Regional coupled-downscaling of climate and weather

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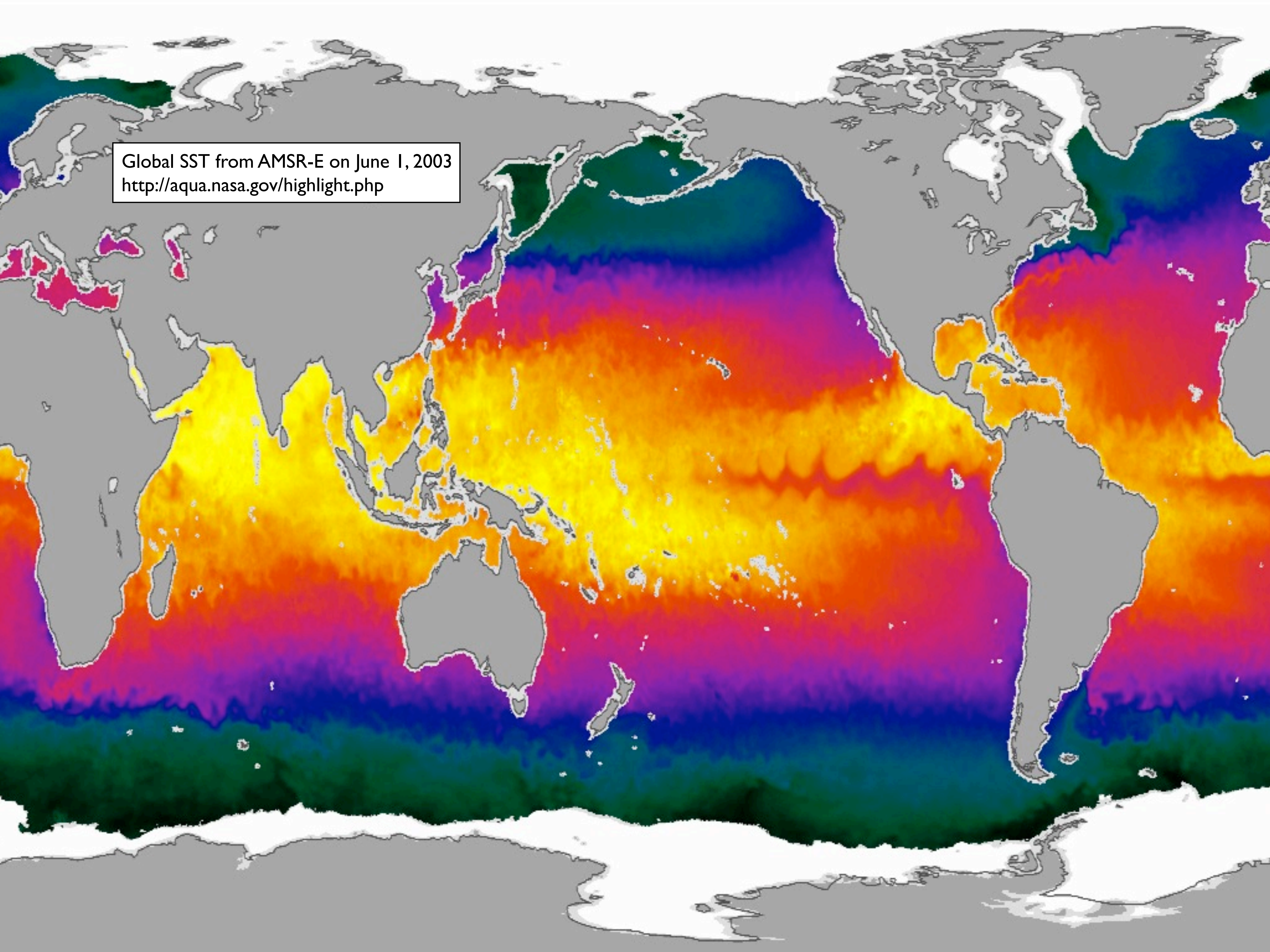
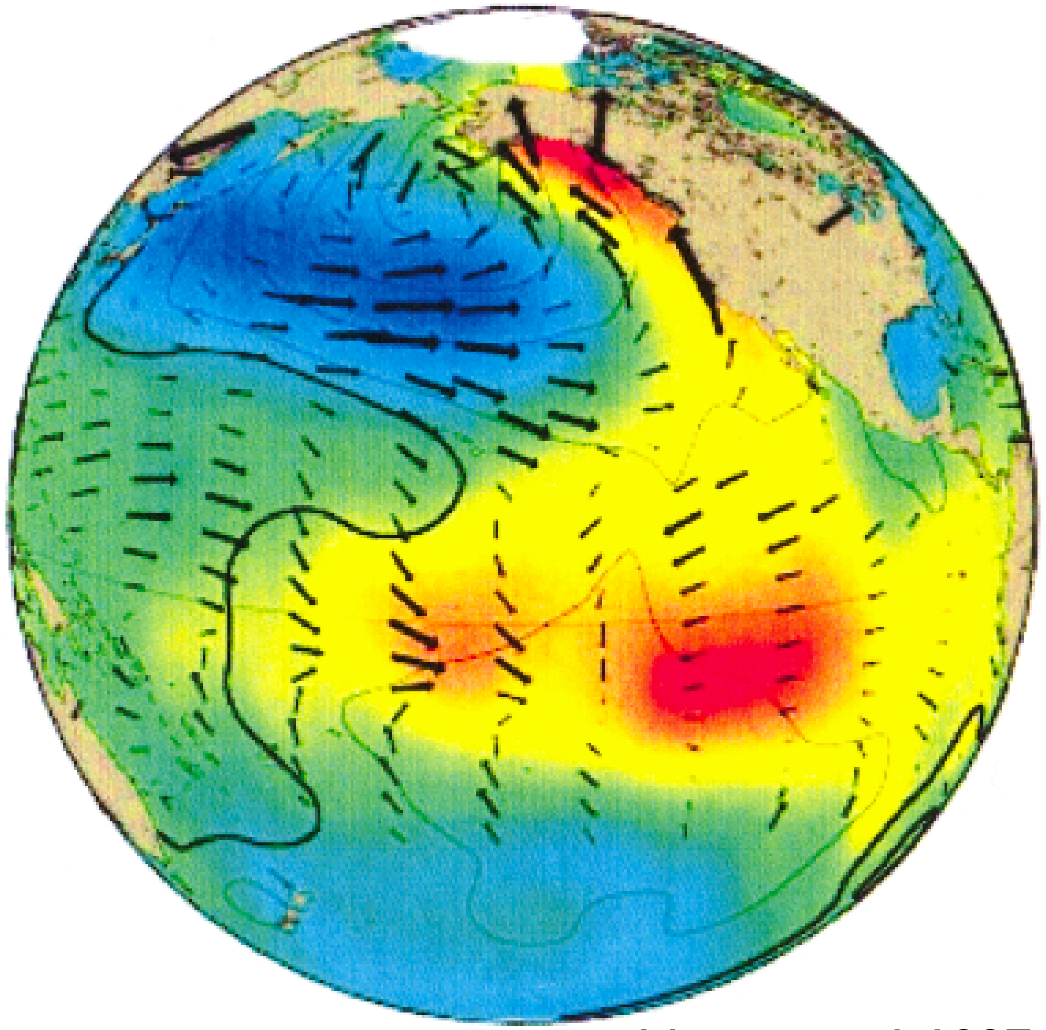
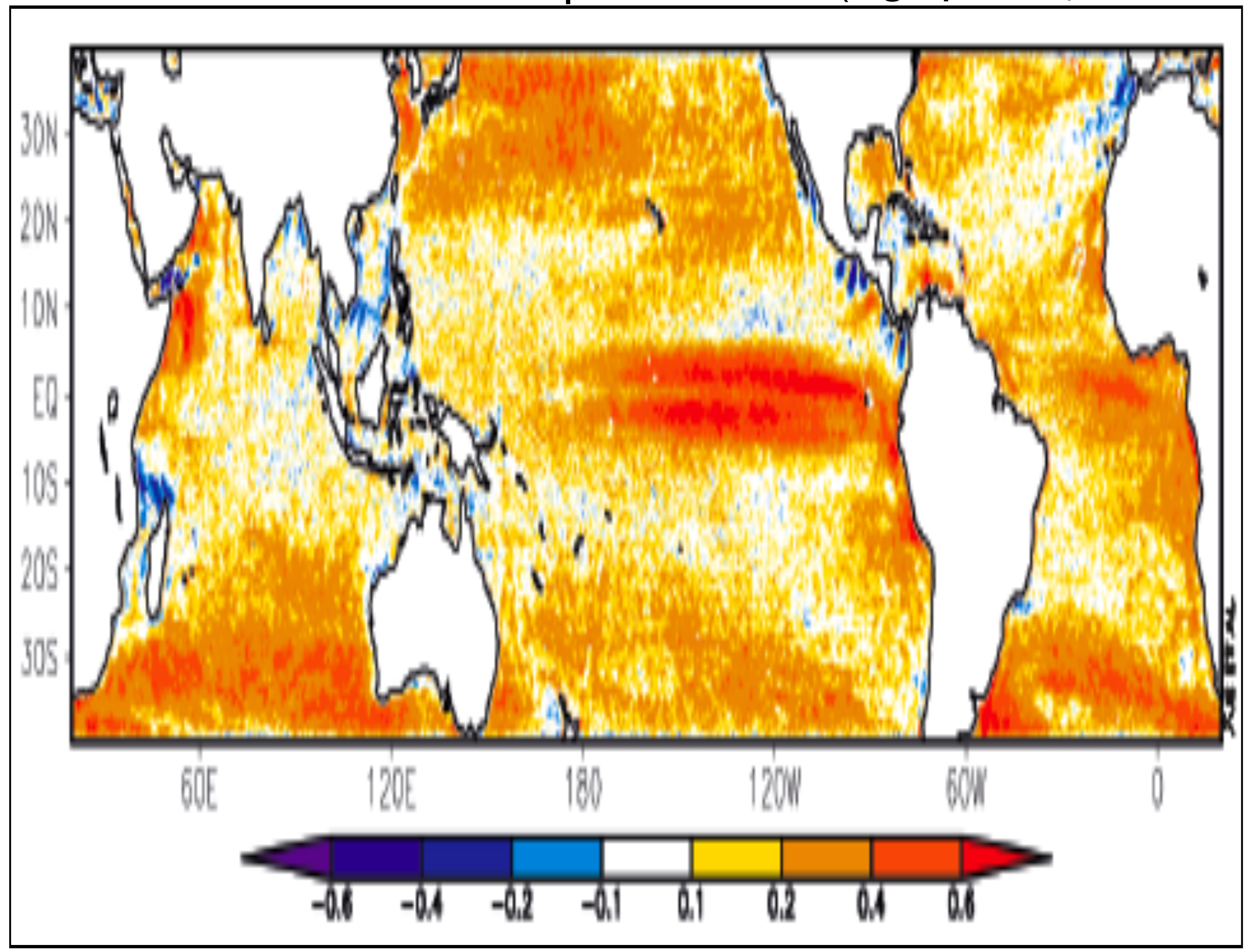

Global SST from AMSR-E on June 1, 2003
http://aqua.nasa.gov/highlight.php

Air-sea interaction on basin-scale and ocean mesoscale



Matuna et al. 1997

Corr. Coef. of wind speed and SST (high-passed)



Xie et al. 2004

- SST, Wind, SLP regressed onto the Pacific Decadal Oscillation Index
- Negative correlation of wind and SST: Atmosphere forcing the ocean

- Positive correlation (Ocean ➔ Atmosphere)
- Negative correlation (Atmosphere ➔ Ocean)
- Lack of coherent atmospheric response.
- Models need to capture fully-coupled process.

Coupled process on ocean mesoscale and regional climate

- I use a regional coupled model as a primary research tool to study

1. Mesoscale O-A interaction and feedback to coupled system
    - Tropical Instability Waves
    - Coastal upwelling and filaments in California Current System and Arabian Sea

2. Regional processes on large-scale climate variability
    - Synoptic African Easterly Waves and the marine ITCZ
    - Barrier layer in Bay of Bengal and Indian Monsoon
    - Mesoscale feedback in the KOE region

Current research questions and outline of today's talk

- I am improving model and coupled downscaling technique to address additional and unique research questions;

  - *Climate*: CGCMs used for climate projections do not adequately capture important oceanic features on the equator; eg., Eq. currents and TIWs.
    - Their participation in shaping ocean warming pattern is left unexplored in the literatures.

    ✓ Can we use a regional coupled downscaling to examine response/impact of such processes in a changing climate?
    - Goal: Assess change in equatorial ocean and TIWs under global warming in the tropical Atlantic sector

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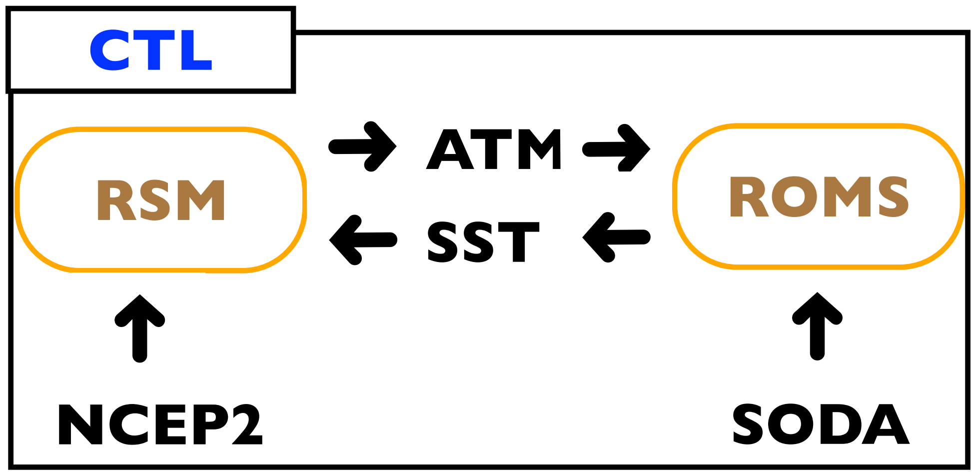
  - *Weather*: A-GCMs now produce stronger storms by increasing resolutions or embedding a regional model.
    - ✓ How important is the oceanic feedback (on more relevant spatial scale) to storm intensities (cold wakes and ocean mesoscale eddies)?
    - Goal: Quantify impact of ocean state on rapid intensification of Hurricane Katrina (2005)

1. *Equatorial* Atlantic Ocean’s response to global warming forcing

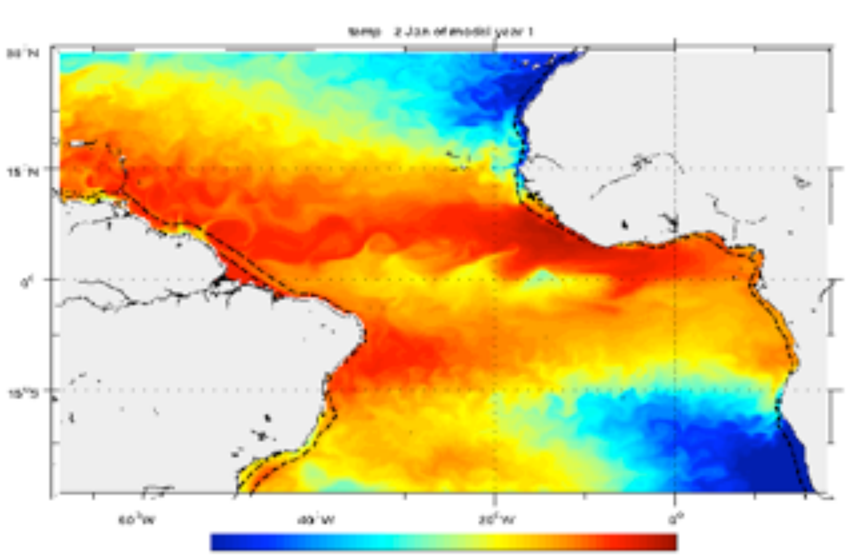
Model and experiments

Scripps Coupled Ocean-Atmosphere Regional Model (Seo, Miller and Roads, 2007, *J. Climate*)



SODA (Simple Ocean Data Assimilation reanalysis:) 0.5X0.5,monthly

- **CTL**: RSM (NCEP2 6hrly) + ROMS (SODA monthly)
- 25 km ROMS + 50 km RSM
- Daily coupling based on Fairall et al. (1994)
- 28-yr. integration: 1980-2007
- CO2=348 PPM



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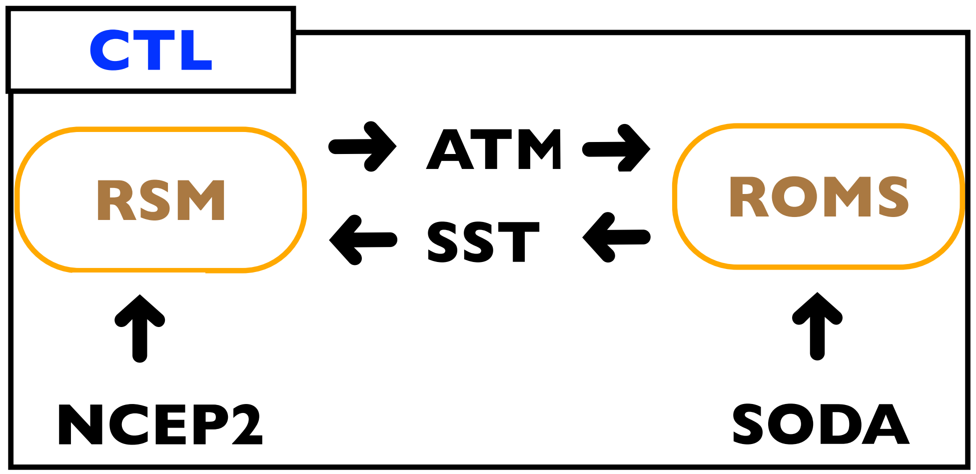

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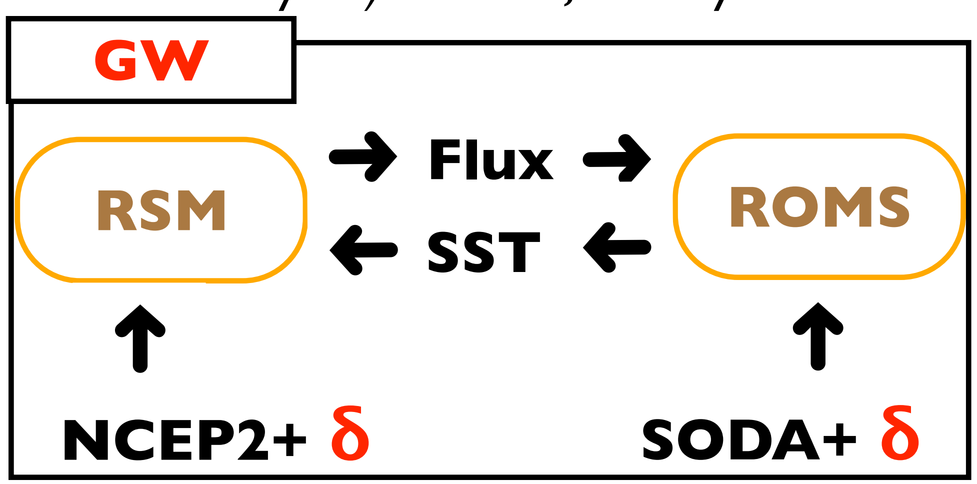
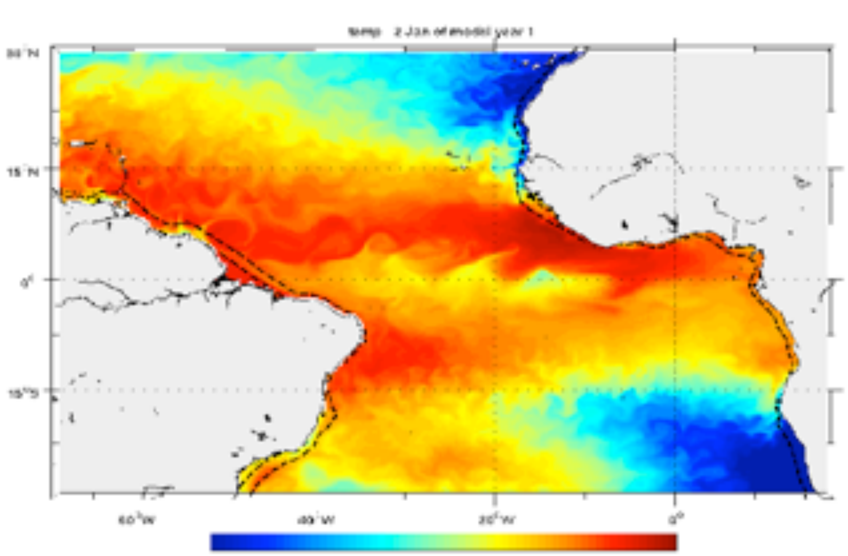


- δ=GFDL CM2.1 monthly difference: (2045-2050: A1B)-(1996-2000: 20C); 10-member ensemble mean
- **GW**: RSM (NCEP2 6-hrly+δ) + ROMS (SODA monthly+δ)
- CO_2=521.75 PPM; CH_4 and N_2O fixed to present-day values



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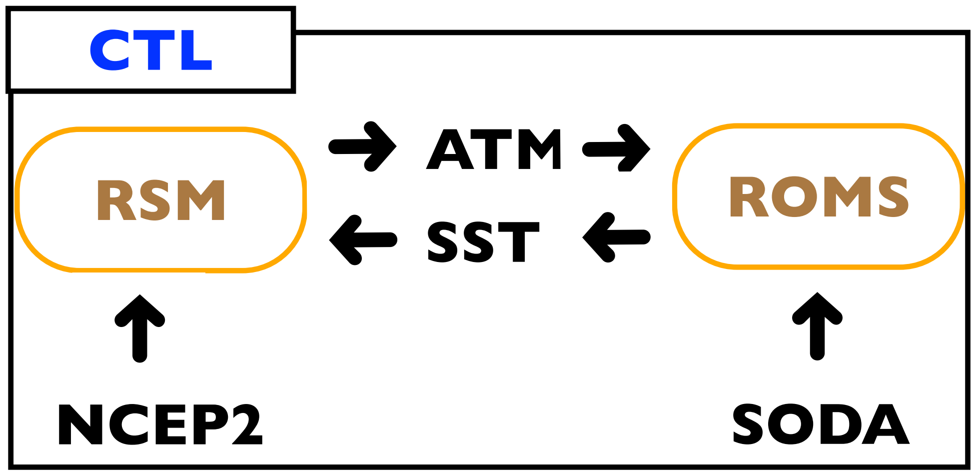

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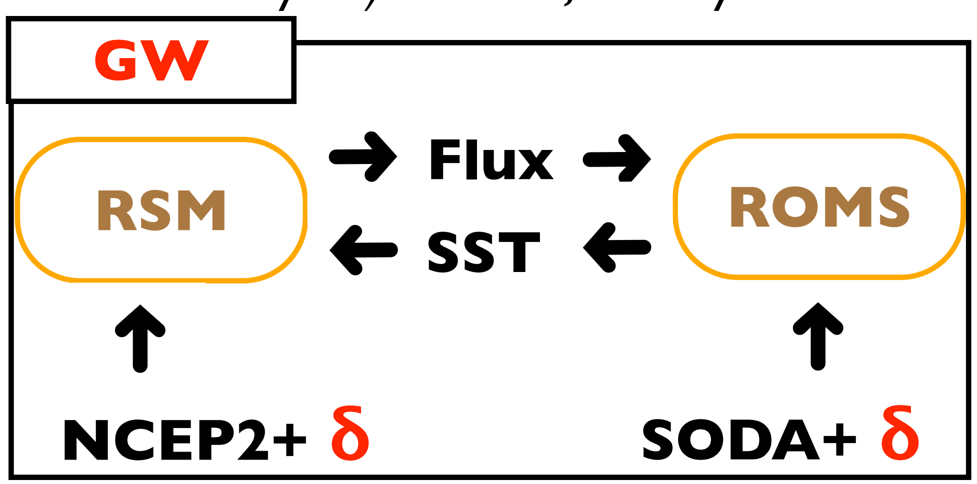

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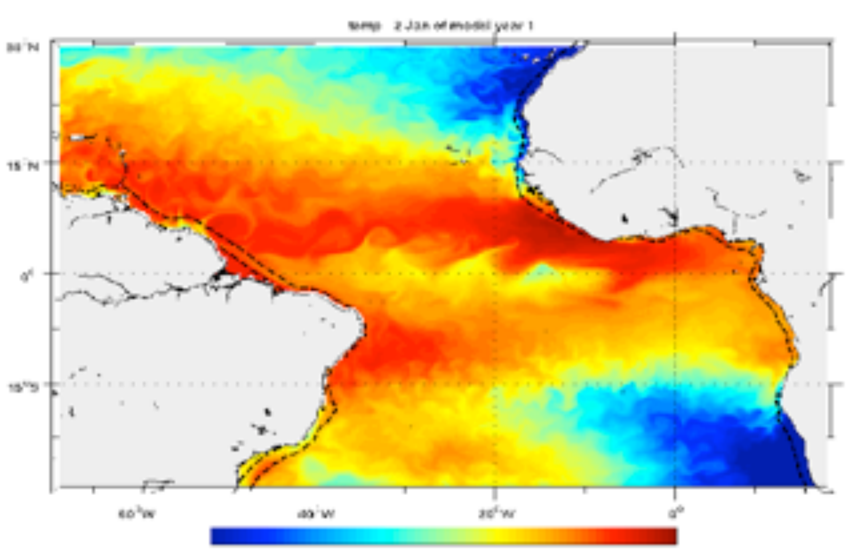
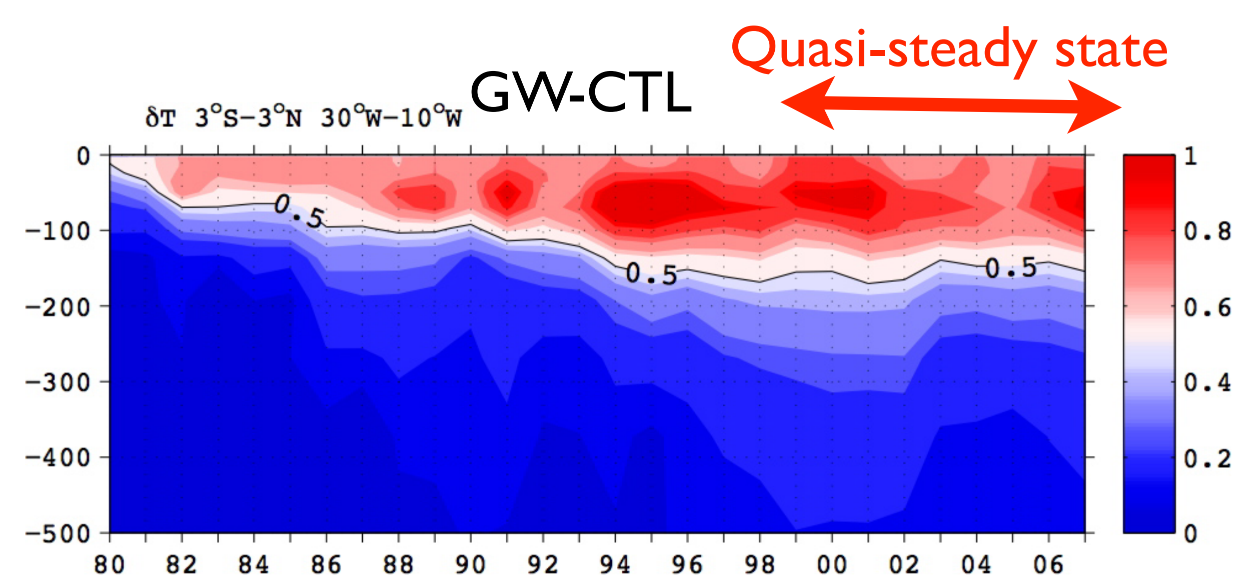
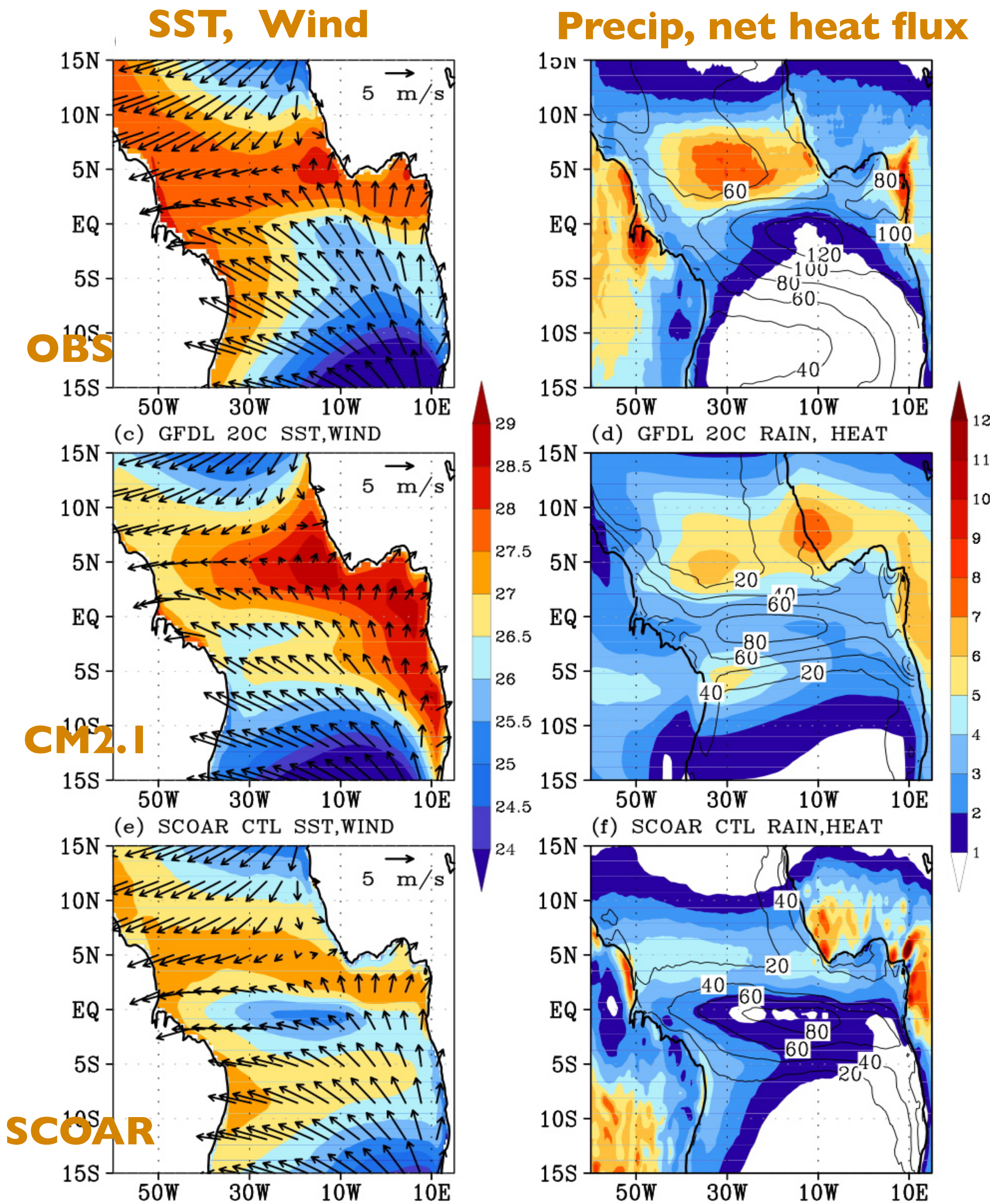




Simulation of present-day climate



- Improved zonal SST gradient and equatorial cold tongue via downscaling.

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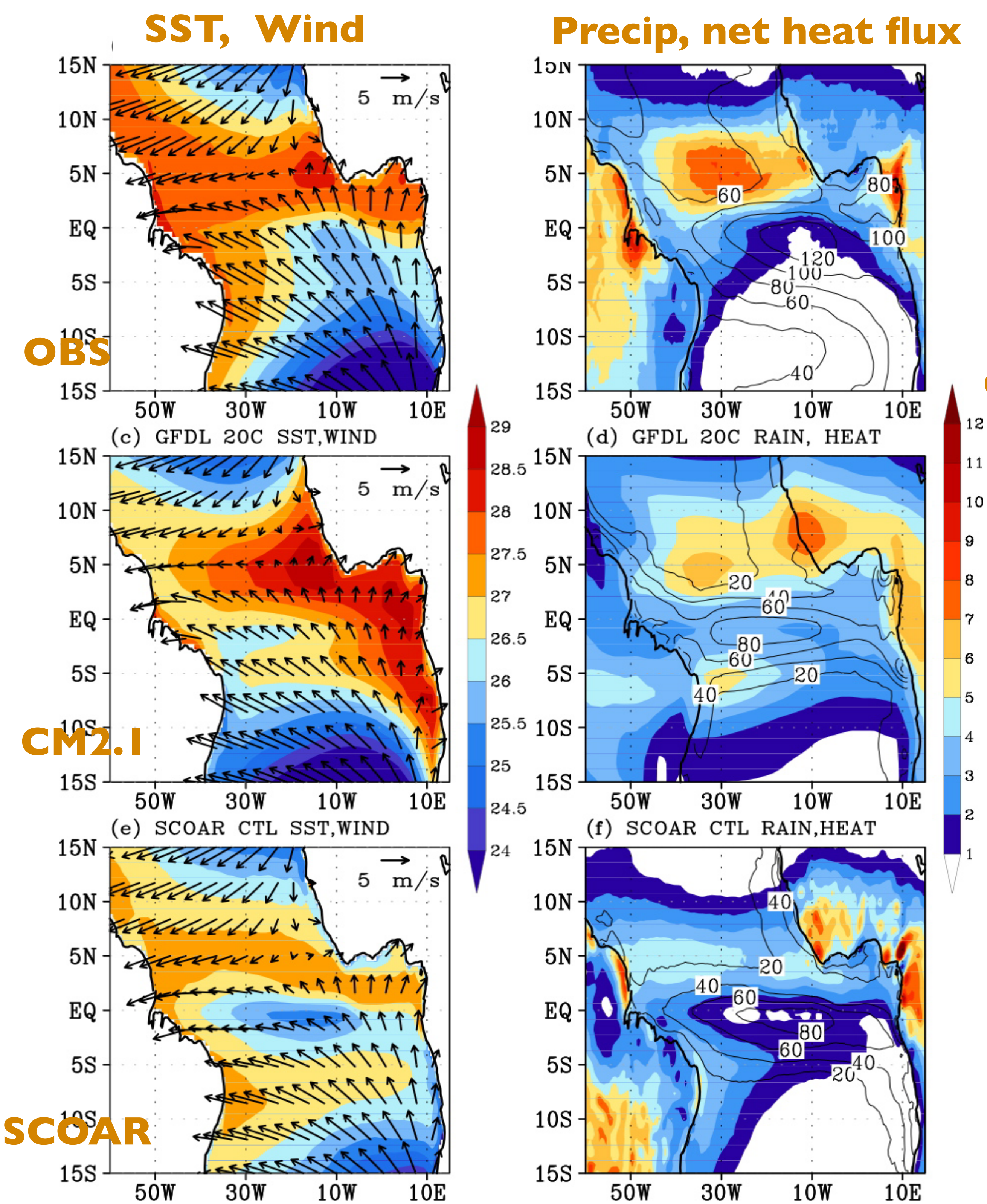
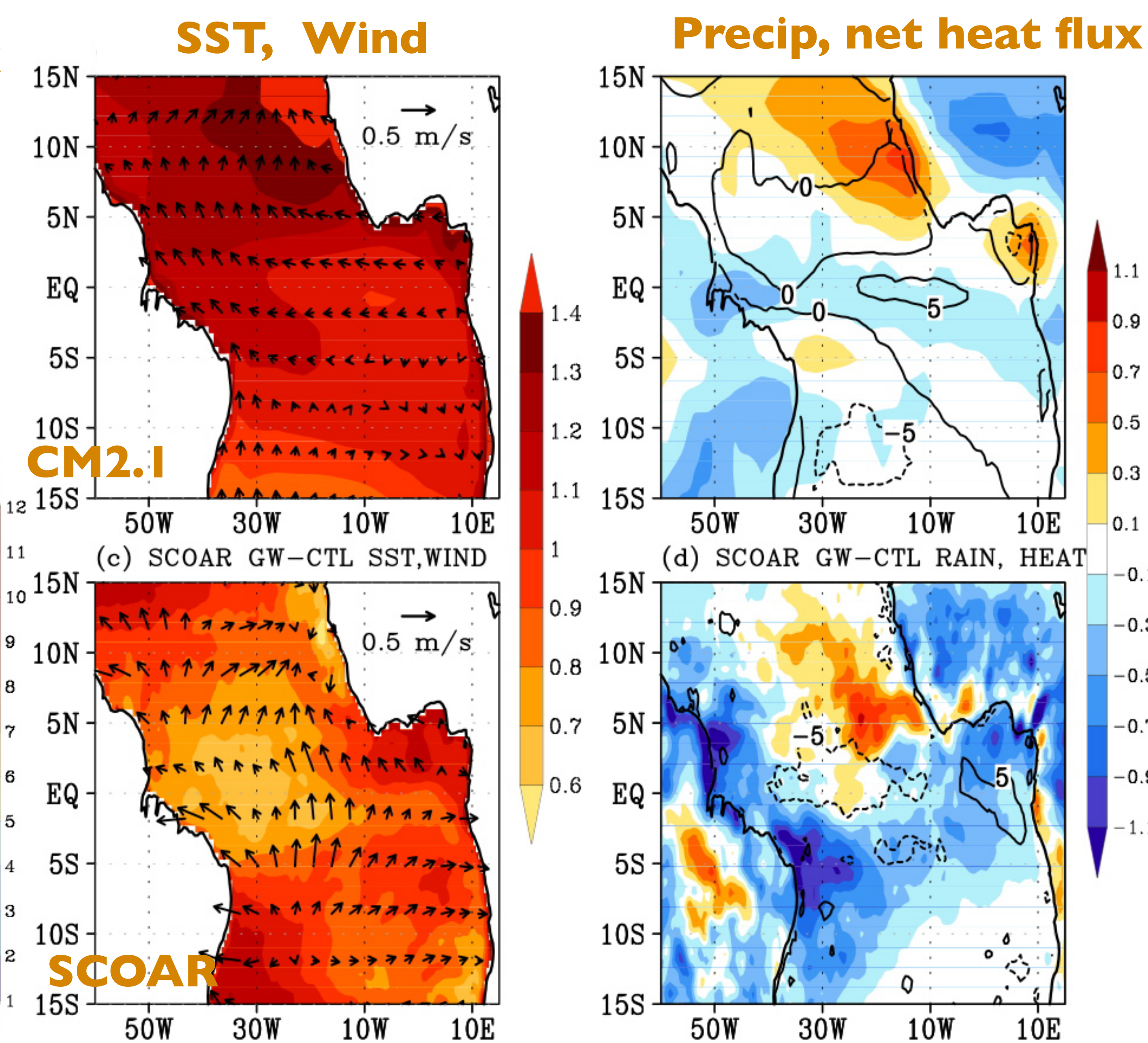


GW response (GW-CTL)



- Reduced warming in the equator
- Intensified cross-equatorial meridional winds and surface divergence across the equator.
  - Linked to a change in large-scale atmospheric convection and circulation.

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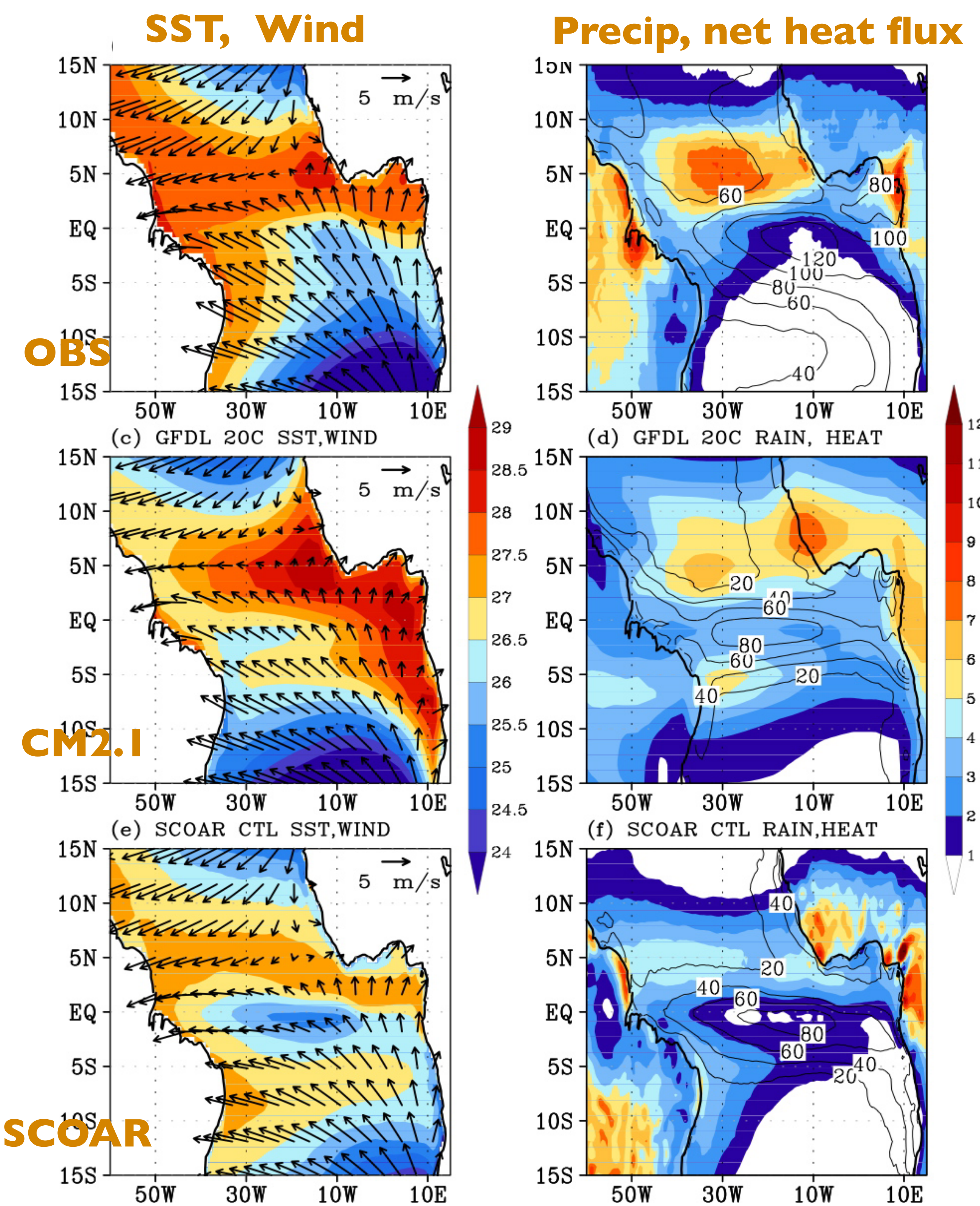

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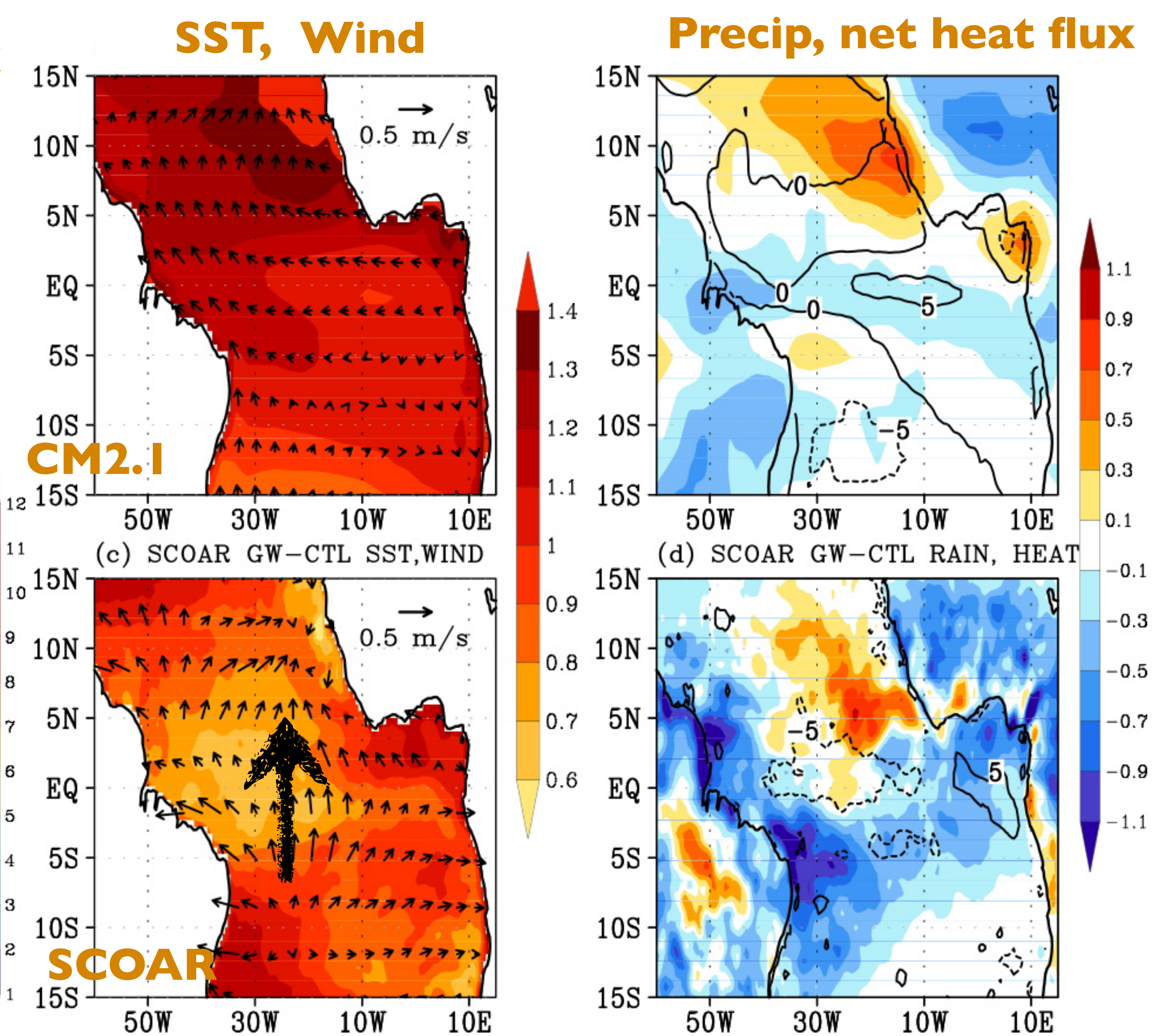

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1. Reduced warming on the equator?

2. Change in equatorial ocean in response to change in wind?

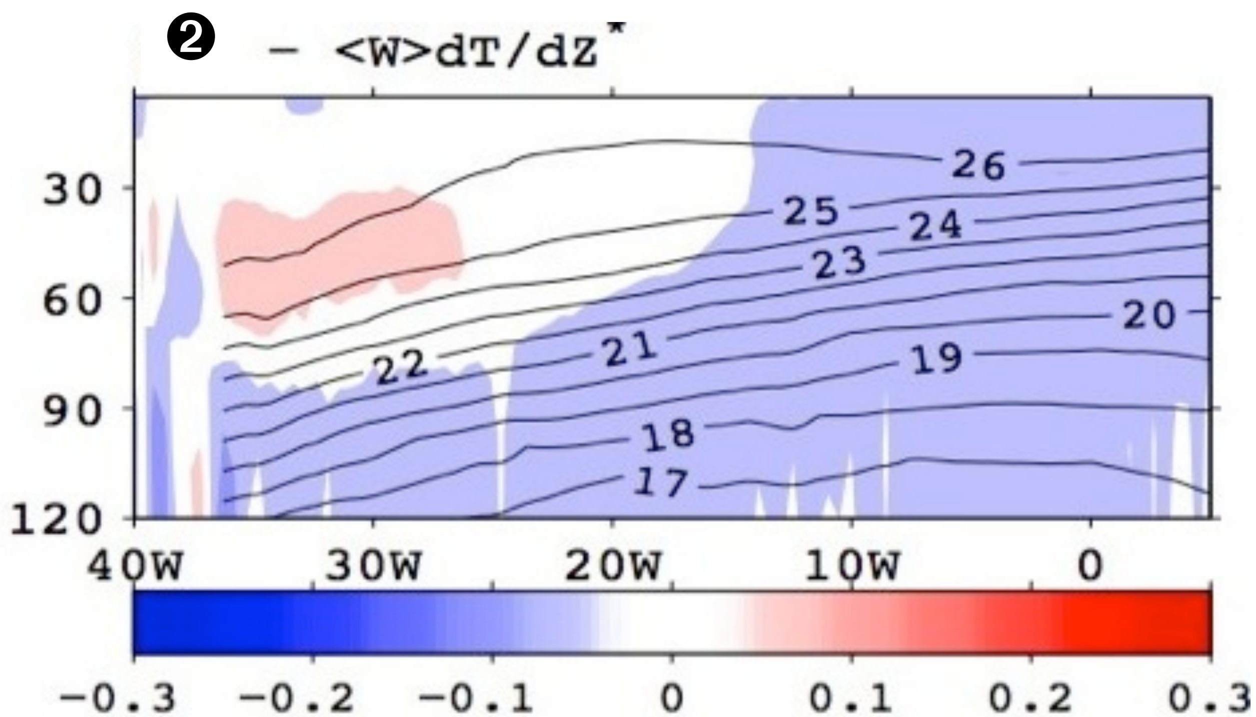
Why reduced waring in cold tongue?
Let's look at change in vertical temperature advection..

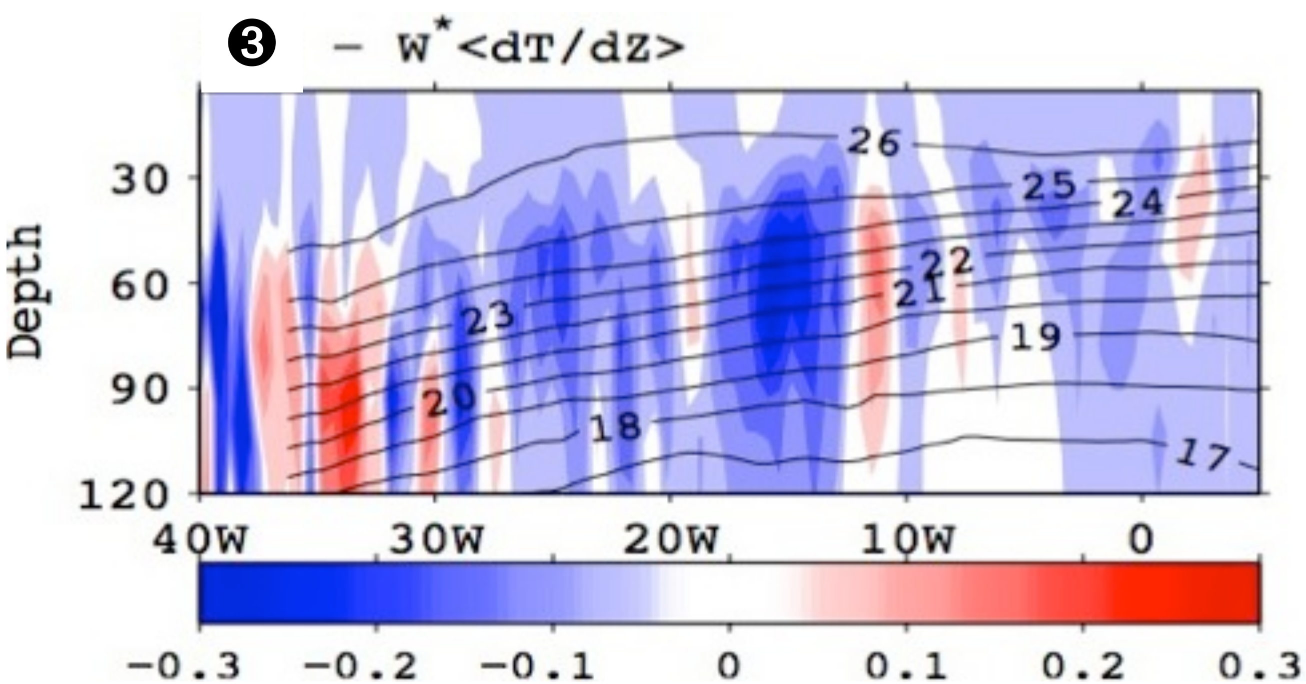
❶ ❷ ❸

$$-w\frac{\partial T}{\partial z} = -\langle w\rangle\left\langle\frac{\partial T}{\partial z}\right\rangle - \langle w\rangle\frac{\partial T^*}{\partial z} - w^*\frac{\partial\langle T\rangle}{\partial z} - w^*\frac{\partial T^*}{\partial z}$$

<>: climatological mean (CTL)

*: Perturbation from global warming (GW-CTL)





ocean dynamical thermostat (Clement et al. 1996)

❶: climatological equatorial upwelling

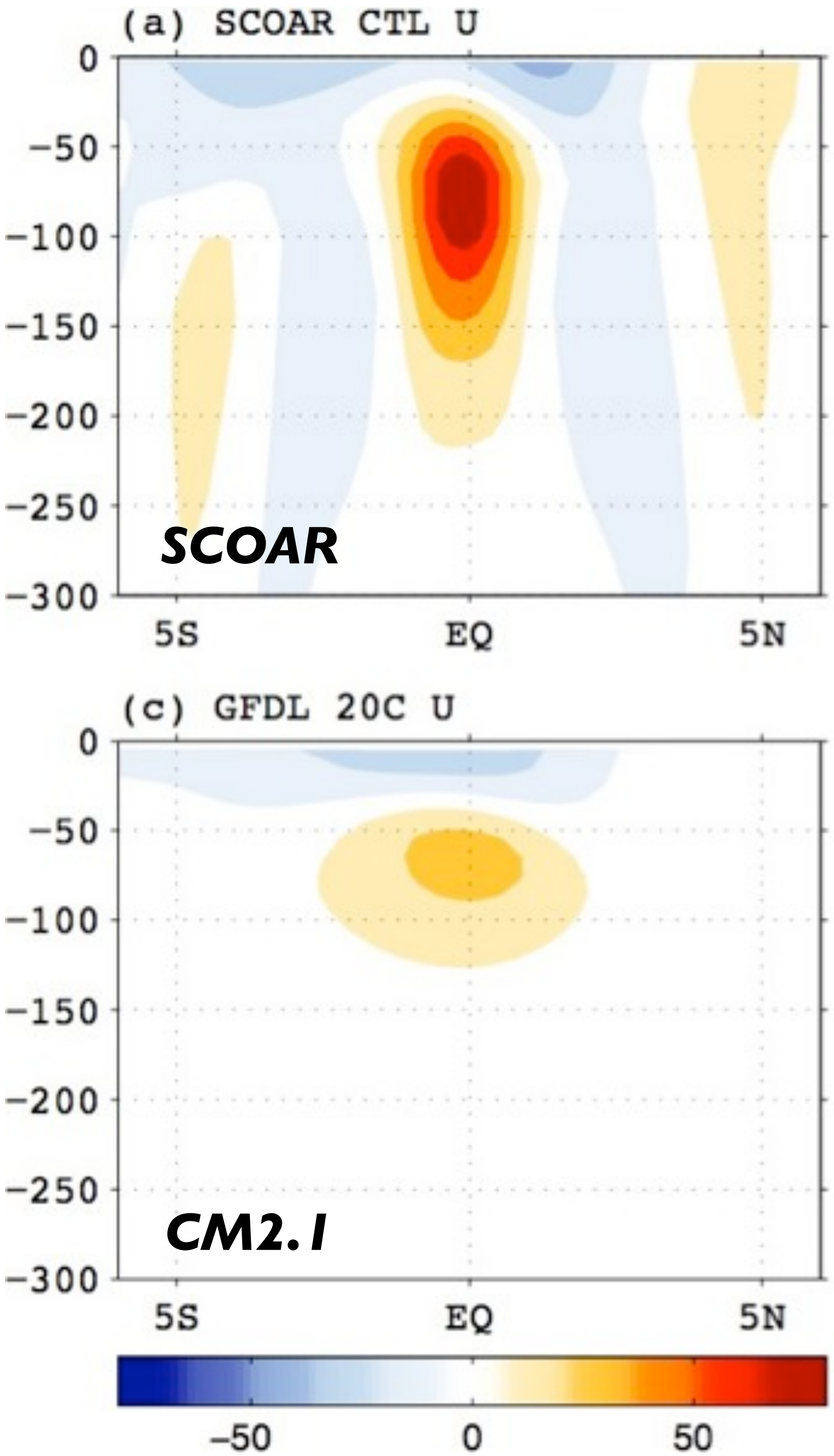
❷: Weak warming (cooling) in the west (east) due to thermal stratification

❸: Stronger cooling by *increased vertical velocities (determined by the cross-equatorial winds and divergence).*

An ocean dynamical thermostat mechanism is at work in the equatorial Atlantic, but the dominant mechanism (❸) is different from Pacific (❷).

Change in equatorial zonal currents

Climatological zonal currents



Current speed [cm]

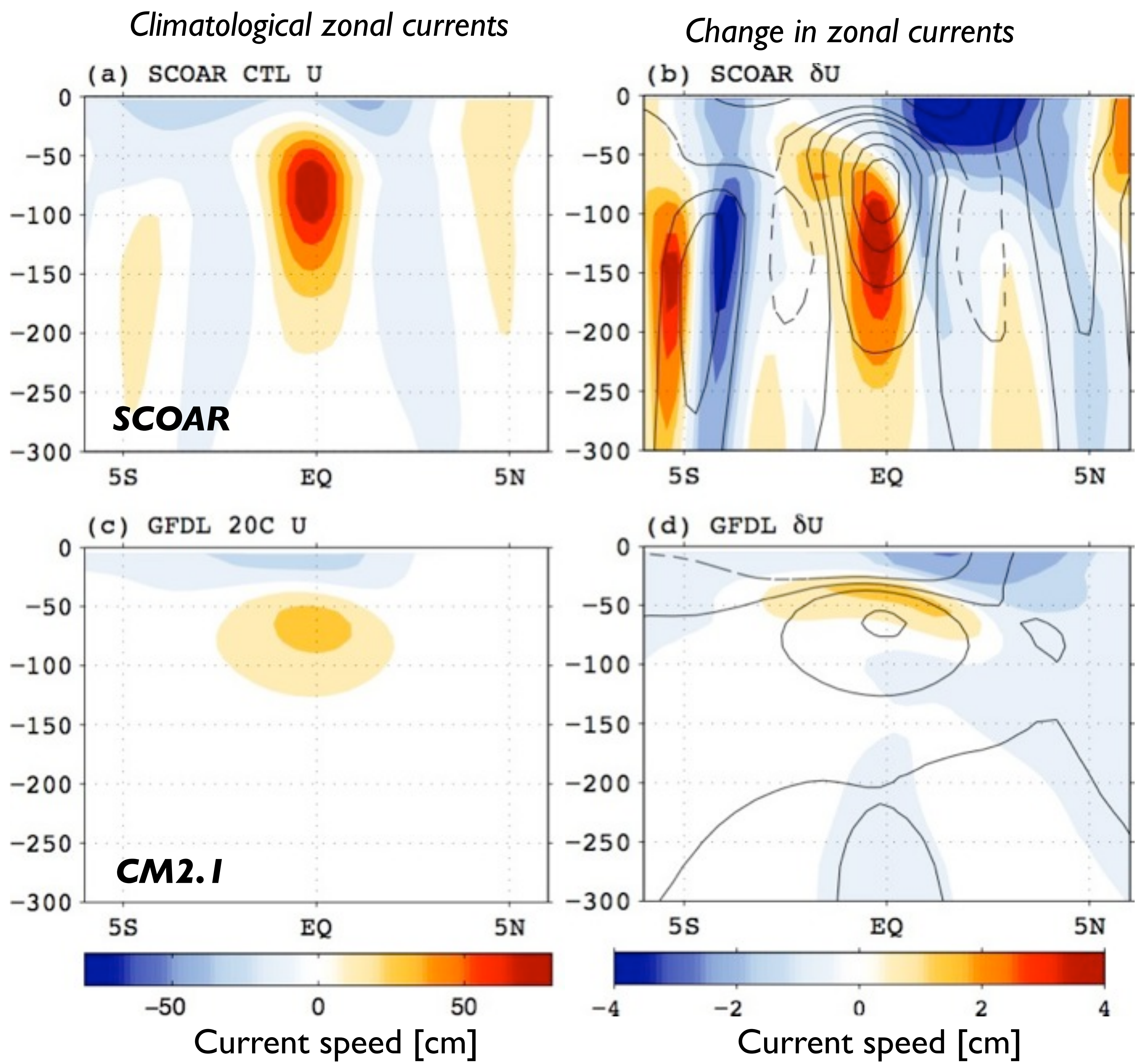
Change in zonal currents

Current speed [cm]

30°W-10°W, 1998-2007

- CM2.1 underestimates the strength of EQ. currents.
- EUC/SEC/NECC are more realistic (stronger) in SCOAR.
- Stronger EUC is associated with stronger northward cross-equatorial wind (*Philander and Delecluse, 1983; Yu et al. 1997*).

Change in equatorial zonal currents



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Change in atmospheric circulation ➜ changes in ocean current ➜ equatorial dynamic instability

EKE Equation

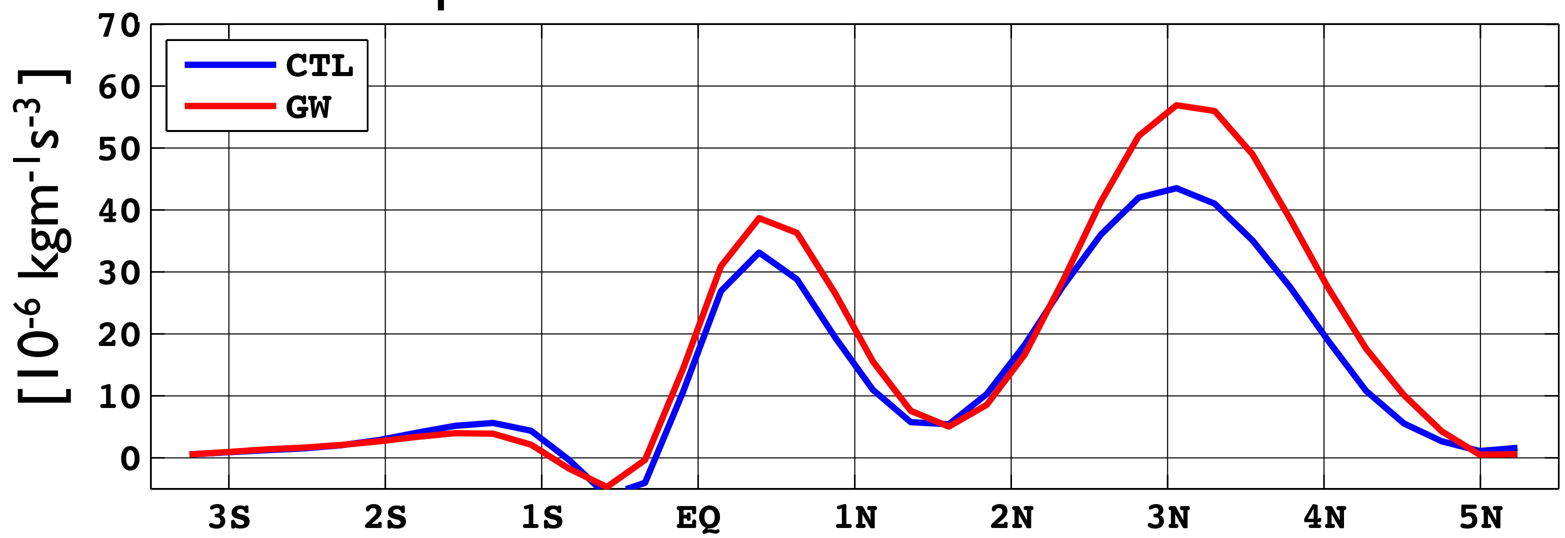
BC BT

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

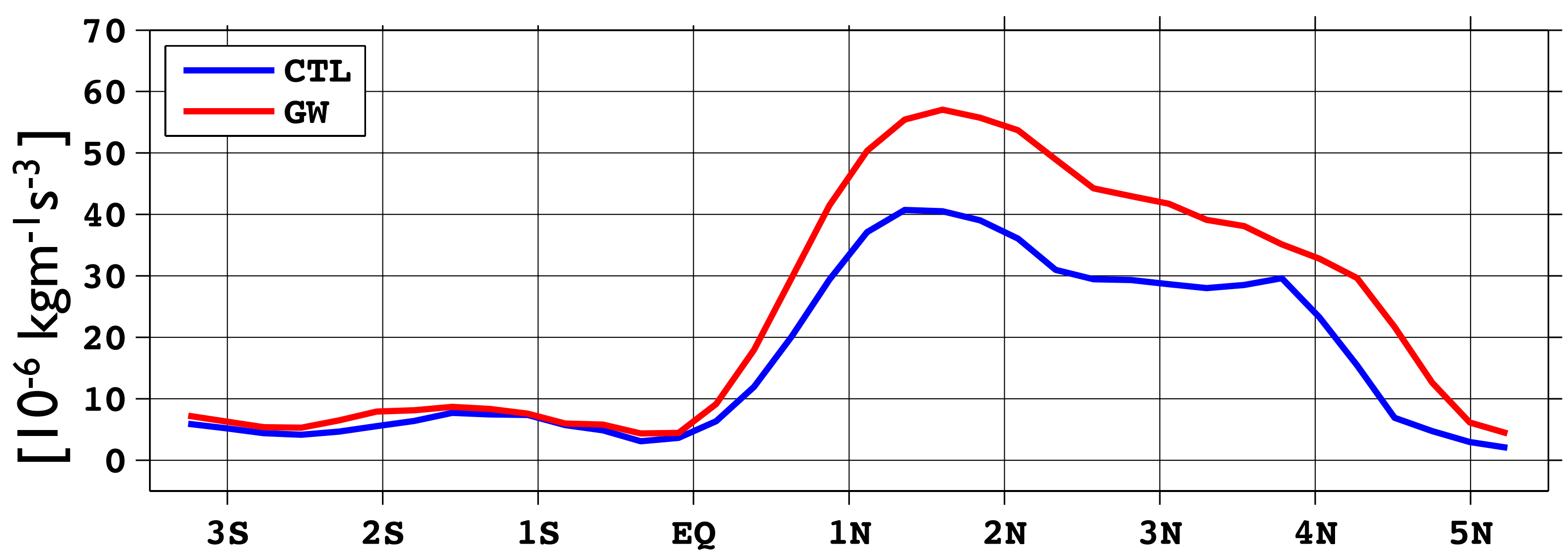
$$+\rho_o A_h \vec{u}'\cdot\nabla^2\vec{u}' + \rho_o\vec{u}'\cdot(A_v\vec{u}'_z)_z + \vec{u}'_{sfc}\cdot\vec{\tau}'_z$$

Masina et al. 1999

Barotropic conversion

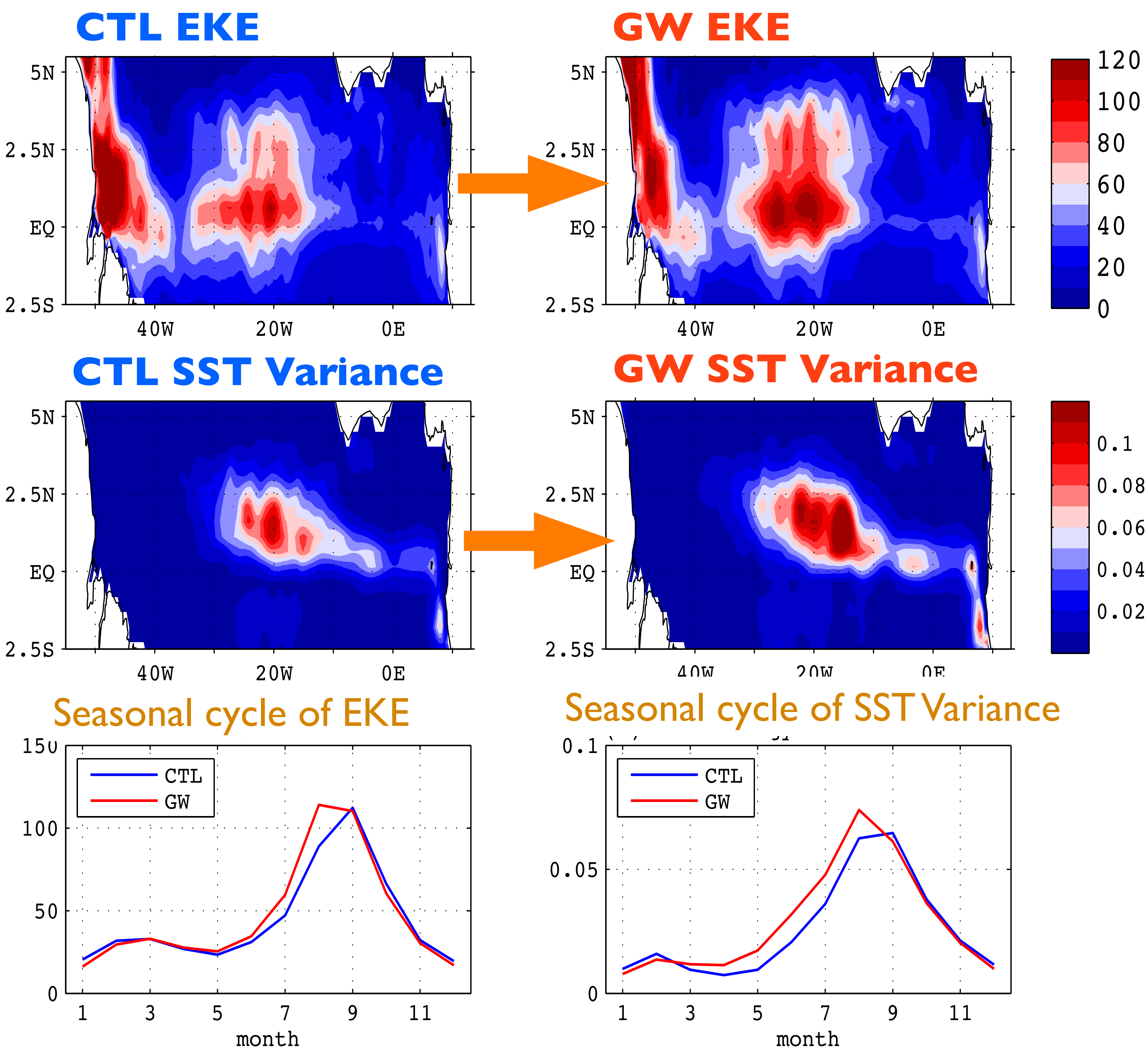


Baroclinic conversion



- Barotropic and baroclinic conversions are main energy sources for TIWs.
- Both BT and BC are strengthened under the environmental changes associated with global warming

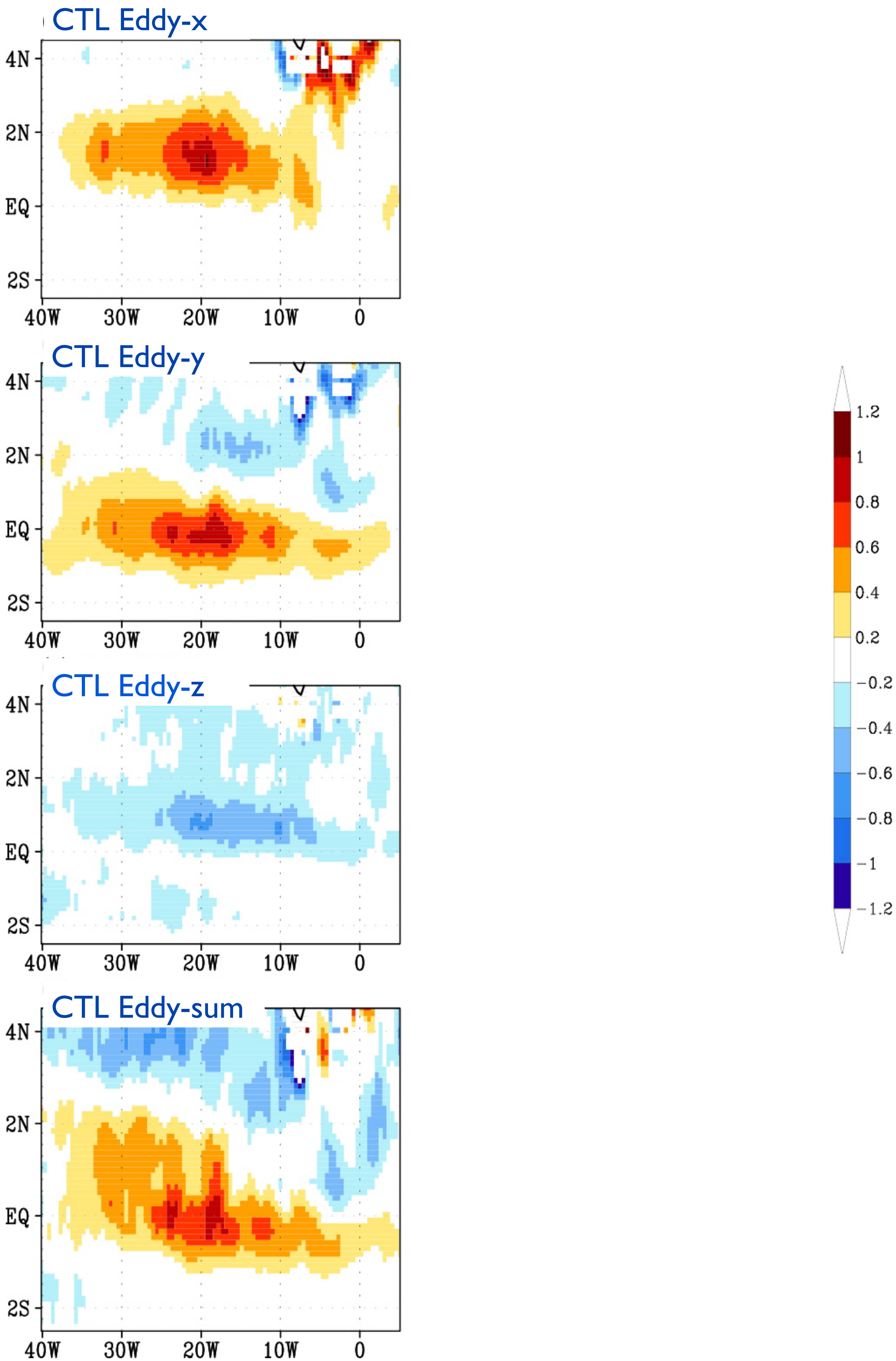
Strengthening of TIWs (20-40 day band-pass filtered EKE and SST variance)



- EKE and TIW-SST variance all become stronger during the cold season (~30%).

Eddy temperature advection

30°W-10°W, 1998-2007



- CTL: Eddy-x and Eddy-y are warming cold tongue, while Eddy-z cools, with net warming.

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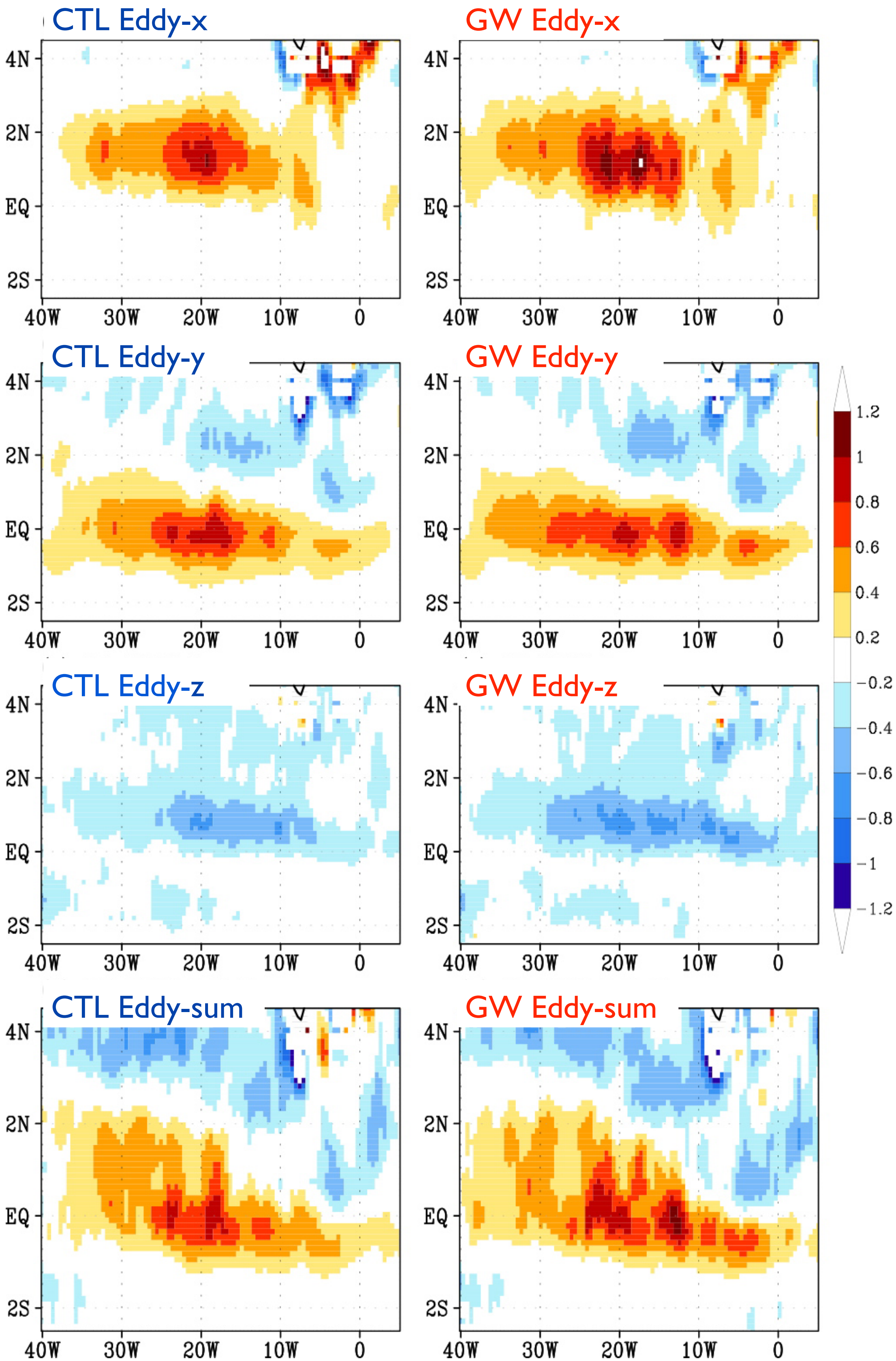

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- GW-CTL: All components of eddy temperature advection increases, leading to a greater net warming at the equator.

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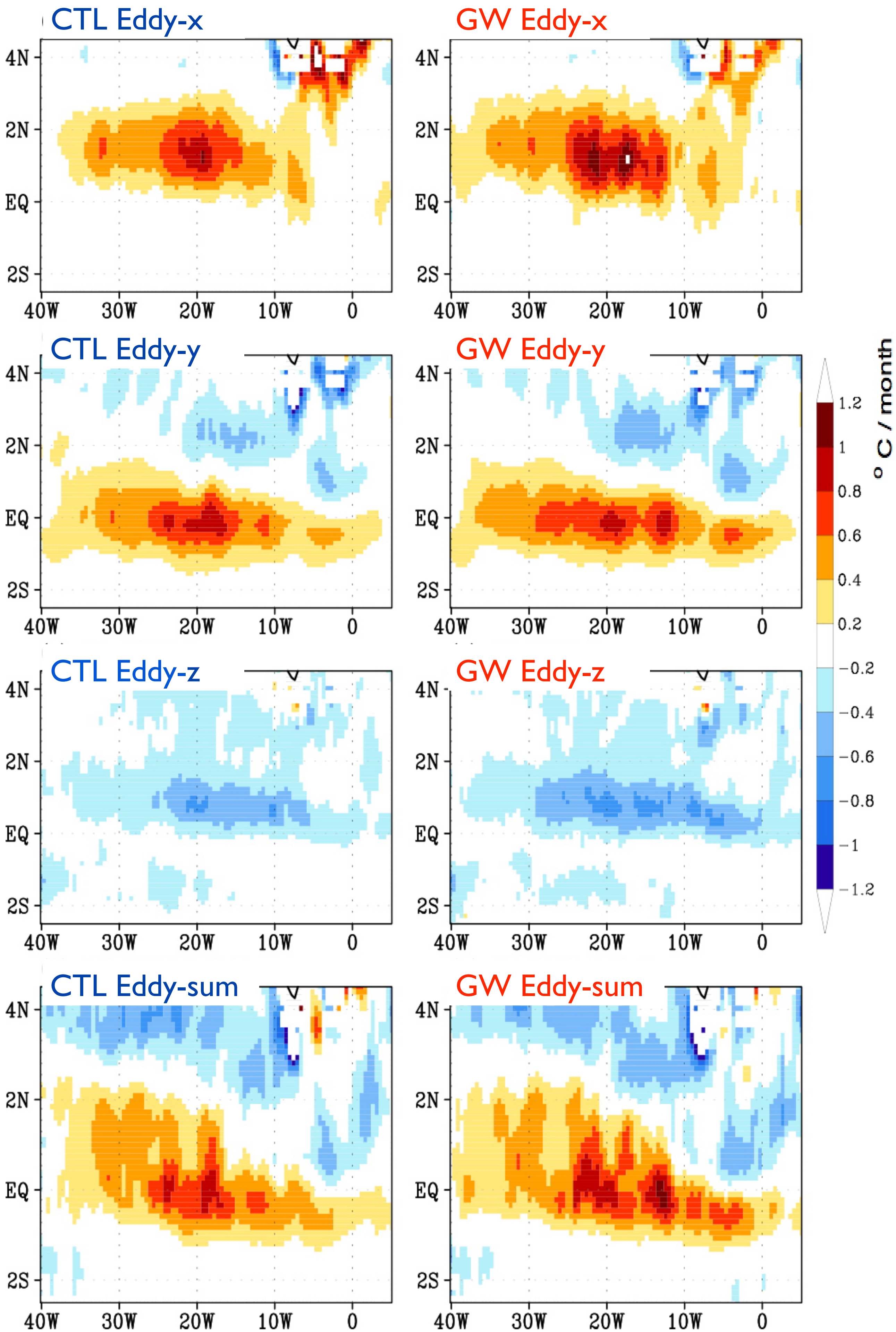
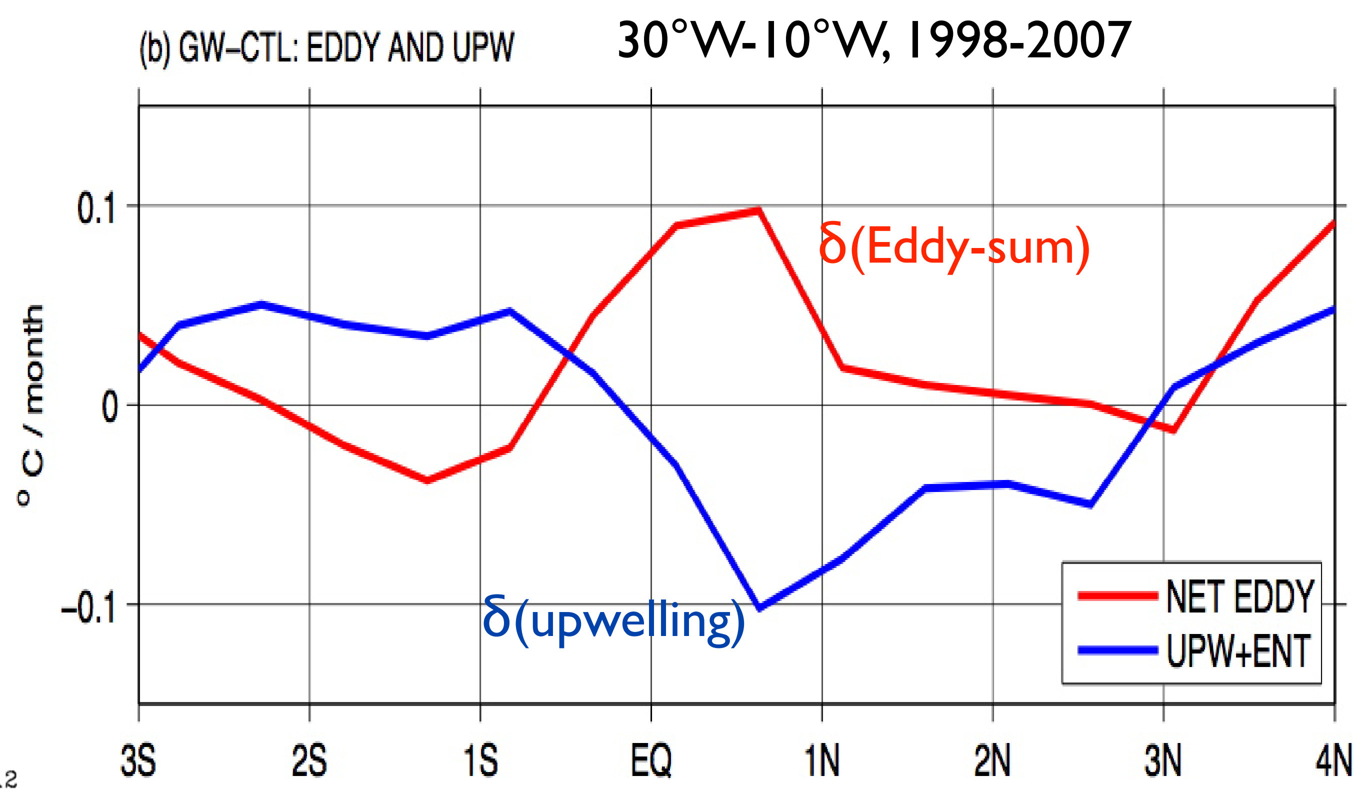




- CTL: Eddy-x and Eddy-y are warming cold tongue, while Eddy-z cools, with net warming.
- GW-CTL: All components of eddy temperature advection increases, leading to a greater net warming at the equator.
- TIW-heat flux (generated via downscaling) partly compensates for cooling due to enhanced upwelling (driven by change in circulation).

Summary of Part I

• Downscaling improves the simulation of zonal contrast and cold tongue variability in the equatorial Atlantic.

• Equatorial currents and mesoscale variabilities are better captured via downscaling.

• Large-scale atmospheric convection drives cross equatorial winds and surface divergence.➔ Equatorial upwelling increases and currents intensify. ➔ Dynamic instability enhances variability of TIWs. ➔ Eddy heat flux (generated via downscaling) impacts mean state (generated via downscaling).

• Need to explicitly resolve high-frequency processes in the model for global warming research.

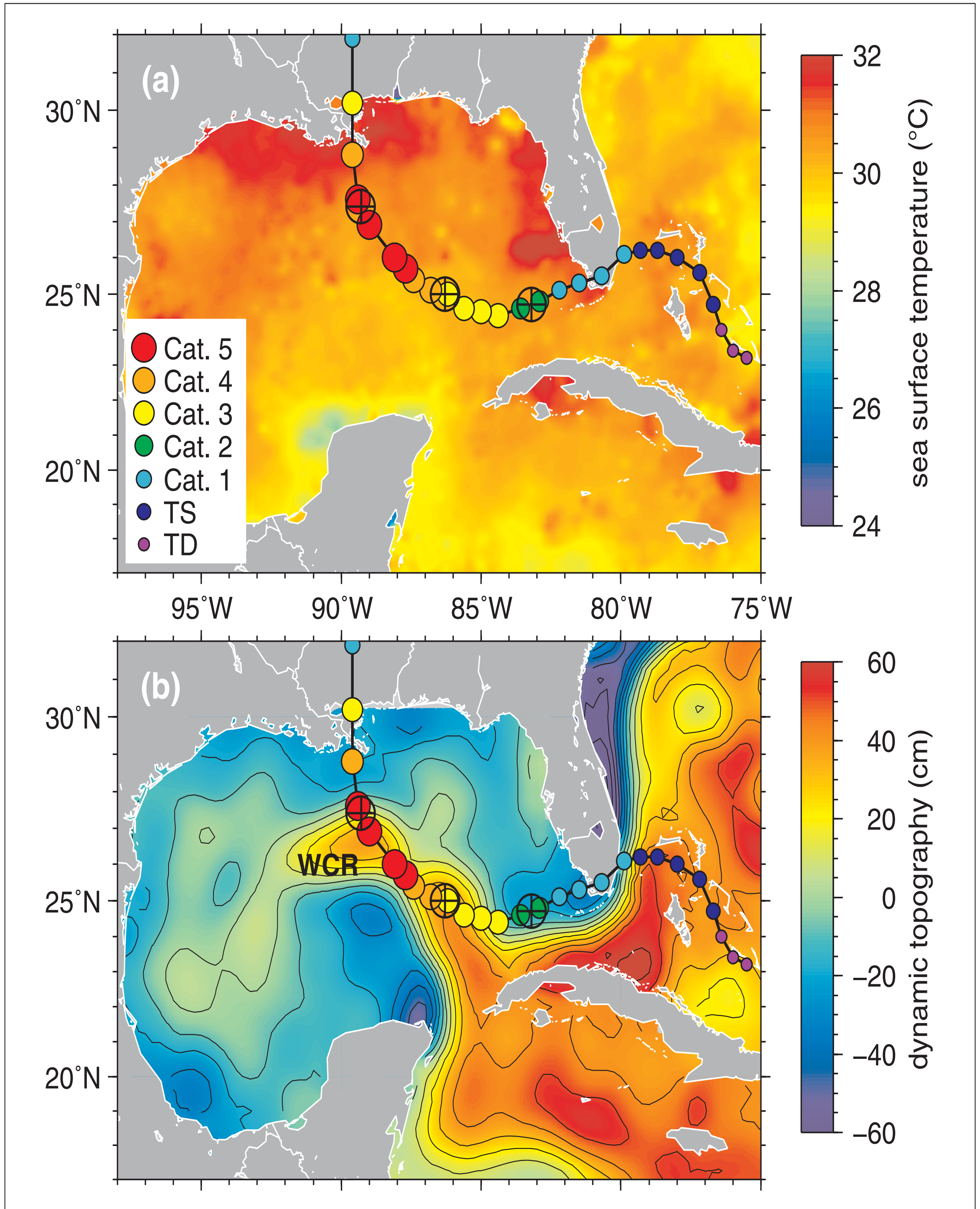
• ***Exploratory research***: The first coupled downscaling of climate change scenarios

  • More coordinated regional downscaling efforts for climate change scenarios in the upcoming AR5 *will* follow to resolve spatial scales important for climate change projection and adaptation (e.g, CORDEX).

2. Impact of ocean state on TC intensity

➔ Case study: Hurricane Katrina (2005)

Rapid intensification over high dynamic topography:
SST alone or upper ocean heat content (UOHC)?



- Satellite altimeter data indicate that **Katrina intensified over areas of anomalously high dynamic topography (high UOHC)** rather than areas of unusually warm surface waters.

Scharroo et al. 2005 EOS

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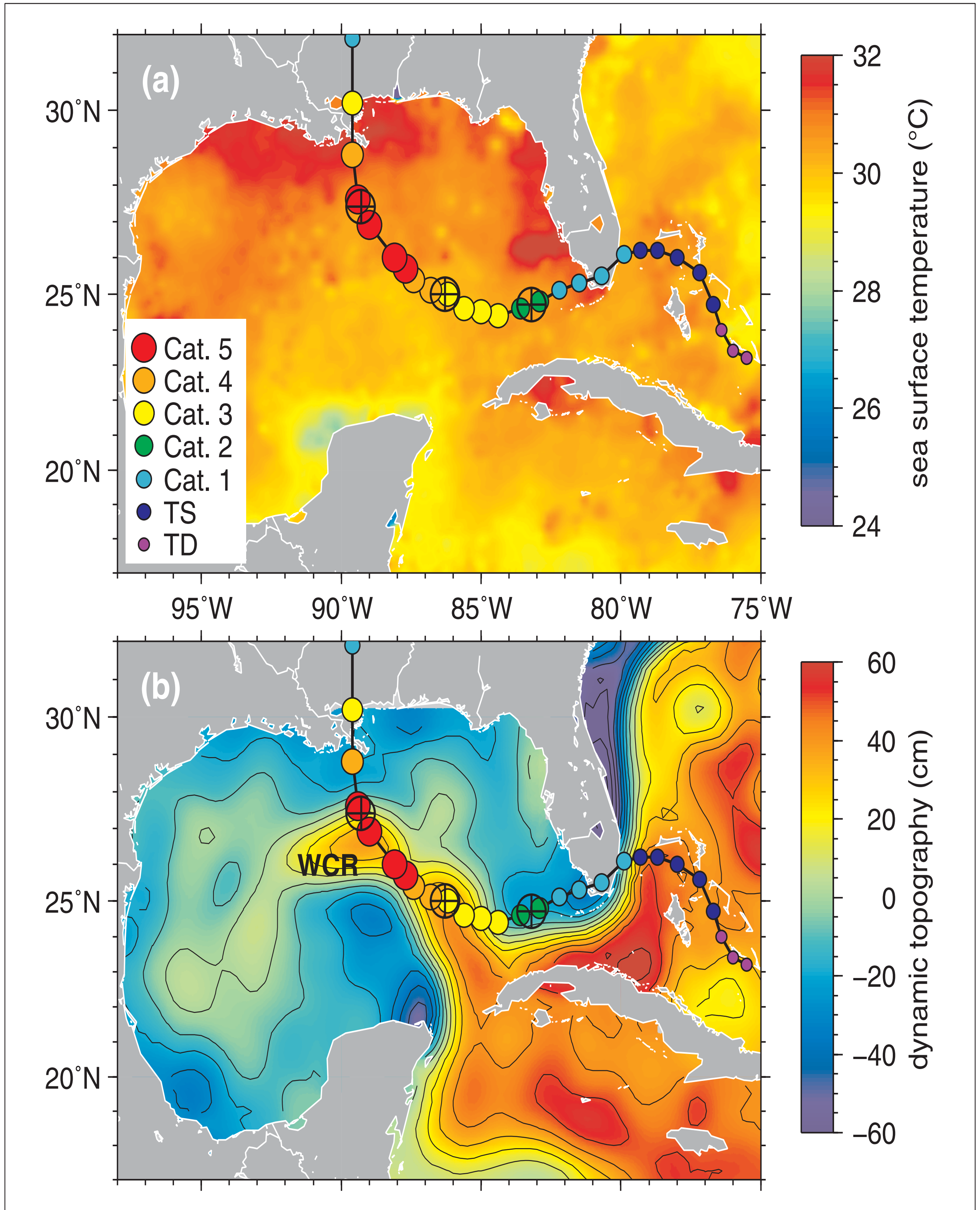

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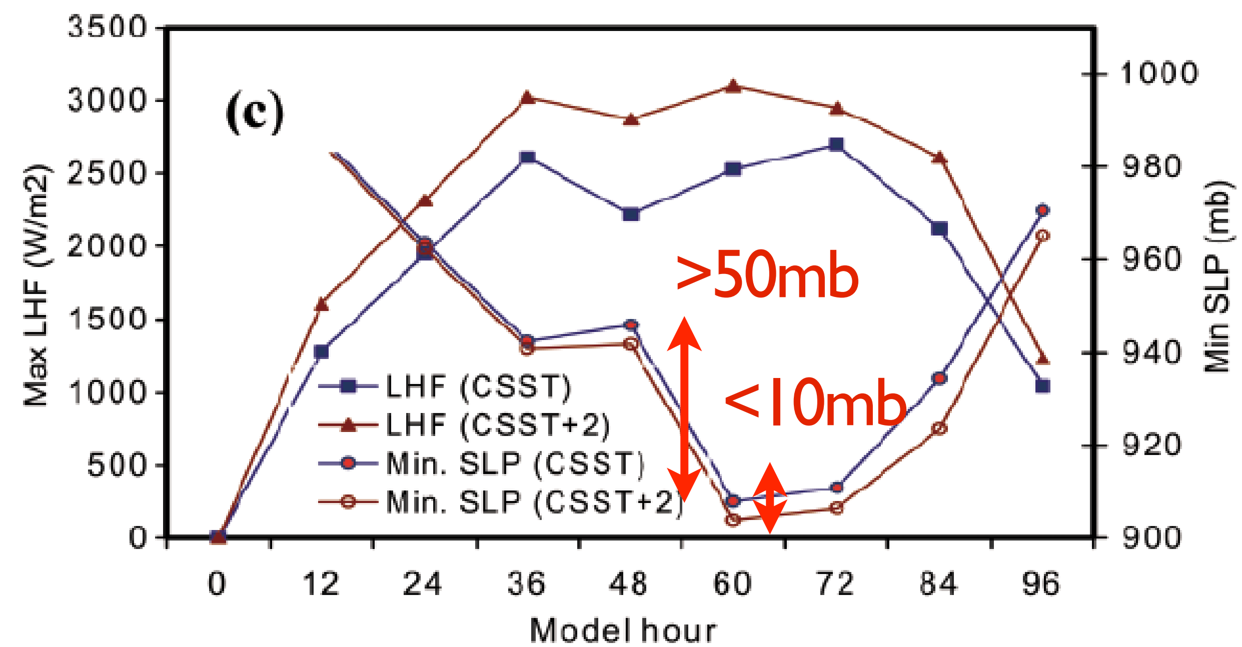

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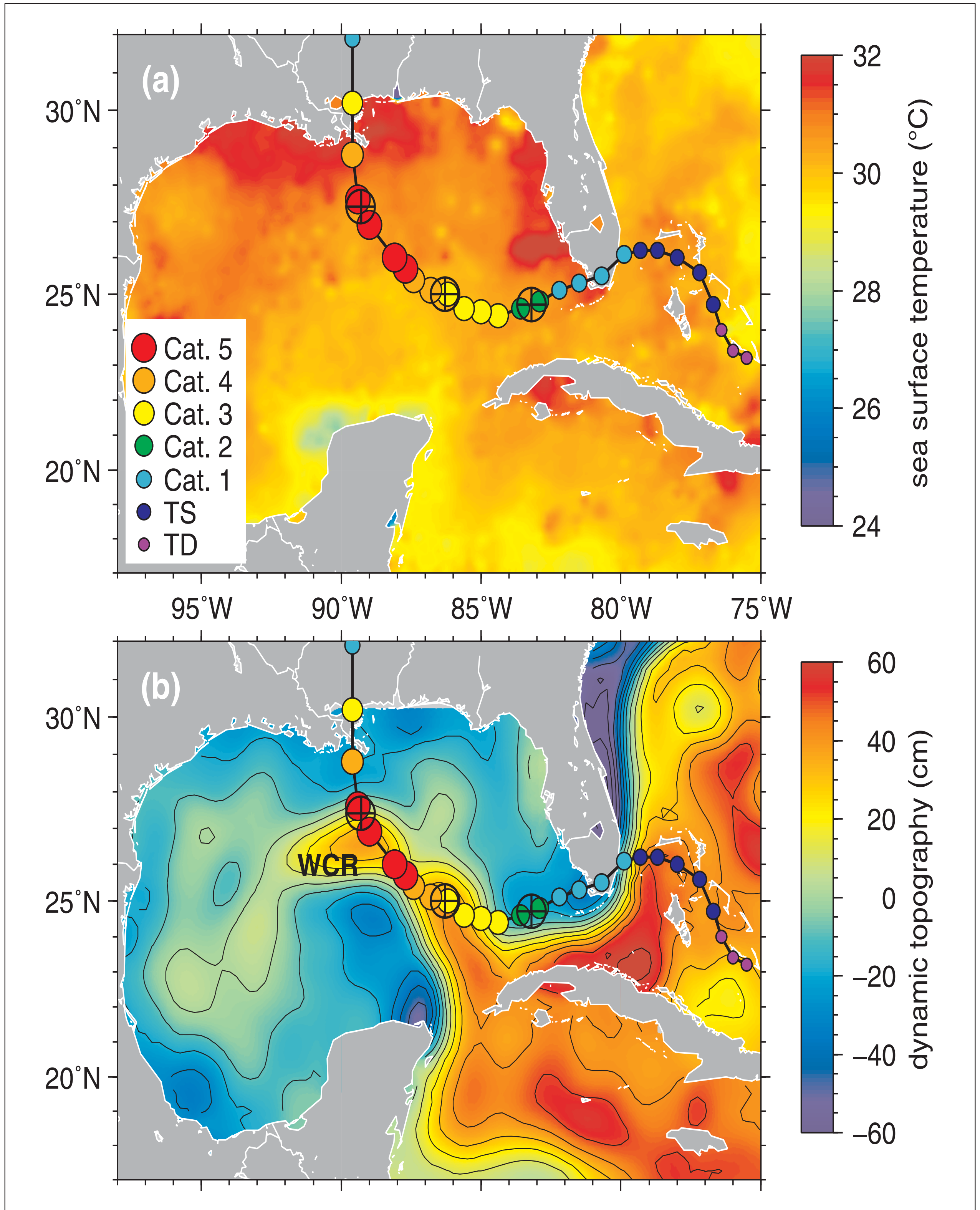

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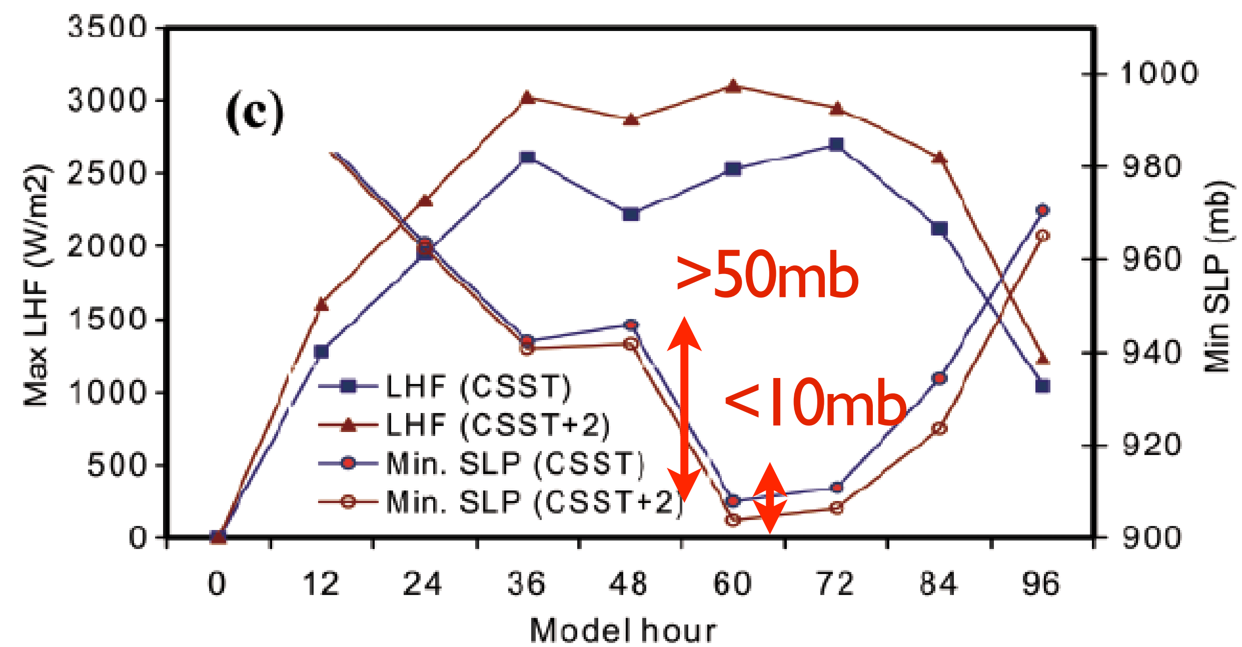

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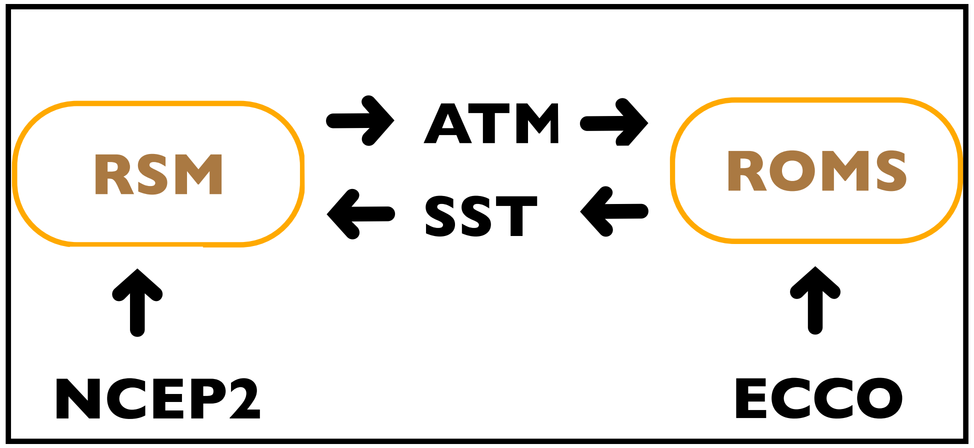
- **How much of intensification of Katrina in 2005 was due to ocean impact?** Can we quantify it using a fully coupled-model?

Coupled experiment: SCOAR



ECCO (Estimating the Circulation and Climate of the Ocean)
kf066b, 1X1,10-daily, 1993-2008, Assimilates altimeter data

- 15 km ROMS + 15 km RSM with matching grids
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- 120-hr. coupled integration: Aug. 26 00Z - Aug. 31,00Z, 2005.

SST (color), wind (vector), rainfall (contour, mm/day)

SSH (color), current (vector), SLP (contour)

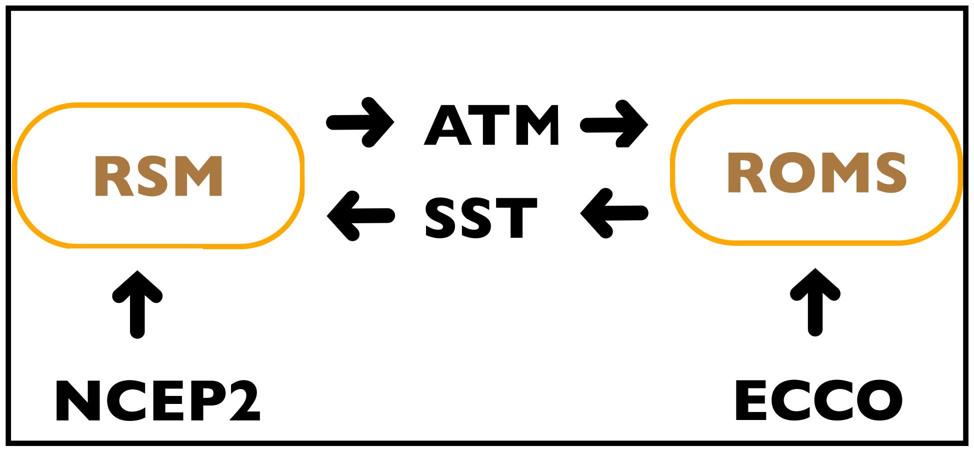
[°C]

[m]

15 m/s

1 m/s

Coupled experiment: SCOAR



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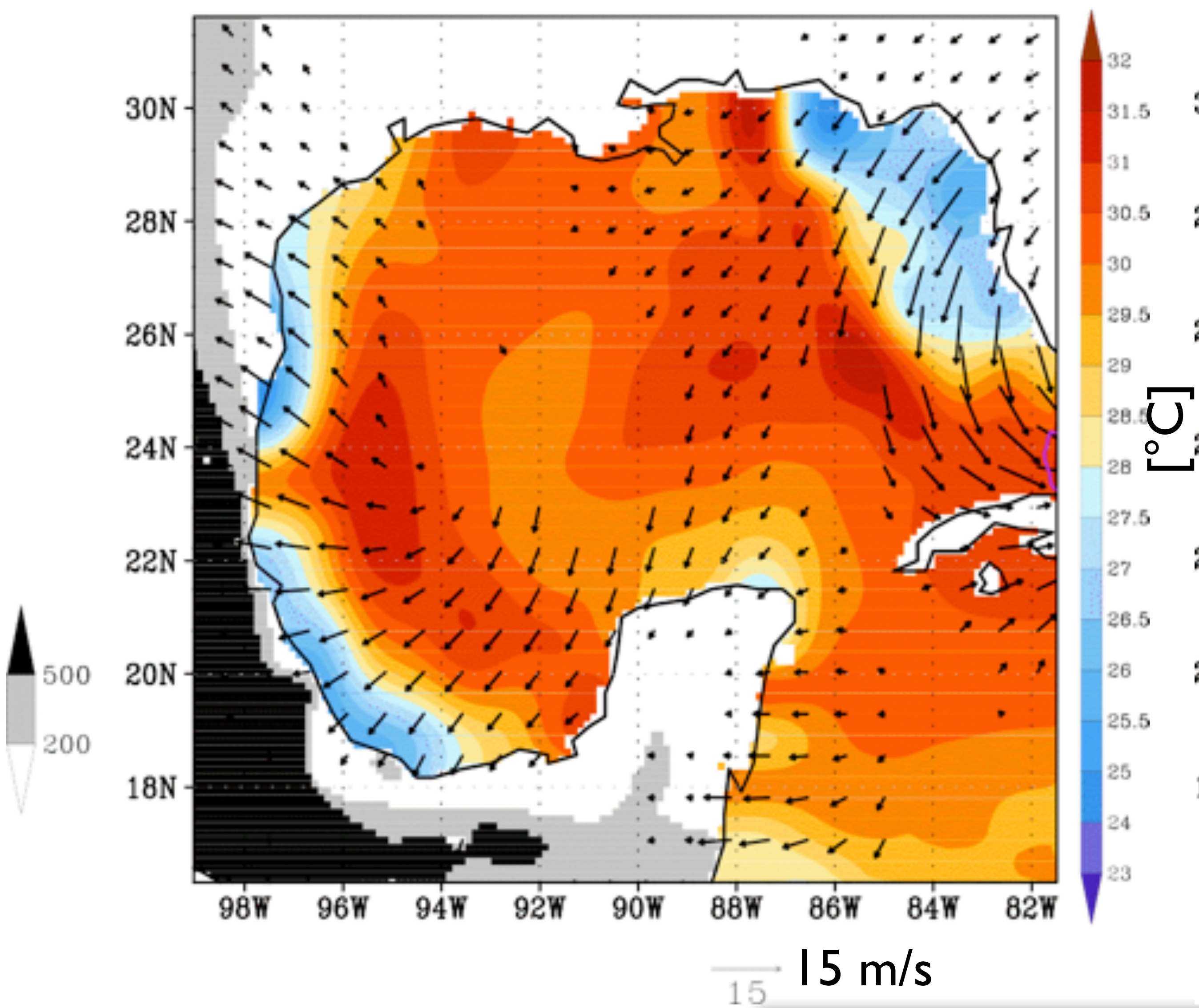

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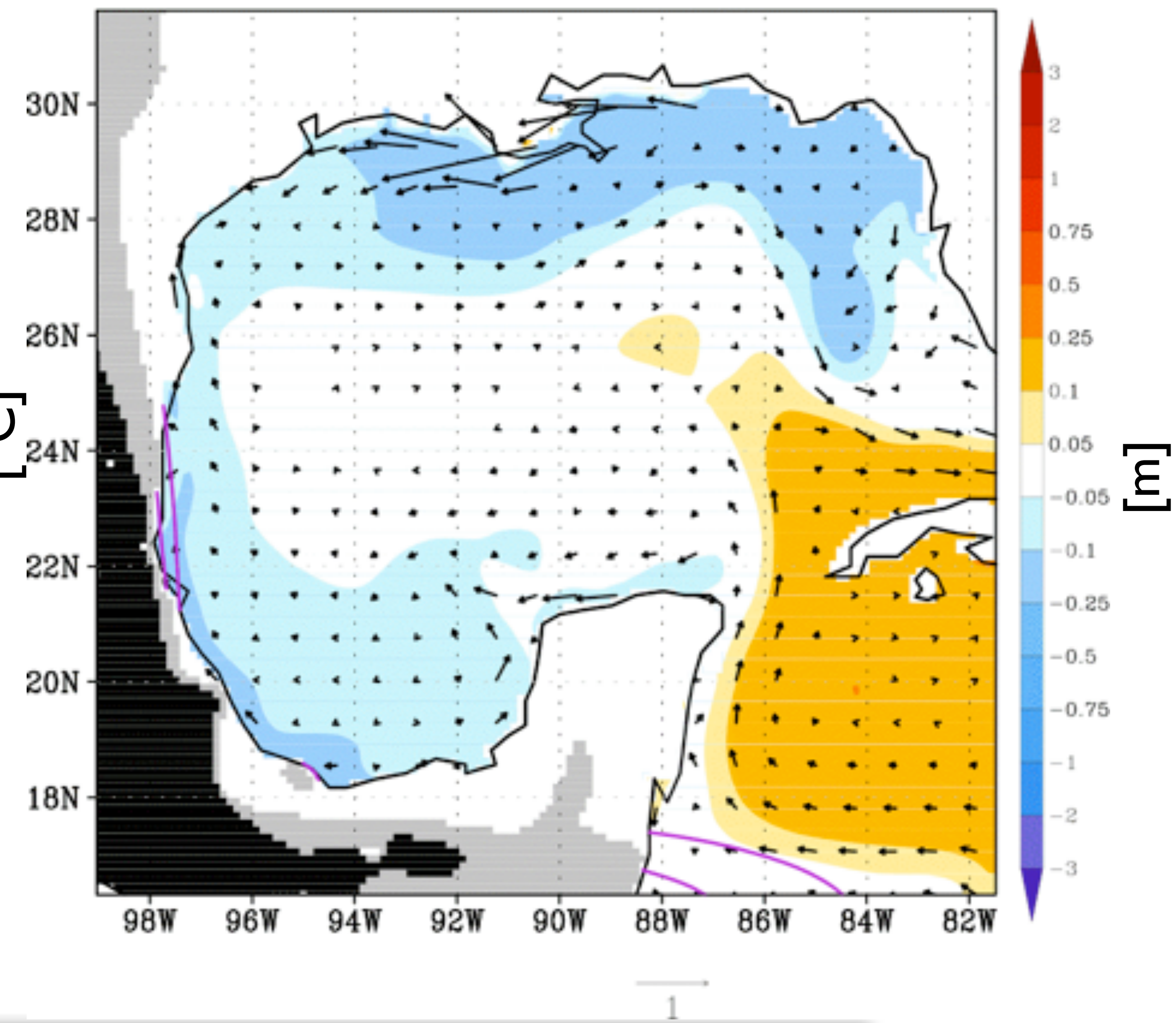

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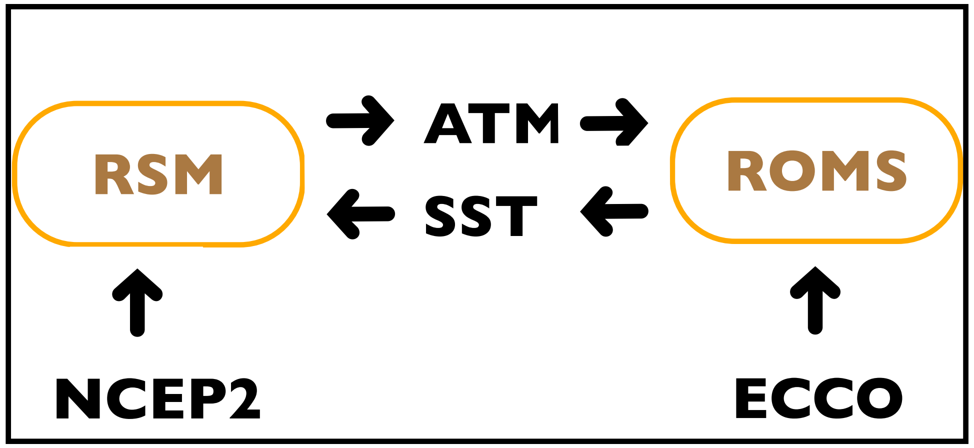

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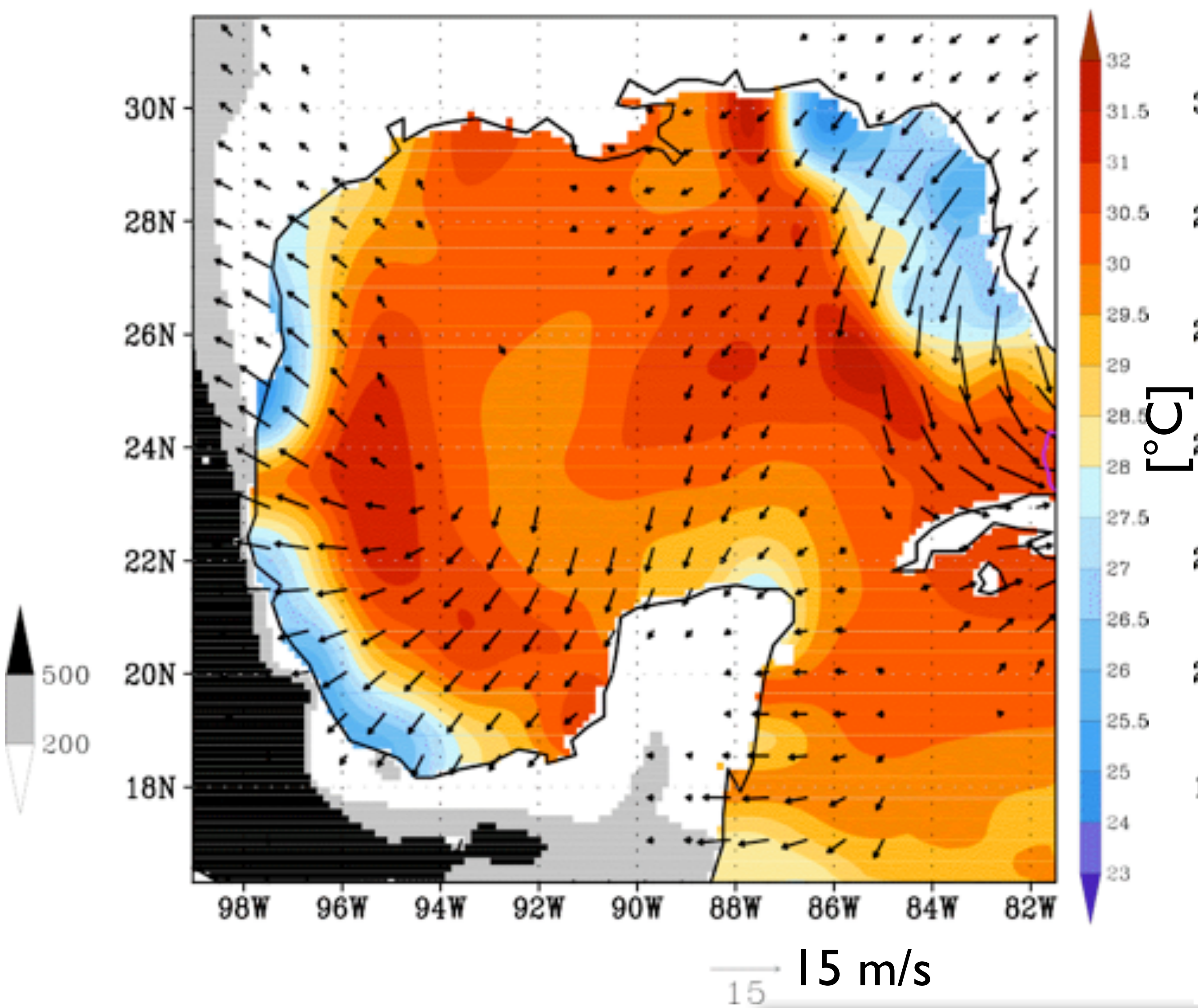

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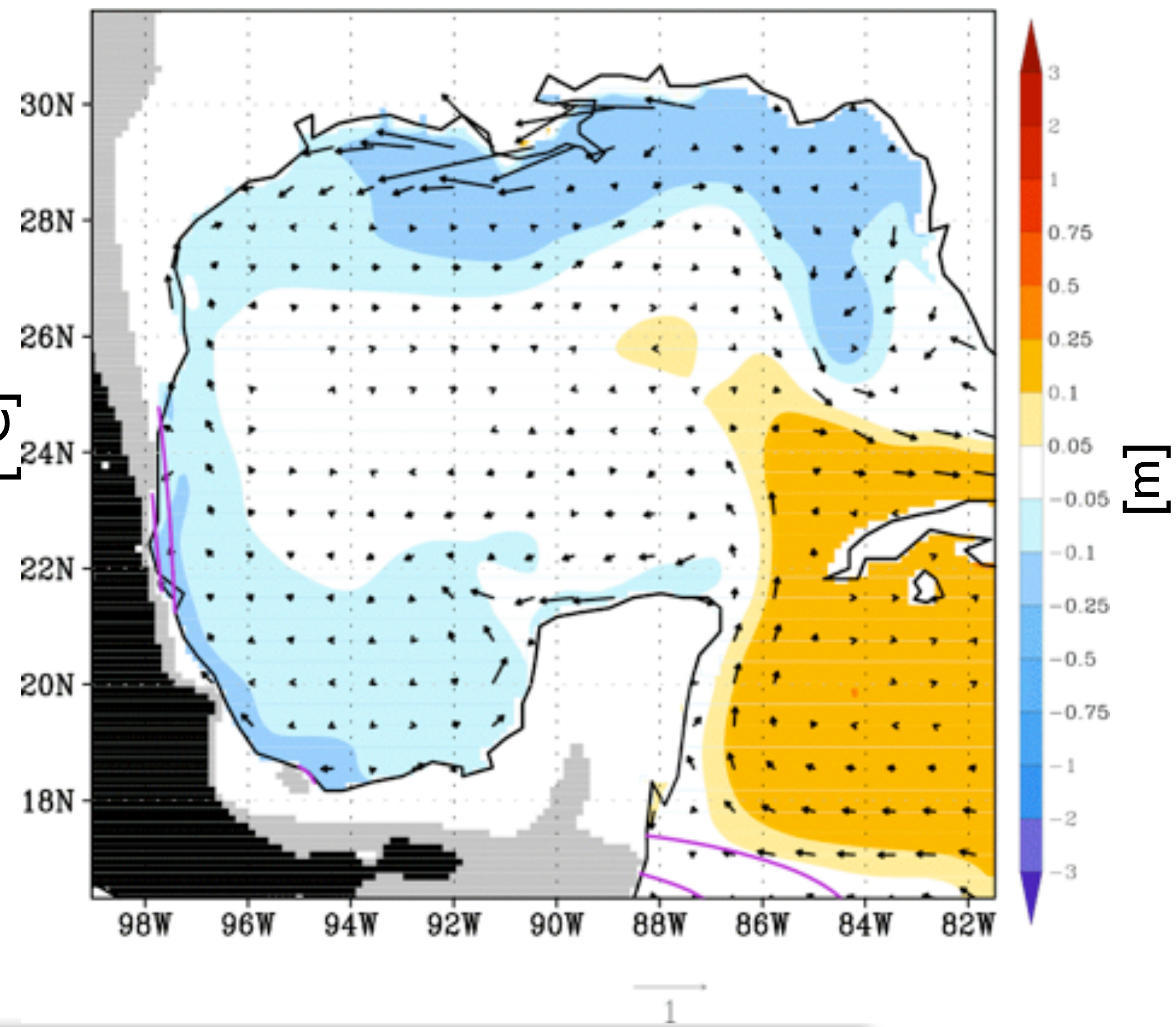
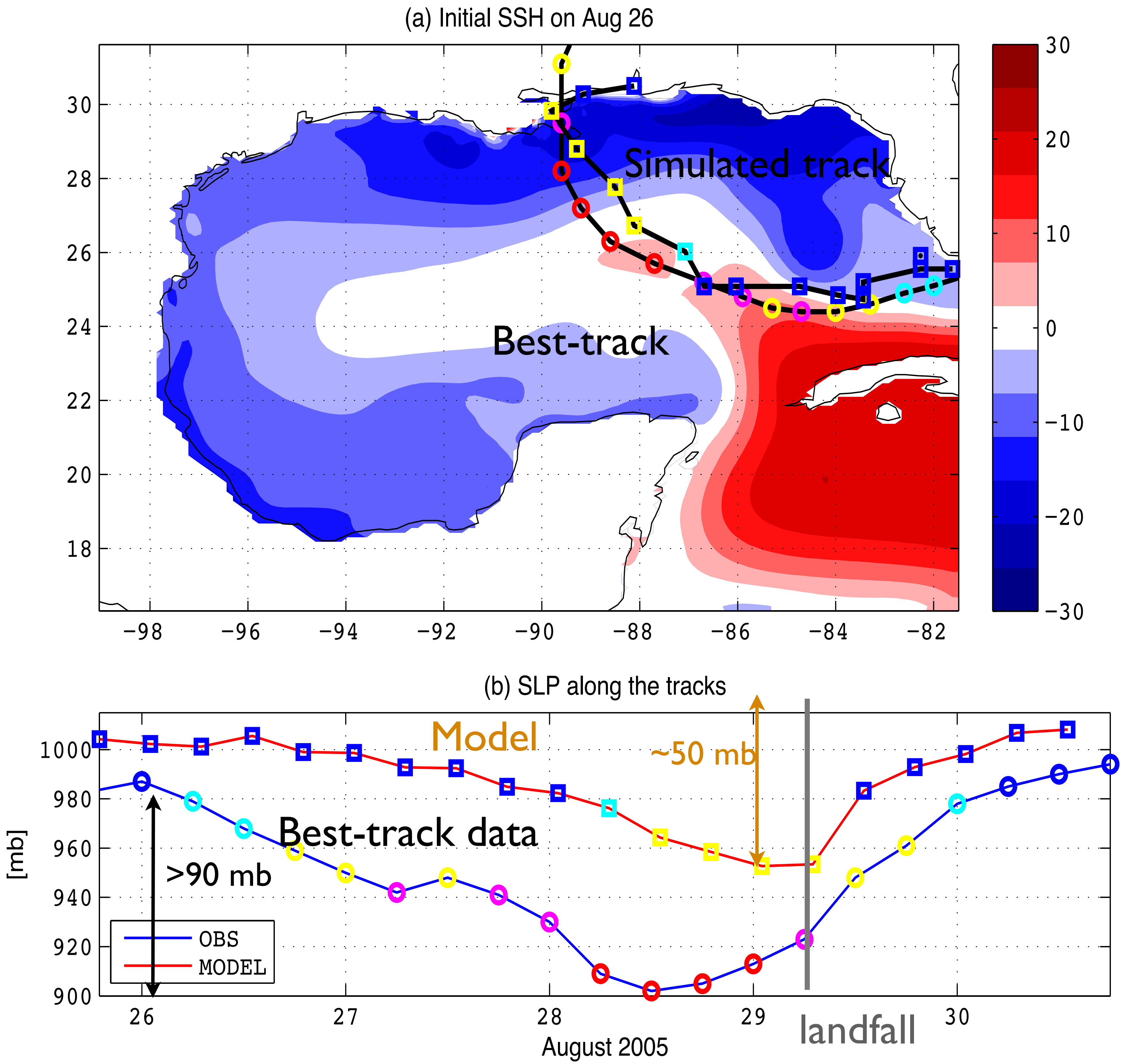


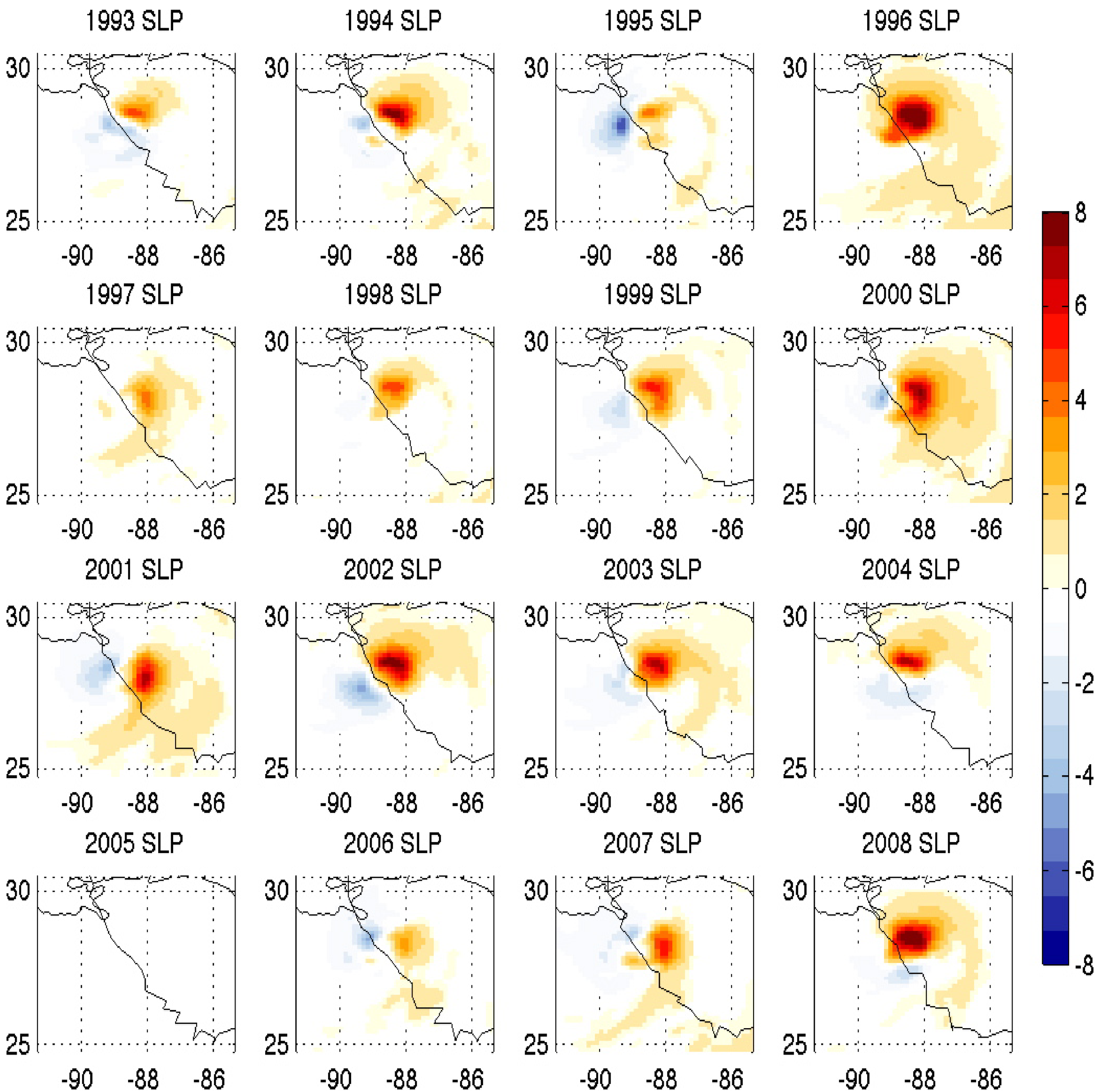
Model verification; track and intensity



- The simulated track is slightly shifted eastward.
- Intensity is underestimated.
- Intensification in the model is 50 mb (cf >90 mb in the obs).

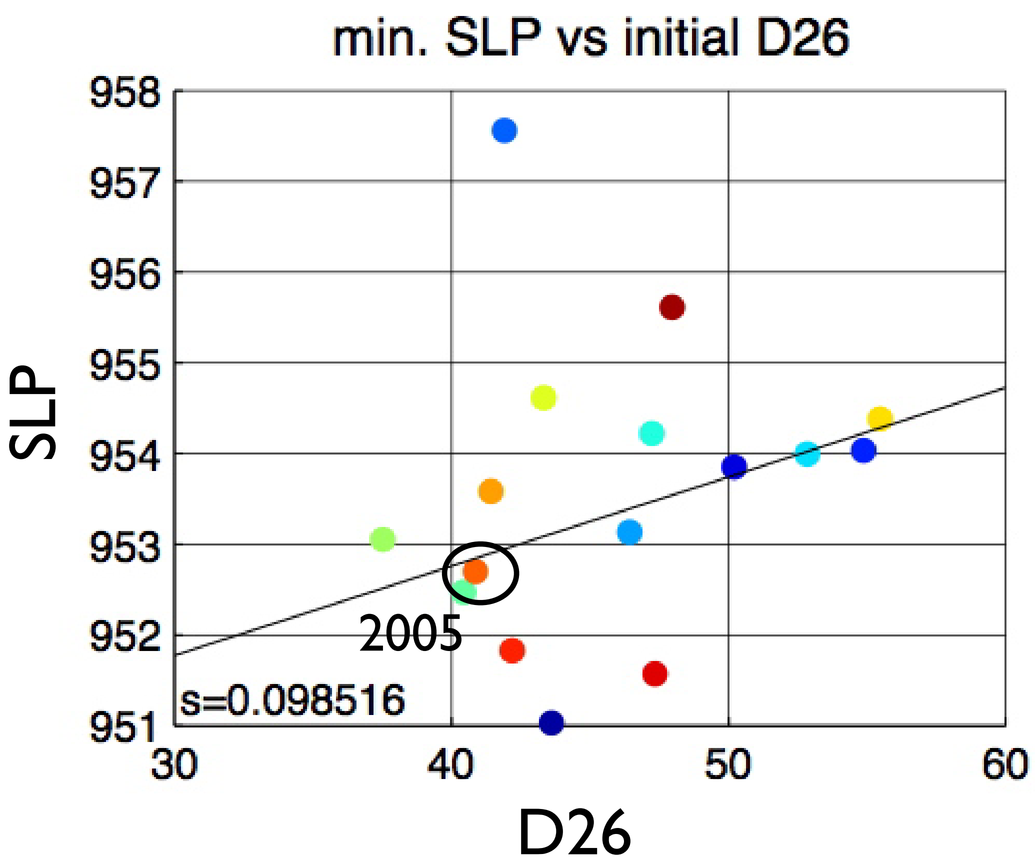
- Now let the same atmospheric conditions in 2005 August interact with ocean states in different years from 1993-2008.

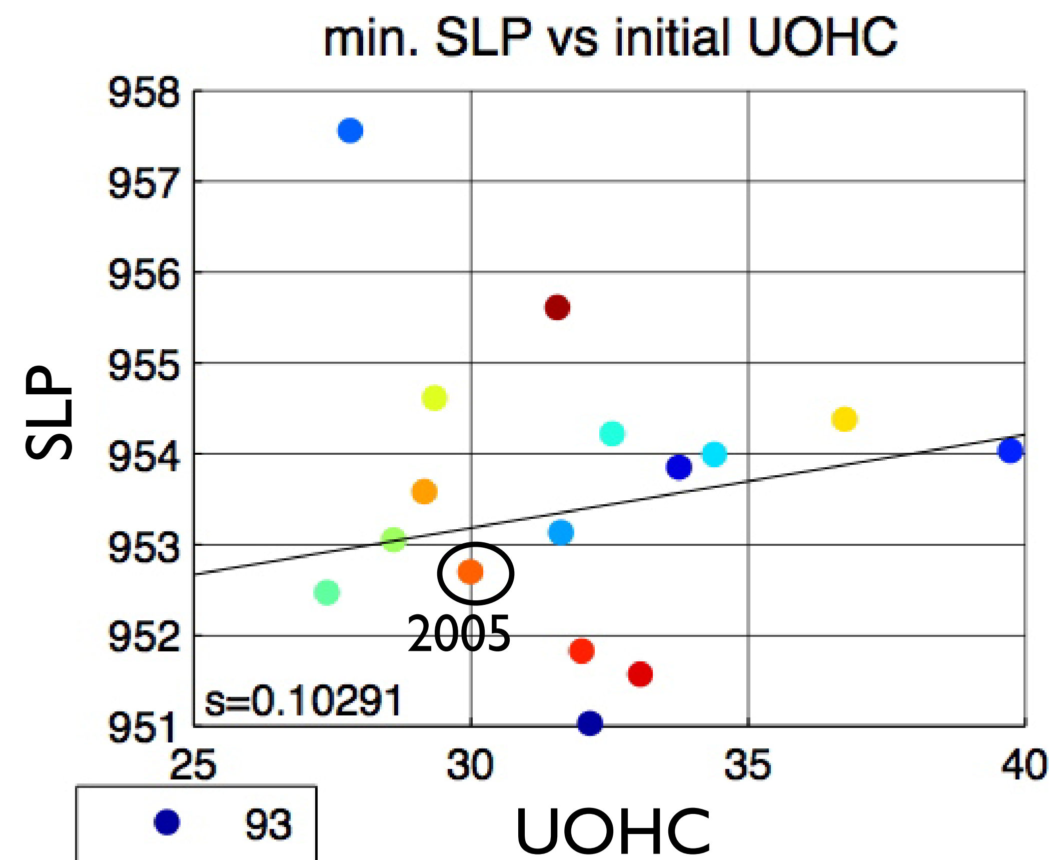
ΔSLP (each year minus 2005) after 74 hrs from initialization

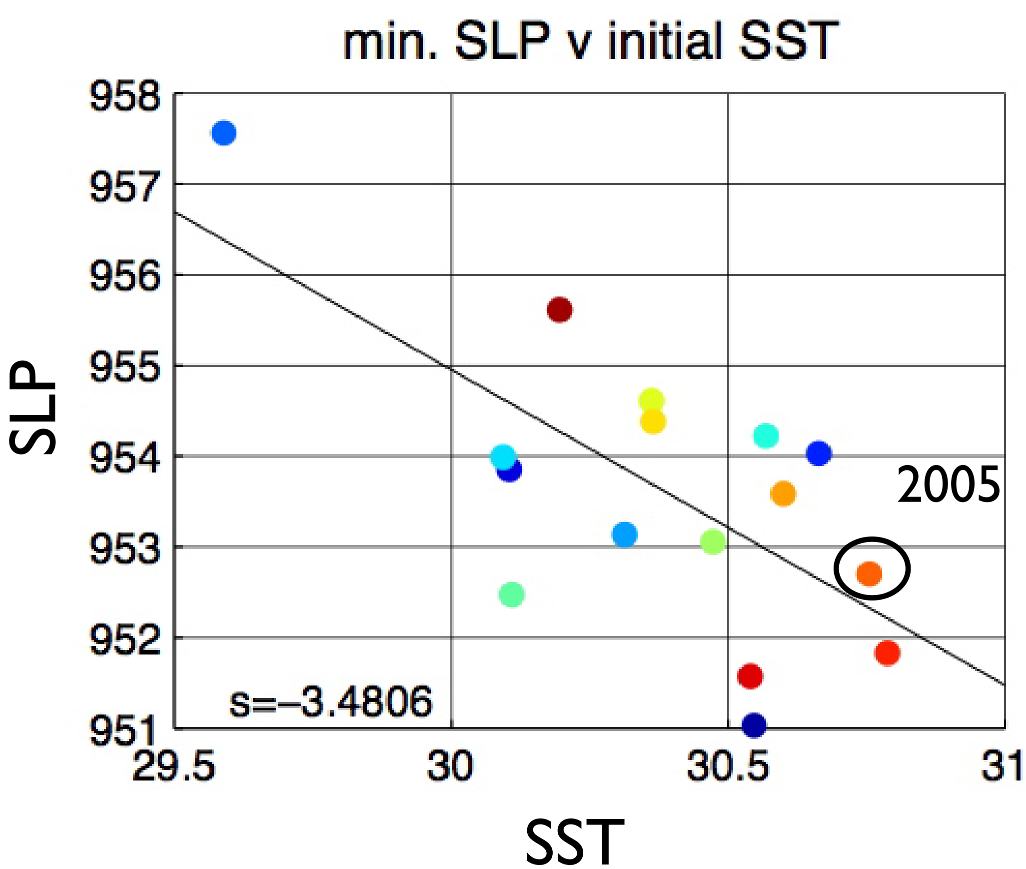


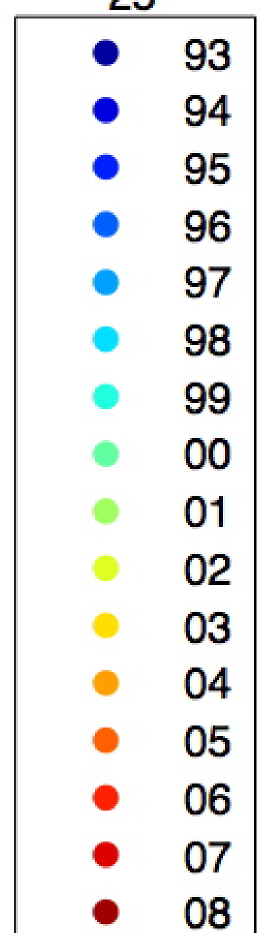
- Tracks are similar. Most of the storm generation and evolution are driven by atmospheric conditions.
- But, the maximum intensity of storm is affected by different ocean states.
- Intensity is generally weaker in other years compared to 2005.
- Indicating that 2005 ocean state was favorable to the intensification of Katrina.
- **What is the relative impact of SST and UOHC?**
- UOHC (or Hurricane Heat Potential, Leipper and Volgenau 1972) is defined as the integrated heat content down to depth of T=26C (**D26**).

Sensitivity of Katrina intensity to ocean states in different years





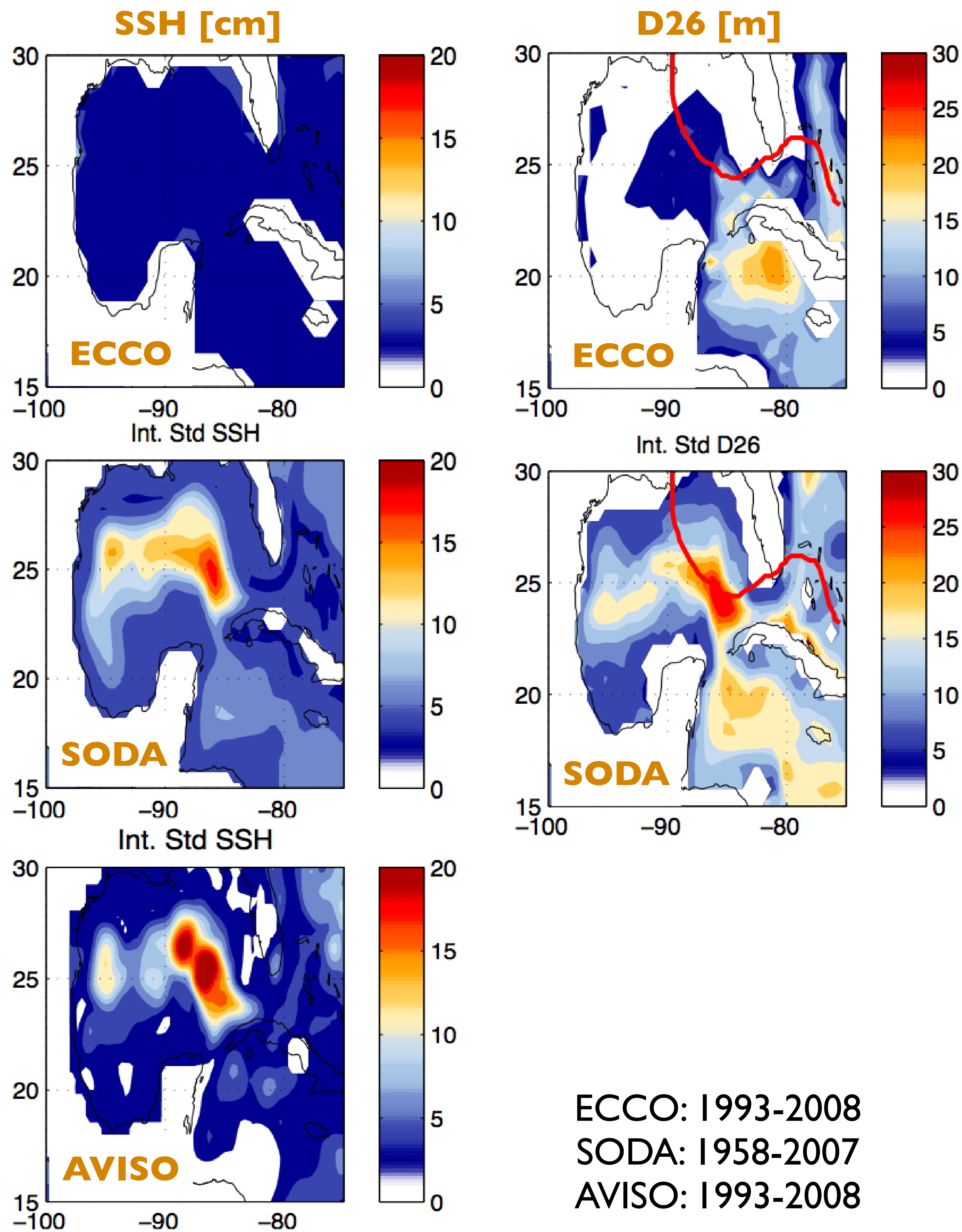




- Intensity of storm was more sensitive to the initial SST; ~6mb.
- D26 or UOHC shows an incorrect correlation with SLP.
- However...

Interannual variability of dynamic topography is underestimated in ECCO.

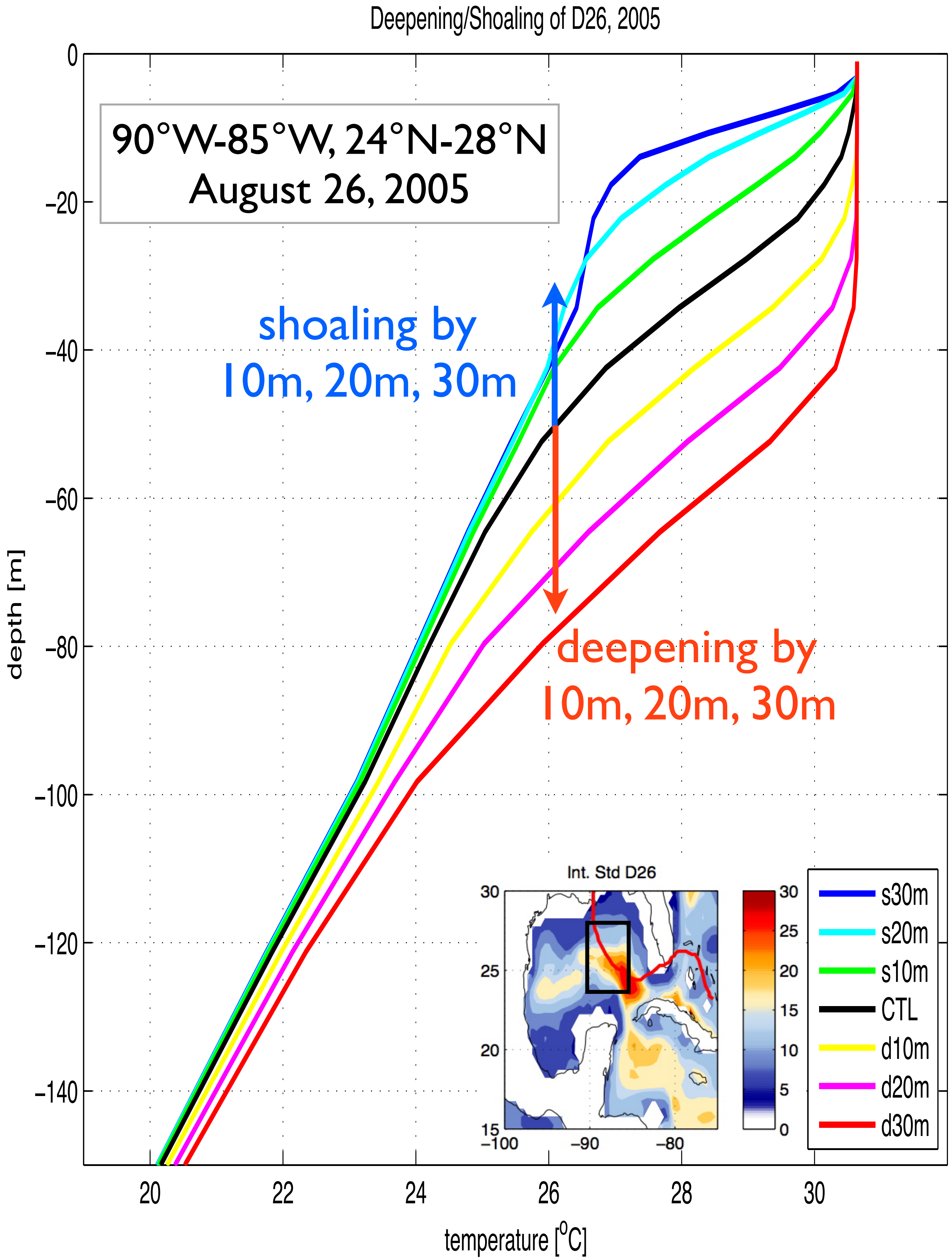
- SODA suggests interannual variability of D26 of **~30 meters** where Katrina passed over.



ECCO: 1X1,10-daily; kf066b
SODA: 0.5X0.5, monthly, No assimilation of altimeter data

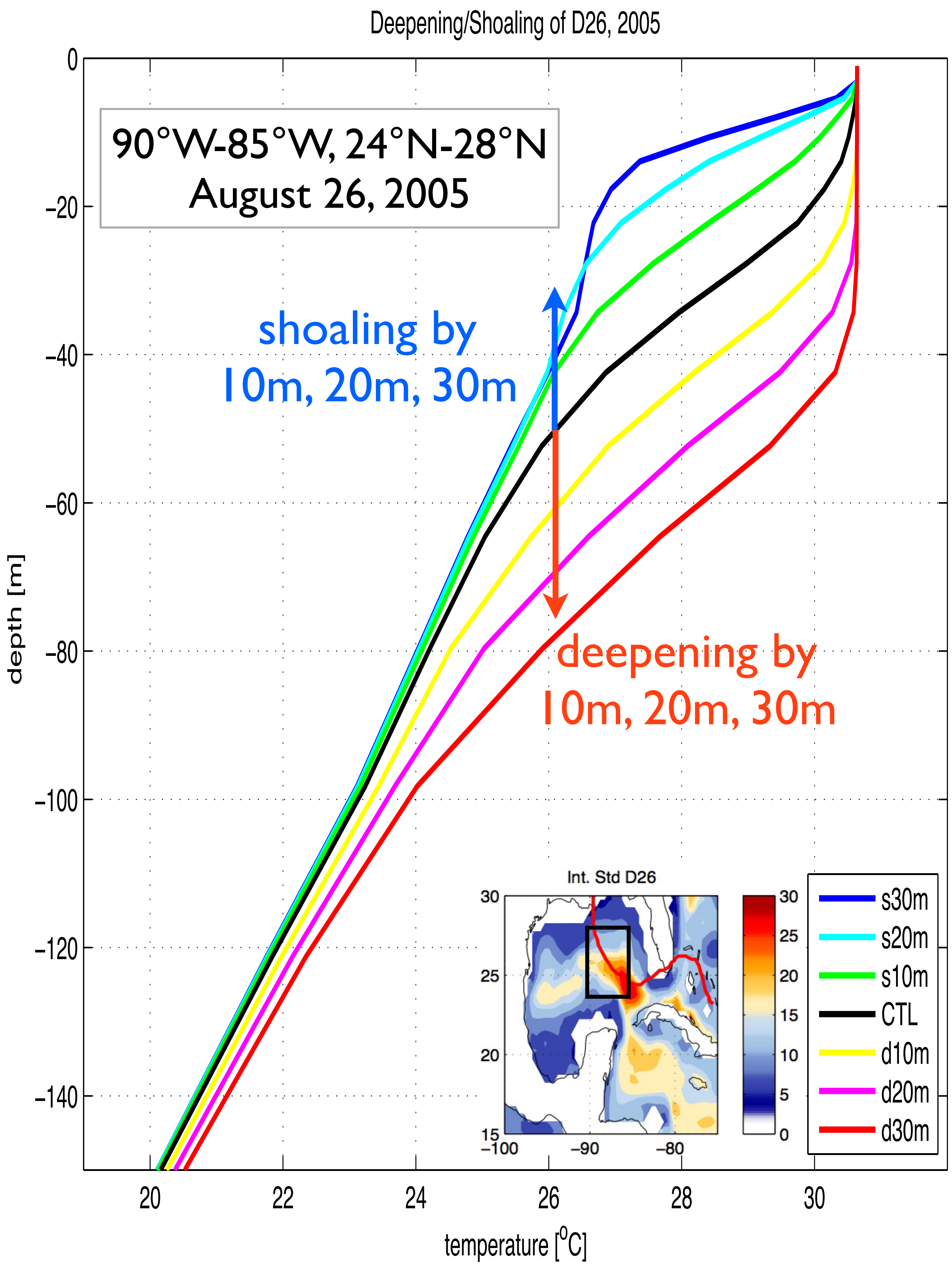
ECCO: 1993-2008
SODA: 1958-2007
AVISO: 1993-2008

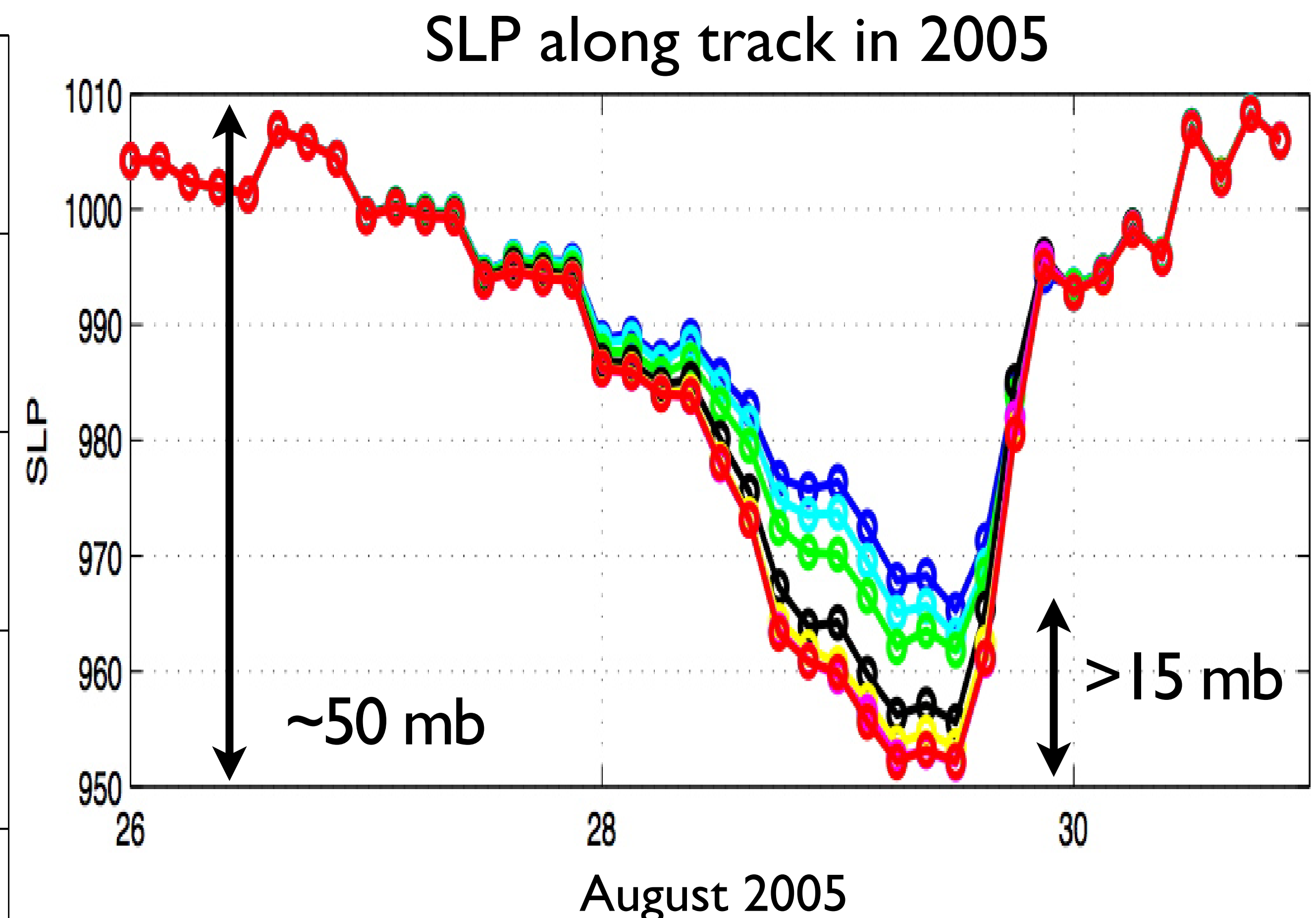
Alter D26 in initial conditions



- Alter depth of 26°C isotherm, increasing/ decreasing the heat content of the ocean.
- ±30 m change in D26 gives >15 mb change in SLP in 2005 ➔ Corresponds to 30% of SLP variation.

Alter D26 in initial conditions





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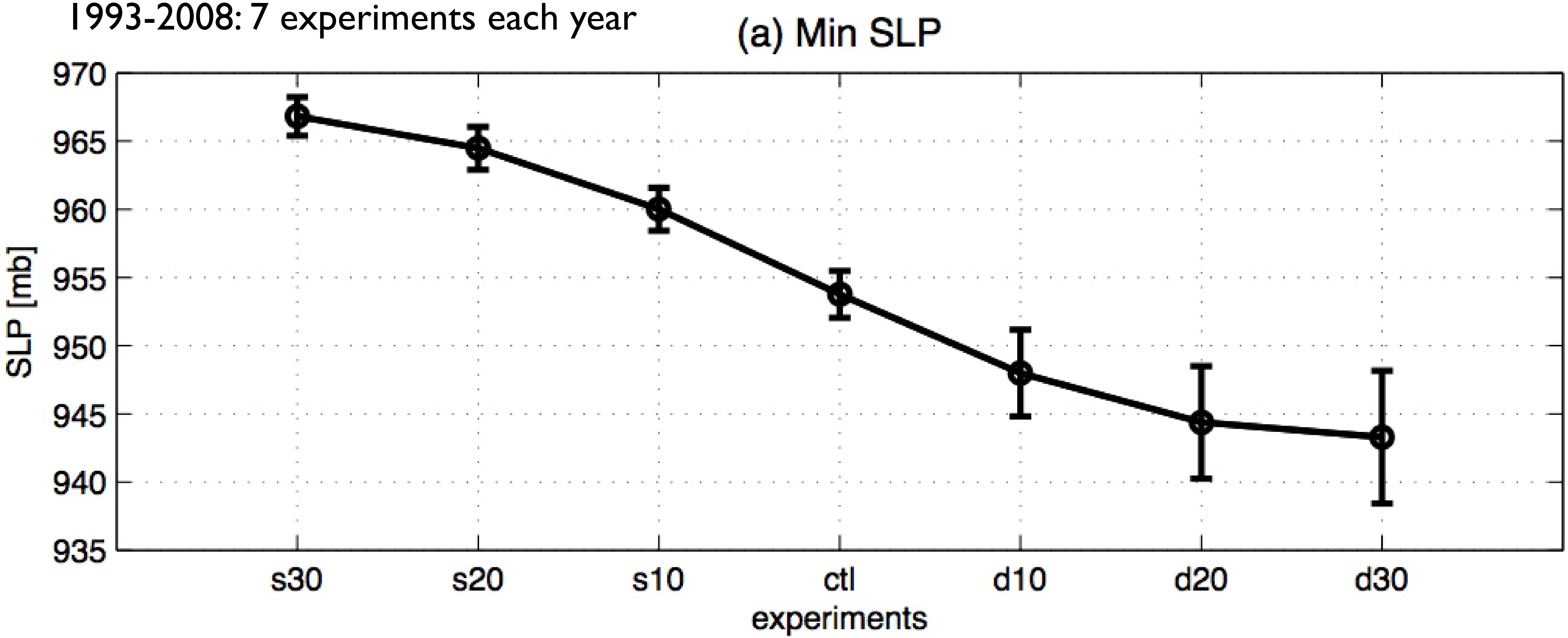
Storm intensities in sensitivity experiments

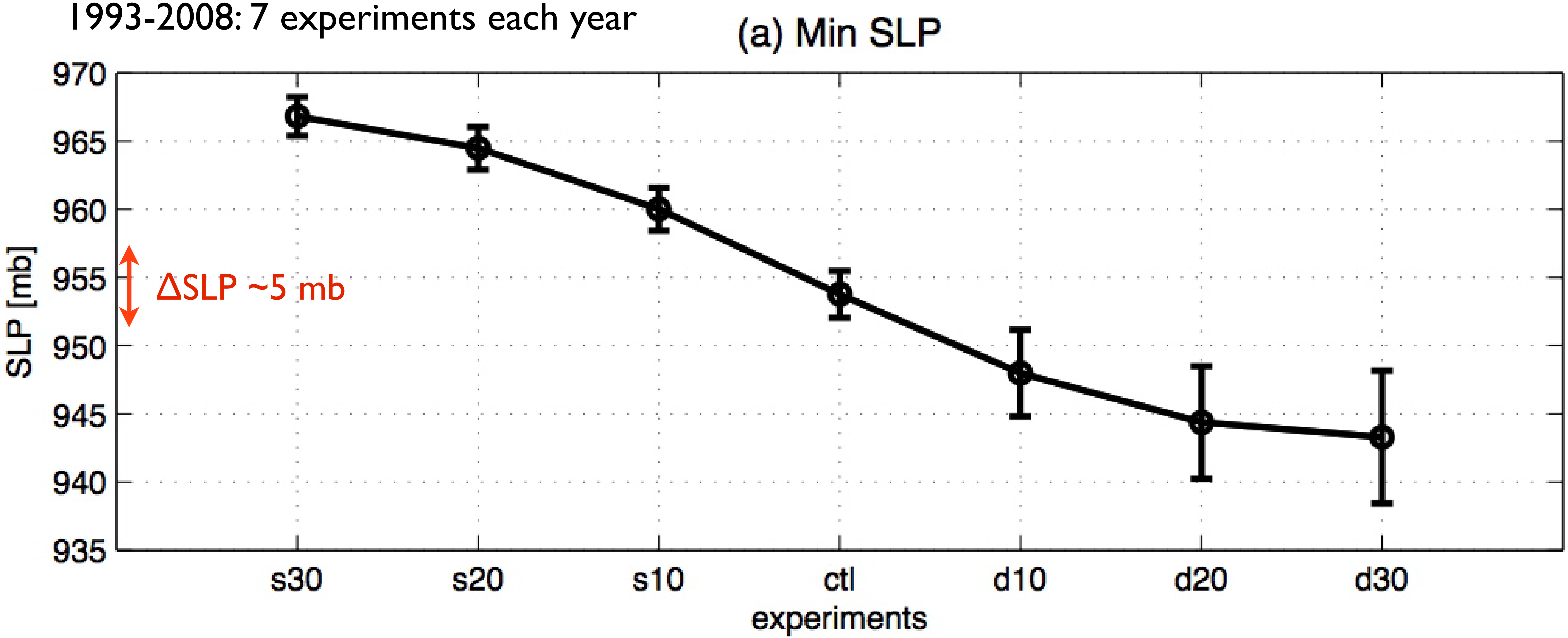
1993-2008: 7 experiments each year



- TC intensity is negatively correlated with D26.
- Variability is greater in warmer ocean conditions than colder ocean conditions.

Storm intensities in sensitivity experiments

1993-2008: 7 experiments each year



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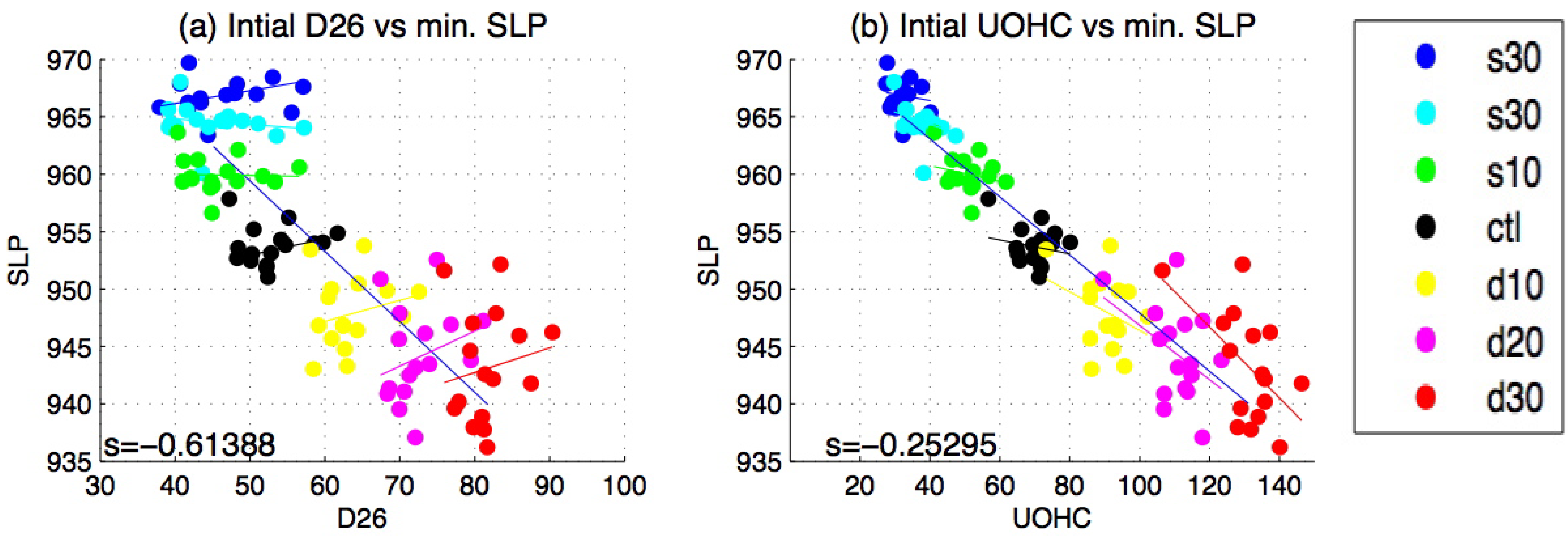
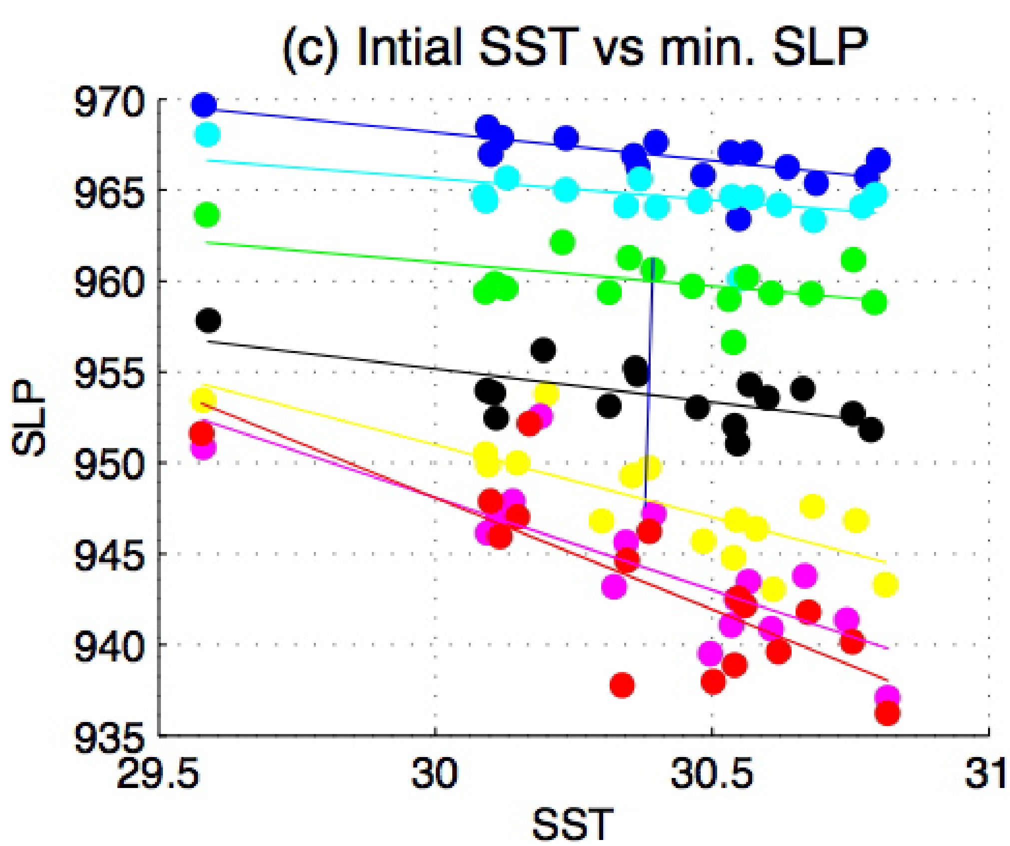
Min. SLP and initial ocean state





- Interannual SST variation is negatively correlated to storm intensities; ~5-15 mb.
- The same SST can cause greater SLP variation for different D26.

- Interannual D26 variation has an incorrect sign of correlation with SLP.
  - If interannual D26 variability is increased to match that of the observations, then SLP has a robust negative correlation with D25; >25 mb.

- UOHC reflects these two features.

Summary of Part 2

- For *strong* TCs, UOHC (D26+SST) is a more useful predictor, than SST alone, for the intensification (e.g., Leipper and Volgenau, 1972, Goni et al. 2003...).
- In the experiments, D26 generates a wider range of intensity response of TCs.
- Inclusion of dynamic topography in a statistical prediction model does improve intensity forecast in the NHC (up to ~20%).

✓ Storms will likely become fewer but more intense in a changing climate.

✓ Oceanic heat content will increase under global warming.

- The connection and impact of the two may become more important.

Concluding remarks

- Regional coupled downscaling is a powerful research tool for
  - air-sea interaction and climate dynamics on all time-spatial scales,
  - role of ocean and atmosphere in regional climate change,
  - interdisciplinary regional prediction system on weather and climate

Thanks!