Applications of a regional coupled model to studies of global warming and hurricane-ocean interaction

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Outline

1. **Climate simulation**: downscaling projection of global warming scenario ➔ Role of oceanic eddies and currents in Atlantic.

2. **Weather simulation**: Impact of ocean state (SST, D26, UOHC) on TC intensity ➔ Case study of Hurricane Katrina

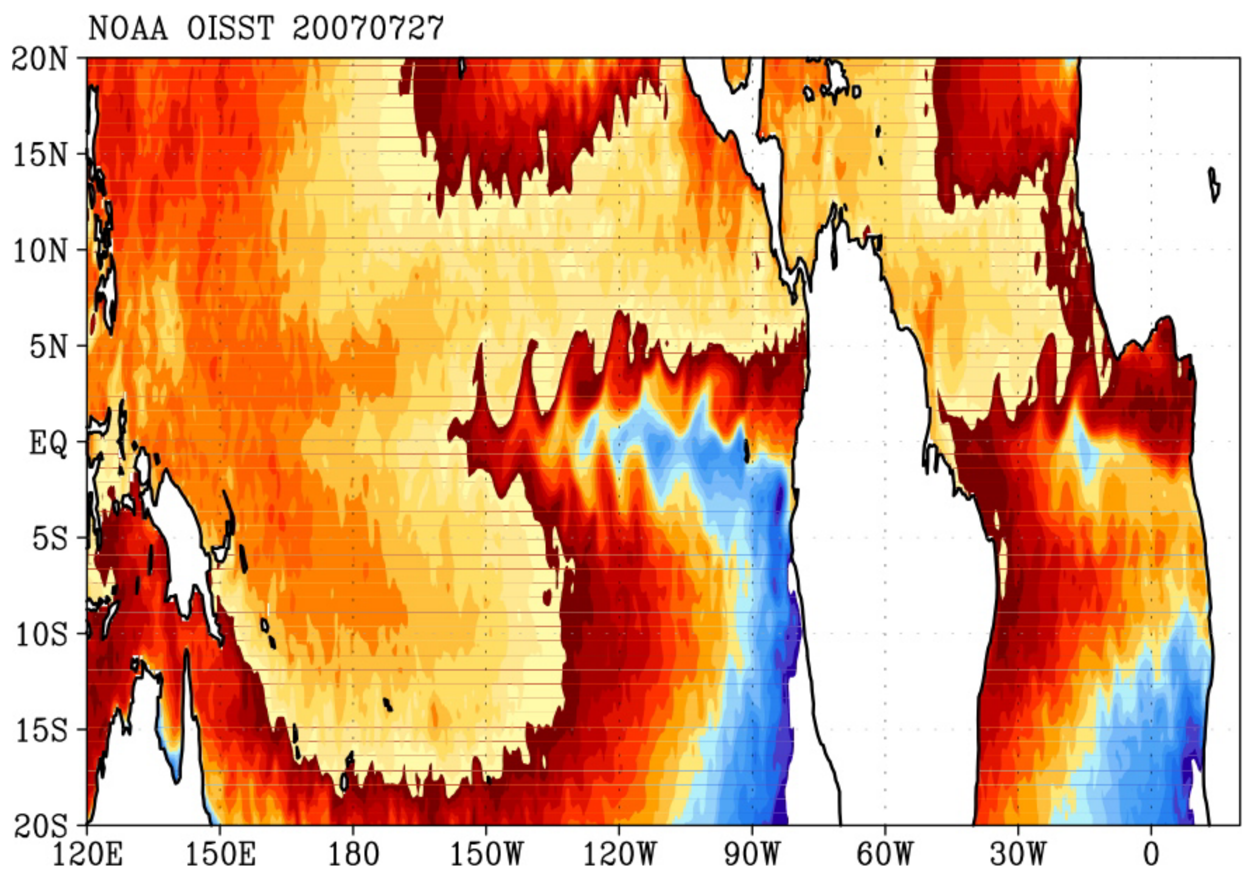
1. *Equatorial* Atlantic Ocean's response to global warming forcing

• CGCMs for projections of climate change need to resolve all the relevant feedback processes.

• Example: Tropical instability waves (TIWs)

• Not well-resolved in IPCC-AR4 models and their impact is unexplored.

• So we need to resolve them by downscaling.



SST snapshots from NOAA OI SST (25 km) on July 27, 2007

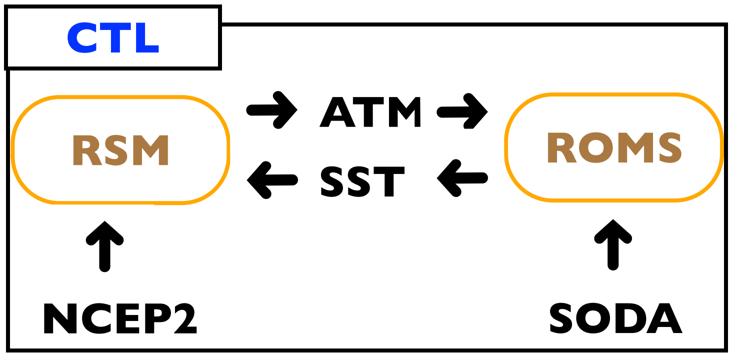
Model and experiments

Scripps Coupled Ocean-Atmosphere Regional Model

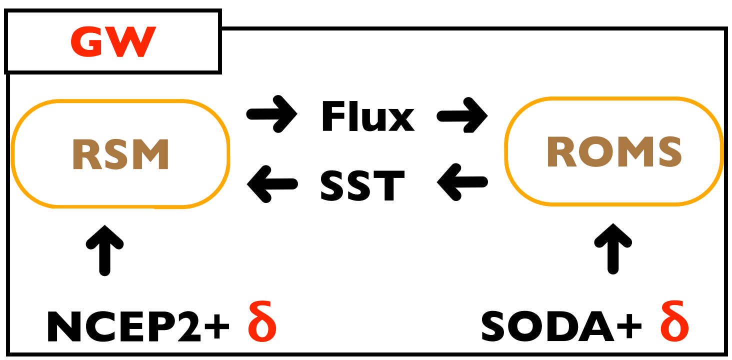
(Seo et al. 2007, *J. Climate*)

Atmosphere: Regional Spectral Model (Scripps RSM)

Ocean: Regional Ocean Modeling System (ROMS)

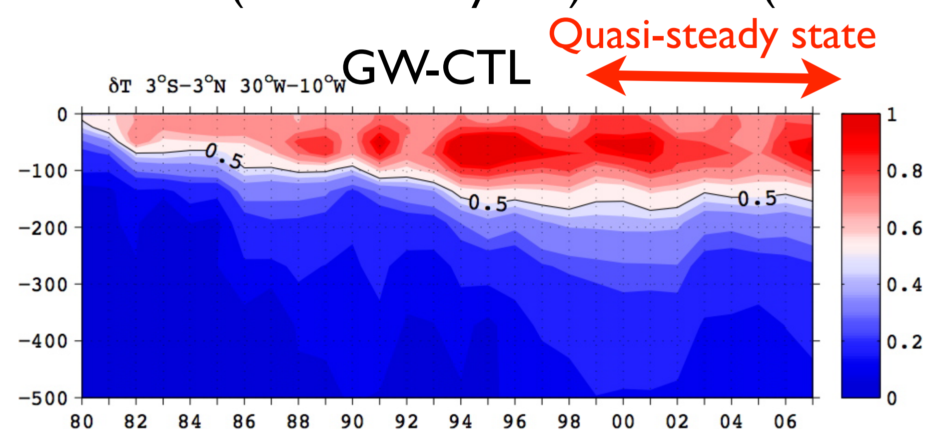


- **CTL**: RSM (NCEP2 6hrly) + ROMS (SODA monthly)
- 25 km ROMS + 50 km RSM
- Daily coupling based on Fairall et al. (1994)
- 28-yr. integration: 1980-2007
- Atmospheric spectral nudging > 1000 km

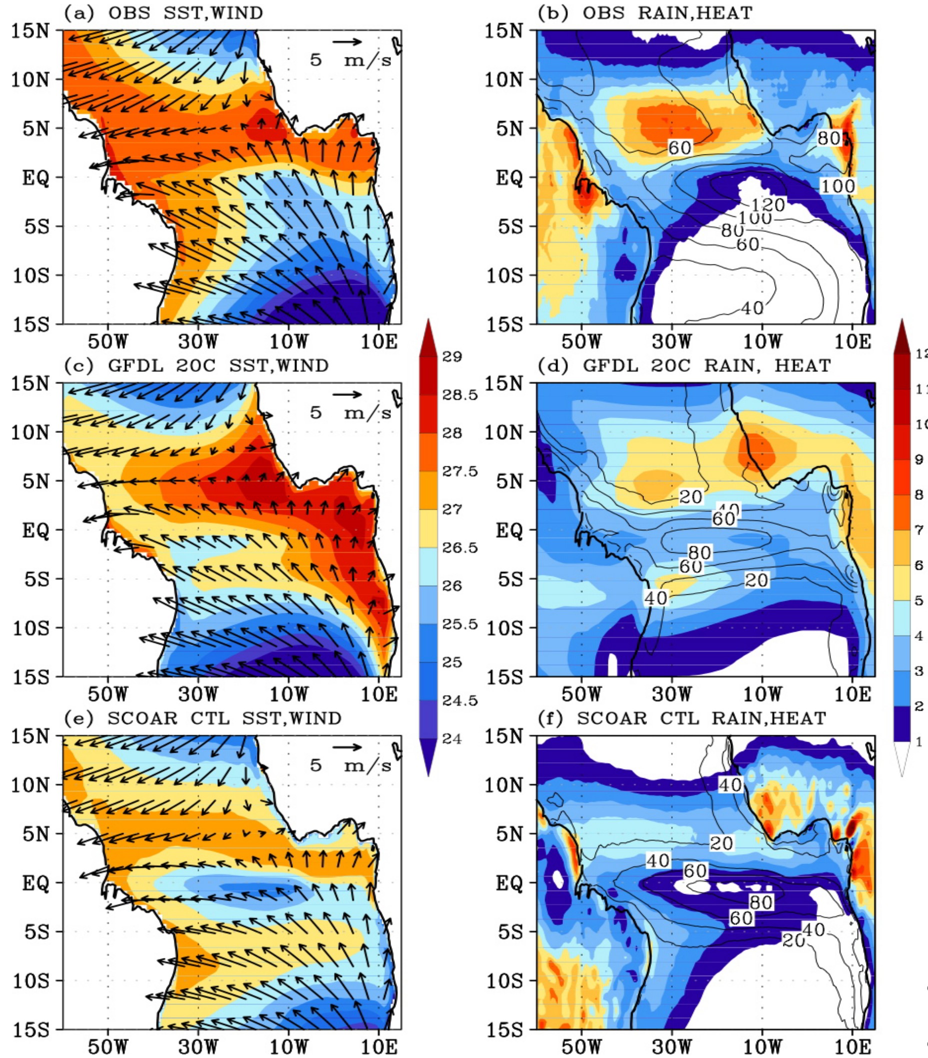


pseudo global warming experiment

- 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)

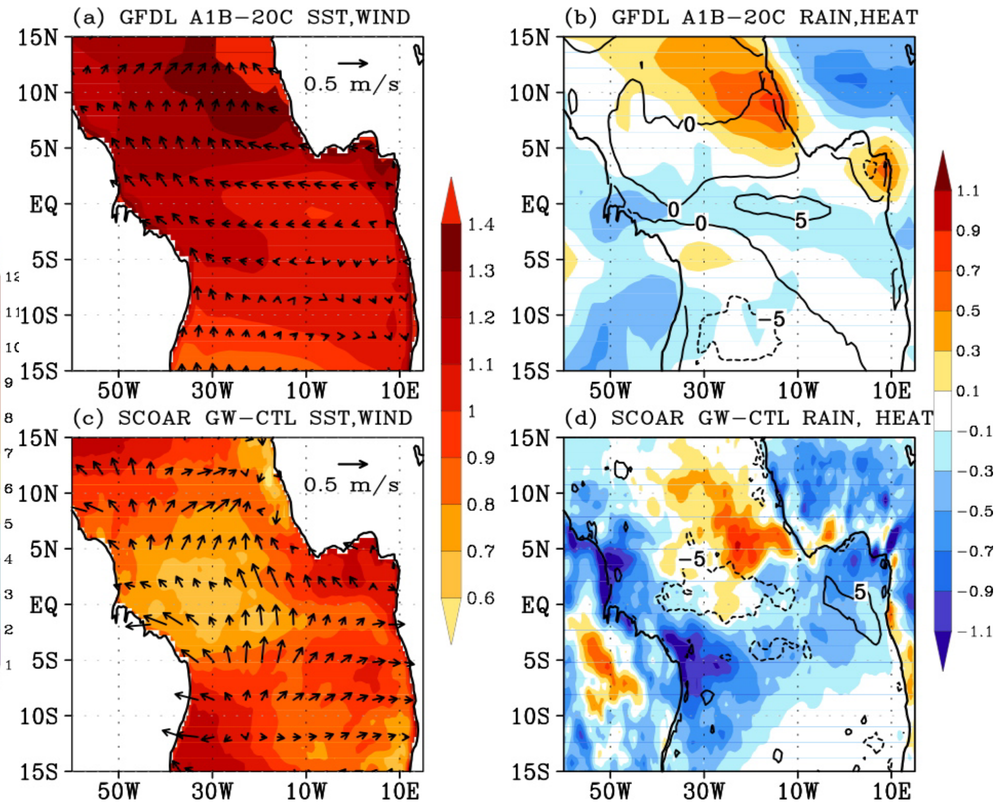


Simulation of present-day climate



• Zonal SST gradient and equatorial cold tongue in SCOAR

GW response (GW-CTL)



• Reduced warming in the equator
• Intensified cross-equatorial meridional winds and surface divergence

Why reduced waring in cold tongue?

➔ Eg., Change in vertical temperature advection within cold tongue

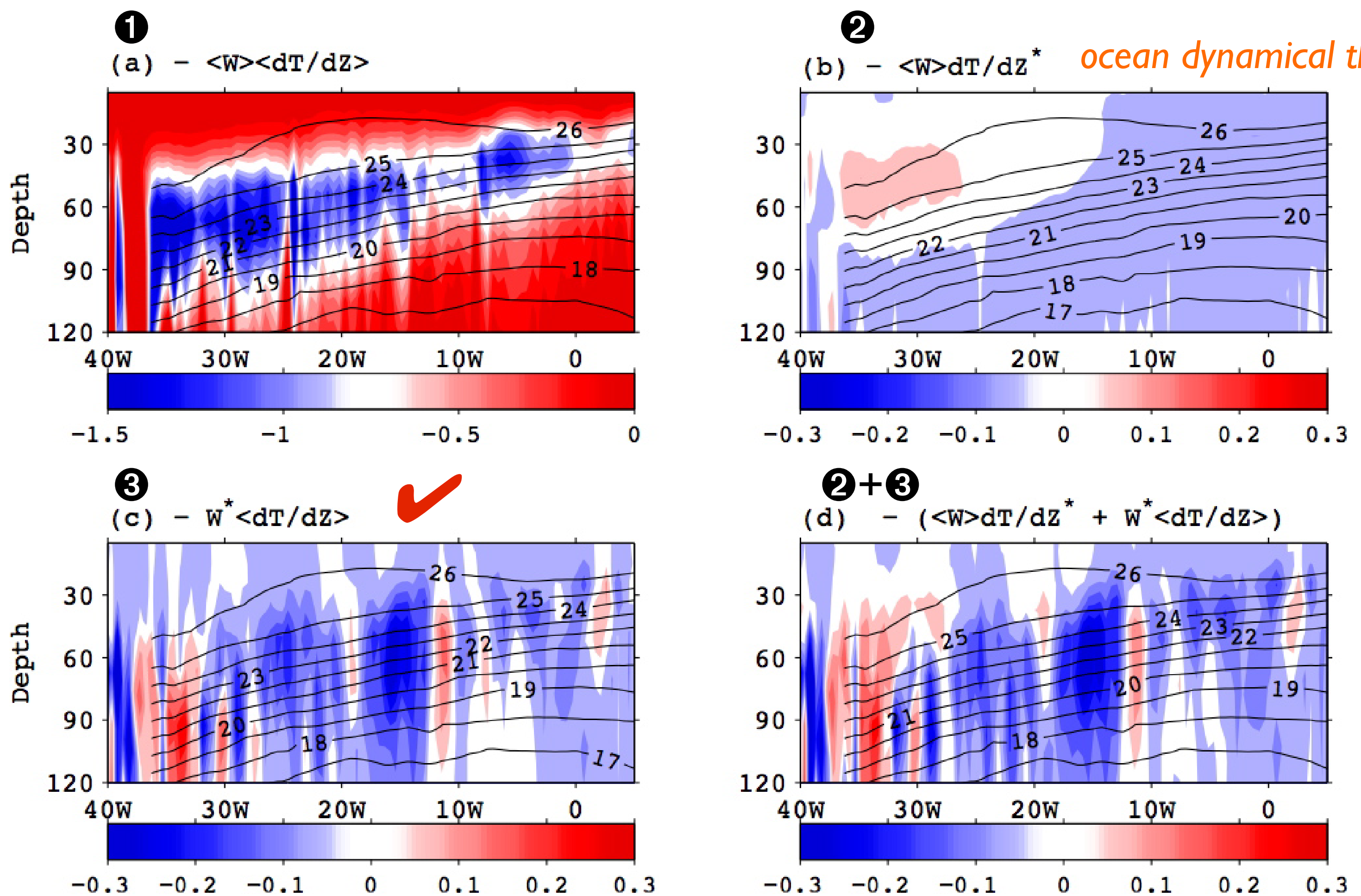
❶ ❷ ❸ ✔ ❹

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

<>: climatological mean (CTL)

*: Perturbation from global warming (GW-CTL)

ocean dynamical thermostat (Clement et al. 1996)



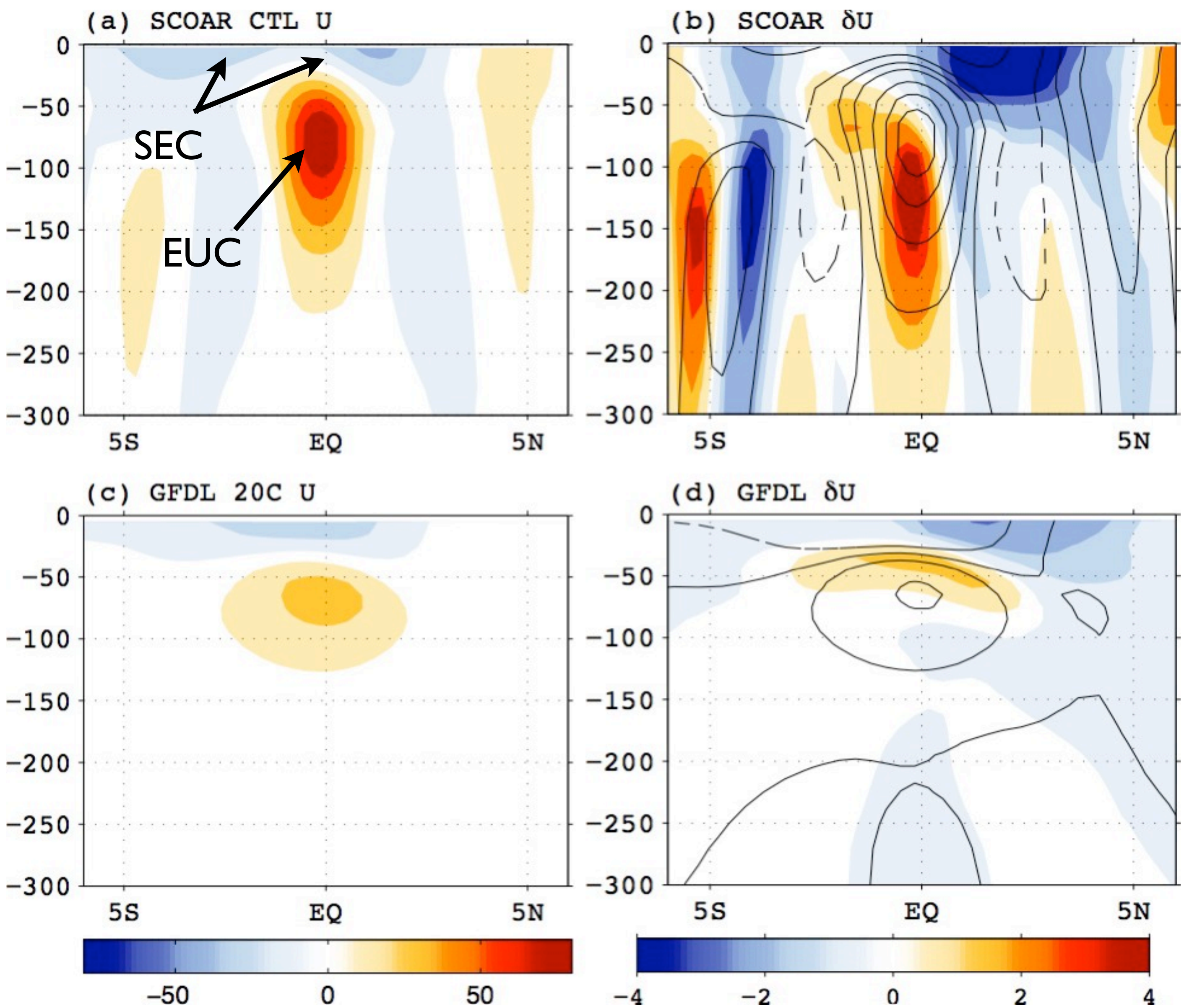
❶: climatological equatorial upwelling

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

❸: Stronger cooling by ***increased vertical velocities***

cf., an ocean dynamical thermostat in the Pacific and the Atlantic.

Change in equatorial zonal currents and equatorial instability

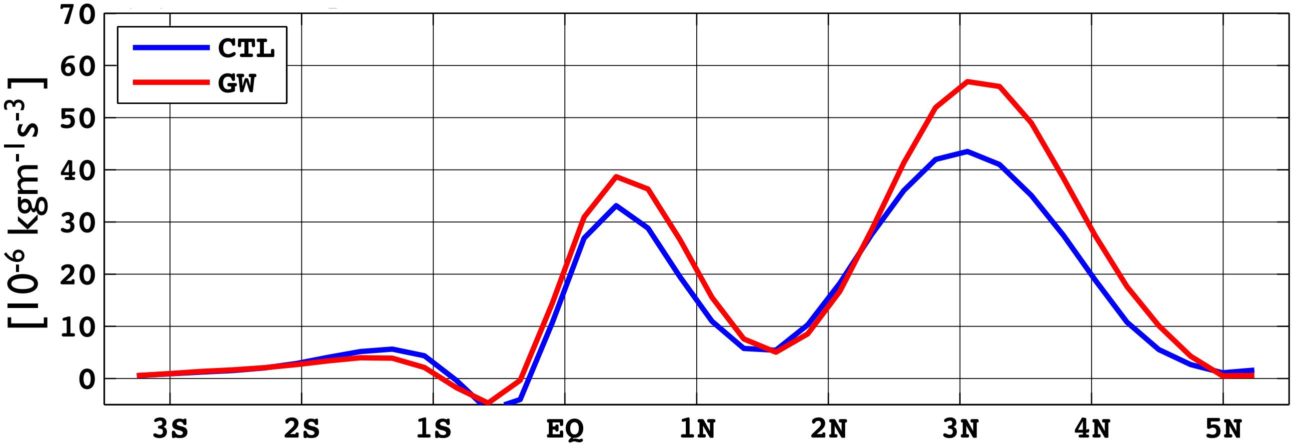


- 30°W-10°W
- EUC/SEC/NECC/TJ are more realistic (stronger) in SCOAR.

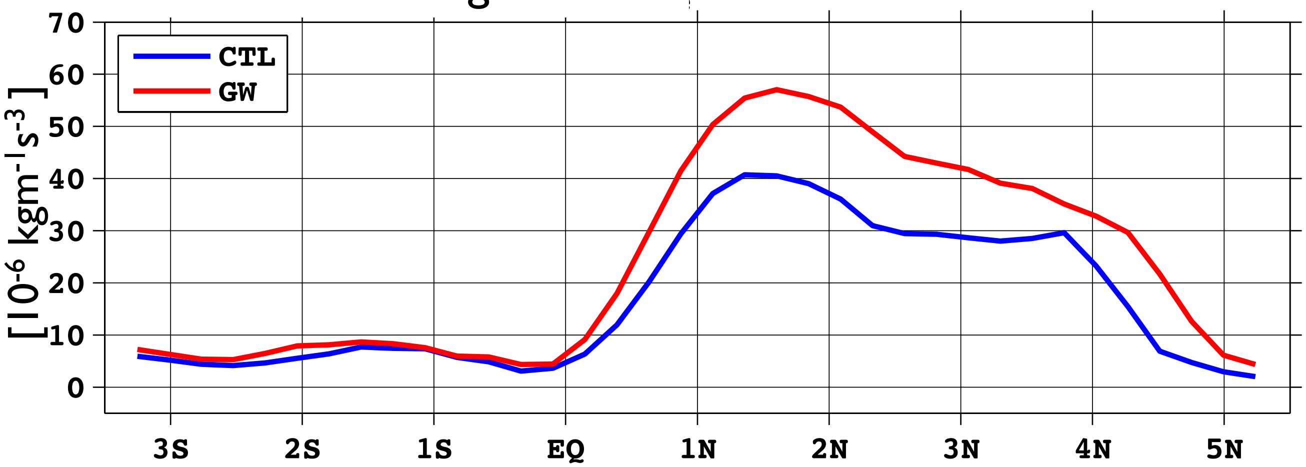
- Stronger northward cross-equatorial wind ➔ Stronger EUC (*Philander and Delecluse, 1983*)

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

Barotropic convergence rate

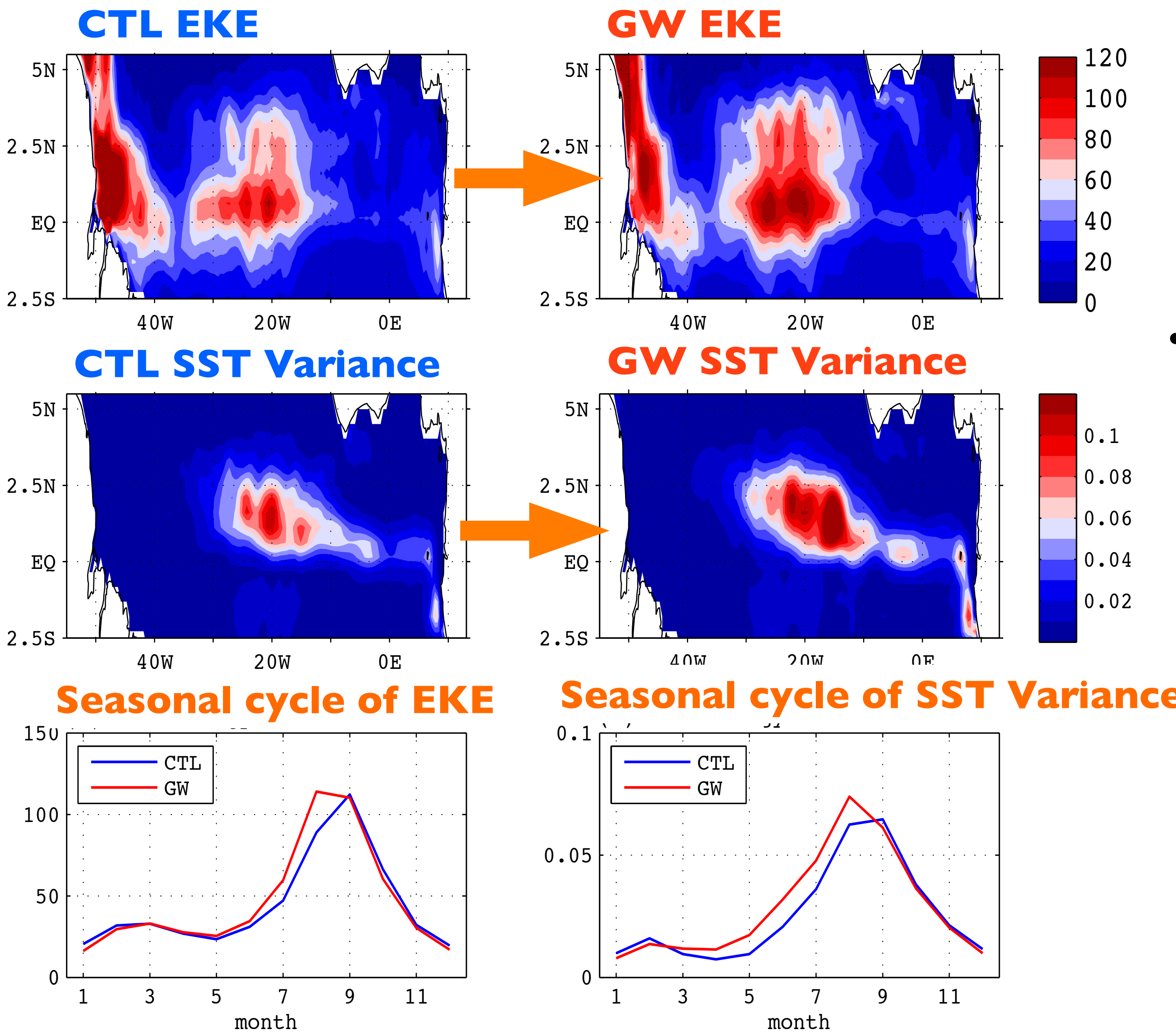


Baroclinic convergence rate



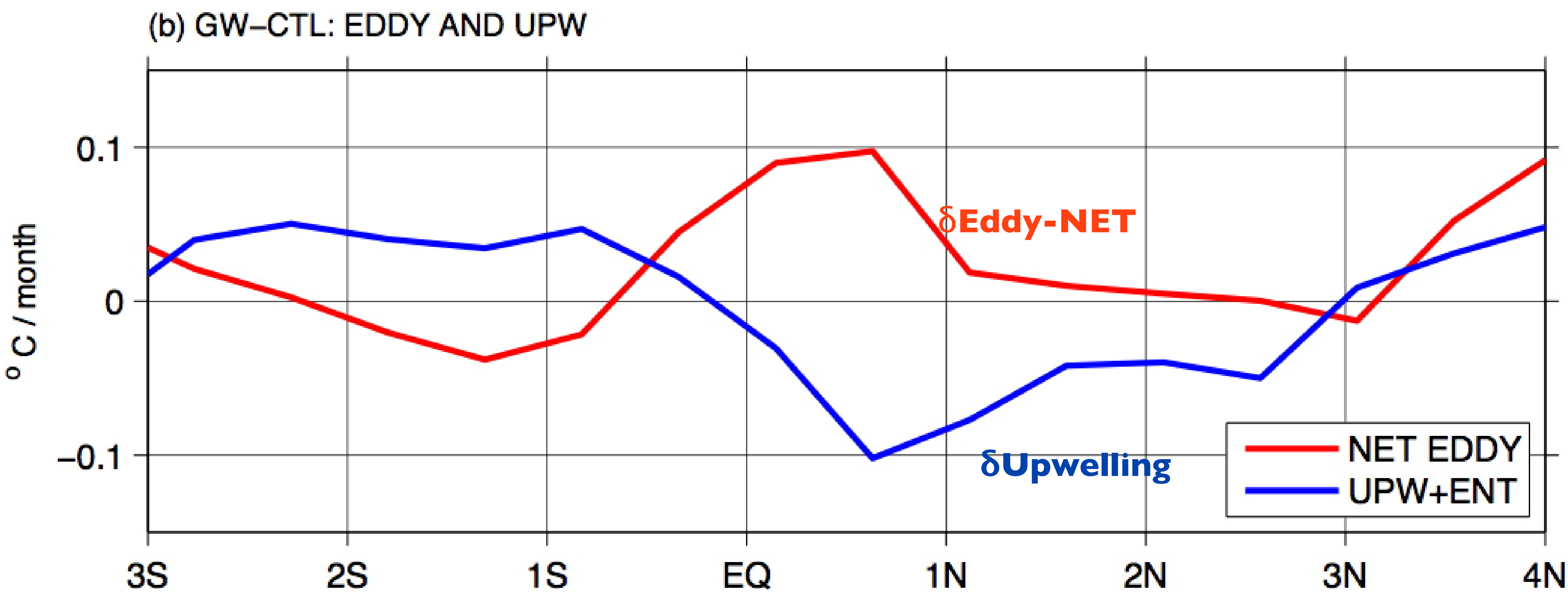
- Barotropic and baroclinic convergence are dominant energy sources for the TIWs.
- Both BT and BC are strengthened under the environmental changes associated with global warming

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%).

Annual mean mixed layer ocean heat budget (30°W-10°W)



• Equatorial upwelling (cooling) increases due to the increased vertical velocities associated with the surface divergence. cf. the tropical Pacific.

• Net eddy heat flux by TIWs is warming in CTL and increases under global warming forcing, damping the effect of increased upwelling.

Summary of Part I

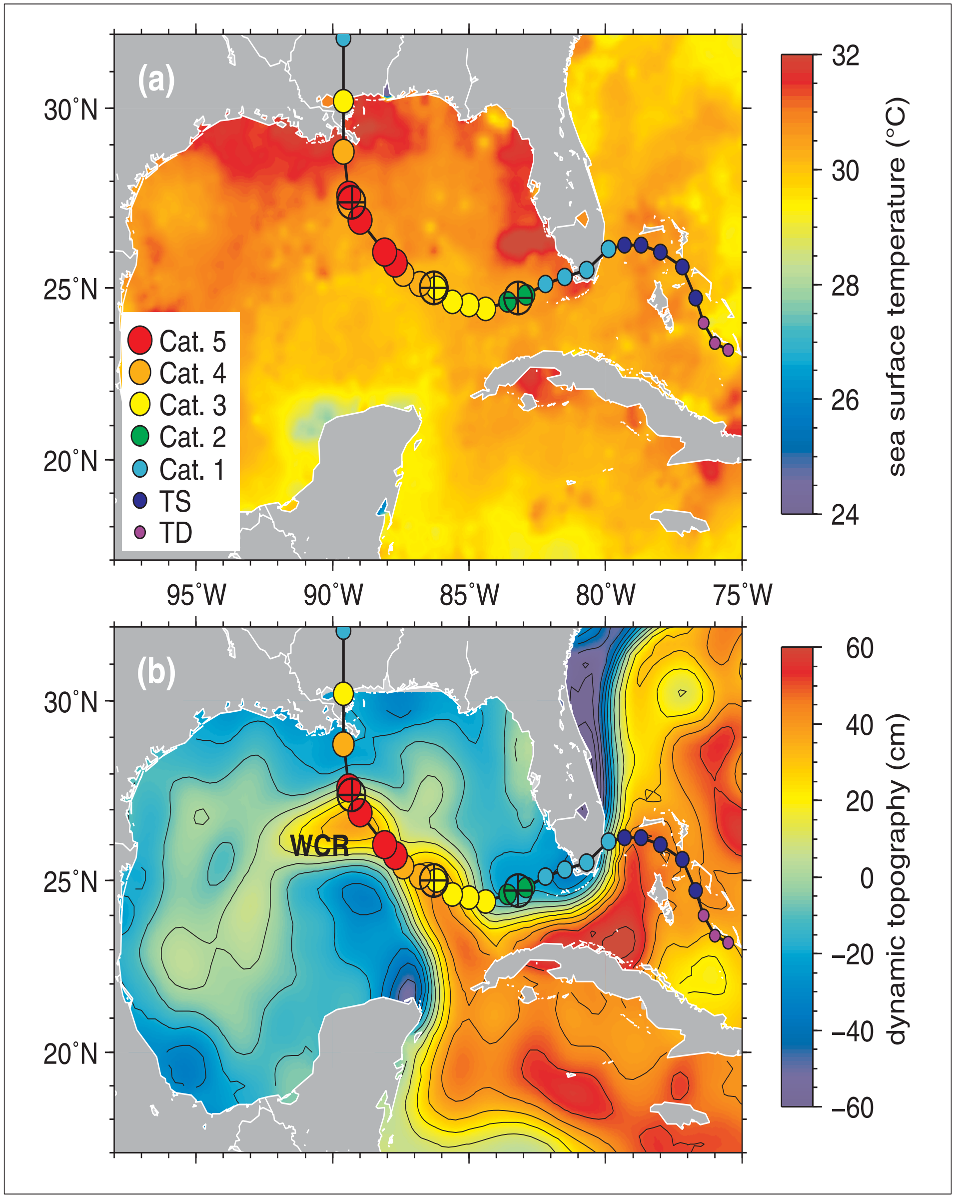
- *Exploratory research*: The first coupled downscaling of climate change scenarios
- Downscaling captures equatorial currents and mesoscale variabilities
- **Upwelling increases. Currents intensify. TIWs strengthen. Impact spatial pattern of mean state warming.**
    - Need to resolve high-freq. processes in the model for global warming research.
- *Challenge*: Drift in mean state in a long-term integration.
    - *Need a consistent nudging technique for large-scale circulations both of the ocean and atmosphere.*

2. Impact of ocean state on TC intensity

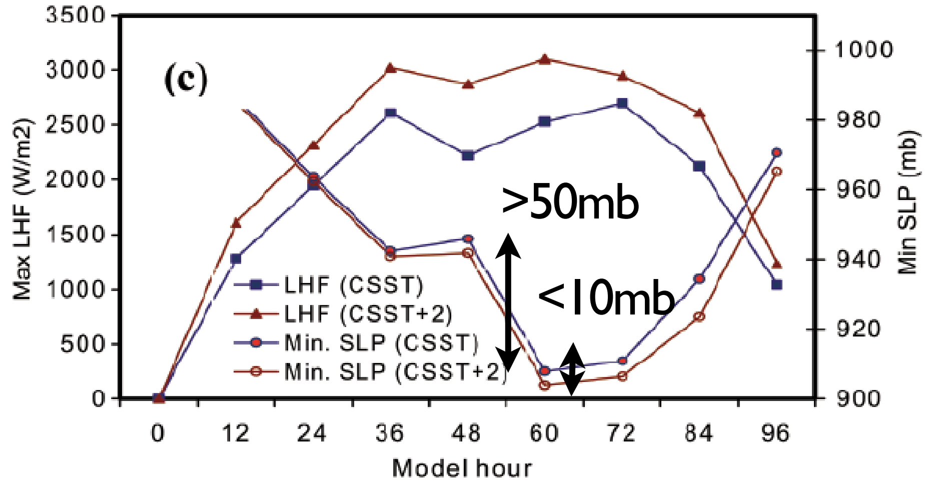
➔ Hurricane Katrina

Rapid intensification over high dynamic topography:

SST alone or upper ocean heat content?



Scharroo et al. 2005 EOS



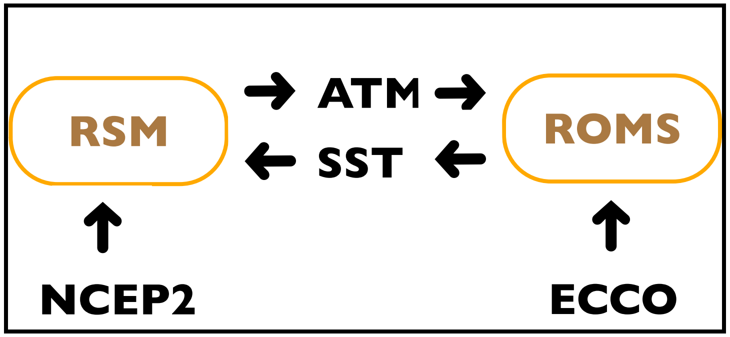
Comment by **Sun et al. 2006 EOS**

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

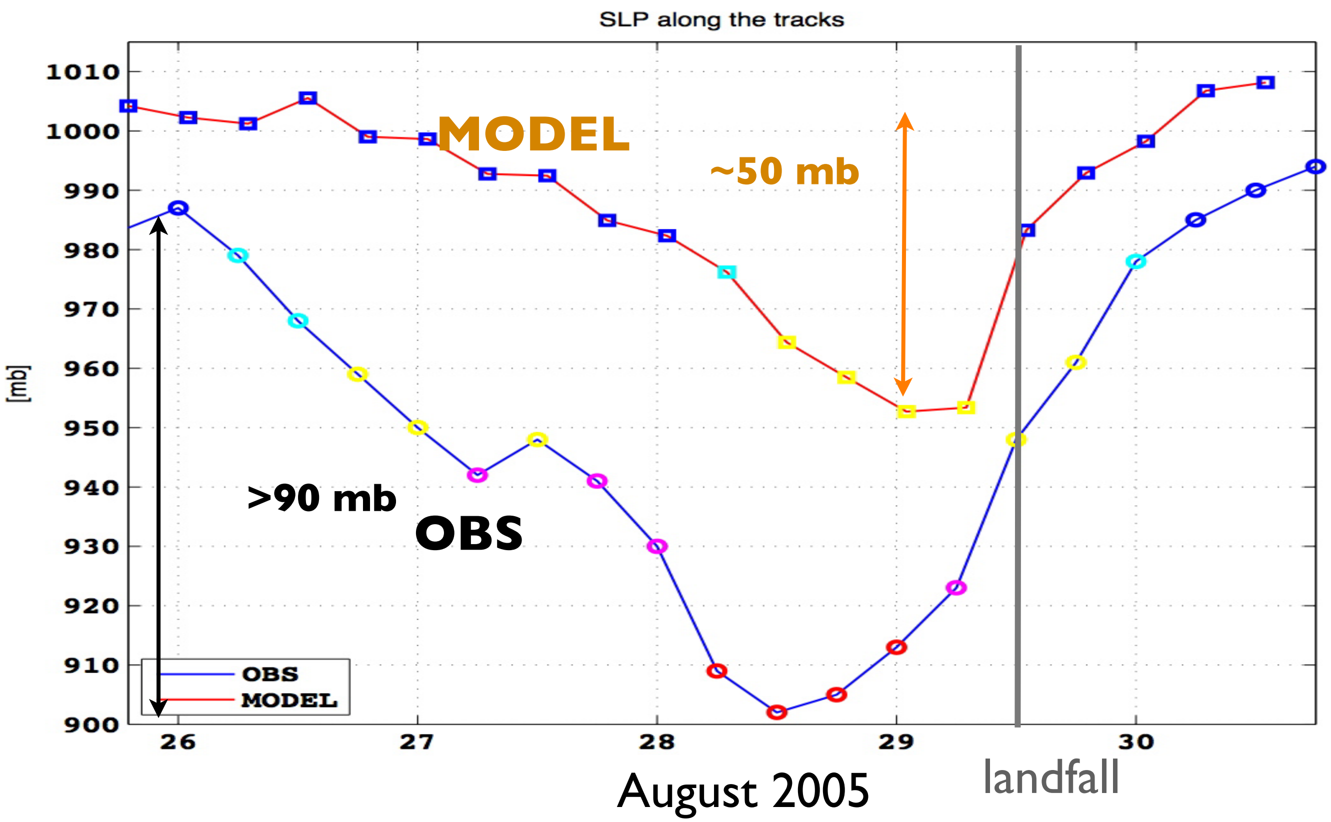
- "SST+2°C" suggests ~10mb; cf, 50 mb increase during RI period over warm eddy.

- **How much of intensification of Katrina in 2005 was due to ocean impact (SST , D26, UOHC)?** Can we quantify this?

Coupled experiment: *Scripps Coupled Ocean-Atmosphere Regional Model*



- RSM (NCEP2 6hrly) + ROMS (ECCO kf066b 10-daily 1°X1°)
- 15 km ROMS + 15 km RSM with matching grids
- 1-hourly coupling based on Fairall et al. (1994)
- 120-hr. integration: Aug. 26 00Z - Aug. 31,00Z, 2005

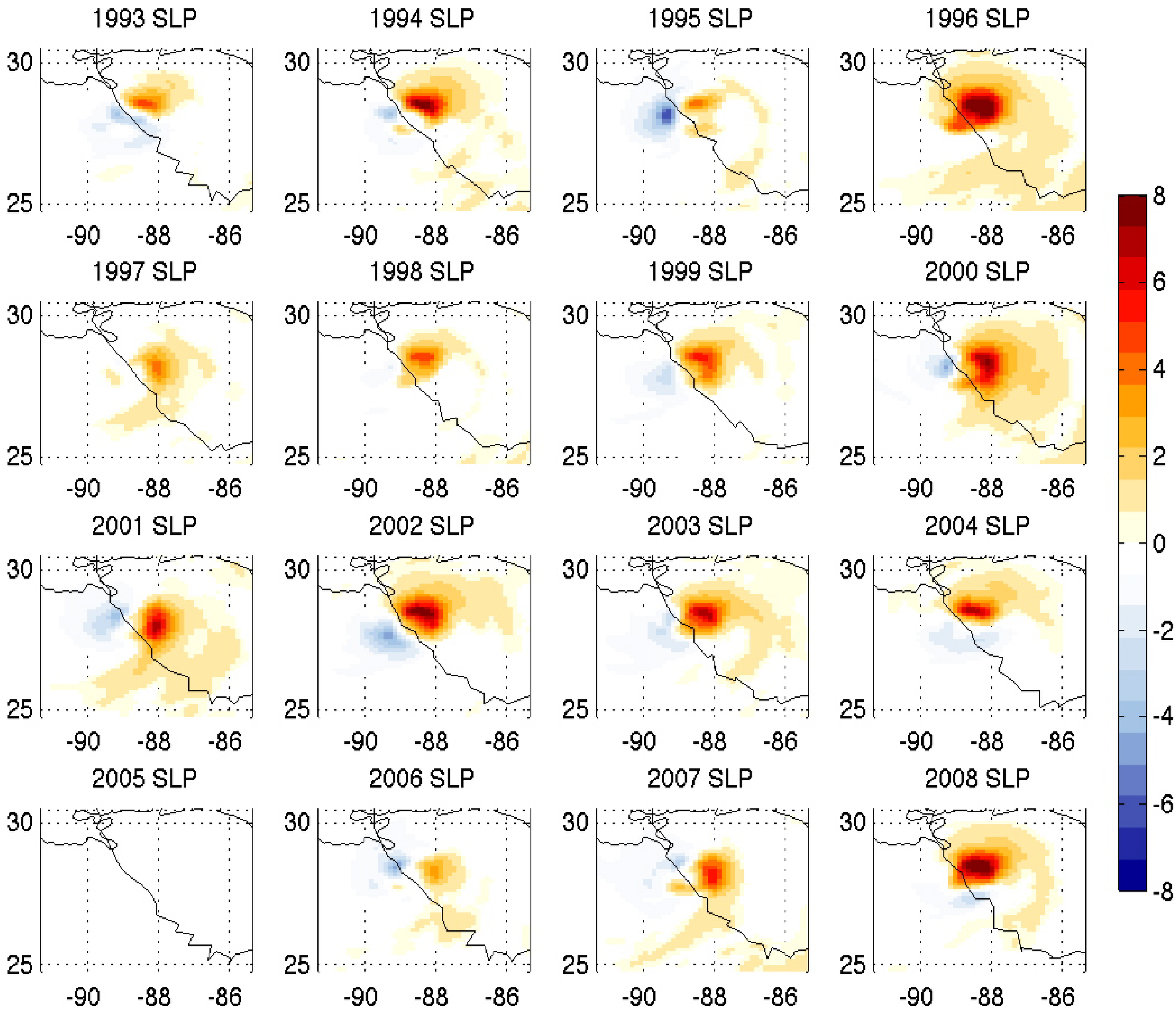


- Simulated Katrina is weak.
- Rapid intensification is underestimated

➔ Need enough time for the storm to spin-up from the initial fields.

➔ We need a good initial maximum wind speed. Bogussing the initial vortex in the NCEP is needed.

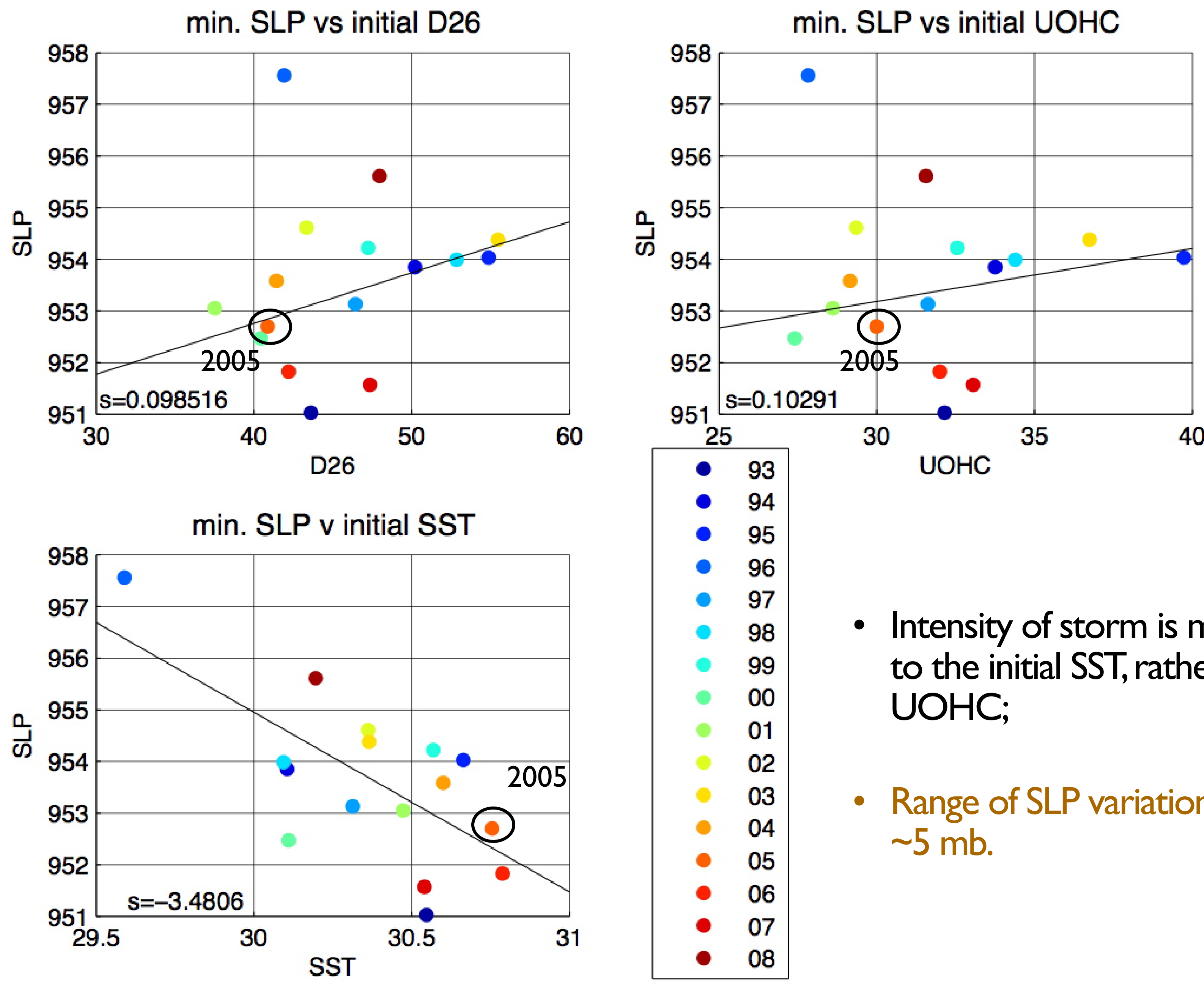
ΔSLP (each year minus 2005) after 74 hrs from initialization



- The same Katrina of 2005, is coupled to ocean states of different years (1993 to 2008).
- Katrina is generally weaker compared to 2005.
- Indicating that 2005 ocean state was favorable to the intensification of Katrina. → "*The Perfect Ocean*" for Katrina.
- **So, is weaker Katrina in other years due to SST or UOHC?**

→ We have to look at the oceanic *initial* conditions.

Sensitivity of Katrina intensity to ocean states in different years

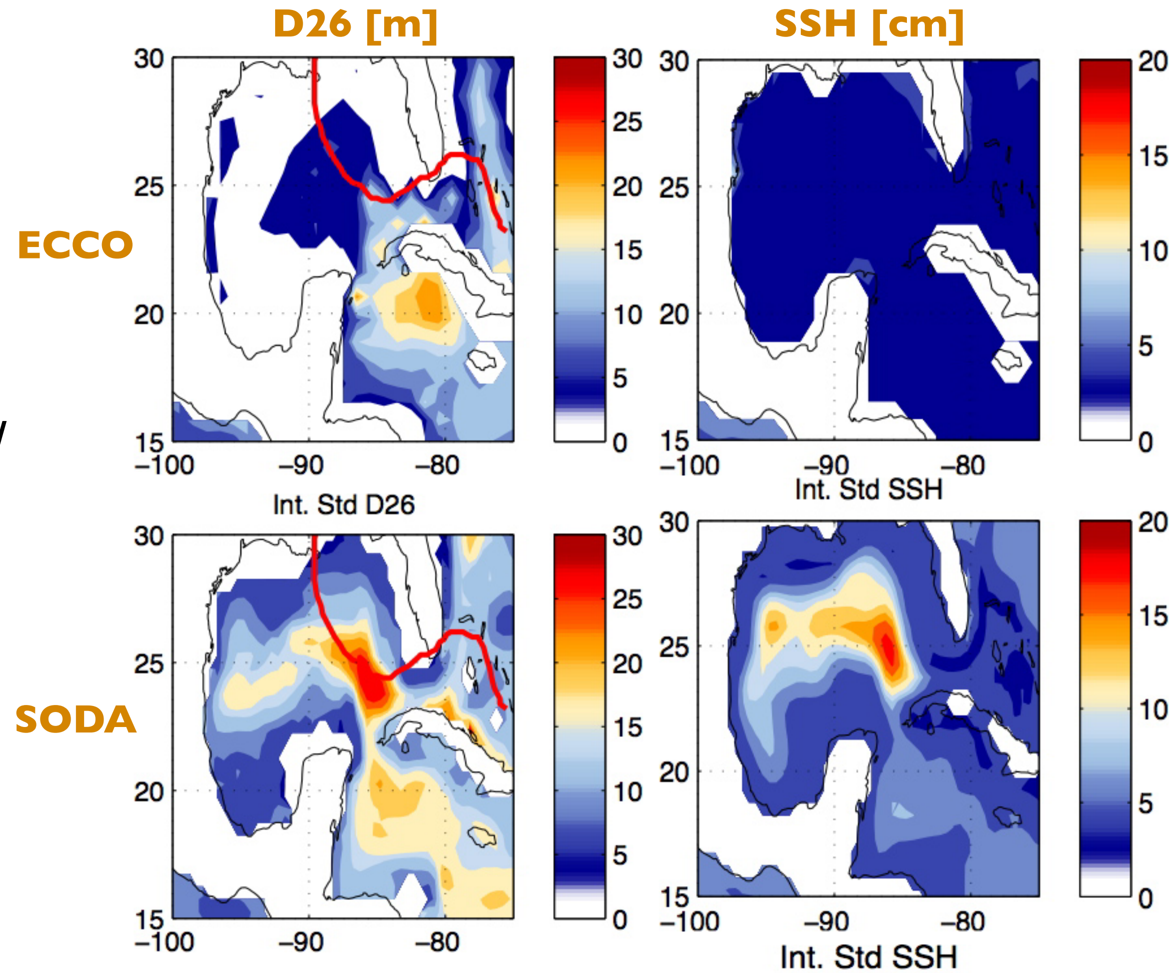


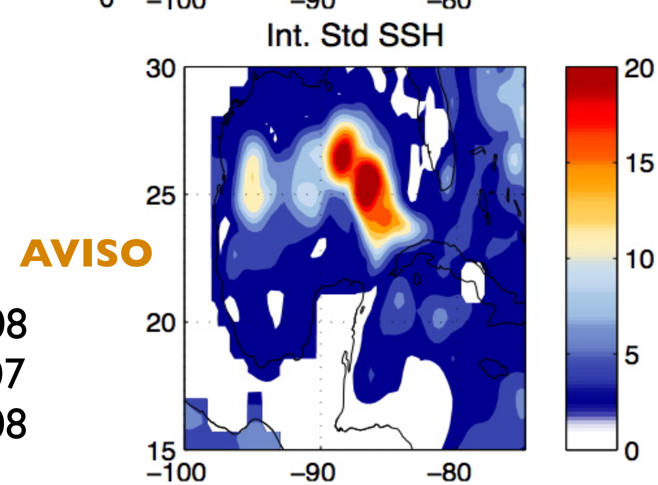
- Intensity of storm is more sensitive to the initial SST, rather than D26 or UOHC;
- Range of SLP variation due to SST is ~5 mb.

Interannual variability of ECCO D26 is underestimated.

- Interannual variability of D26/ SSH in ECCO is too weak compared to that of SODA and AVISO altimeter data.

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

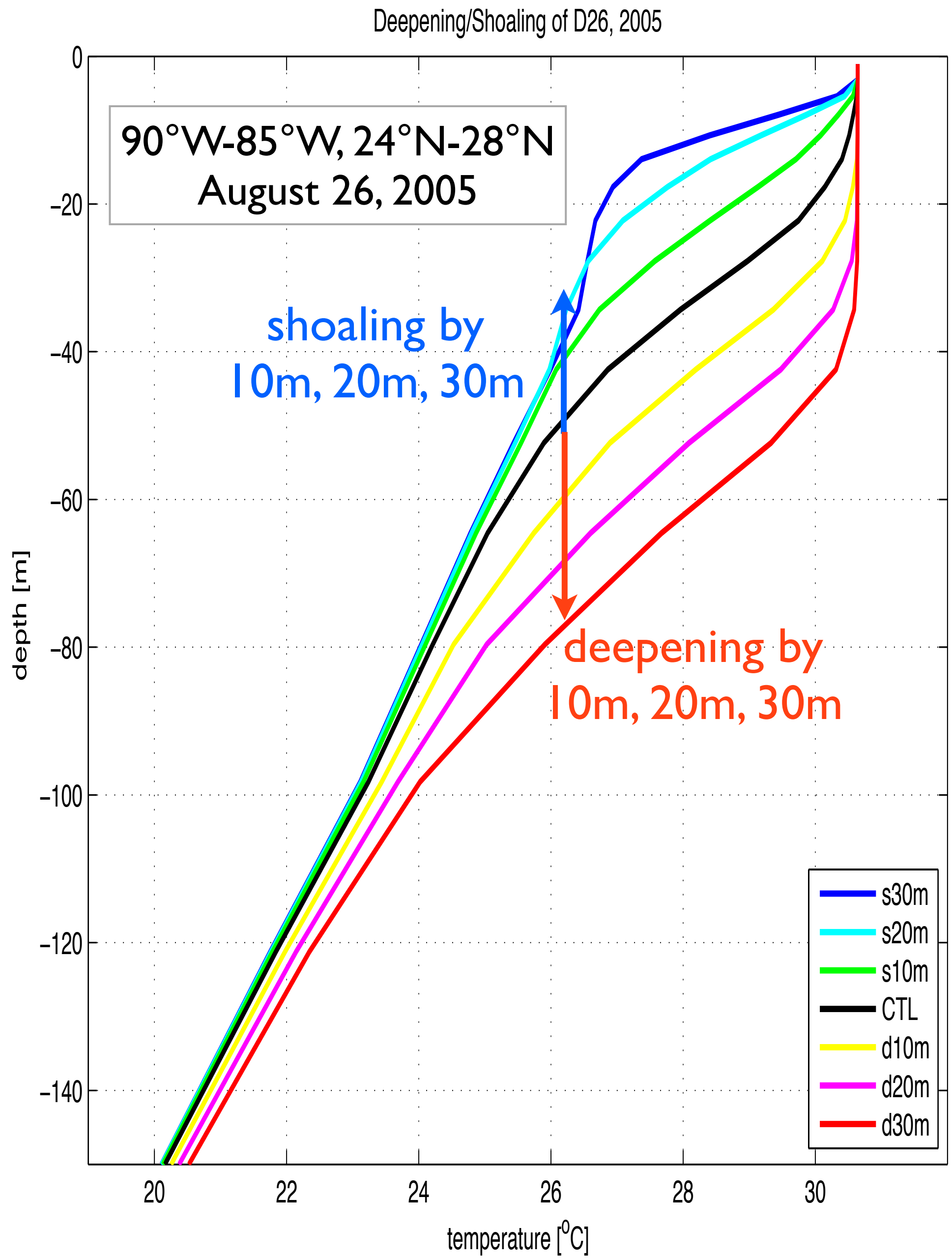




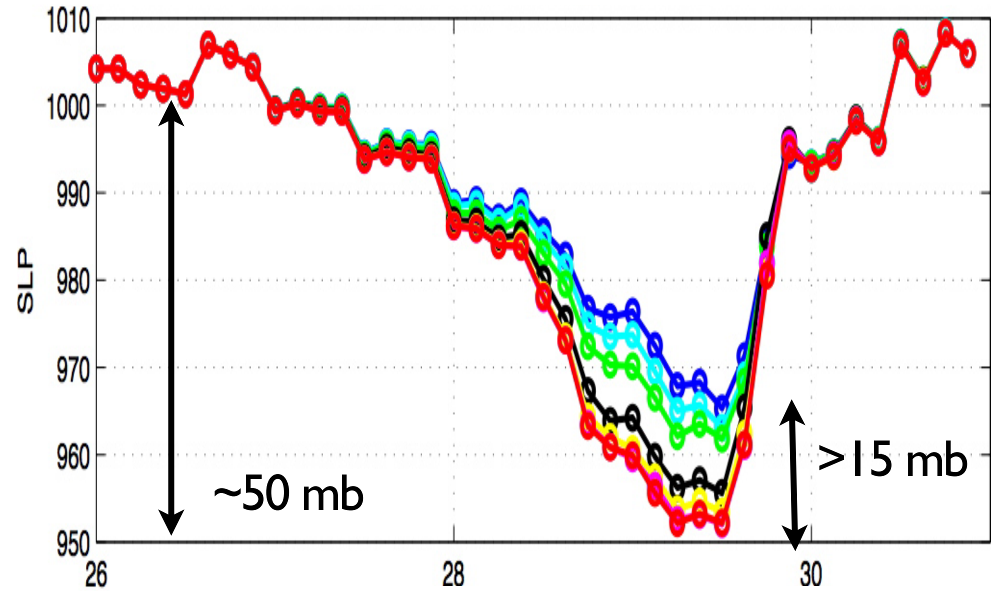
ECCO: 1X1,10-daily; kf066b
SODA: 0.5X0.5, monthly, No assimilation of altimeter data

ECCO: JUN-NOV, 1993-2008
SODA: JUN-NOV, 1958-2007
AVISO: JUN-NOV, 1993-2008

Alter D26 in initial conditions without changing SST



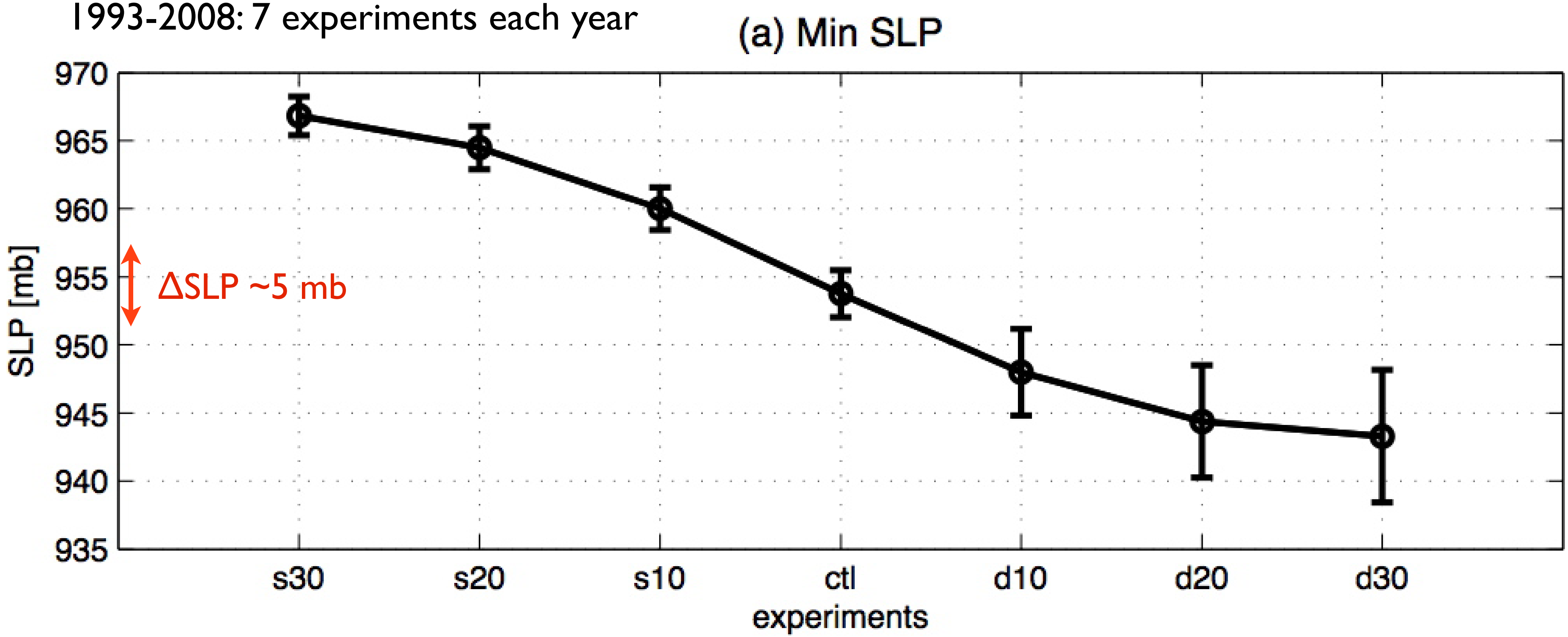
SLP along track in 2005



- 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 reduction in CTL case.

Storm intensities in sensitivity experiments

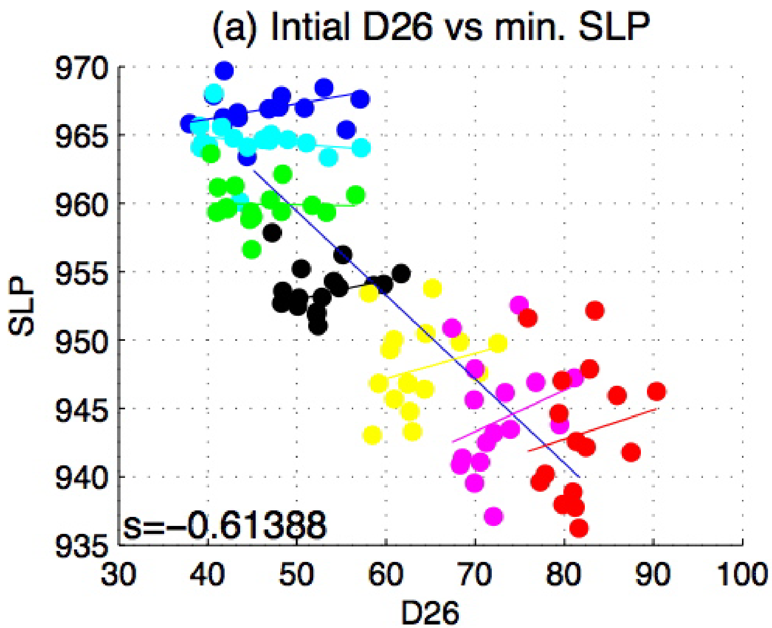
1993-2008: 7 experiments each year

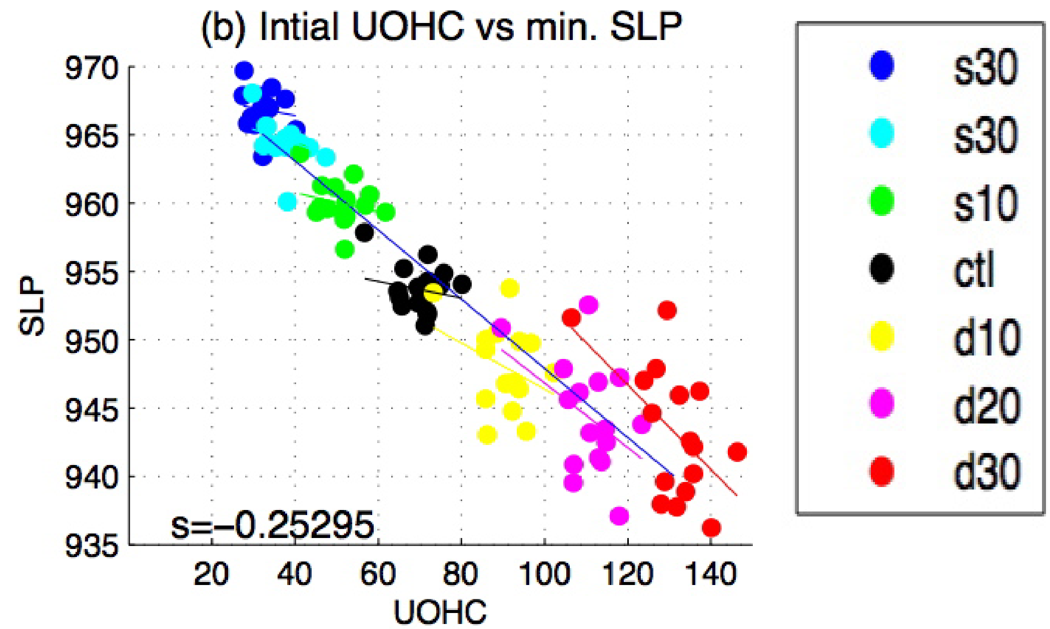


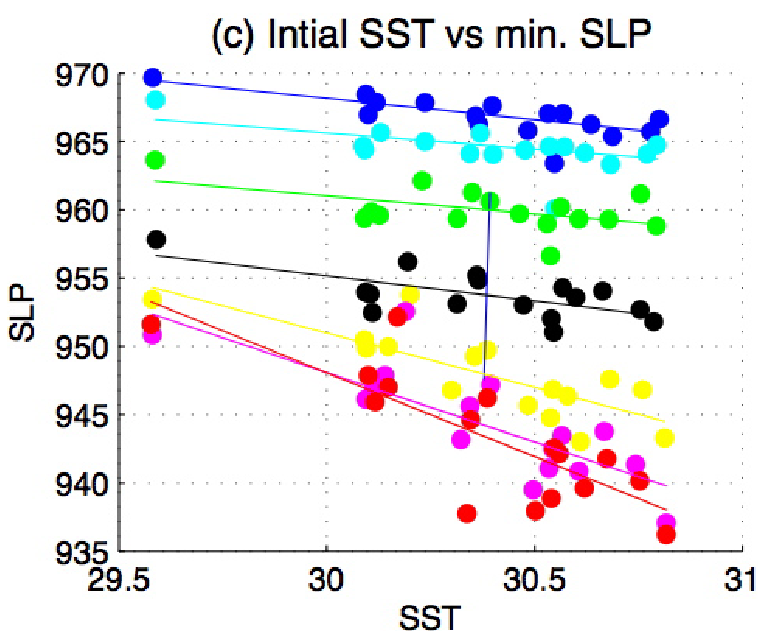
- TC intensity is negatively correlated with D26.
- Variability is greater in warmer ocean conditions than colder ocean conditions.

➔ Sensitivity of storm intensity is greater for warmer ocean.

Min. SLP and initial ocean state







- Interannual SST variation is negatively correlated to storm intensities; the range of SLP sensitivity is ~5-15 mb depending on D26.
- However, the same SST can cause large SLP variation depending on D26.

- Interannual D26 variation has an incorrect correlation with the SLP
- However, when interannual D26 variability is increased to match the observations, then SLP has a robust negative correlation with SLP with >25 mb.

- UOHC reflects these two features.

Summary of Part 2

- For strong TCs, UOHC (D26+SST) is an useful predictor, than SST alone, for the intensification.
- Inclusion of dynamic topography in the statistical prediction model improves intensity forecast; NHC (up to ~20%) and JTWC (~1%).
- Ocean dynamical topography may give wide range of predictability of intense TCs from *weekly* to *interannual*.
- In this set of experiments, D26 produces wider ranges of intensity response of TCs than SSTs.
  - Since an intense TC interacts with ocean more strongly, the estimate here is likely higher with stronger storms -- work in progress to add realistic initial maximum wind speed.
  - Need better oceanic initialization; other oceanic analyses products with better information of dynamic topography.

Outlook

- Understanding of regional processes in a changing climate is important.
    - The US west cost and other coastal upwelling regions are good initial targets because of important interactions involving ocean dynamics, coastal meteorology, air-sea coupling and bio-geochemistry.
- As the WRF is being embedded within CCSM to produce stronger TCs, it is important to provide ocean feedback on more appropriate spatial scales (e.g., reduced self-induced cooling).
    - We need the generalized oceanic nested grids within POP in coordination with WRF/CAM for key regions of cyclogenesis of the global ocean.

Thanks