High-resolution Regional Climate Modeling

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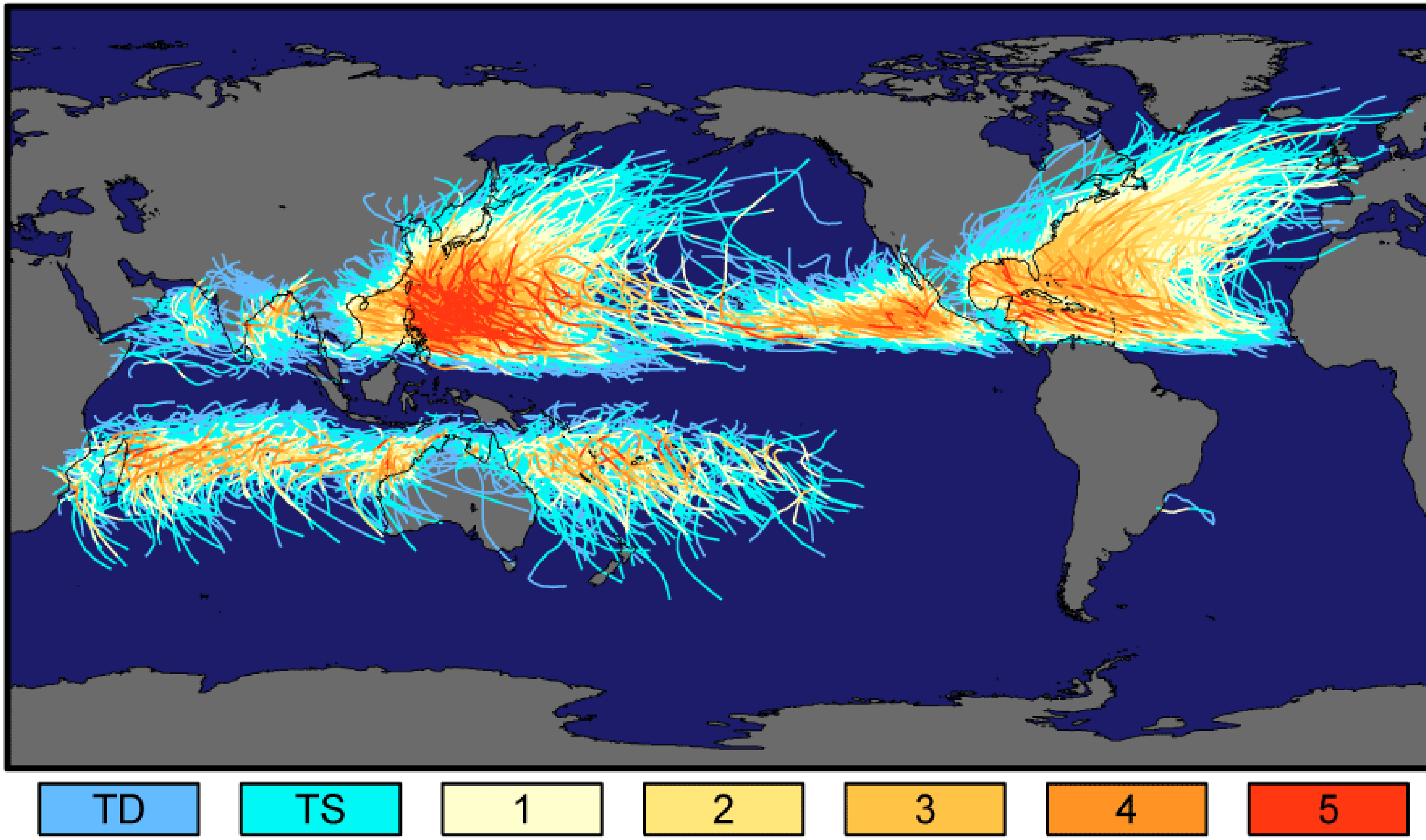
Hurricane Katrina
August 28, 2005

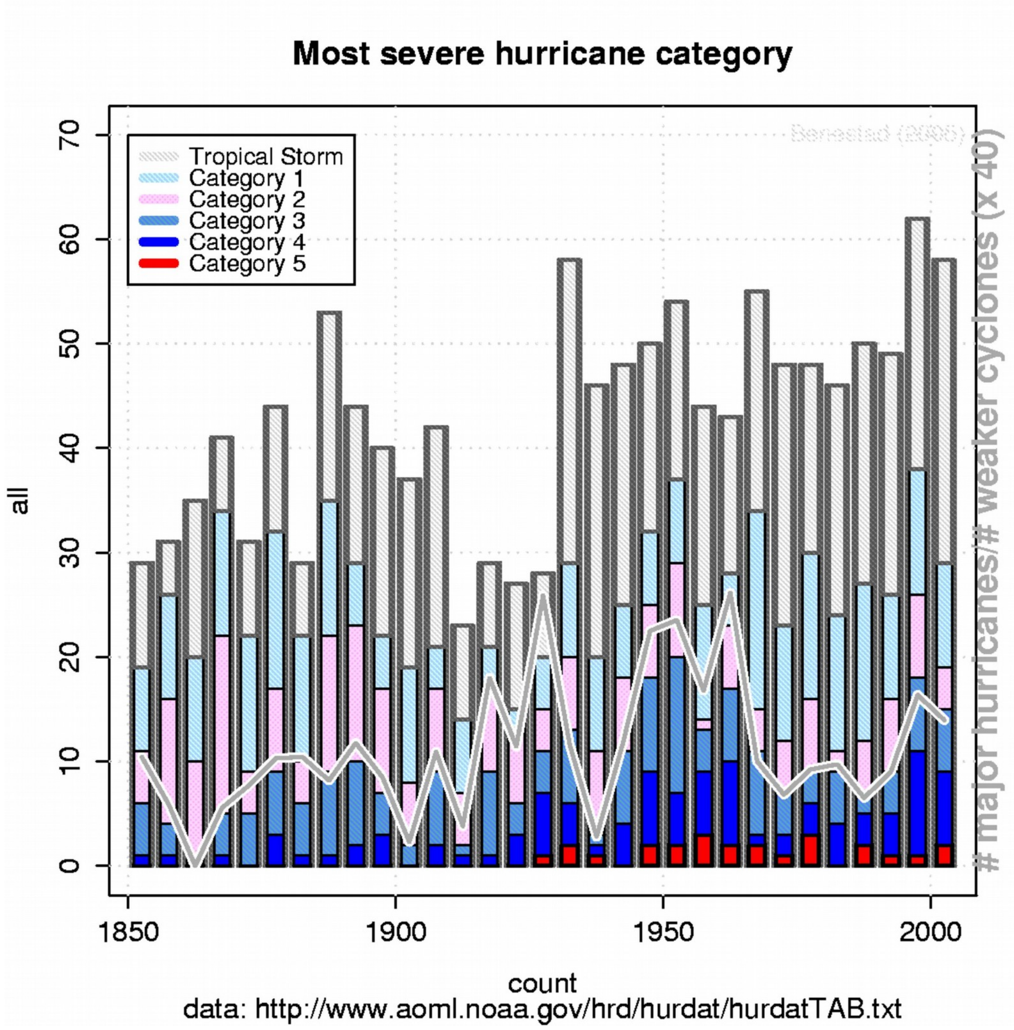

OCTOBER 3, 2005
POLITICS OF CRONYISM ■ GENERATION JIHAD ■ NEIL YOUNG SINGS
TIME
ARE WE MAKING
HURRICANES
WORSE?
■ THE IMPACT OF GLOBAL WARMING
■ THE COST OF COASTAL DEVELOPMENT
■ PLUS: CHARTING THE
GULF COAST DESTRUCTION

Tracks and Intensity of All Tropical Storms



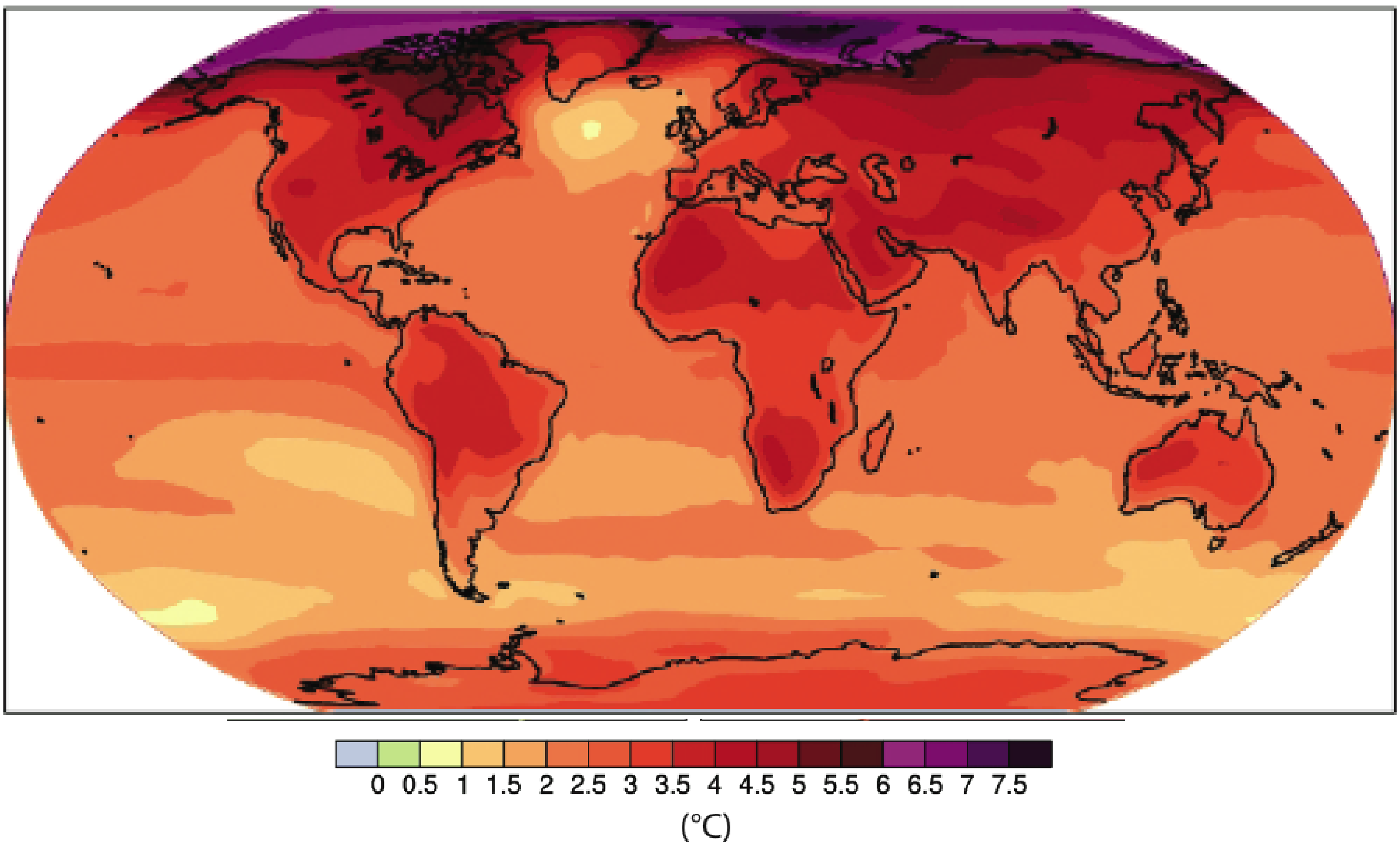
Saffir-Simpson Hurricane Intensity Scale

Variability in tropical storm numbers



IPCC AR4 Projection of Global Surface Temperature (2090-2099) for A1B "business as usual" Scenario

Global mean warming = 2.8°C



Climate Change and Hurricanes

Emanuel (2005), Holland and Webster (2007)

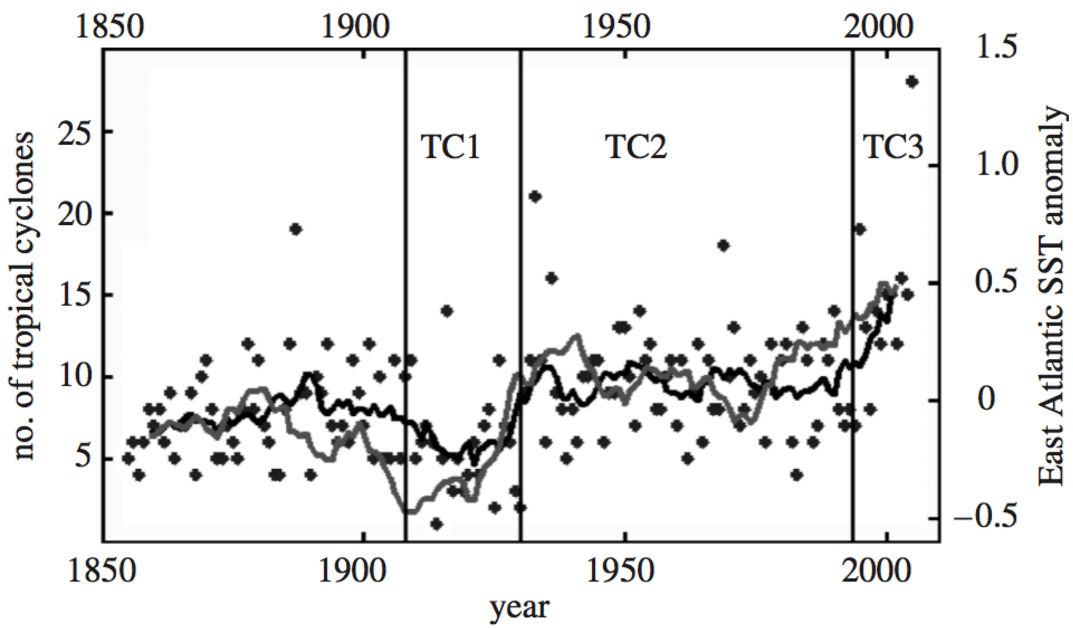
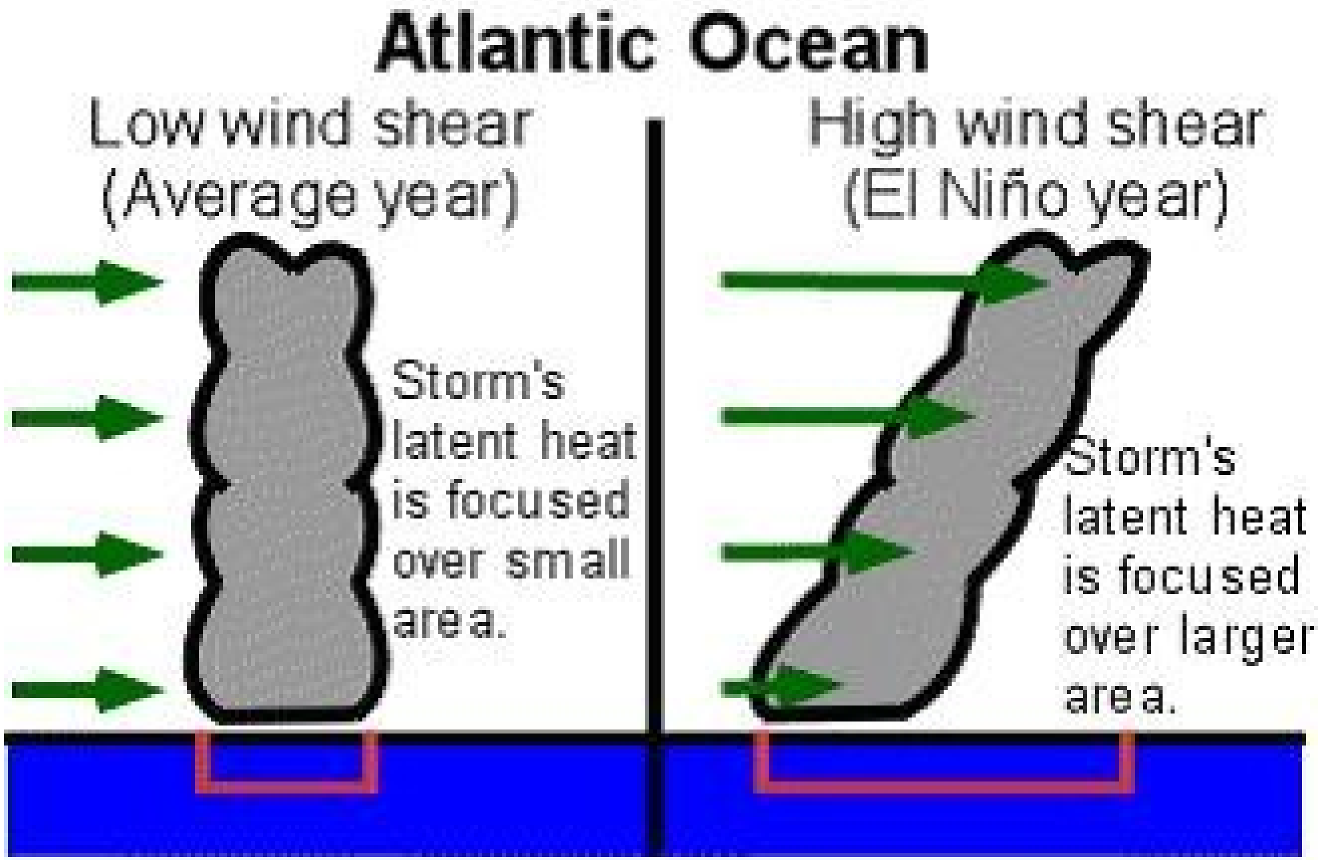


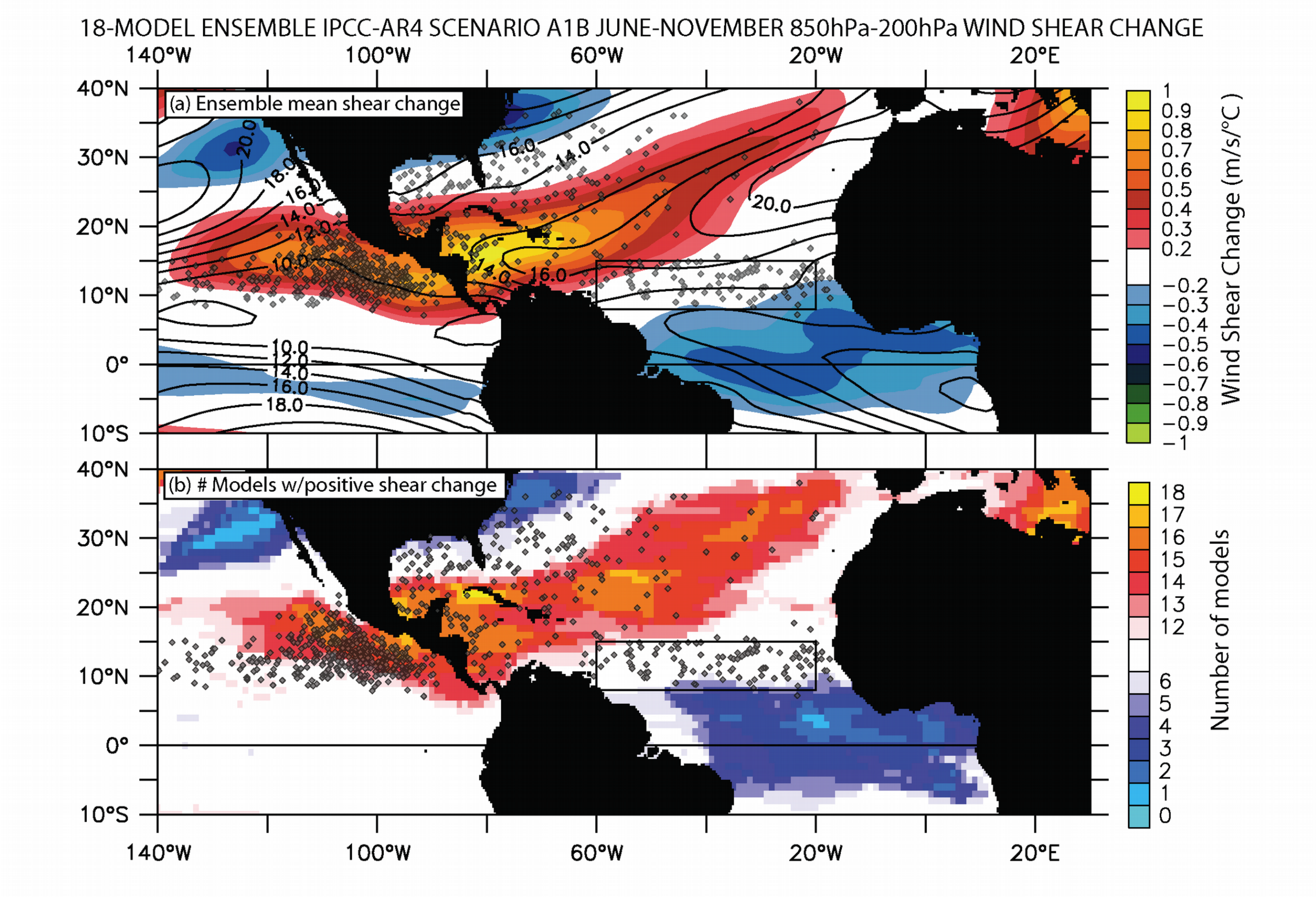
Figure 1. Tropical cyclone occurrence (dots indicate annual totals and the black line is a 9-year running mean) in the North Atlantic together with East Atlantic sea surface temperature (SST) anomalies for the hurricane season (grey line) from 1855 to 2005. TC1–TC3 refer to climate regimes discussed in the text.



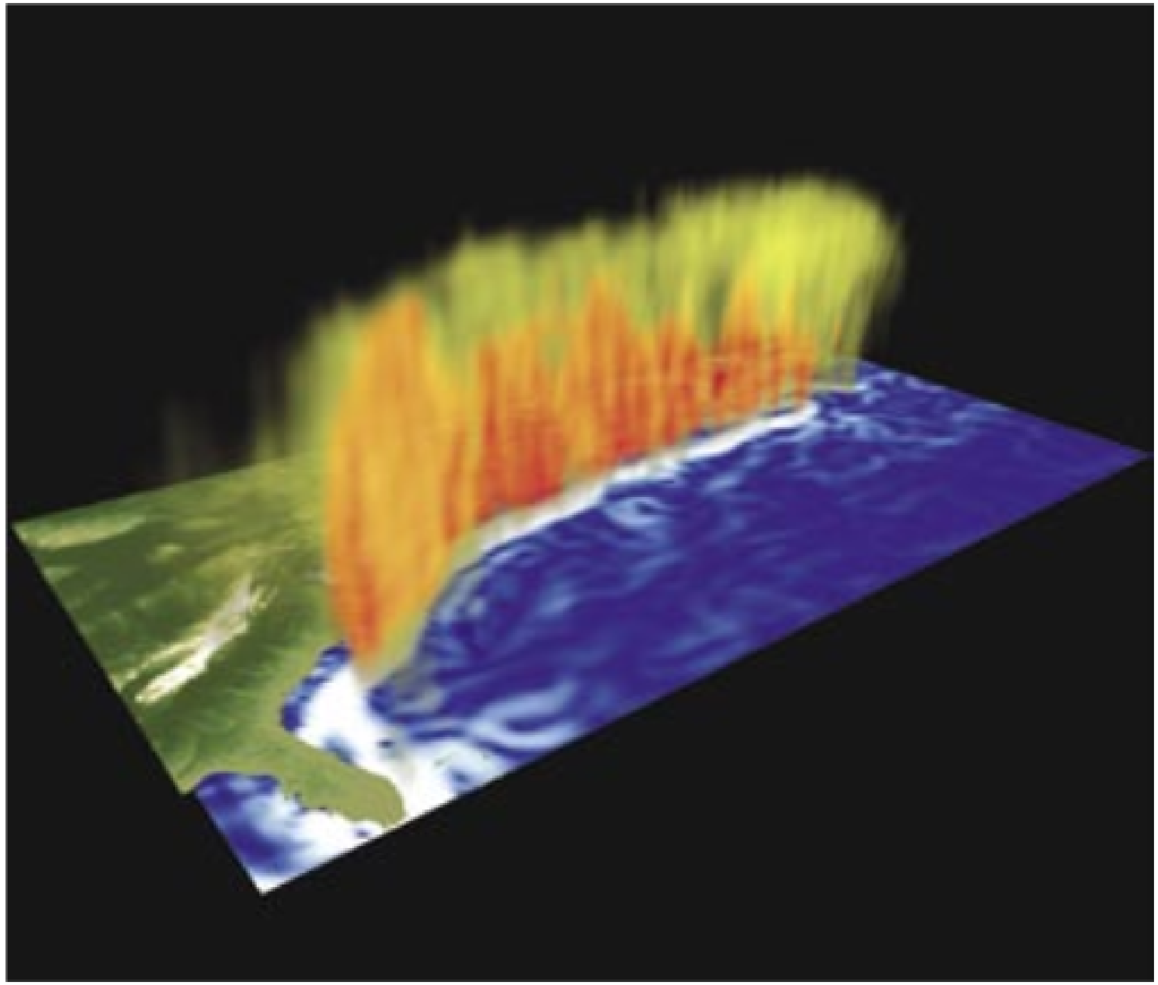
Atlantic Ocean
Low wind shear
(Average year)
Storm's latent heat is focused over small area.
High wind shear
(El Niño year)
Storm's latent heat is focused over larger area.

Increased Tropical Atlantic wind shear in model projections of global warming

Vecchi & Soden, GRL (2007)



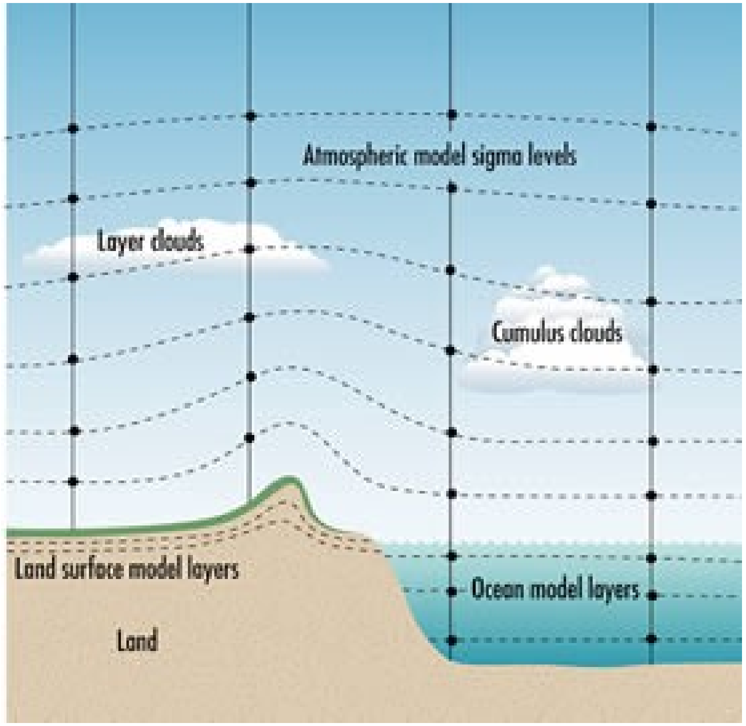
The Gulf Stream's Pathway to Impact Climate



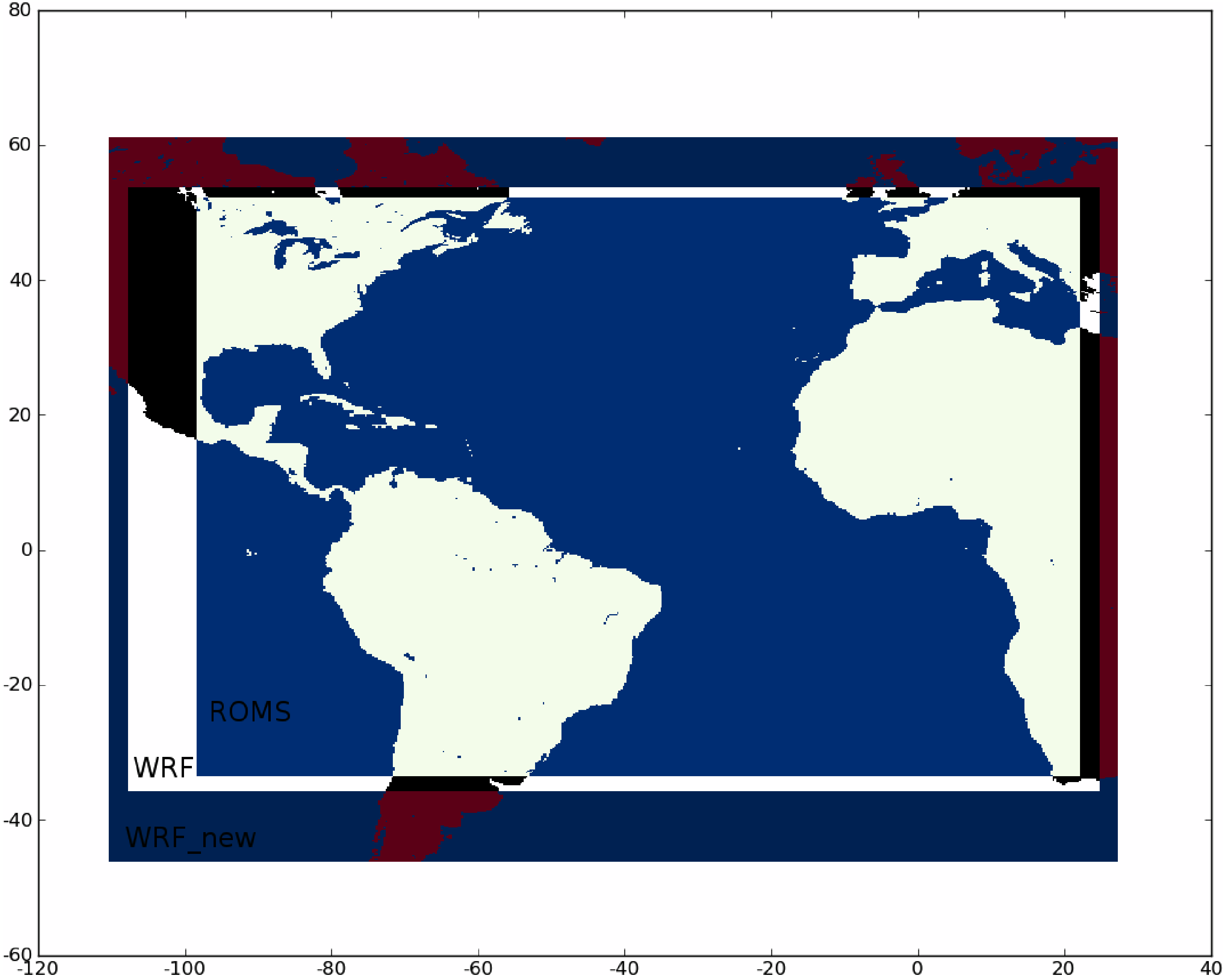
Graphic representation of the Gulf Stream surface current speeds in blue-white (white is the fastest) and upward wind velocities in yellow-red (red for stronger winds), along with land-surface topography of eastern North America. Image, courtesy of Fumiaki Araki and Shintaro Kawahara at JAMSTEC, was made for cover of *Nature* issue.

Minobe et al. (2008)

Computer Models of Climate



Coupled Regional Climate Model Domain



Atmospheric component:
Weather Research & Forecasting Model (WRF)

Developed at NCAR

27-km/9-km horizontal resolution, 35 vertical levels

Timestep Δt = 90 Seconds

NCEP-NCAR reanalysis for boundary conditions and initial conditions

Physics parameterizations:

WSM 3-class simple ice (Microphysics), RRTM (LW-Radiation), Goddard SW-Radiation, YSU PBL scheme,

Kain-Fritsch cumulus convection scheme

Oceanic component:
Regional Ocean Modeling System (ROMS)

- **Developed at Rutgers University/UCLA**
- **9-km Horizontal Resolution & 30 levels for the Atlantic Basin**
- **Δ t= 10 minutes. Boundary conditions derived from Levitus observational data.**

Coupling strategy

- Atmosphere and ocean exchange fluxes of momentum, energy, and freshwater
- Atmosphere and ocean model on same spatial grid
  - 27 km and 9 km grids
- Coupling every hour

Computational performance on Ranger (TACC)

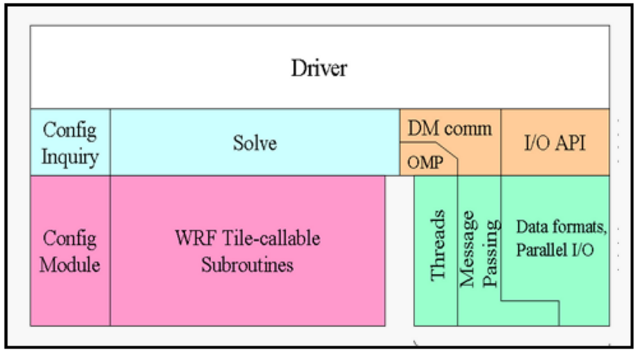
WRF 30 km (460x466x28 grid)

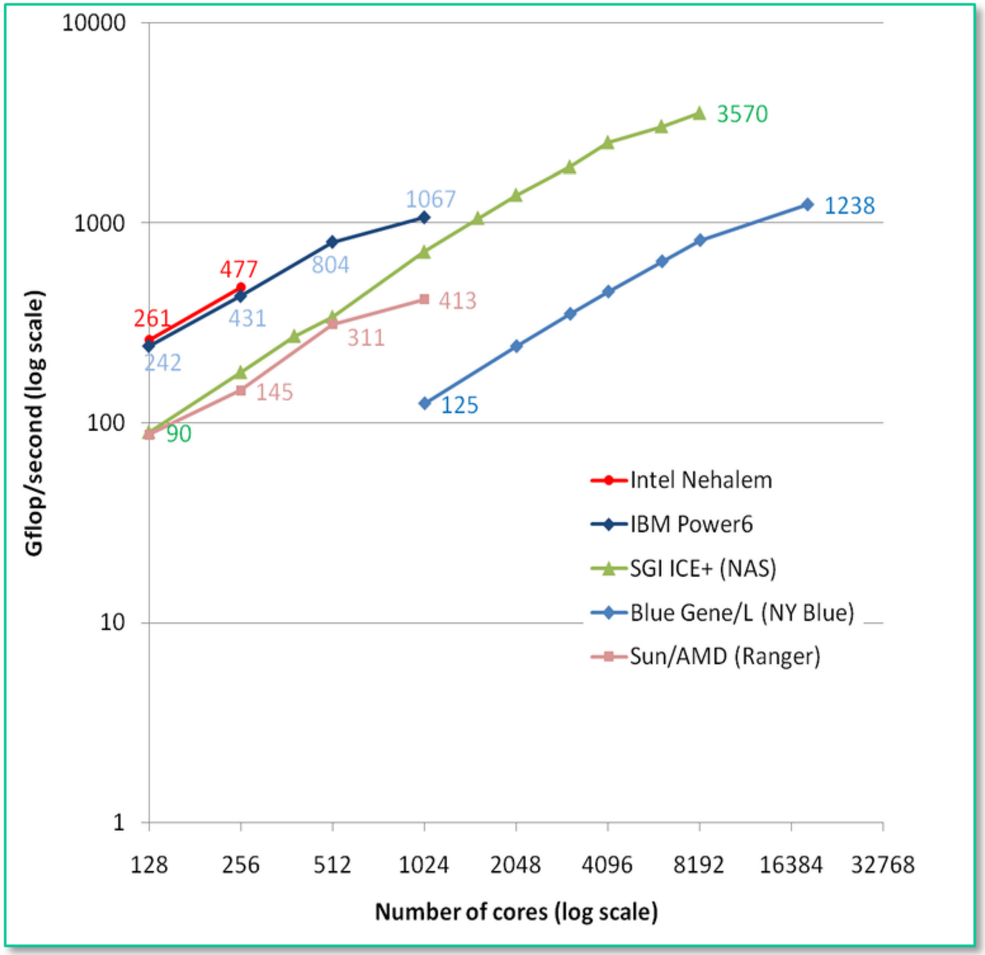
CPUs	Wall clock hrs for 1 yr run
128	57
256	36
384	28

The ocean model is about 20 times faster than the atmospheric model, for the same grid!

WRF on High Performance Systems

- Community model designed for HPC
  - Keys are performance and portability
  - Multi-level domain decomposition supports both shared and distributed memory parallelism
  - WRF software framework portable over range of system architectures



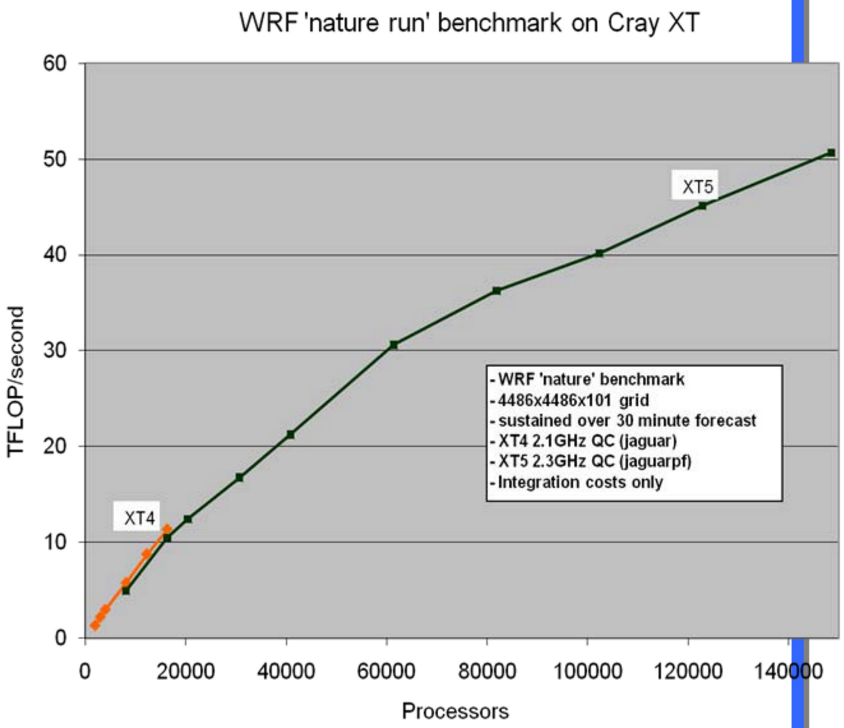


WRF 2.5km CONUS Benchmark
http://www.mmm.ucar.edu/wrf/WG2/bench

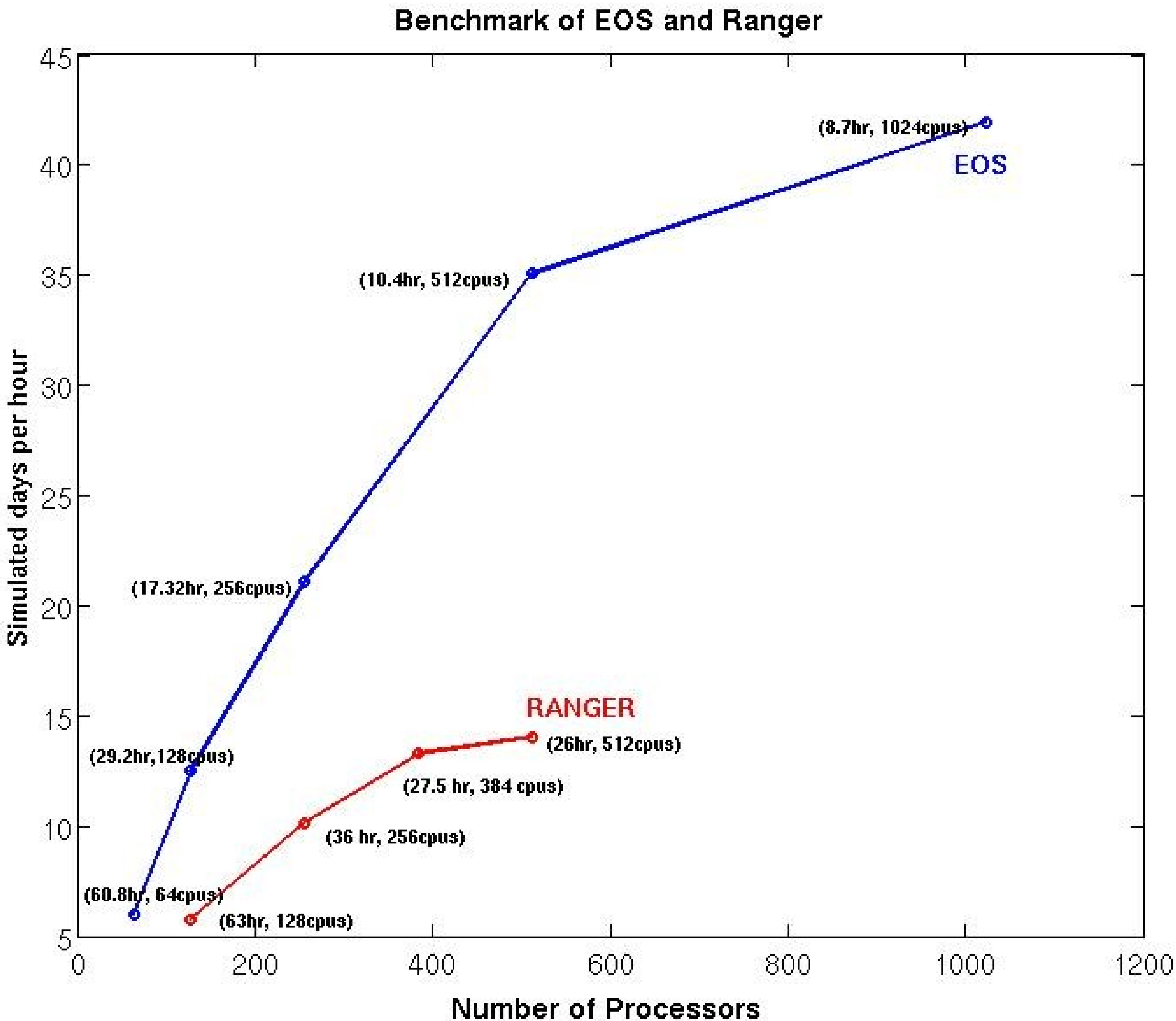
John Michalakes

WRF Scaling

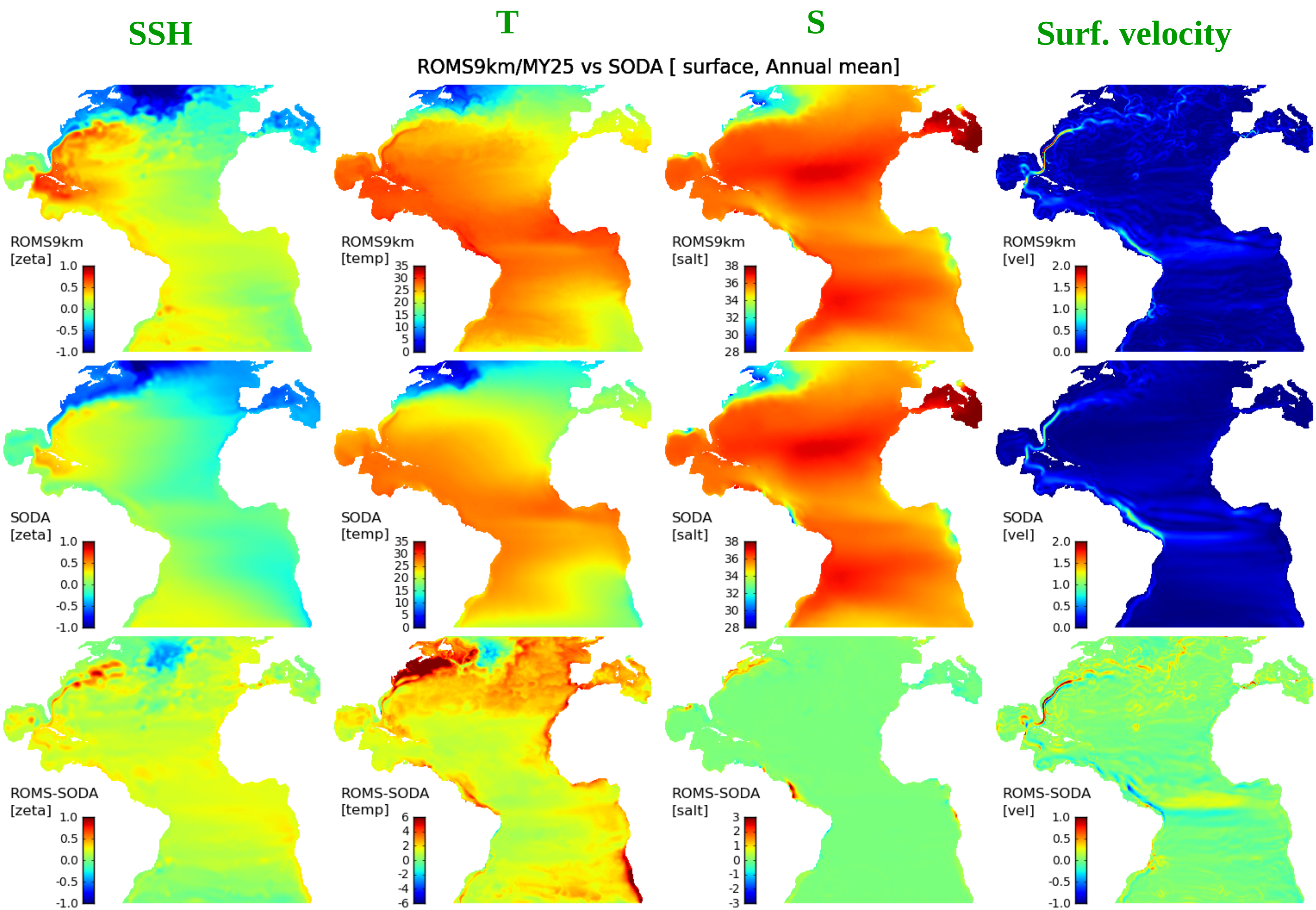
- WRF Nature Run
  - 2 billion cell hemispheric run at 5km
  - 50 TF/s on 150K cores (Cray XT5)
  - Weak scaling; low simulation rate
- Current work on Blue Gene/P
  - 12km/4km/1.3km Hurricane Bill
  - ~1000km square moving nest covering entire storm
  - 4K nodes/16K processors
  - Simulation rate is about 15:1
- Need to look at node-speed for strong scaling



courtesy Peter Johnsen, Cray


Benchmark of EOS and Ranger
Simulated days per hour
Number of Processors
EOS
RANGER
(8.7hr, 1024cpus)
(10.4hr, 512cpus)
(17.32hr, 256cpus)
(29.2hr,128cpus)
(60.8hr, 64cpus)
(26hr, 512cpus)
(27.5 hr, 384 cpus)
(36 hr, 256cpus)
(63hr, 128cpus)
45
40
35
30
25
20
15
10
5
0
200
400
600
800
1000
1200

Annual mean bias: Uncoupled 9 km ROMS forced with CORE2 fluxes

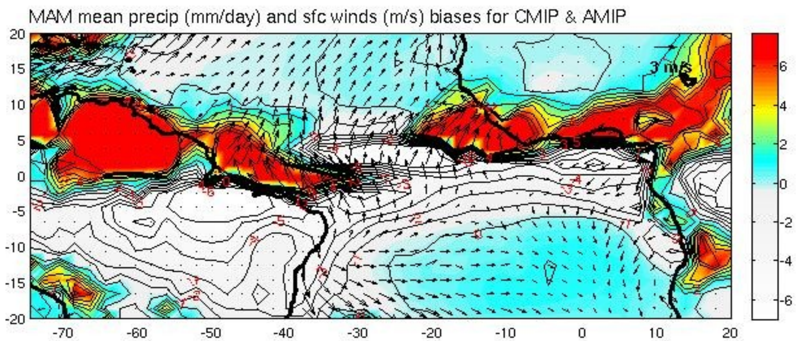


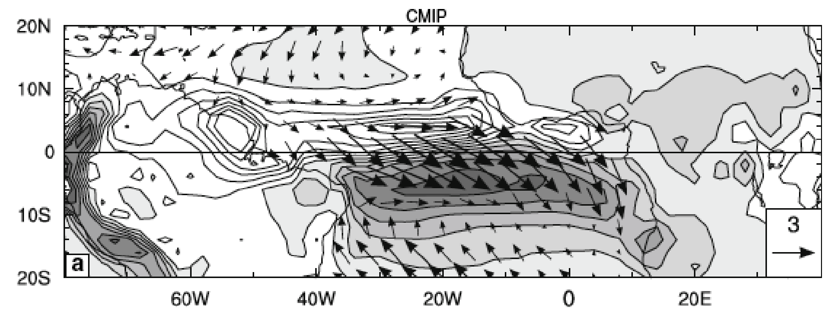
MAM Precipitation and wind bias:
27km WRF coupled with 9km ROMS vs. Global CGCMs

Regional Model

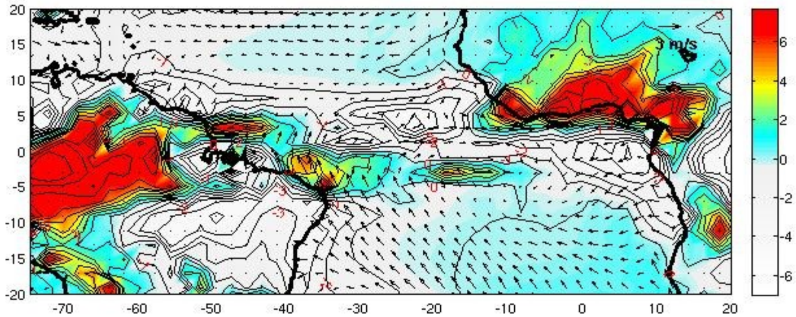
Global Model

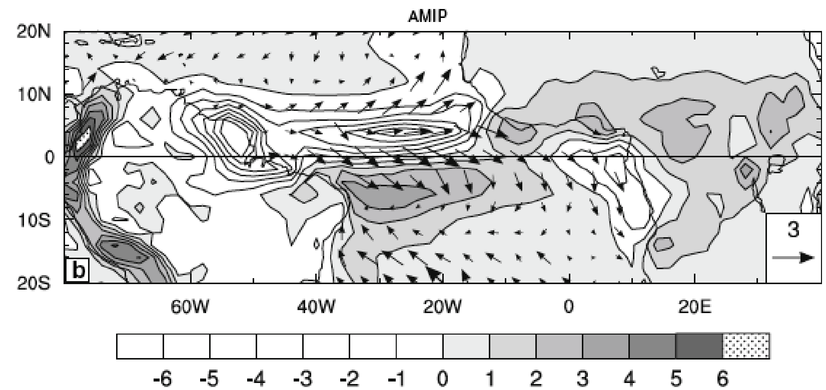
Coupled



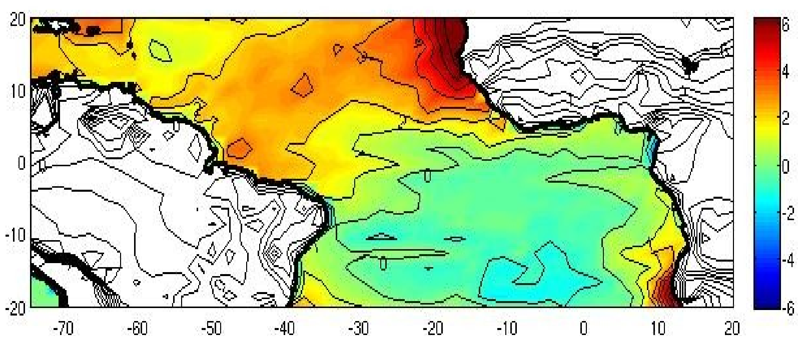


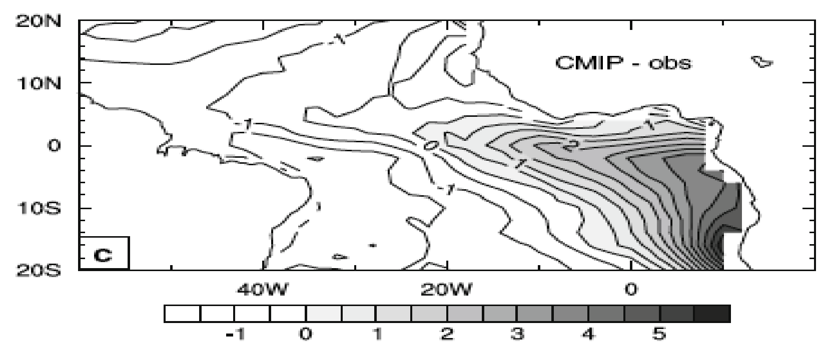
Uncoupled



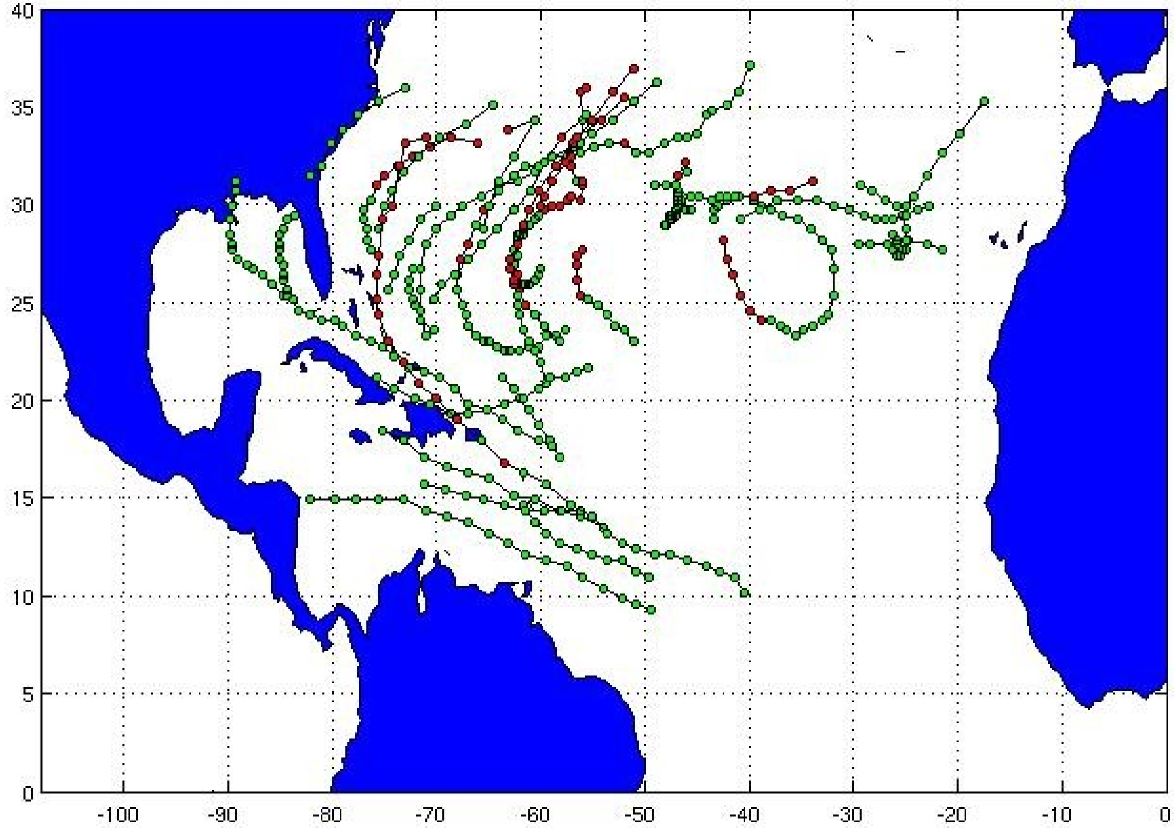


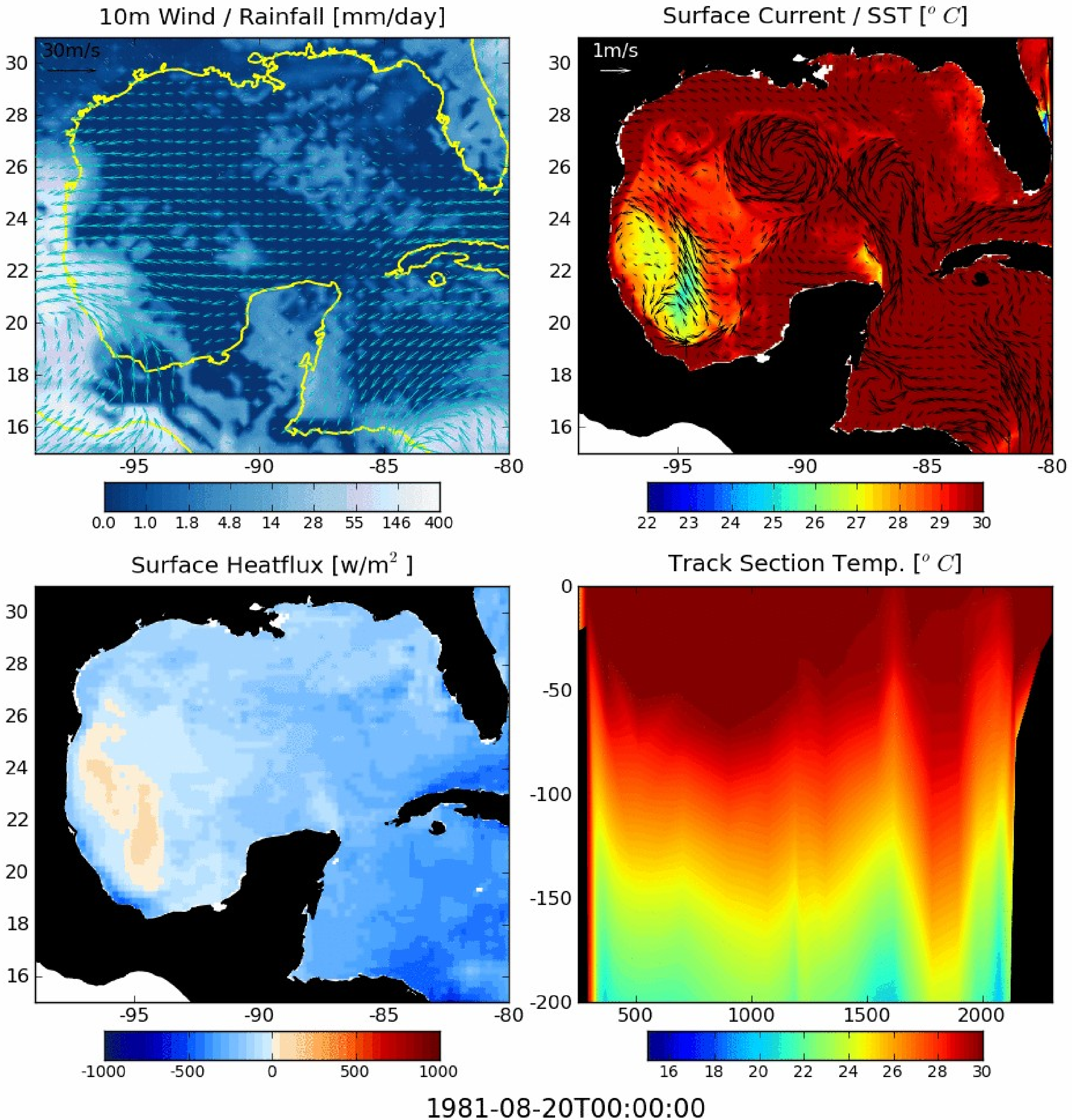
Coupled-Obs.





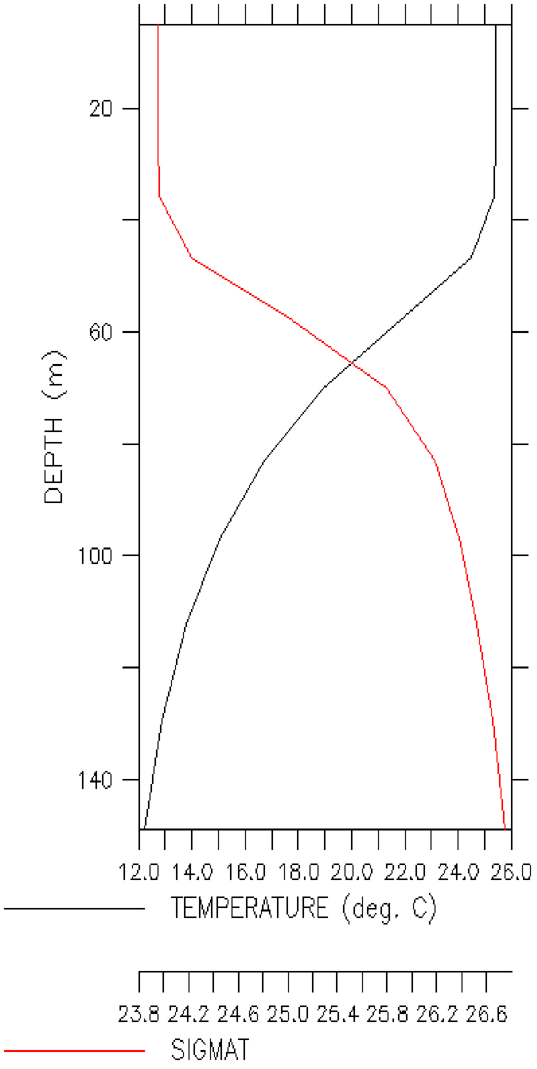
CRCM simulation: Tropical cyclone tracks



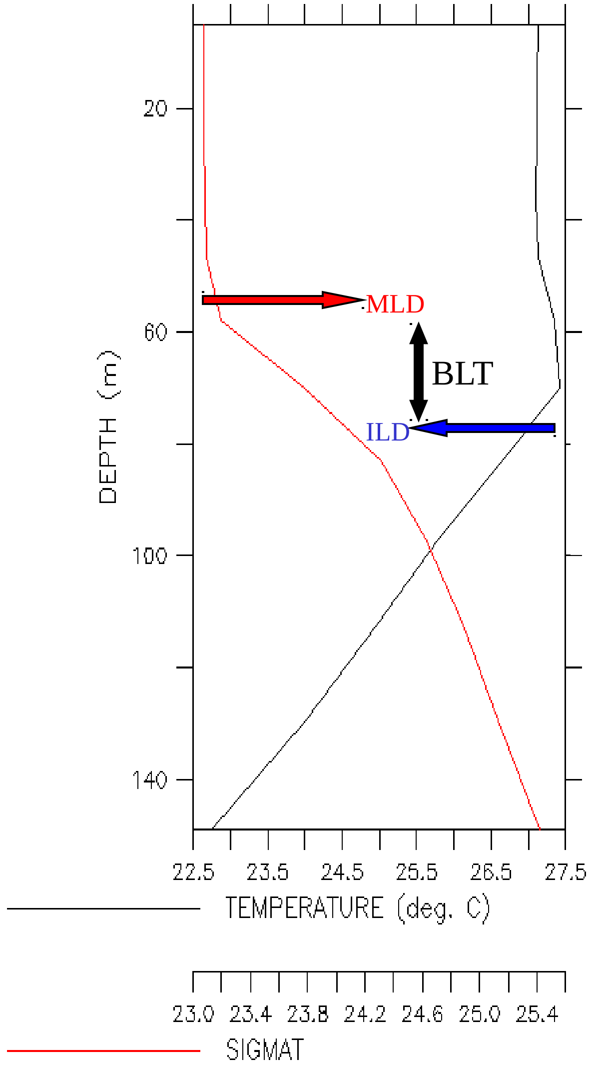


10m Wind / Rainfall [mm/day]
30m/s
Surface Current / SST [$^o C$]
1m/s
Surface Heatflux [w/m^2]
Track Section Temp. [$^o C$]
1981-08-20T00:00:00

Barrier Layer (BL) in the ocean:
Isothermal layer deeper than mixed layer



Typical vert. profile

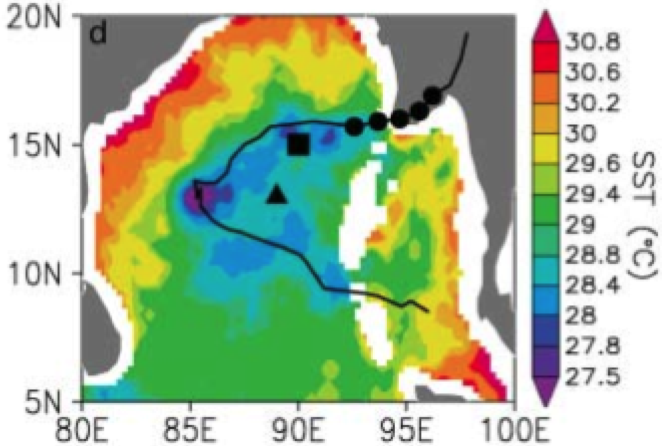


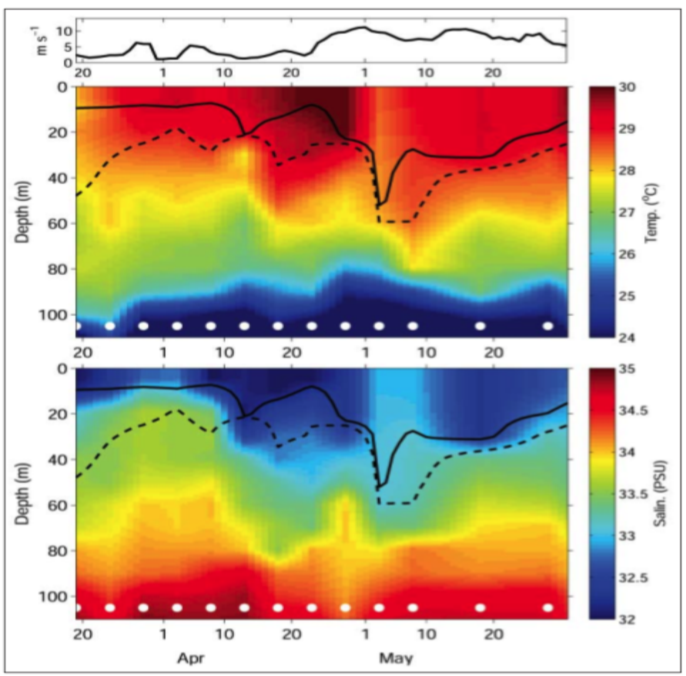
Vert. profile with a Barrier Layer

$$BLT = D_{T-0.2} - D_\sigma$$

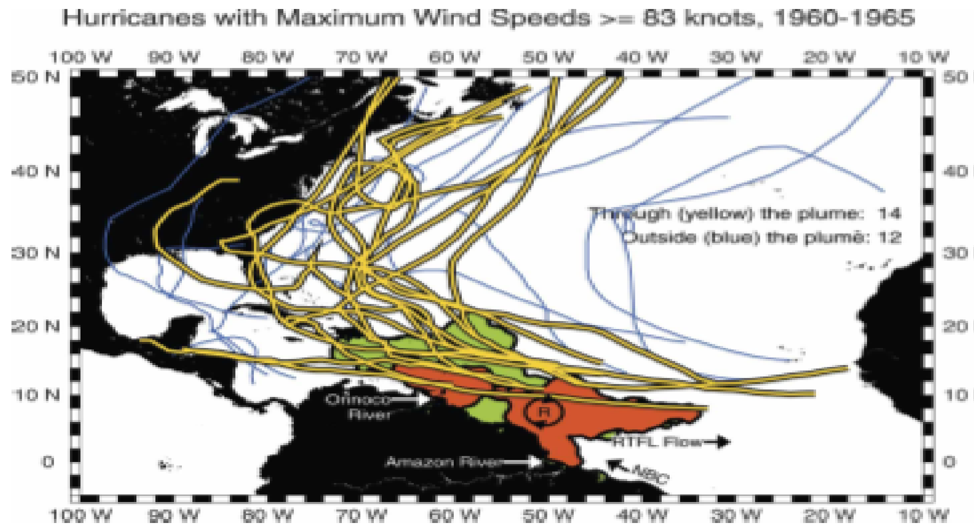
$$\Delta_\sigma = \sigma_\theta(T_{10} - 0.2, S_{10}, P_0) - \sigma_\theta(T_{10}, S_{10}, P_0)$$

Barrier Layers and tropical cyclones





McPhaden et al., 2009



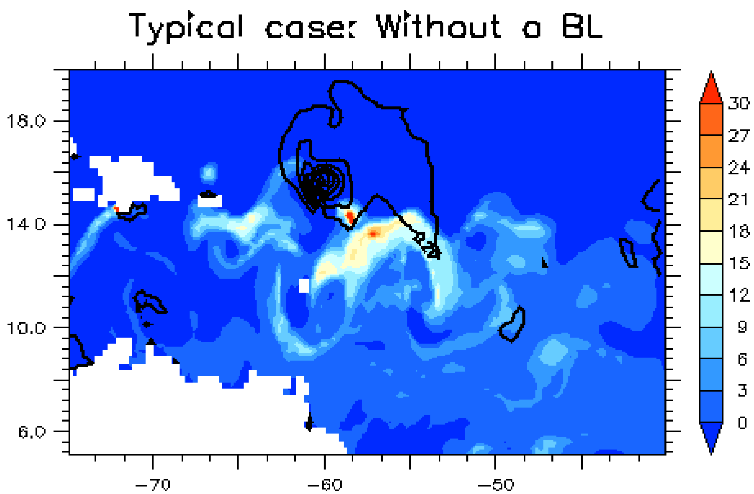
Ffield., 2006

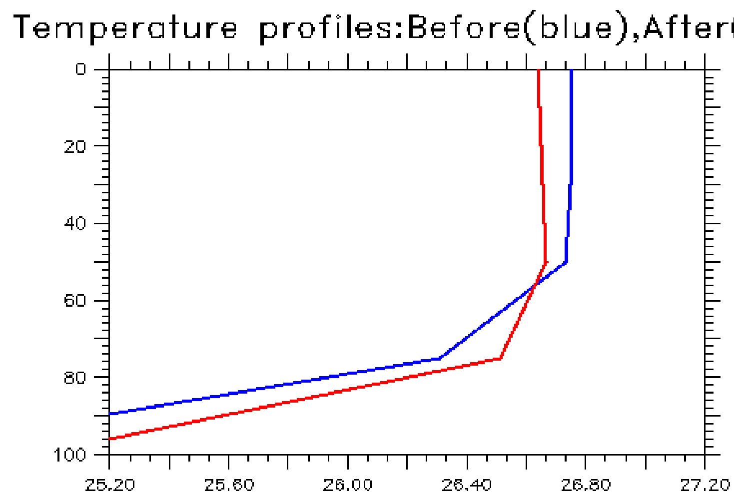
$$V_{max} = \sqrt{\frac{C_k}{C_d}\frac{(T_s - T_o)}{T_o}(K_s - K_d)}$$

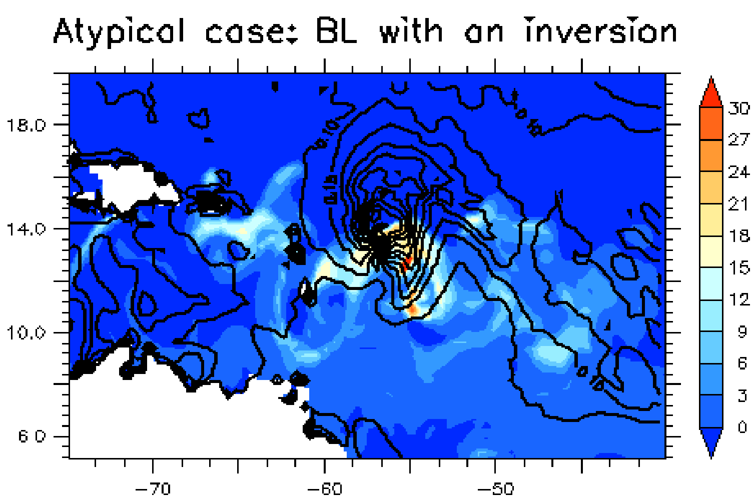
Emanuel, 1986

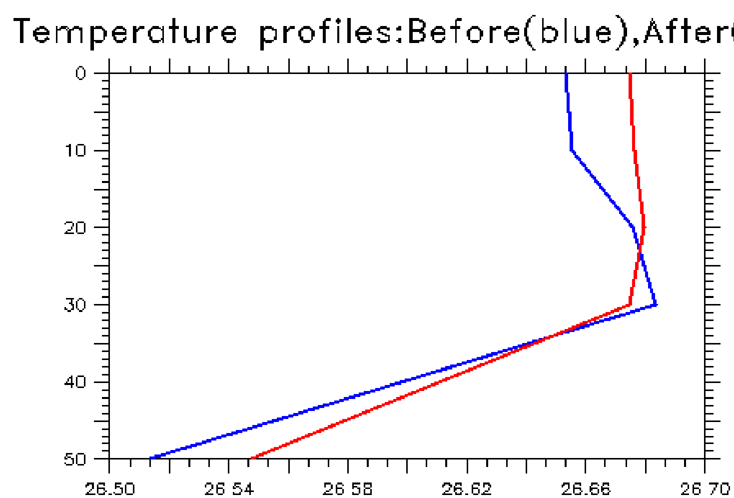
Surface SST cooling : Negative feedback factor

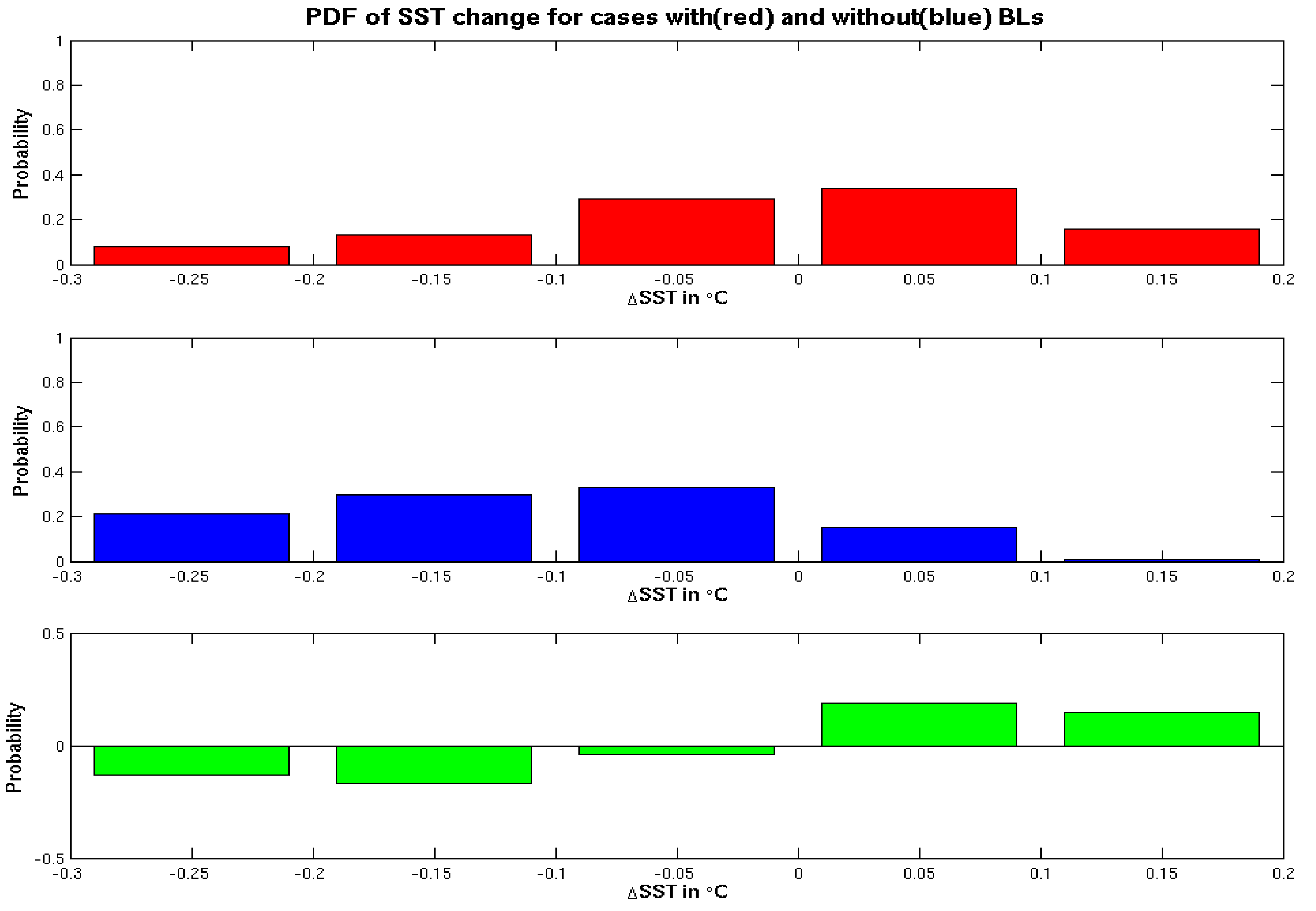
Comparison of SST response for cases with and without a BL





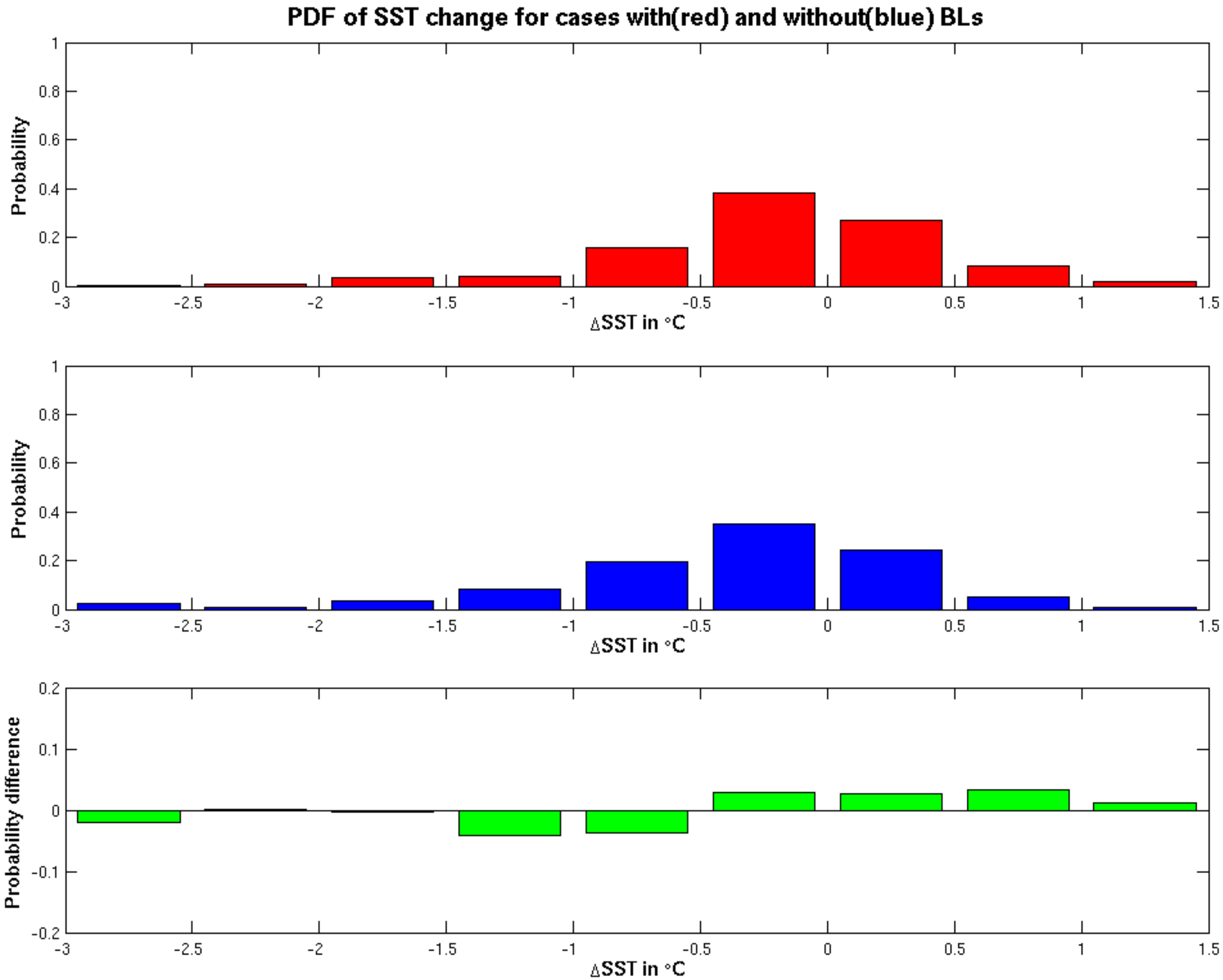






mean ΔSST_{BL} = 22% of mean ΔSST

Observational analysis



SST data (1998 - 2007):
TRMM

Hurricane tracks:
NOAA-AOML

Monthly maps of BLT :
SODA 2.0.4

mean ΔSST_{BL} = 51% of mean ΔSST

Conclusions

- Coupled regional climate model produces hurricane-like vortices

- Ocean mixing in the hurricane wake is quite sensitive to vertical stratification

  - *occasionally the mixing can lead to warming!*

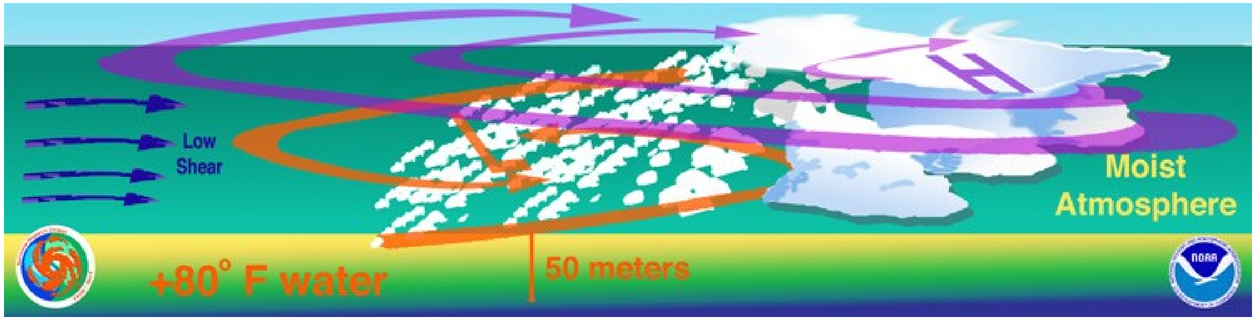
- Ocean mixing in the hurricane wake does not contribute significantly to poleward oceanic heat transport

Coupled Regional Climate Model (CRCM)

- **Regional atmospheric model coupled to regional ocean model**
- **Lateral b.c. from global coupled model or reanalyses**

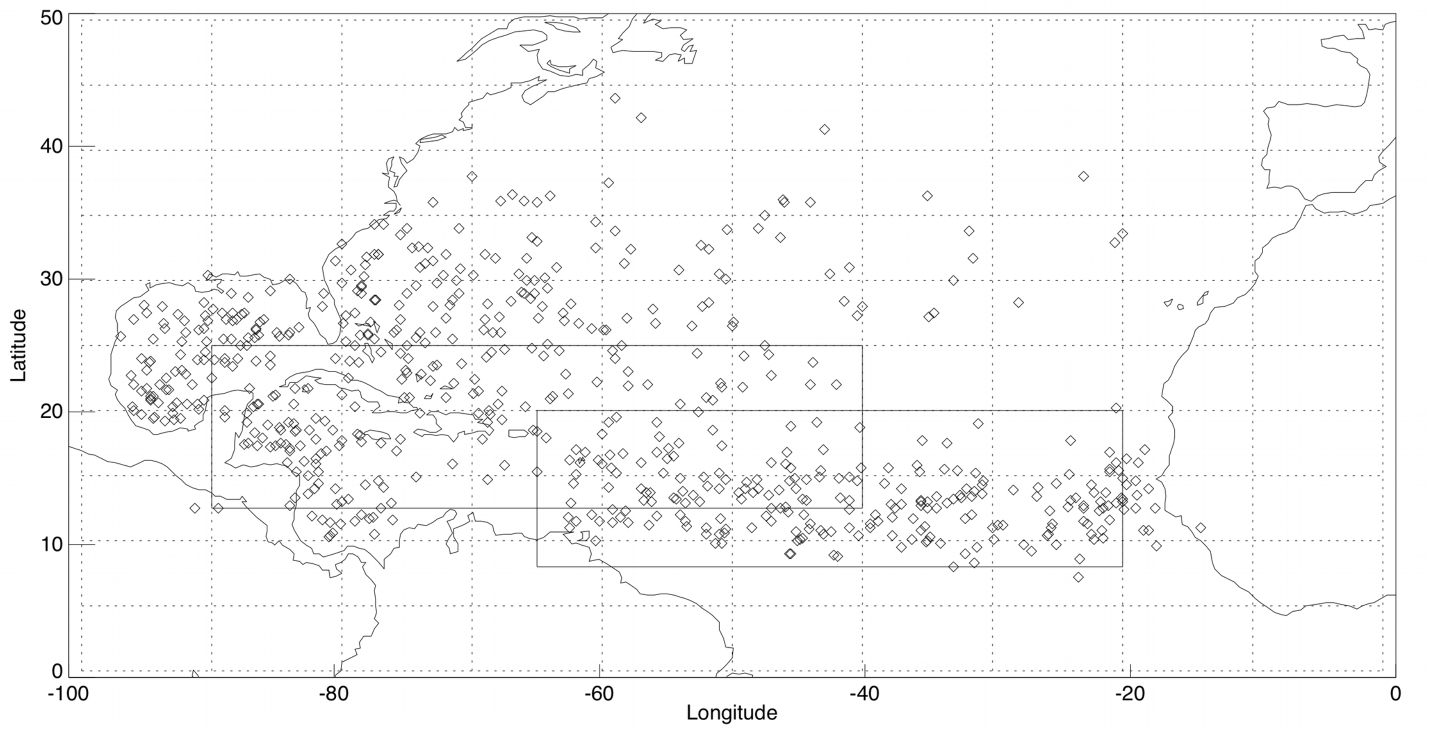
Environmental precursors for hurricane genesis

Gray (1968, 1979)



- **Sea surface temperatures > 26 degrees C**
  - **Sufficiently deep mixed layer (> 50m)**
- **Deep conditional instability**
  - **Cooling with height, mid-tropospheric moisture**
- **Low values (< 10 m/s) of vertical shear between 850 hPa and 200 hPa**
- **Sufficiently removed from equator for Coriolis effect**
- **Pre-existing disturbance with cyclonic vorticity**

Research Domain



Hurricane genesis in Atlantic basin from 1958 to 2008

Space: Tropical Atlantic

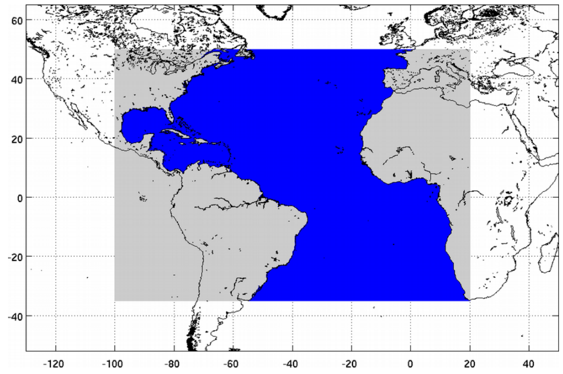
Main Development Region (MDR): 8N – 20N, 20W – 65W

Time: Hurricane season (July – October)

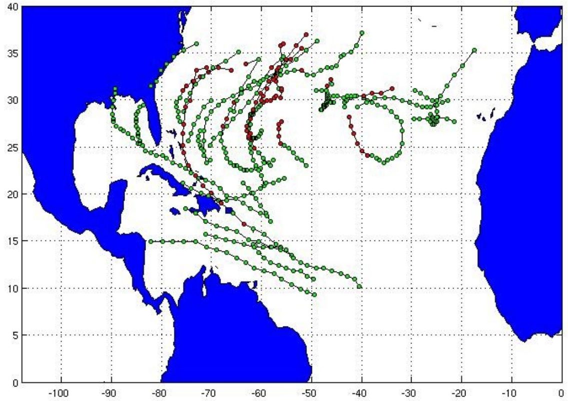
Coupled Regional Climate Modeling in the Atlantic Sector

R. Saravanan, P. Chang, J.-S. Hsieh, M.-K. Li, G. Creager, G. Almes
Texas A&M University

- **Atmospheric model: WRF (27km)**
- **Ocean model: ROMS (27km and 9km)**
- **Both models use the Arakawa C-grid**
- **Atmospheric and oceanic lateral b.c. from global reanalyses/models**

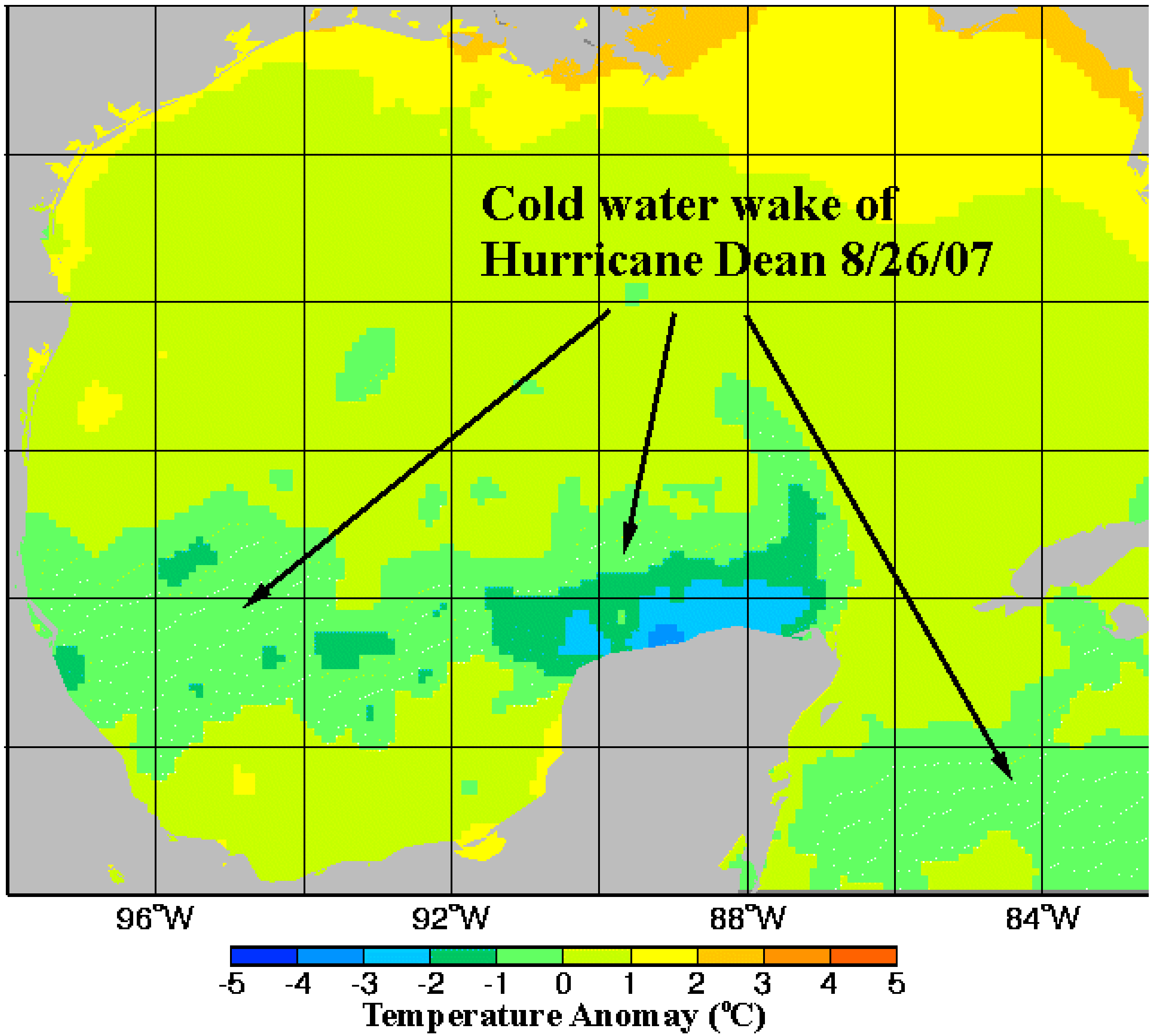


- **Objectives**
  - ***Address tropical biases in coupled models***
  - ***Study air-sea interaction at very high resolution***
- **Analysis**
  - ***Surface flux imbalance and model bias***
  - ***Hurricanes and air-sea interaction***



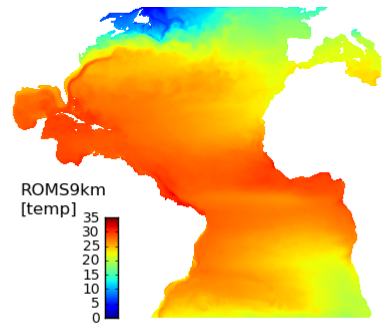
Outline:

- Tropical cyclones and climate change
- Time-slice experiments and air-sea coupling
- Coupled regional climate model
- Ocean mixing and the barrier layer
- Conclusions



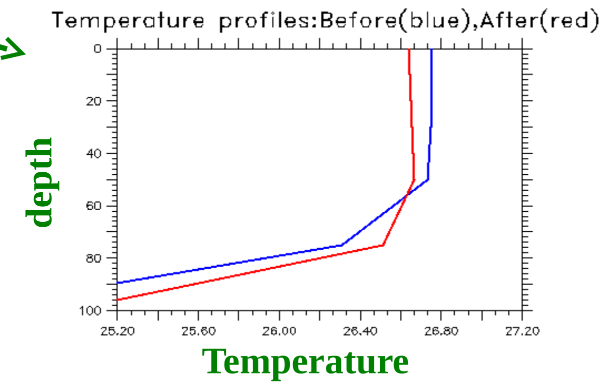
Cold water wake of
Hurricane Dean 8/26/07
96°W
92°W
88°W
84°W
-5 -4 -3 -2 -1 0 1 2 3 4 5
Temperature Anomay (°C)

Some Results

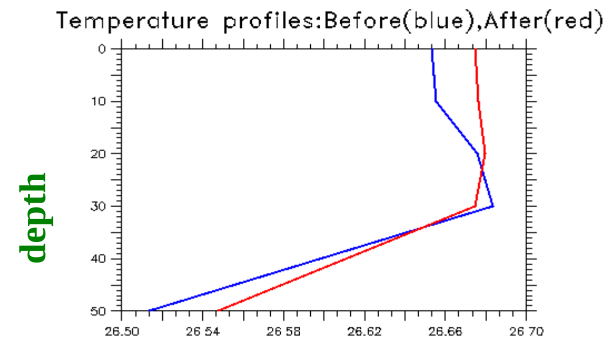


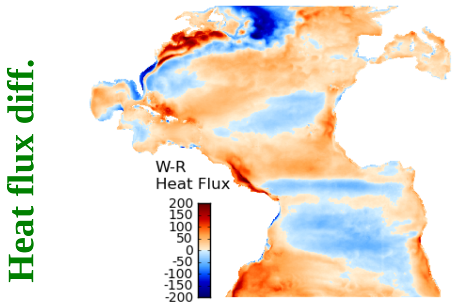
- **Need higher ocean resolution to simulate Gulf Stream separation**
  - *27km WRF coupled to 9km ROMS*
  - *Better load balancing: WRF 60%, ROMS 40%*
- **Hurricanes and oceanic Barrier Layers**
  - *Usually a hurricane leaves cold SST wake*
  - *But Barrier Layers can reverse this effect!*
- **Surface flux imbalances**
  - *What the ocean wants vs. what the atmosphere provides*
  - *Largest errors in tropical SST still found near the coastal upwelling regions*

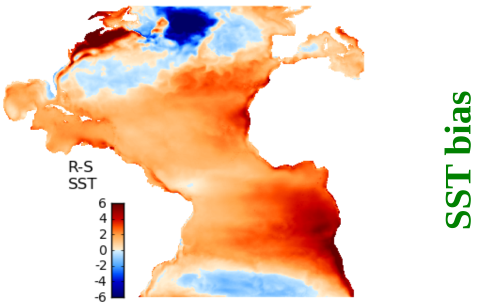
Without Barrier Layer



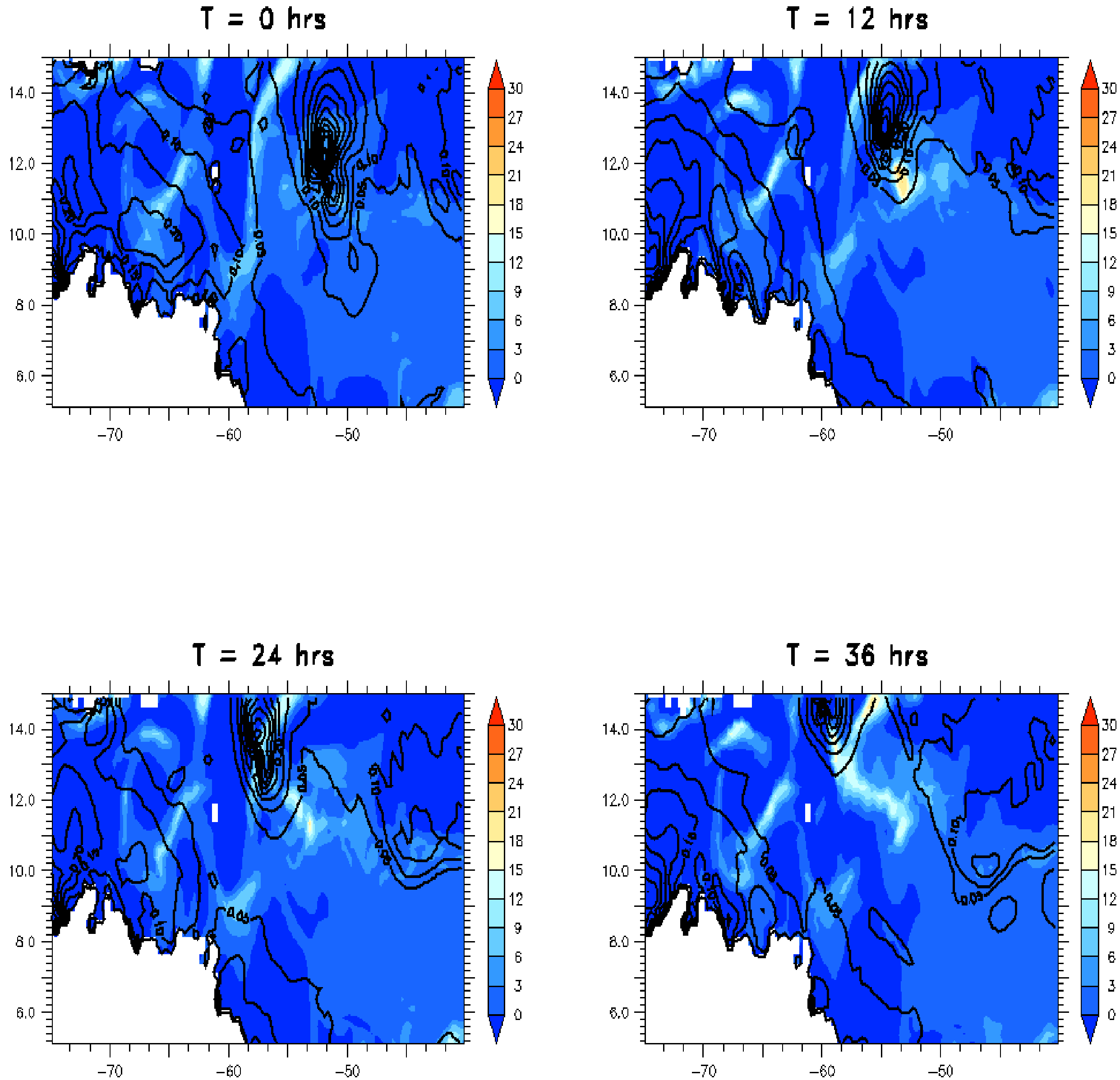
With Barrier Layer







BL formation in the wake of tropical cyclones

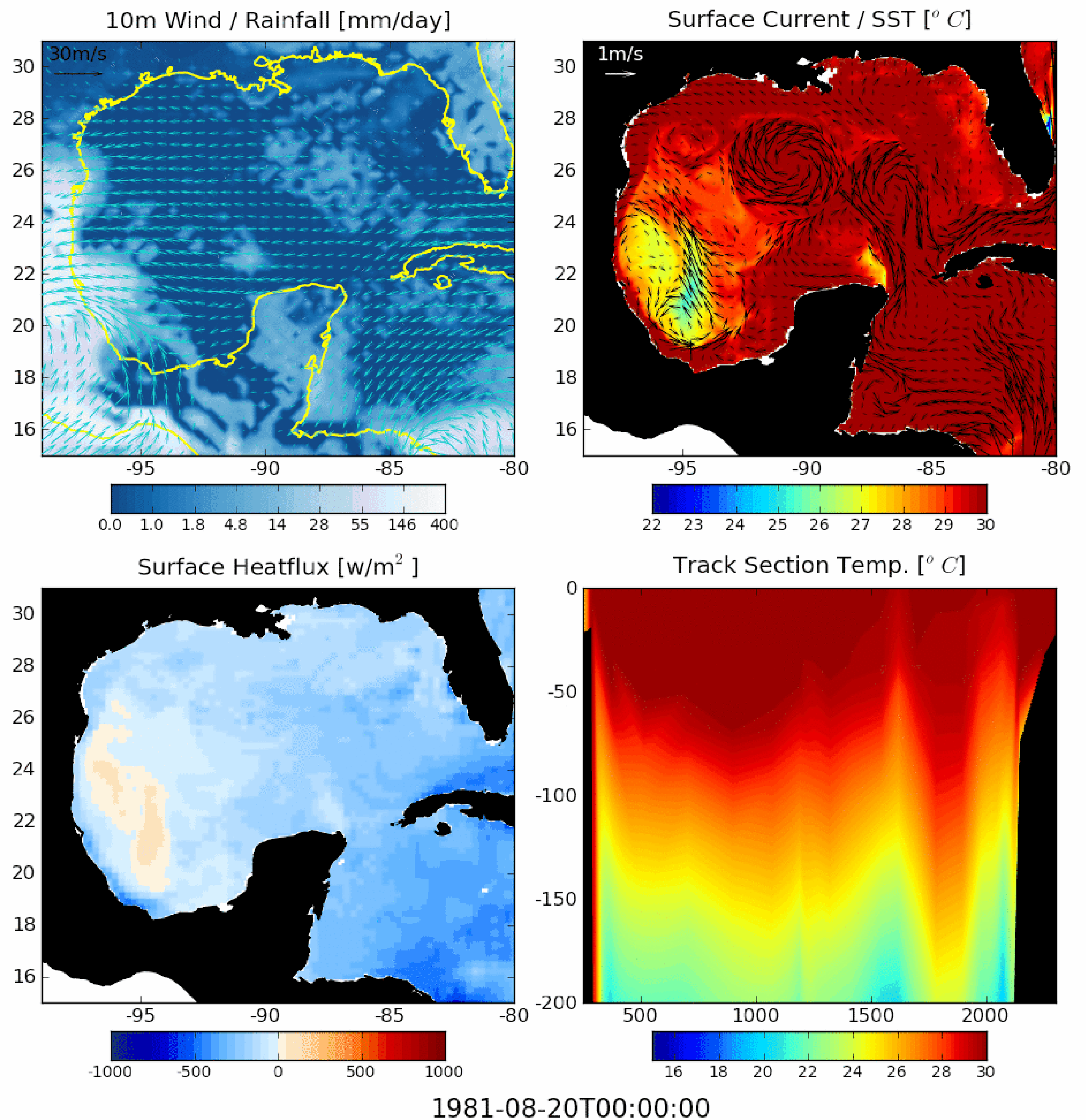


Framework of study

Regional Coupled Model (RCM)

ROMS(27 km) - WRF (30 km)

Initial and boundary conditions derived from NCEP re-analysis and Levitus data


10m Wind / Rainfall [mm/day]
30m/s
30 28 26 24 22 20 18 16
-95 -90 -85 -80
0.0 1.0 1.8 4.8 14 28 55 146 400
Surface Current / SST [^{o} C]
1m/s
30 28 26 24 22 20 18 16
-95 -90 -85 -80
22 23 24 25 26 27 28 29 30
Surface Heatflux [w/m^2]
30 28 26 24 22 20 18 16
-95 -90 -85 -80
-1000 -500 0 500 1000
Track Section Temp. [^{o} C]
0 -50 -100 -150 -200
500 1000 1500 2000
16 18 20 22 24 26 28 30
1981-08-20T00:00:00