Development of the Atmospheric Component of the Next Generation GFDL Climate Model

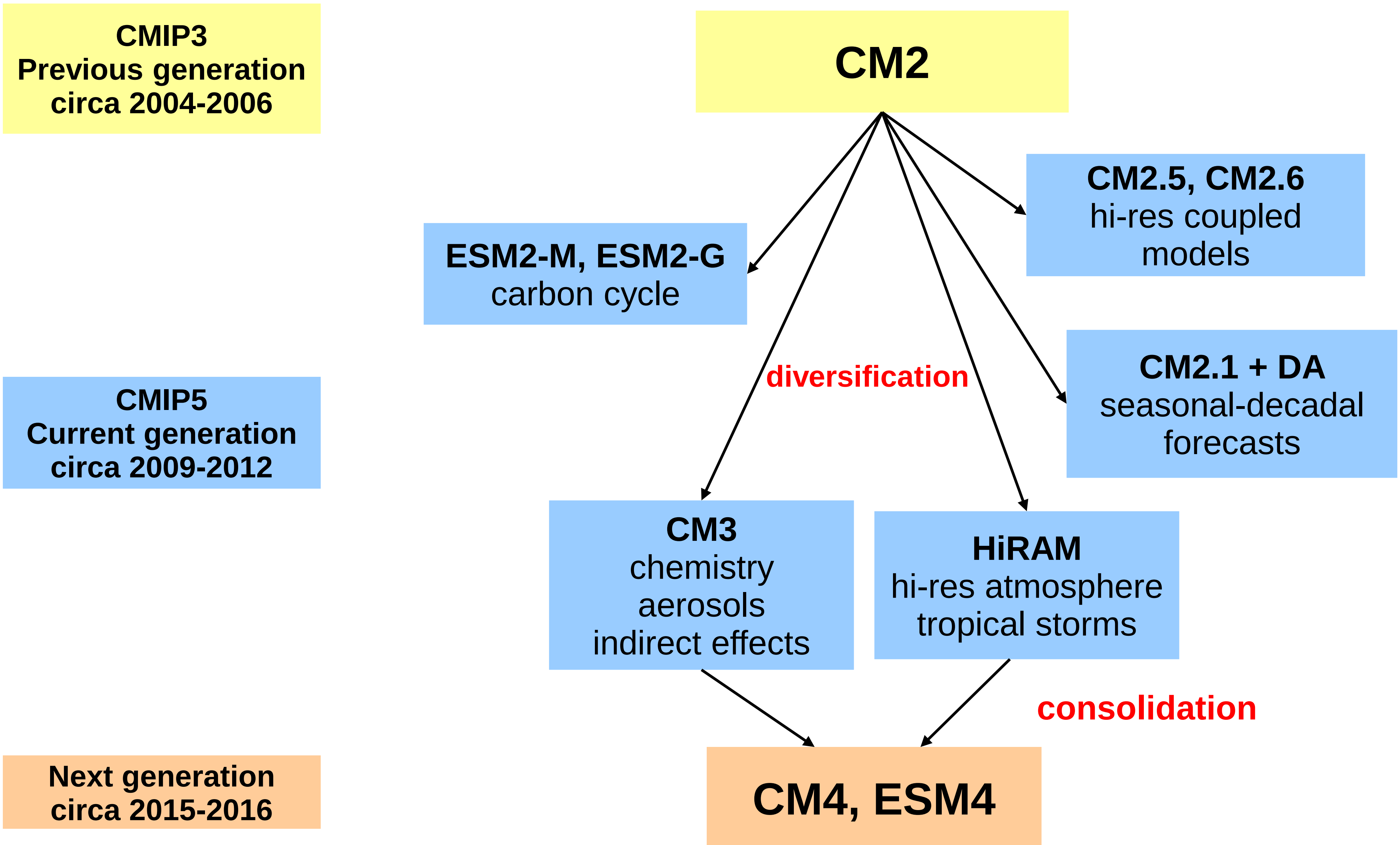
Ming Zhao, Chris Golaz, Isaac Held,

and the entire GFDL Model Development Team (MDT)

30th session of the CAS/WCRP
Working Group on Numerical Experimentation
(WGNE-30)

College Park, Maryland, USA
23-26 March 2015

Recent history of GFDL climate models



GFDL Strategic Science Plan (2011) endorsed goal of high resolution Earth System Model combining strengths of GFDL's diverse modelling streams

GFDL has a Model Development Team (MDT)

Goal of the MDT:

In the 2013-2016 time frame, design and develop GFDL's best attempt at a climate model suitable for

- projection of climate change up to several hundred years into the future,
- attribution of climate change over the past century,
- prediction on seasonal to decadal time scales

keeping in mind the needs for improved regional climate information and assessments of diverse climate impacts.

The model will be capable of running from emissions in regard to both the carbon cycle and aerosols.

MDT structure:

- Steering Committee
- Working Groups (atmosphere, ocean, land, sea-ice, ecology/biogeochemical)
- Diagnostic and Evaluation Team

GFDL next generation climate model (CM4)

Next generation CM4

- AM4 atmosphere, **50km** resolution, plus **100km** atmosphere option
- MOM6 ocean, **1/4 deg** resolution, plus **1 deg** ocean option
- LM4 land (soil, river, lake, snow, vegetation,…)
- SIS2 sea ice

Resolution determined by 1) Lab's experience regarding resources needed to develop and utilize a model for centennial-scale climate projections: at least 5 years/day throughput on no more than 1/8 of computational resource; 2) Existing computational resources.

Previous generation CM3

- AM3 atmosphere, **200 km** resolution
- MOM4 ocean, **1 deg** resolution
- LM3 land
- SIS1 sea ice (GFDL Sea Ice Simulator)

AM4 prototype model (merging AM3 and HIRAM)

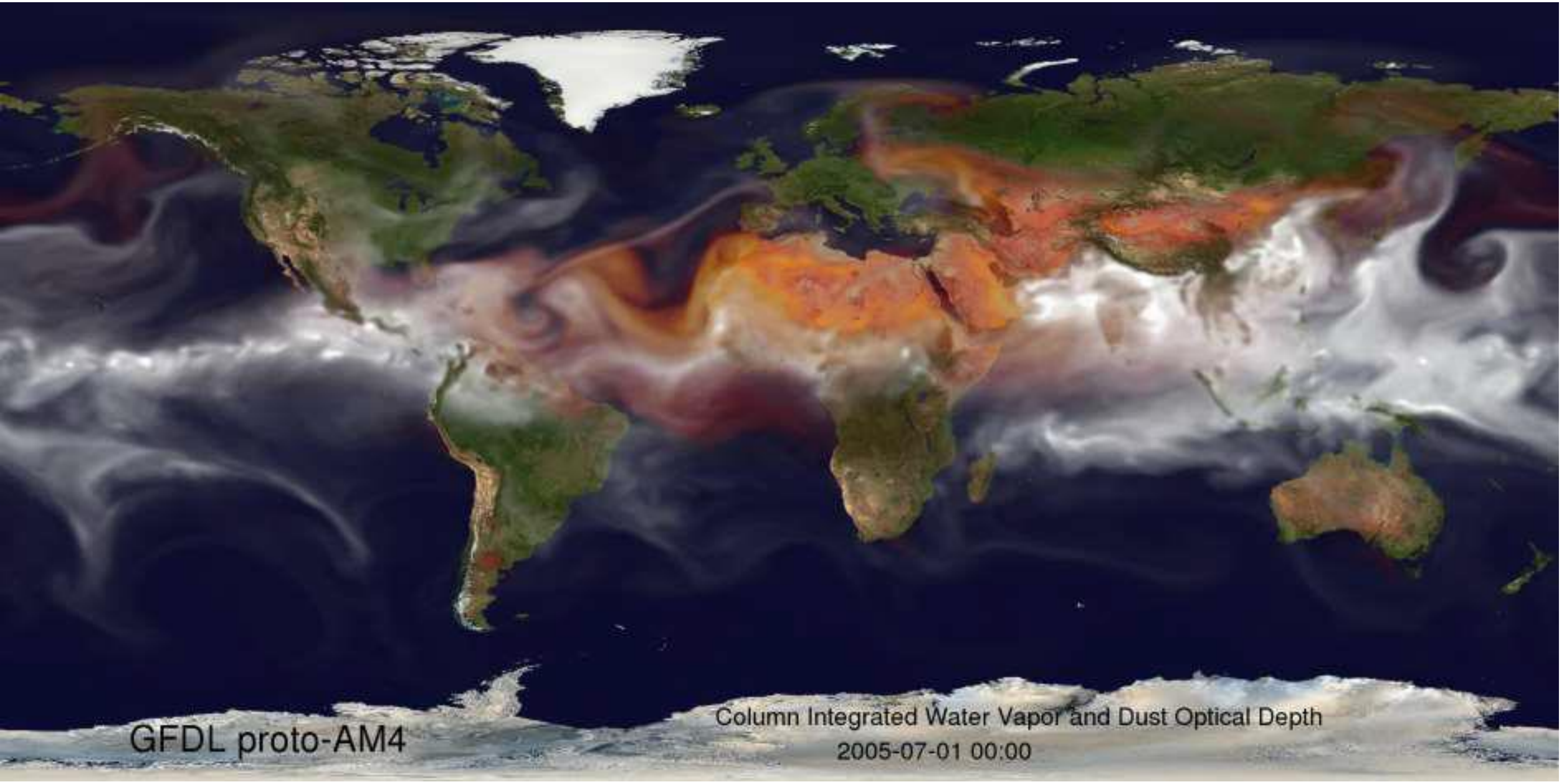
- FV-dynamic core on cubed-sphere (50km, L48, Shiann-Jian Lin)
- Online transport of aerosols, driven by emission
- Simplified chemistry for aerosol sources/sinks
- Aerosol cloud interactions (Ming et.al 2006, 2007)
- **Convection** (**AM3-like and HiRAM-like configurations**)
- Large-scale cloud (Tiedtke 1993 + prognostic liquid drop number)
- Microphysics (Rotstayn,1997, 2000, Jakob-Klein 2000)
- PBL (Lock et. al 2000)
- Radiation (GFDL, Schwarzkopf/Freidenreich/Ramaswamy 1999)

New development:

- **balance between innovation and incremental bias reduction**
- **increase physical realism while also improving simulation fidelity**

Example of AM4 capabilities we are working towards

Aerosols plus hurricanes

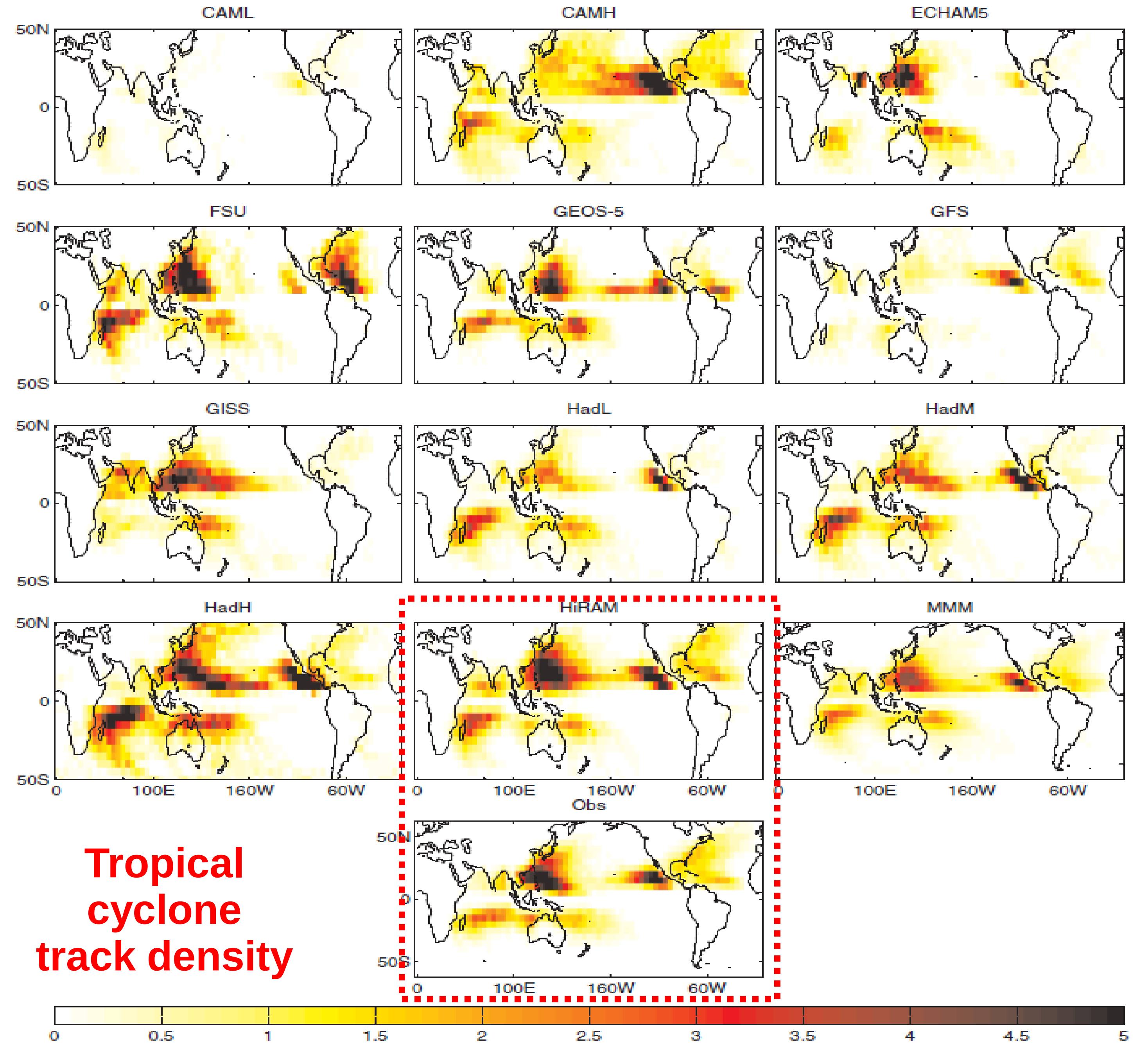


dust (orange) and column water vapor (white)

Why HiRAM-like model? HiRAM performs outstandingly in simulations of tropical cyclones (US CLIVAR Hurricane Working Group)

Model resolutions range from 28km to 130km

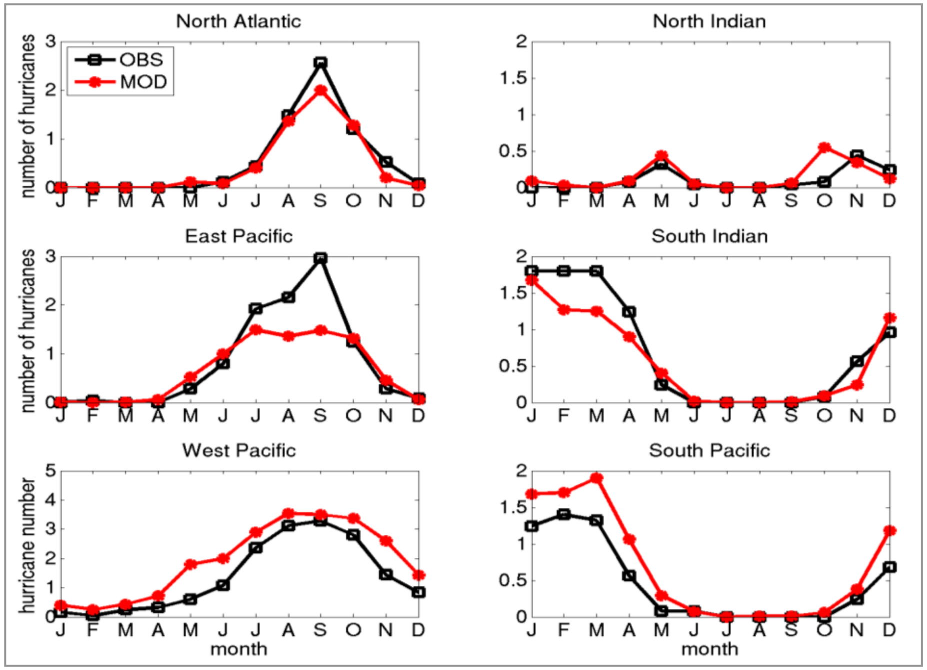
Shaevitz et. al (2014, JAMES) conclude: ***"Overall the models were able to reproduce the geographic distribution of TC track density in the observations, with the HIRAM, in particular, demonstrating the most similarity to observations."***



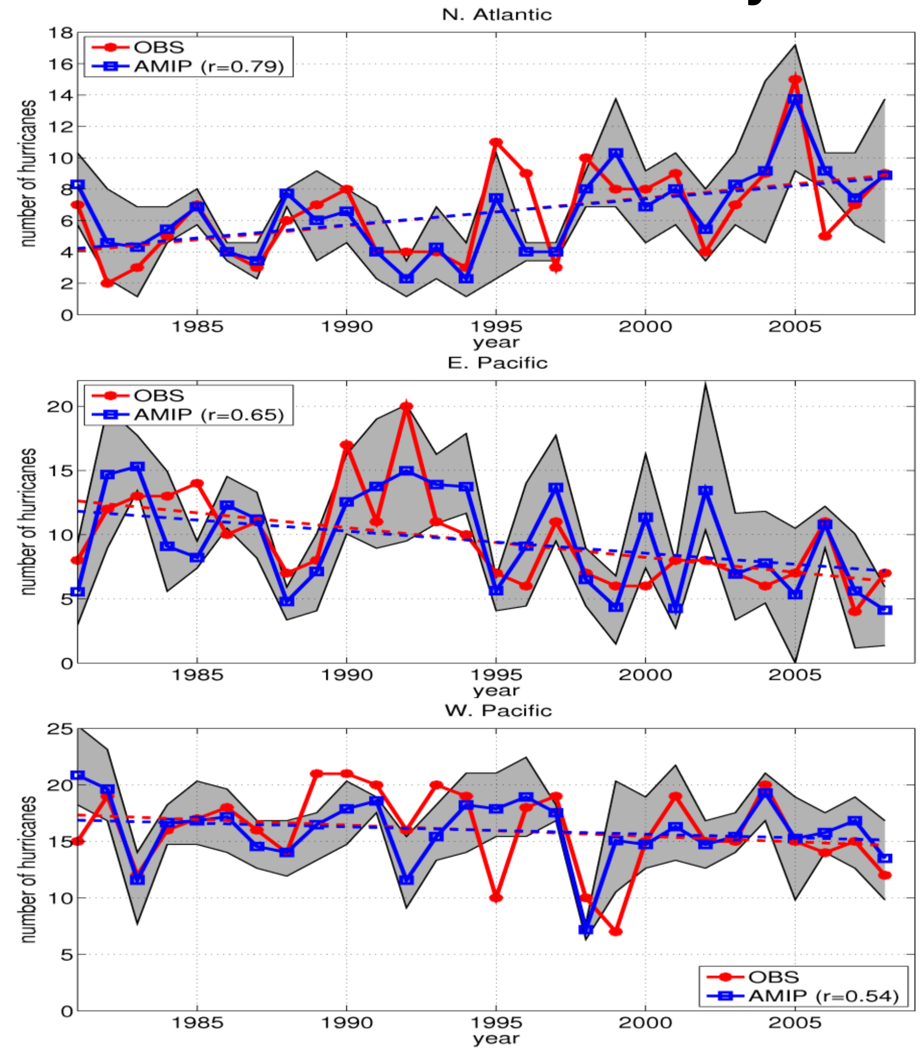
Tropical cyclone track density

Why HiRAM-like model? HiRAM captures seasonal cycle, inter-annual variability, decadal trends of hurricanes over multiple ocean basins

Seasonal Cycle



Inter-annual variability



Shaevitz et. al (2014, JAMES) conclude:
"In simulations forced with historical SSTs, the models were able to reproduce the inter-annual variability of TC frequency in the N. Pacific and Atlantic basins, with HiRAM and GEOS-5 models showing particularly high correlation with observations in those basins."

Red: observations
Blue: HiRAM ensemble mean
Shading: model spread

Major biases in AM4 prototype models motivate further development of convection scheme for bias reduction

Two initial AM4 prototype models differ only in convection scheme:

- **AM3-like (Donner deep + UW Shallow Cu)**
- **HIRAM-like (modified UWShCu for both shallow and deep)**

Both perform well in simulations of mean climate in AMIP mode but suffer from major biases in coupled simulations:

- **Equatorial Pacific SST and precipitation biases**
- **Precipitation and cloud response to ENSO**
- **Madden-Julian-Oscillation**
- **Tropical cyclones (weak TC activities in AM3-like model)**

A new double-plume convection (DPC) scheme incorporates recent findings on key processes of modeling convection and MJO

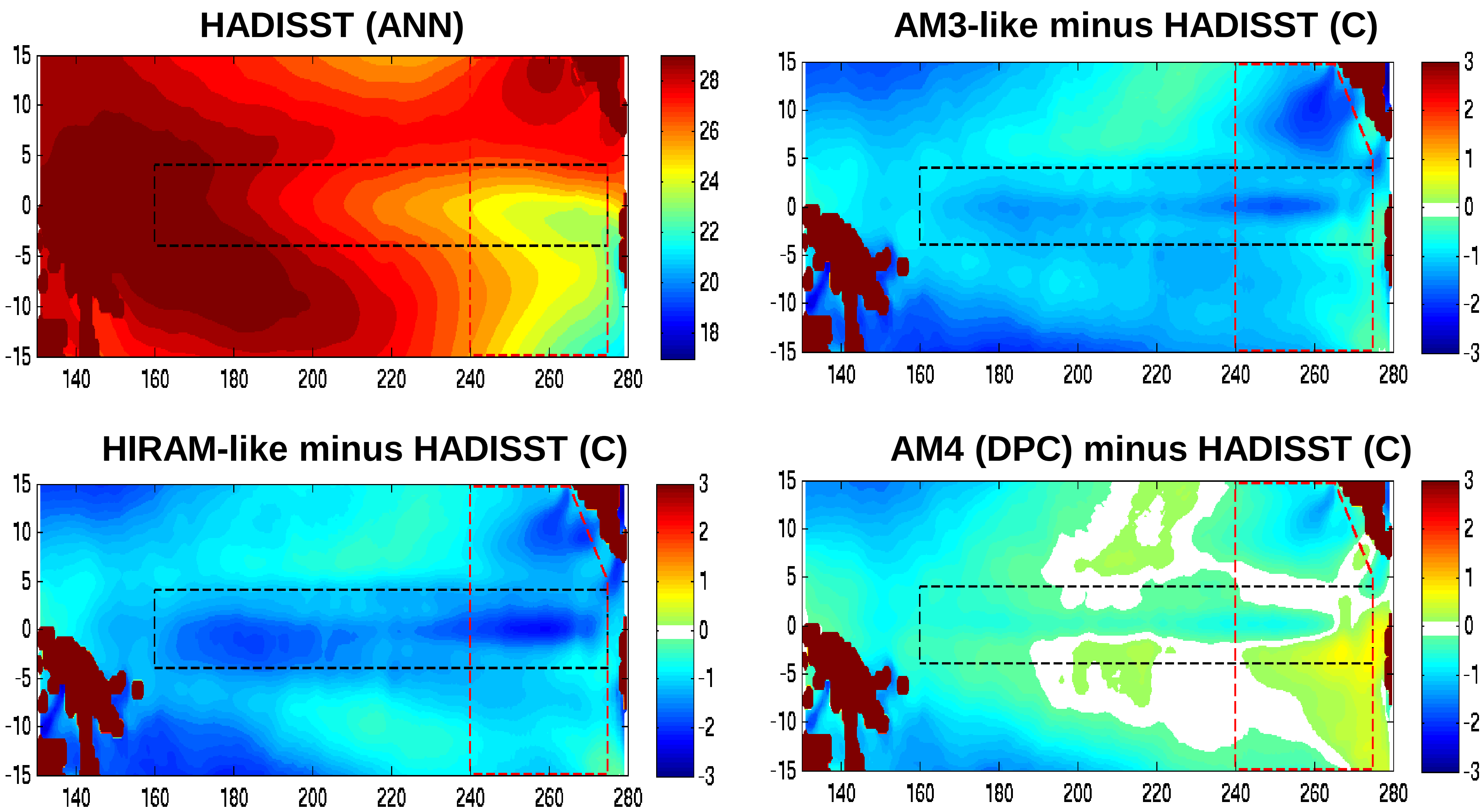
Base on single bulk plume model used in HIRAM (Bretherton et. al 2004):

- Include an additional plume with entrainment dependent on ambient RH for representing deep/organized convection
- Include cold-pool driven convective gustiness & precipitation re-evaporation
- Enhance shallow cumulus moistening ahead of deep/organized convection
- Calibrate convective microphysics and cloud radiative effect (CRE) using observed response of LW and SW CRE to ENSO and MJO
- Quasi-equilibrium cloud work function for deep convection closure

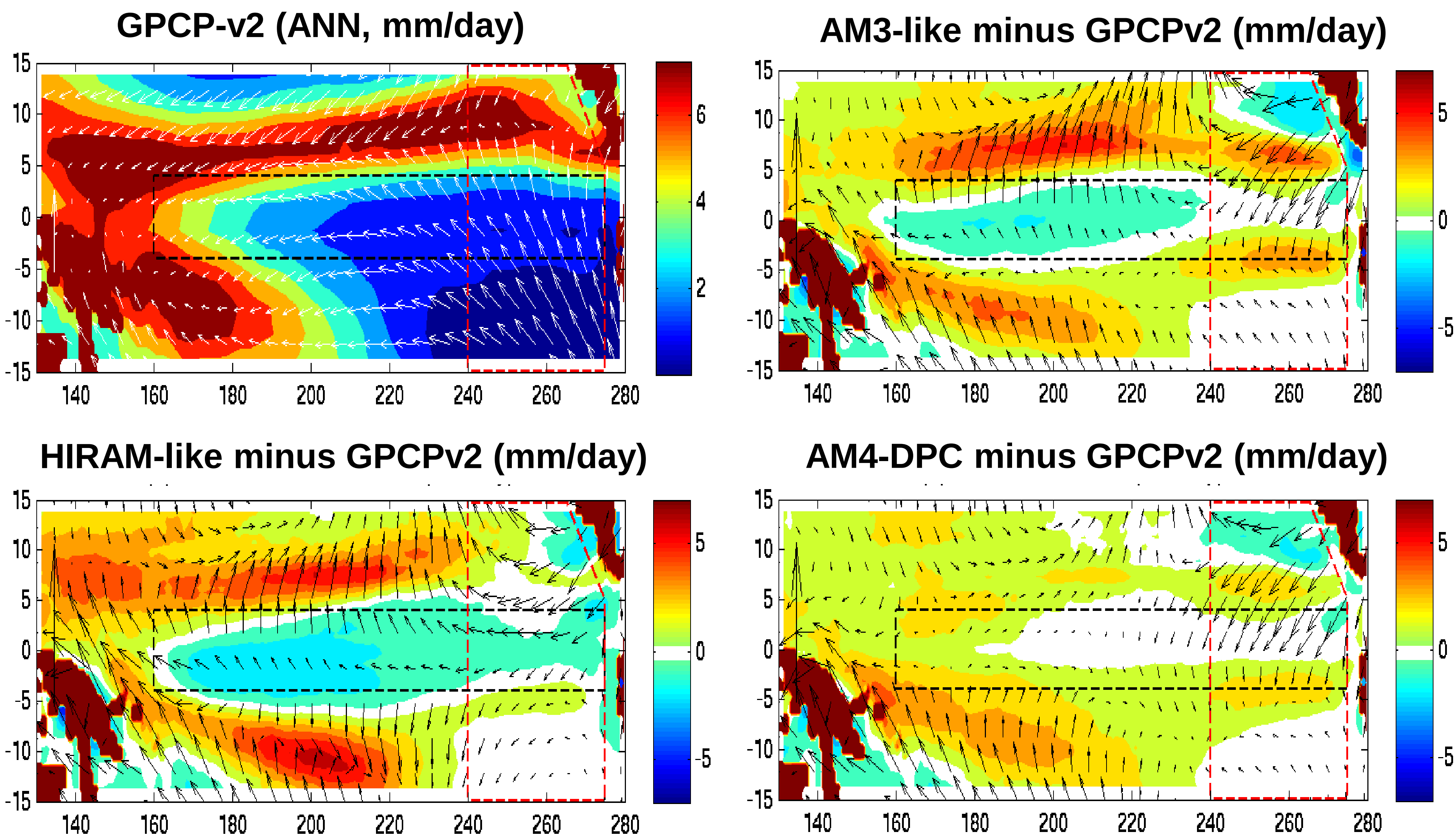
AM4 using DPC

- **significantly reduces the equatorial Pacific cold and dry bias**
- **improve simulation of precipitation and cloud response to ENSO**
- **improve MJO simulation**
- **maintain a competitive simulation of global TC statistics**

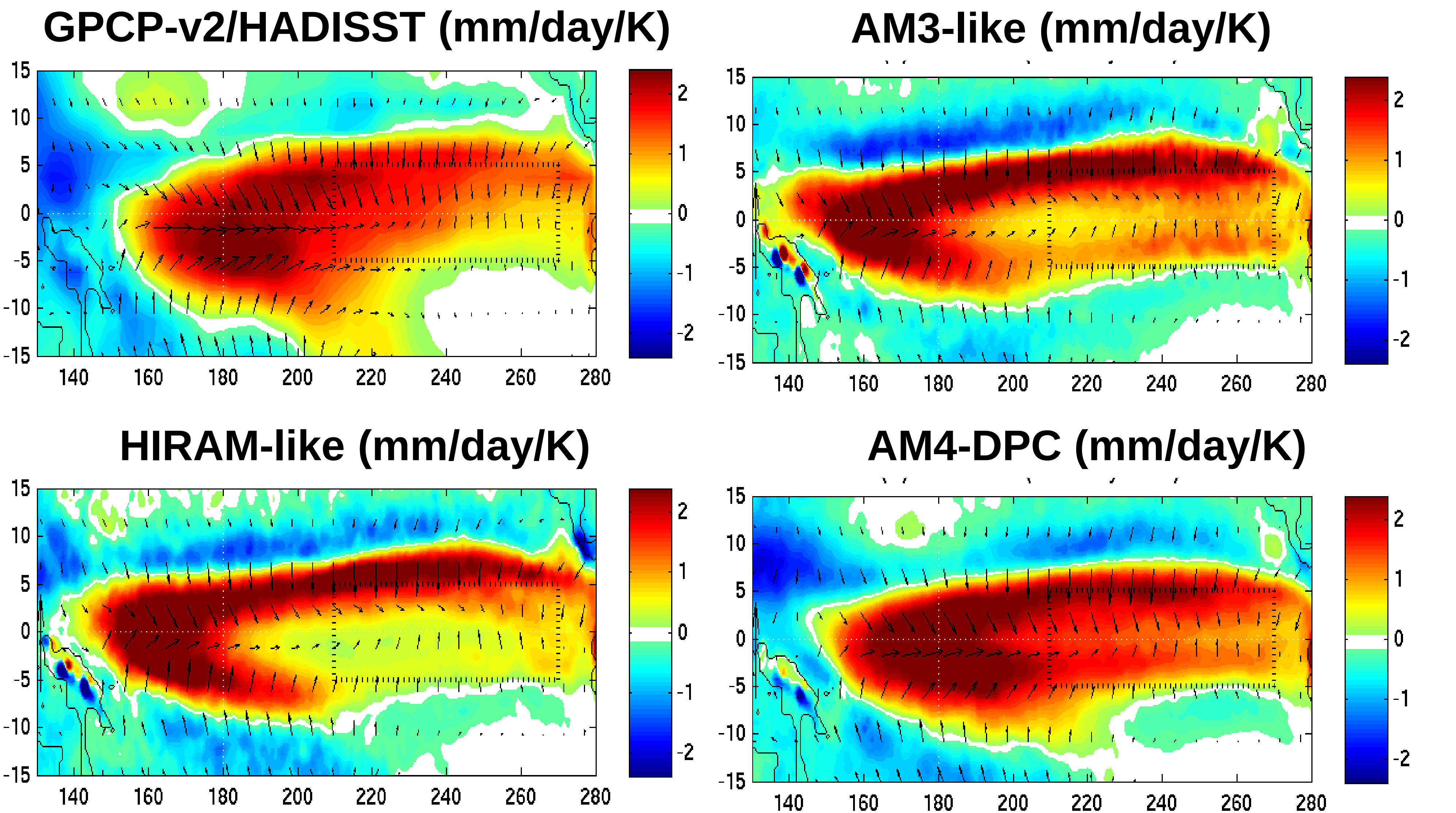
AM4-DPC improves equatorial Pacific SST cold bias
(all coupled to identical ocean and tuned in TOA balance)



AM4-DPC improves equatorial Pacific precipitation bias (all coupled to identical ocean and tuned in TOA balance)

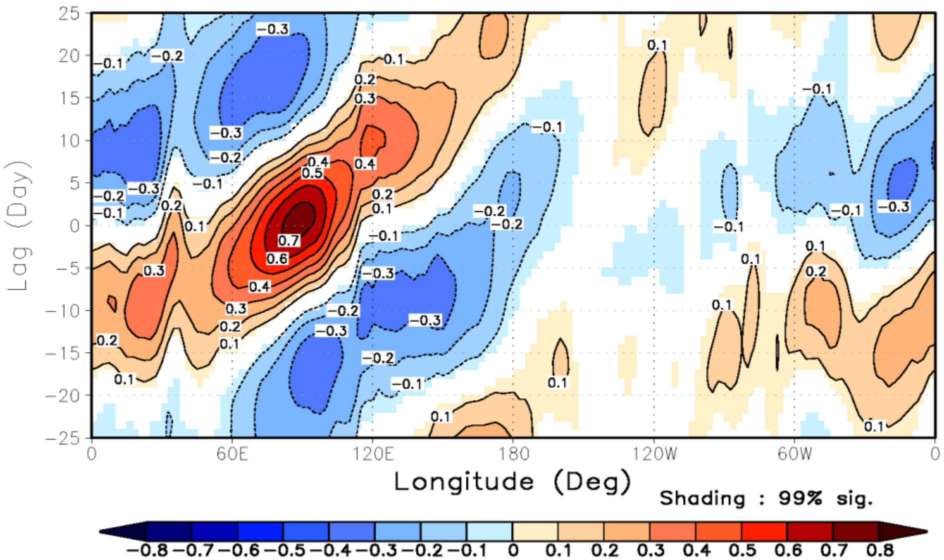


AM4-DPC improves equatorial precipitation response to ENSO (all coupled to identical ocean and tuned in TOA balance)

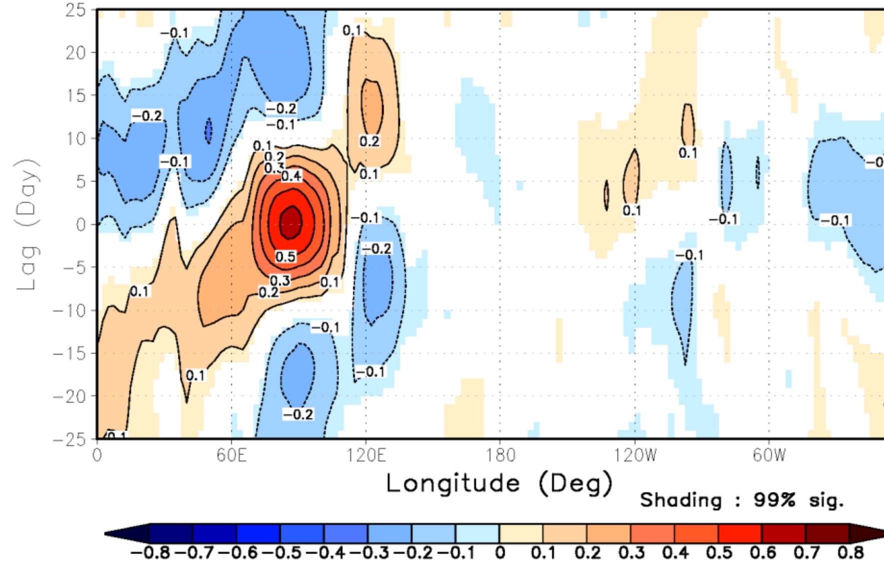


AM4-DPC improves MJO simulations (Lag-Longitude diagram) analysis using US CLIVAR MJO standard diagnostic package

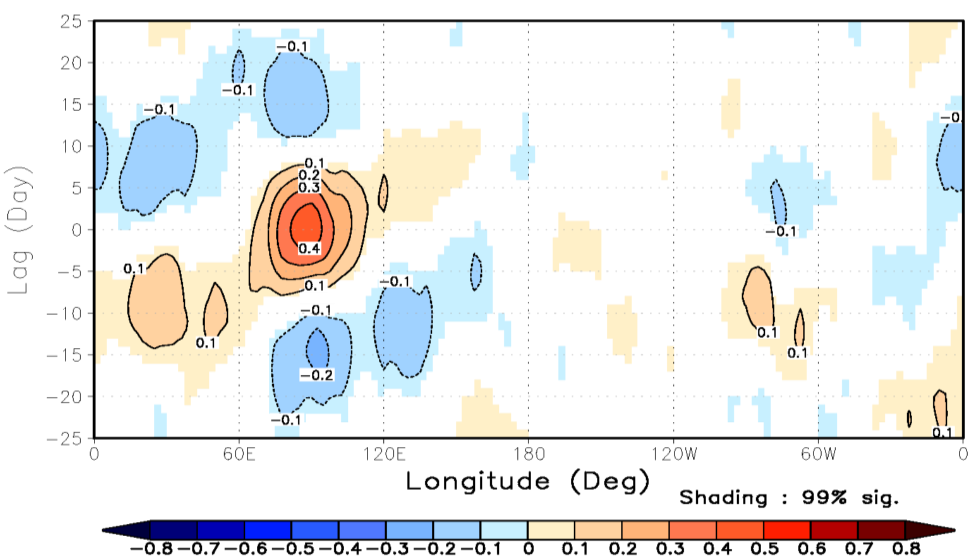
OLR (AVHRR, Nov-Apr)



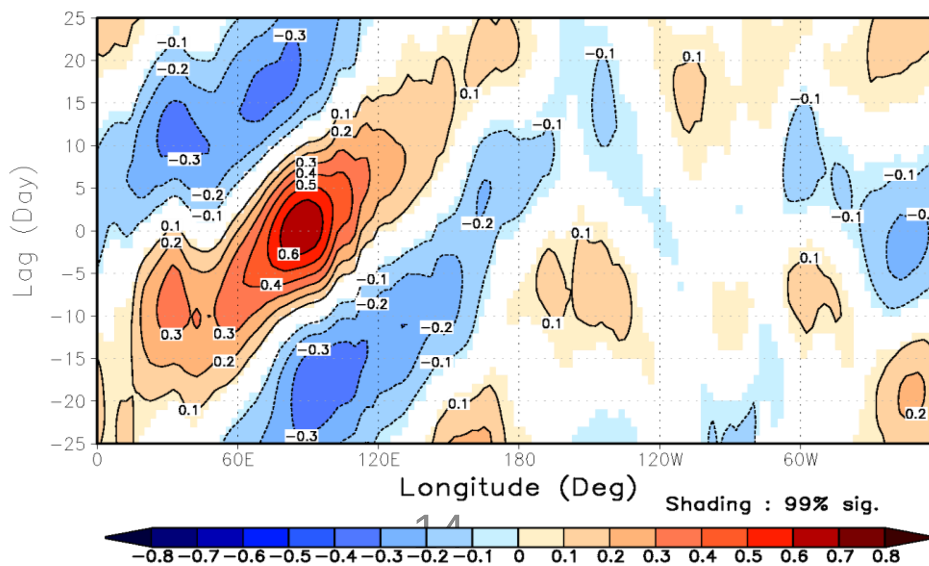
OLR (AM3-Like, Nov-Apr)



OLR (HIRAM-Like, Nov-Apr)

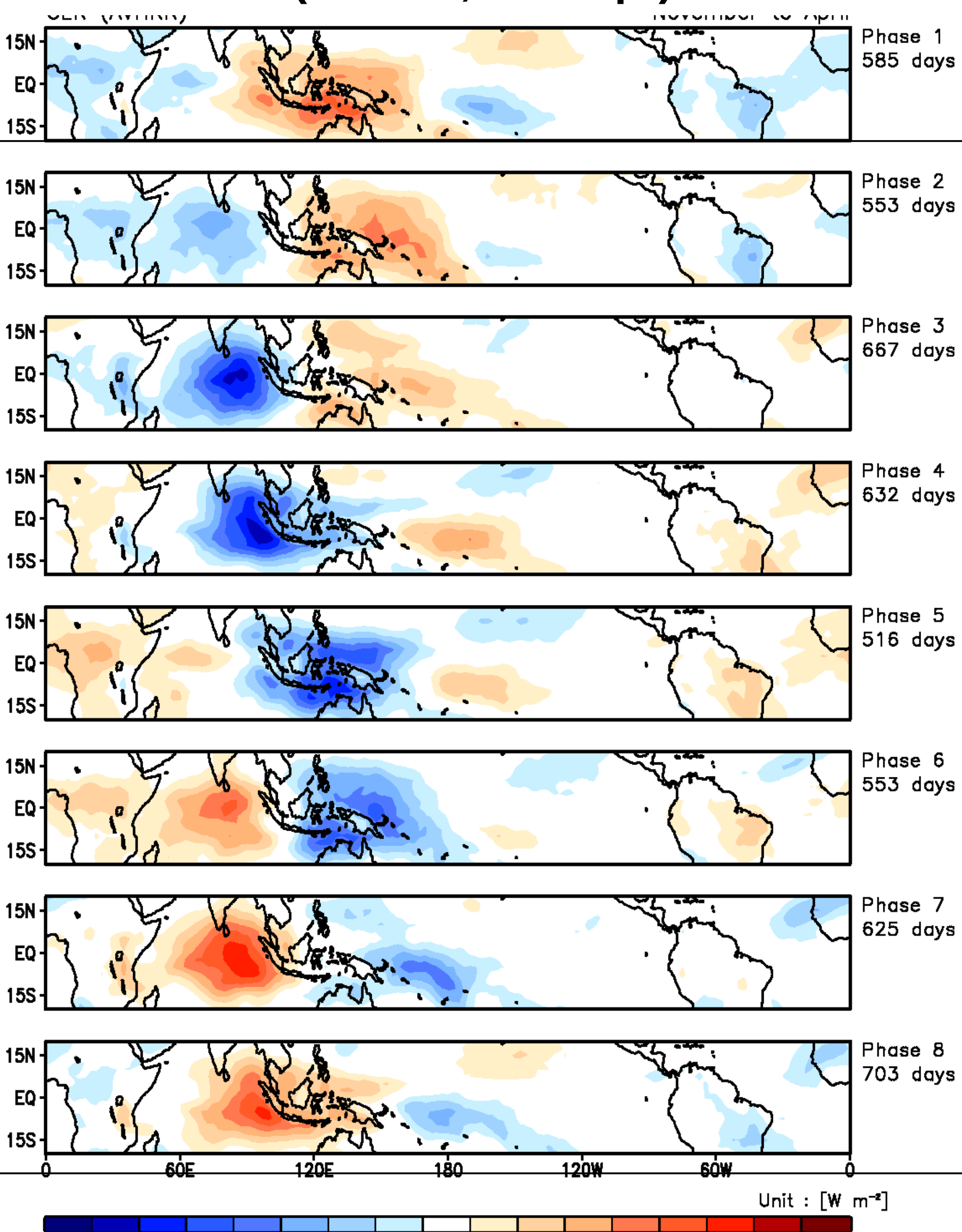


OLR (AM4-DPC, Nov-Apr)

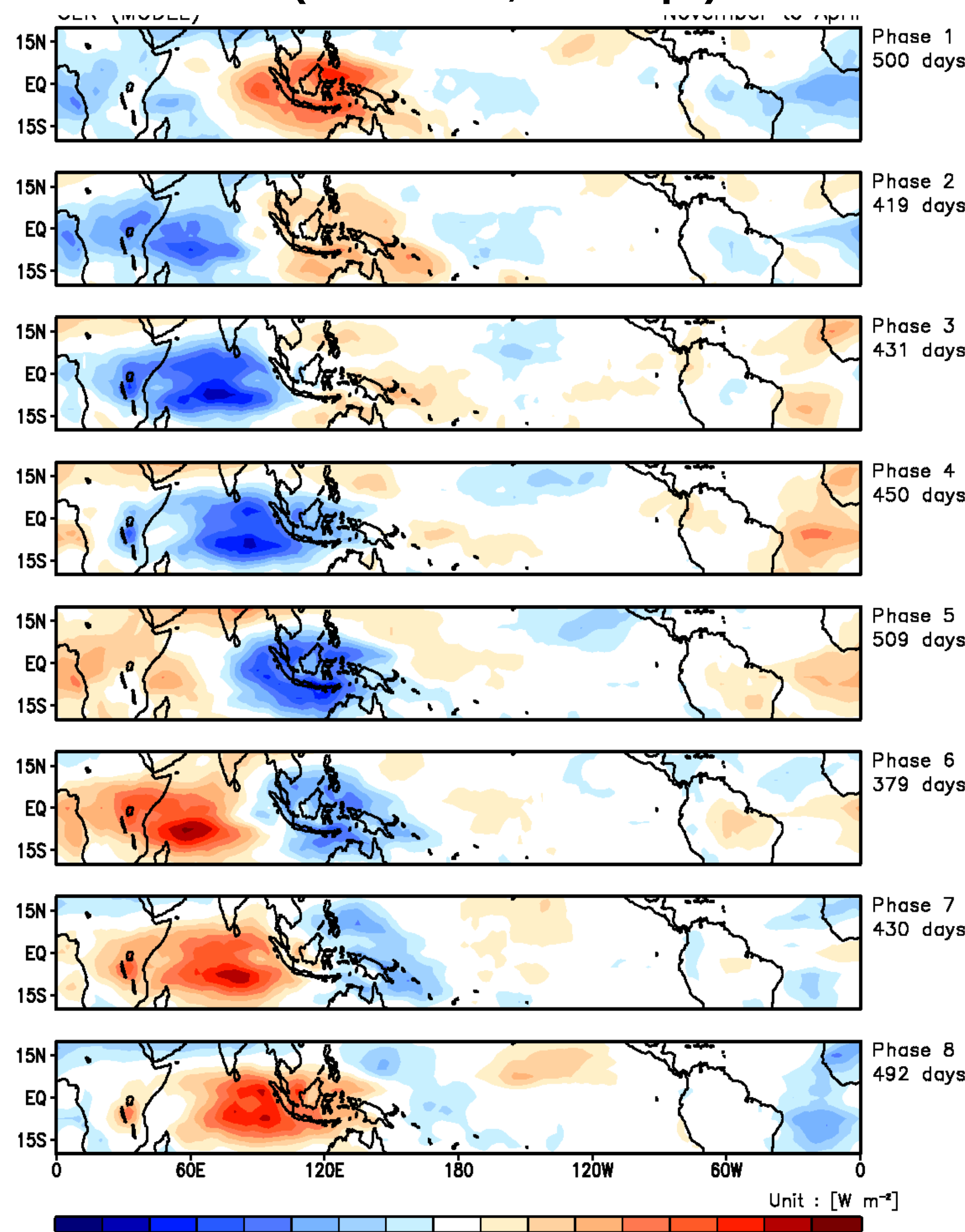


AM4-DPC simulated MJO life-cycle composite (winter season) analysis using US CLIVAR MJO standard diagnostic package

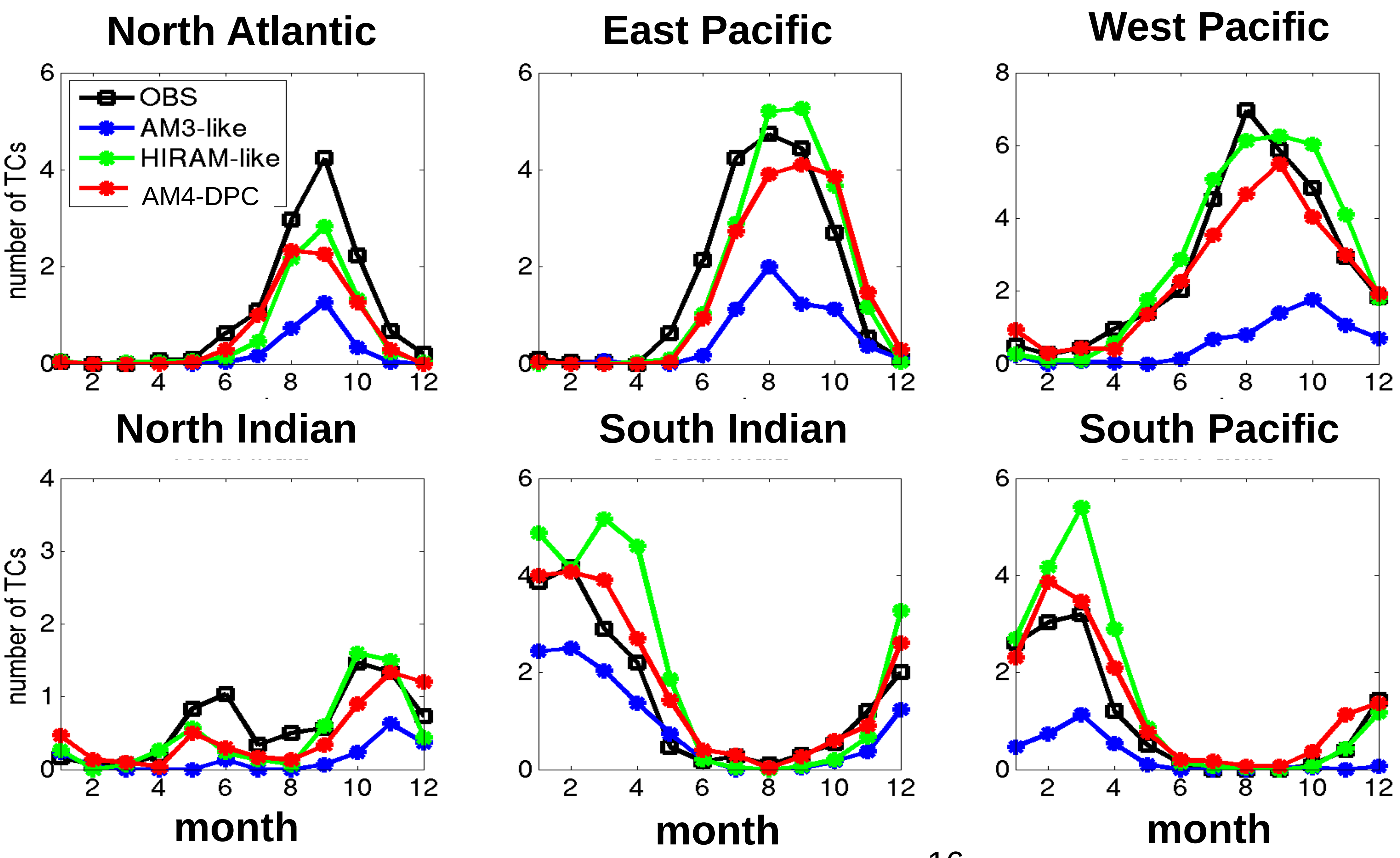
OLR (AVHRR, Nov-Apr)



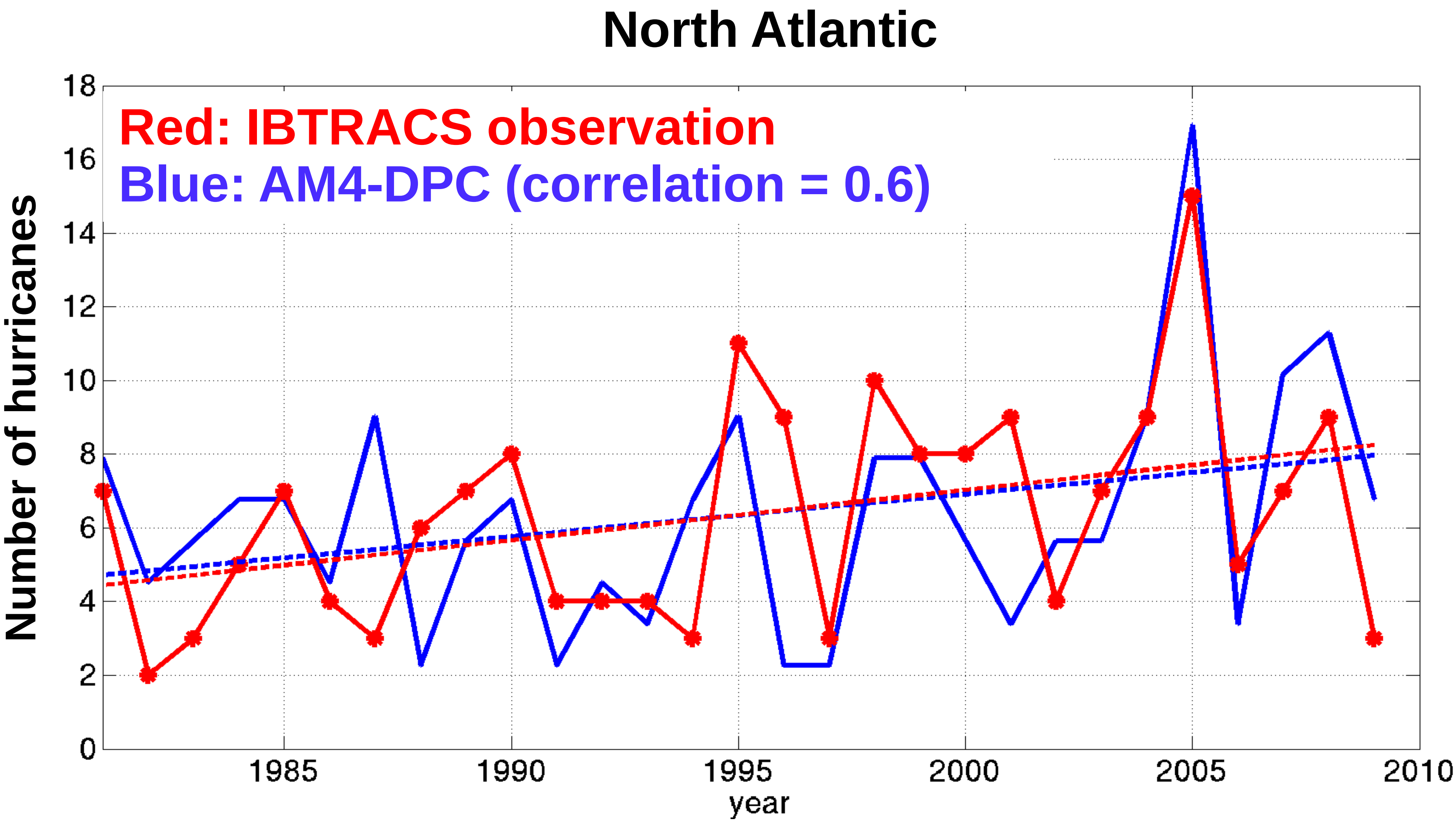
OLR (AM4-DPC, Nov-Apr)



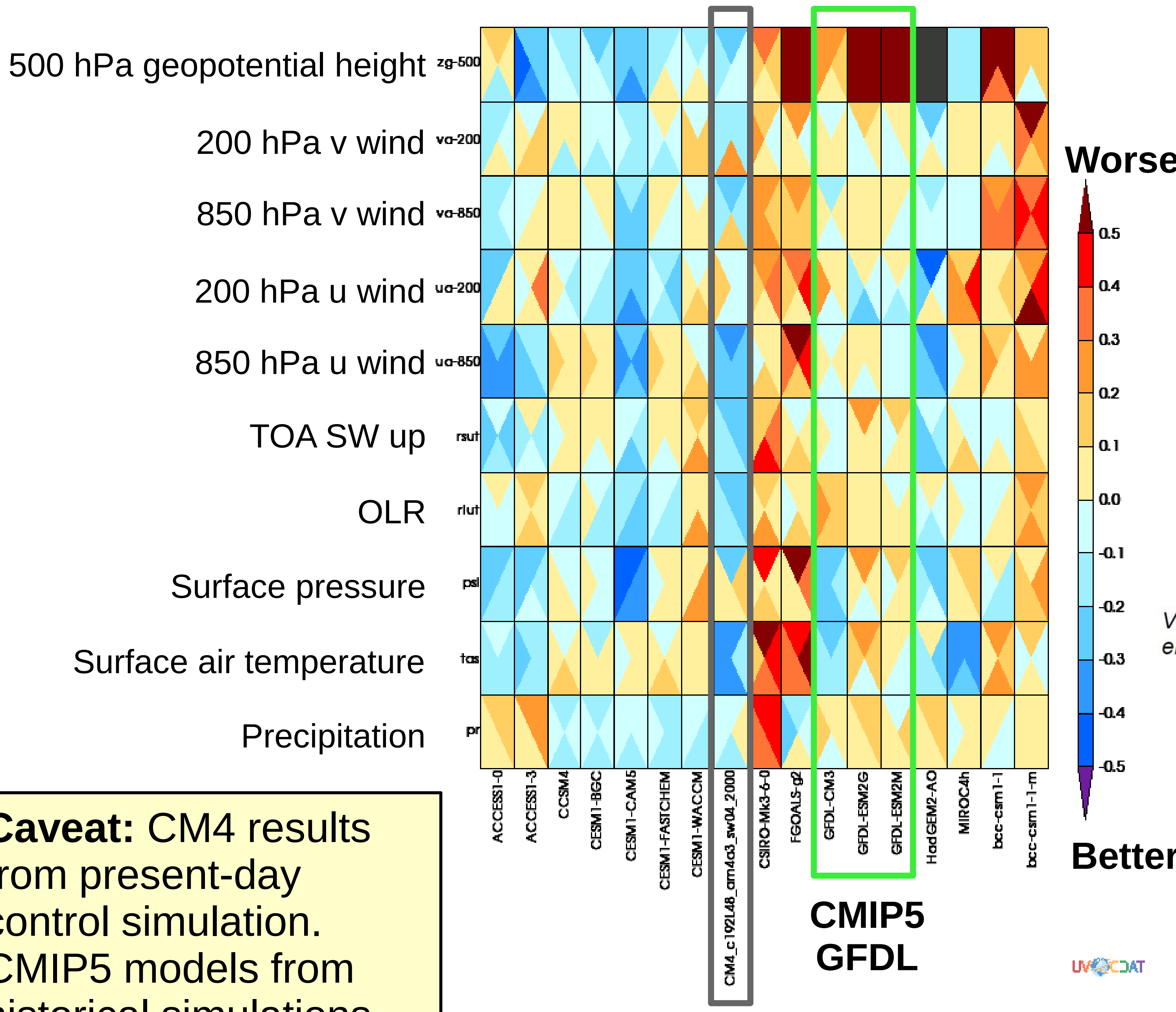
AM4-DPC maintains competitive simulation of TC statistics (all coupled to identical ocean and tuned in TOA balance)



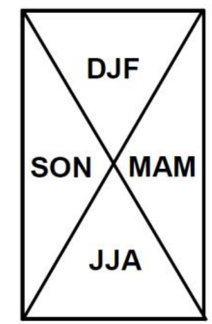
AM4-DPC maintains competitive simulation of TC statistics



Comparison of mean climate with other CMIP5 models



PCMDI Metrics



Values are RMS error normalized by the ensemble median (Gleckler et al. 2008)

Caveat: CM4 results from present-day control simulation. CMIP5 models from historical simulations.

Credit:
Erik Mason
John Krasting
Peter Gleckler

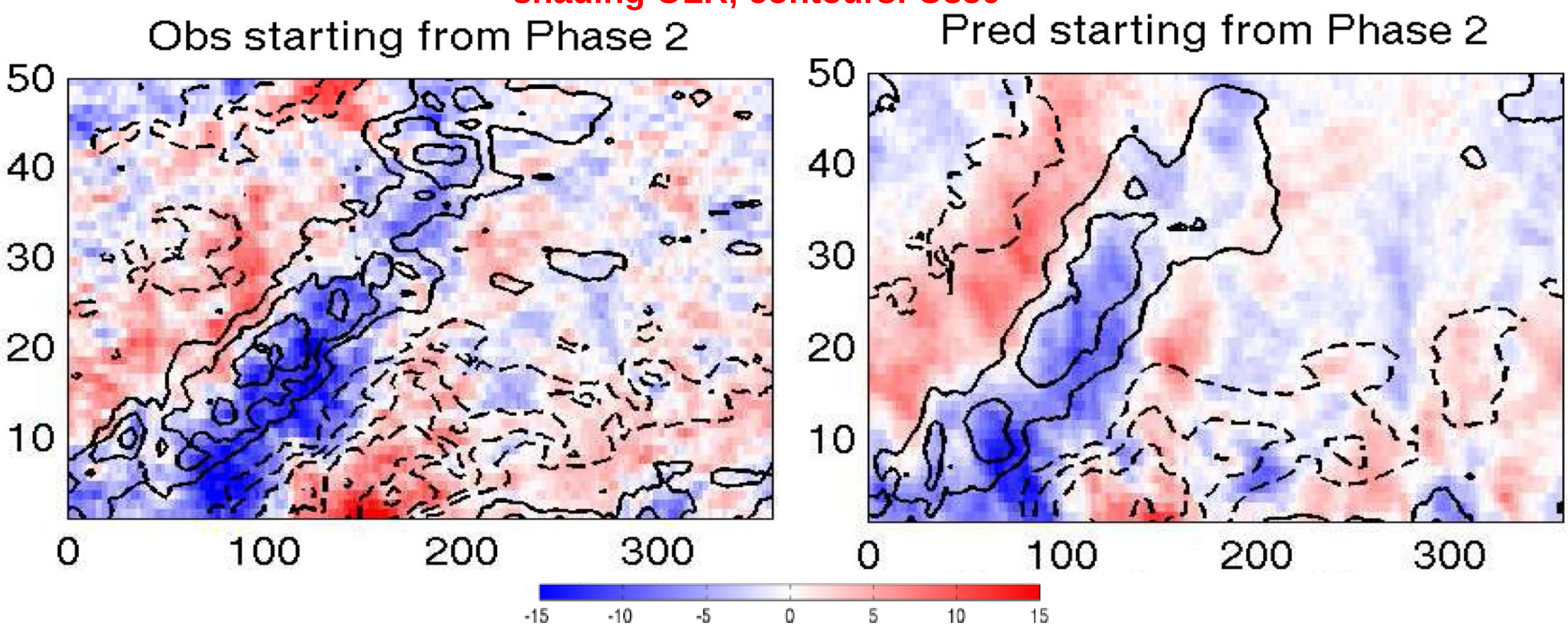
Running DPC in prediction mode

Multi-year MJO hindcast experiments (Xiang et. al 2015, under review)

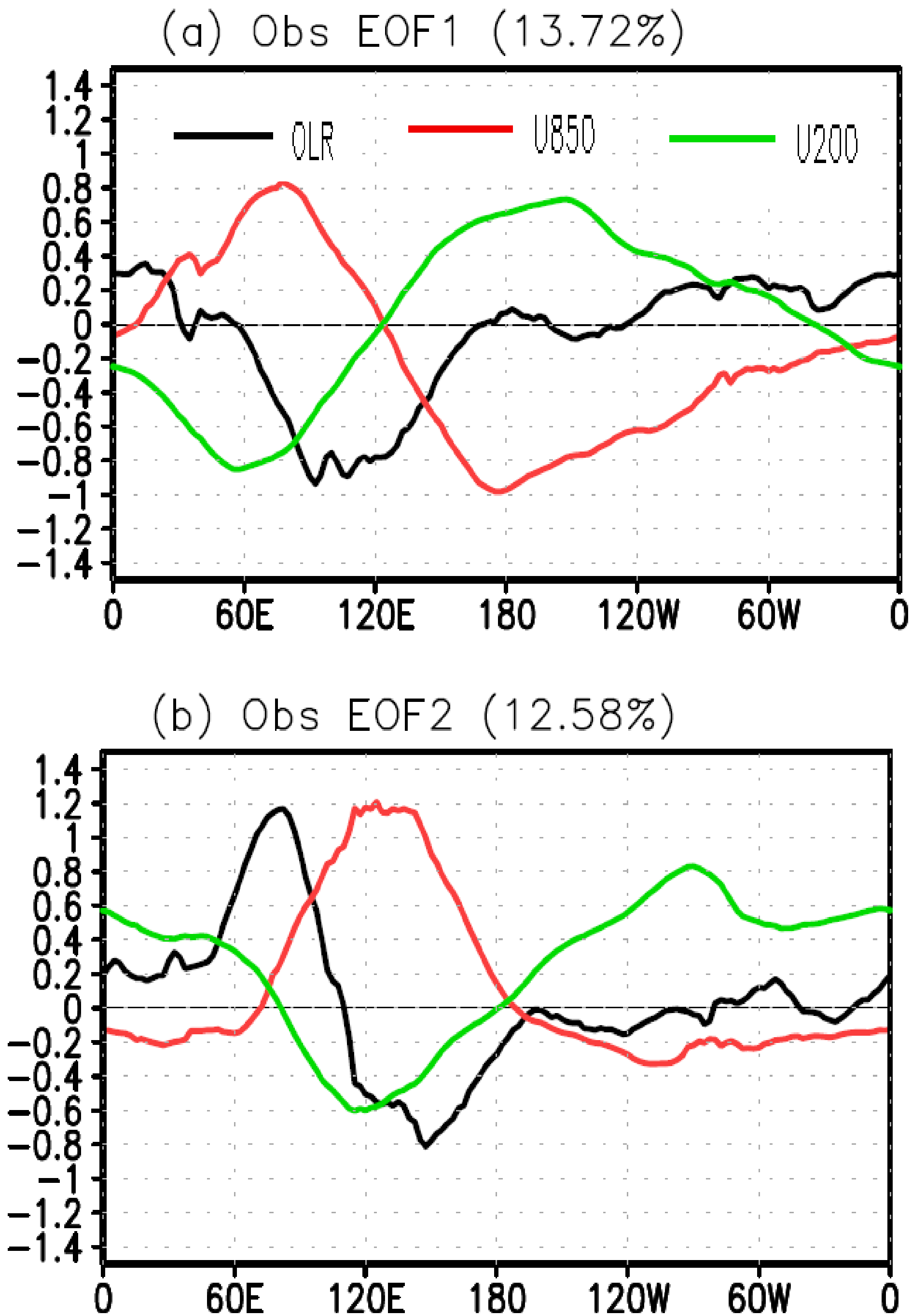
(following YOTC and ISVHE: Intraseasonal Variability Hindcast Experiment)

Period	2003-2013 (11 yr) (November to April)
ATM initialization	Nudging U, V, T, HGT, Surface pressure to GFS analysis (6hour)
Ocean initialization	Nudging SST to NOAA daily SST (1 day)
Cases	Once every 5 days (1st, 6th, 11th, 16th, 21st, 26th)
Ensemble	6 (00Z, 04Z, 08Z, 12Z, 16Z, 20Z)
Integration	50 days

shading OLR, contours: U850



Method for evaluating MJO hindcast skill



Wheeler & Hendon 2004, Lin et. al 2008
Gottschalck et. al 2010

model and observational data are projected onto the observed combined EOFs (OLR, U850, U200)

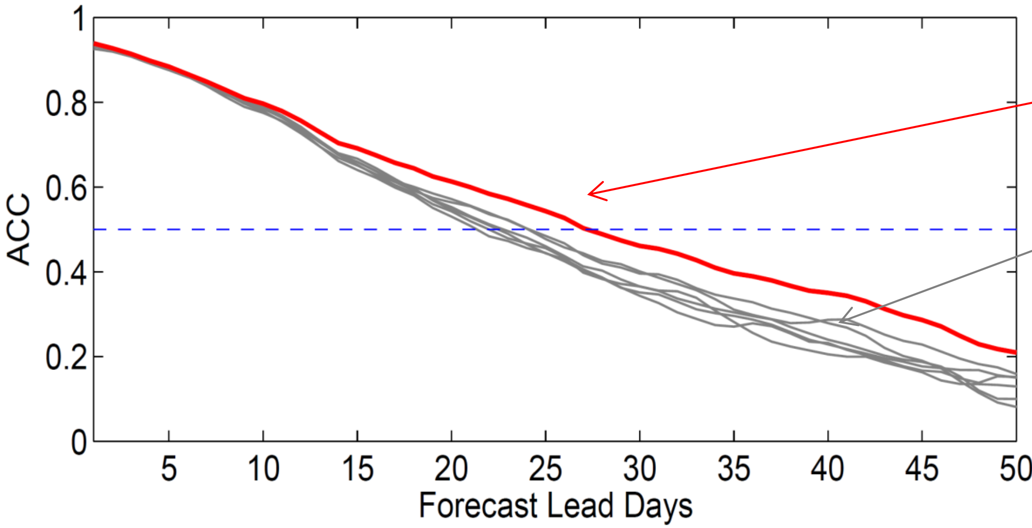
Projection coefficients normalized for RMM1 and RMM2 index

$$\mathrm{ACC}(\tau) = \frac{\sum_{t=1}^{N}[a_1(t)b_1(t,\tau) + a_2(t)b_2(t,\tau)]}{\sqrt{\sum_{t=1}^{N}[a_1^2(t) + a_2^2(t)]}\sqrt{\sum_{t=1}^{N}[b_1^2(t,\tau) + b_2^2(t,\tau)]}}$$

$$\mathrm{RMSE}(\tau) = \sqrt{\frac{1}{N}\sum_{t=1}^{N}[|a_1(t) - b_1(t,\tau)|^2 + |a_2(t) - b_2(t,\tau)|^2]}$$

a1, a2: observed RMM1 and RMM2 (normalized)
b1, b2: predicted RMM1 and RMM2 (normalized)

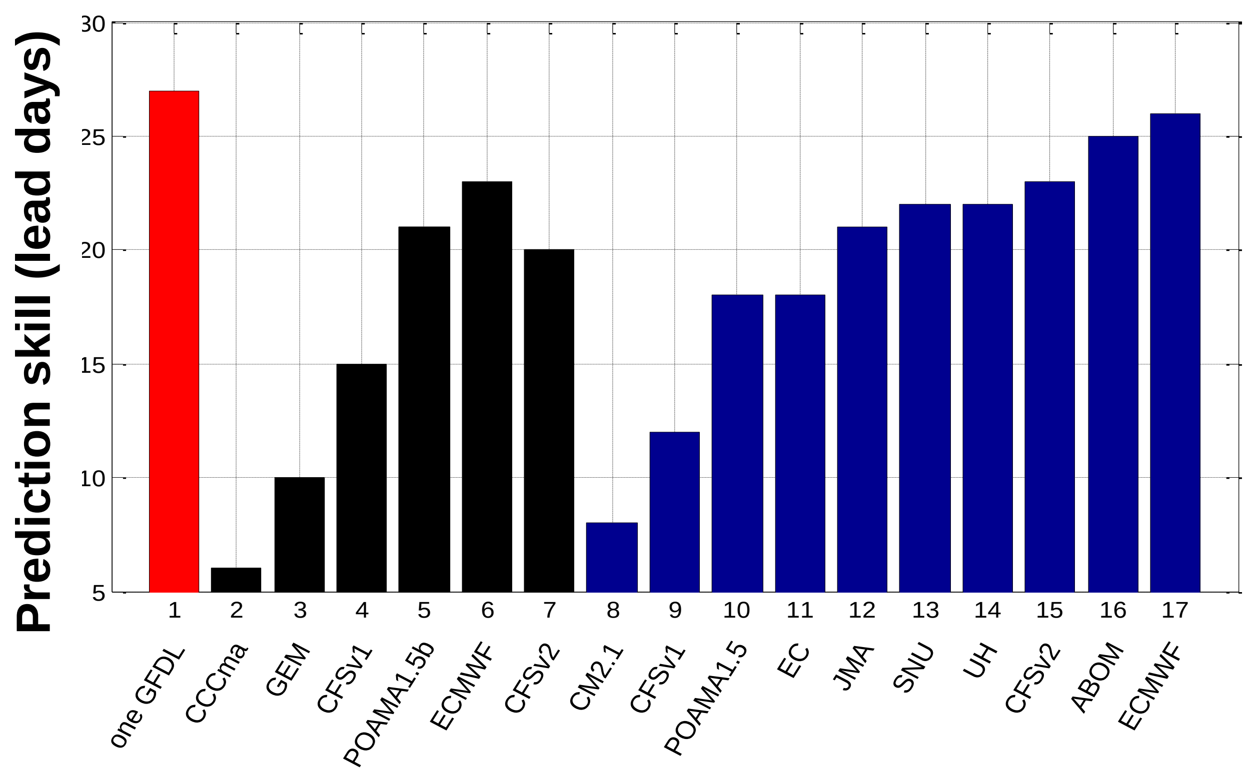
MJO hindcast skills and comparison with other models
(Xiang et. al 2015, under review)



Red: multimember ensemble mean

Gray: individual members

Forecast lead days for ACC=0.5



Red: GFDL model using DPC

Blue: ISVHE participating model results (unpublished)

Black: previously published (may not be winter season only)

Summary

- AM4/CM4 is starting to take shape, targeting for higher resolution for both atmosphere and ocean with a goal to improve both physical realism and simulation fidelity (mean, variability: TC, MJO, ENSO…)
- AM4 prototype models (AM3-like & HiRAM-like) forced by the observed SSTs provide good simulation of mean climate but suffer from major biases when coupled with ocean, motivating development of a double plume convection (DPC) scheme.
- The DPC scheme used in AM4
  - significantly reduces the equatorial Pacific cold and dry bias
  - improve simulation of precipitation and cloud response to ENSO
  - improve MJO simulation
  - maintain a competitive simulation of global TC statistics
- The DPC scheme has also been tested in multi-year hindcast experiments, showing substantial skill in MJO and TC prediction

Some on-going and future work

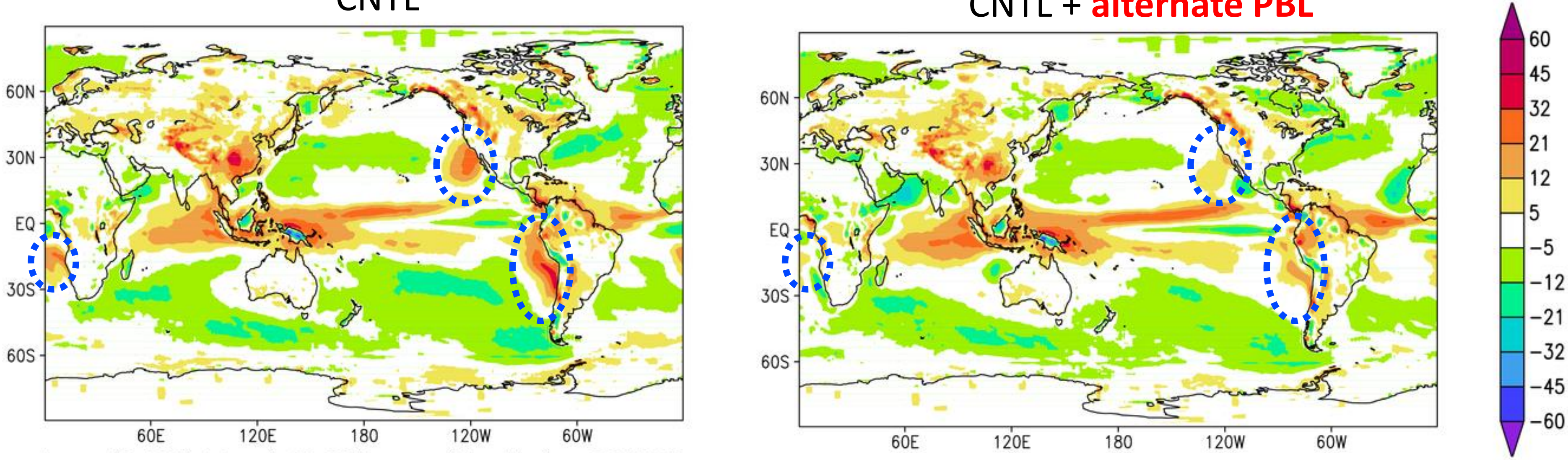
PBL turbulence, large-scale cloud, microphysics

- Unified large-scale cloud, turbulence (CLUBB)
- Microphysics and aerosol cloud interactions (M-G microphysics)

Atmosphere simulations with fixed SST

CNTL

CNTL + **alternate PBL**



bias = 0.60; corr = 0.91; rms = 9.0

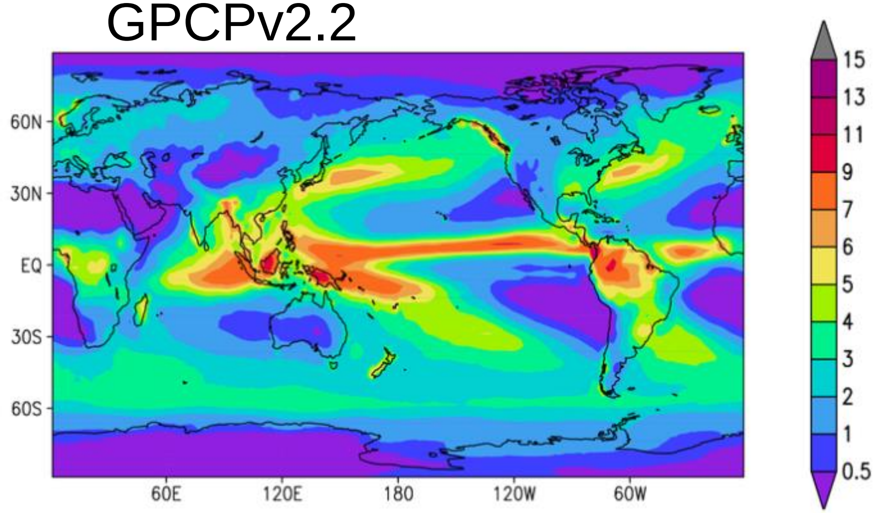
bias = 0.31; corr = 0.91; rms = 8.9

Biases in marine stratocumulus shortwave cloud radiative effect

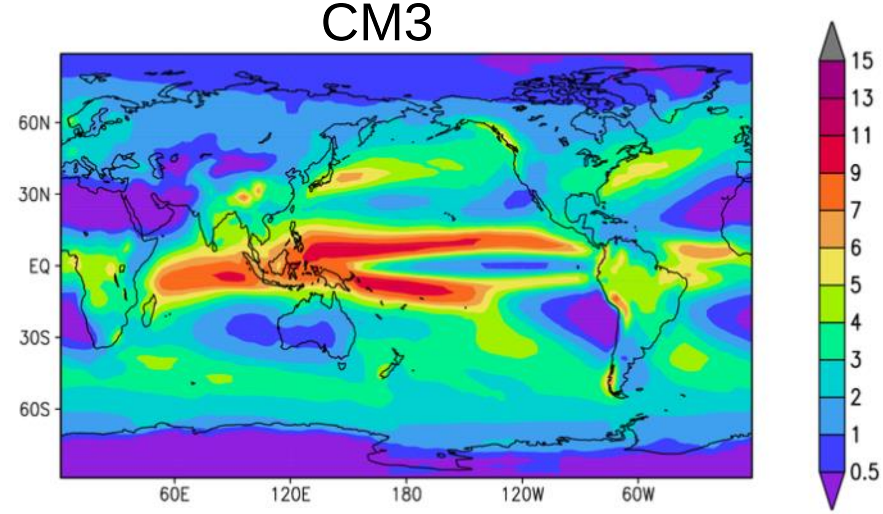
END

Annual precipitation

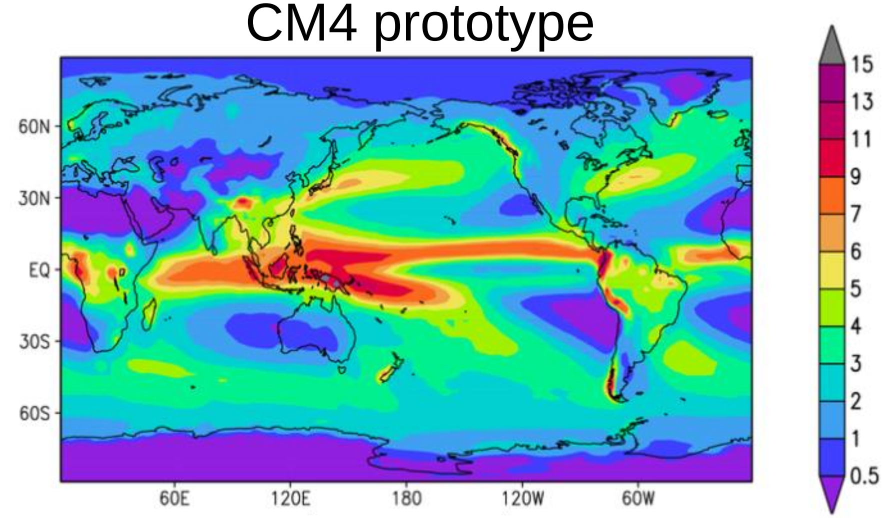
Observations (mm/day)
GPCPv2.2



Models
CM3



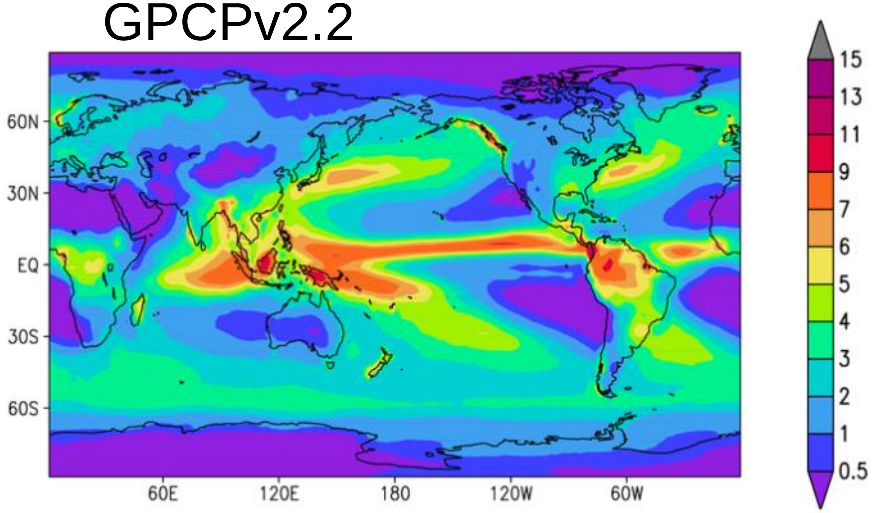
CM4 prototype



Present-day coupled simulations
30 year climatology

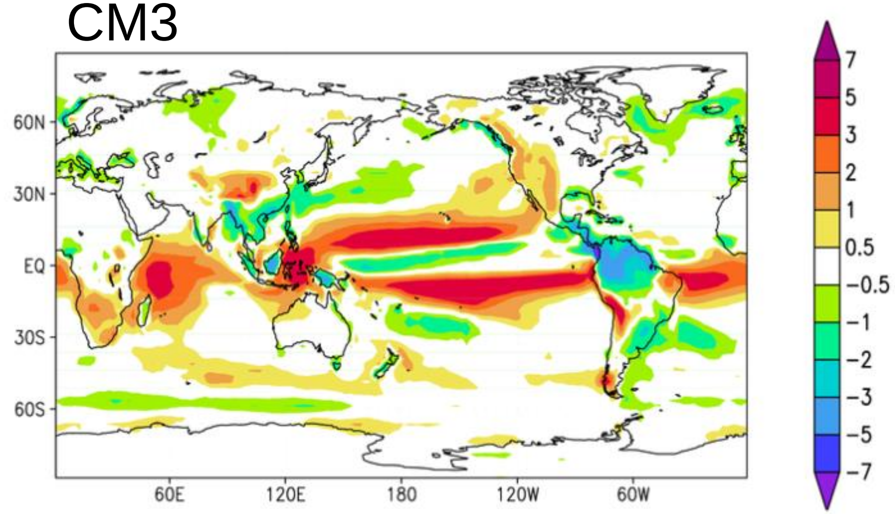
Annual precipitation

Observations (mm/day)
GPCPv2.2



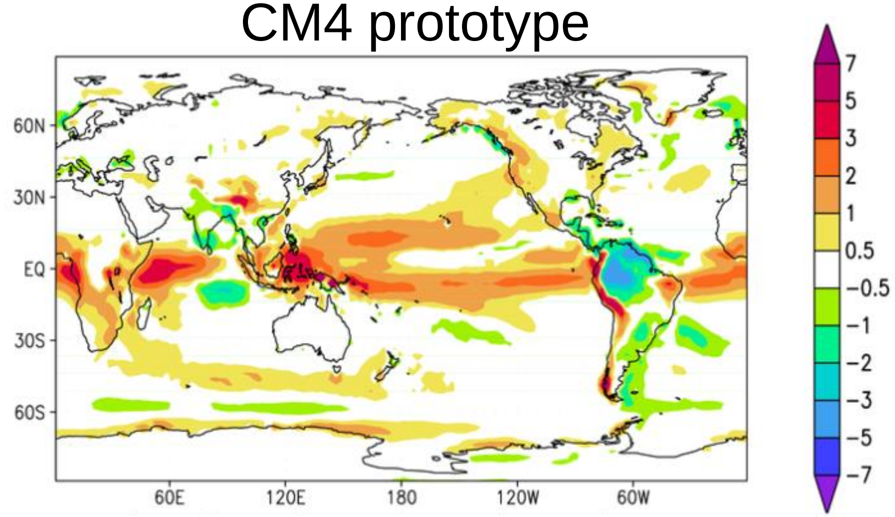
mean = 2.68, std = 1.916

Model minus observations
CM3



bias = 0.29, corr = 0.81, rms = 1.28

CM4 prototype

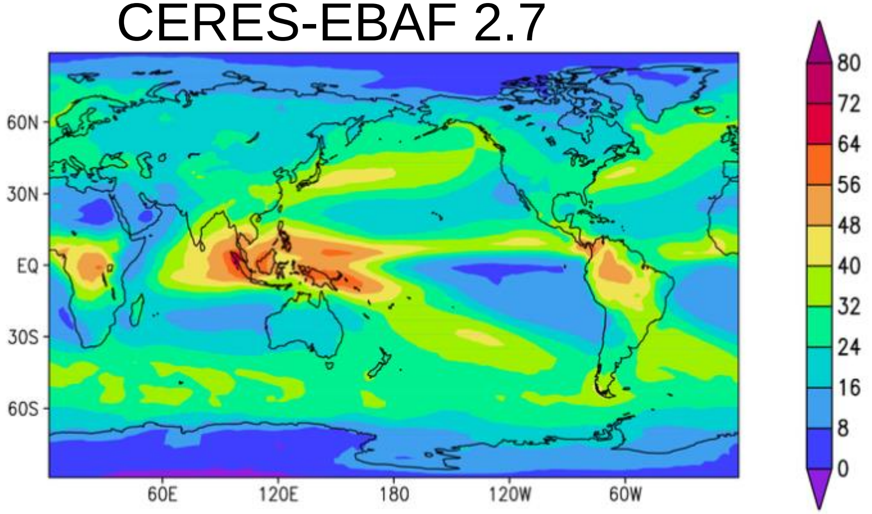


bias = 0.34, corr = 0.89, rms = 1.03

Present-day coupled simulations
30 year climatology

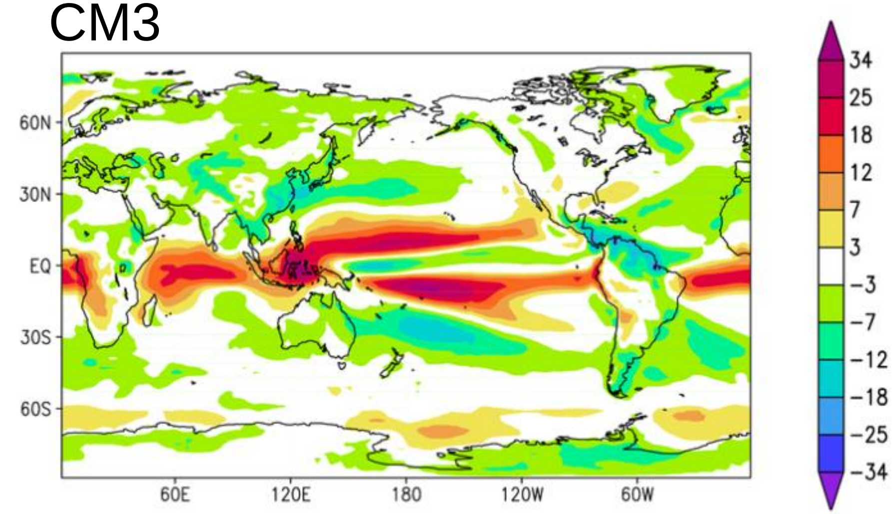
Longwave cloud radiative effects

Observations (W m^{-2})
CERES-EBAF 2.7



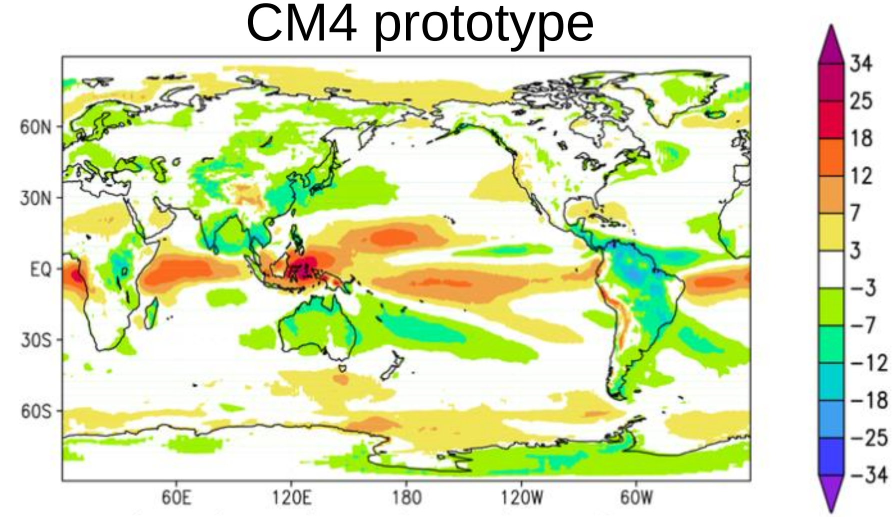
mean = 26.07, std = 11.17

Models minus observations
CM3



bias = -0.03, corr = 0.84, rms = 7.58

CM4 prototype

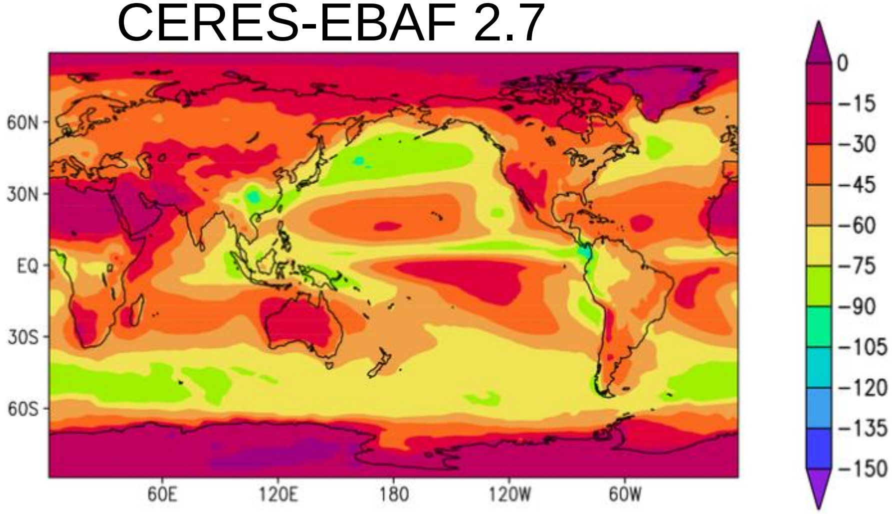


bias = 0.02, corr = 0.90, rms = 5.17

Present-day coupled simulations
30 year climatology

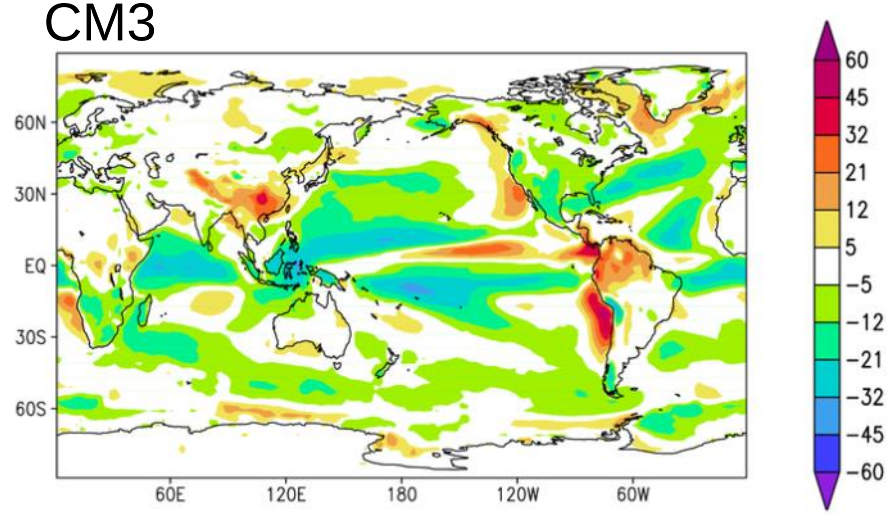
Shortwave cloud radiative effects

Observations (W m^{-2})
CERES-EBAF 2.7



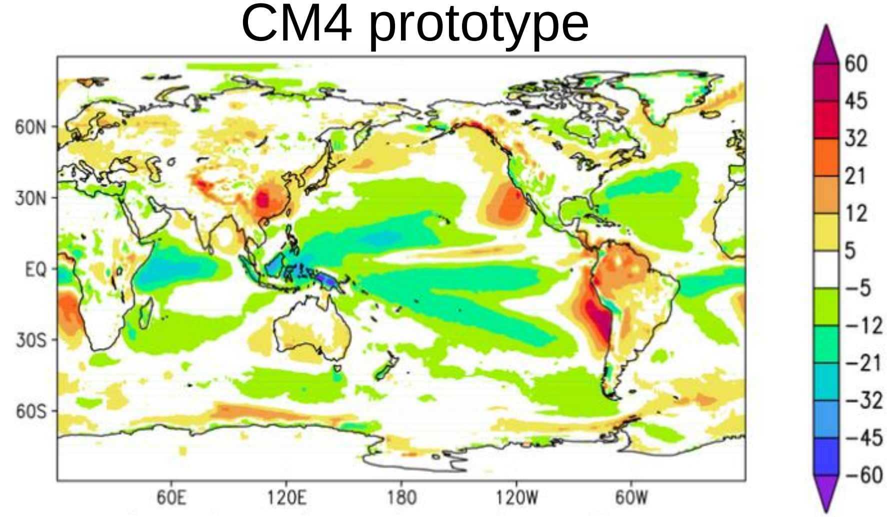
mean = -47.17, std = 20.37

Models minus observations
CM3



bias = -3.71, corr = 0.89, rms = 10.94

CM4 prototype

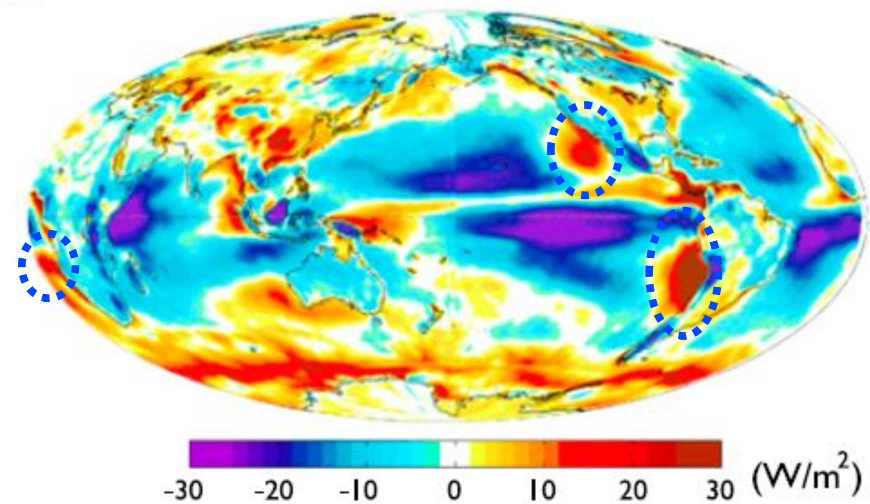


bias = -1.30, corr = 0.90, rms = 9.36

Present-day coupled simulations
30 year climatology

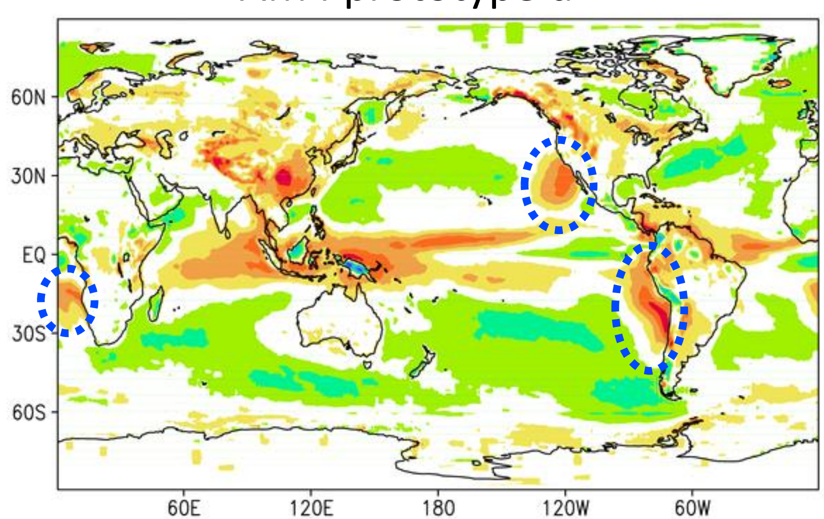
Biases in marine stratocumulus
Shortwave cloud radiative effect

Biases in 20 CMIP5 models
Hwang and Frierson (2013)



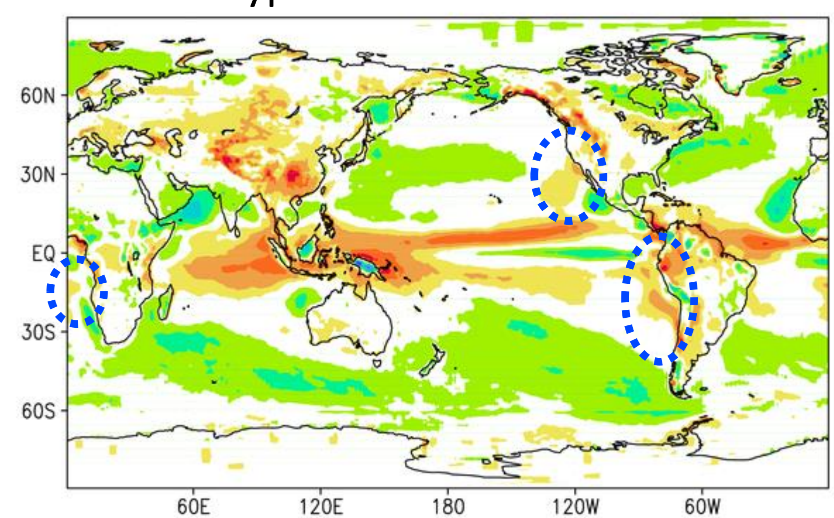
Atmosphere simulations with fixed SST

AM4 prototype d

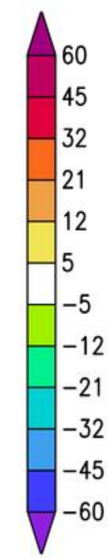


bias = 0.60; corr = 0.91; rms = 9.0

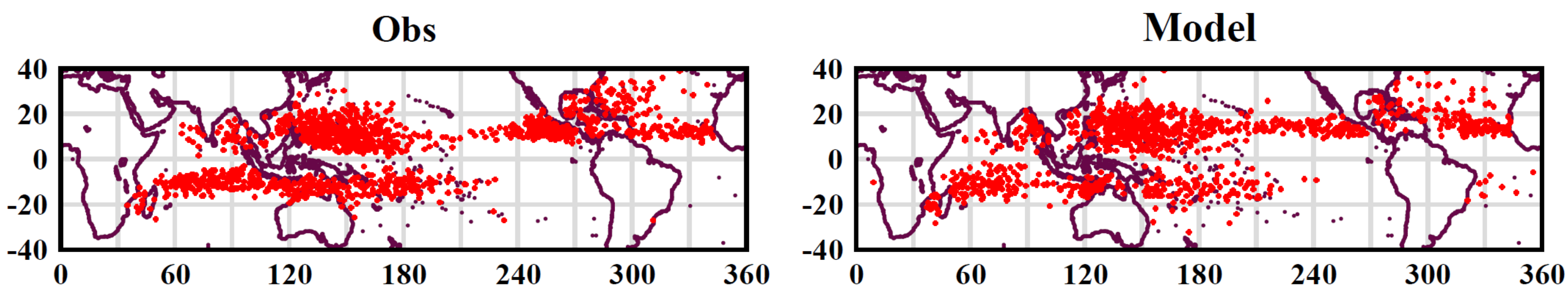
Prototype d + alternate PBL



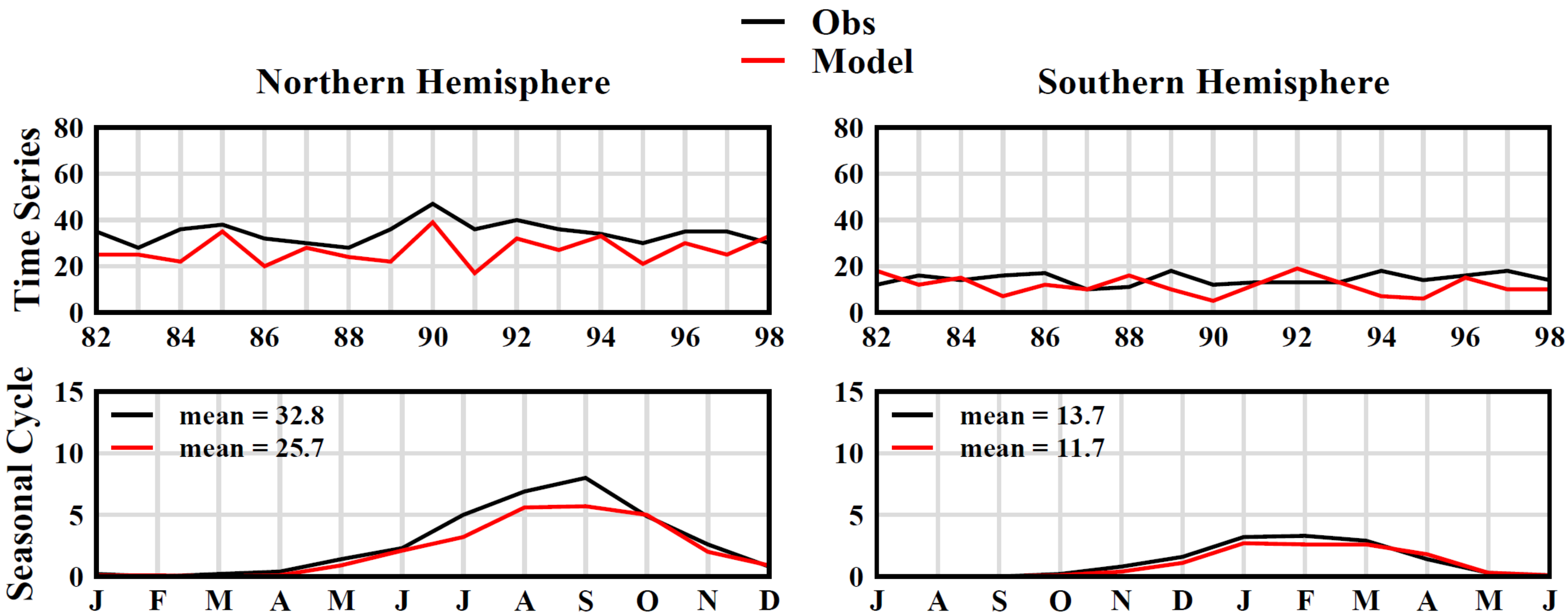
bias = 0.31; corr = 0.91; rms = 8.9



Tropical cyclones

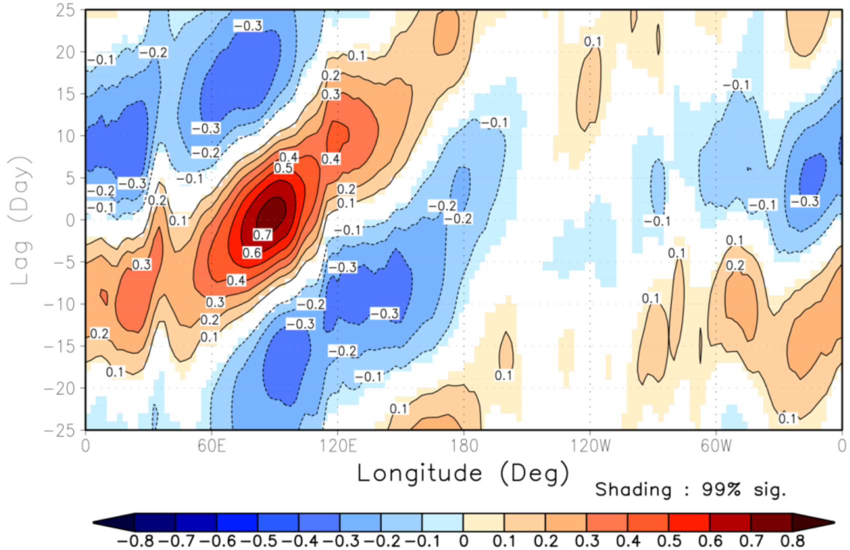


Tropical cyclone counts

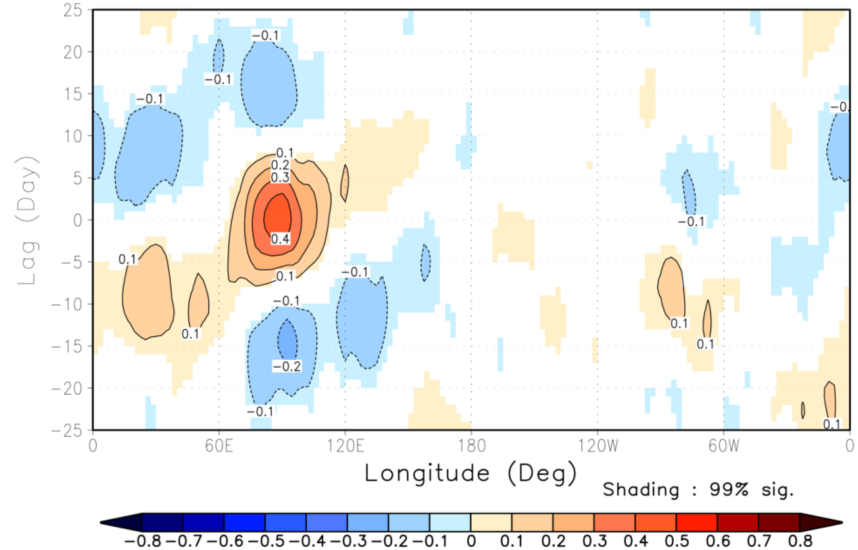


Madden-Julian Oscillation (MJO)
OLR Lag correlation, Winter (Nov-Apr)

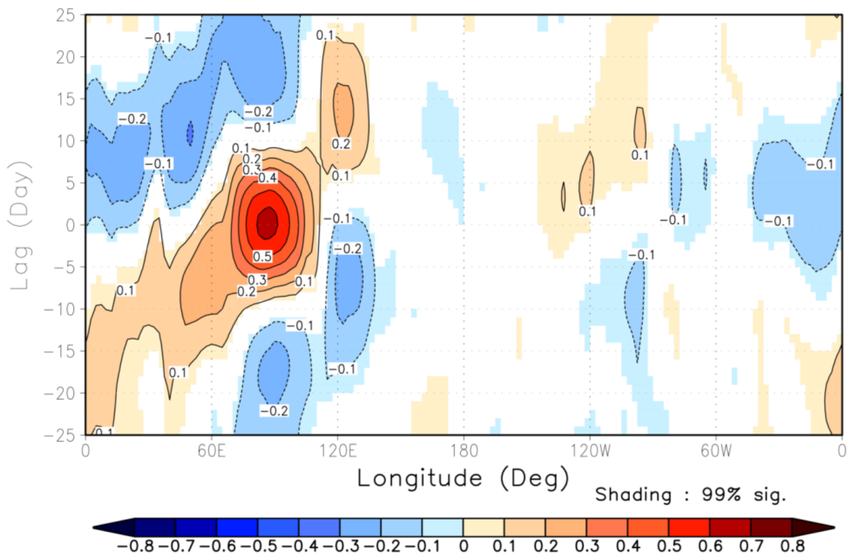
Observations



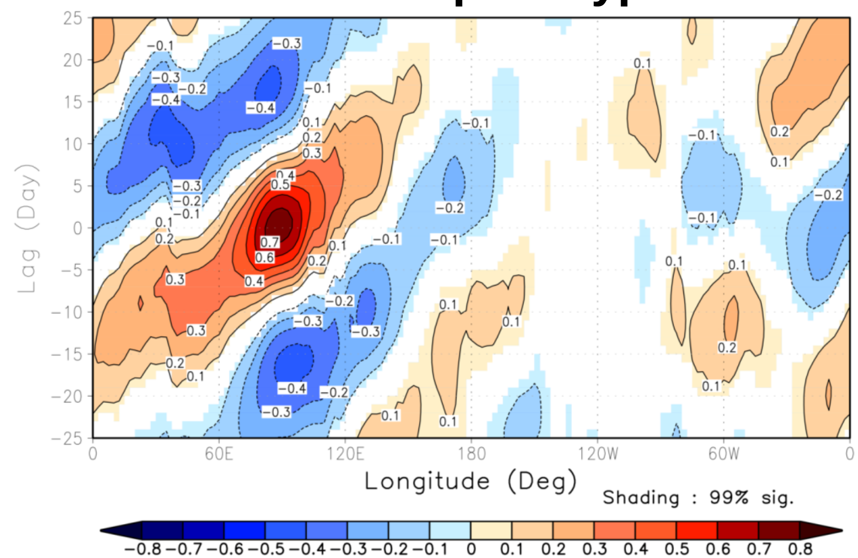
HiRAM-like convection



AM3-like convection



CM4 prototype

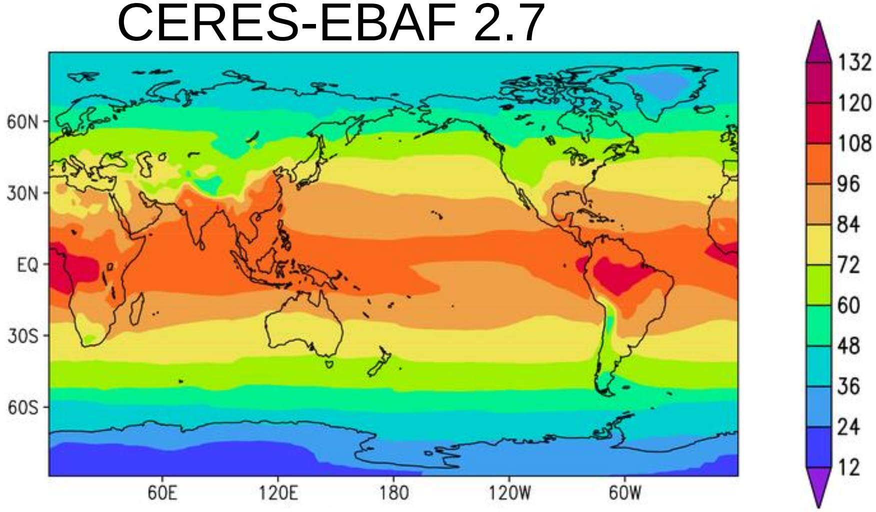


Zhao et al. (in prep.)

New shortwave water vapor continuum

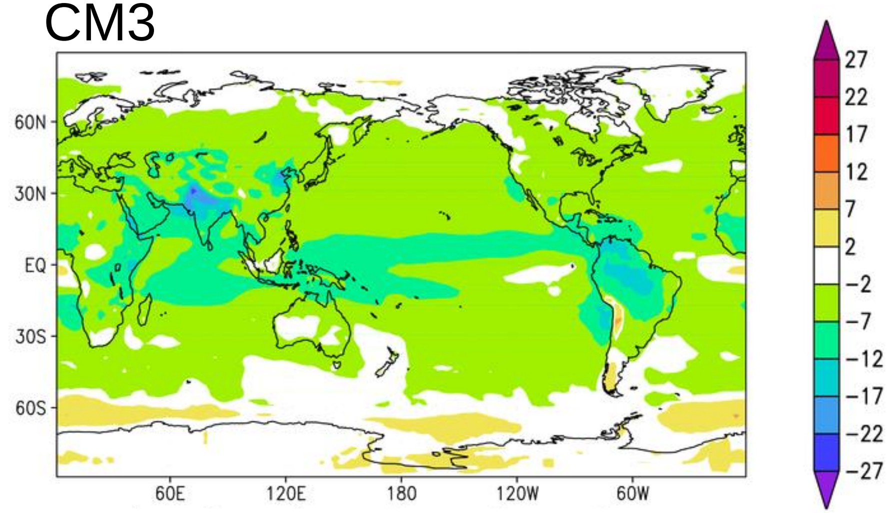
SW absorbed in the atmosphere

Observations (W m^{-2})
CERES-EBAF 2.7



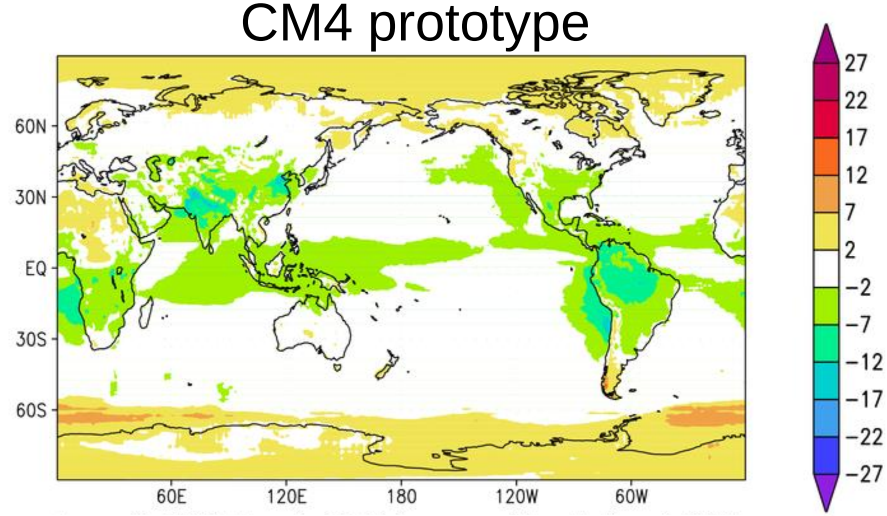
mean = 77.85, std = 20.43

Models minus observations
CM3



bias = -4.29, corr = 0.99, rms = 5.49

CM4 prototype



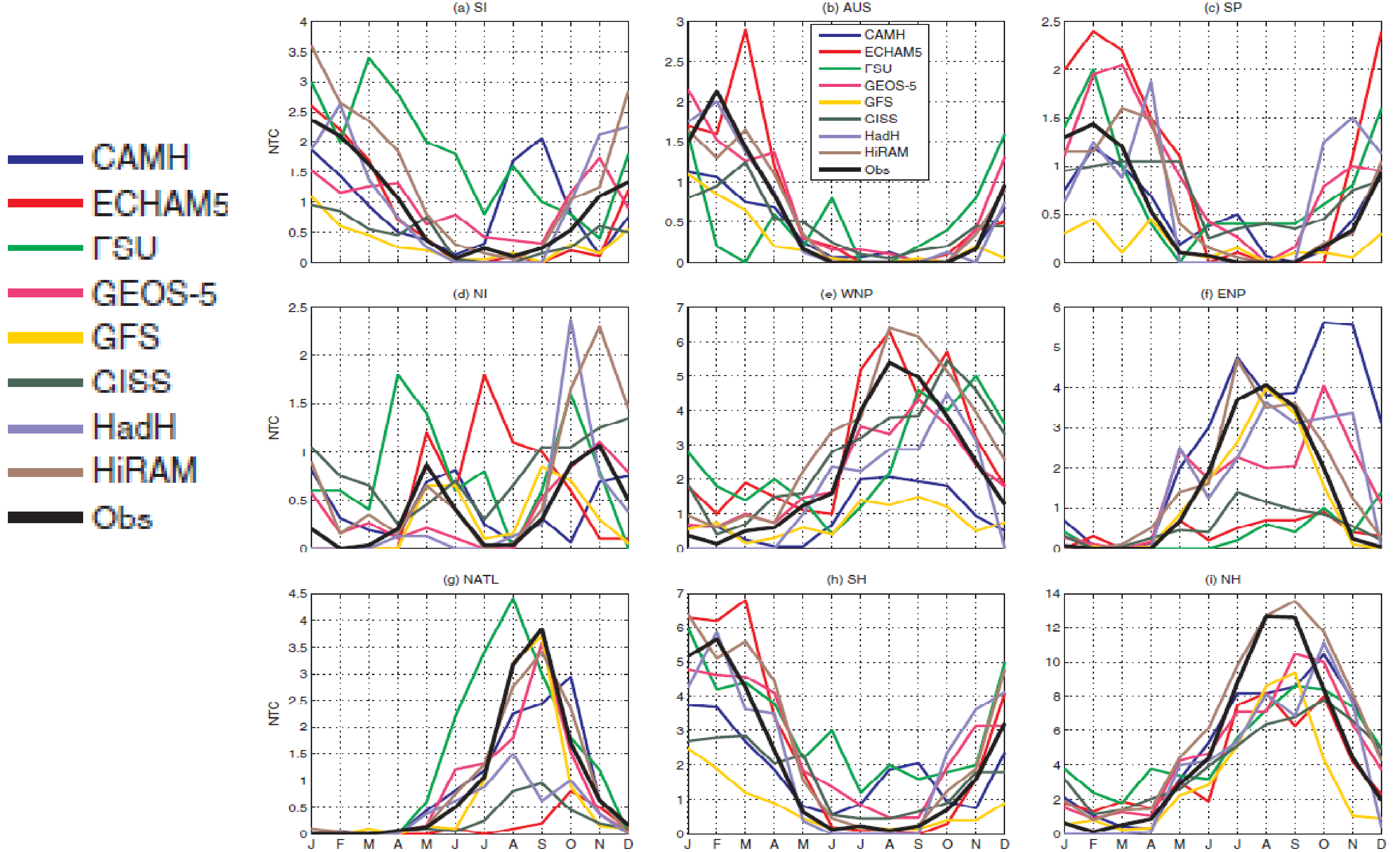
bias = -0.77, corr = 0.99, rms = 2.94

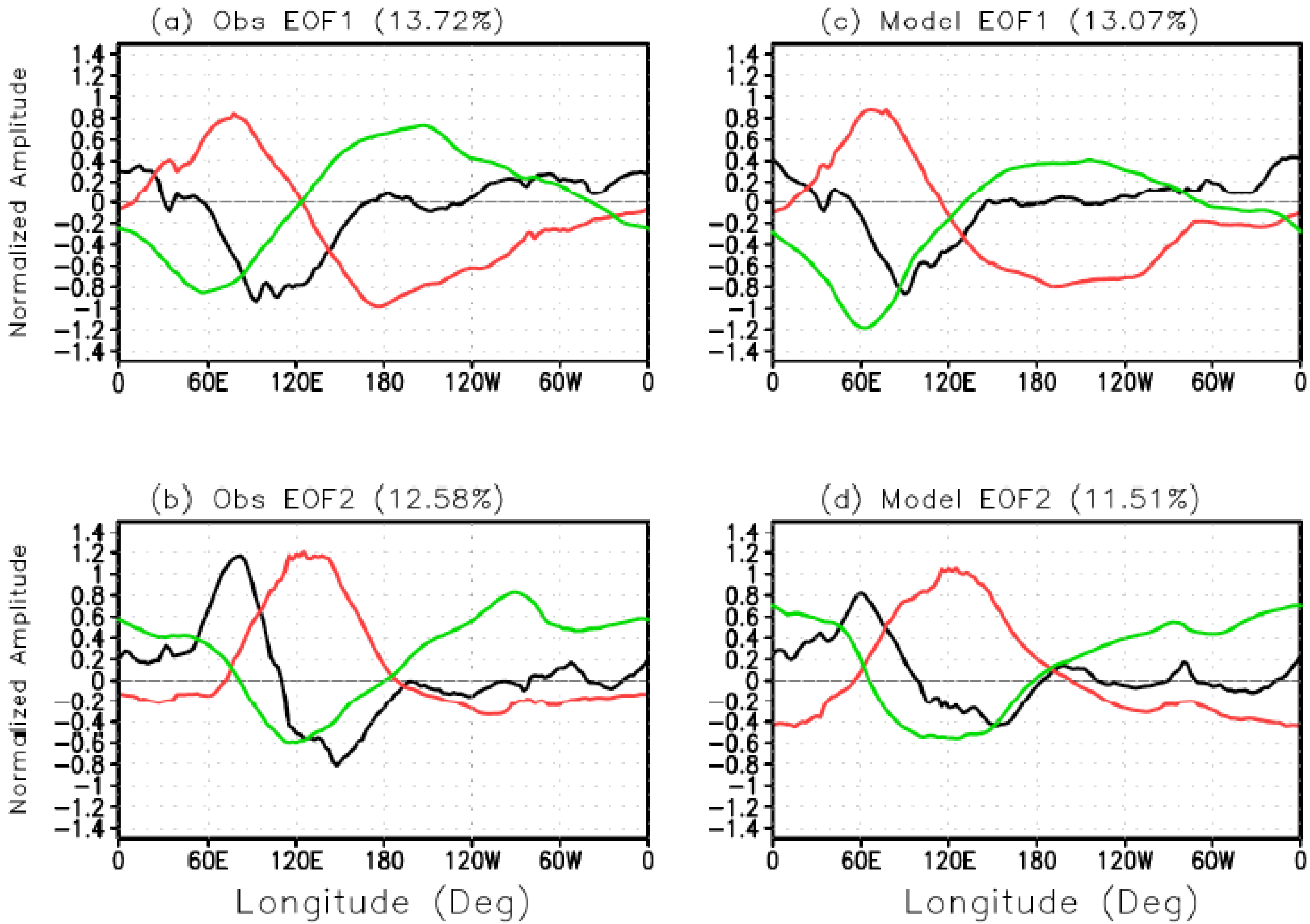
Present-day coupled simulations
30 year climatology

Credit:
David Paynter
Dan Schwarzkopf
Stuart Freidenreich

HiRAM captures seasonal cycle, inter-annual variability, decadal trends of hurricanes over multiple ocean basins

Seasonal Cycle




(a) Obs EOF1 (13.72%)
(c) Model EOF1 (13.07%)
(b) Obs EOF2 (12.58%)
(d) Model EOF2 (11.51%)
Normalized Amplitude
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
0
60E
120E
180
120W
60W
Longitude (Deg)