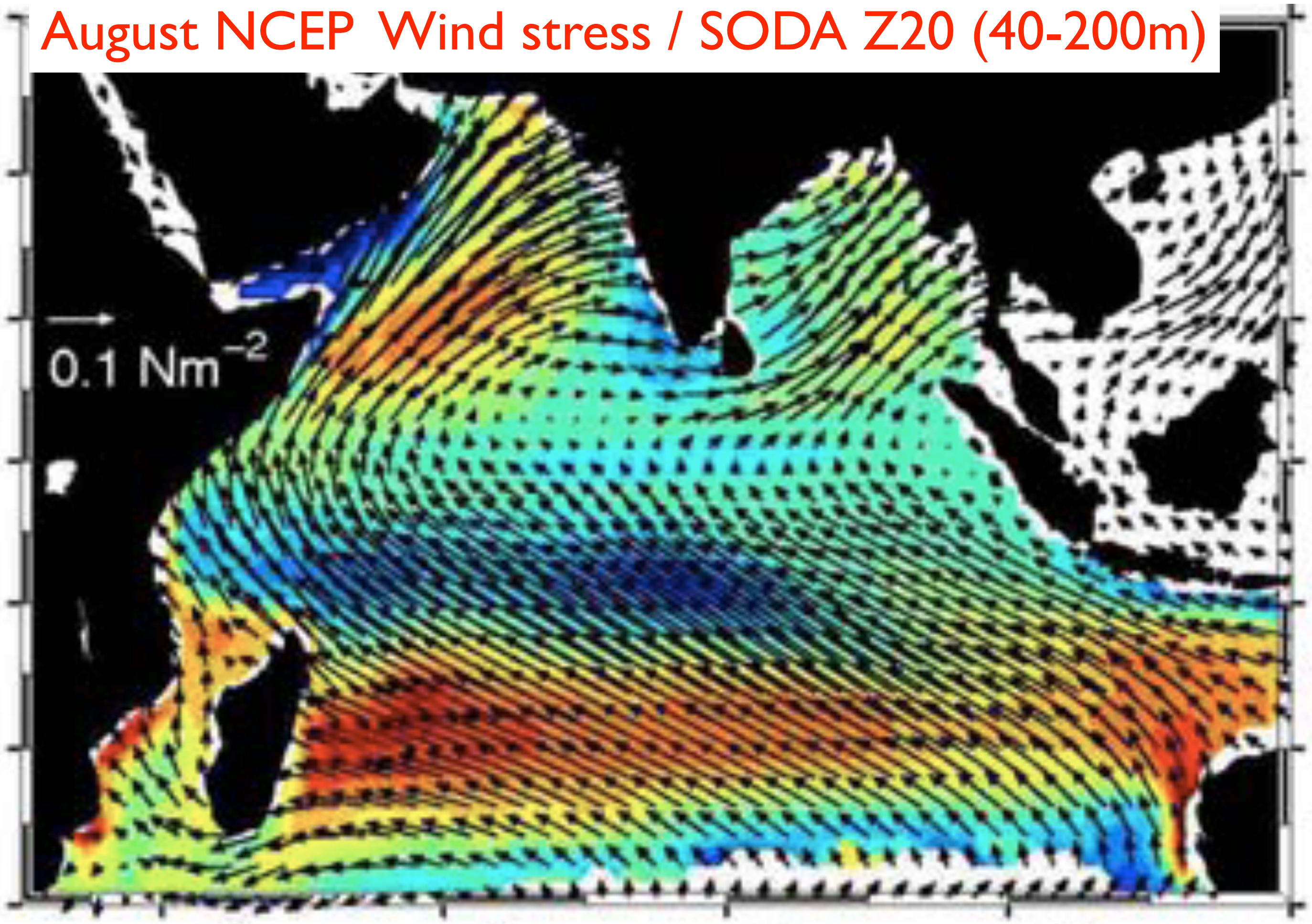
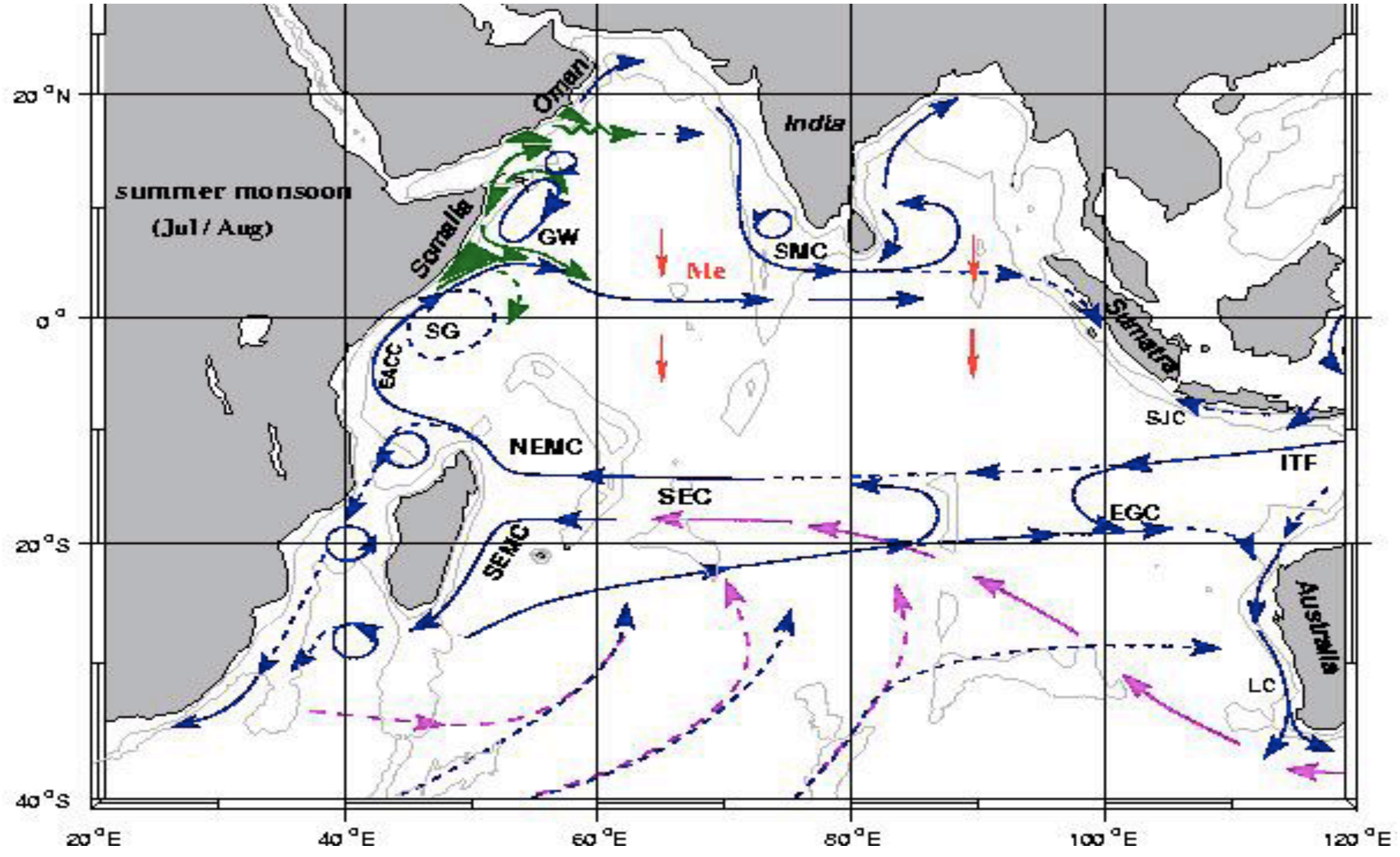
CLIVAR WBC Workshop, Phoenix
January 15, 2009

Wind and current in the Indian Ocean during summer monsoon



August NCEP Wind stress / SODA Z20 (40-200m)

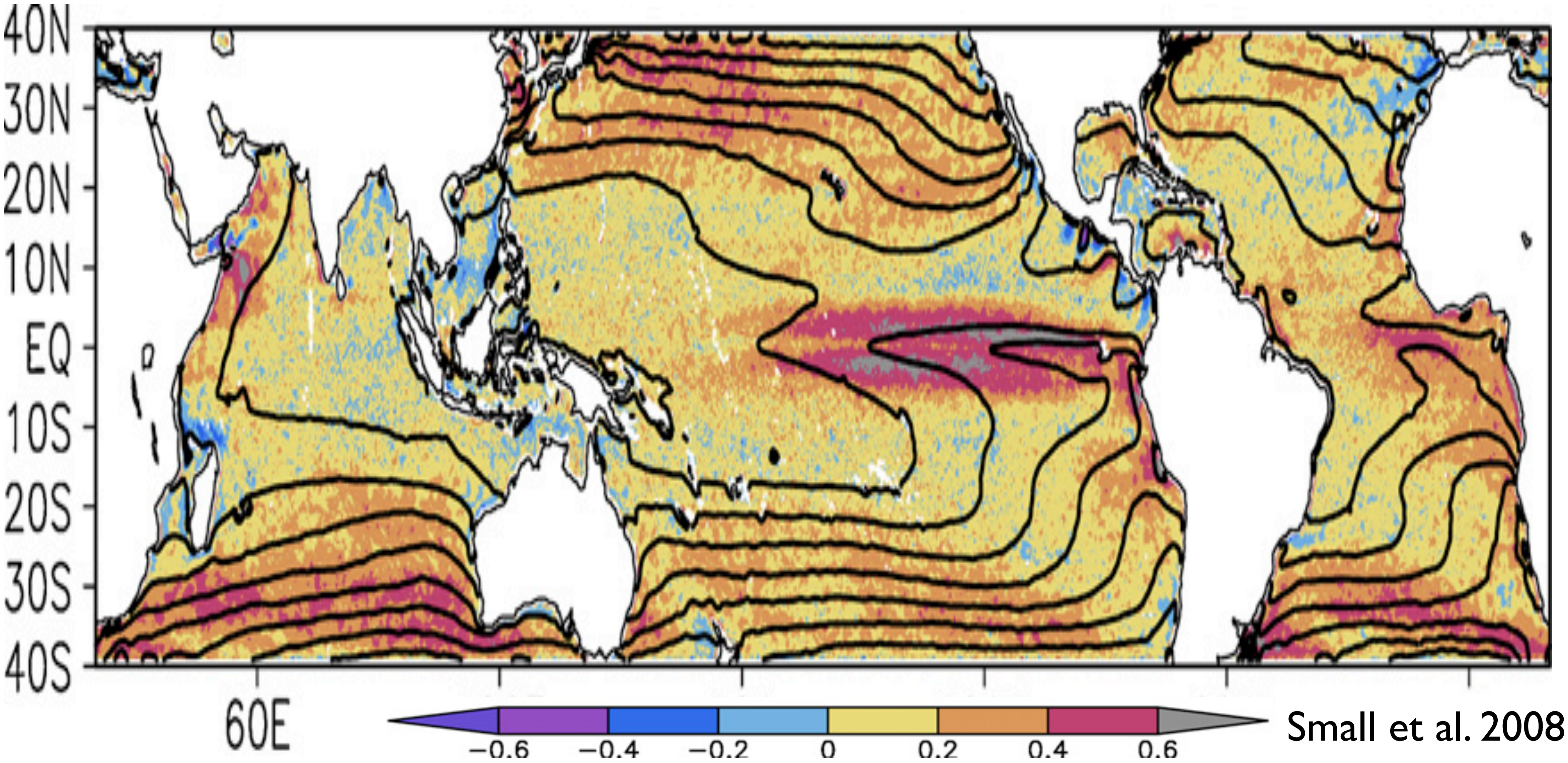


Schematic representation of ocean current in SW monsoon

- Summer monsoon ➔ Somali Jet (>13 m/s)
- Somali Current (~2 m/s), anticyclonic Great Whirl.
- Costal upwelling, cold filaments and cold wedges.

Schott, McCreary, Xie 2009

Correlation of high-passed SST and wind speed



Small et al. 2008

- Large positive correlations found in the western Arabian Sea and the eastern equatorial Pacific

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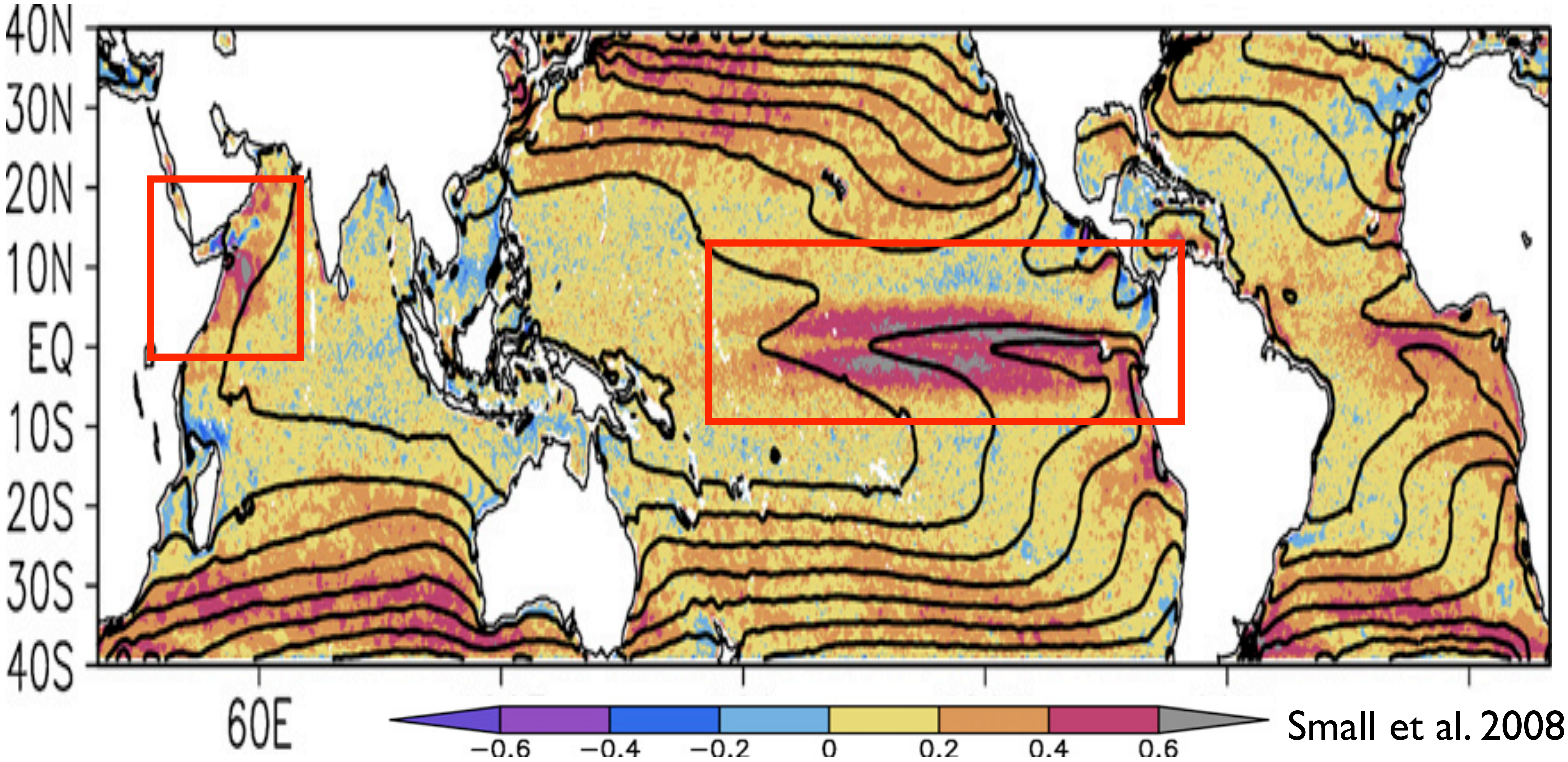
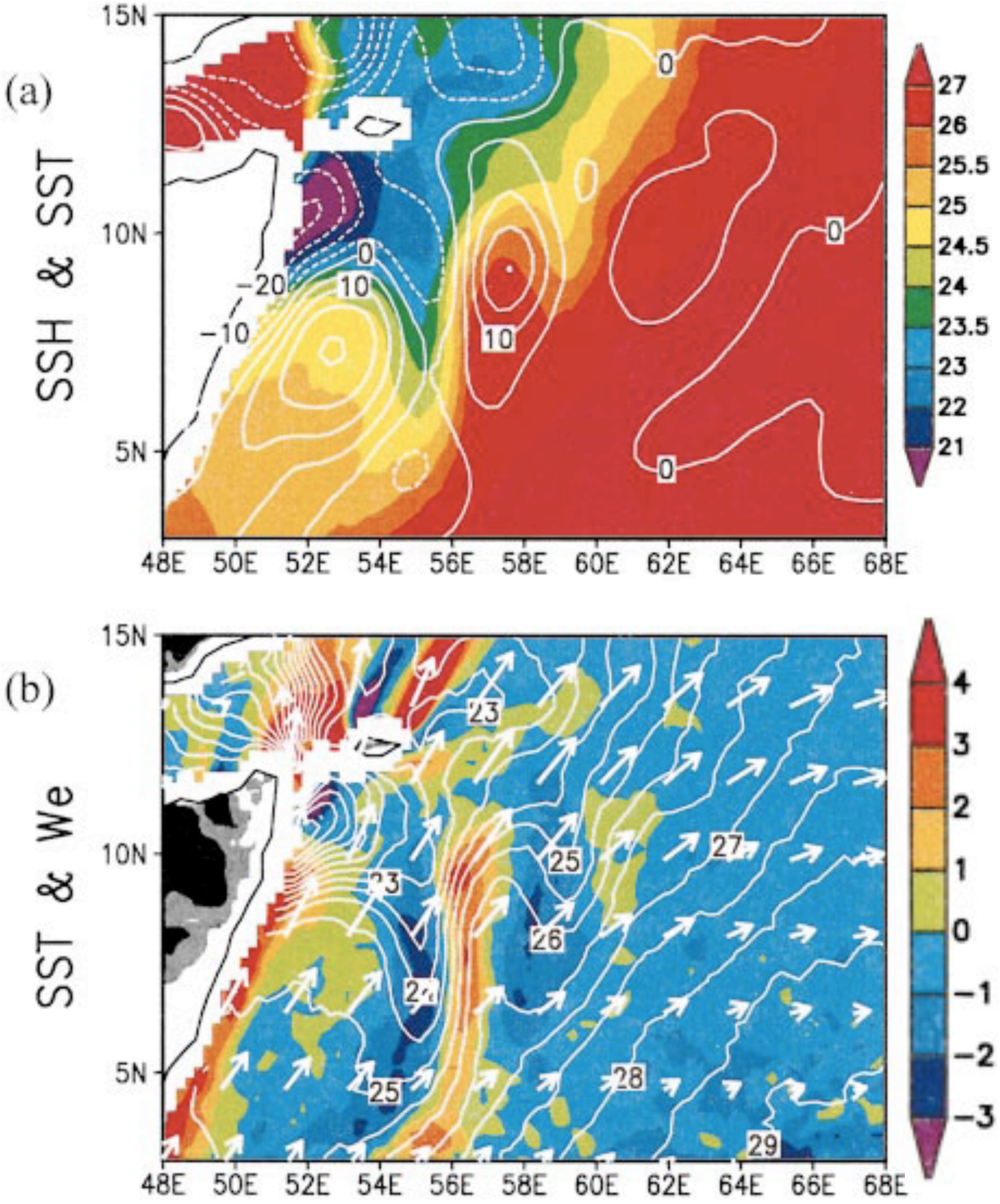


Small et al. 2008

- Large positive correlations found in the western Arabian Sea and the eastern equatorial Pacific

Observations of ocean-atmosphere interaction over cold filaments during summer monsoon (Vecchi et al. 2004)



15 Jul–15 Aug, 1999–2002

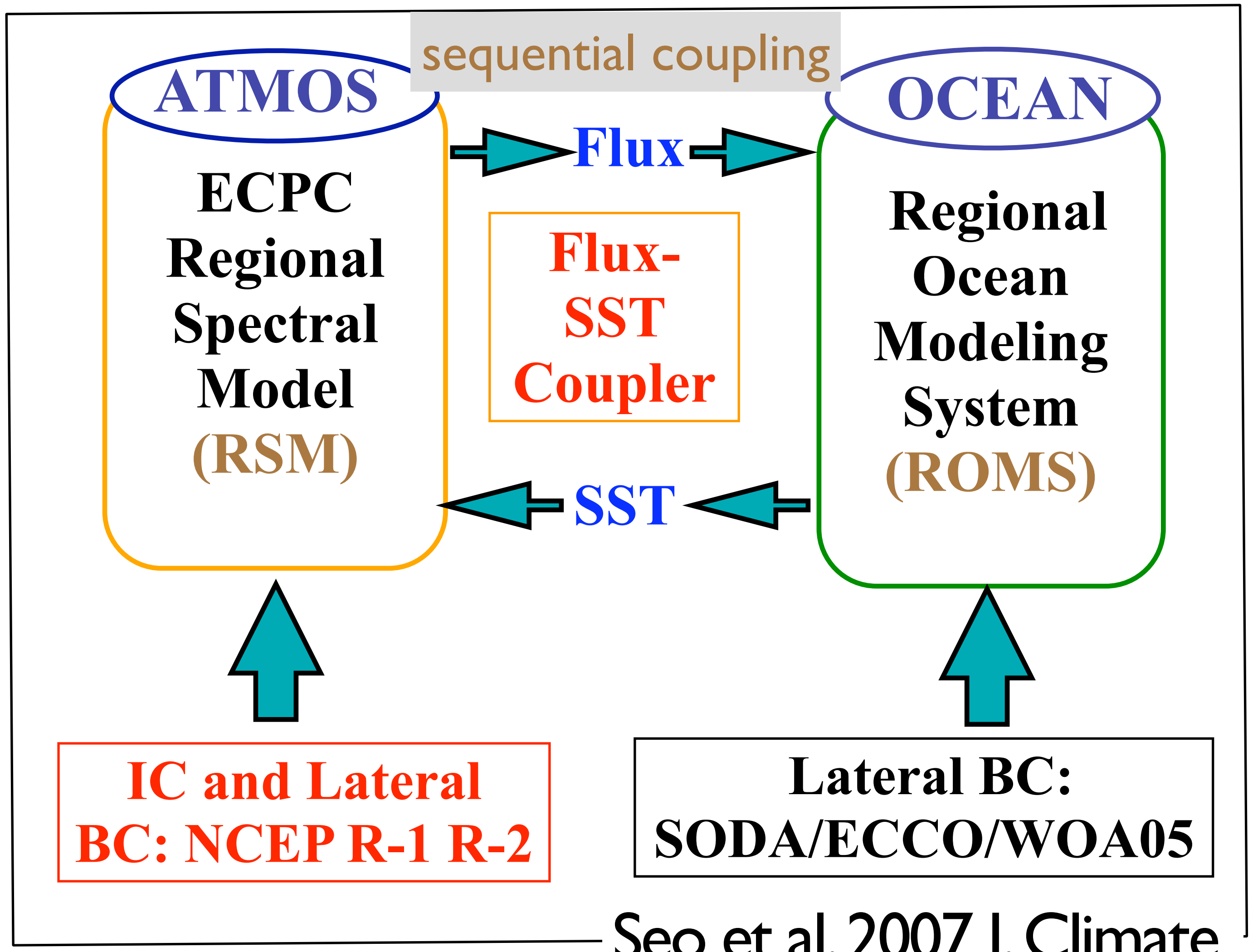
- Images from TRMM and QuikSCAT
- Generation of Ekman velocities of 2-3 m/day at the cold filaments
- This Wek is additional to the large-scale Ekman pumping.
- Main question: how important is Wek for the oceanic vertical structure and velocity?
- We need a high-resolution (*both ocean and the atmosphere*) coupled model to give detailed structure of the coupled system

Outline

- Fully-coupled high-resolution coupled model (SCOAR)
- Wind and heat flux response to the cold filaments
- Ekman pumping velocity and dynamic feedback
- Turbulent heat flux and thermodynamic feedback
- Summary

Seo, Murtugudde, Jochum, and Miller, 2008:
Modeling of Mesoscale Coupled Ocean-Atmosphere Interaction and its Feedback to Ocean in the Western Arabian Sea. *Ocean Modelling*, **25,** 120-131

Scripps Coupled Ocean-Atmosphere Regional (SCOAR) Model: Indian Ocean



sequential coupling

ATMOS

ECPC Regional Spectral Model (RSM)

Flux

Flux-SST Coupler

SST

OCEAN

Regional Ocean Modeling System (ROMS)

IC and Lateral BC: NCEP R-1 R-2

Lateral BC: SODA/ECCO/WOA05

Seo et al. 2007 J. Climate

- Higher model resolution; Identical resolution (0.26°) of ocean and atmosphere.
- Dynamical consistency with the NCEP Reanalysis forcing
- Greater portability

1. Study mesoscale coupled ocean-atmosphere interaction:
2. relation with the regional climate:

- 0.26° res. ocean and atmosphere
- daily coupling
- 1993-2006

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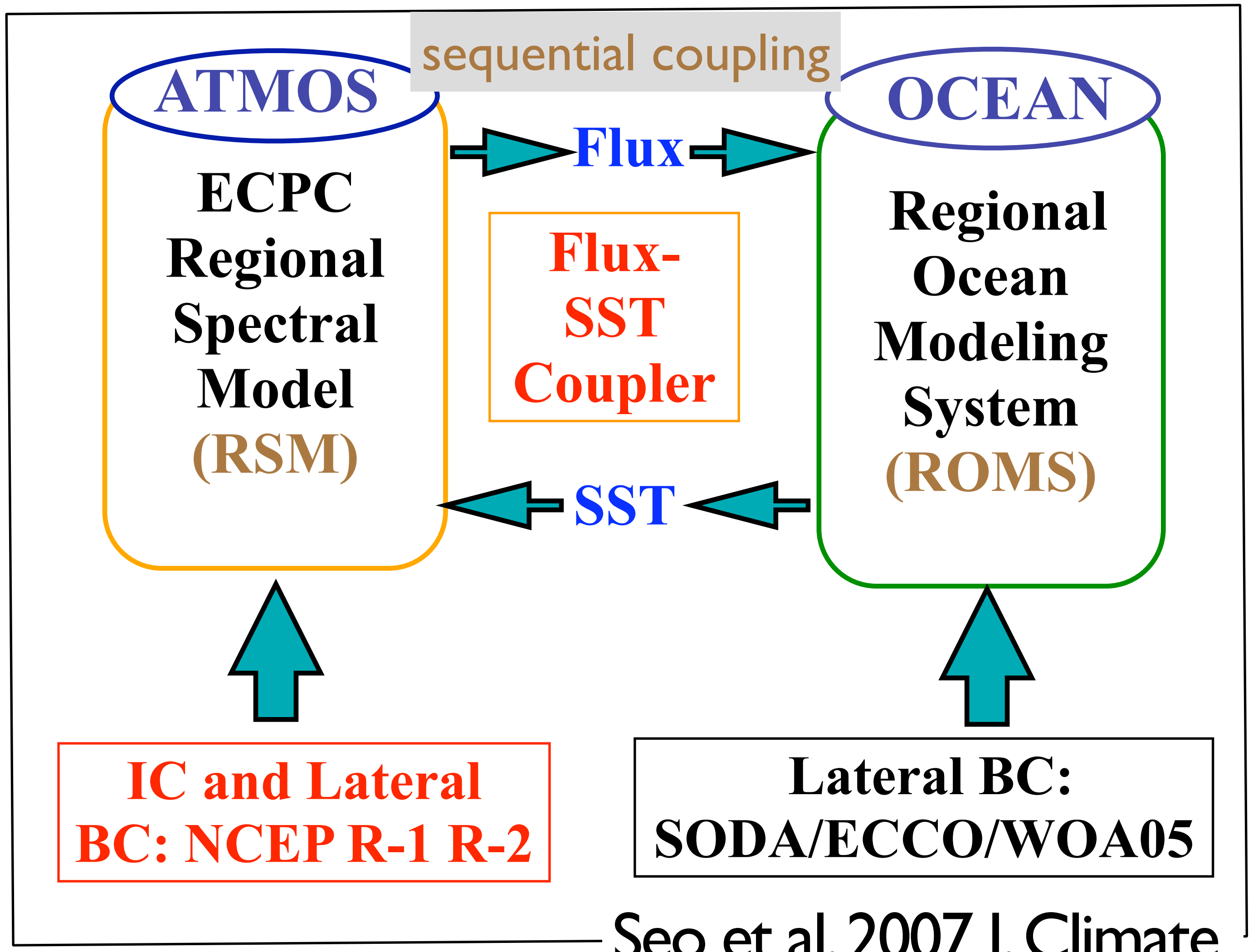

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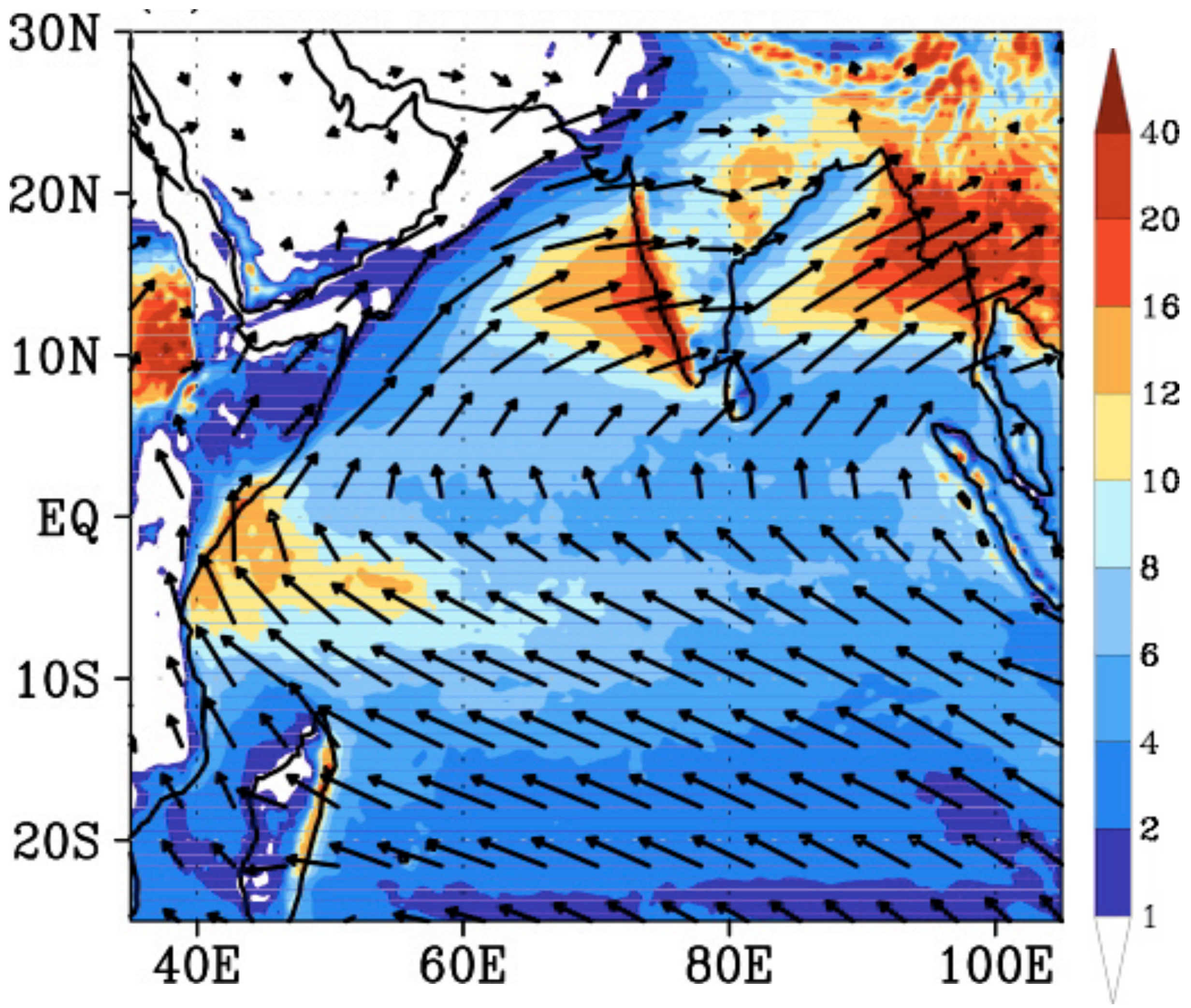
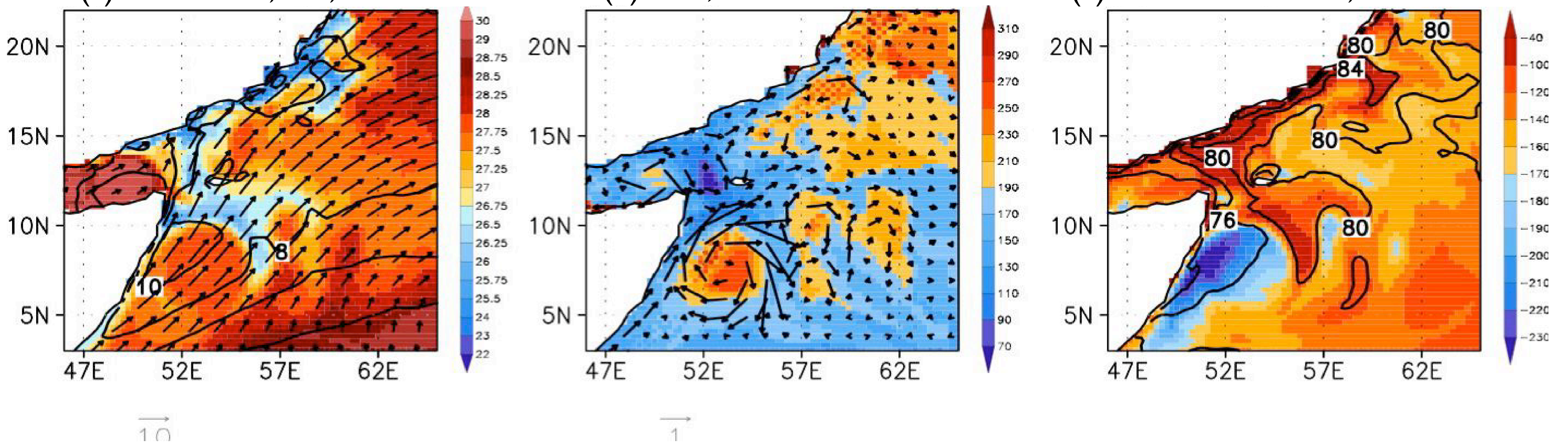


Simulated mean properties of the western Arabian sea



(a) Model SST, WS, 2002 AUG

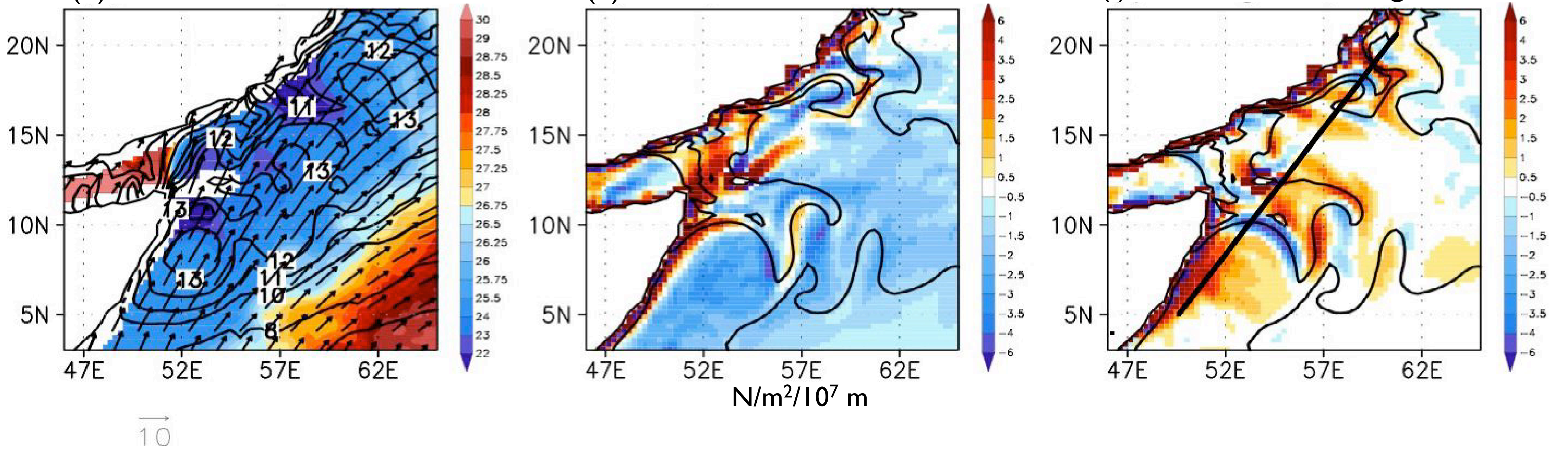
(b) Z20, SFC CURRENT

(c) Latent Heat Flux, RH at 1000 hPa

(d) OBS SST, WS, 2002 AUG

(e) Wind Stress Curl, SST

(f) Wind Stress Divergence, SST



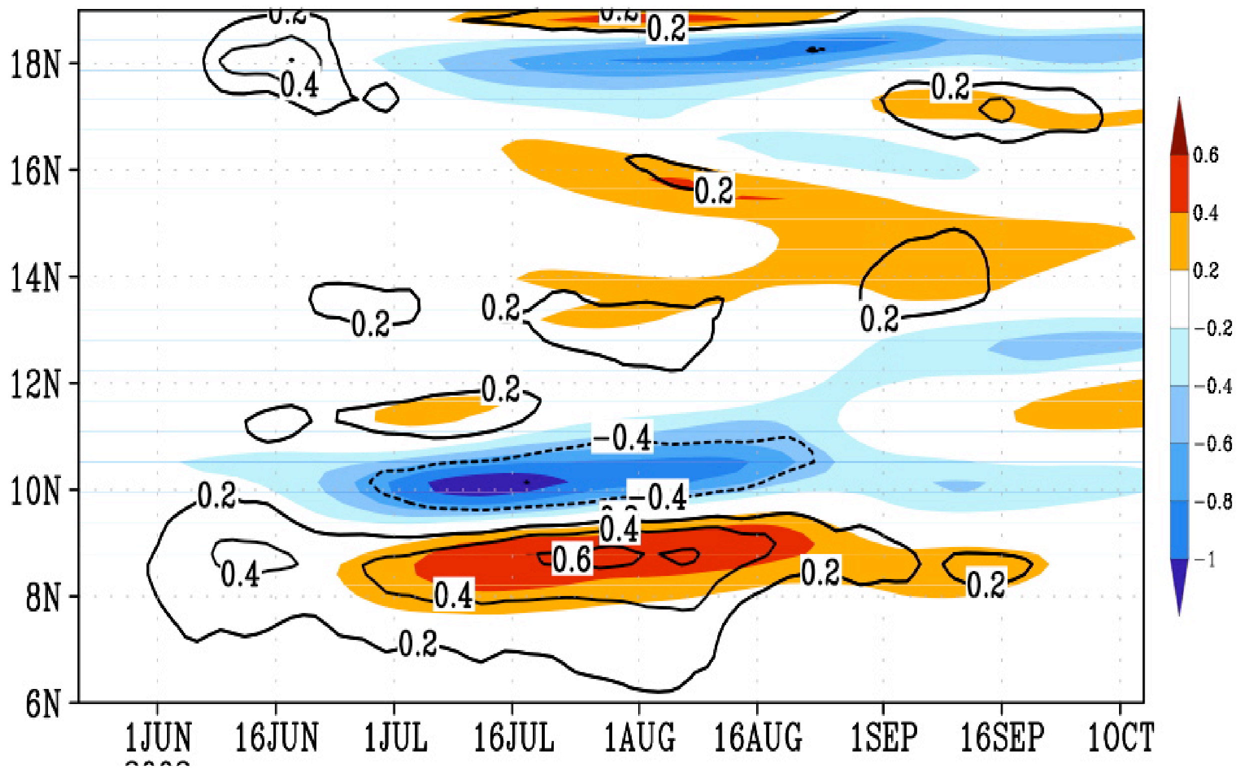
- Warm bias and weak Somali Jet in the model, but key features are reasonably well captured:
  - Large wind speed over the Great Whirl
  - Wind stress derivatives and SST gradients
  - Surface heat flux and the SST

August 2002 mean quantities
0.26° resolution RSM/ROMS daily coupled

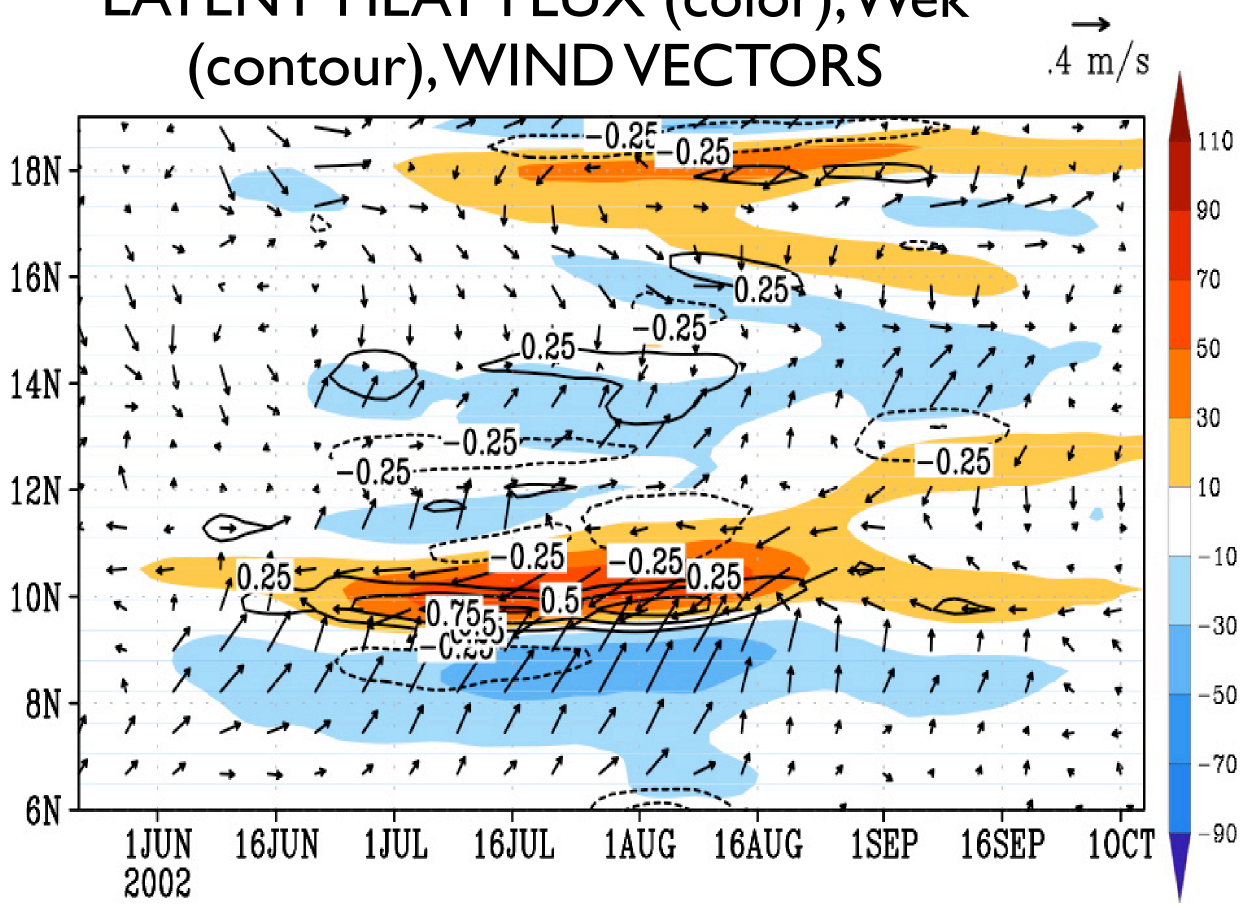
Local mesoscale ocean-atmosphere covariability

Model spatio-temporal covariability of ocean and atmosphere

SST (color), WIND SPEED (contour)

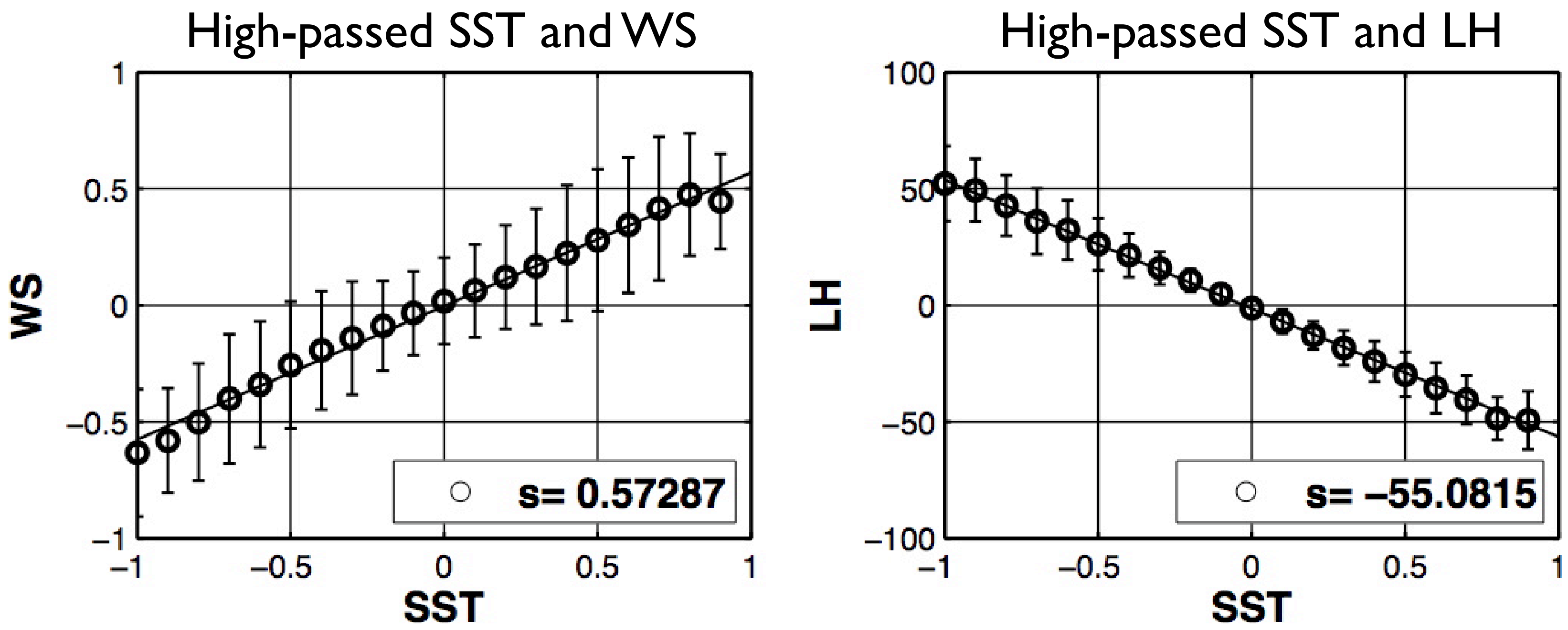


LATENT HEAT FLUX (color), Wek (contour), WIND VECTORS



- Cold filament develops in the beginning of June and reaches its maximum (<1° C) in July.
- In-phase response of surface wind to SST: southwesterly over warm water and northeasterly over cold water.
- Out-of-phase response from the latent heat flux: a damping effect.
- Large Ekman pumping velocity along the max. SST gradient (~ 1m/day)

Linear relationship between mesoscale SSTs vs wind speed (WS) and surface fluxes


High-passed SST and WS

High-passed SST and LH

JJAS 1995-2006

- When spatially highpass filtered, SST and WS (SST and LH) exhibit a linear positive (negative) relationship.
- Wind-SST relationship is not obvious in background fields.
- Eddies reduce the latent heat flux out of the ocean by twice in the model.

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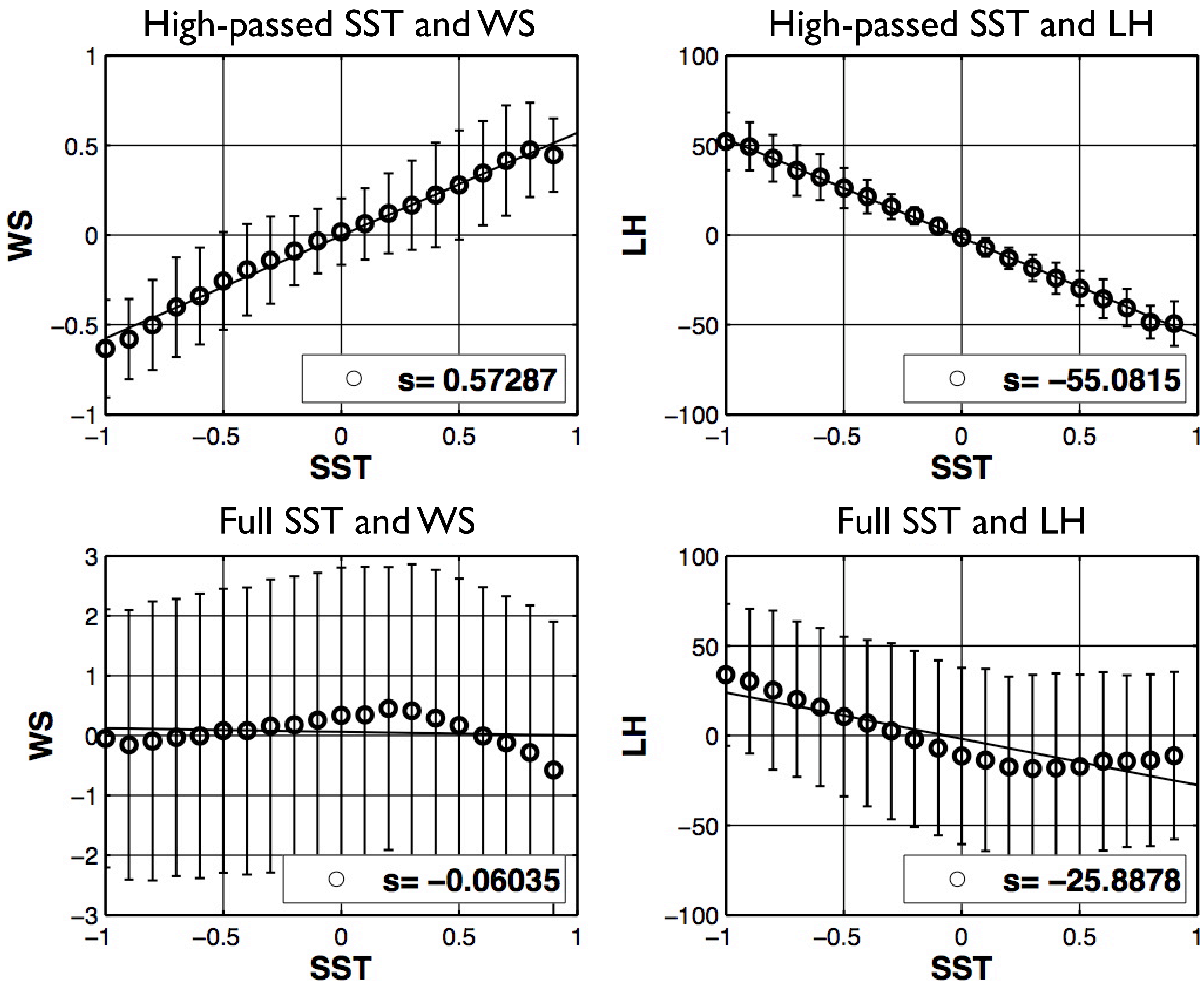

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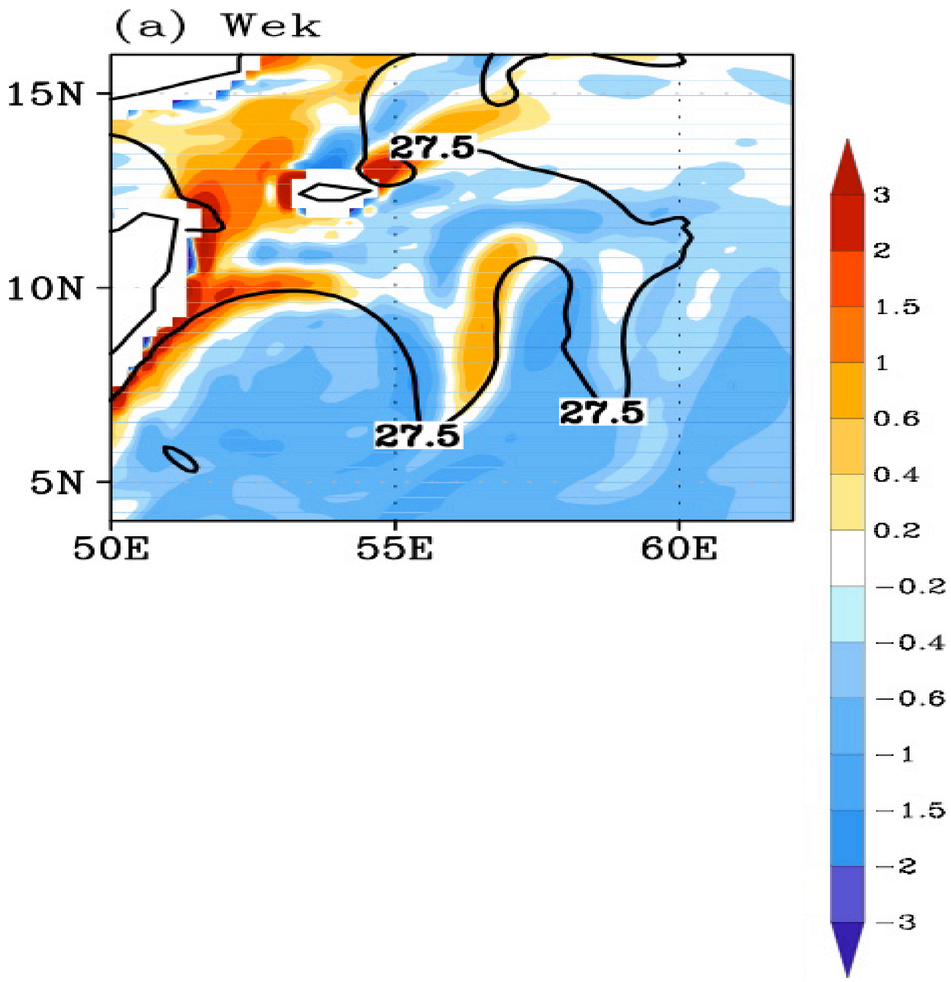
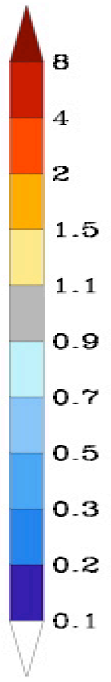
Ekman pumping and oceanic vertical velocity

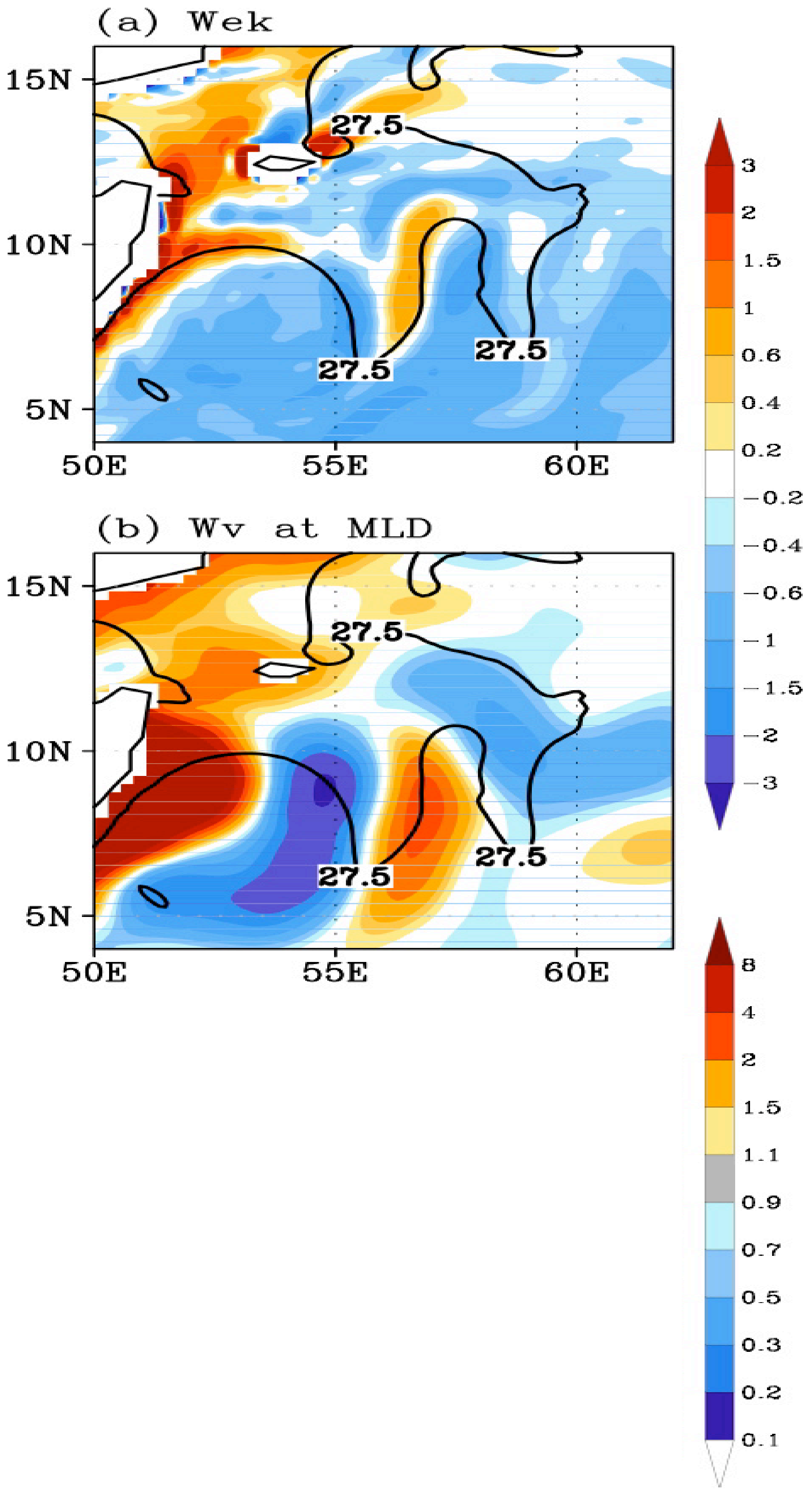




August 2002

Direct comparison of *Wek* with the oceanic vertical velocity (*W* at the base of mixed layer)

- The narrow band of Wek reaches >1 m/day, concentrated along the cold wedge.
- W is ~±2-3 m/day in the vicinity of cold filaments
- The ratio is ~O(1) over the region of maximum Wek along the cold filaments
- This will affect the evolution of cold filament and other oceanic mesoscale eddies (Vecchi et al . 2004)



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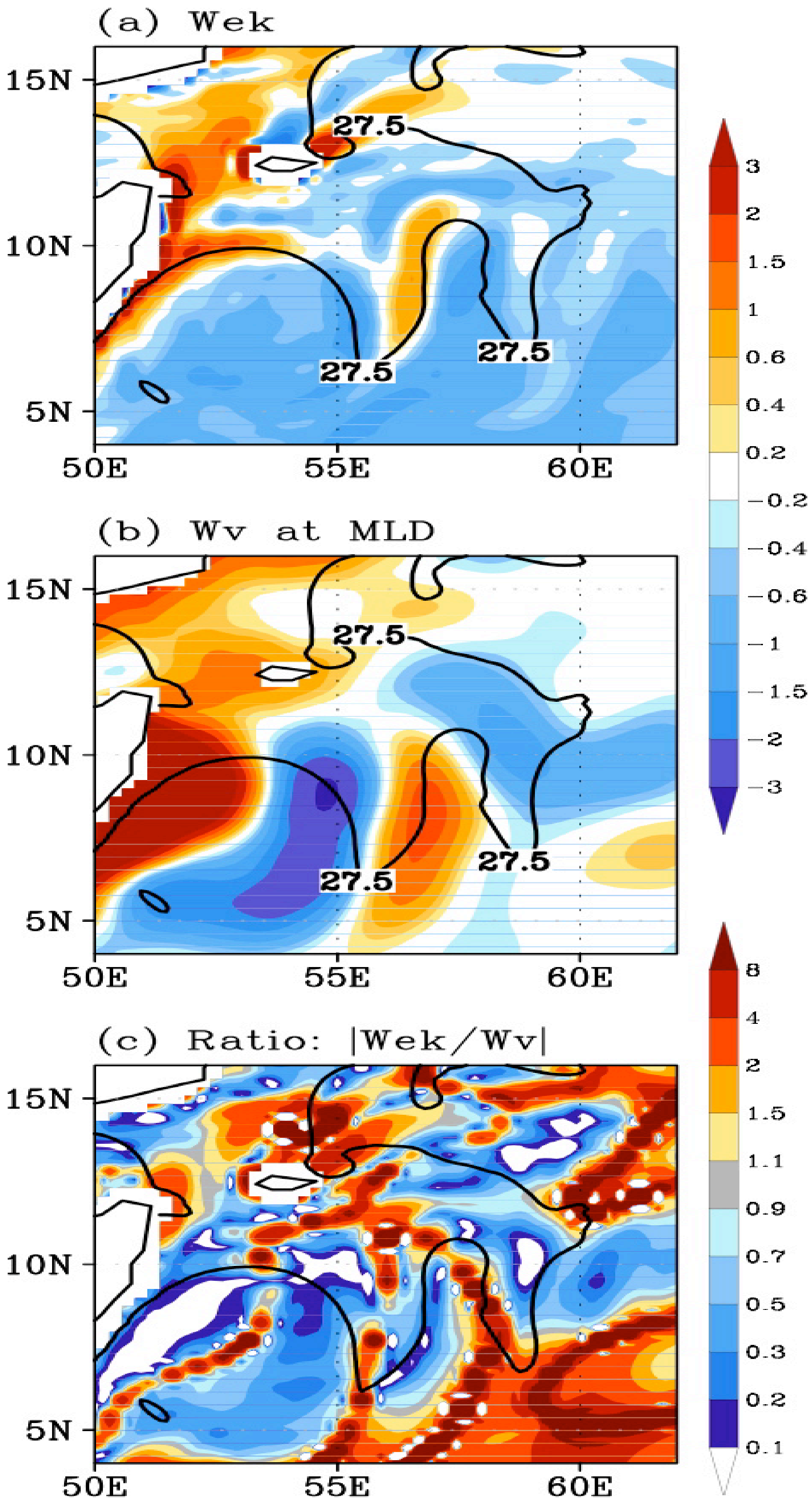

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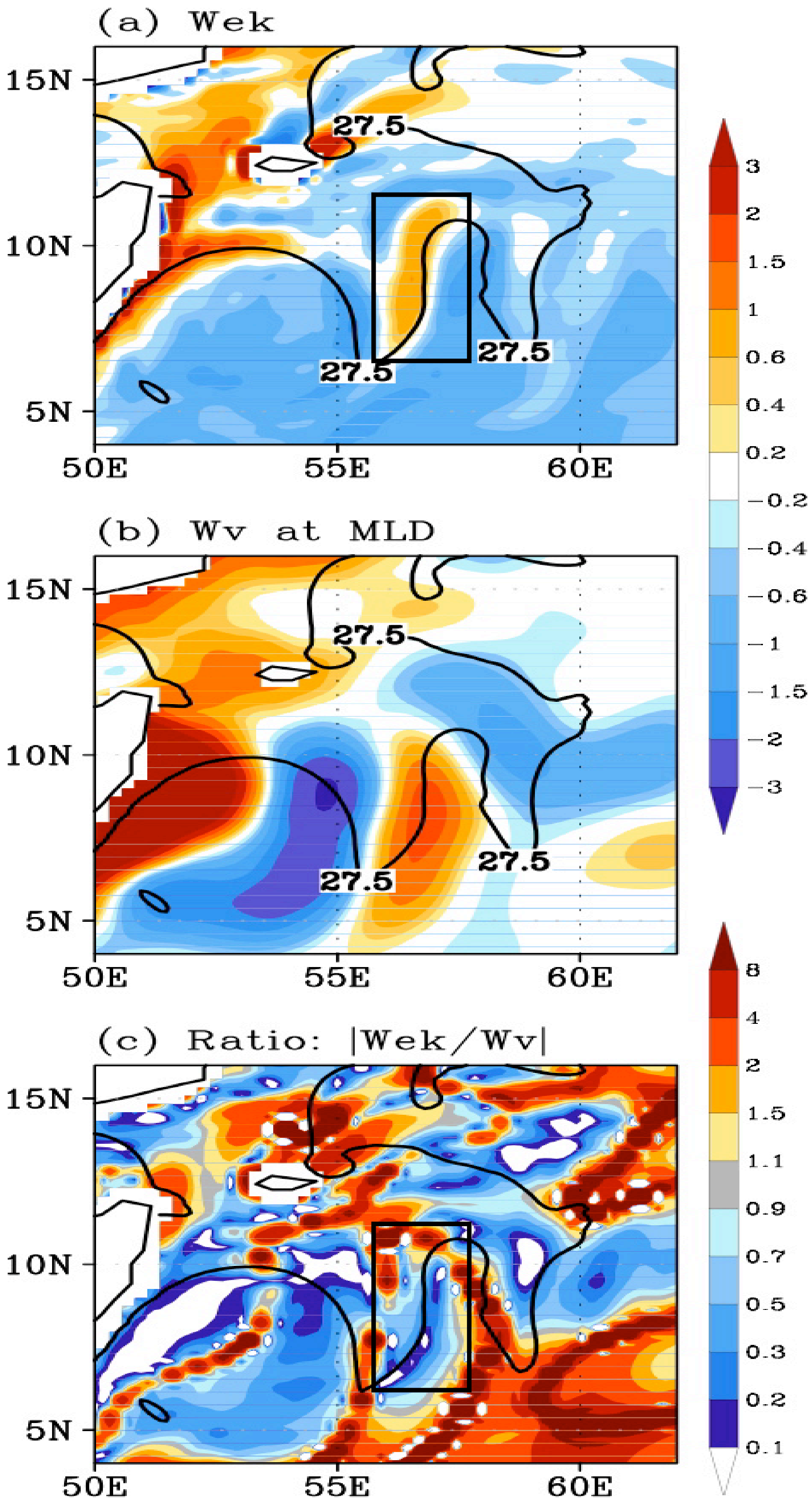

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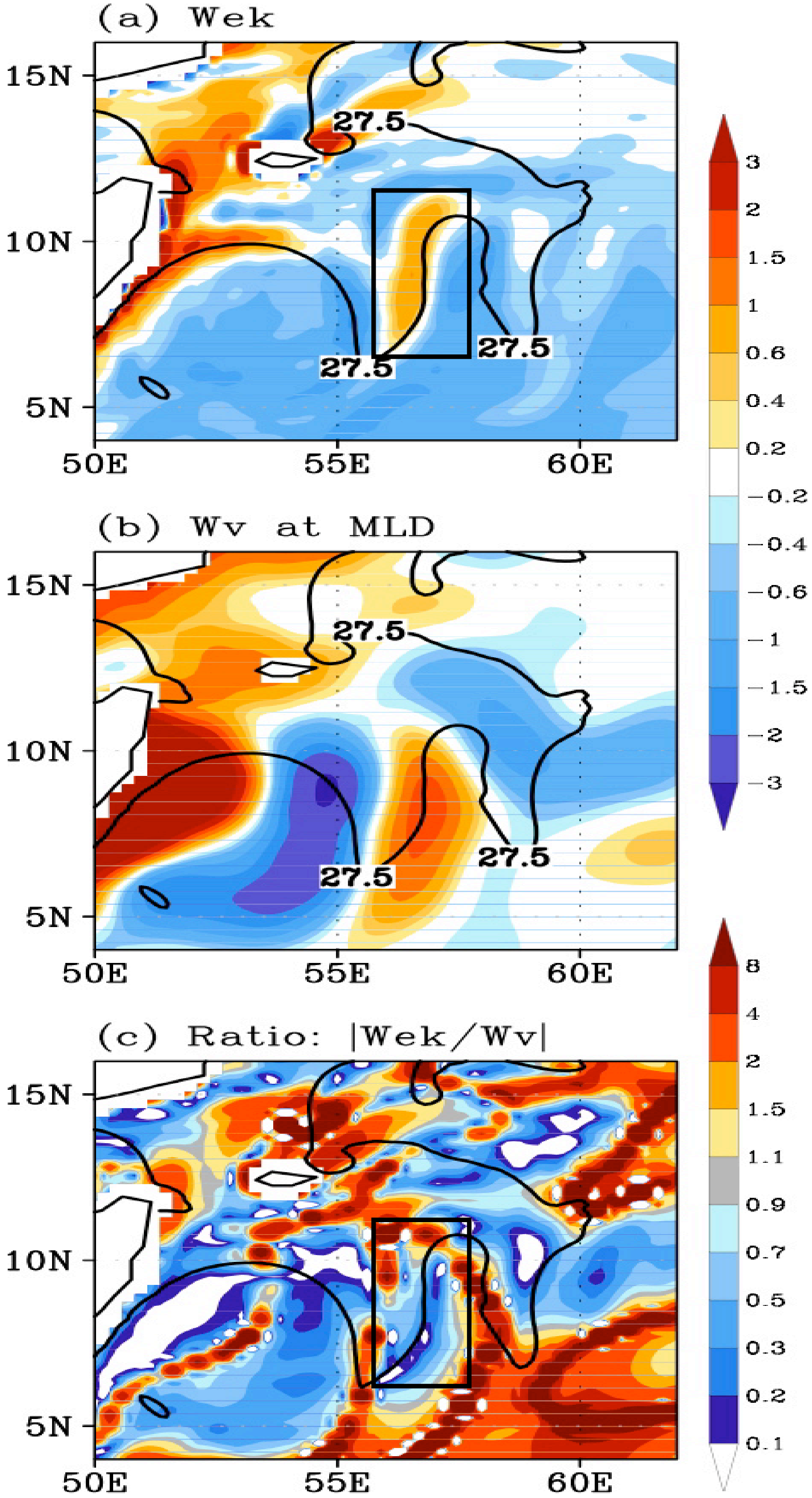


August 2002

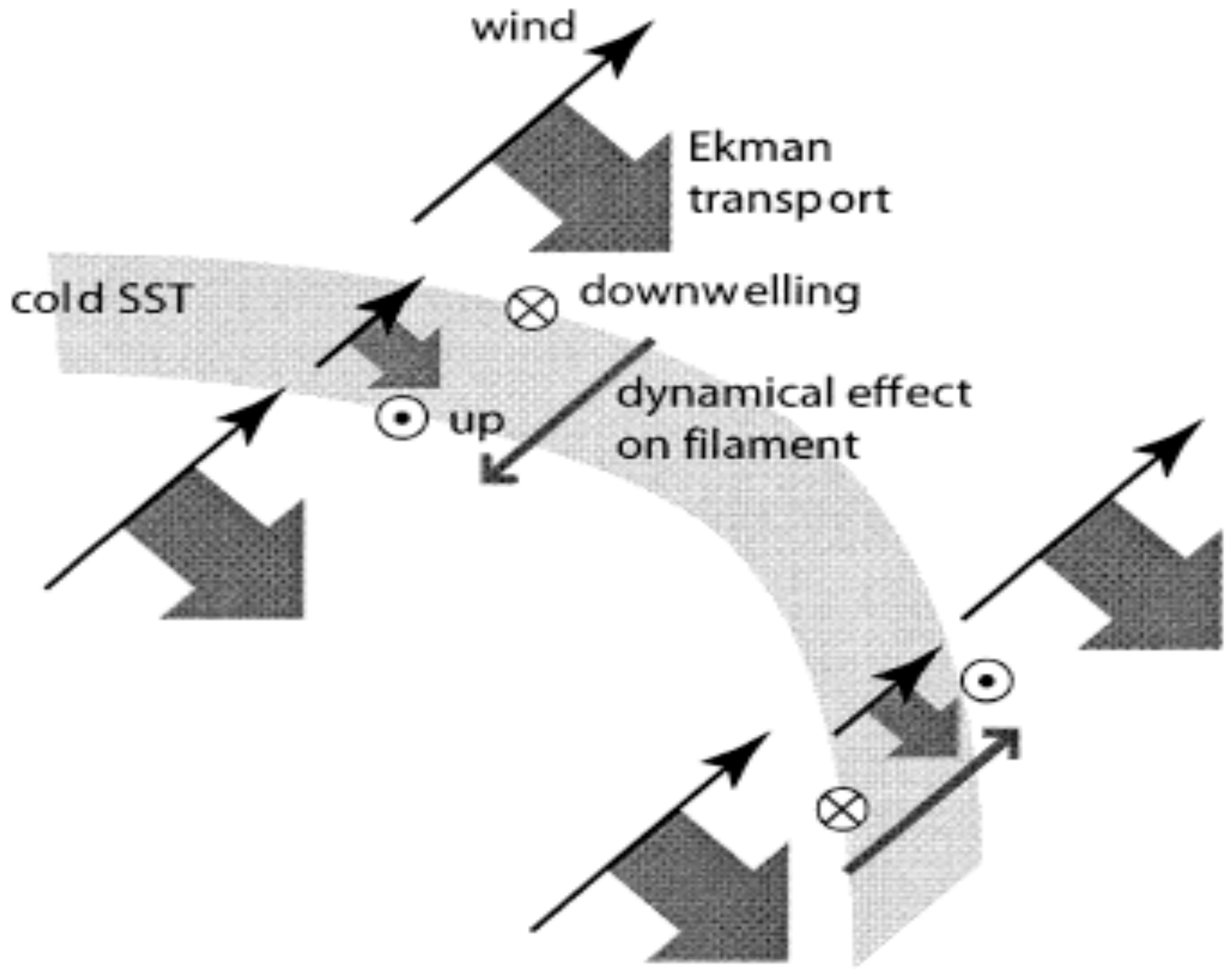
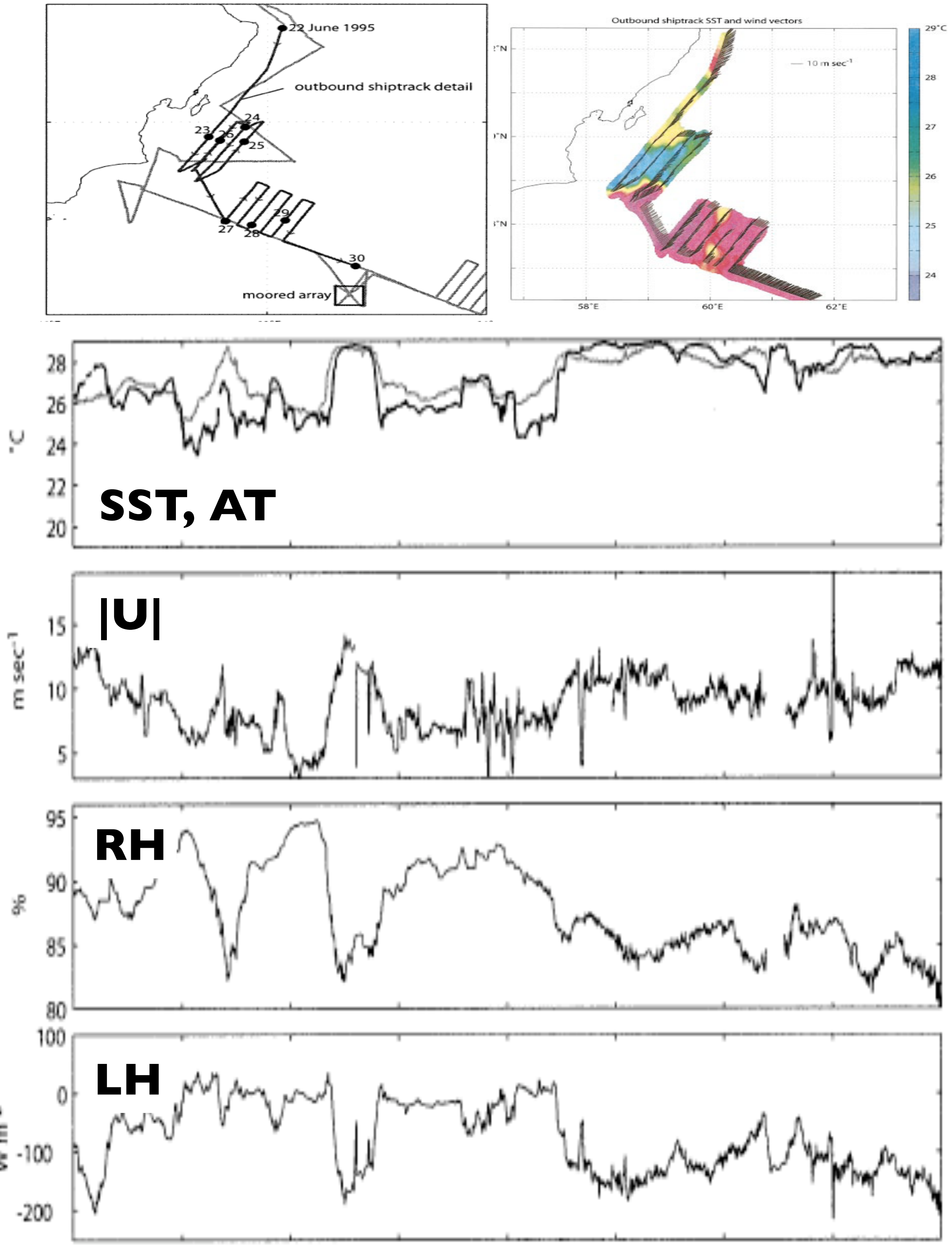


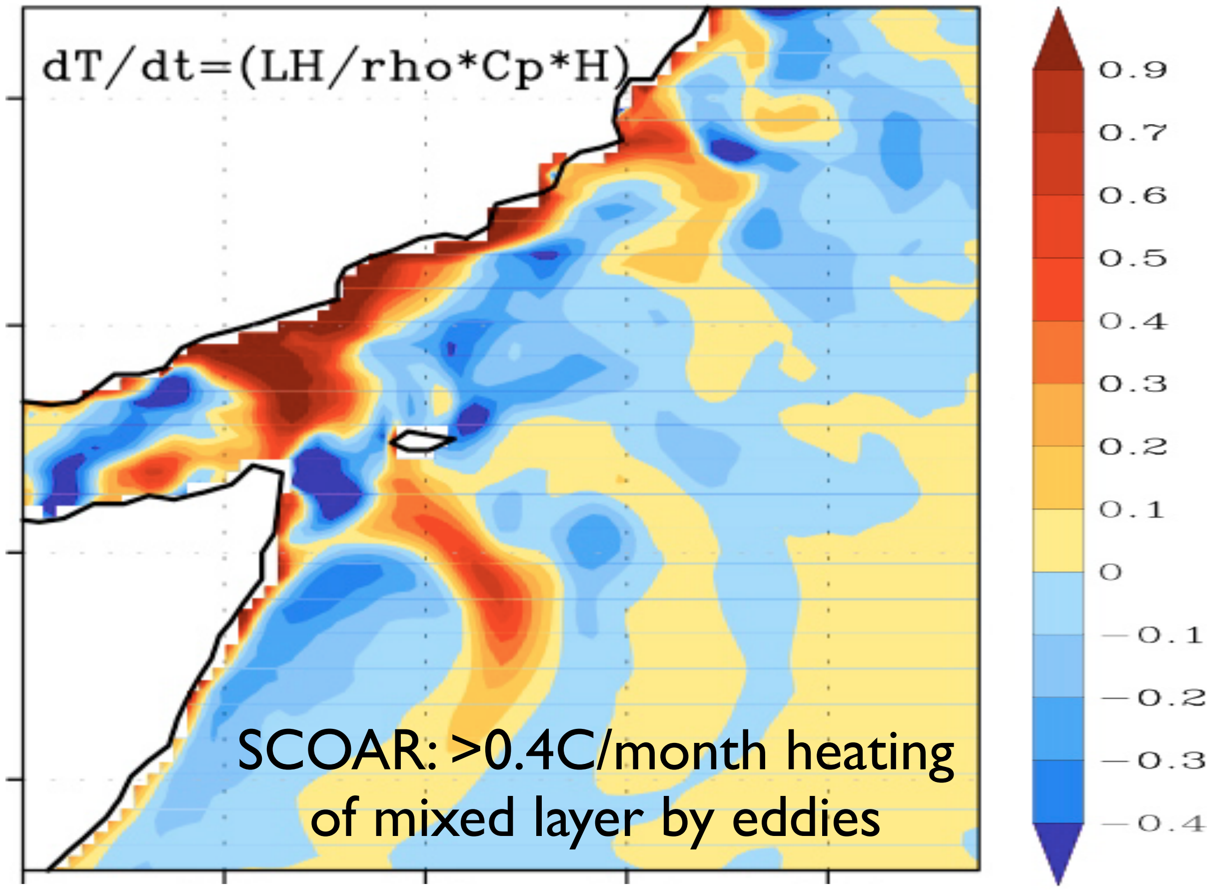
FIG. 9. Schematic of cold filaments and wind curl. Upwelling and downwelling Ekman pumping anomalies are dependent on the orientation of the filament to the mean wind direction.

- This will affect the evolution of cold filament and other oceanic mesoscale eddies (Vecchi et al . 2004)

Effect of mesoscale air-sea interaction on ocean heat balance



Cruise track of the R/V Thompson, Omani coast, Vecchi et al. 2004



SCOAR: >0.4C/month heating of mixed layer by eddies

- Response in surface heat flux to the mesoscale SSTs can affect the upper ocean heat budget (0.4-0.8°C/month)
- For a 12-yr mean, warming effect is roughly 0.1-0.2°C/month.

Conclusion

- 0.26° SCOAR model has been used to study the mesoscale air-sea interaction and feedback effect in the western Arabian Sea. (Seo et al. 2008, *Ocean Modelling*, **25,**120-131)

- ***Dynamic feedback***: In agreement with the satellite observations, additional Ekman velocity (1m/day) is induced in the vicinity of the cold wedges. The model results suggest that this additional Wek is comparable in magnitude to the total vertical velocity of the cold filaments.

➔ The observed mesoscale air-sea interaction could affect the vertical structure and evolution of the mesoscale eddy.

Conclusion (2)

- ***Thermodynamic feedback***: mesoscale eddies create additional latent heat into/out of the ocean (10-15 W/m^2). This additional surface heat flux warms (cools) the cold filament (warm eddy) at the rate of 0.3-0.4°C/month for a single season with strong eddy activity, and 0.1-0.2°C/month in a 12-yr mean.

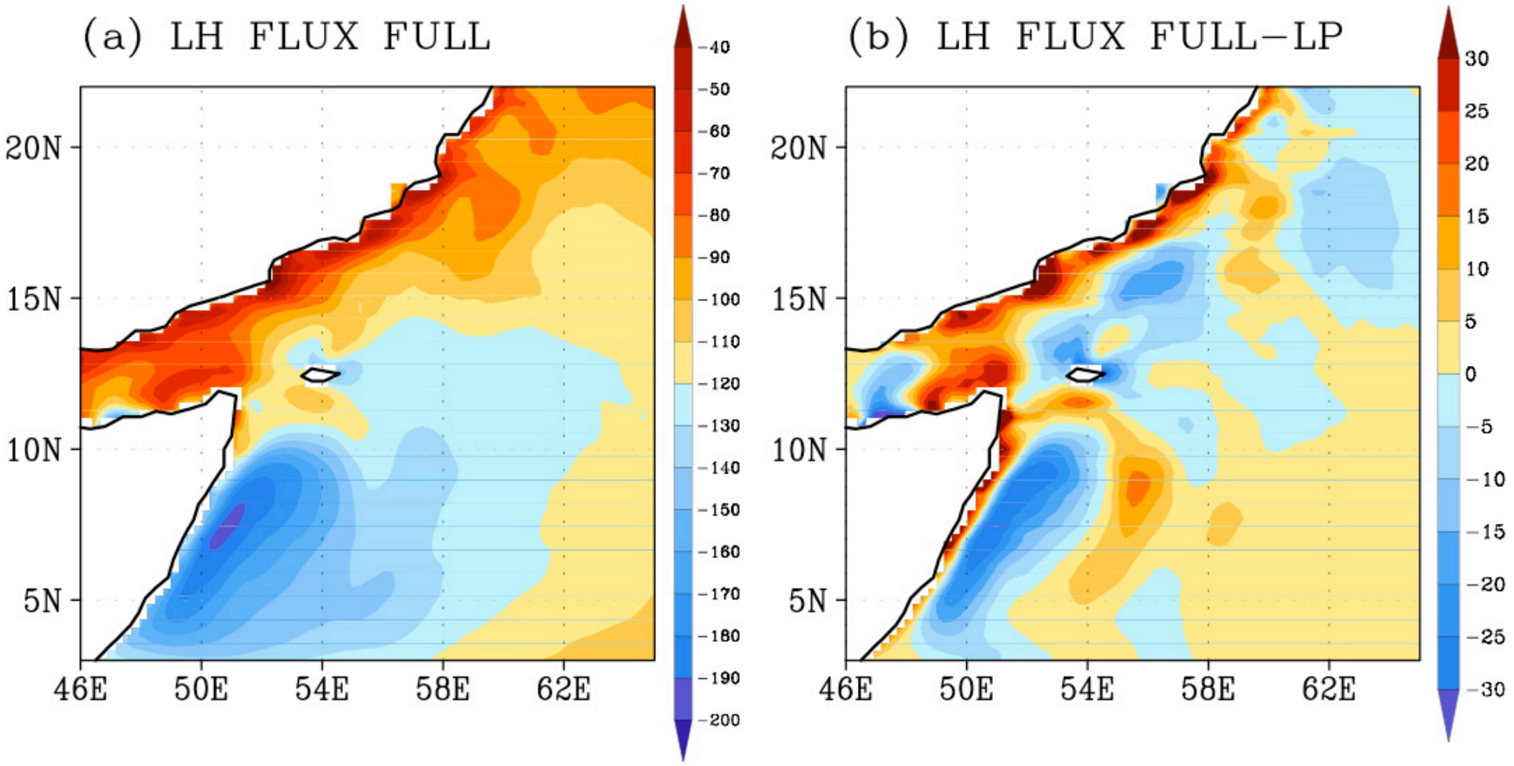
➔ How does this long-term oceanic heat gain by eddies rectify the low-frequency variability of the SST and the monsoon?

➔ How do we better assess the role of the thermodynamic feedback to the ocean and its long-term influence on the SST?

Any long-term effects of latent heat flux on the SST?

Thanks!

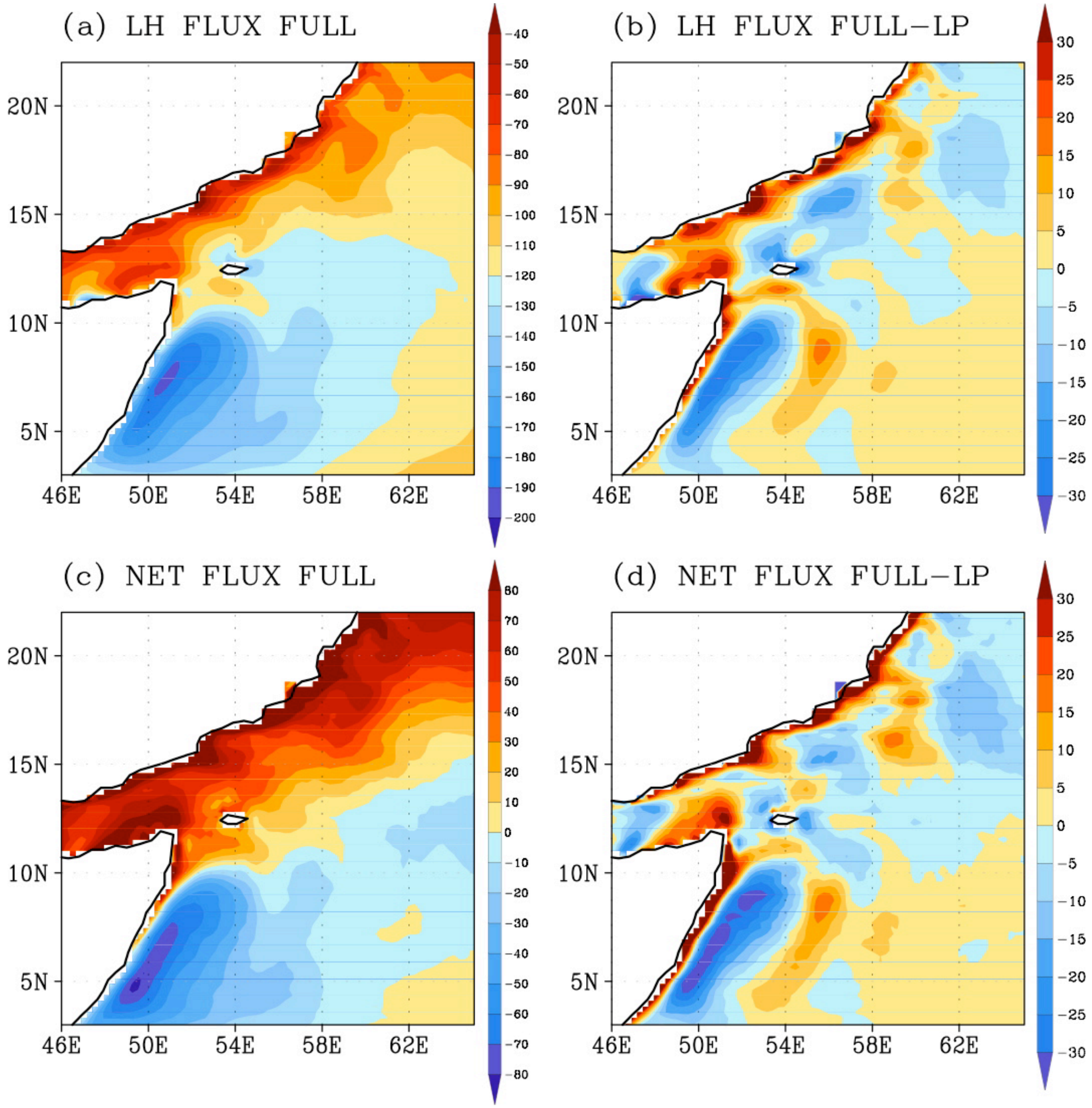
Latent heat flux induced by mesoscale eddies



- $LH=\rho LC_HU(q_a-q_s)$
- Difference map (full field minus spatially averaged field) represents the additional LH flux input to the ocean: 10-15W/m^2 for a 12-yr mean.
- Difference map of total heat flux fields is similar to that of LH ➔ LH flux variability is the dominant factor in the net heat flux fields.

JJAS 1995-2006

Latent heat flux induced by mesoscale eddies



JJAS 1995-2006

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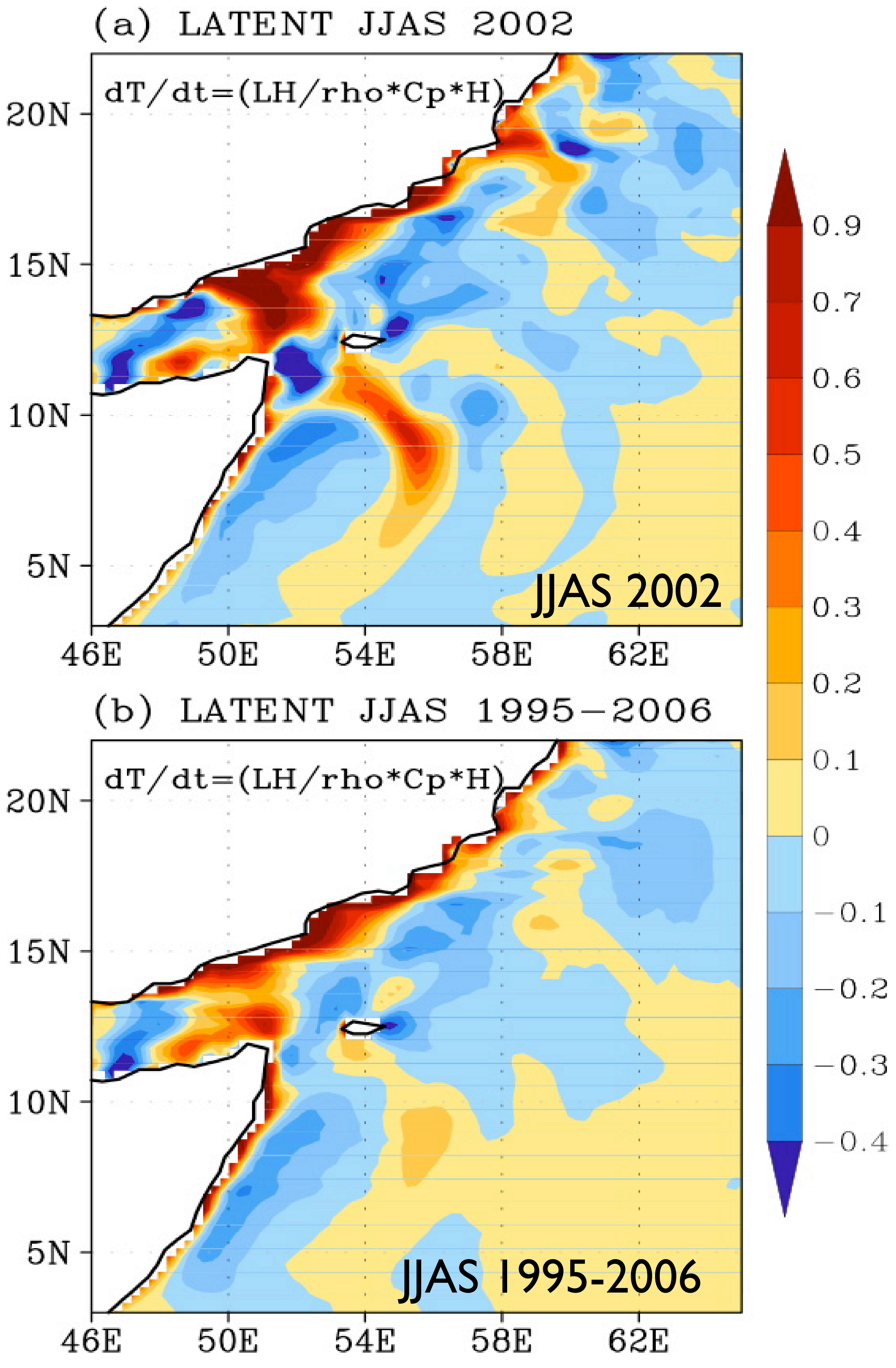
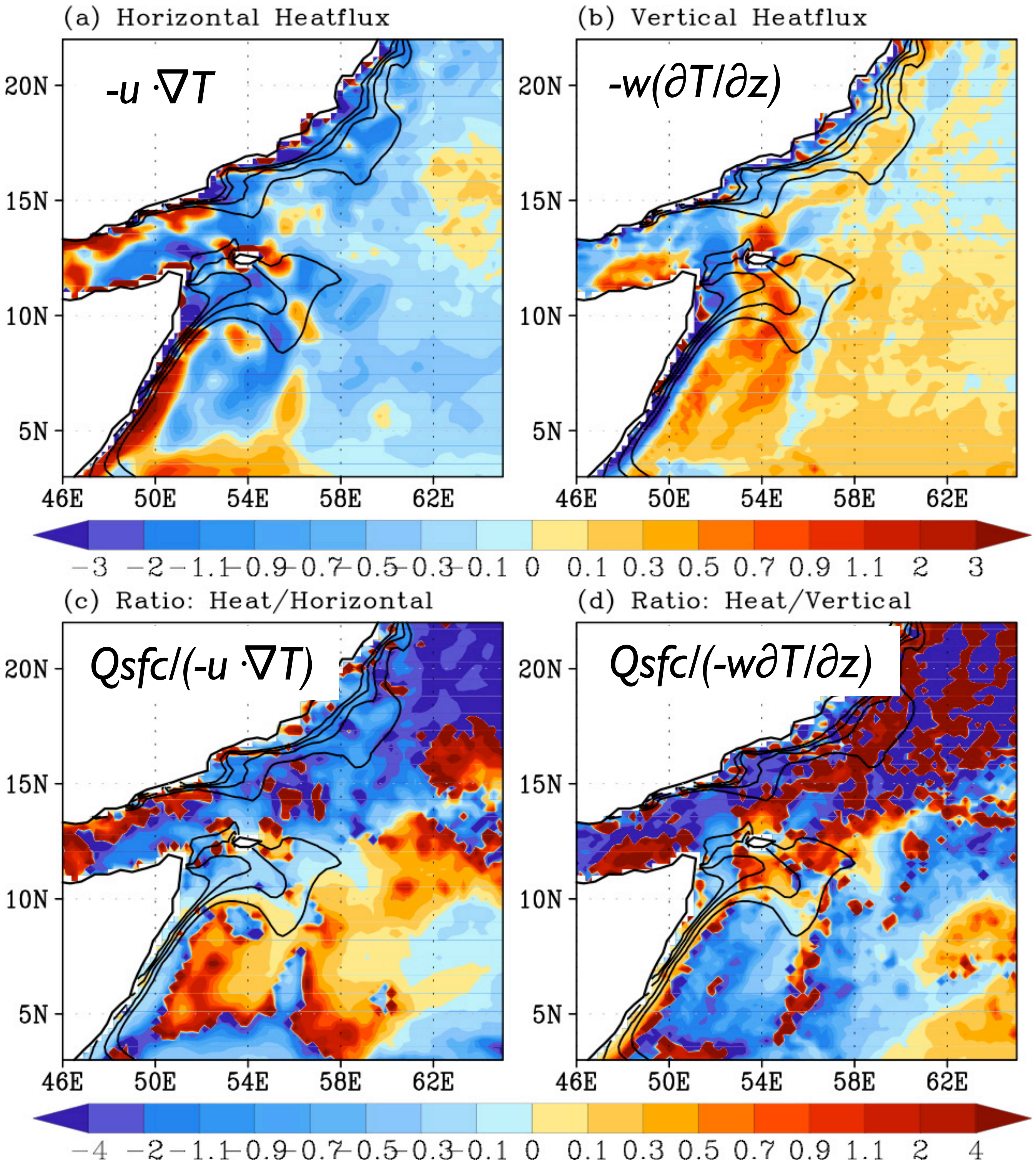


One-dimensional balance

- $\partial T/\partial t=\Delta LH/\rho C_p H$ (Full minus Lowpassed)
- With the shoaled mixed layer (H), the additional heat flux can warm mixed layer > 0.4°C/month for a single year of strong eddy activity (JJAS 2002). (The RMS of SST this season was 0.4-0.8°C.)
- For a 12-yr mean, warming effect is roughly 0.1-0.2°C/month.
- Oceanic heat gain: How does this additional heat rectify the low-frequency variability of SST and monsoon?

Comparison with horizontal and vertical heat flux of the ocean

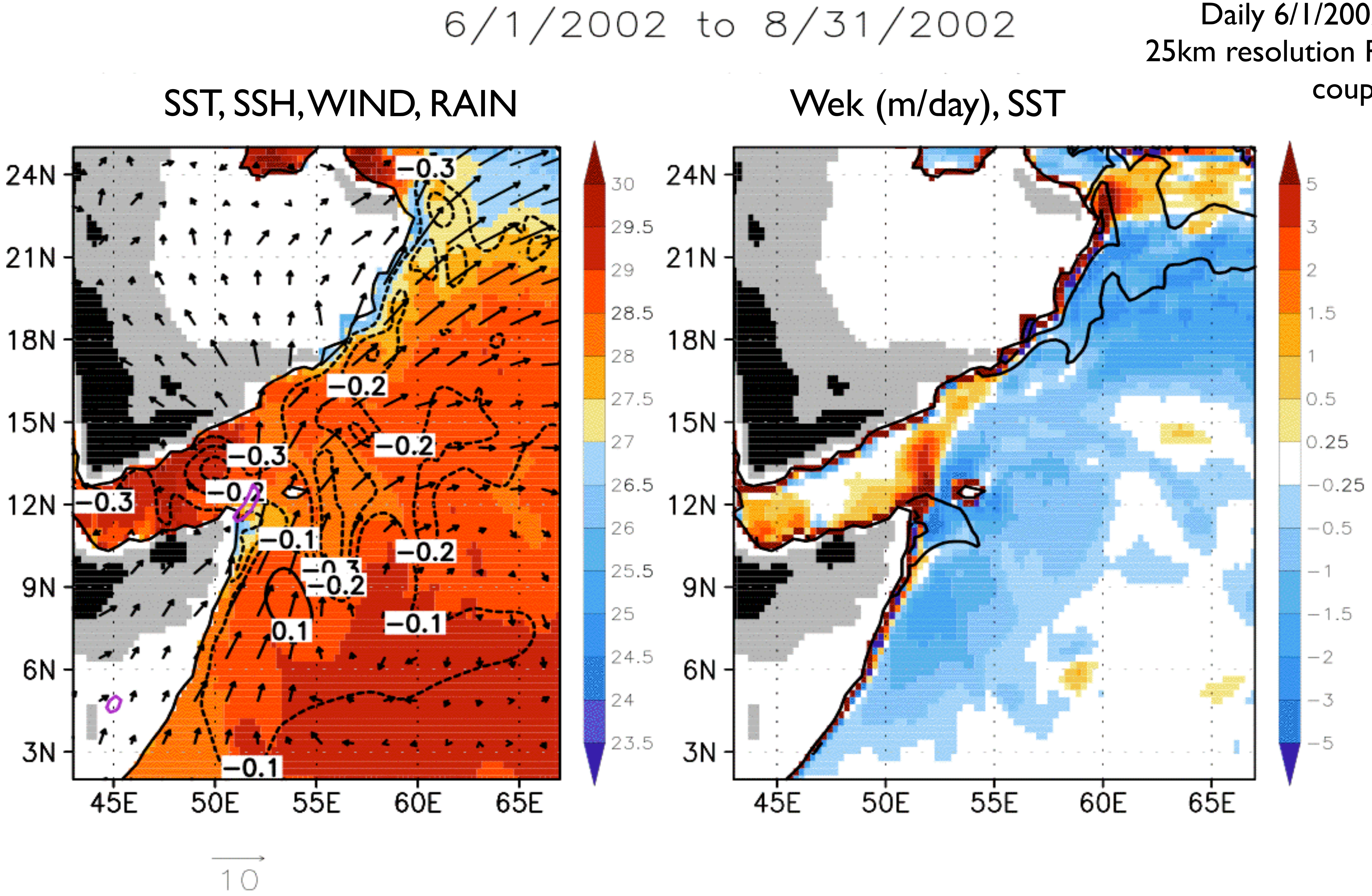


JJAS 1995-2006

Each term is averaged over the mixed layer depth

- Mean $-u \cdot \nabla T$ is a strong cooling effect over most of the coastal region (2-3°C/month).
- $-w\partial T/\partial z$ is a warming effect underneath the Great Whirl and cooling the filament.
- Dominance of lateral heat flux is well documented and the ratio of $Qsfc/(-u \cdot \nabla T)$ is generally small.
- Surface heating $(Q/\rho C_p H)$ can be comparable to $-w\partial T/\partial z$ in the region of the GW and cold filaments (localized large ratio).

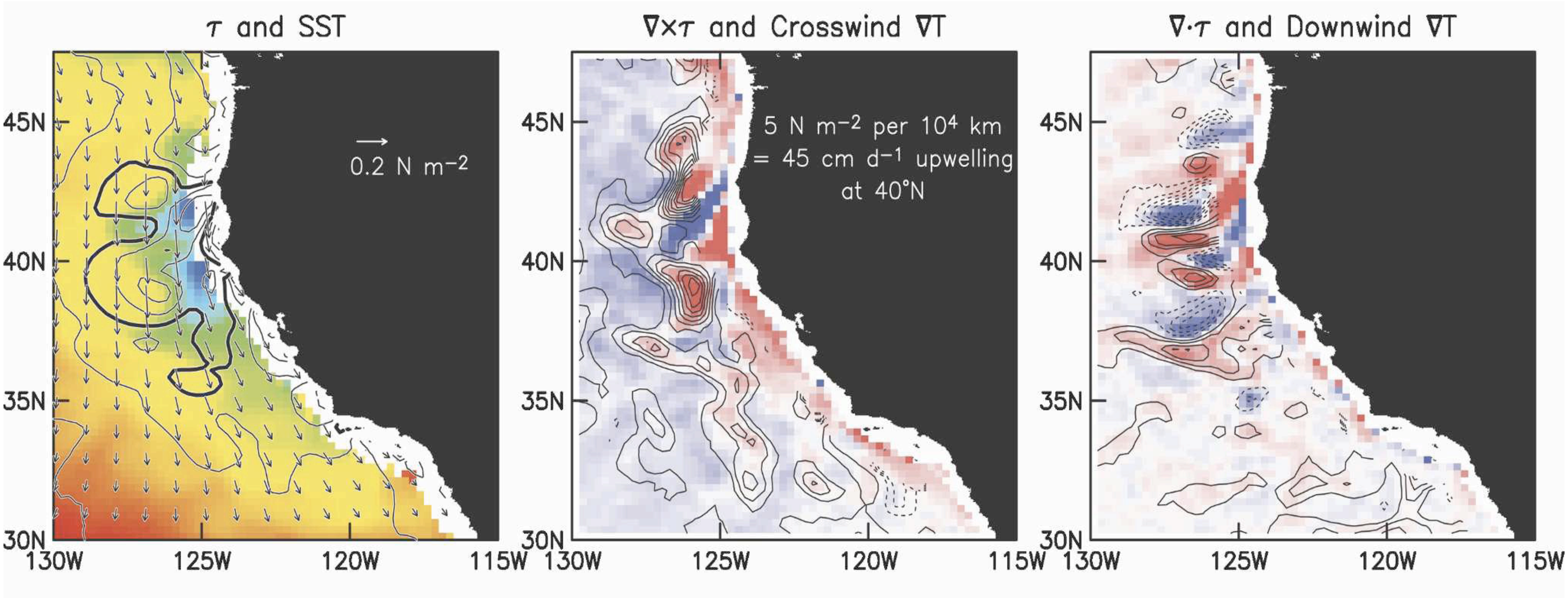
Influence of SST filaments on Ekman pumping velocity



Daily 6/1/2002-8/31/2002
25km resolution RSM/ROMS daily coupled

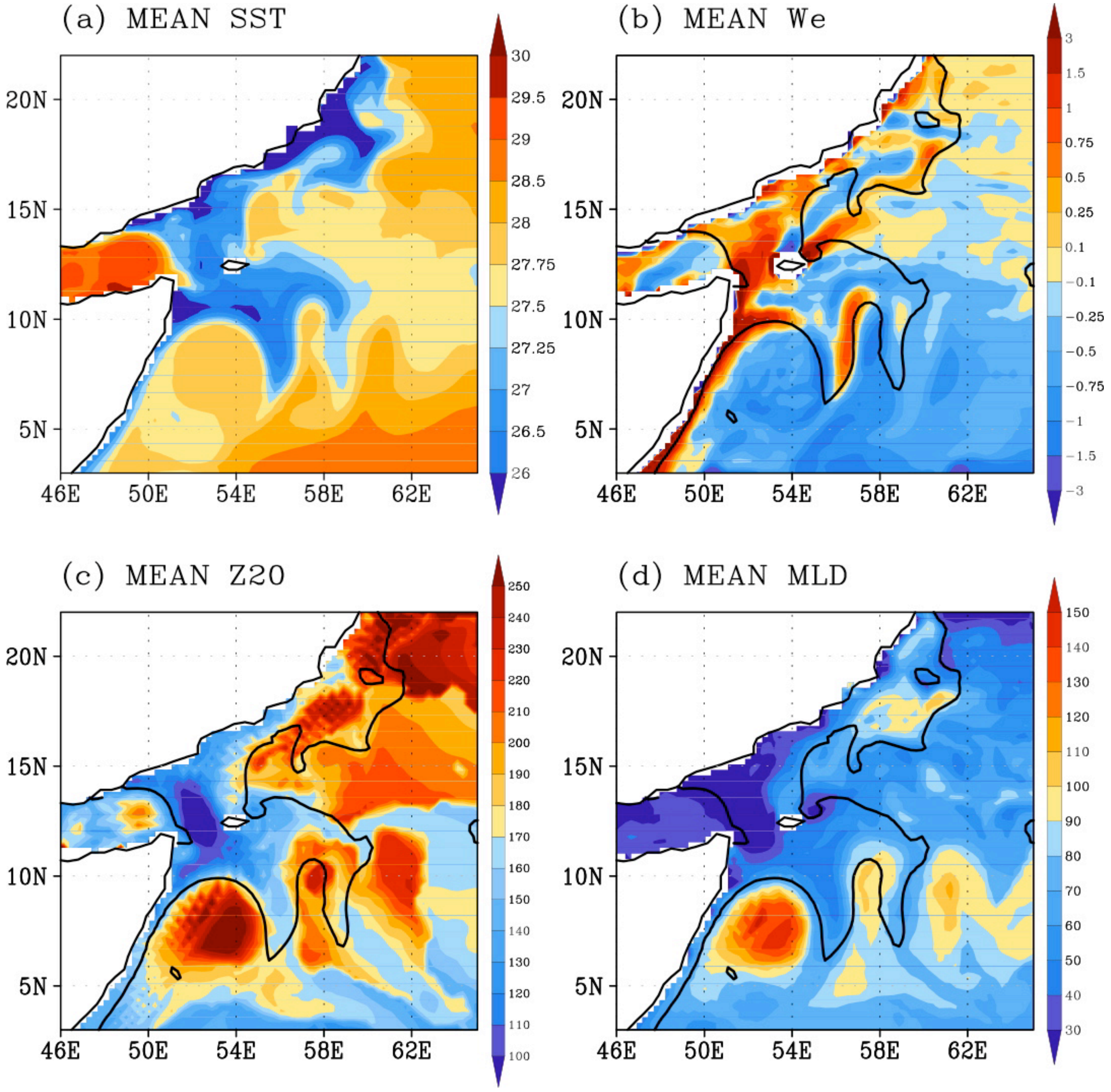
- The coupled model captures key aspects of the observed oceanic influence on surface wind stress: the maximum Wek (curl) where winds blow along the isotherms.

California Current System (Chelton et al. 2007)



- Correspondence of wind stress curl to the SST gradients is the evidence of oceanic influence on the atmosphere through mesoscale o-a coupling. The implied upwelling velocity is ~0.45 m/day at 40°N.
- This indicates a potentially significant dynamic feedback effect to the ocean, which in turn changes SST.

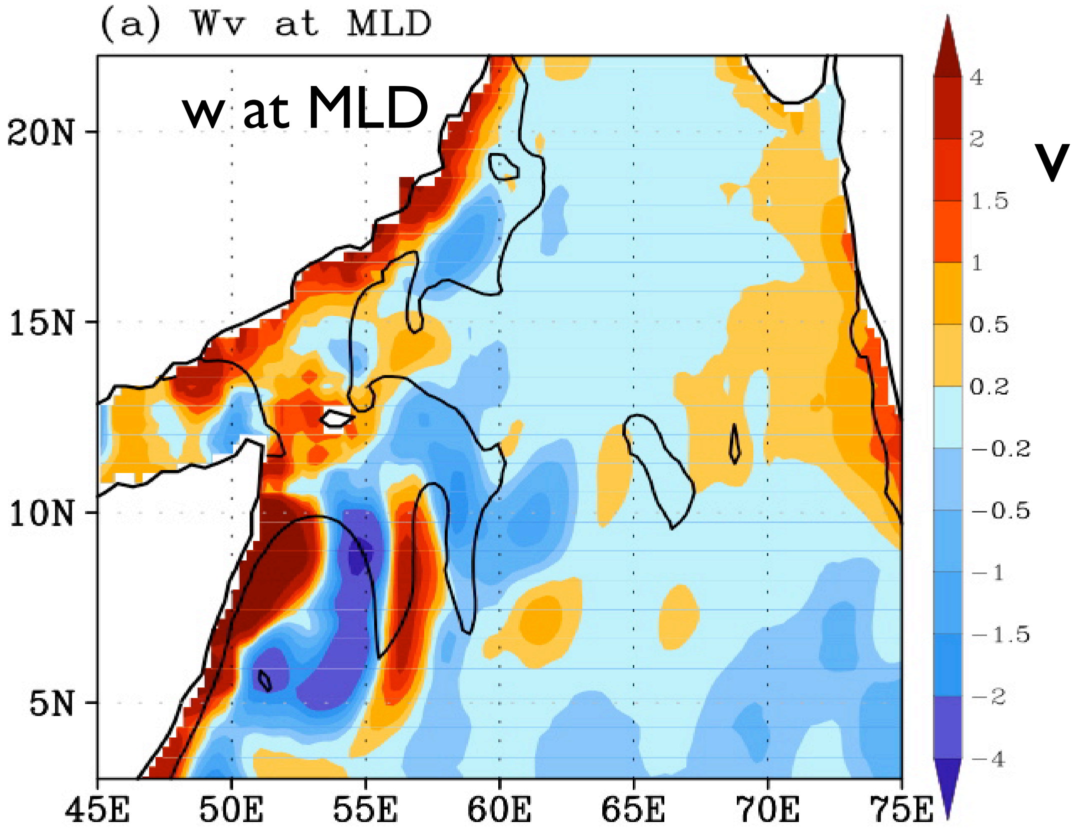
Ekman pumping velocity and thermocline depth



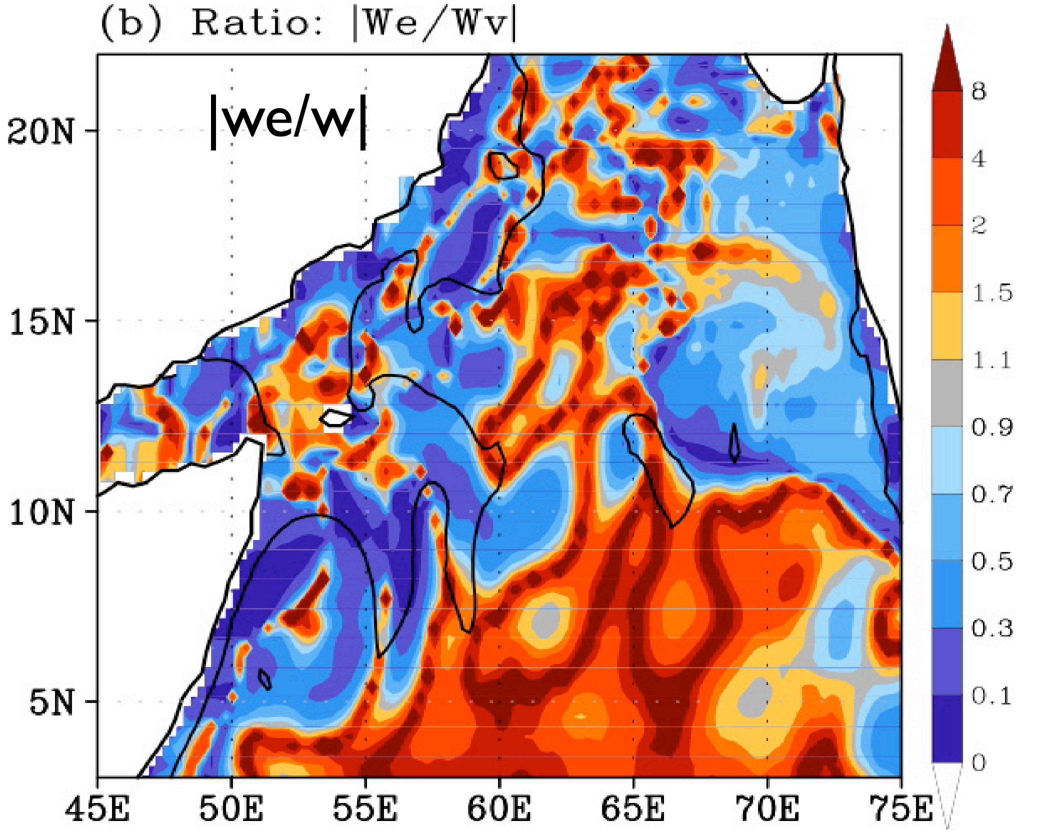
August 2002

- The narrow band of Ekman upwelling & downwelling velocities reaches 2 m/day, occurring sufficiently far away from the coast, concentrated along the cold wedge.
- This feature persists over a month following the evolution of SST filament.
- Mean thermocline depth (mixed layer depth) underneath the cold filament is about 150m (70m).
- This implies that the imposed small-scale Ekman pumping velocities alter the oceanic vertical structure (Vecchi et al. 2004).

Direct comparison of *we* with the oceanic vertical velocity (*w* at the base of mixed layer)



(a) Wv at MLD

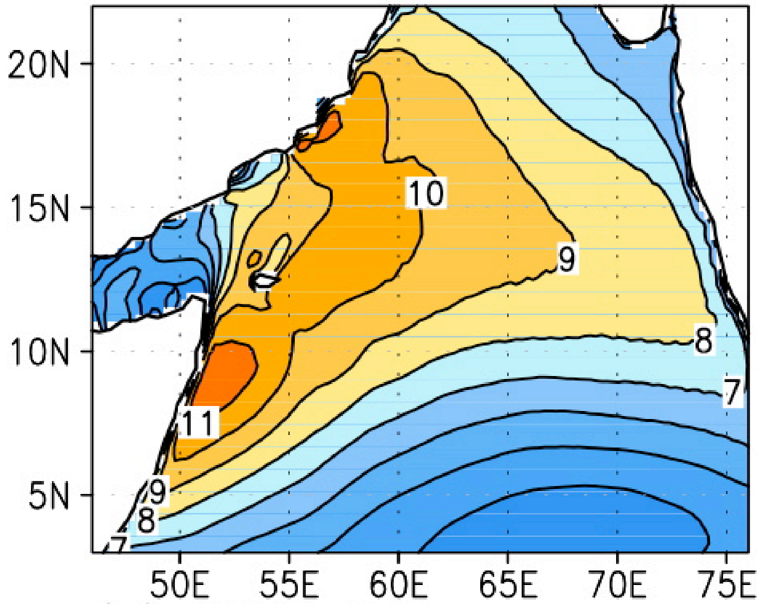


(b) Ratio: |We/Wv|

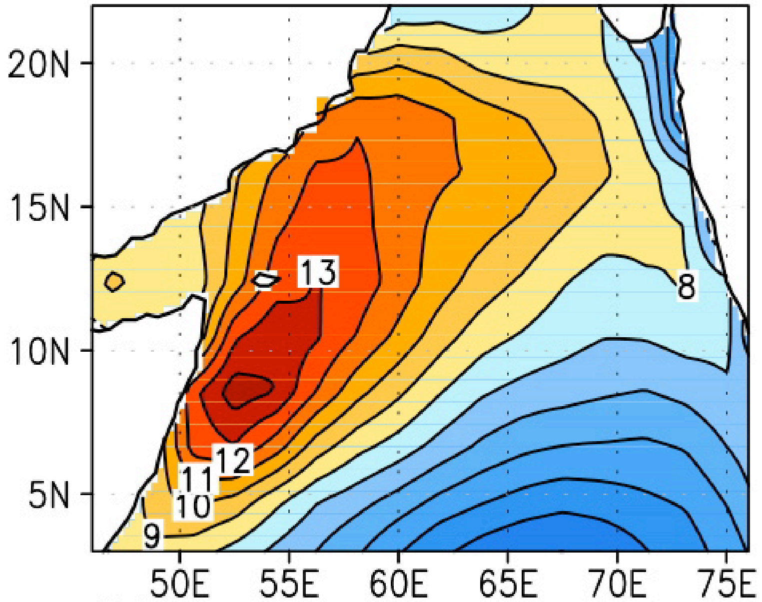
August 2002

- w is >>±4 m/day in the vicinity of cold filaments but generally small in the open ocean
- This is maybe due to the submesoscale process discussed in Mahadevan et al. 2008.
- The ratio is largely 10-30% near the cold filaments ➔ Oceanic mesoscale eddies induce additional we through the observed relation.
- In the some part of the open ocean, the ratio is generally large (>>1) ➔ Oceanic w is small and large-scale Ekman forcing dominates.

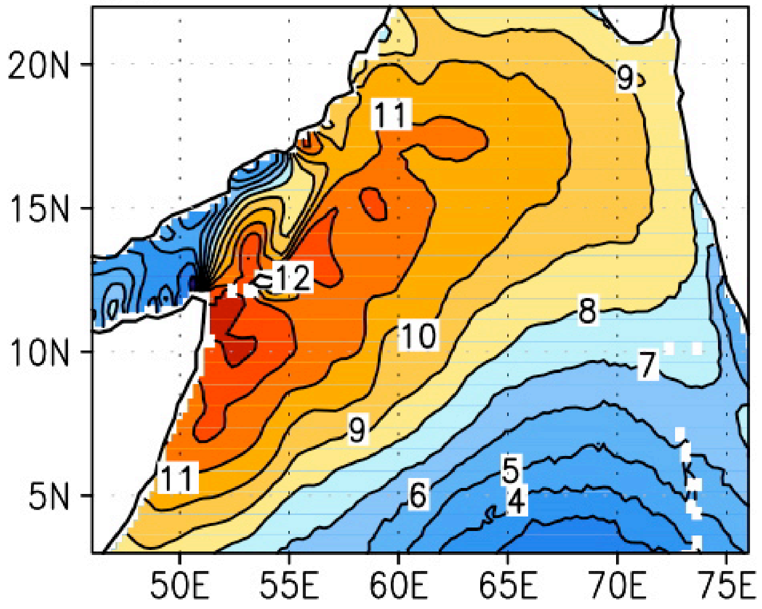
(a) Model



(b) NCEP RA2



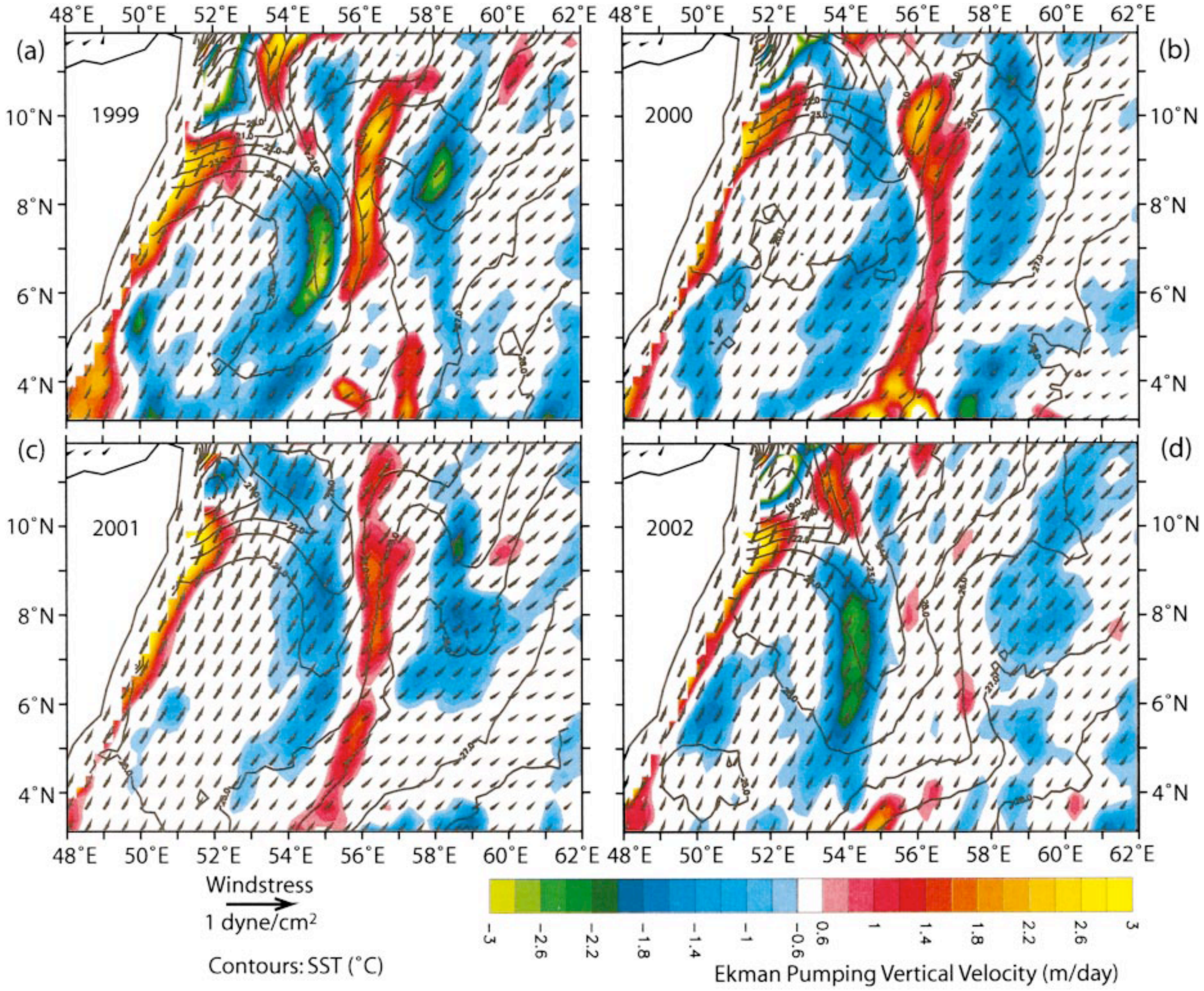
(c) QuikSCAT



August 10-m wind speed climatology

- Despite RSM’s spectral nudging (of waves longer than 1000 km, Kanamaru and Kanamitsu, 2007), SW monsoon flow is too weak in the model.
- ➔ Excessive warm bias in the Arabian sea

Generation of Ekman pumping velocity due to oceanic influence on the wind



- An important finding of their study: the generation of Ekman up/down-welling velocity of 2-3 m/day over cold filaments (through varying winds: Chelton et al. 2001).
- This *we* is *additional* to the large-scale Ekman pumping.
- This *we* persists over a month following SST.
- Main question: how important is this *we* for the oceanic vertical structure and velocity?

Covariability of SST, wind stress divergence and curl

Daily 6/1/2002-8/31/2002

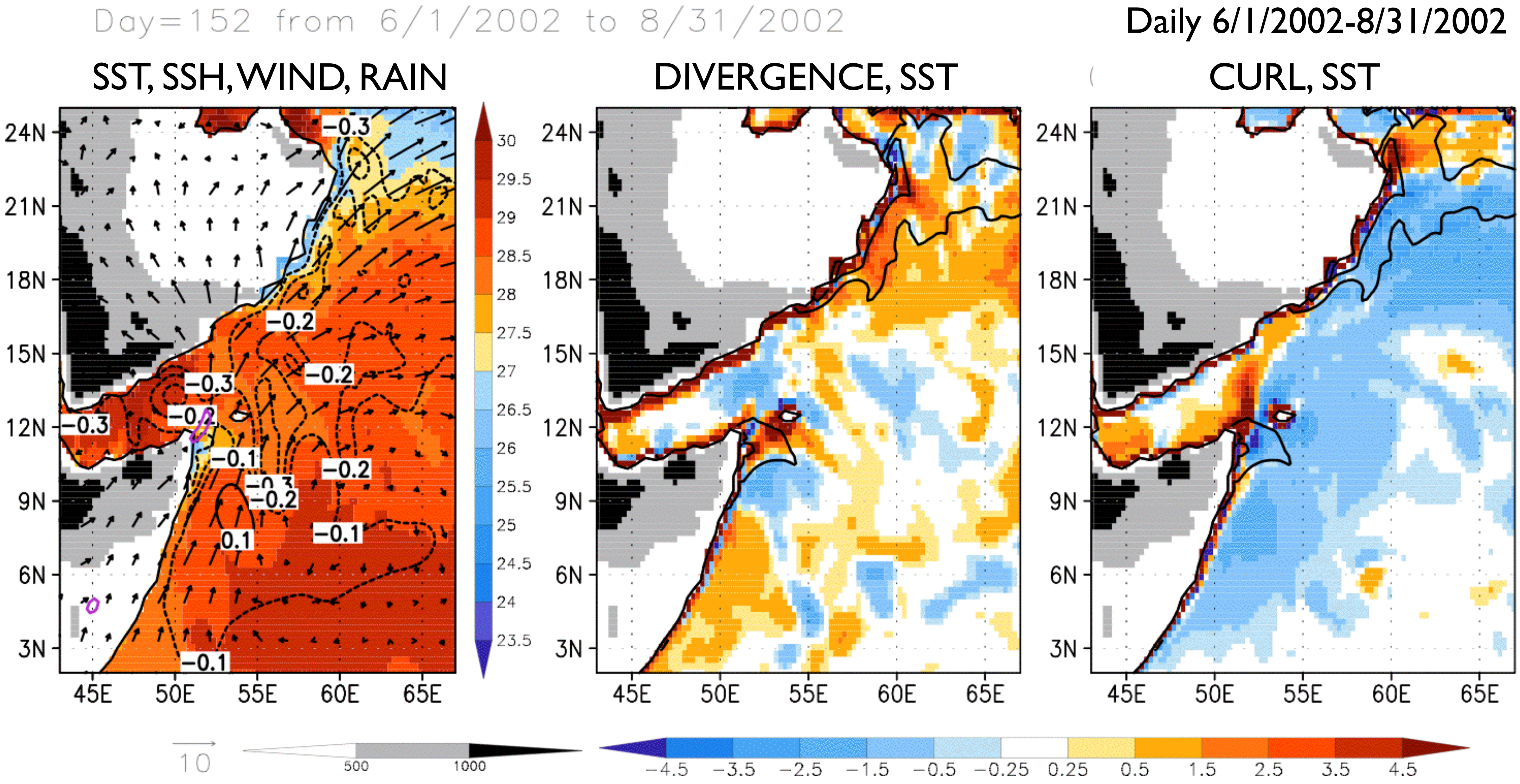
SST, SSH, WIND, RAIN

DIVERGENCE, SST

CURL, SST

- The coupled model captures key aspects of the observed oceanic influence on surface wind stress: the maximum divergence (curl) where winds blow across (along) the isotherms.

Covariability of SST, wind stress divergence and curl



Day=152 from 6/1/2002 to 8/31/2002

Daily 6/1/2002-8/31/2002

SST, SSH, WIND, RAIN

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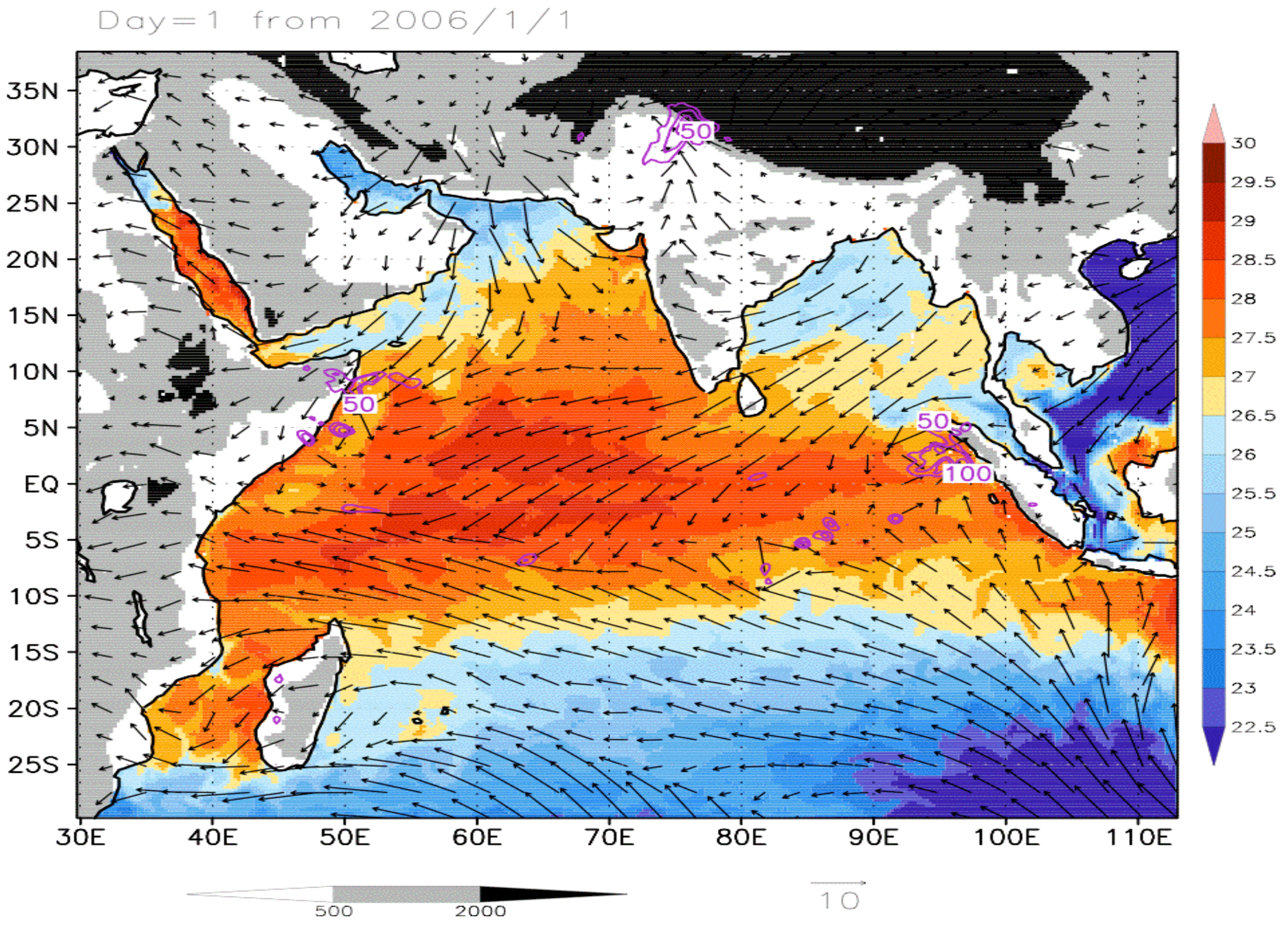
Model domain and daily animation of 2006 (1/1-12/31)

- Identical 0.26° horizontal resolution
- 322*282*28* (20)
- Daily coupling
- 1993-2006
- OBC: East and South with monthly WOA05 T/S climatology
- No river runoff

1. Air-sea interaction and monsoon variability
2. Intra-seasonal o-a interaction and MJO and ITF.
3. Bay of Bengal salinity and SST
4. Tropical cyclones in the SWIO and BoB

* color shade: SST (22.5-30C)
* black arrow: 10m winds
* purple contours: rainfall
(50,100,200 mm/day)

Model domain and daily animation of 2006 (1/1-12/31)



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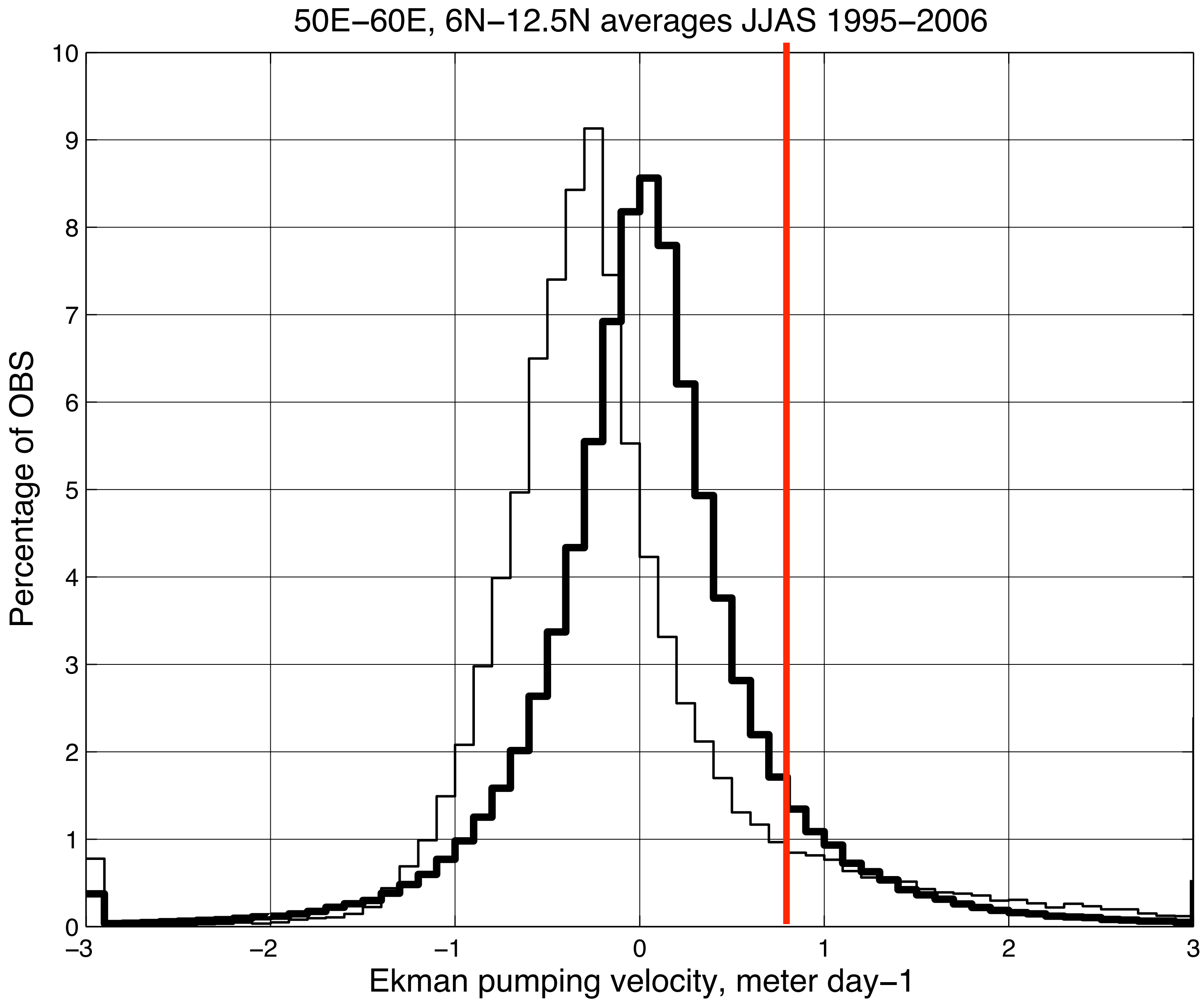
- Daily coupling
- 1993-2006
- OBC: East and South with monthly WOA05 T/S climatology
- No river runoff

1. Air-sea interaction and monsoon variability
2. Intra-seasonal o-a interaction and MJO and ITF.
3. Bay of Bengal salinity and SST
4. Tropical cyclones in the SWIO and BoB

* color shade: SST (22.5-30C)
* black arrow: 10m winds
* purple contours: rainfall (50,100,200 mm/day)

How does Ekman pumping velocity due to the mesoscale eddy compare with that due to the large-scale mean wind?



JJAS 1995-2006

Similar analysis by O'Neill et al. (2003) and Chelton et al. (2005).

- PDFs of we (thin line) computed from summertime mean wind stresses, and (thick line) computed from anomalous wind stresses exhibit a comparable dynamic ranges.
- The RMS value of *we'* is 0.8 m/day. Approximately 10% of the mean we exceeds this RMS value
- Greater than 18% of the *we'* (both positive and negative) is larger than this RMS value.
- *we'* could be as important as mean we.