High-resolution Coupled Regional Climate Modeling in the Atlantic Sector: Simulating the mean state and hurricane activity

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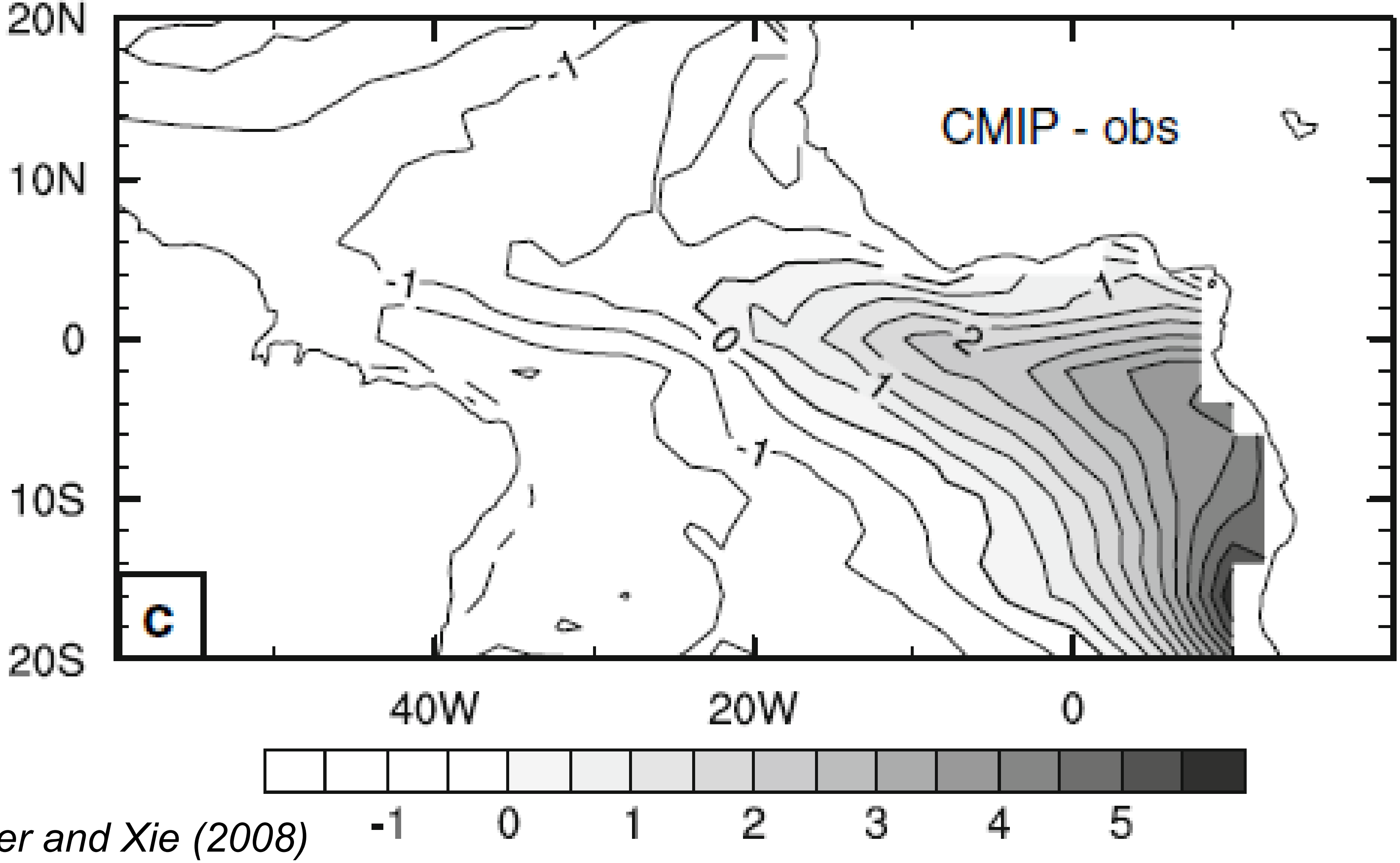
High resolution modeling of extreme events

- **Goal: To study the impact of air-sea coupling on extremes**
  - **Coupling can *directly* affect the extremes (e.g. hurricanes)**
  - **Coupling can affect the mean state simulation, which can *indirectly* affect the spatial and temporal characteristics of extremes**

- **Methodology:**
  - **Use a regional coupled model (27km – 9km resolution)**
  - **Focus on the Atlantic basin and adjoining continental areas**

AOGCM bias of summer (JJA) tropical Atlantic SST

- Eastern equatorial Atlantic
- Southeastern tropical Atlantic

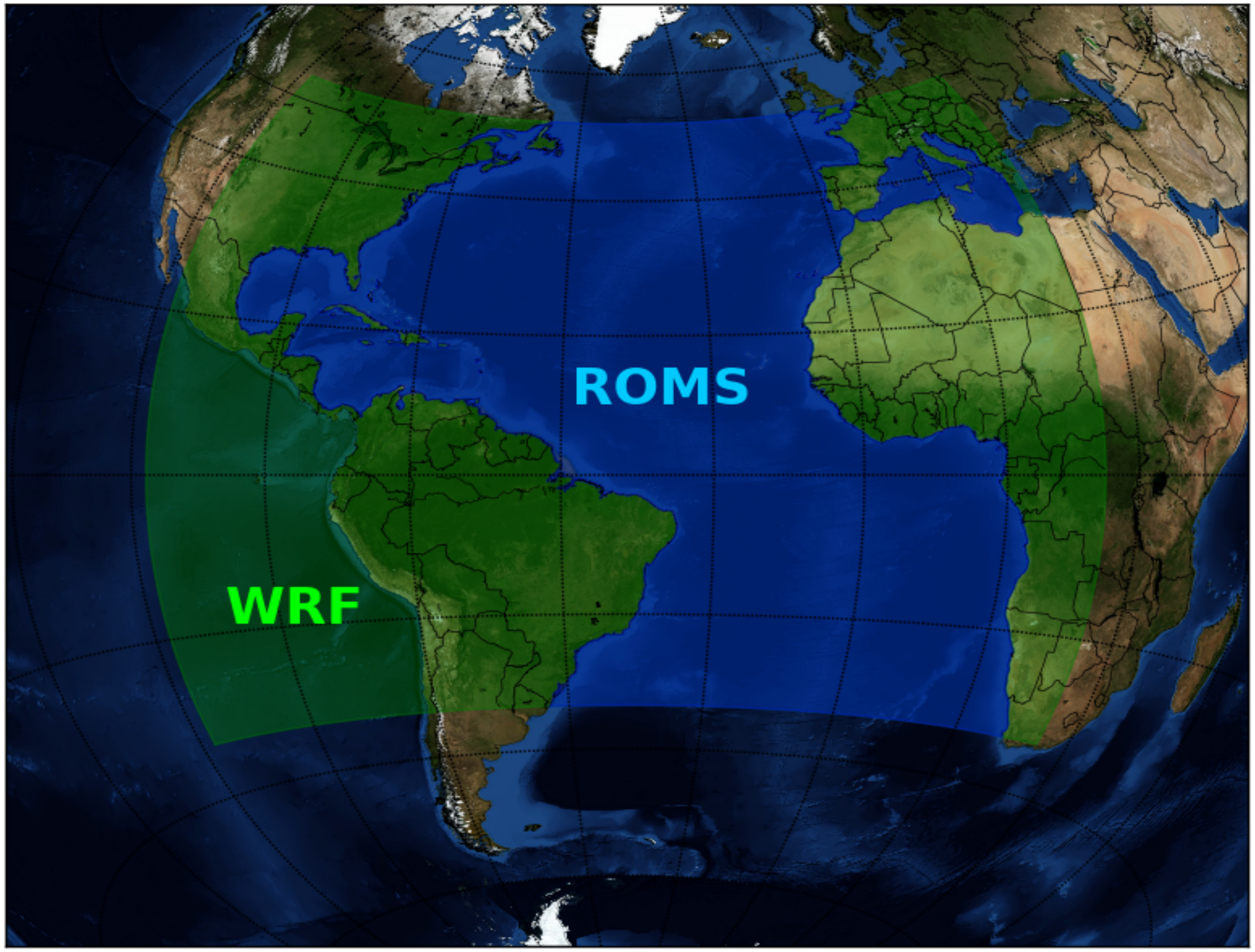


Richter and Xie (2008)

SST biases in Tropical Atlantic simulations

- **Large warm bias in Eastern Equatorial Atlantic (EEA) and South Eastern Tropical Atlantic (SETA)**
  - Is it caused by errors in the atmospheric model, the ocean model, or both?
  - Is it due to local errors or remote errors?
- **Some hypotheses proposed:**
  - Under-representation of low-level clouds (Huang et al., 2007)
  - Under-representation of coastal upwelling (Large & Danabasoglu, 2006)
  - Sub-surface ocean advection (Xu et al., 2011)
  - Equatorial trade wind bias associated with Amazon convection errors (Richter & Xie, 2008)
  - Spurious barrier layers in the ocean (Breugem et al., 2008)

Texas A&M Coupled Regional Climate Model (CRCM)



	Domain	*Grid(XYZ)*	*ΔXY*	*Δt*
WRF	107°W-25°E, 33°S-52°N	1537x1123x27	9km	20s
ROMS	98°W-21°E, 33°S-52°N	1391x1123x30	9km	600s

Climate model tuning

Whack-a-mole!

Uncoupled and coupled simulations

Designed based on atmospheric parameterization sensitivity to test relationship between equatorial Atlantic trade wind and SST bias

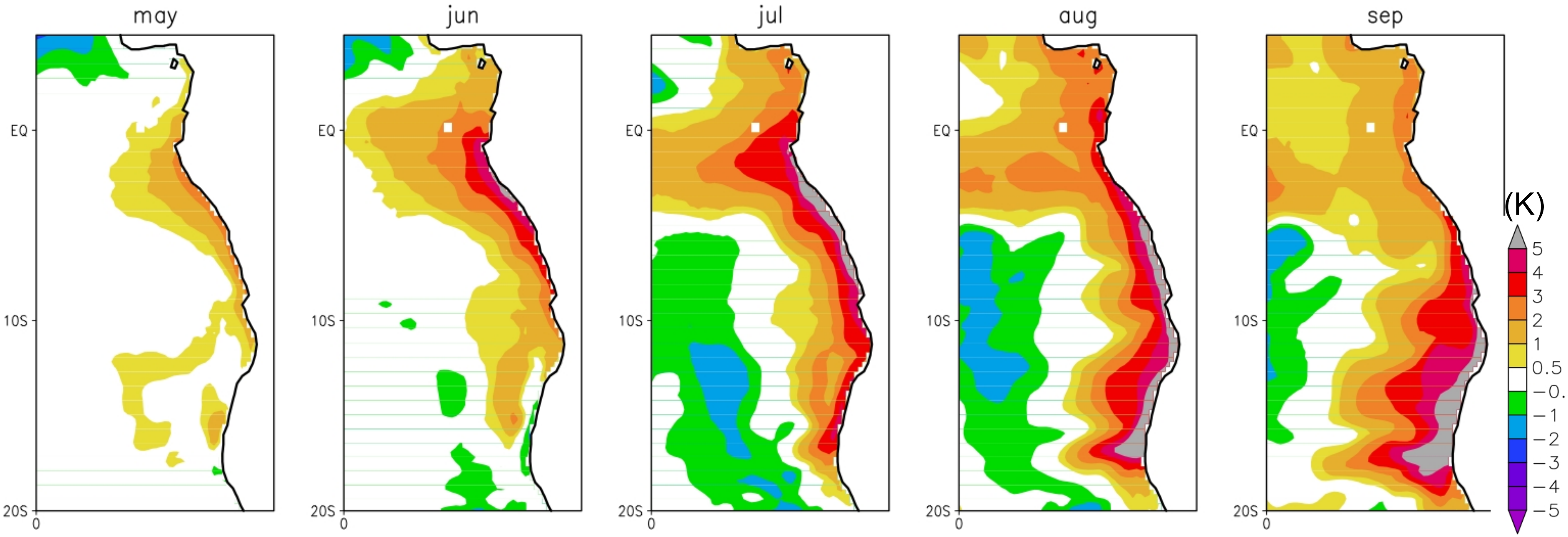
Four simulations:

- "Uncoupled wet"
- "Uncoupled dry"
- "Coupled wet"
- "Coupled dry"

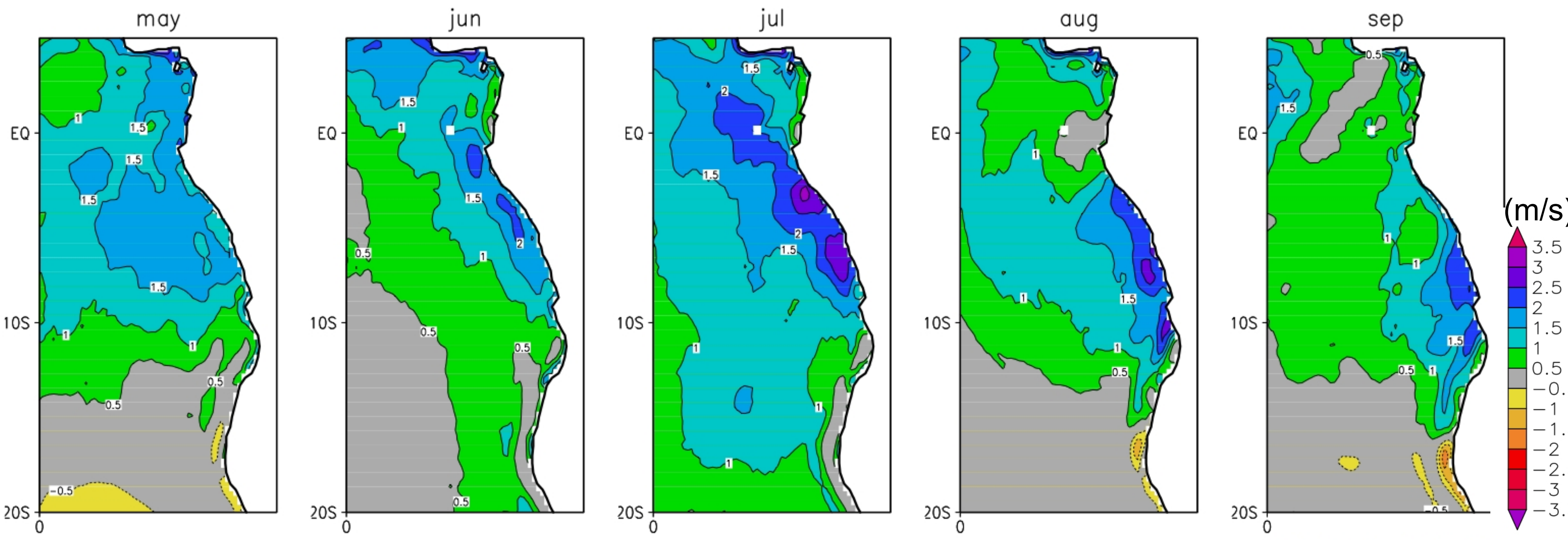
	Simulation name	
Parameterization	**"Dry"**	**"Wet"**
convection	KF	BM
SW/LW radiation	CAM/CAM	Goddard/RRTM
PBL	YSU	YSU
LSM	Noah	Noah
microphysics	Lin	Lin

Role of Bjerknes feedbacks

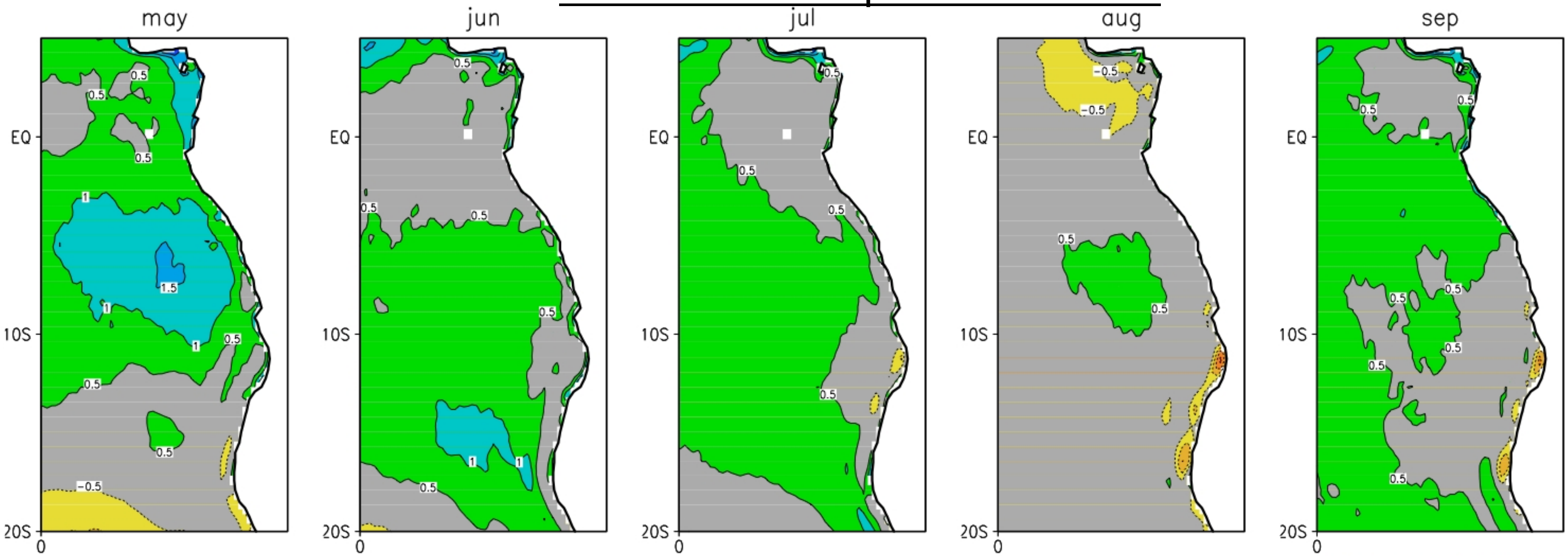
SST bias: "wet case"



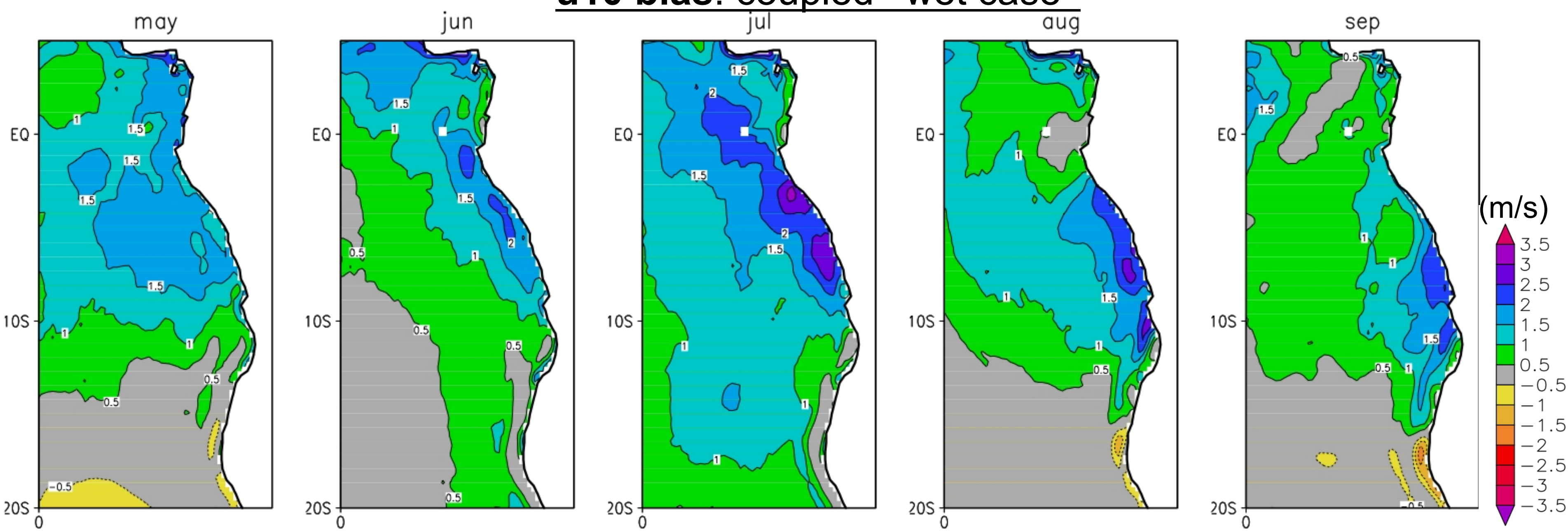
u10 bias: "wet case"



u10 bias: uncoupled "wet case"



u10 bias: coupled "wet case"



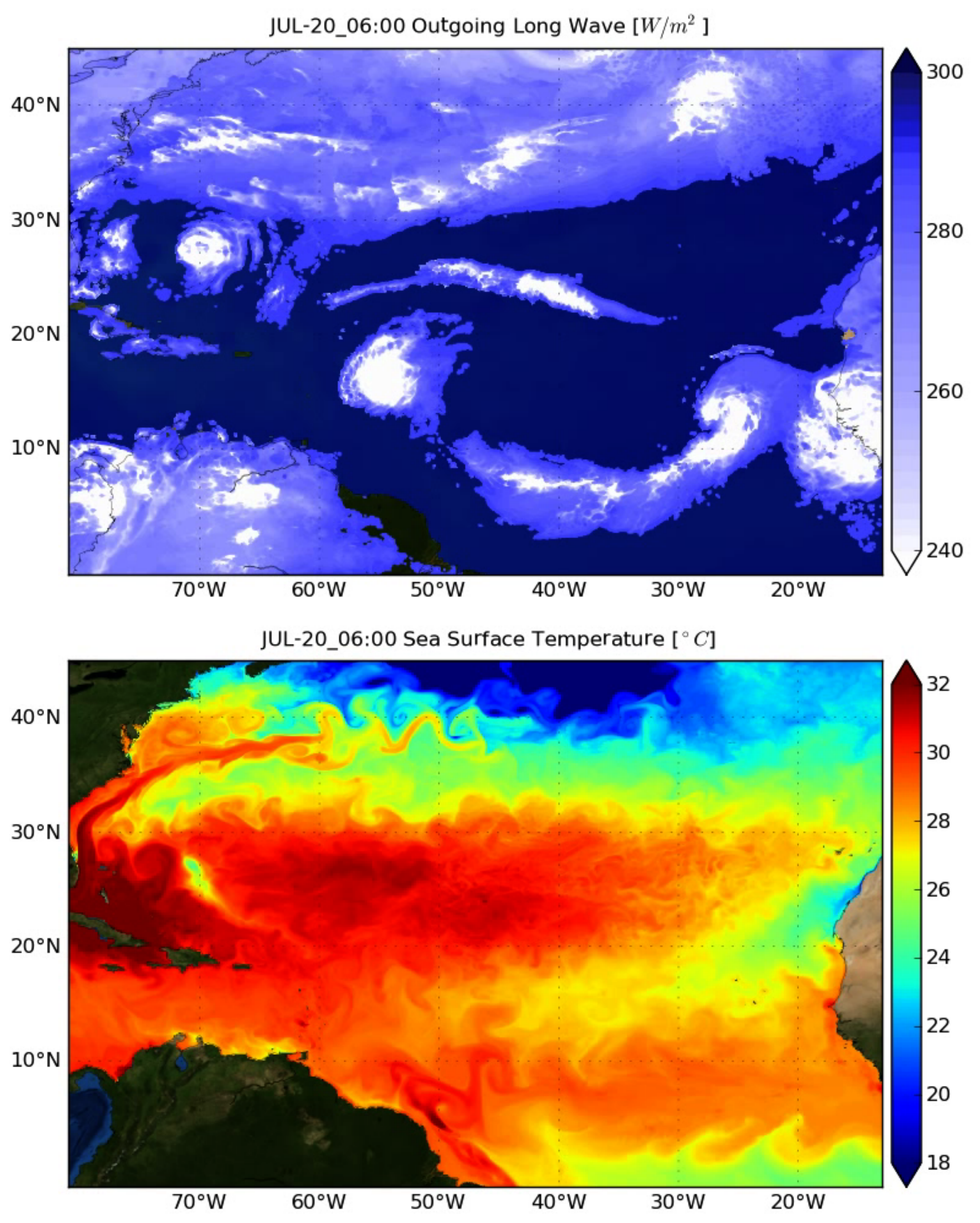
Hurricanes and air-sea interaction

- **Hurricanes: a low-probability, high impact event**
  - **Intensity is more difficult to predict than track**

- **Interaction with ocean can limit hurricane intensity**
  - **air-sea interaction has bigger effect on the intensity and the track**
  - **Slow moving hurricanes can interact with**
    - ***Oceanic mixed layer***
    - ***Oceanic "barrier layer" (see poster by Balaguru et al.)***
    - ***Oceanic eddies (e.g., Loop current eddy)***

Simulated Atlantic Hurricanes

- CRCM simulates realistic Tropical Cyclones (TCs) in the Atlantic, although the strength of the TCs is generally weaker than observed
- CRCM captures intense cooling in the wake of TCs, indicative of strong air-sea interactions



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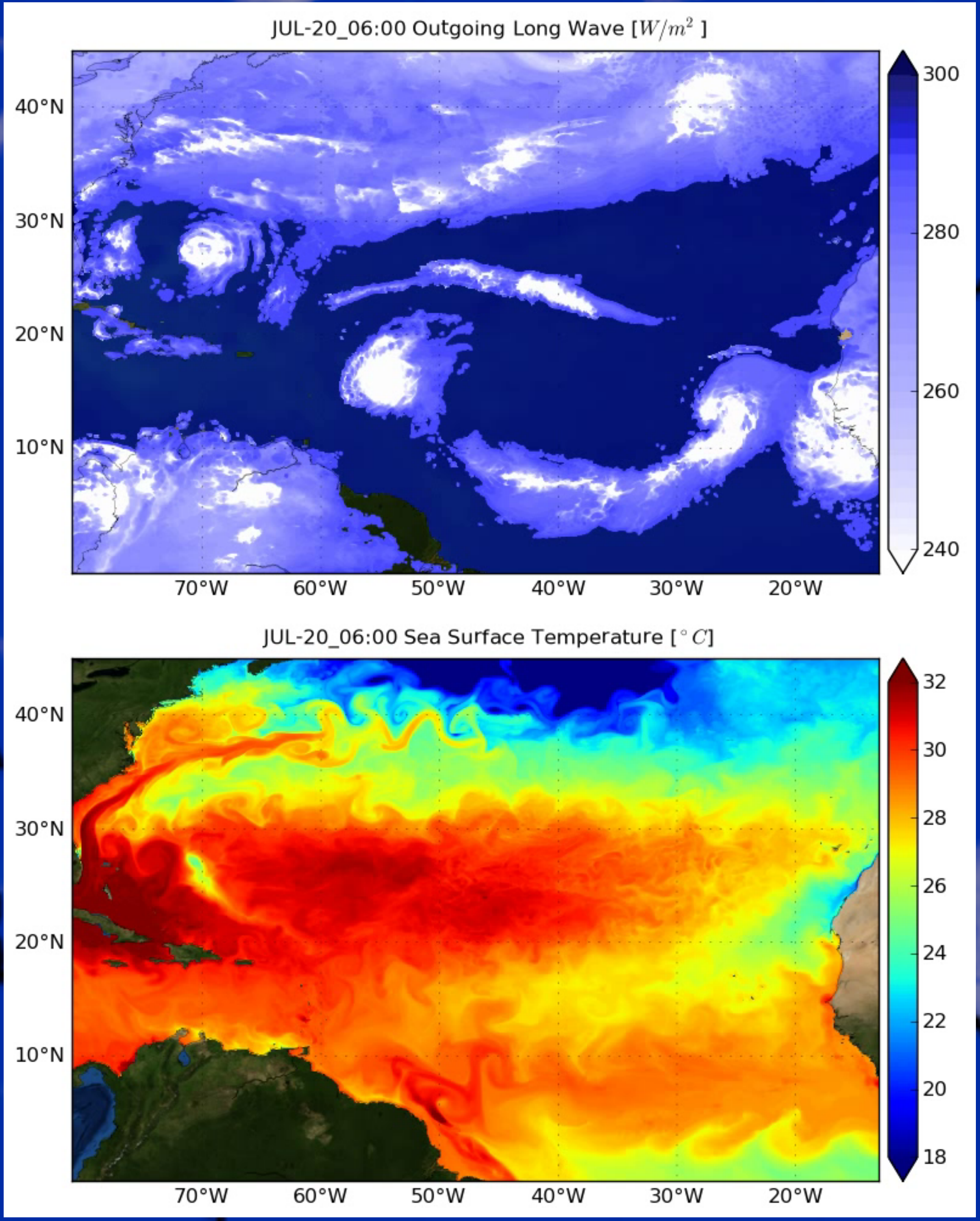
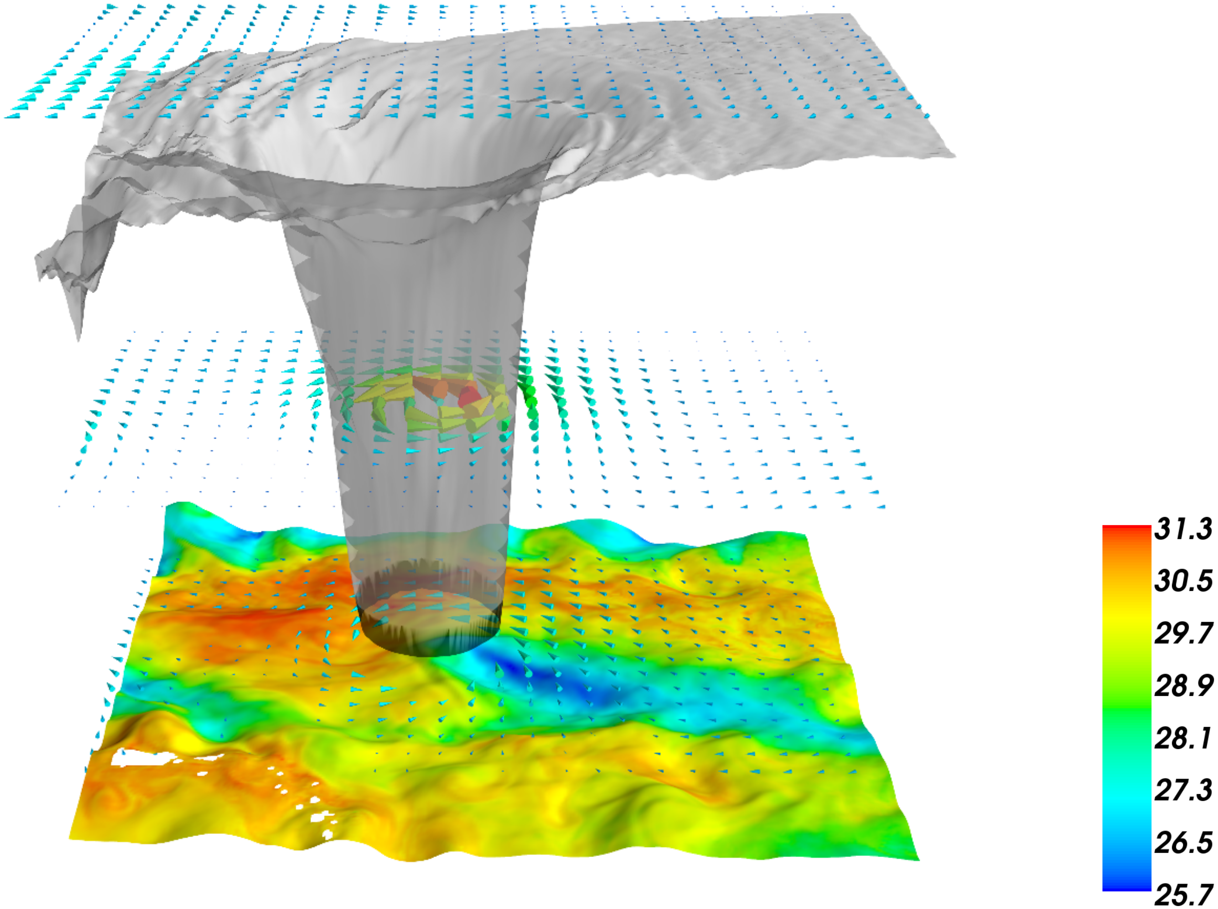
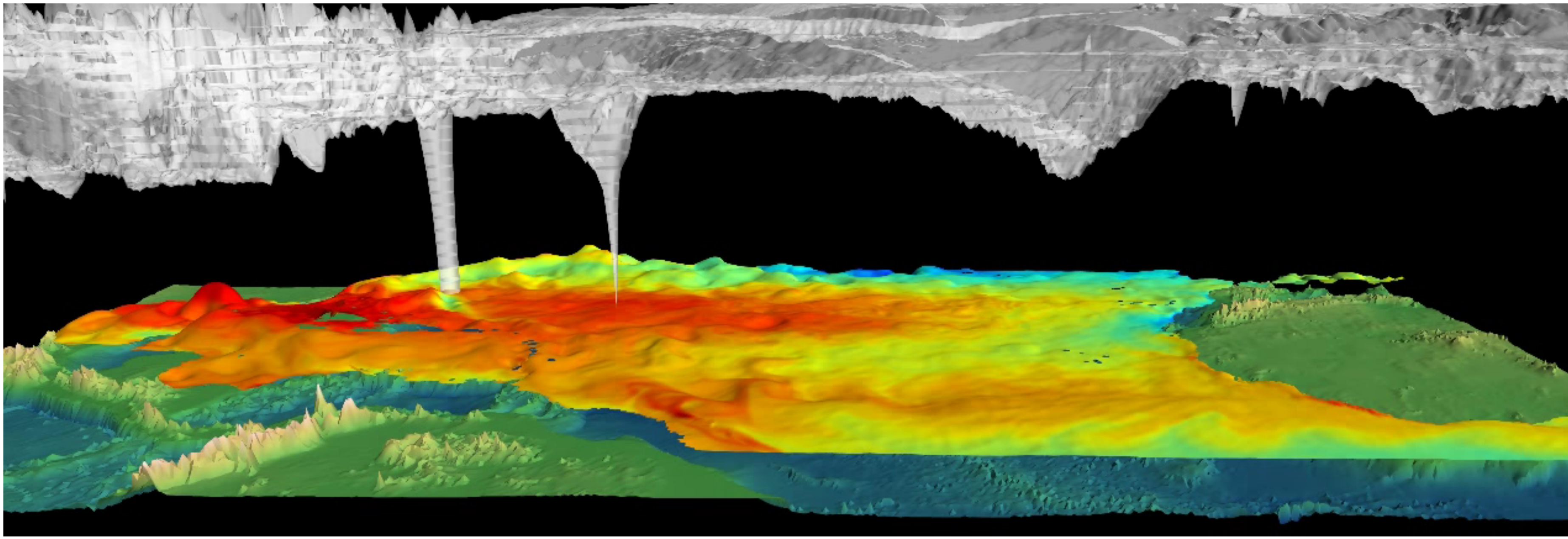


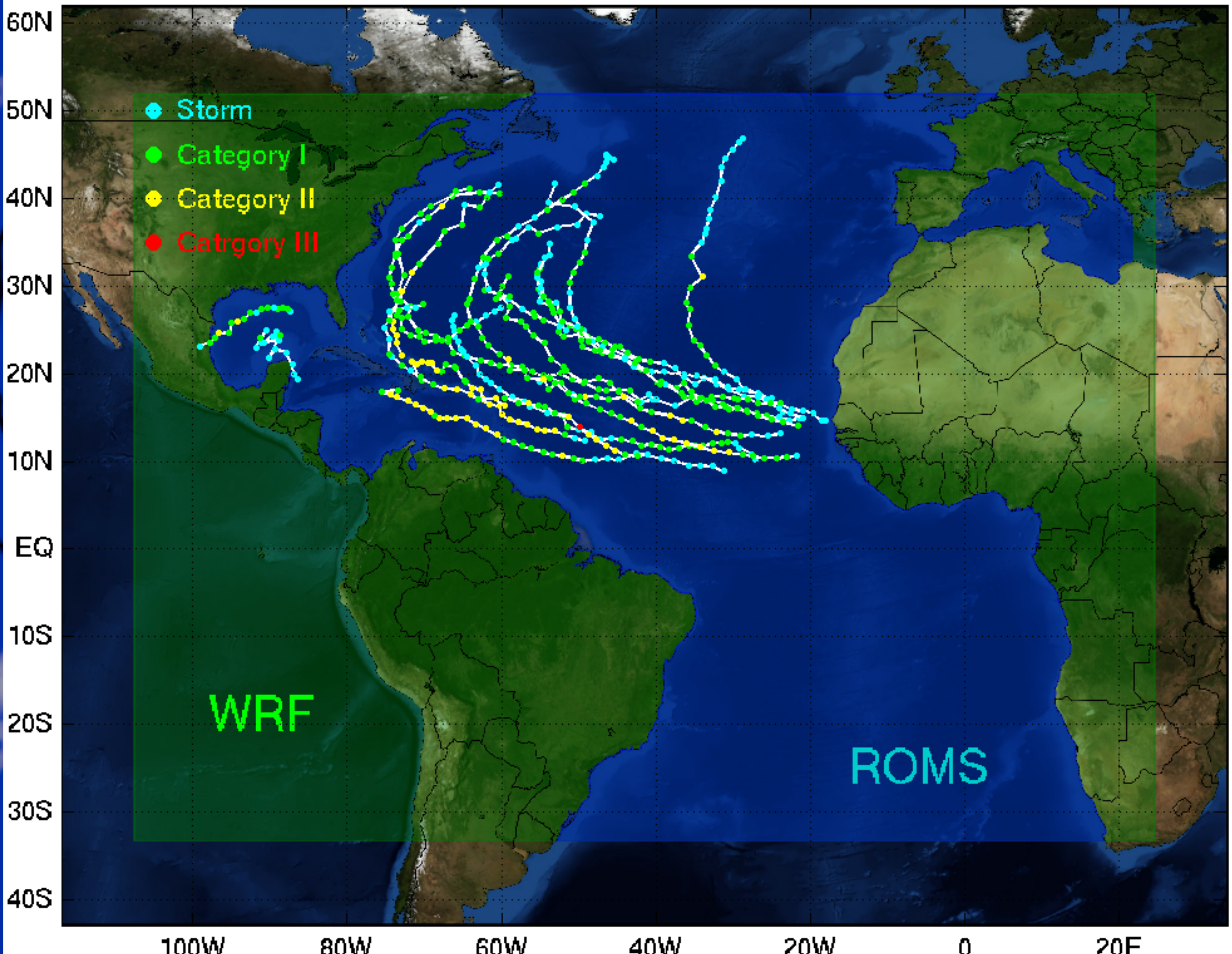
Simulated hurricane





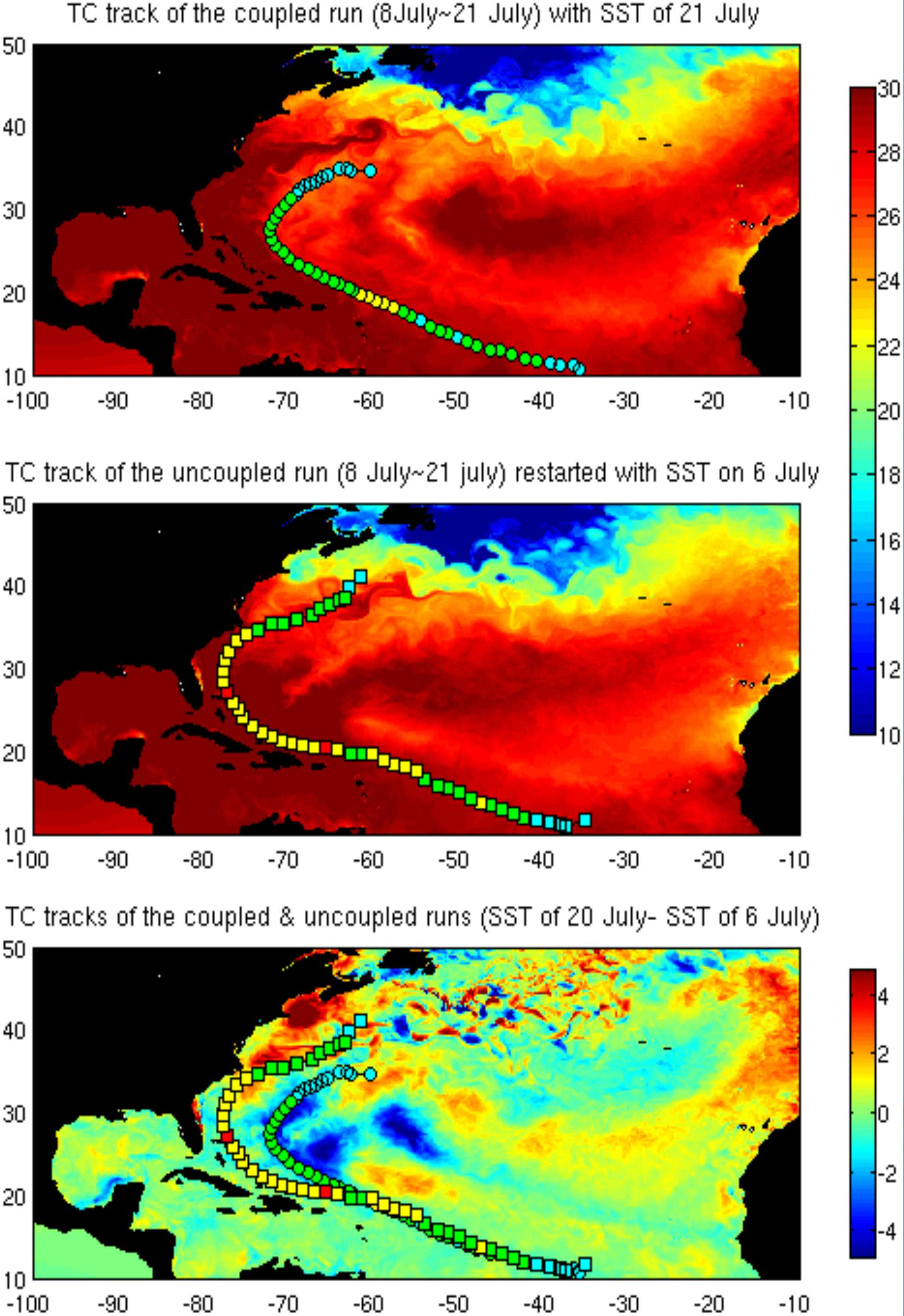
"Perfect Model" Experiments

- *Coupled (atmosphere+ocean) Control Simulation:*
  - *A single CRCM simulation May 1 to October 30*
    - *WRF initial and boundary conditions: NCEP Reanalysis*
    - *ROMS initial condition: from long spin-up run*
    - *ROMS boundary condition: from SODA reanalysis*
- *Uncoupled ensemble of atmosphere-only runs:*
  - *Select an ensemble of TCs (19) from the control simulation*
  - *Initialize WRF at the beginning of each TC from the control simulation*
  - *Keep SST constant at its initial value*



60N
50N
40N
30N
20N
10N
EQ
10S
20S
30S
40S
100W
80W
60W
40W
20W
0
20E
Storm
Category I
Category II
Catrgory III
WRF
ROMS

Examples of Simulated TCs in CRCM and WRF-only runs

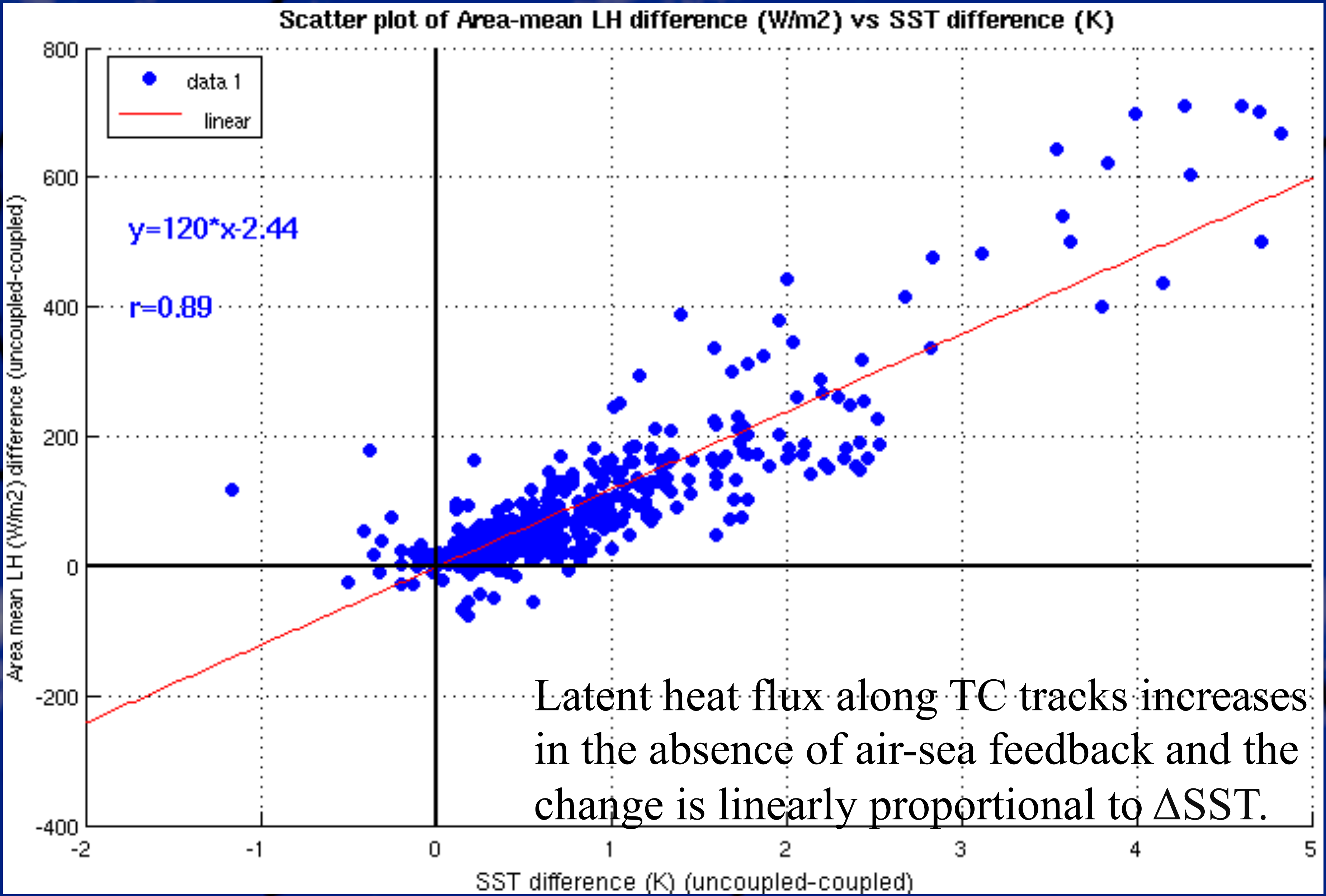


Coupled (atmosphere+ocean)

Atmosphere-only

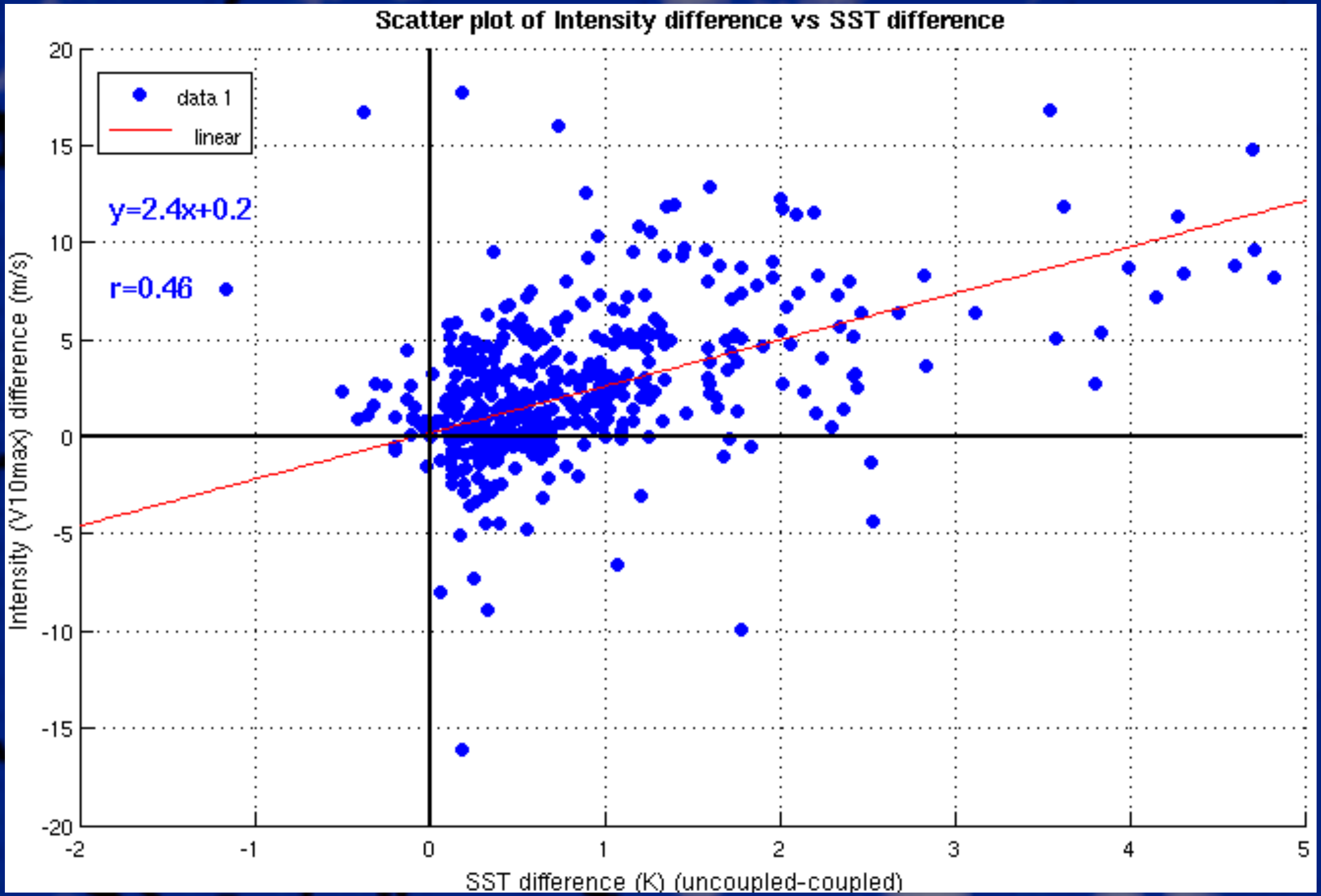
Surface temperature difference

Latent Heat Flux vs. ΔSST



Latent heat flux along TC tracks increases in the absence of air-sea feedback and the change is linearly proportional to ΔSST.

Effect of Air-Sea Coupling on TC Intensity



- Psfc ~ 6.3 mb/°C•ΔSST
- TC radius ~ 15km/°C•ΔSST
- $V10_{max}$ ~ 2.4m/s/°C•ΔSST

<ΔSST>=0.83°C
Max(ΔSST)=4.83°C
<$V10_{max}$> ~ 2.0m/s
TC strength change ~ 6%

Some conclusions

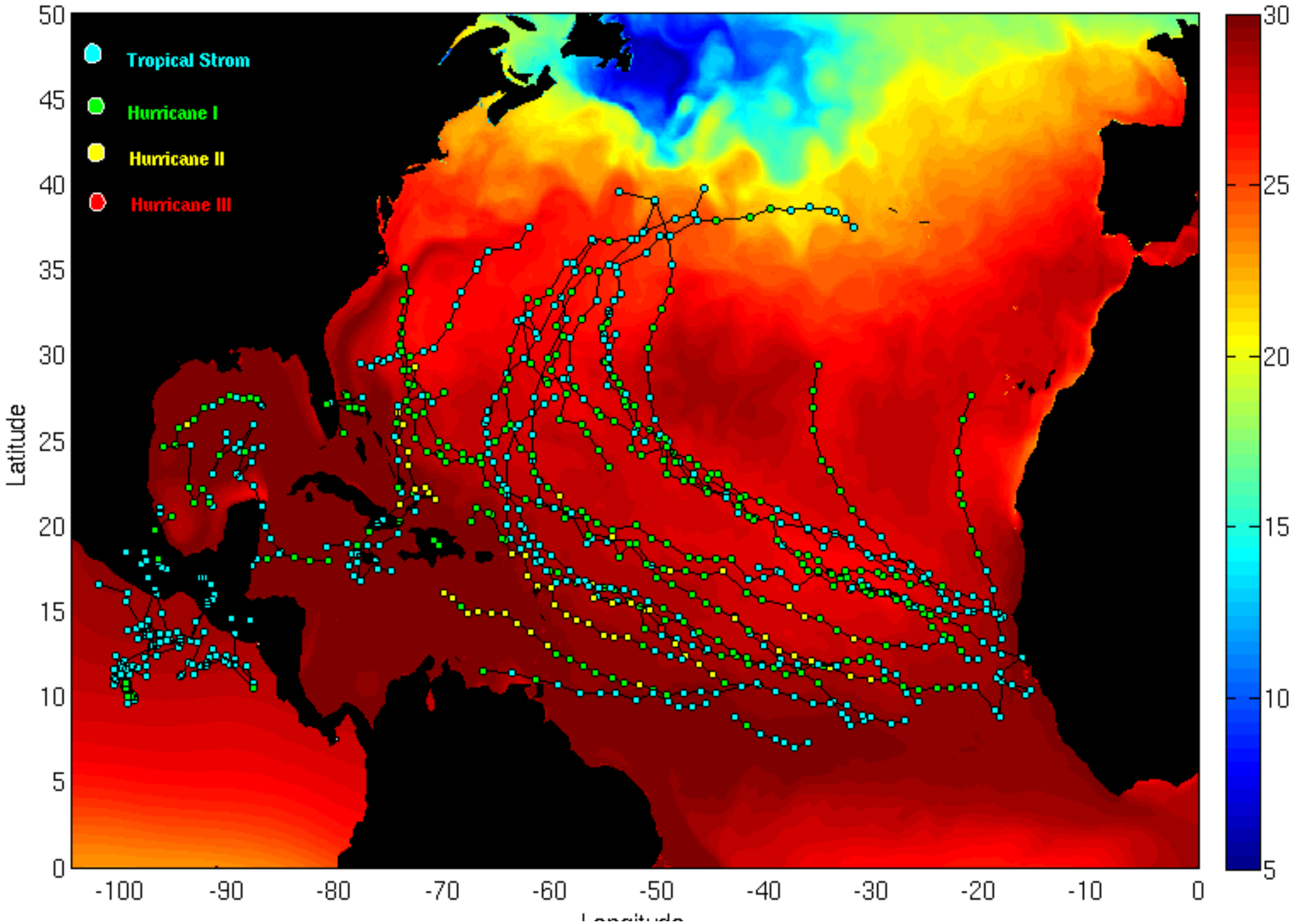
- **Warm bias in Eastern Equatorial Atlantic is likely due to local trade wind bias**
  - Seen in the uncoupled model but amplified in the coupled model by Bjerknes feedback
  - Remote convection errors or barrier layer biases not a major factor

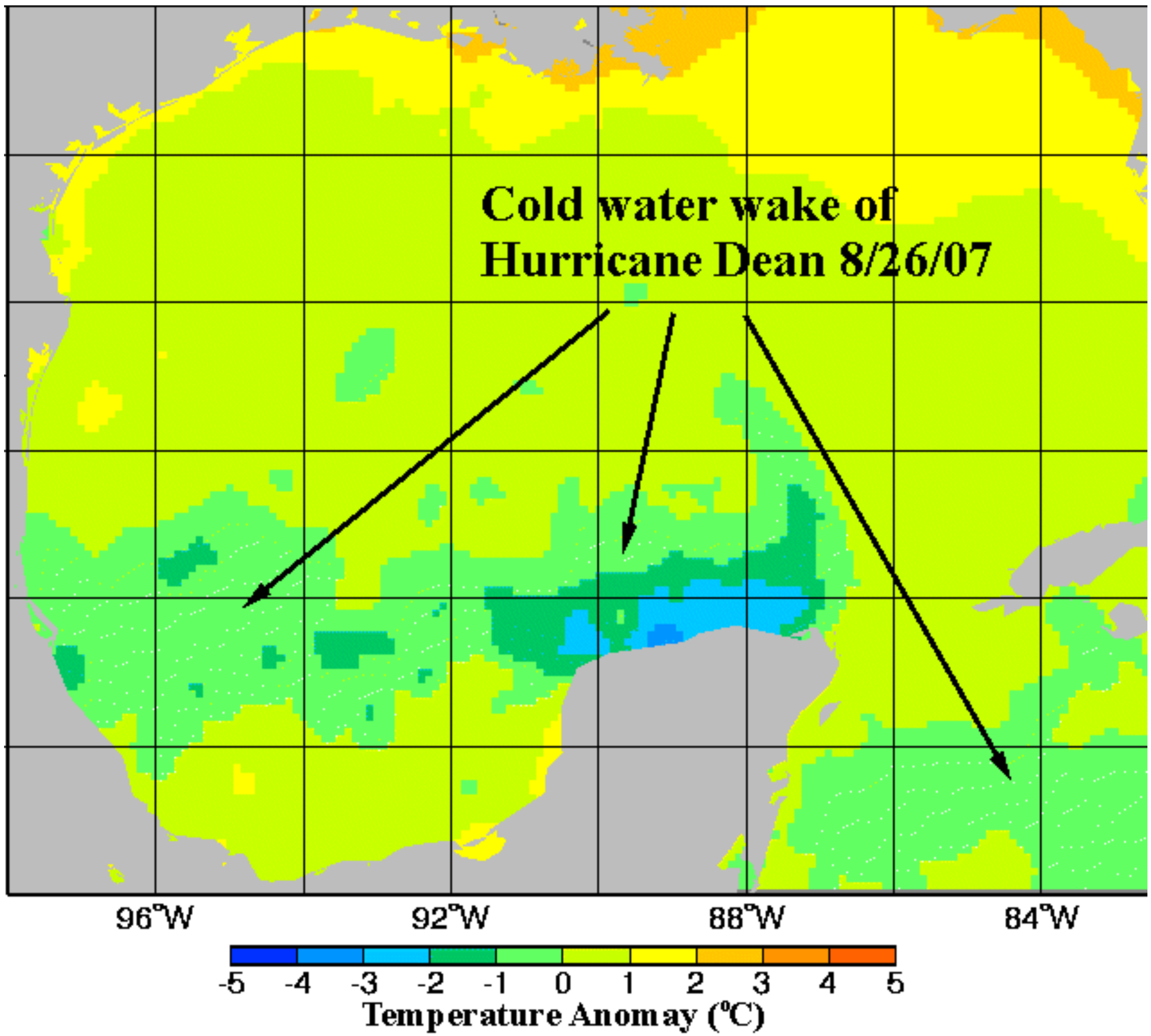
- **"Perfect model" experiments can capture the impact of air-sea coupling onhurricane evolution**
  - Track simulations are not that sensitive to air-sea coupling
  - Intensity and size are sensitive to coupling, with coupling acting as a negative feedback that limits hurricane strength and size

Questions

- *How important is ocean-atmosphere interaction in TC development?*
- *In particular, will ocean-atmosphere interaction have an effect on TC's intensity, speed and trajectory?*

Climatology of hurricanes





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)

Texas A&M Coupled Regional Climate Model (TAMU-CRCM)

- **Regional atmospheric model coupled to regional ocean model**
- **Lateral boundary conditions from global coupled model or reanalyses**

Atmospheric component:
Weather Research & Forecasting Model (WRF)

Developed at NCAR

27km and 9km horizontal resolution, 28 vertical levels

NCEP-NCAR reanalysis for boundary conditions and initial conditions

Physics parameterizations:

WSM 3-class simple ice (Microphysics), CAM Radiation, YSU PBL, Thermal Diffusion land scheme, Kain-Fritsch cumulus convection scheme

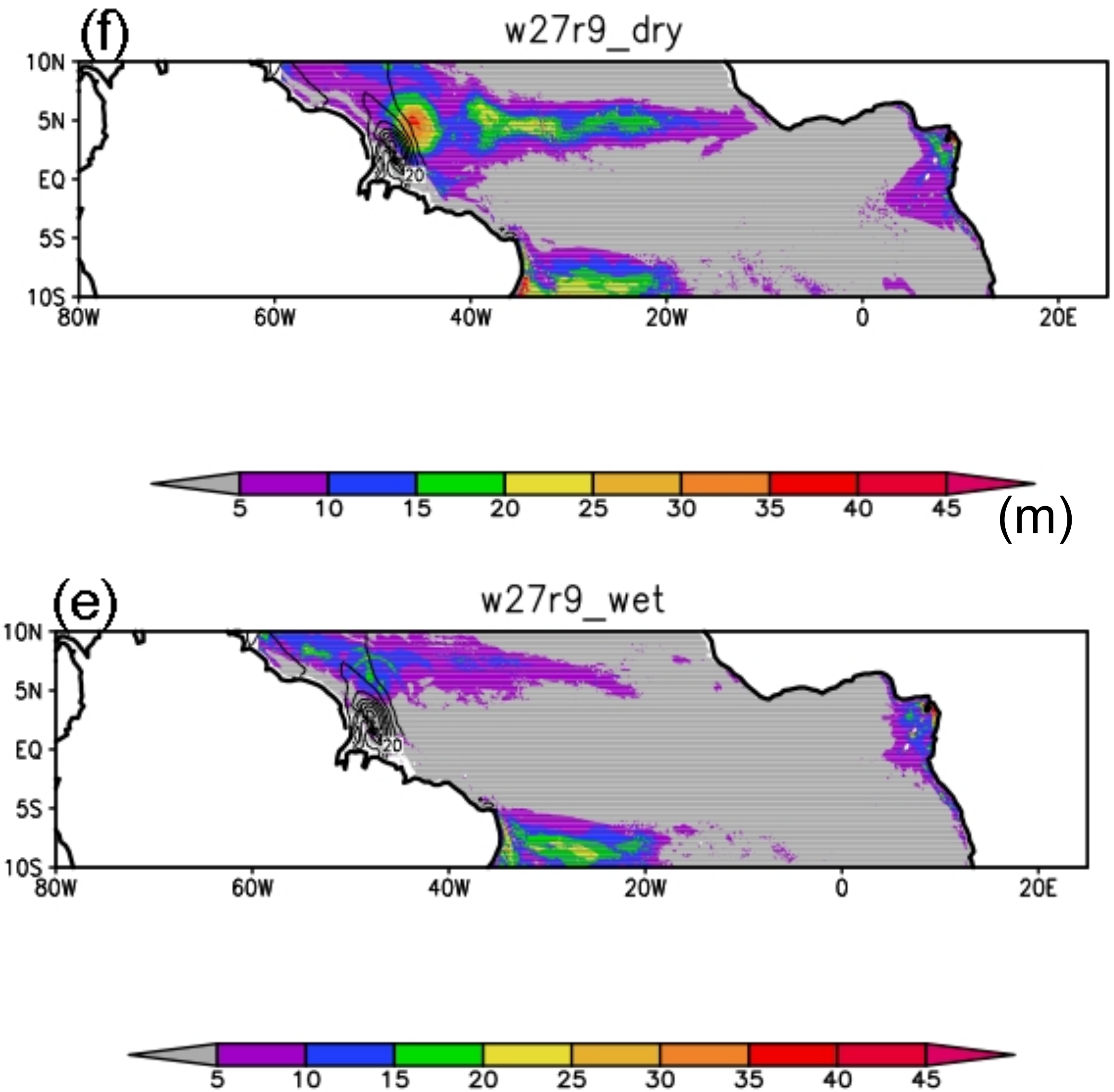
Oceanic component:
Regional Ocean Modeling System (ROMS)

- **Developed at Rutgers University/UCLA**
- **1/12^{o} (9km) Horizontal Resolution & 30 levels**
- **Boundary conditions derived from Levitus observational data.**

- ***NOTE: The ocean model is about 20 times faster than the atmospheric model, for the same horizontal resolution!***

- **Configuration: 3rd-order upstream bias for 3D momentum, 4th-order centered for 2D momentum, harmonic horizontal mixing, recursive MPDATA 3D advection for tracers, quadratic bottom friction, Mellor/Yamada Level-2.5 closure**

JJA barrier layer thickness



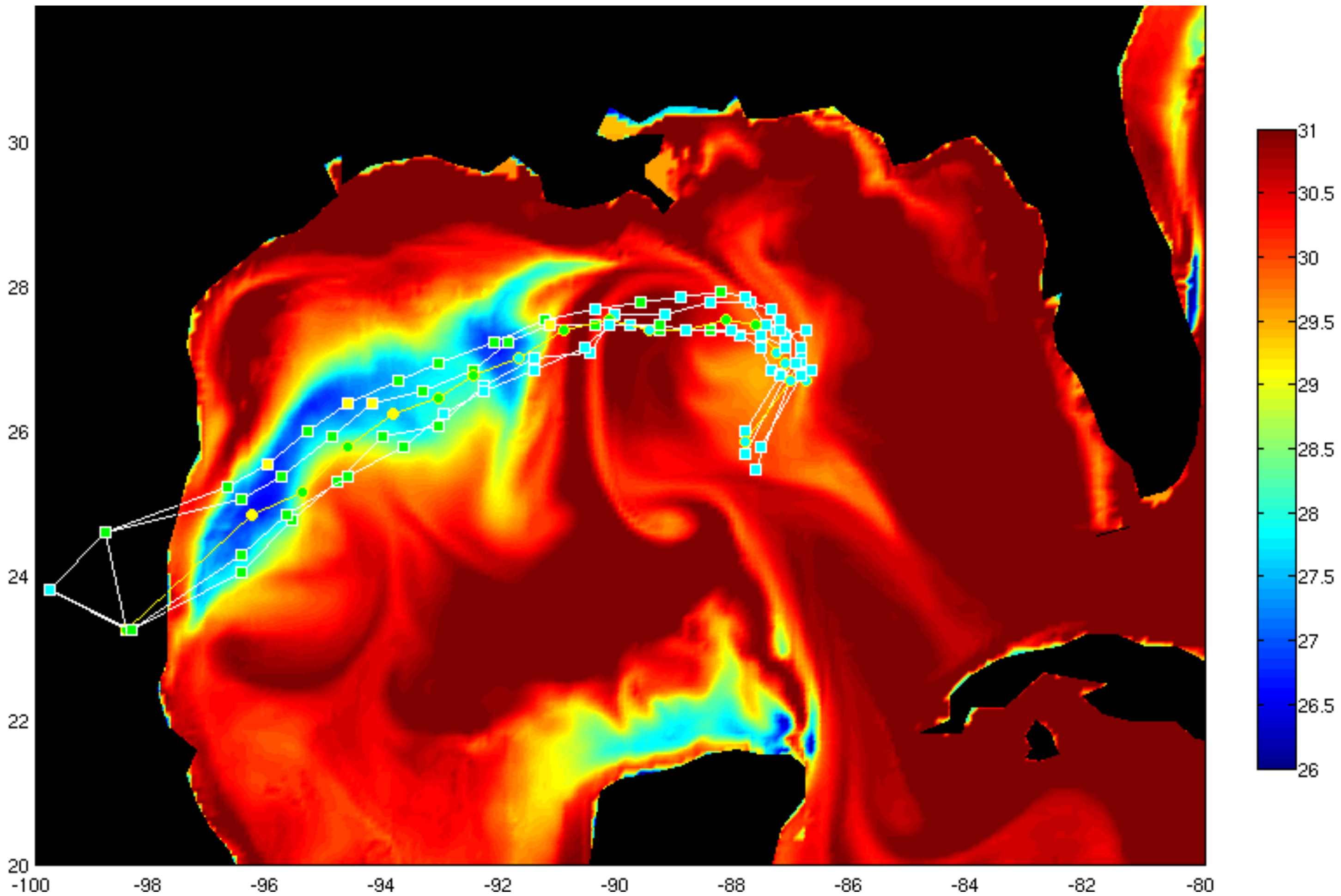
Although Eastern equatorial Atlantic positive rainfall bias exists only in coupled "wet case," a spurious barrier layer is simulated in both the "wet" and "dry" cases.

Effect of air-sea coupling

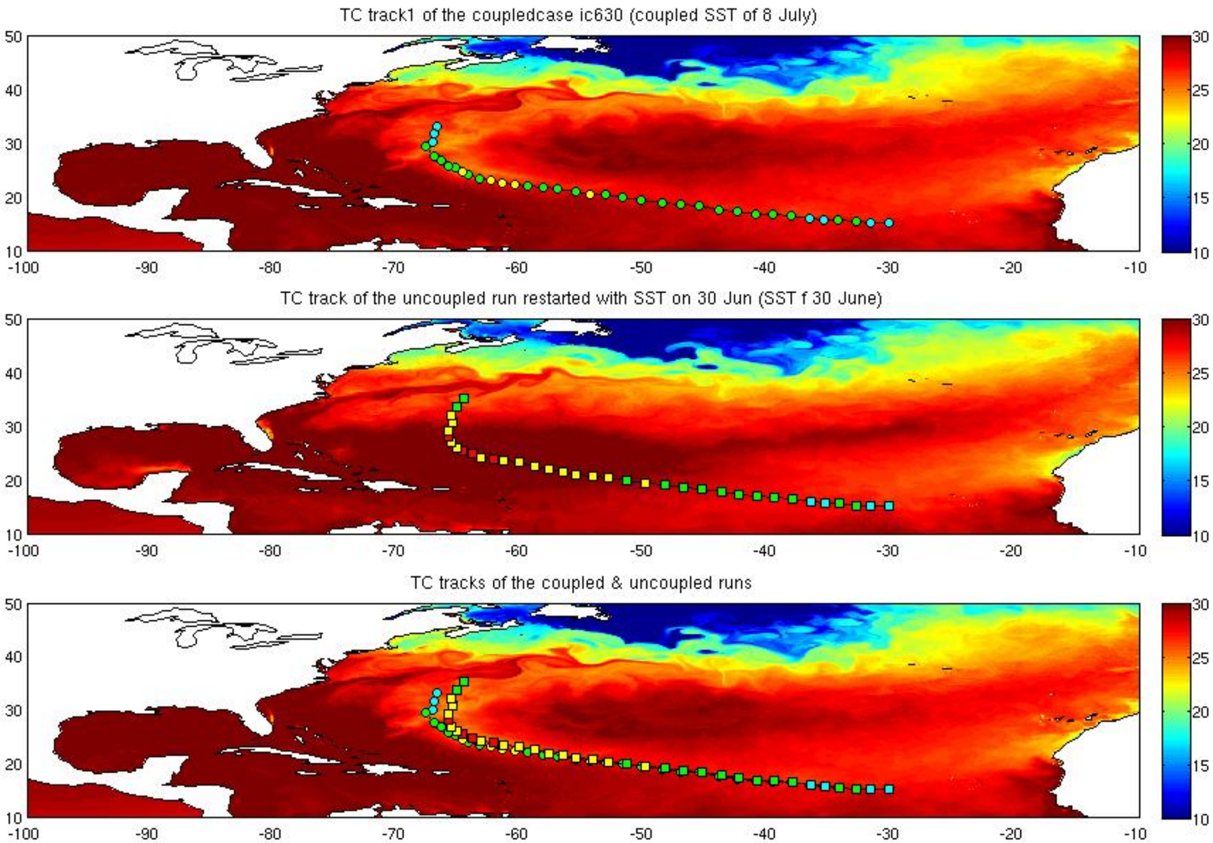
- The most notable effect of air-sea interaction is its impact on TC intensity. On average, WRF-only simulations over-estimate TC intensity by 6%, which is attributable to the lack of surface cooling, resulting in an increase of latent heat flux exchange.

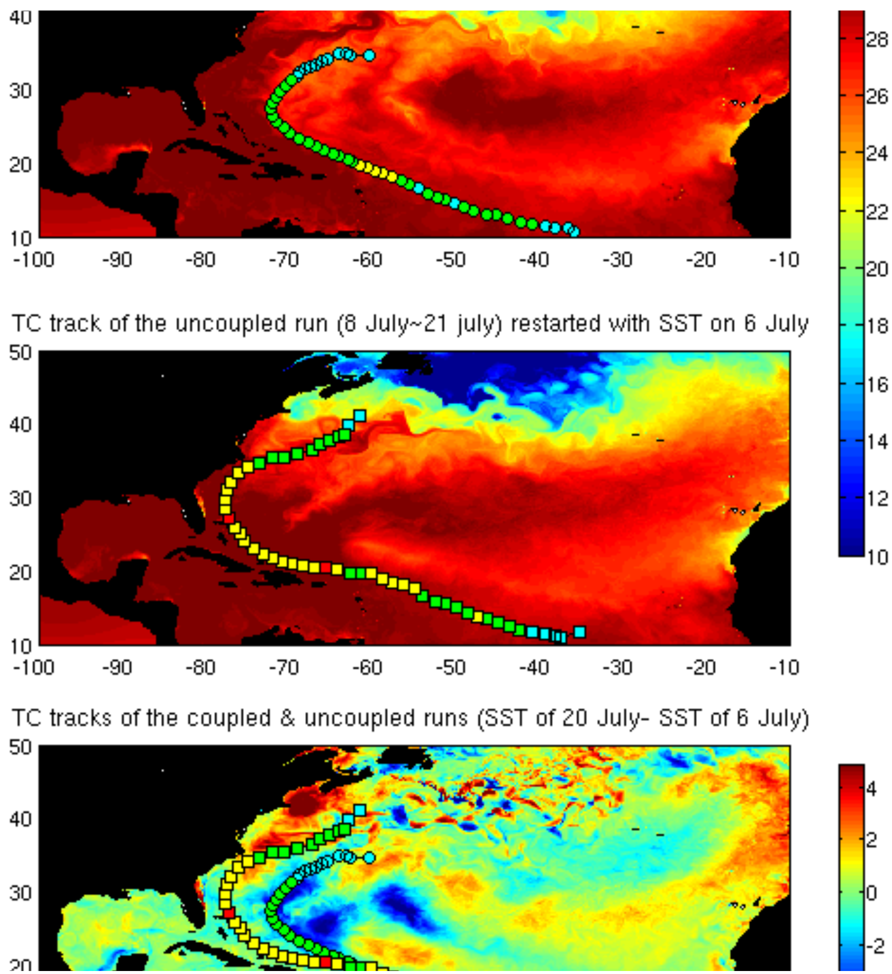
- TC tracks are also affected, albeit to a lesser degree, by air-sea interaction. The uncoupled WRF simulations can accurately track TC trajectories simulated by the coupled model up to 5 days, suggesting that even with a perfect initial condition, uncoupled atmospheric models may only make accurate TC forecasts in short-range.

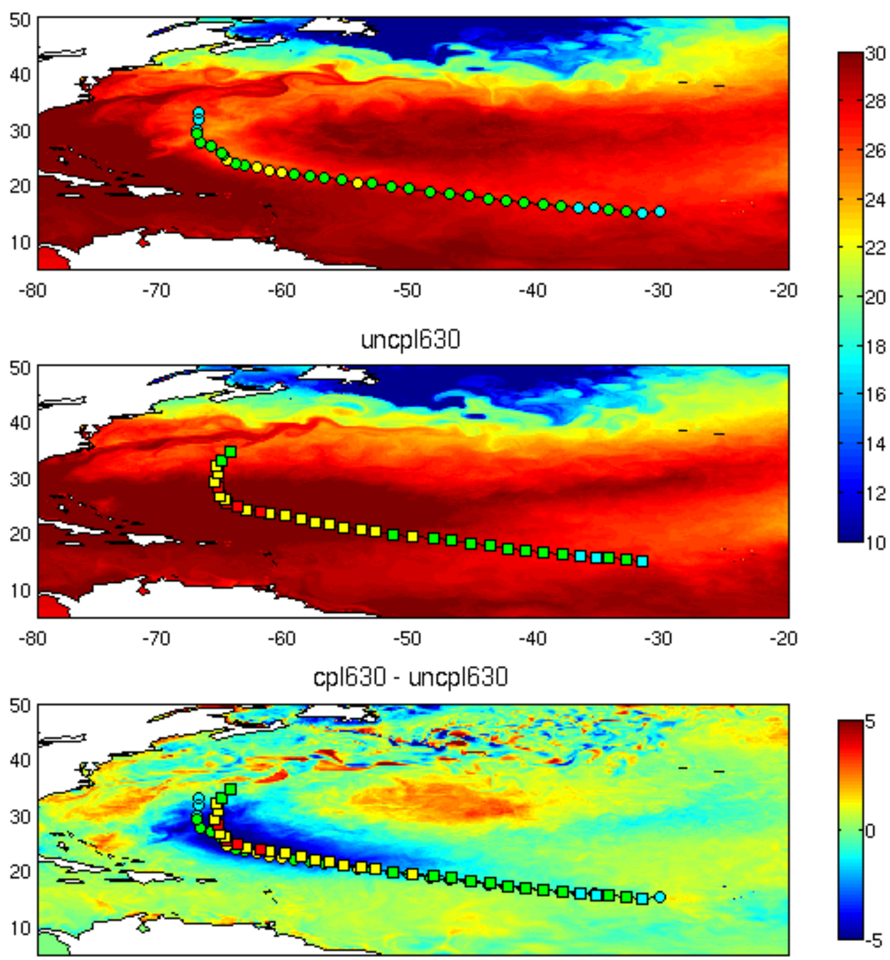
- TC speed is not significantly affected by air-sea feedbacks.



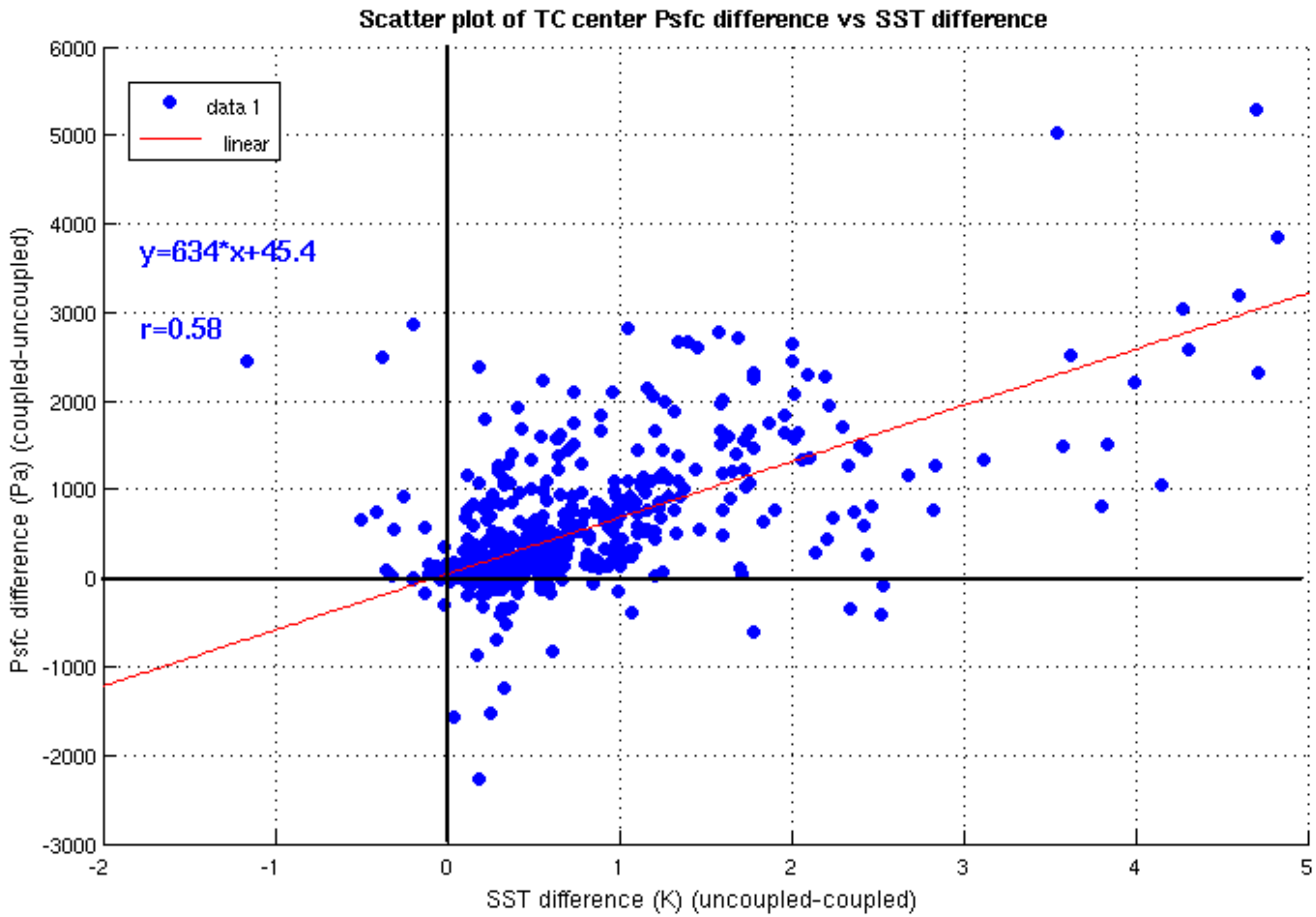
30
28
26
24
22
20
-100
-98
-96
-94
-92
-90
-88
-86
-84
-82
-80
31
30.5
30
29.5
29
28.5
28
27.5
27
26.5
26

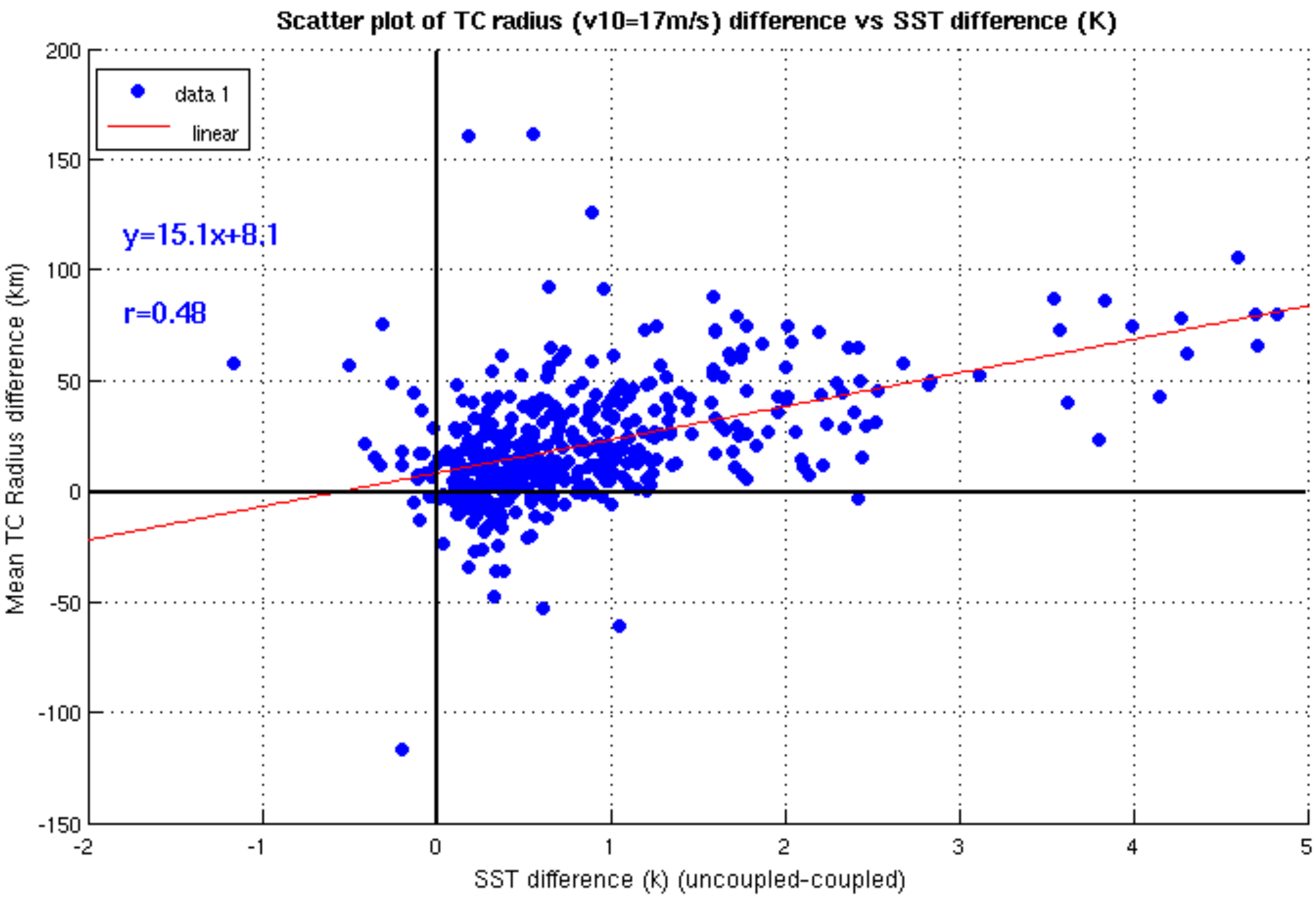

TC track1 of the coupledcase ic630 (coupled SST of 8 July)
TC track of the uncoupled run restarted with SST on 30 Jun (SST f 30 June)
TC tracks of the coupled & uncoupled runs
50
40
30
20
10
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
30
25
20
15
10


TC track of the uncoupled run (8 July~21 july) restarted with SST on 6 July
TC tracks of the coupled & uncoupled runs (SST of 20 July- SST of 6 July)

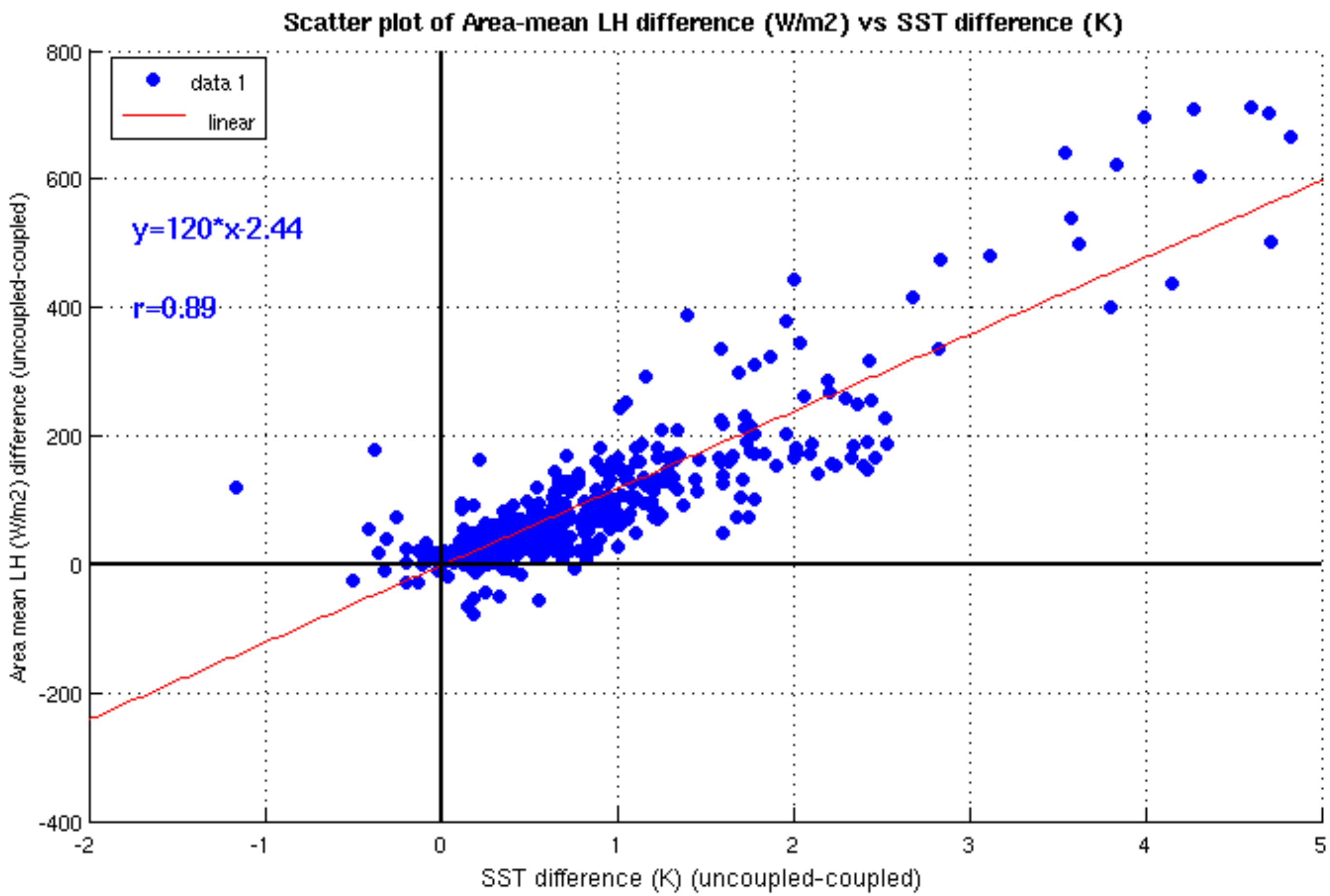


uncpl630
cpl630 - uncpl630


Scatter plot of TC center Psfc difference vs SST difference
data 1
linear
y=634*x+45.4
r=0.58
Psfc difference (Pa) (coupled-uncoupled)
SST difference (K) (uncoupled-coupled)
6000
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-2
-1
0
1
2
3
4
5



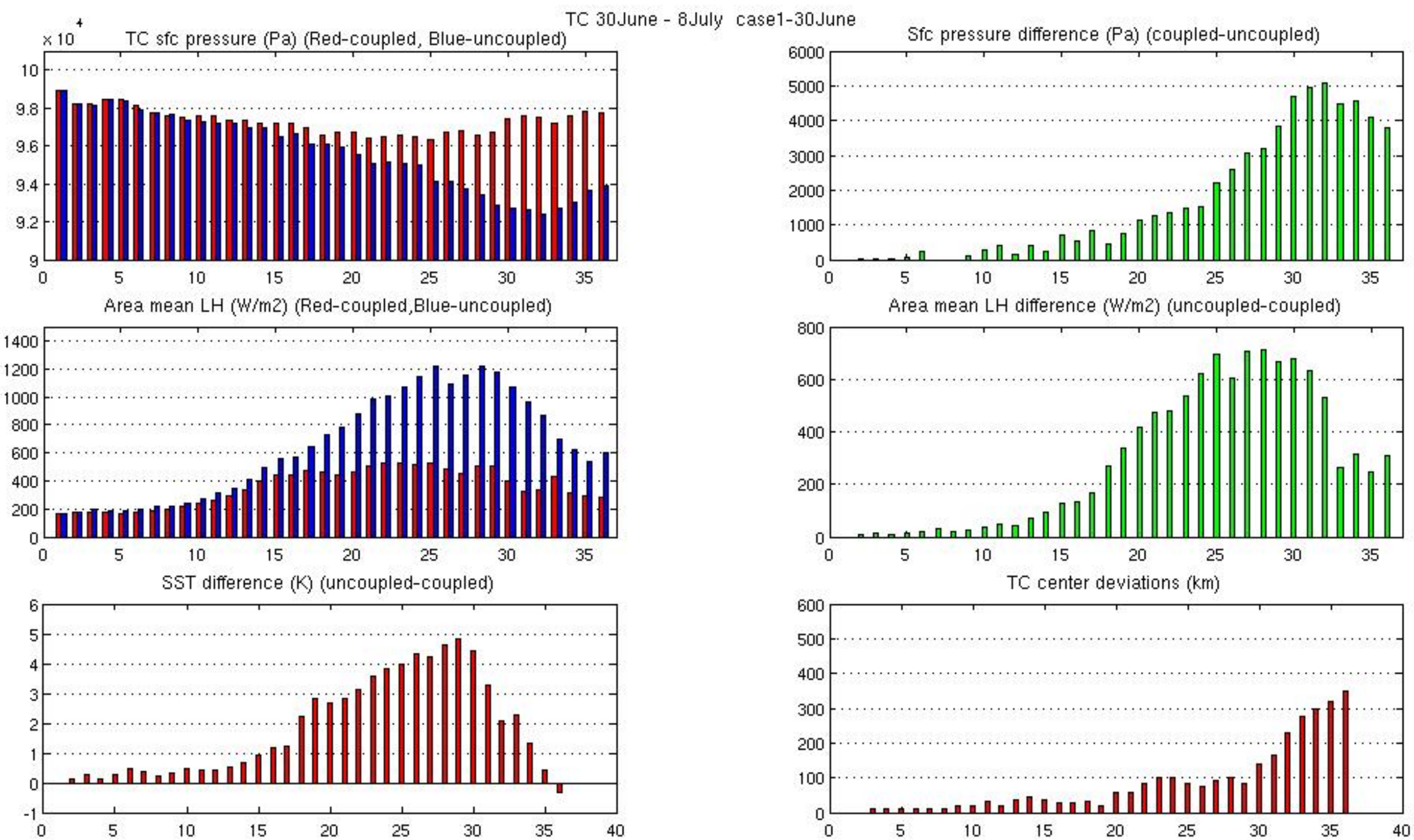
Scatter plot of TC radius (v10=17m/s) difference vs SST difference (K)
data 1
linear
y=15.1x+8.1
r=0.48
Mean TC Radius difference (km)
SST difference (k) (uncoupled-coupled)
200
150
100
50
0
-50
-100
-150
-2
-1
0
1
2
3
4
5



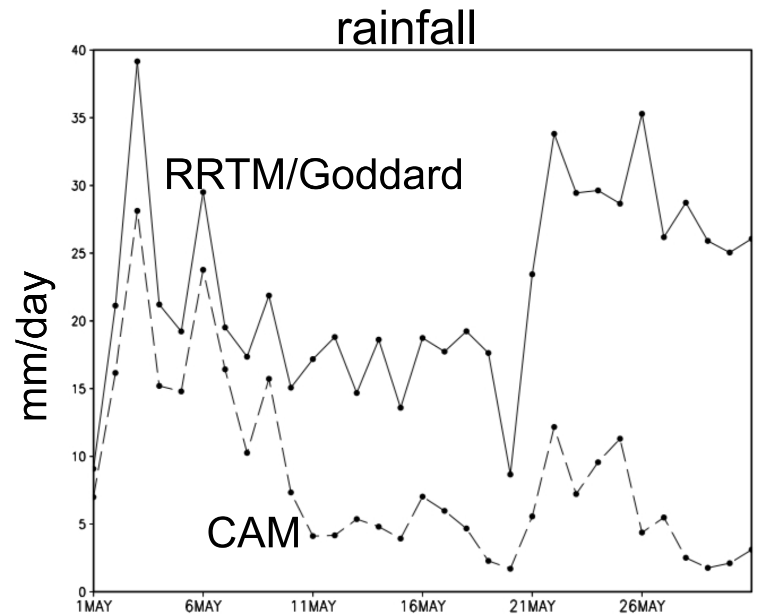
Scatter plot of Area-mean LH difference (W/m2) vs SST difference (K)
data 1
linear
y=120*x-2.44
r=0.89
Area mean LH (W/m2) difference (uncoupled-coupled)
SST difference (K) (uncoupled-coupled)
800
600
400
200
0
-200
-400
-2
-1
0
1
2
3
4
5

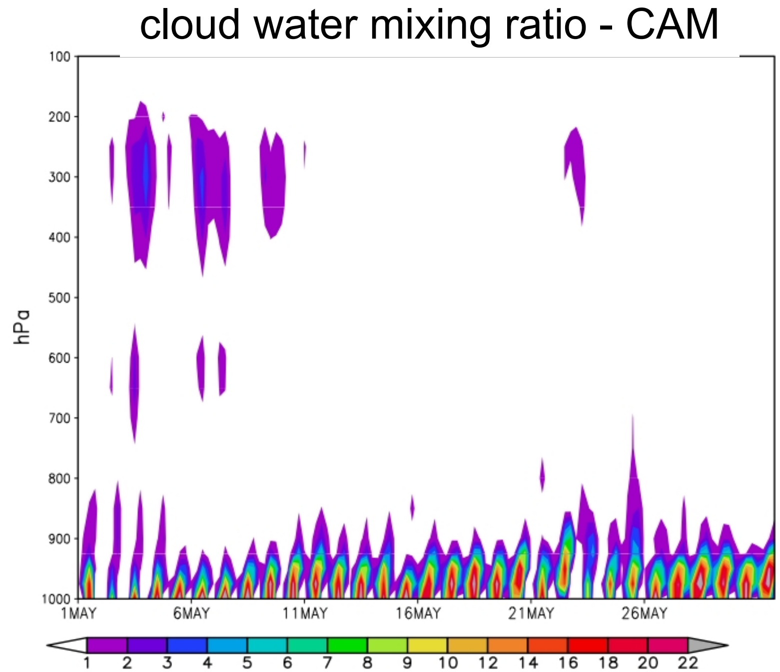
Computational Resources
EOS (eos.tamu.edu)

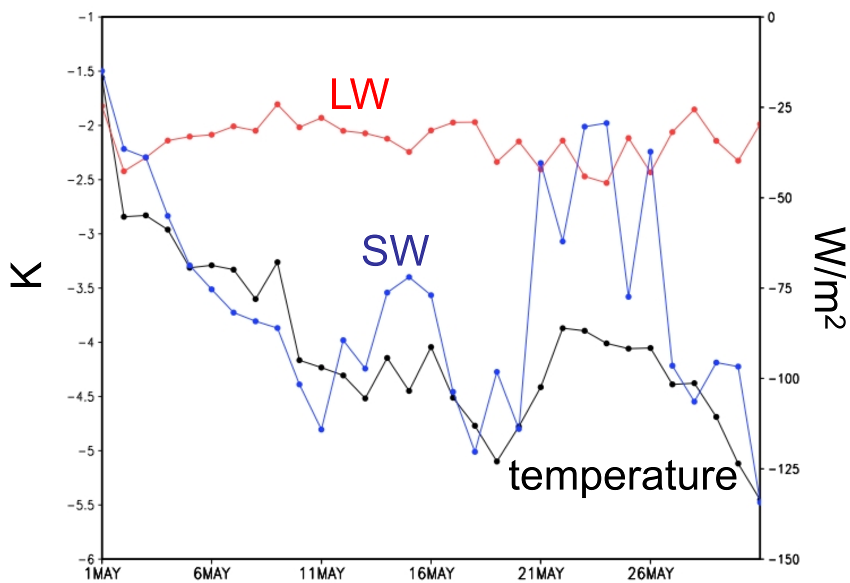
- Linux (RedHat Enterprise Linux and CentOS)
- 324 Nodes, 2592 Processing Cores
- 7,920 GB Memory
- 120 TB disk: DDN S2A9900 RAID Array
- Total Cores Used: 1,024 (976 for WRF, 48 for ROMS)
- Coupling frequency: 1 hour, Output frequency: 6 hours
- Wall-clock computing time: 72 hours
- Model integration time: 158 days (May 1st to Oct 5th)
- Size of Model output: ~ 3 TB

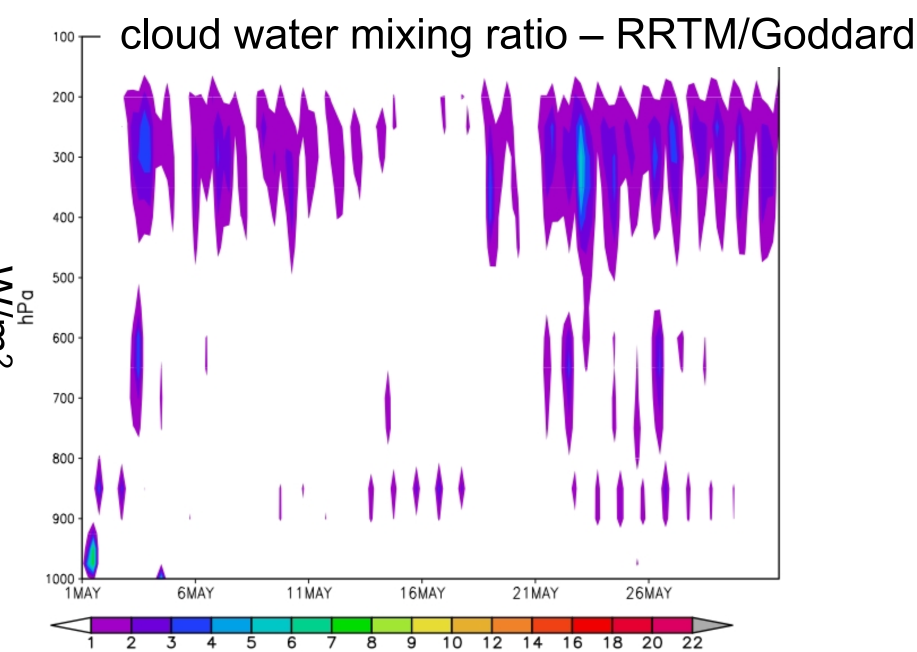

TC 30June - 8July case1-30June
TC sfc pressure (Pa) (Red-coupled, Blue-uncoupled)
Sfc pressure difference (Pa) (coupled-uncoupled)
Area mean LH (W/m2) (Red-coupled,Blue-uncoupled)
Area mean LH difference (W/m2) (uncoupled-coupled)
SST difference (K) (uncoupled-coupled)
TC center deviations (km)

Cloud – insolation – land temperature feedbacks

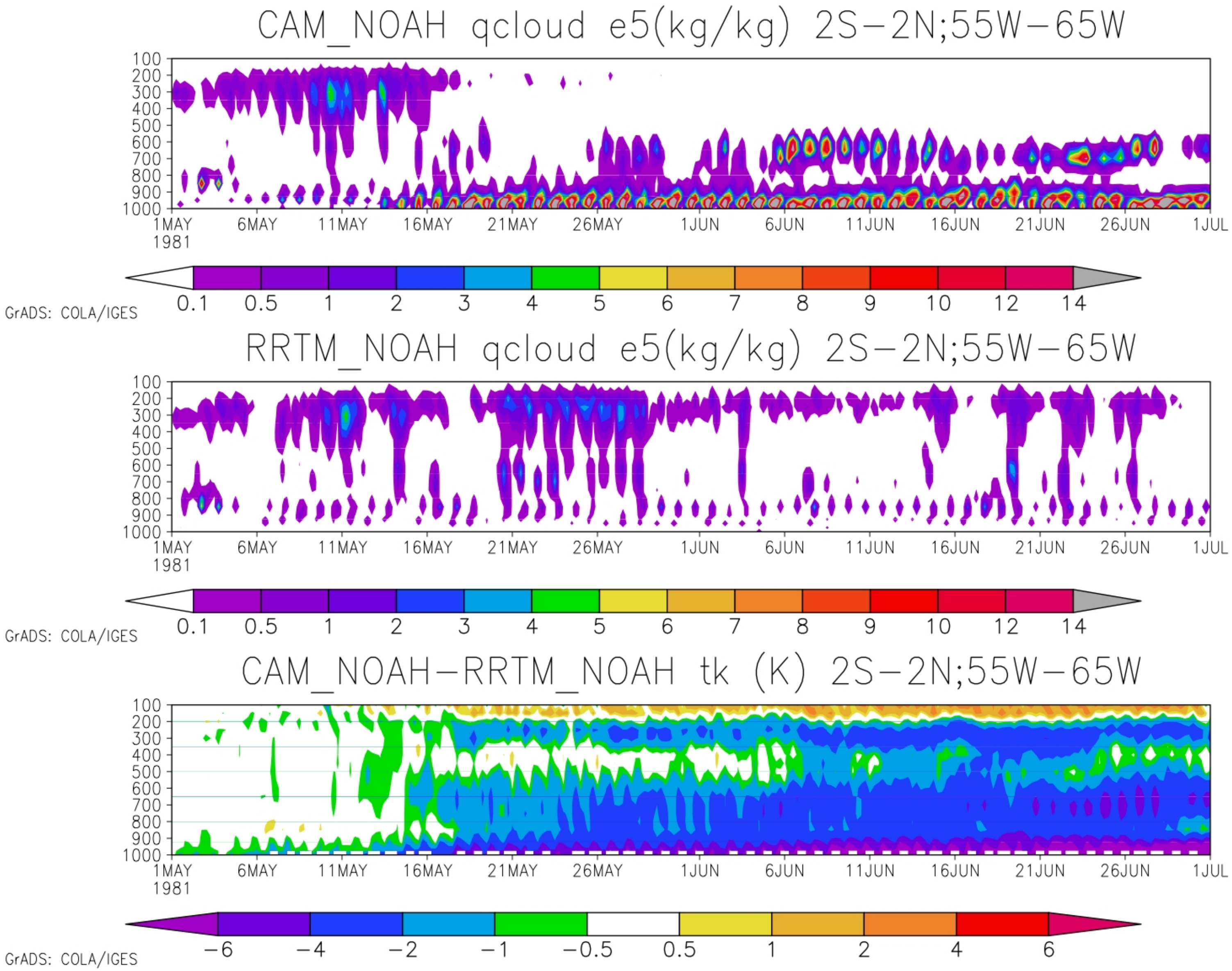


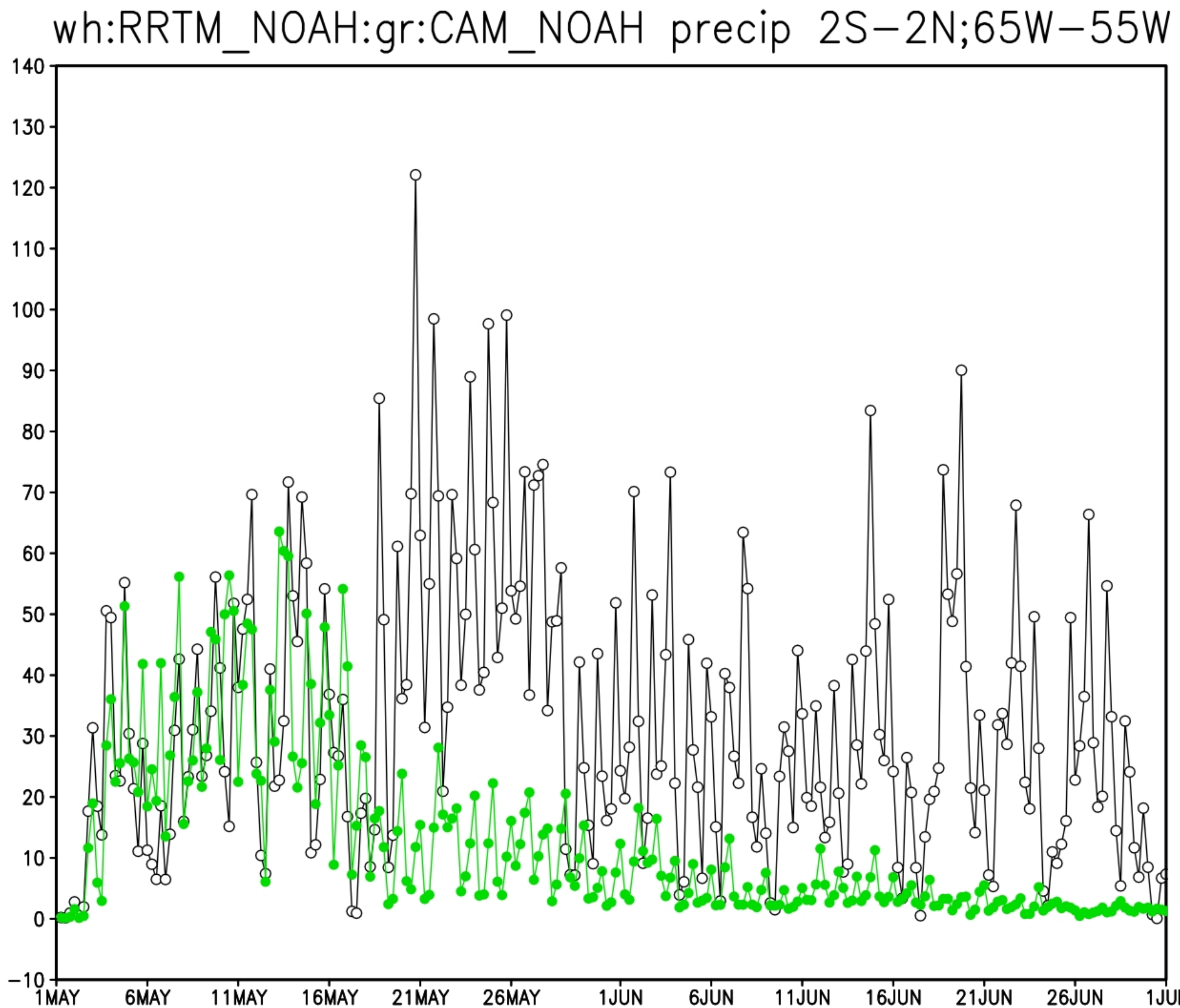


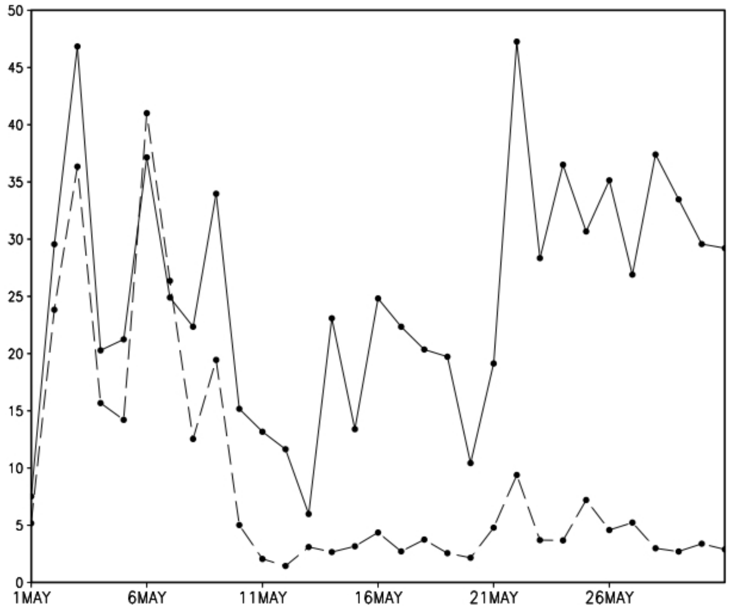


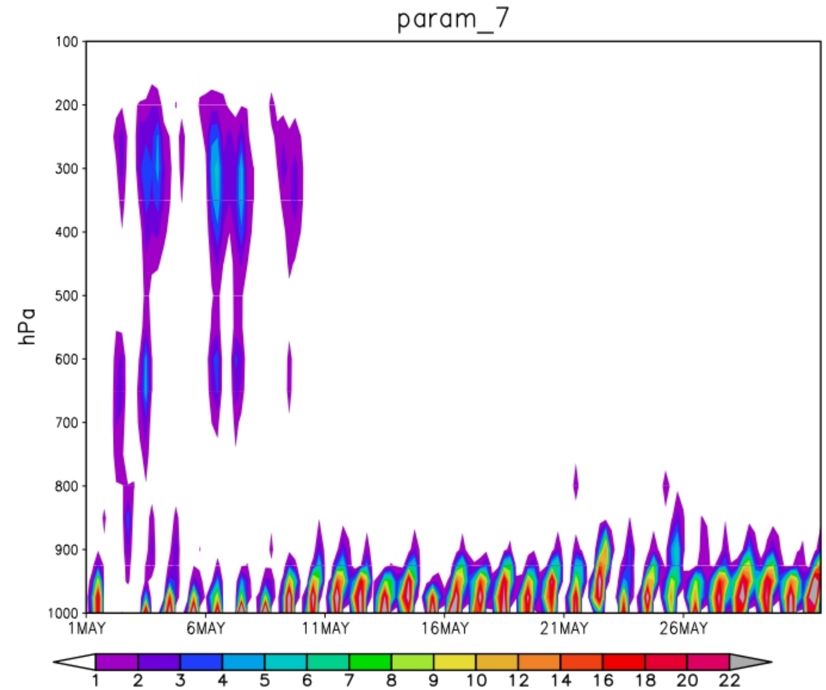


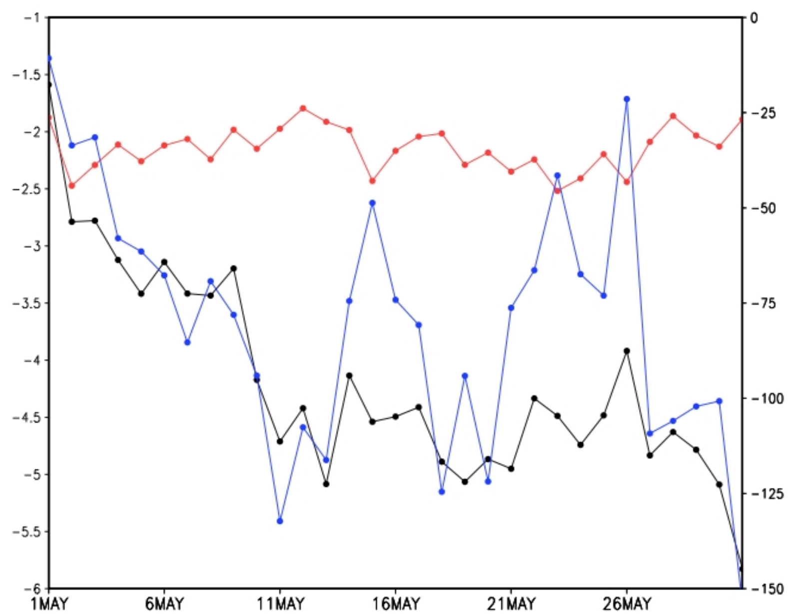
Example of land-atmosphere feedbacks

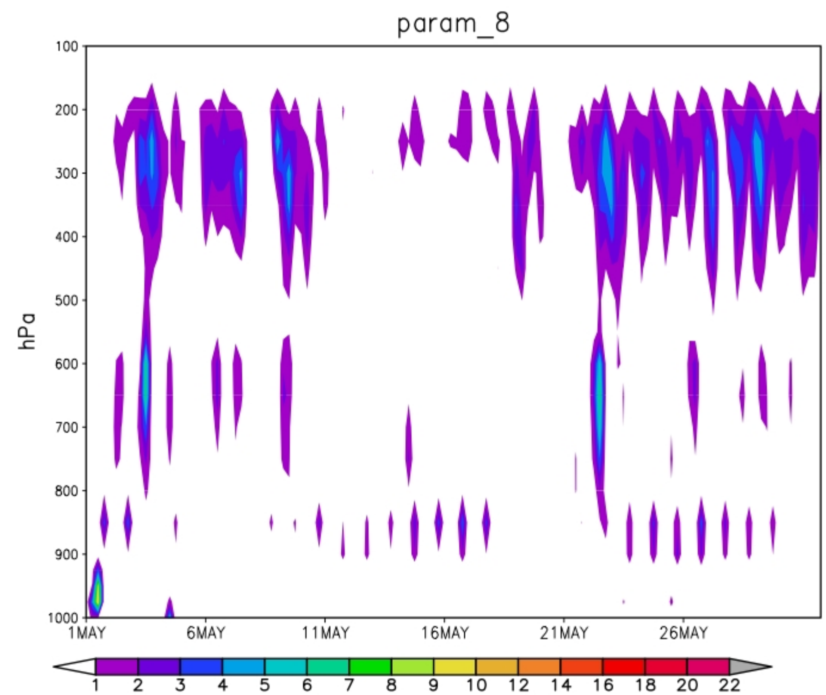



wh:RRTM_NOAH:gr:CAM_NOAH precip 2S–2N;65W–55W
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
1MAY
6MAY
11MAY
16MAY
21MAY
26MAY
1JUN
6JUN
11JUN
16JUN
21JUN
26JUN
1JUL

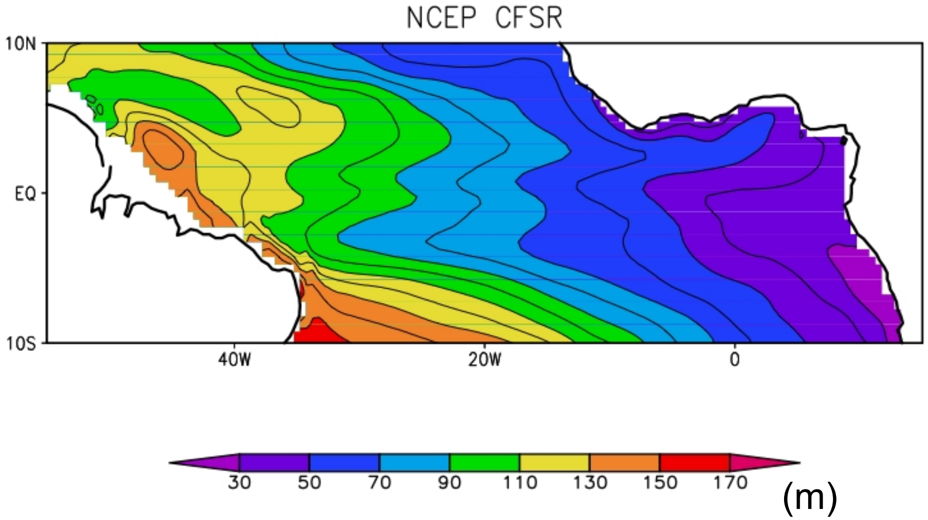

1MAY
6MAY
11MAY
16MAY
21MAY
26MAY

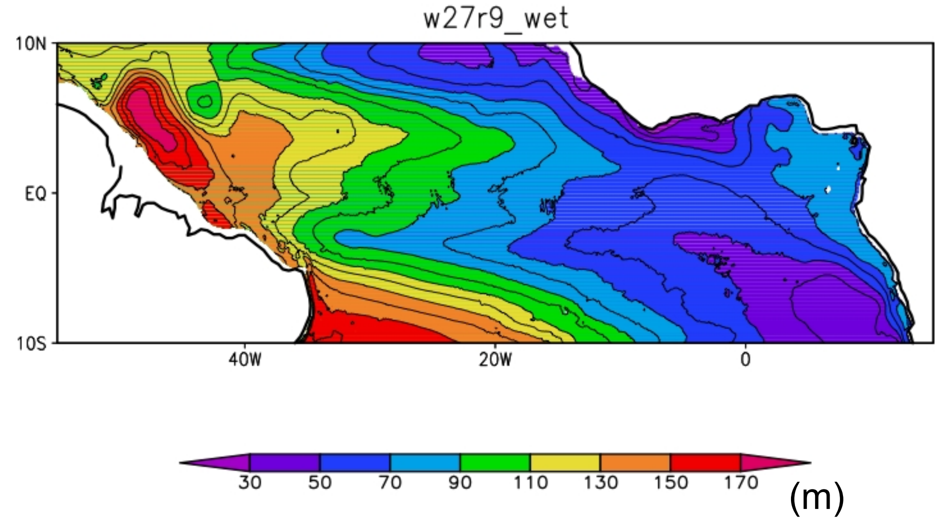

param_7
hPa
1MAY
6MAY
11MAY
16MAY
21MAY
26MAY

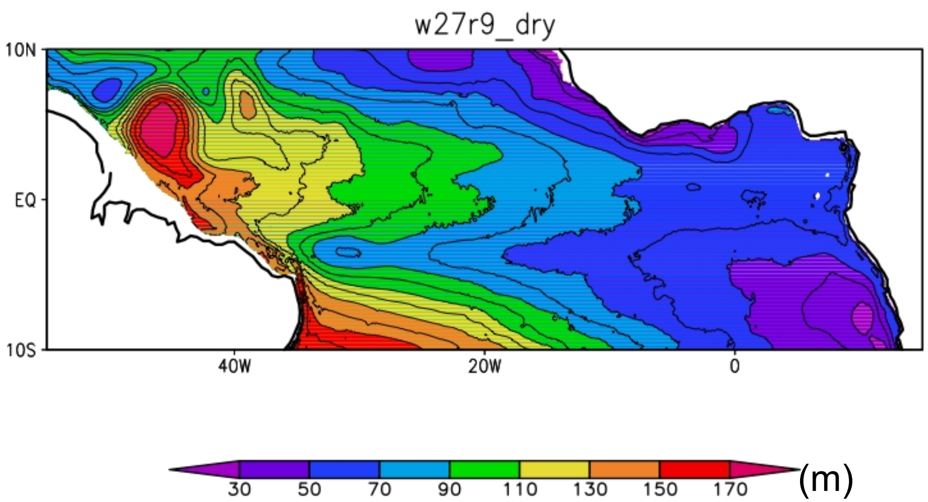

1MAY
6MAY
11MAY
16MAY
21MAY
26MAY

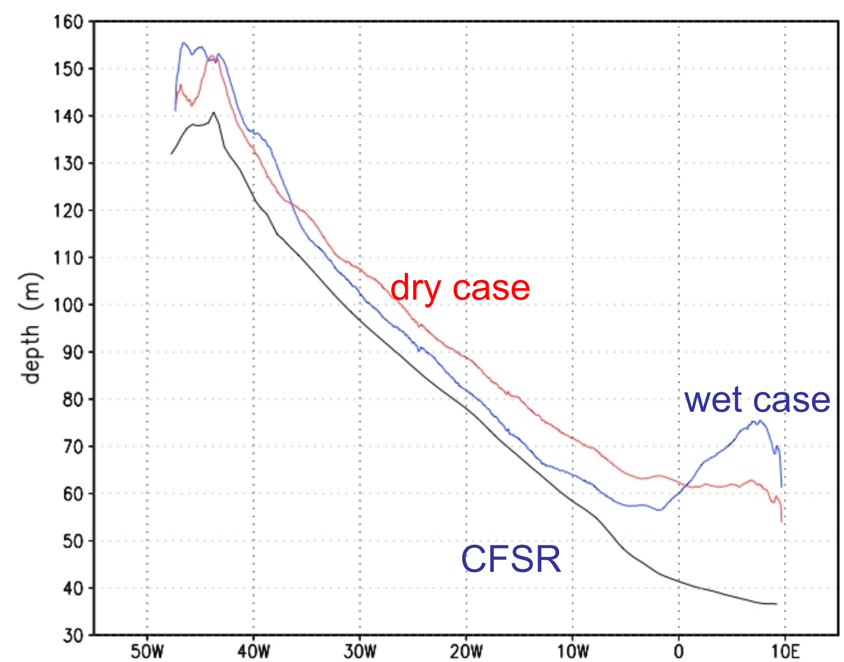

param_8
hPa
1MAY
6MAY
11MAY
16MAY
21MAY
26MAY

Depth of 20°C isotherm – JJA

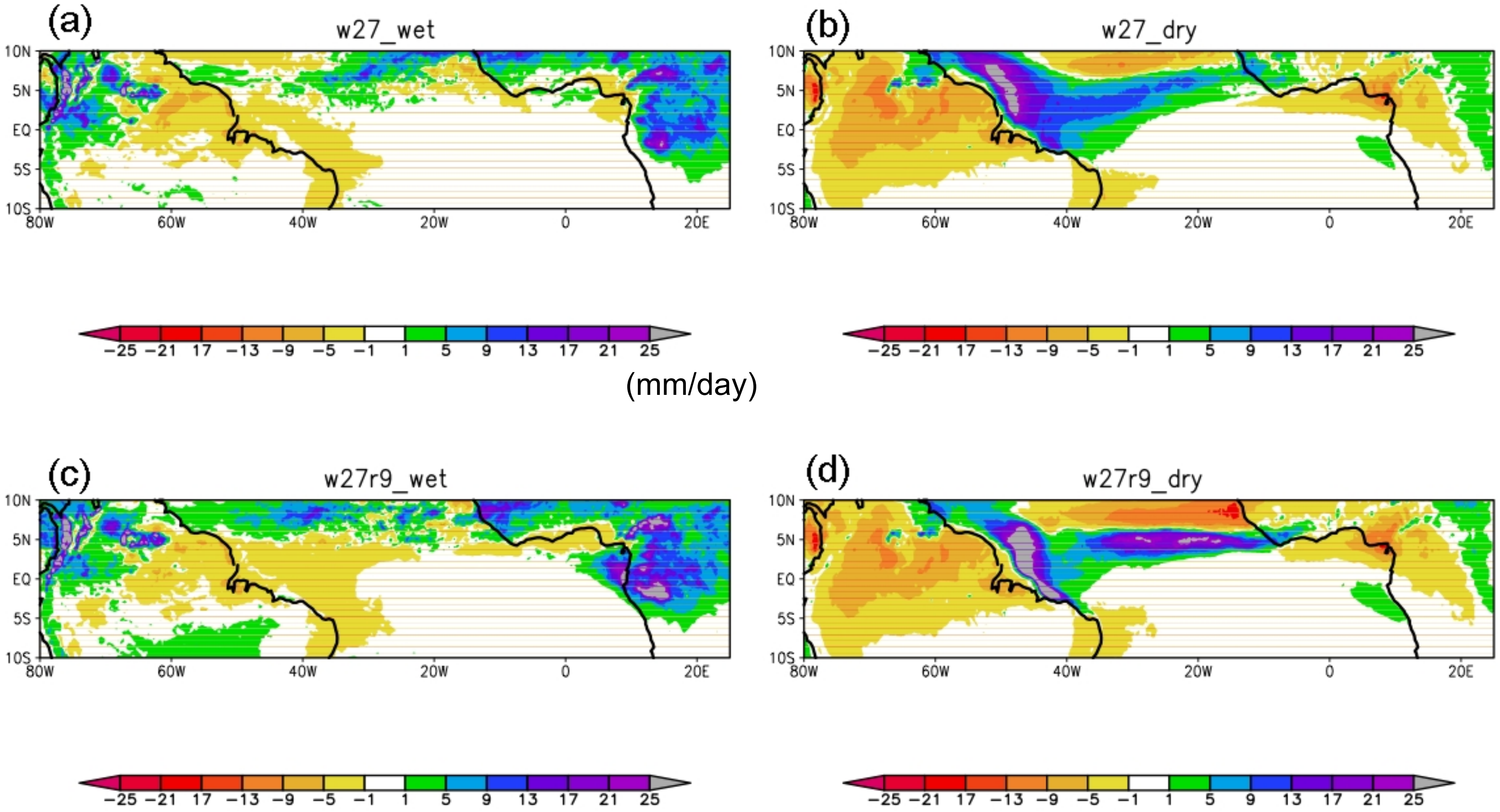






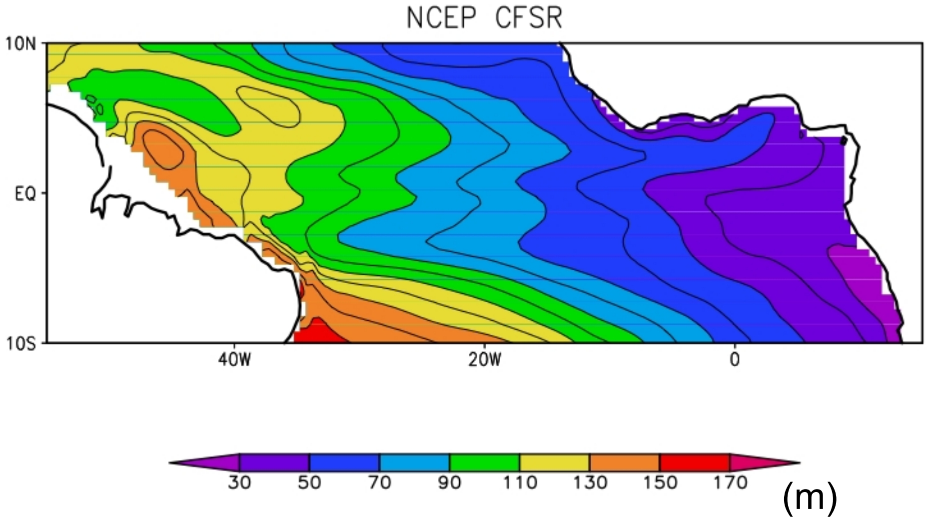


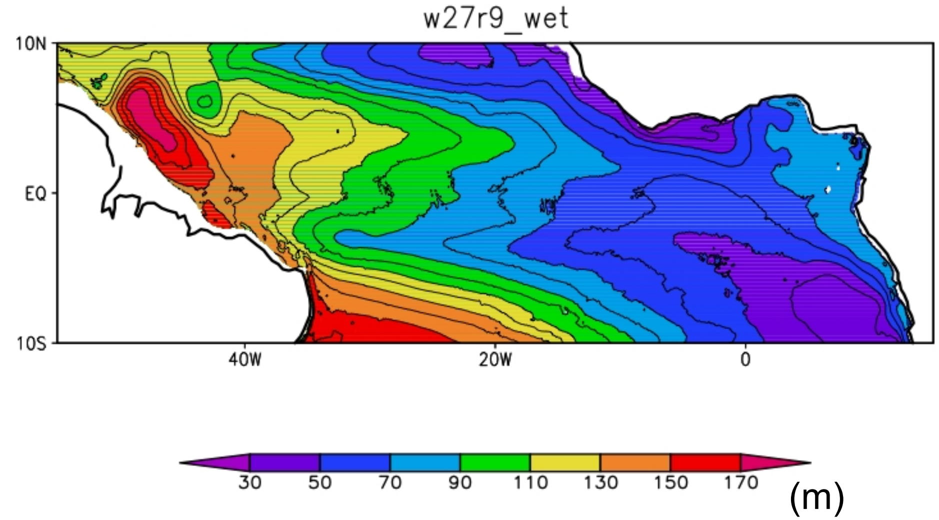
JJA rainfall bias

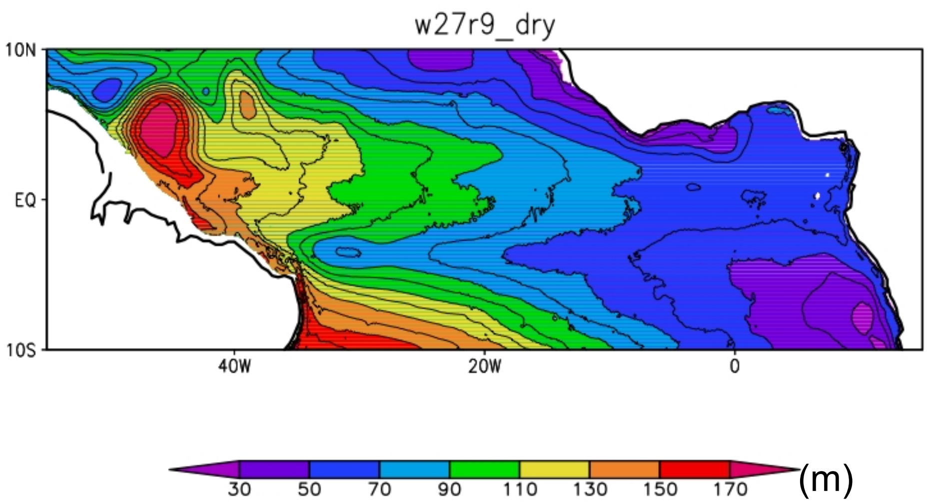


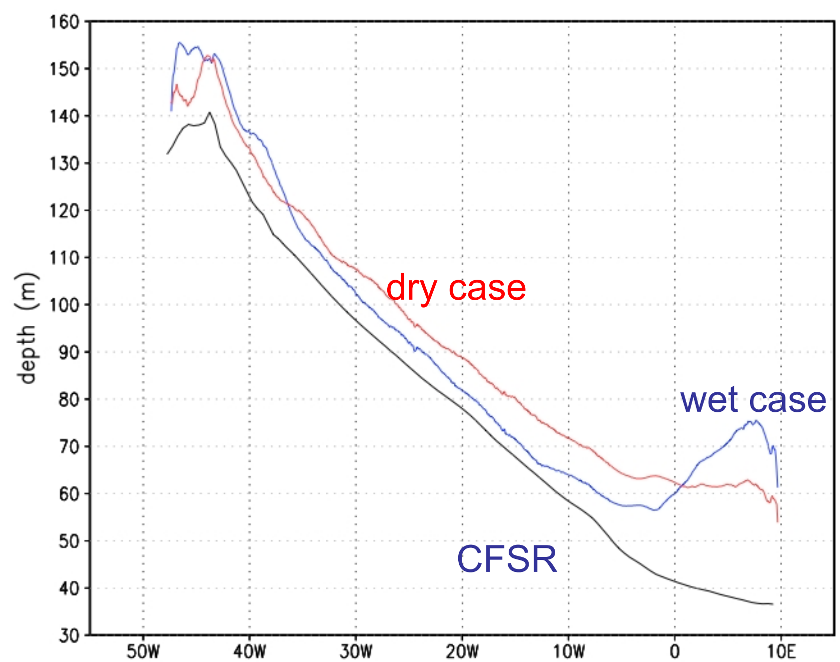
- "dry case" simulates a southward displaced ITCZ that is worsened by coupling.
- wet bias covers warm eastern equatorial SST bias in coupled, but not uncoupled "wet case."

Depth of 20°C isotherm – JJA

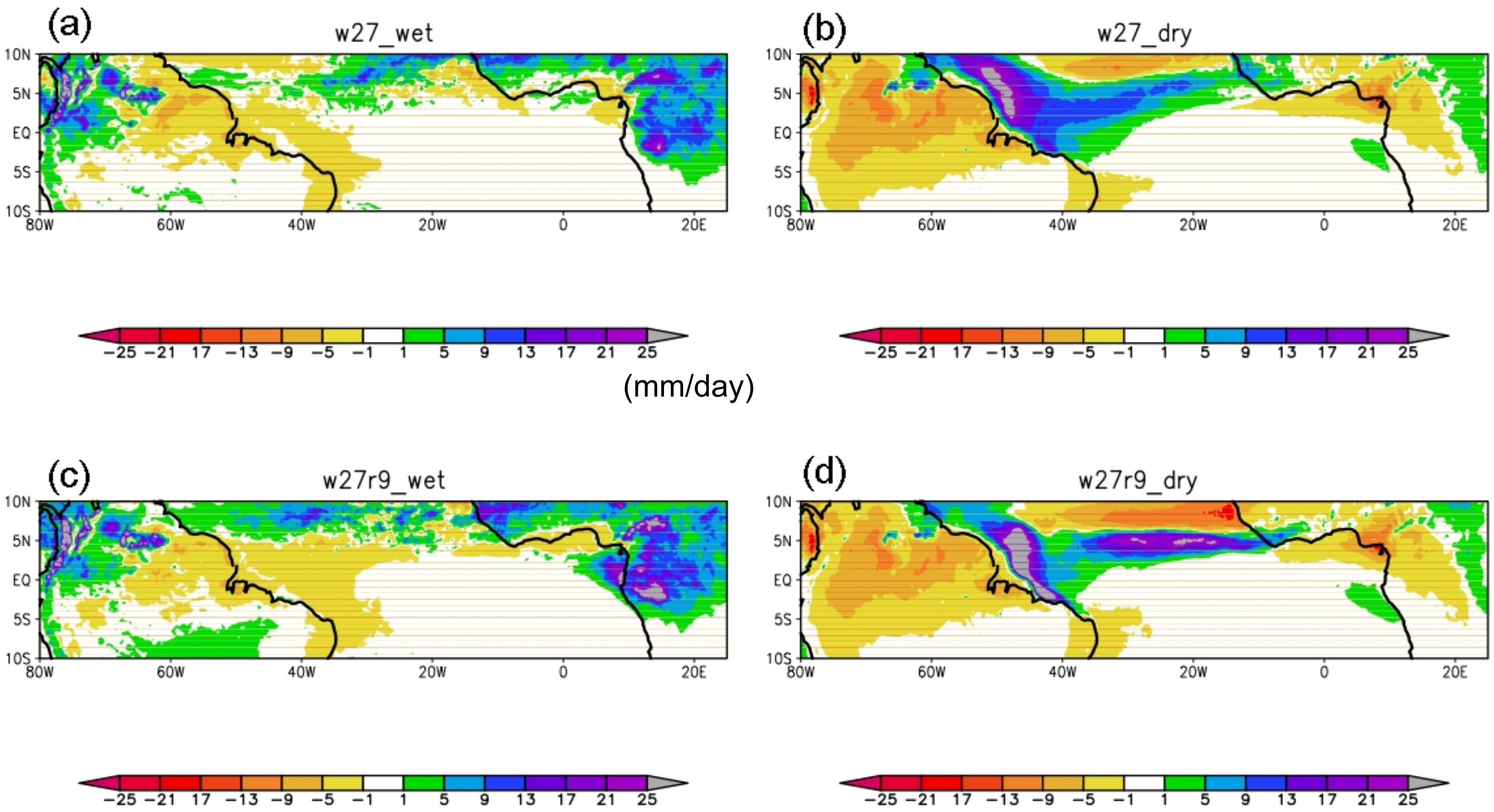




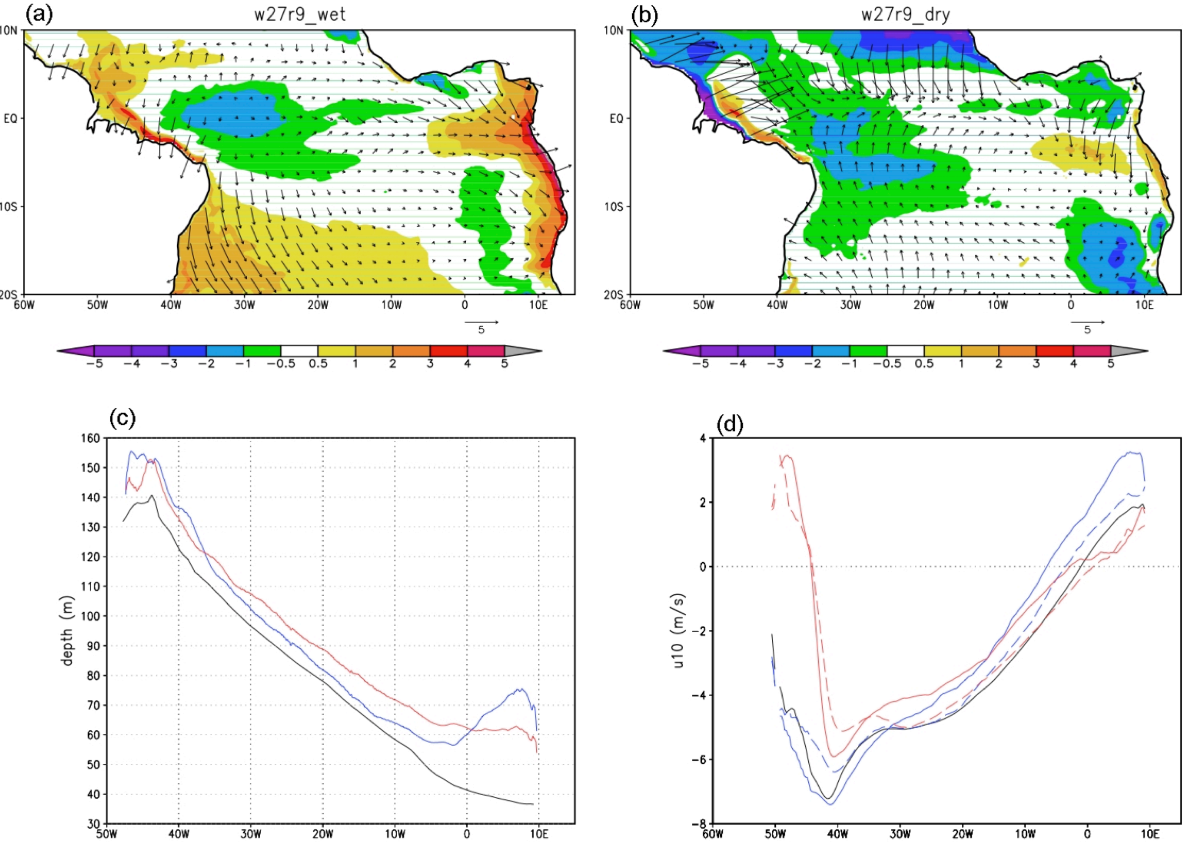




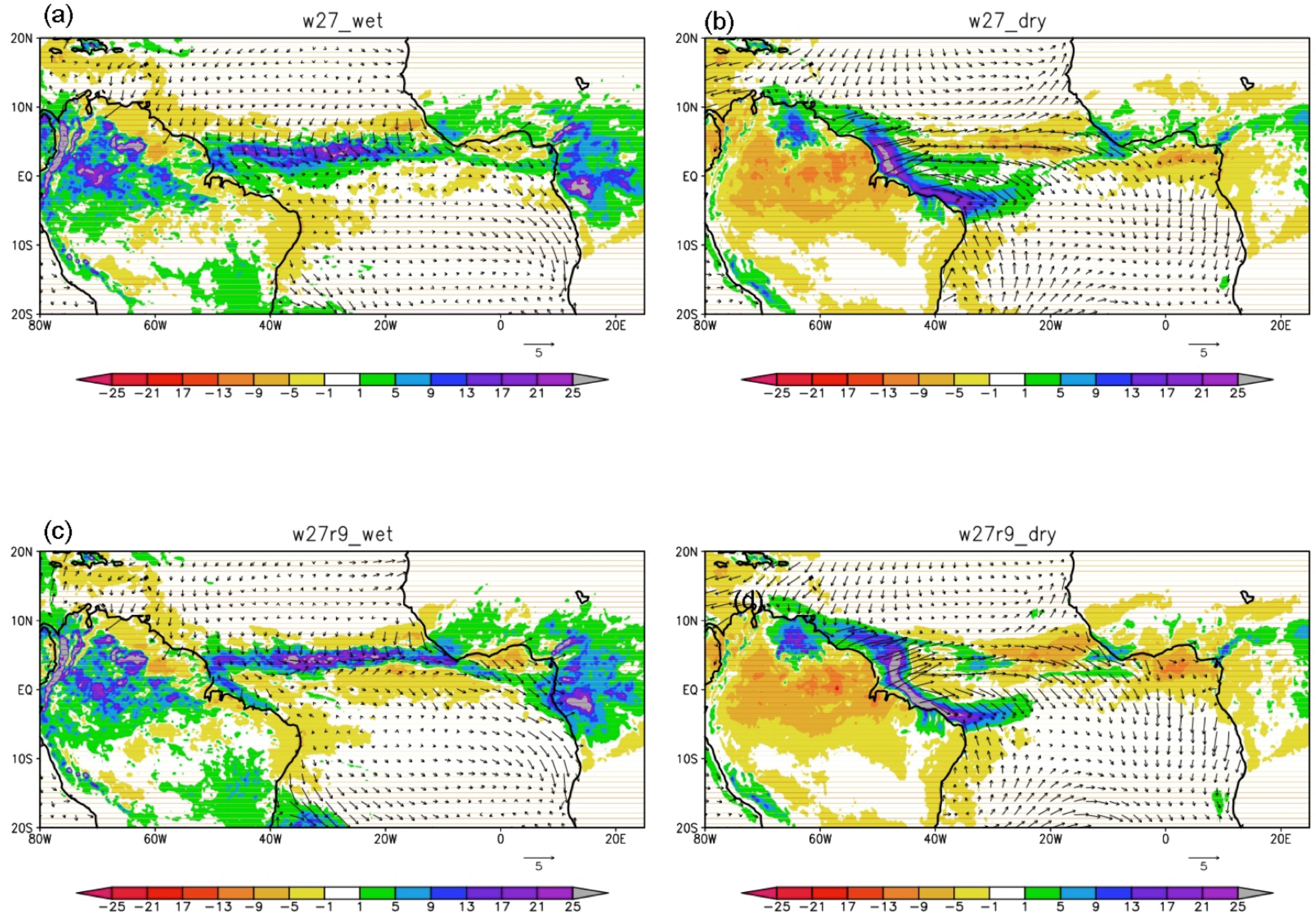
JJA rainfall bias



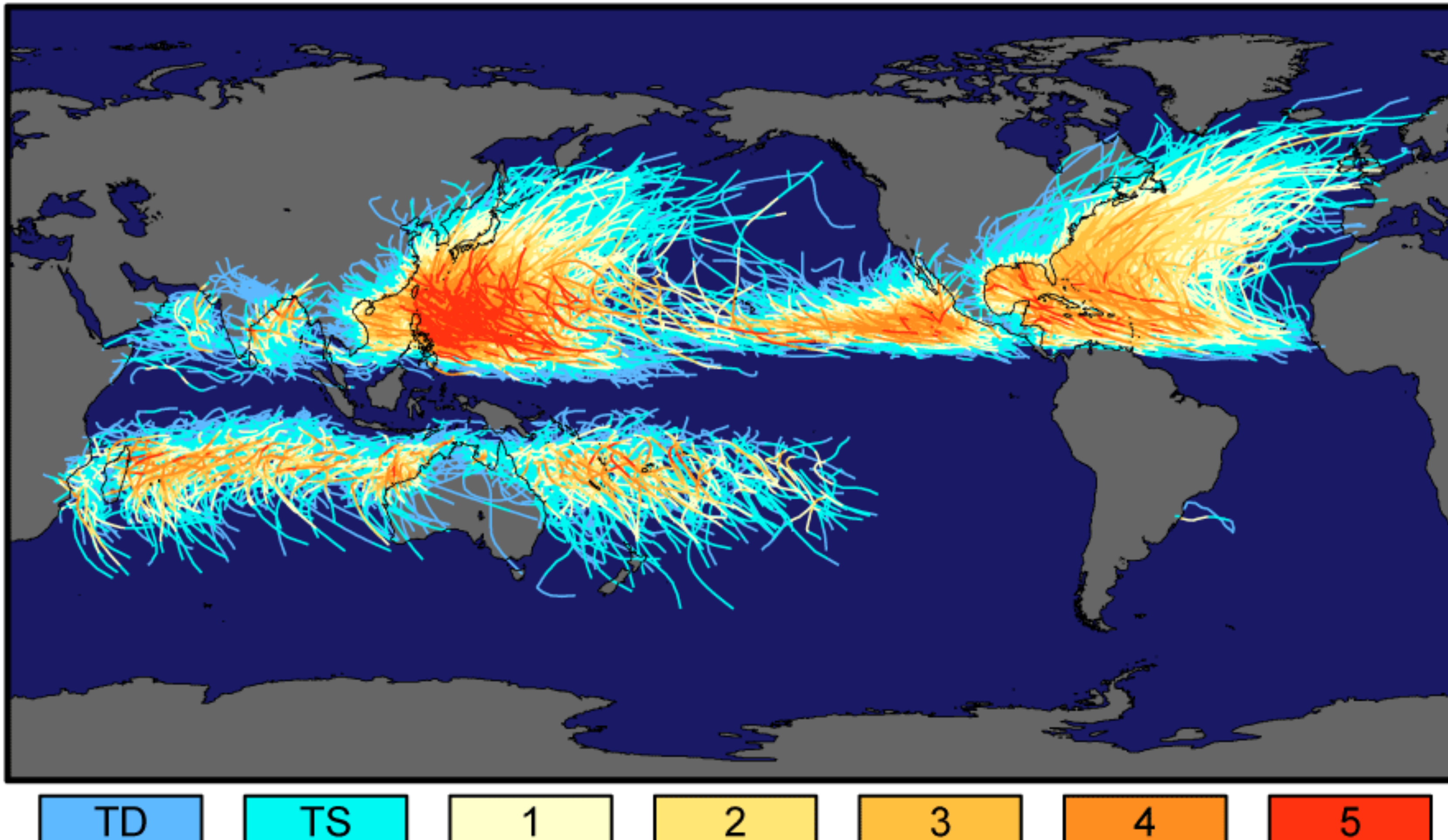
- "dry case" simulates a southward displaced ITCZ that is worsened by coupling.
- wet bias covers warm eastern equatorial SST bias in coupled, but not uncoupled "wet case."


(a)
w27r9_wet
(b)
w27r9_dry
10N
EQ
10S
20S
60W
50W
40W
30W
20W
10W
0
10E
5
−5
−4
−3
−2
−1
−0.5
0.5
1
2
3
4
5
(c)
depth (m)
160
150
140
130
120
110
100
90
80
70
60
50
40
30
(d)
u10 (m/s)
4
2
0
−2
−4
−6
−8

Precipitation biases in regional model



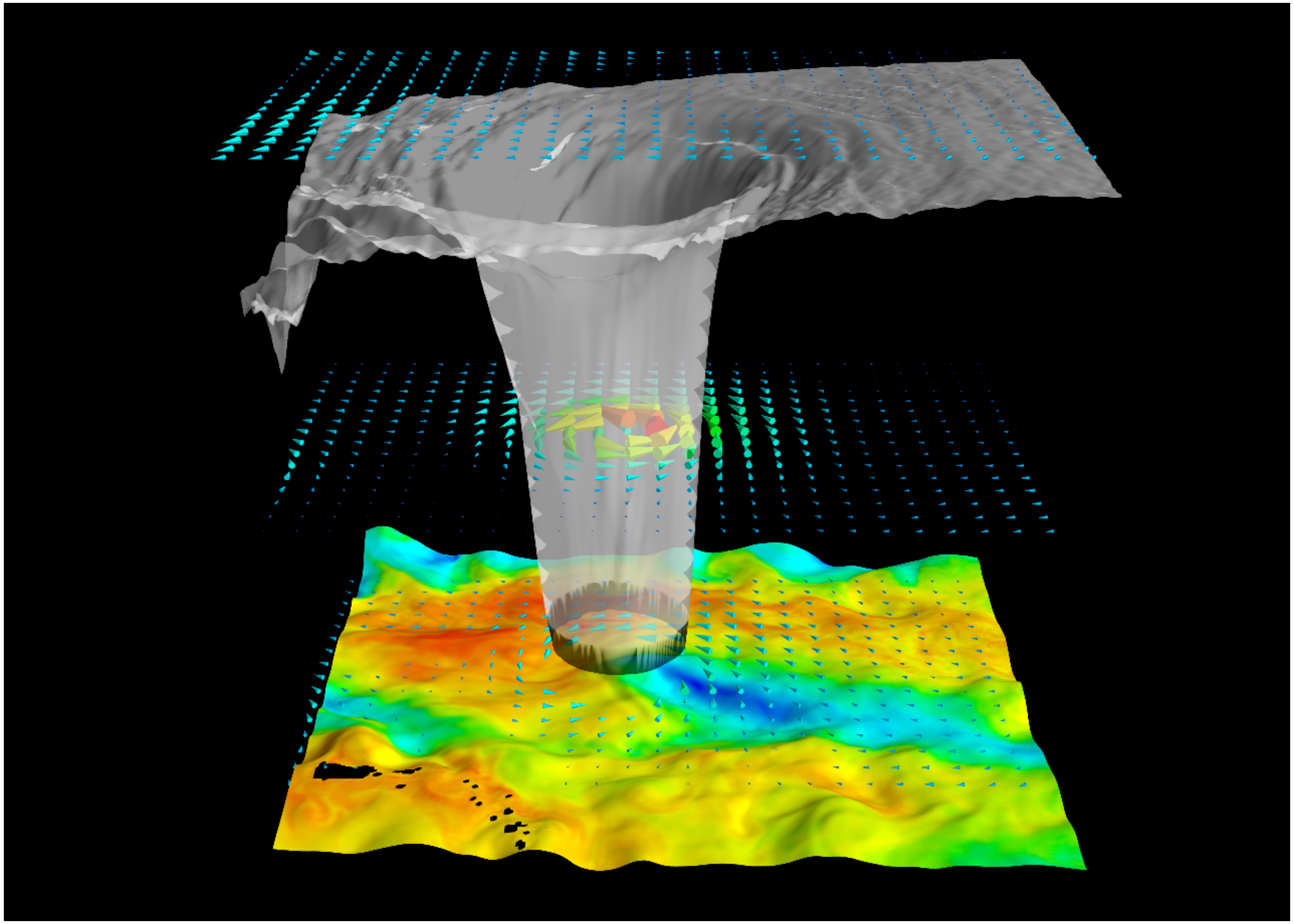
Tracks and Intensity of All Tropical Storms



Saffir-Simpson Hurricane Intensity Scale

Iso-surface of perturbation pressure

(color: surface temperature, arrows: winds)



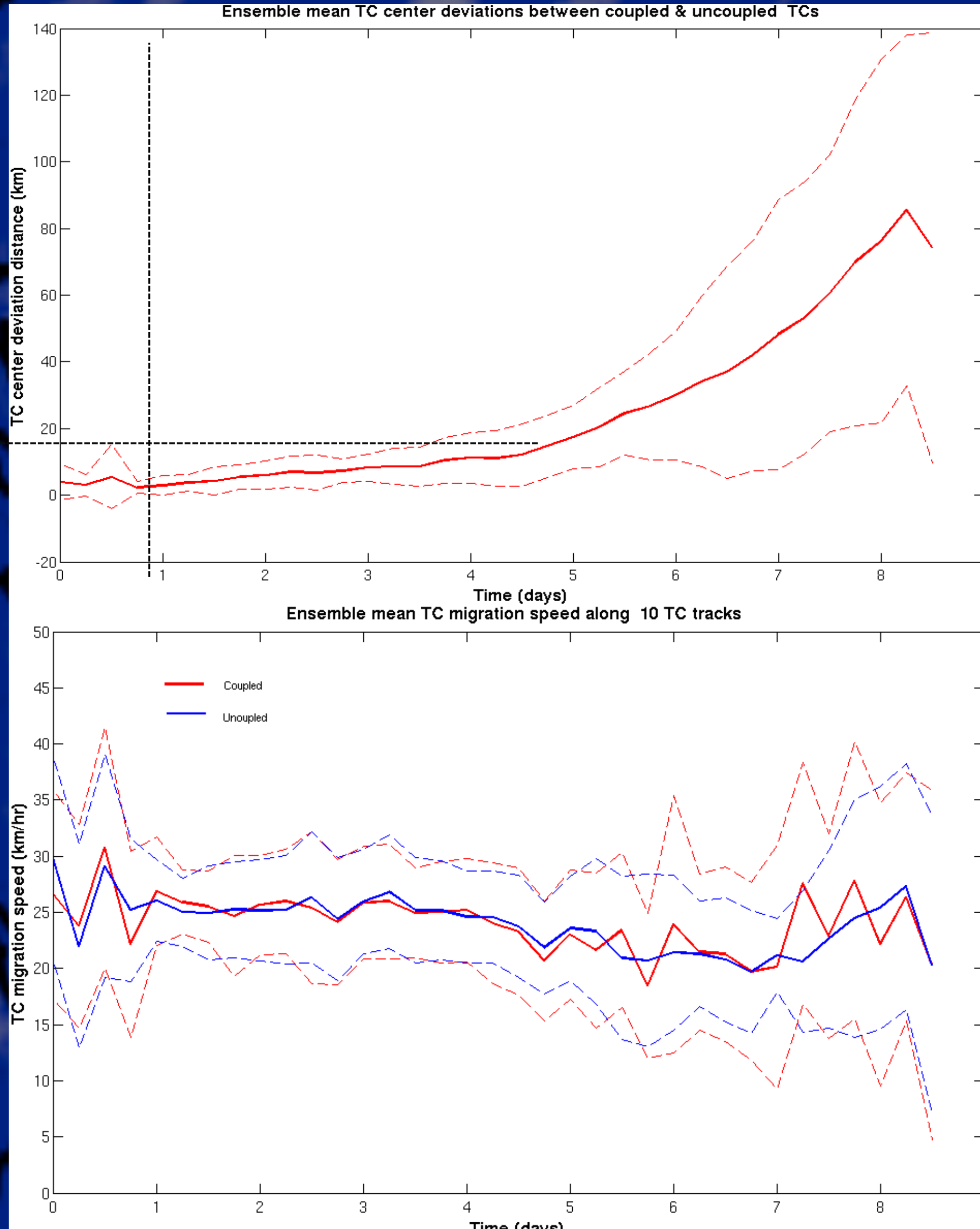
Conclusions

- Coupled regional climate model (CRCM) is a viable approach for high-resolution coupled simulations in the Atlantic region
  - *Less expensive than global high-resolution modeling*

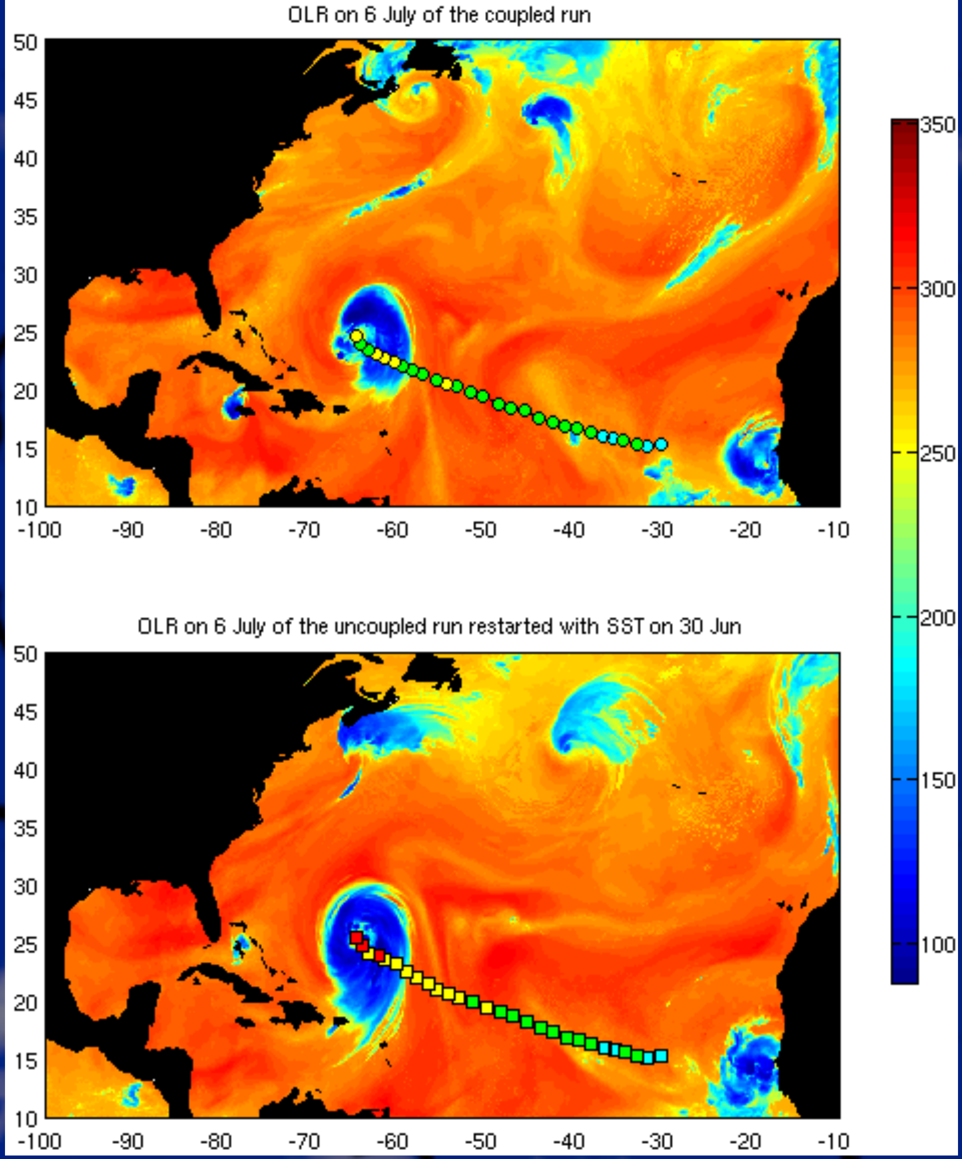
  - *Ability to focus phenomena in one region without being affected by simulation errors in other regions*

- Potential applications
  - *Dynamical downscaling in a coupled system for temperature and rainfall statistics*
  - *Climate change and hurricane statistics*

Air-Sea Feedback Effect on TC Track and Speed



Outgoing Longwave Radiation



Coupled (atmosphere+ocean)

Atmosphere-only