Global Modeling of Tropical Cyclone Activities and Response to 21st Century Warming Using a 50km Resolution GFDL HIRAM

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Workshop on High-Resolution Climate Simulation, Projection, and Application

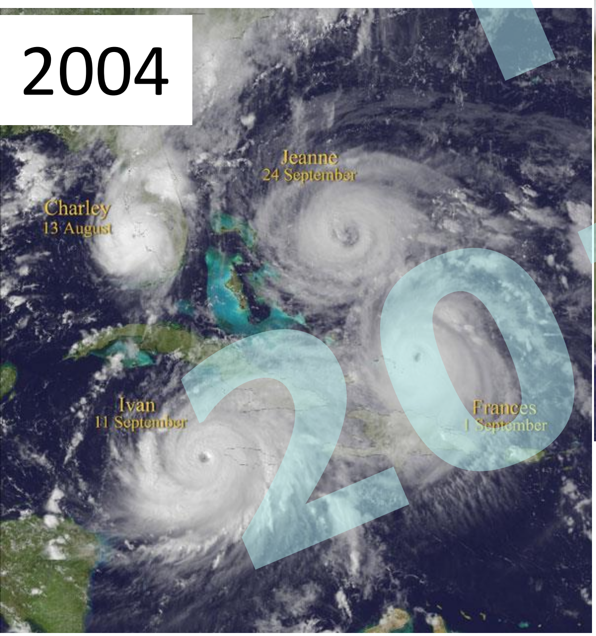
with Isaac Held, Shiann-Jiann Lin, and Gabriel Vecchi

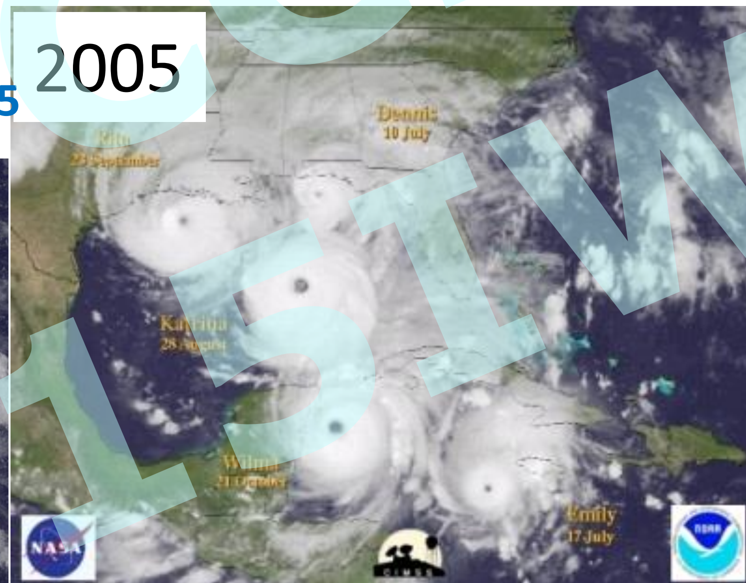
How may tropical cyclones respond to warming?

Knutson et. al 2010 (Nat. Geosci., WMO assessment)

Examples of most recent studies based on CMIP5:
Knutson et. al 2013 (J. Climate) – dynamical downscaling
Camargo 2013 (J. Climate) – explicit simulation and GPI/PI
Emanuel 2013 (PNAS) – simplified dynamical downscaling

Atlantic Tropical Cyclones
Composite for 2004 and 2005





It would be very difficult to answer it without using a high resolution GCM. Resolution is a key, although not the only key!

Challenges in modeling the TC-climate connections

Present-day simulations
(coupled or prescribed SSTs)

Evaluate simulated present-day variability in frequency, intensity, size/structure/energetics

Future projection simulations
(coupled or prescribed SSTs)

Understand the simulated changes in frequency, intensity and size/structure/energetics

Idealized models to improve our understanding

CHALLENGES:

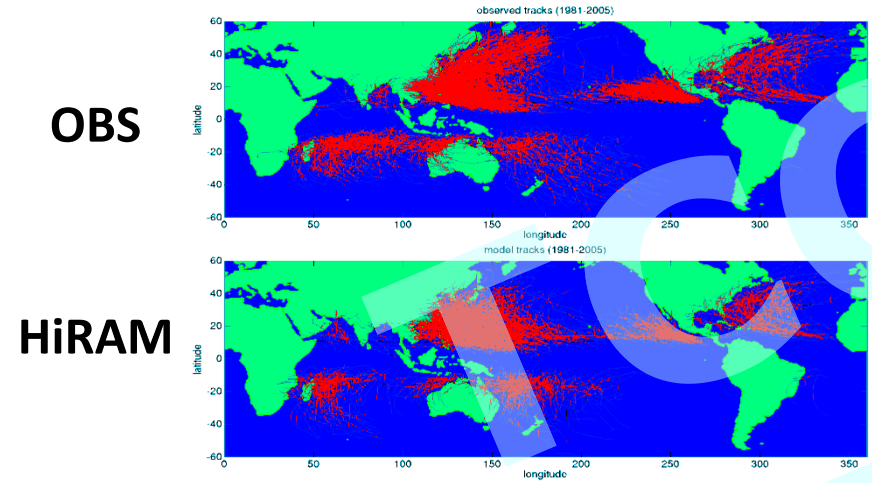
Resolution
Domain size
Integration length
Ensemble size
Physics complexity

COMPROMISE!

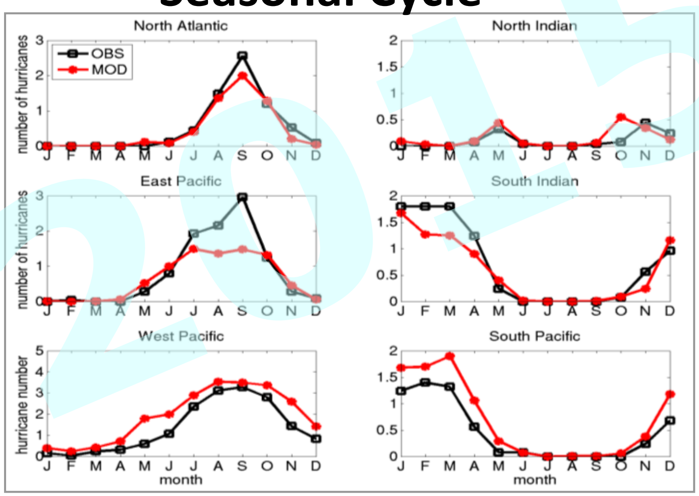
50km
Global
20-30 year
1-5 realization
AMIP + sim.physics
→ A 50km HIRAM

HIRAM simulated global hurricane climatology, seasonal cycle, inter-annual variability, and decadal trends (Zhao et. al 2009)

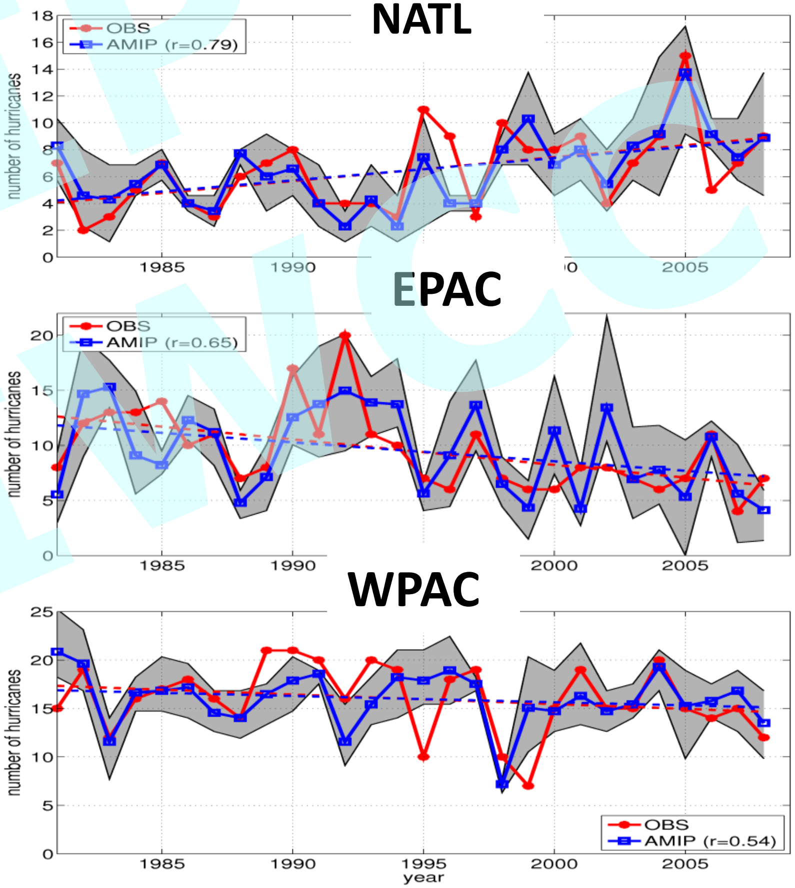
Hurricane Tracks (1981-2005)



Seasonal Cycle



Inter-annual variability



Red: observations

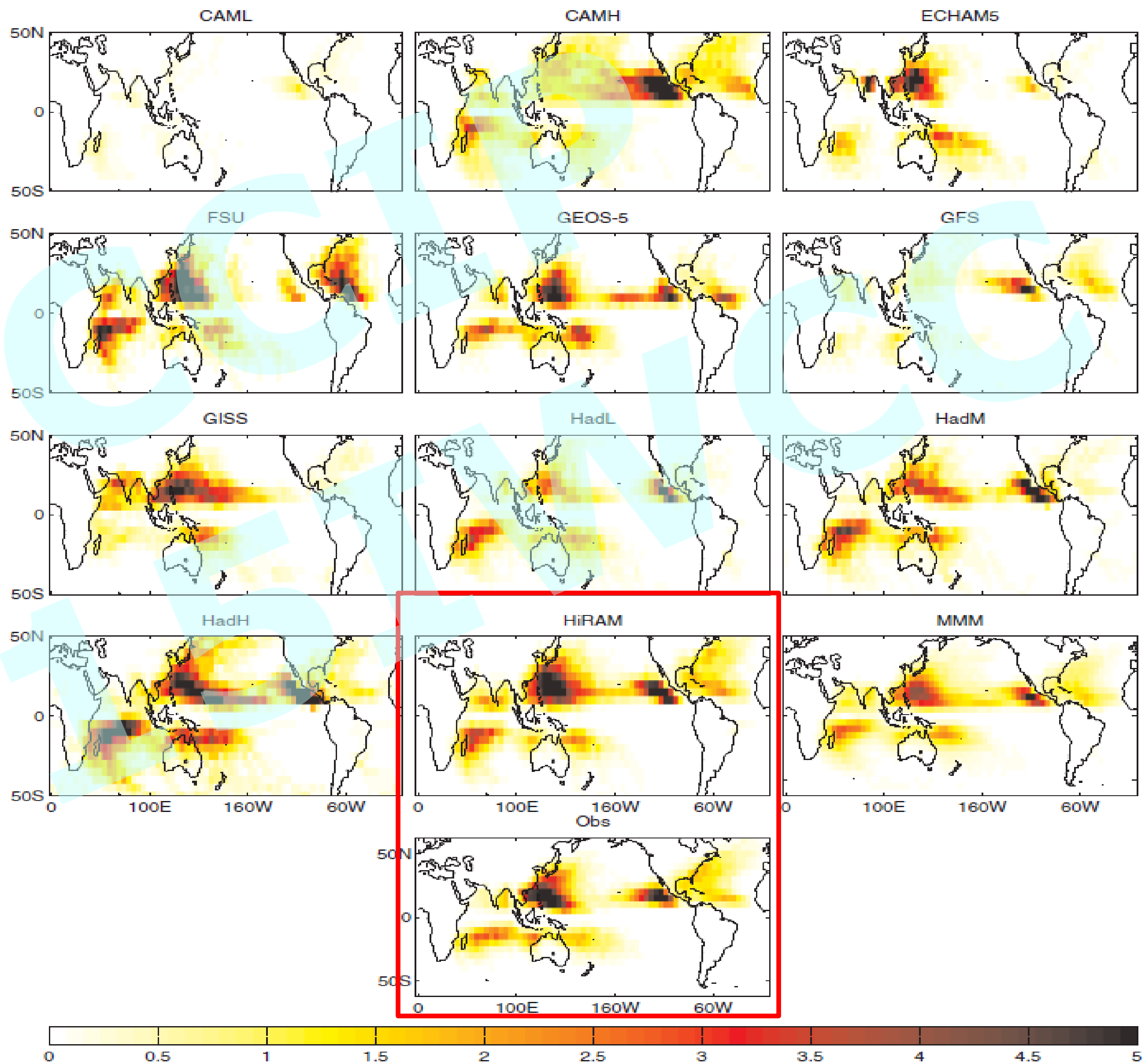
Blue: HiRAM ensemble mean

Shading: model spread

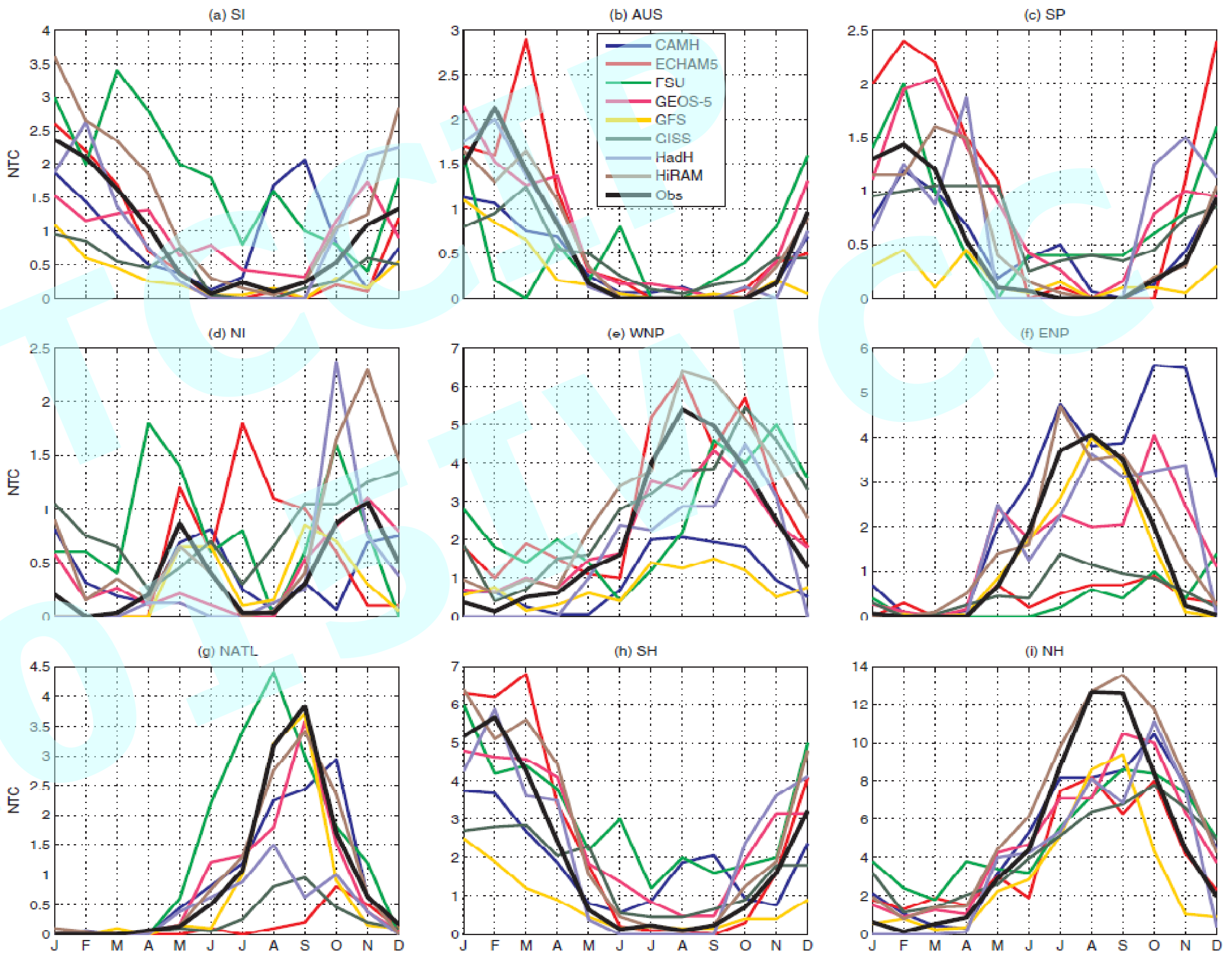
HIRAM performs well in the GCMs participating in the US CLIVAR Hurricane Working Group (Figure: for TC track density)

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."

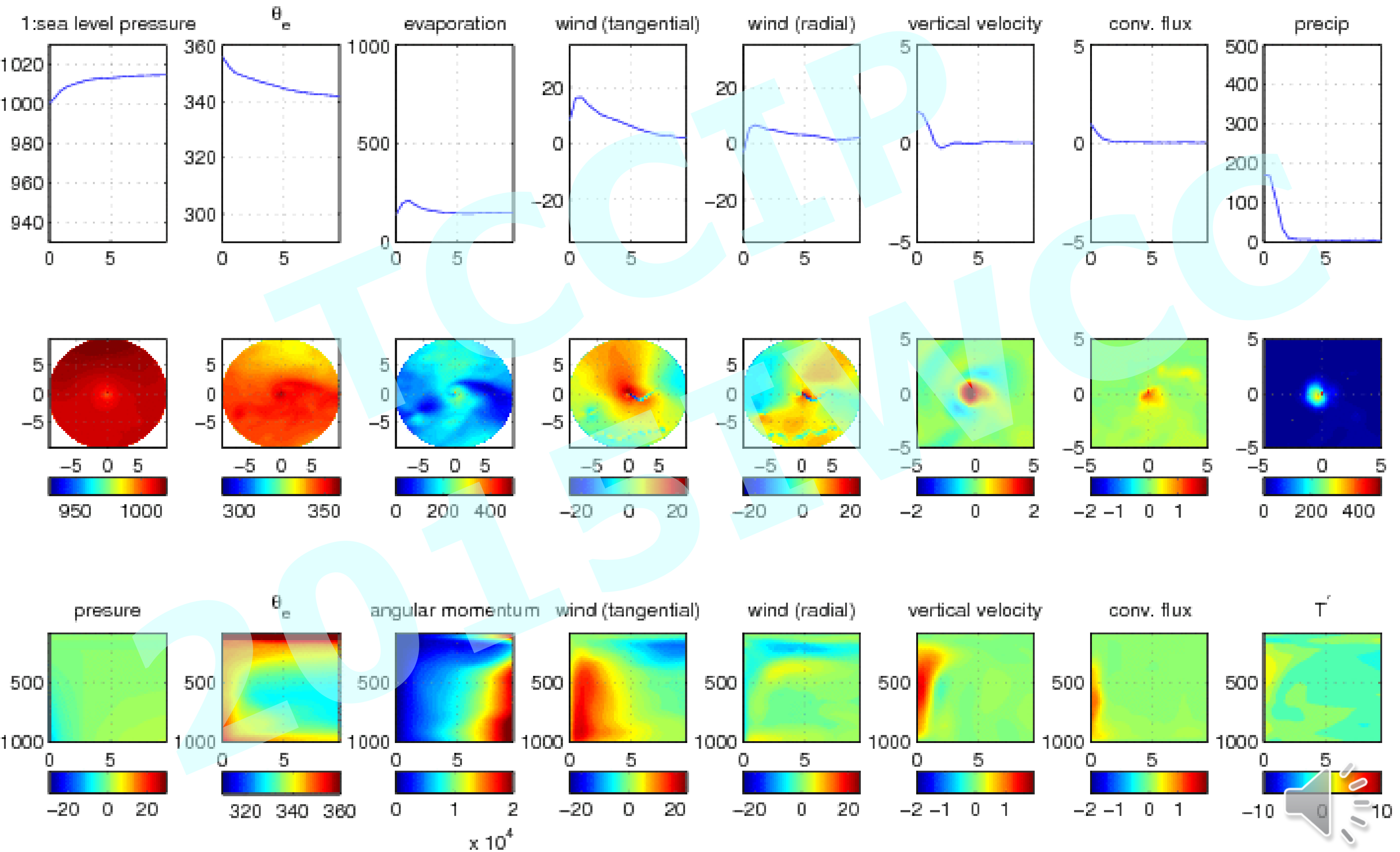


HIRAM performs well in the GCMs participating in the US CLIVAR Hurricane Working Group (Figure: seasonal cycle of TC frequency

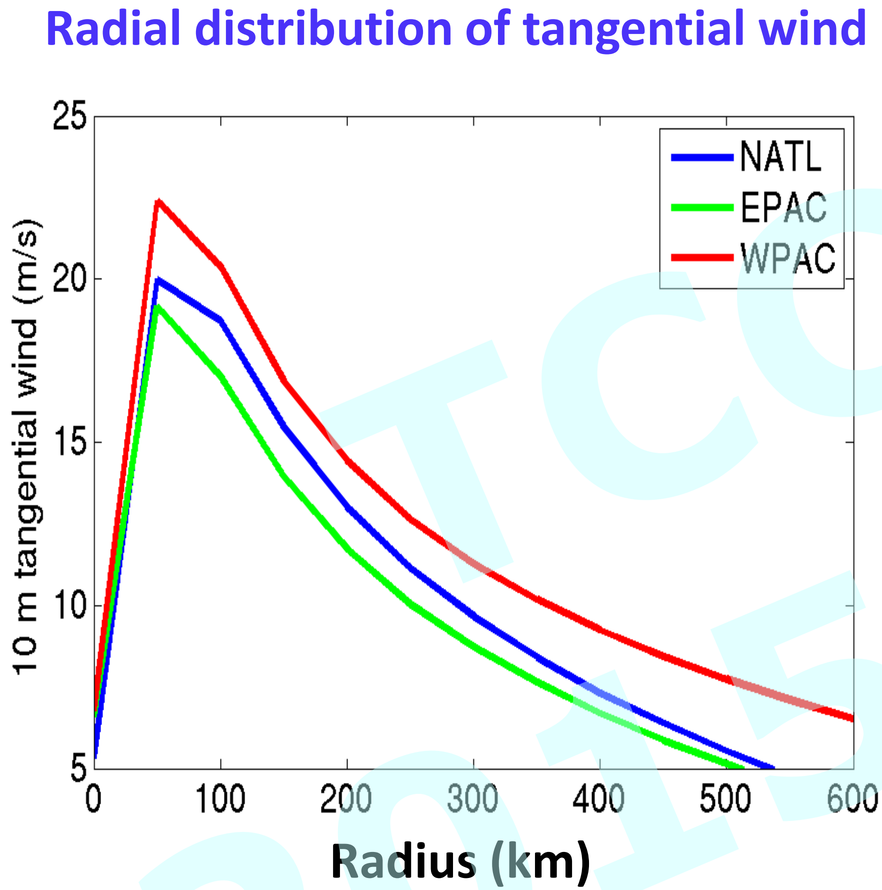


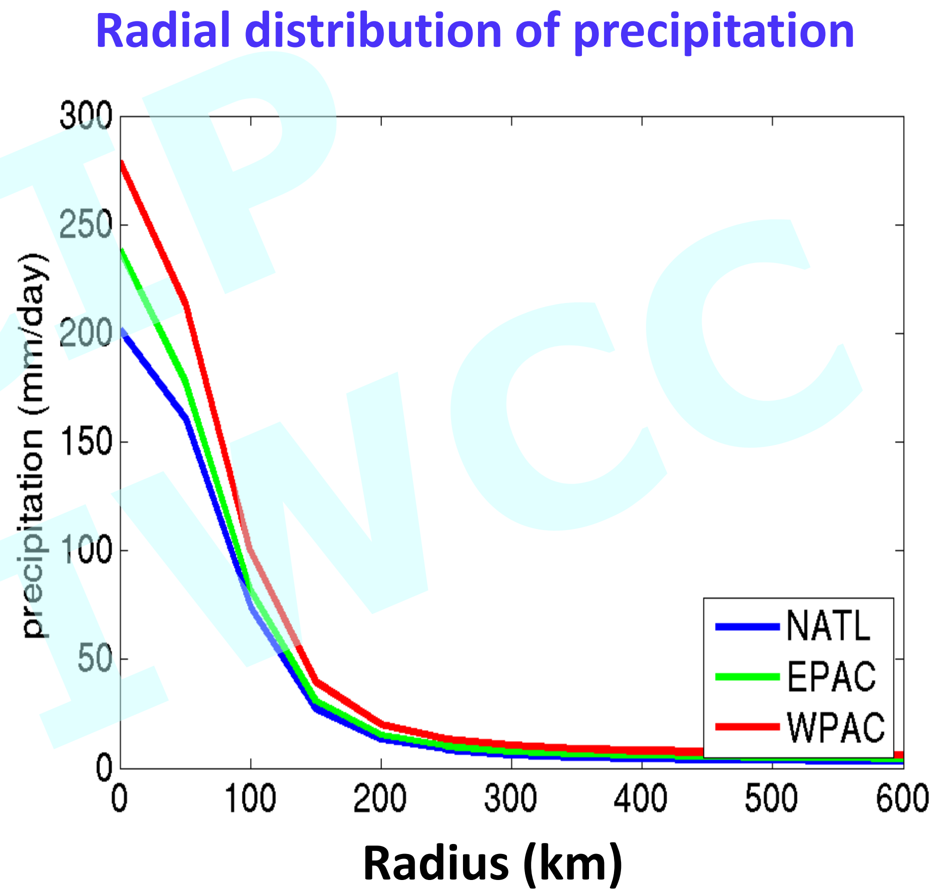
Shaevitz et. al
2014 JAMES

Animation of various dynamical and thermo-dynamical fields following a single TC simulated in a 50km HIRAM



TC size and precipitation statistics in a 50km HIRAM

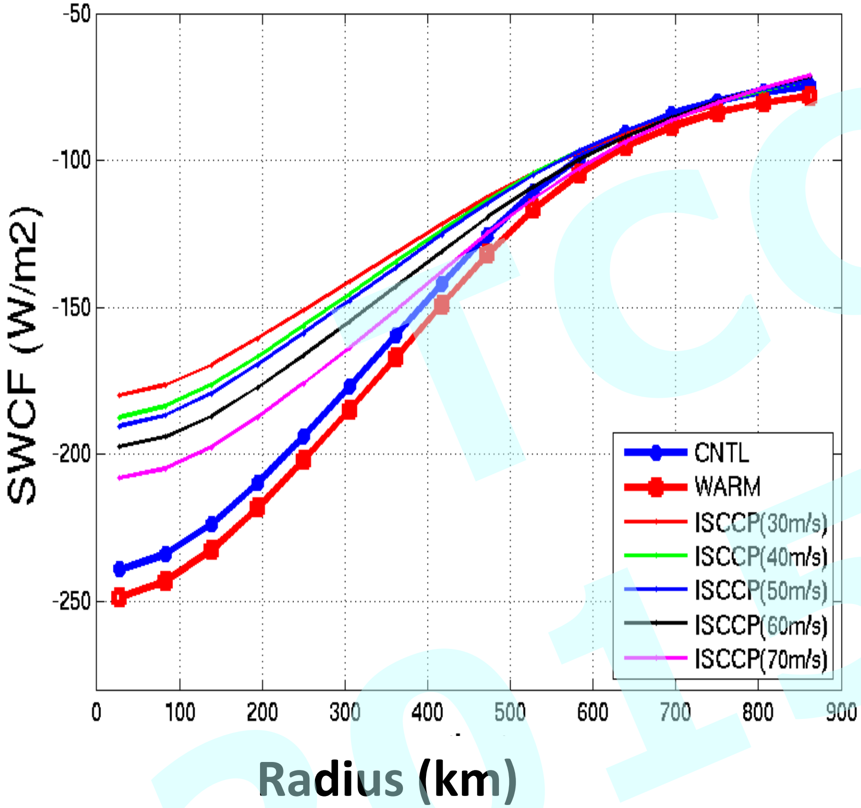




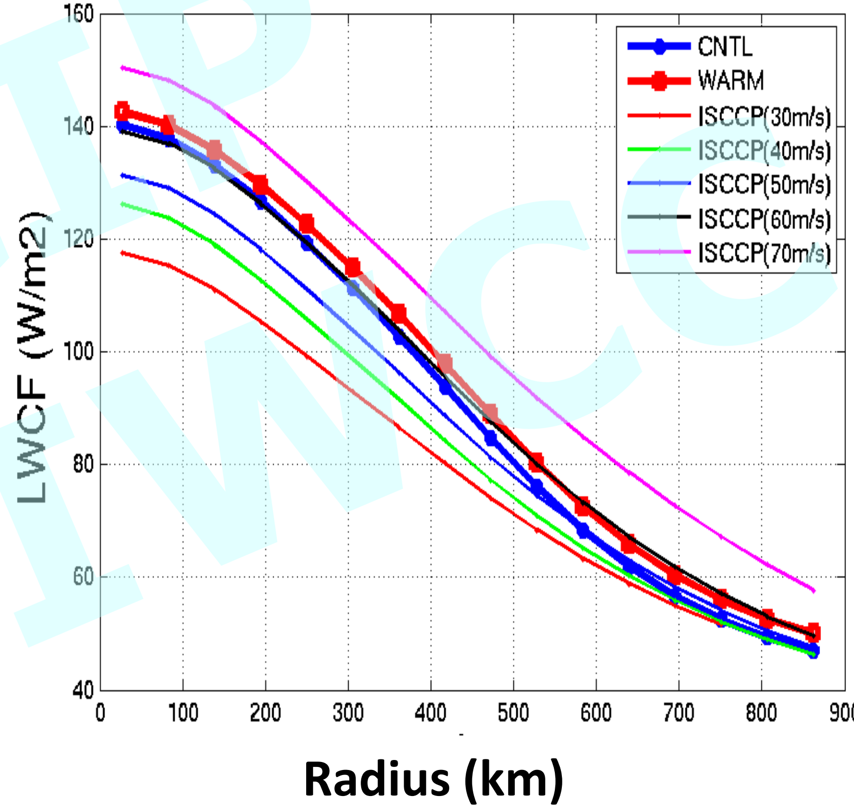
Fields averaged over all simulated TCs for the N. Atlantic, E. Pacific and W. Pacific basins. Model captures the geographical distribution of TC size and precipitation.

TC-associated cloud radiative effect in 50km HIRAM

SW cloud radiative effect



LW cloud radiative effect



Comparison of the 50km HIRAM simulated and ISCCP observed LW and SW cloud radiative effects associated with TCs

Key aspects of the HIRAM for realistic TC simulation

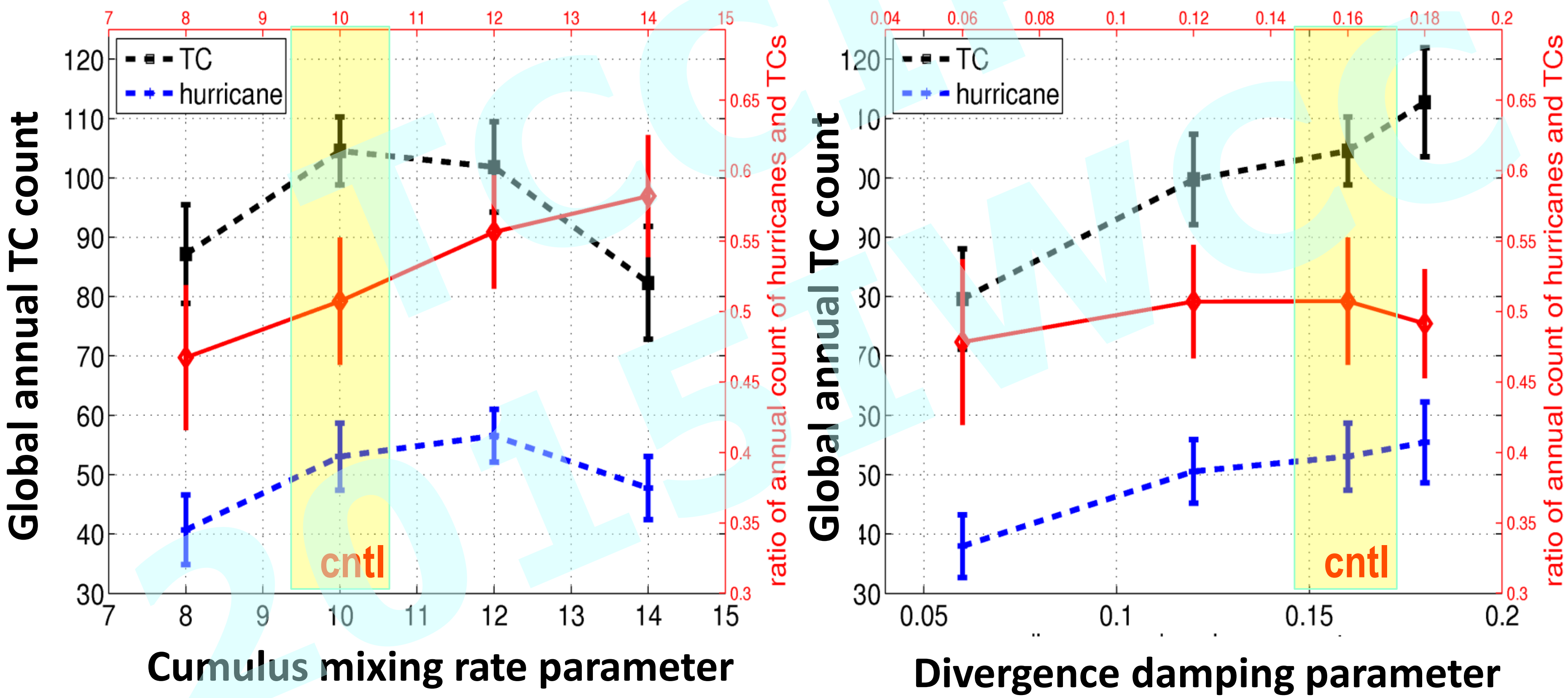
- Advanced finite volume cube-sphere dynamical core
- Less-intrusive convection scheme
  - better simulations of mean climate state and easterly waves
  - participating in IPCC AR5 high-res simulation

Why non-intrusive convection parameterization?

- More systematic avenue towards consistency and convergence as model resolution becomes finer.
- More realistic representation of organized convective system.
- More realistic representation of cloud precipitation microphysics.
- Enhanced tropical transient activity and tropical cyclones.
- Avoid many artifacts in deep convective parameterization.
- One can obtain a high quality simulation with such a scheme in an AGCM forced by observed SSTs.

Sensitivity of global TC frequency to cumulus entrainment rate and divergence damping parameters

Increasing cumulus mixing → **Increasing divergence damping** →



Zhao, Held and Lin 2012 (JAS)

Intensity issue and a statistical adjustment approach

Cumulative frequency distribution

$$F(I) = NP(I)$$

$$\delta F(I) \approx P(I)\delta N + N\delta P(I)$$

A match for model and observed storm life-time maximum wind speed based on equal probability

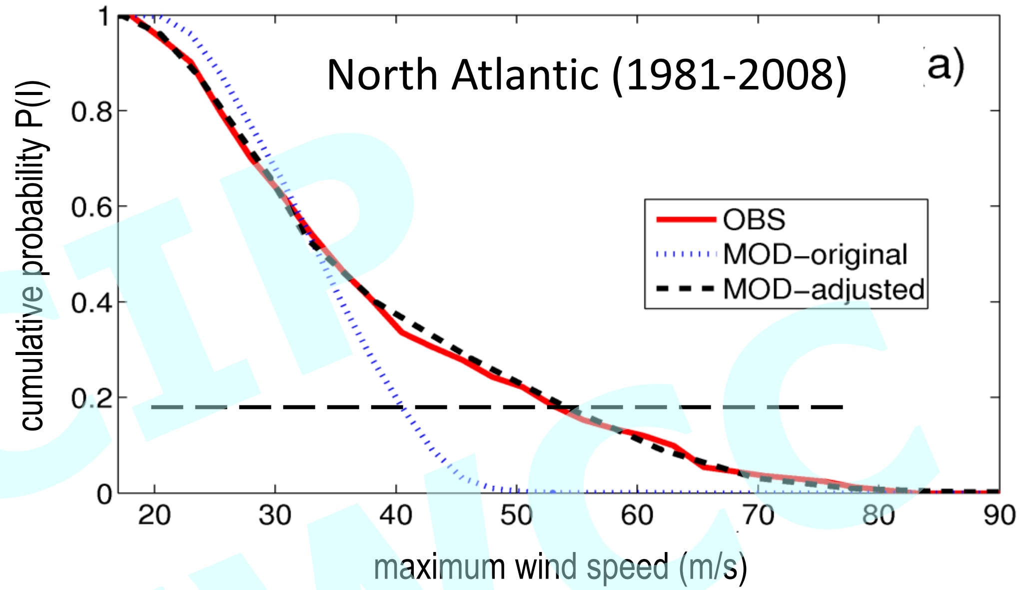
The derived maximum wind speed relationship is approximately bi-linear

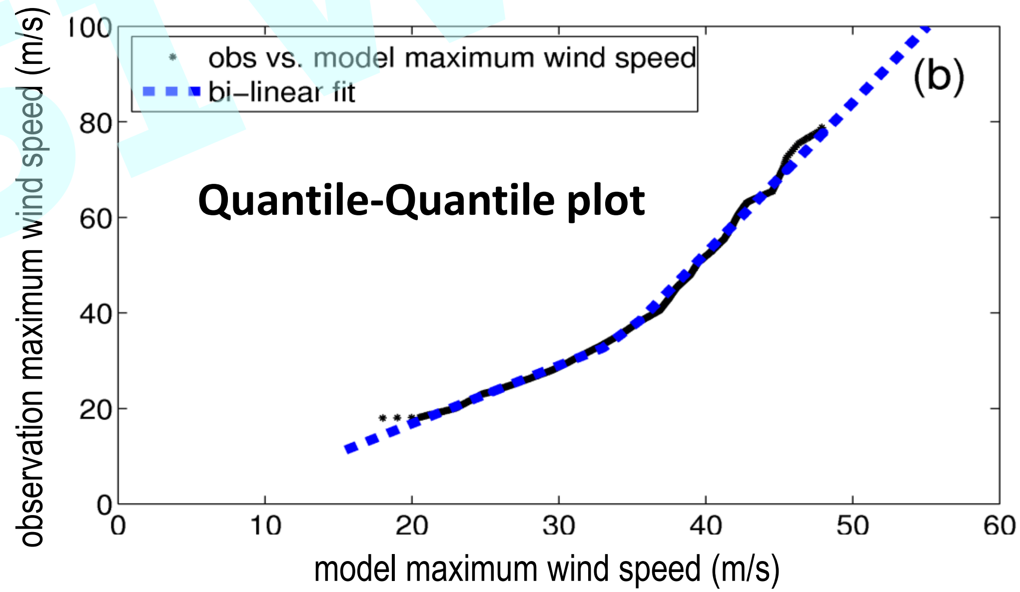
$$I_{fit} = I_T + \alpha(I_{GCM} - I_T); I_{GCM} \le I_T$$

$$I_{fit} = I_T + \beta(I_{GCM} - I_T); I_{GCM} > I_T$$

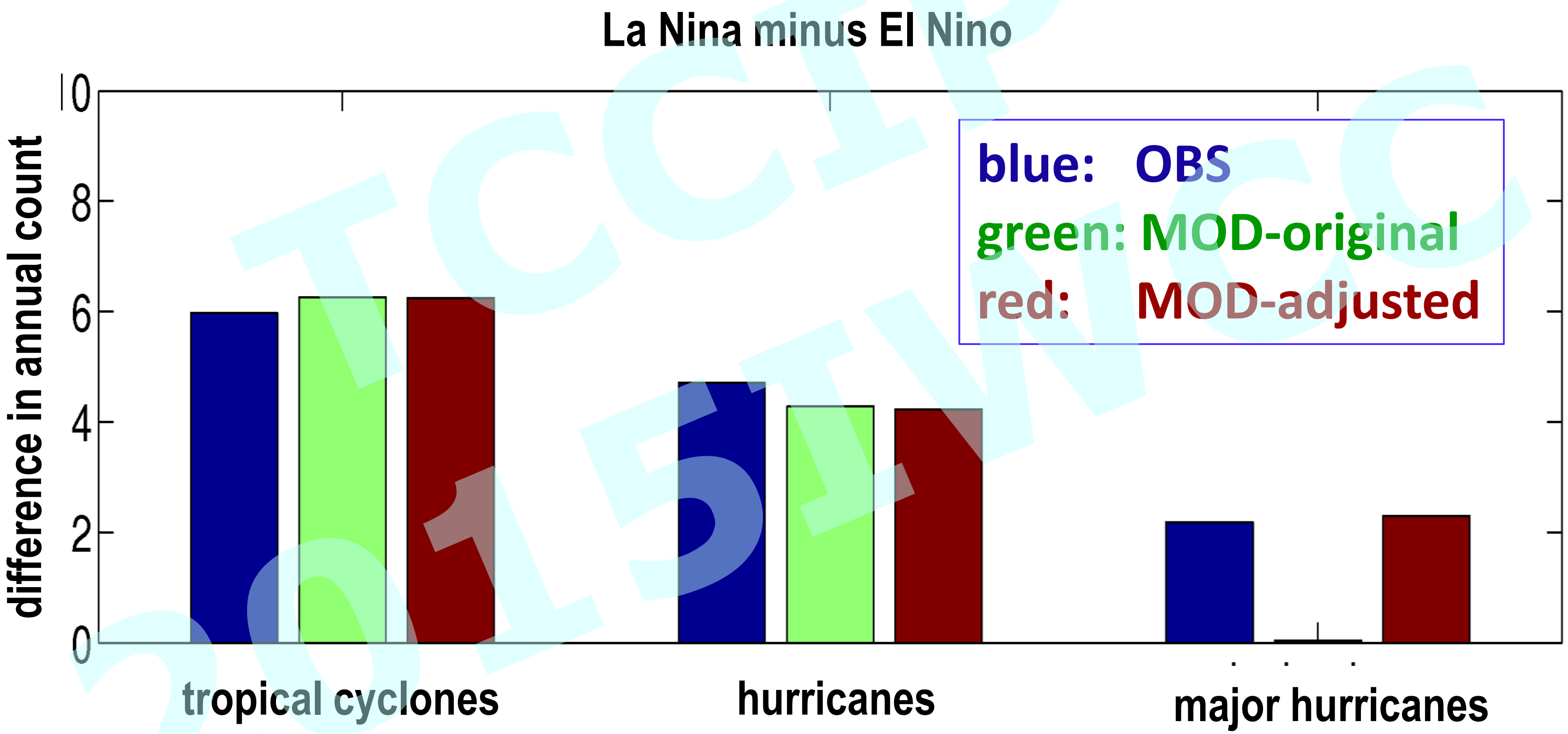
$$\alpha = 1.22; \beta = 3.15; I_T = 34 m/s$$

Zhao and Held 2010, J. Climate





The simple statistical adjustment allows the model to capture variability of Atlantic major hurricanes



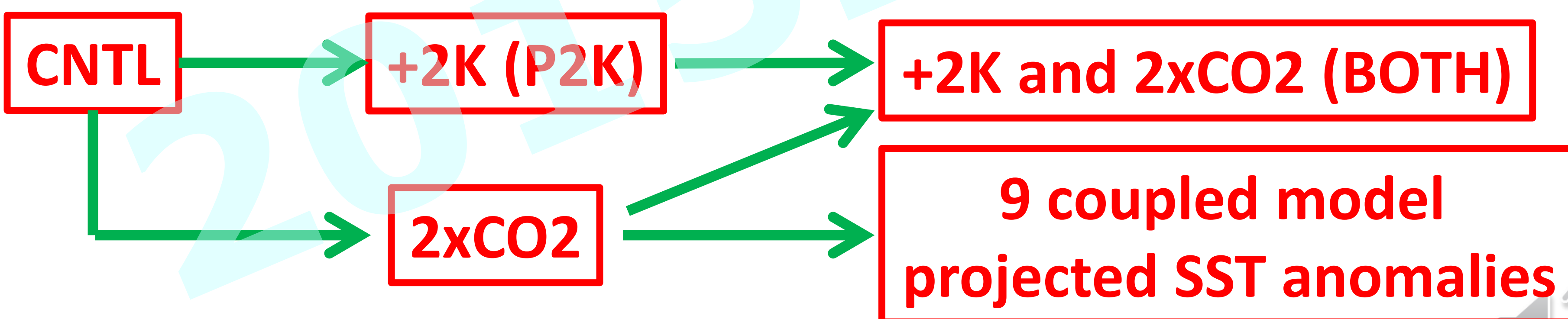
Zhao and Held 2010, J. Climate

Projections for future TC frequency

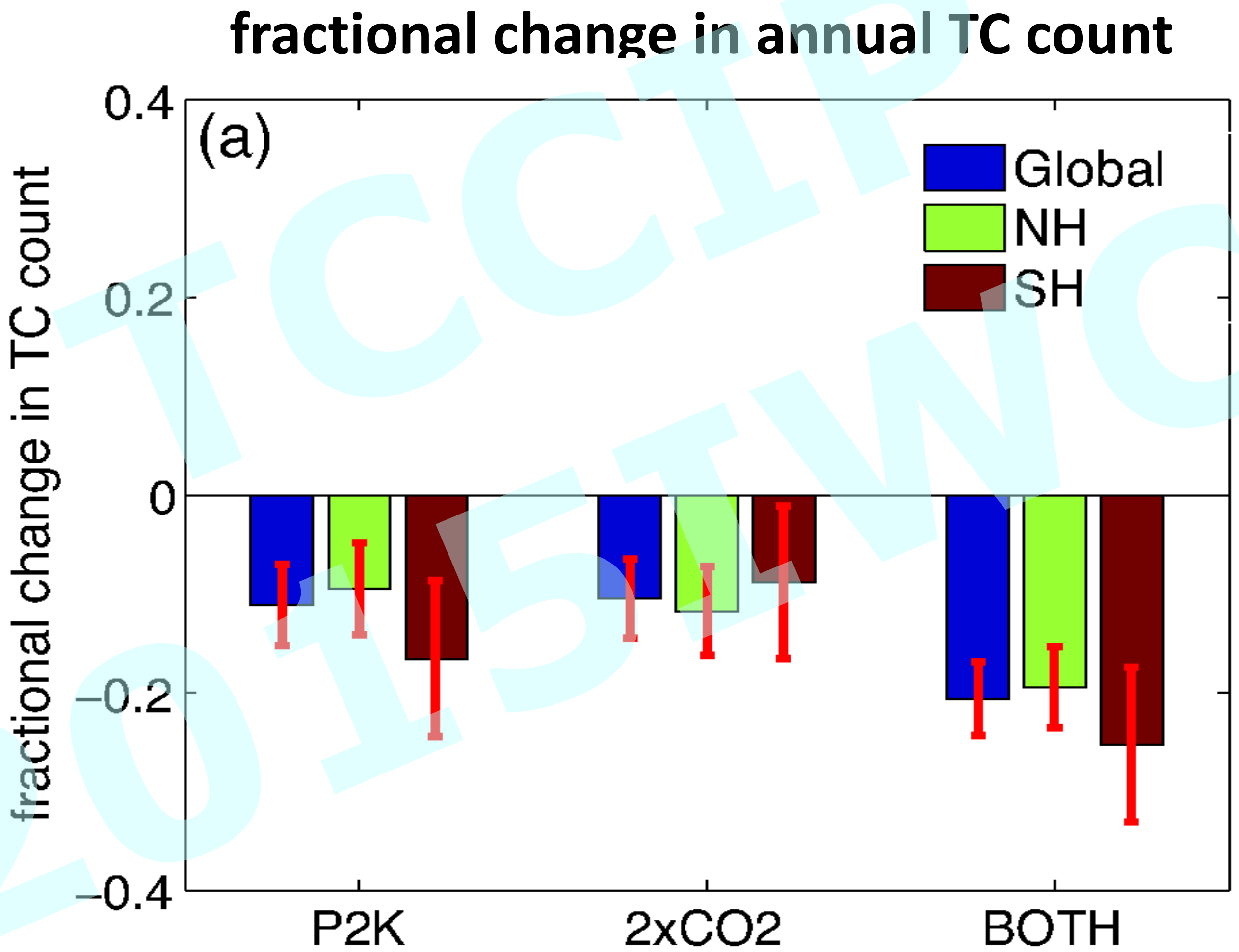
Future projections using a time slice method

$$\delta N = \underbrace{\frac{\partial N}{\partial GHG}\delta GHG}_{(1)} + \underbrace{\frac{\partial N}{\partial \overline{SST}}\delta \overline{SST}}_{(2)} + \underbrace{\frac{\partial N}{\partial RSST}\delta RSST}_{(3)}$$

1. Response to changes in greenhouse gases δGHG
2. Response to changes in global tropical mean SST $\delta \overline{SST}$
3. Response to changes in relative SST (RSST) $\delta RSST$

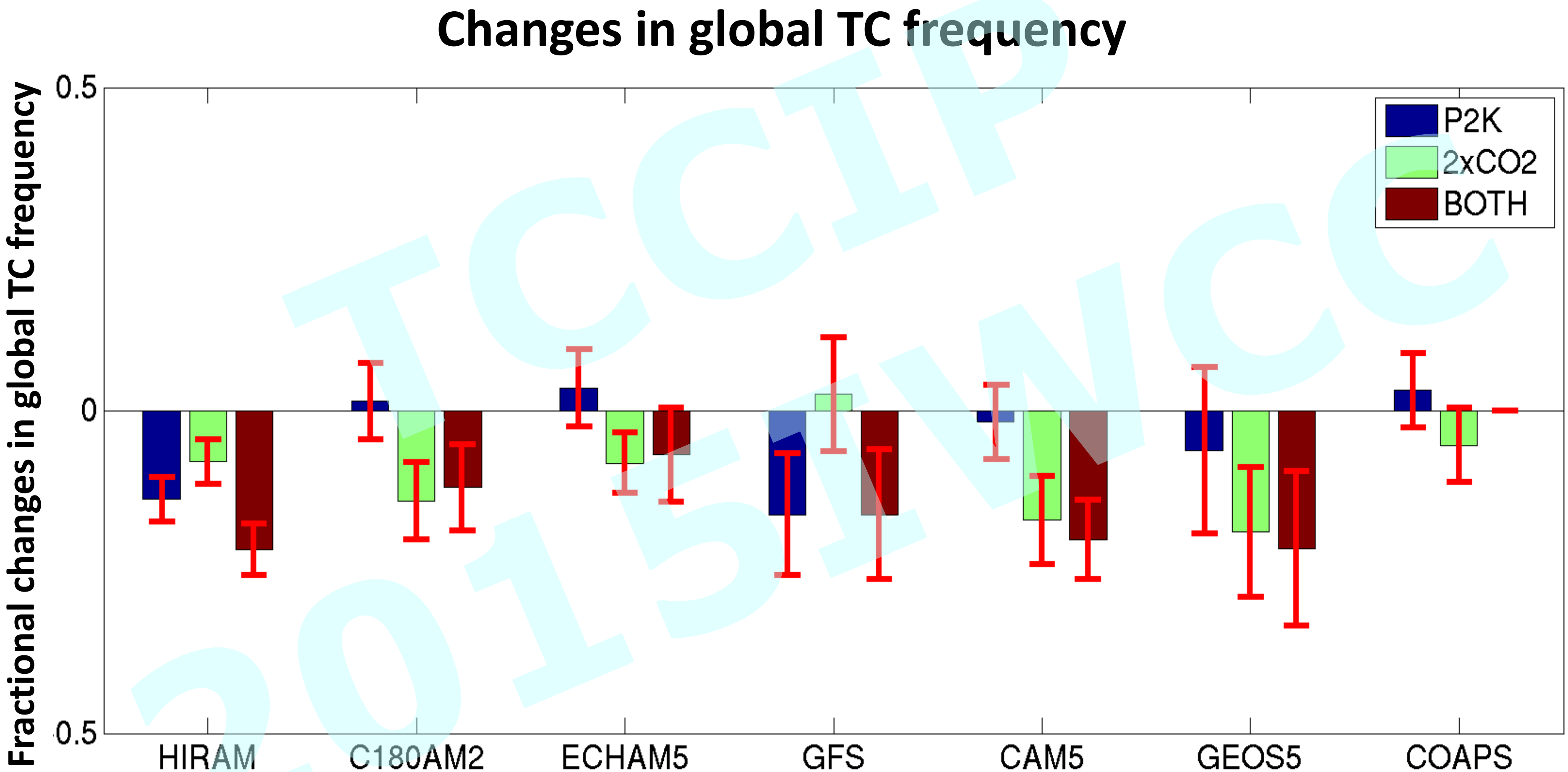


Global TC frequency response to uniform 2 degree SST warming and doubling of atmospheric CO2 concentration



Sugi and Yoshimura 2004, Held and Zhao 2011, J Climate

Global TC frequency response to 2K SST warming and CO2 doubling from the US CLIVAR HWG models



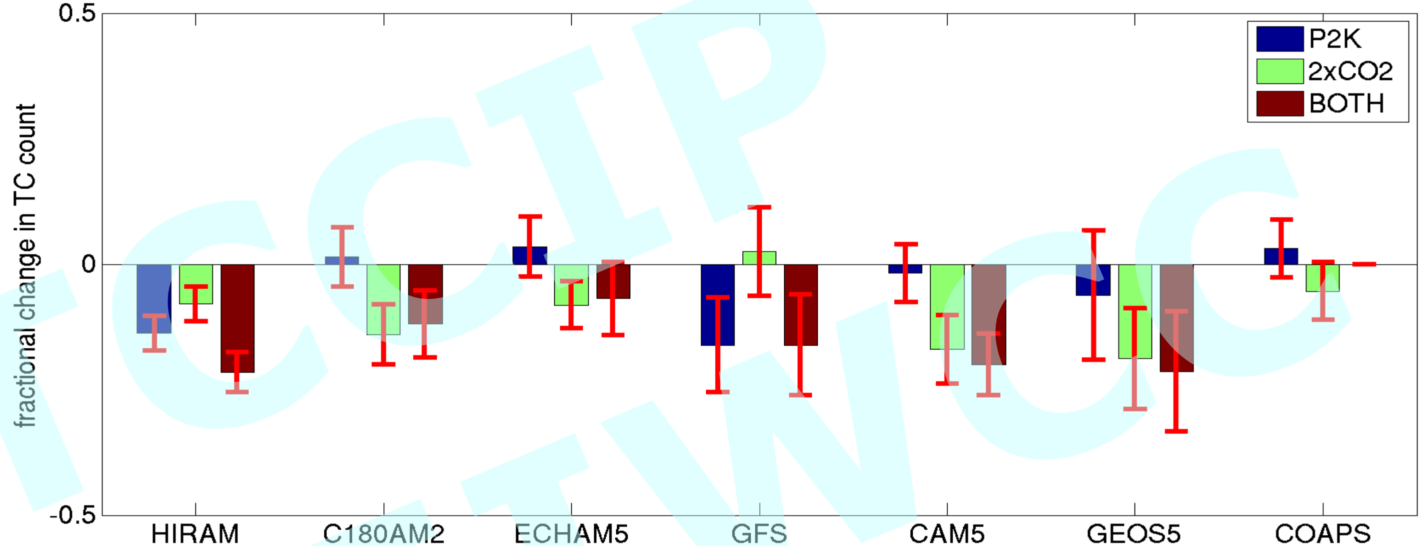
Zhao et. al 2013, CLIVAR newsletter

Mid-tropospheric convective mass flux best explains the simulated TC frequency response for most HWG models

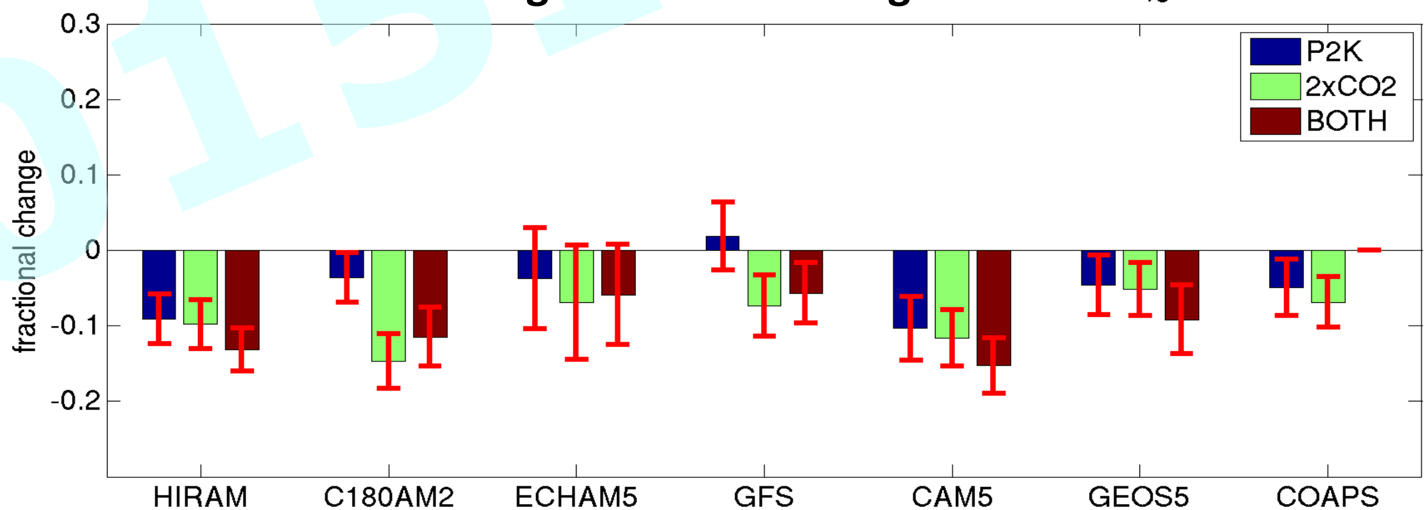
Zhao et. al 2013, CLIVAR newsletter

An index for seasonal-scale convective mass flux measured by 500mb omega weighted by TC genesis frequency from the control simulation

Changes in global TC frequency



Changes in 500mb omega



Mechanisms for global mean reduction

Future projections

$$\delta N = \frac{\partial N}{\partial GHG}\delta GHG + \frac{\partial N}{\partial \overline{SST}}\delta GSST + \frac{\partial N}{\partial RSST}\delta RSST\,(x,y)$$

$$= \frac{\partial N}{\partial M_c}\boxed{\frac{\partial M_c}{\partial GHG}\delta GHG} + \frac{\partial N}{\partial M_c}\boxed{\frac{\partial M_c}{\partial \overline{SST}}\delta GSST} + \frac{\partial N}{\partial M_c}\boxed{\frac{\partial M_c}{\partial RSST}\delta RSST\,(x,y)}$$

$\delta M_c \downarrow$ GLOBAL $\qquad \delta M_c \downarrow$ GLOBAL $\qquad \delta M_c \downarrow\uparrow$ REGIONAL

$$P = M_c q_b \Rightarrow \frac{\delta M_c}{M_c} = \frac{\delta P}{P} - \frac{\delta q_b}{q_b} = \frac{\delta Q_{rad}}{Q_{rad}} - \frac{\delta q_b}{q_b} < 0$$

Held & Soden (2006)

δM_c is non-uniform, monsoonal-like response may be important, significant precipitation move from ocean to land for 2xCO_2 case and opposite for the +2K case, causing more uncertainty across models

Zhao et. al 2013, CLIVAR newsletter

Regional TC frequency response to coupled model projected 21st century warming

Key points:

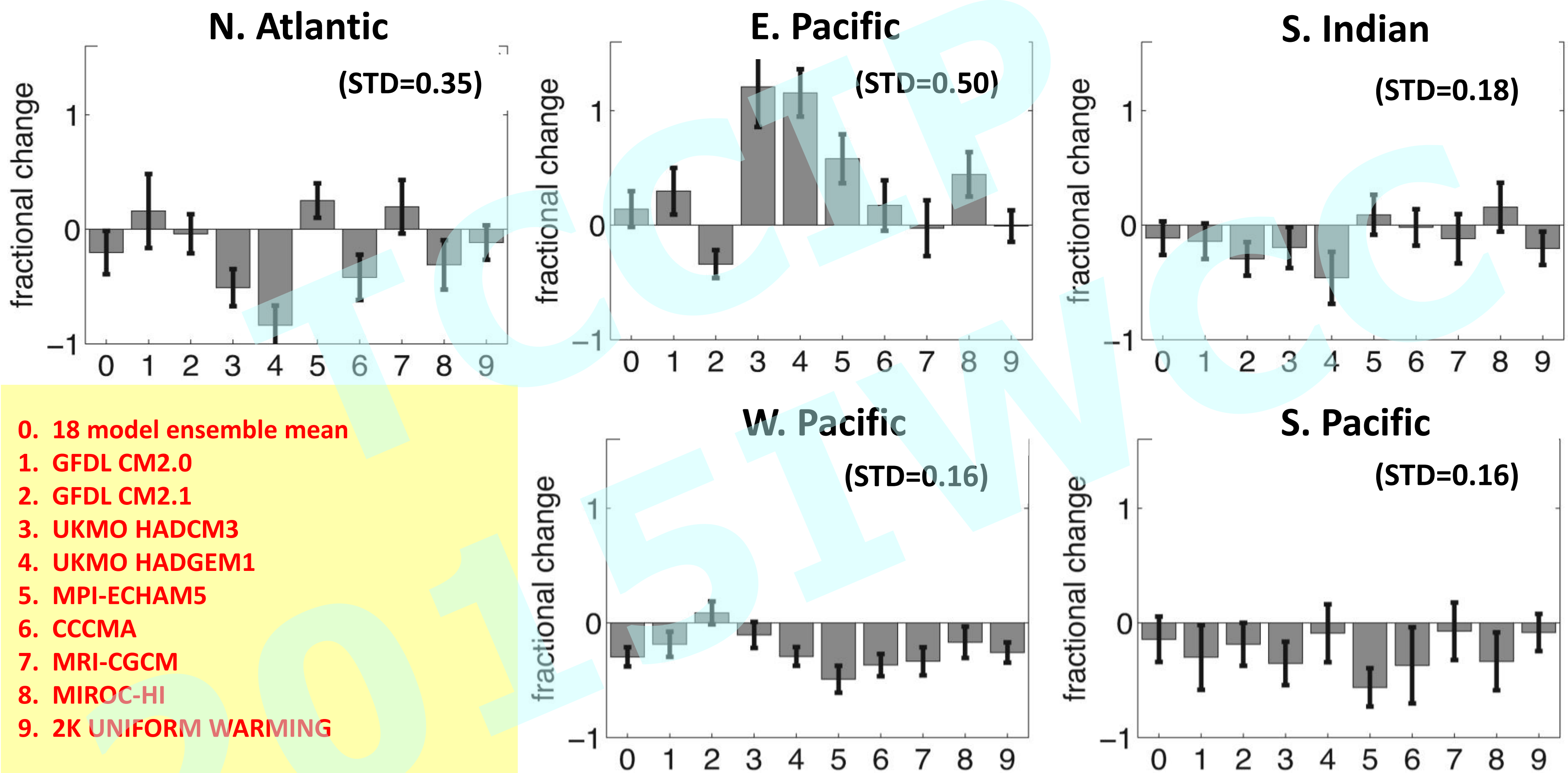
- Quantify the uncertainty due to spatial pattern of SST warming?
- What features of SST distributions are important?
- Atmospheric mechanisms that translate the SSTs into processes that directly control regional TC activities?

SST warming anomalies:

0. 18 model ensemble mean
1. GFDL CM2.0
2. GFDL CM2.1
3. UKMO HADCM3
4. UKMO HADGEM1
5. MPI-ECHAM5
6. CCCMA
7. MRI-CGCM
8. MIROC-HI
9. 2K UNIFORM WARMING

CO2 is doubled for all cases

HiRAM simulated hurricane frequency response to 21st century warming projected by IPCC AR4 coupled models



For each basin, there is large inter-model spread in the magnitude and even the sign of the hurricane frequency response. The differences are entirely due to the different SST projections. *(Zhao and Held, 2012, J. Climate)*

Indices of SSTs and atmospheric properties relevant to hurricane genesis frequency

SSTs → **atmospheric properties** → **hurricanes**

$RSST(m, x, y)$: **relative SST = local – tropical mean SST**

$$\overline{RSST}(x, y) = \frac{\sum_m RSST(m, x, y) G(m, x, y)}{\sum_m G(m, x, y)}$$

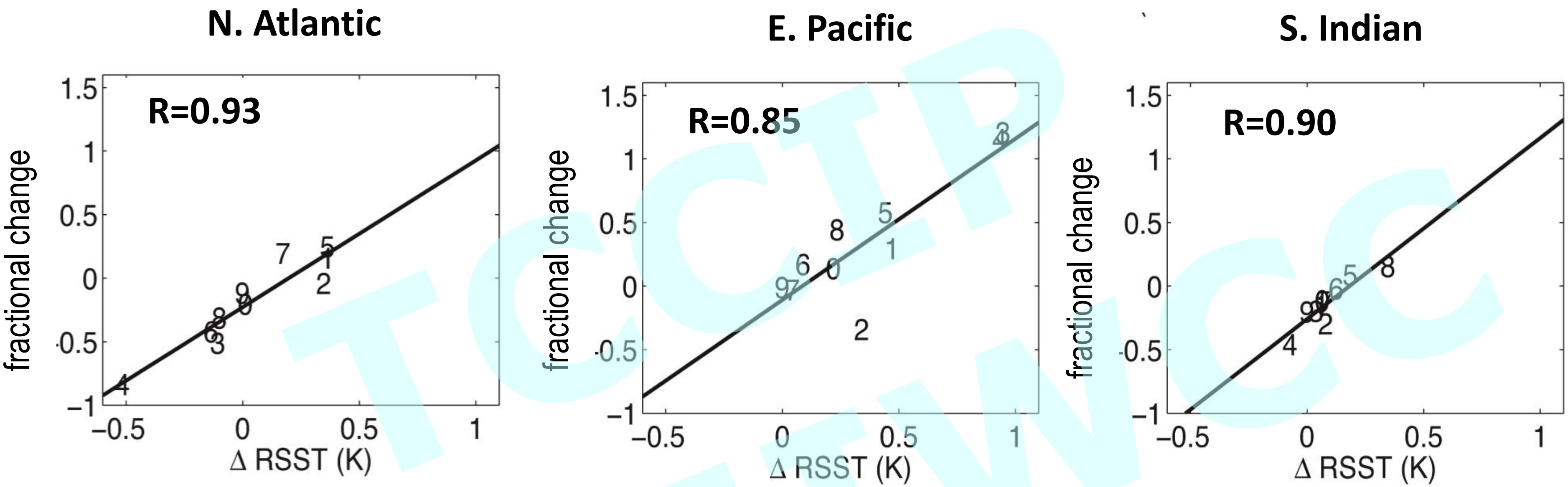
$G(m, x, y)$: climatological storm genesis frequency from the control simulation. *m* = 1-12, *x* = lon, *y* = lat

monthly data used for calculating indices

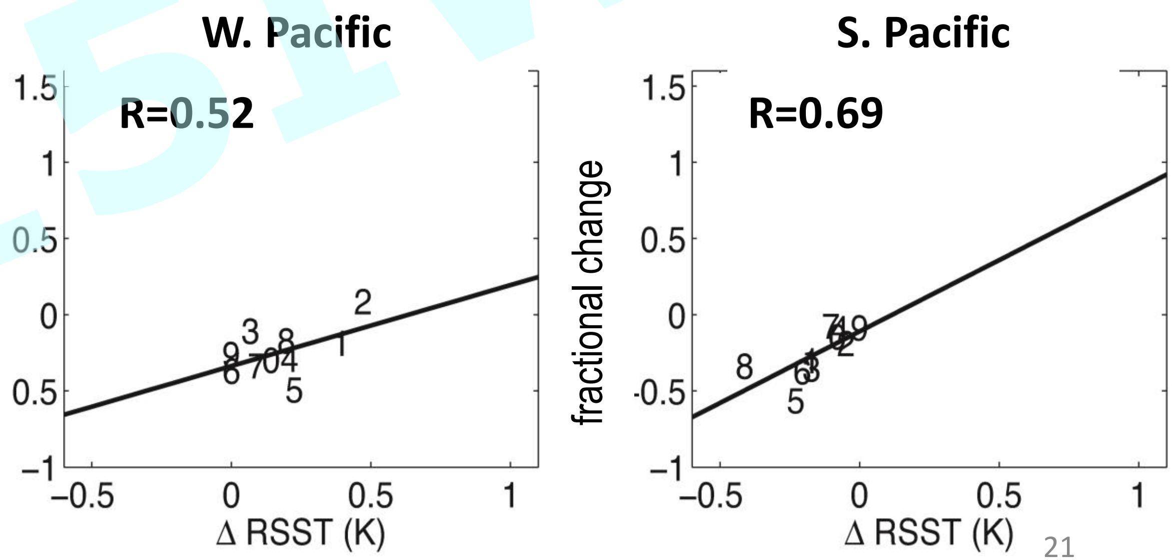
$\omega_{500}(m, x, y)$: **mid-troposphere vertical velocity**

(Zhao and Held, J. Climate 2012)

Most inter-model variation can be explained by the simple relative SST index in the N. Atlantic, E. Pacific and S. Indian



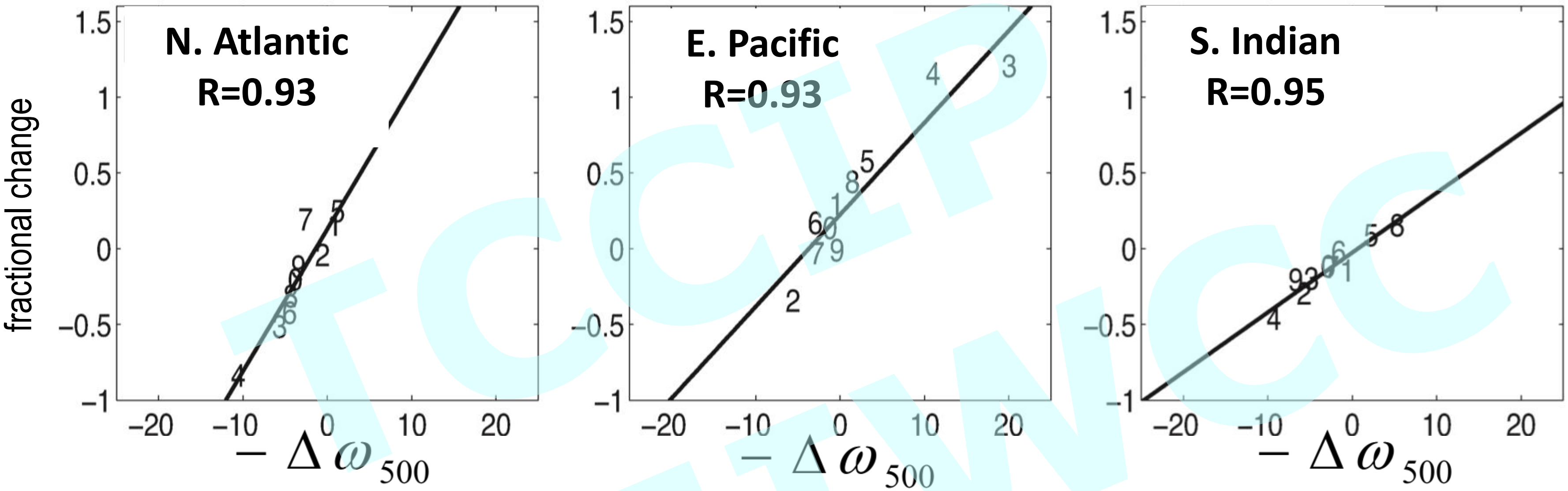
Scatter plots of fractional change in hurricane count vs change in relative SST

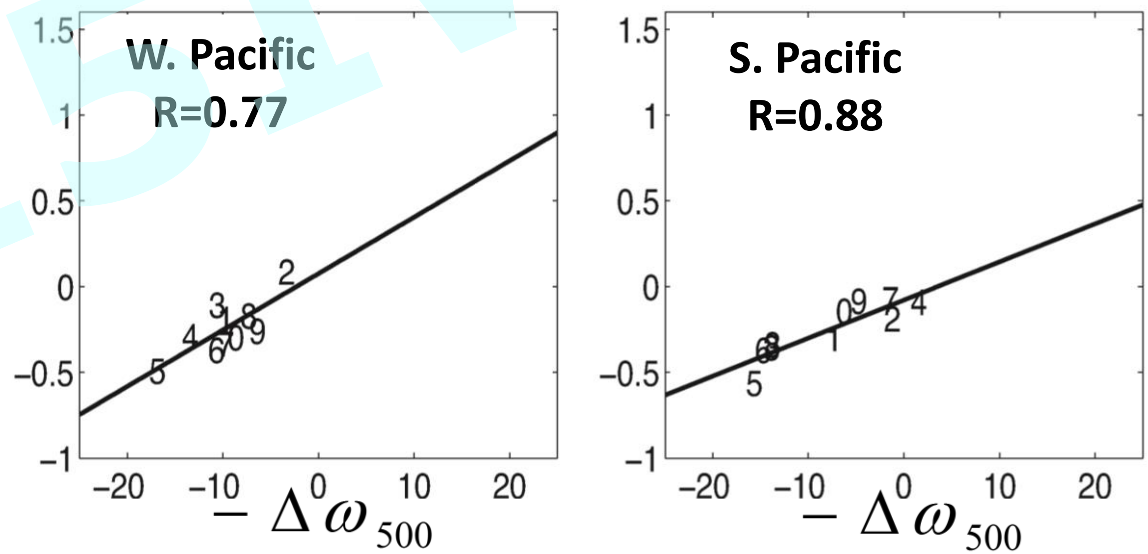


R: correlation coefficient

(Zhao and Held, 2012, J. Climate)

Mid-tropospheric vertical velocity is skillful in explaining the simulated hurricane response for all basins





Scatter plots of fractional change in hurricane count vs change in mid-troposphere vertical velocity (hPa/day).

R: correlation coefficient

(Zhao and Held, 2012, J. Climate)

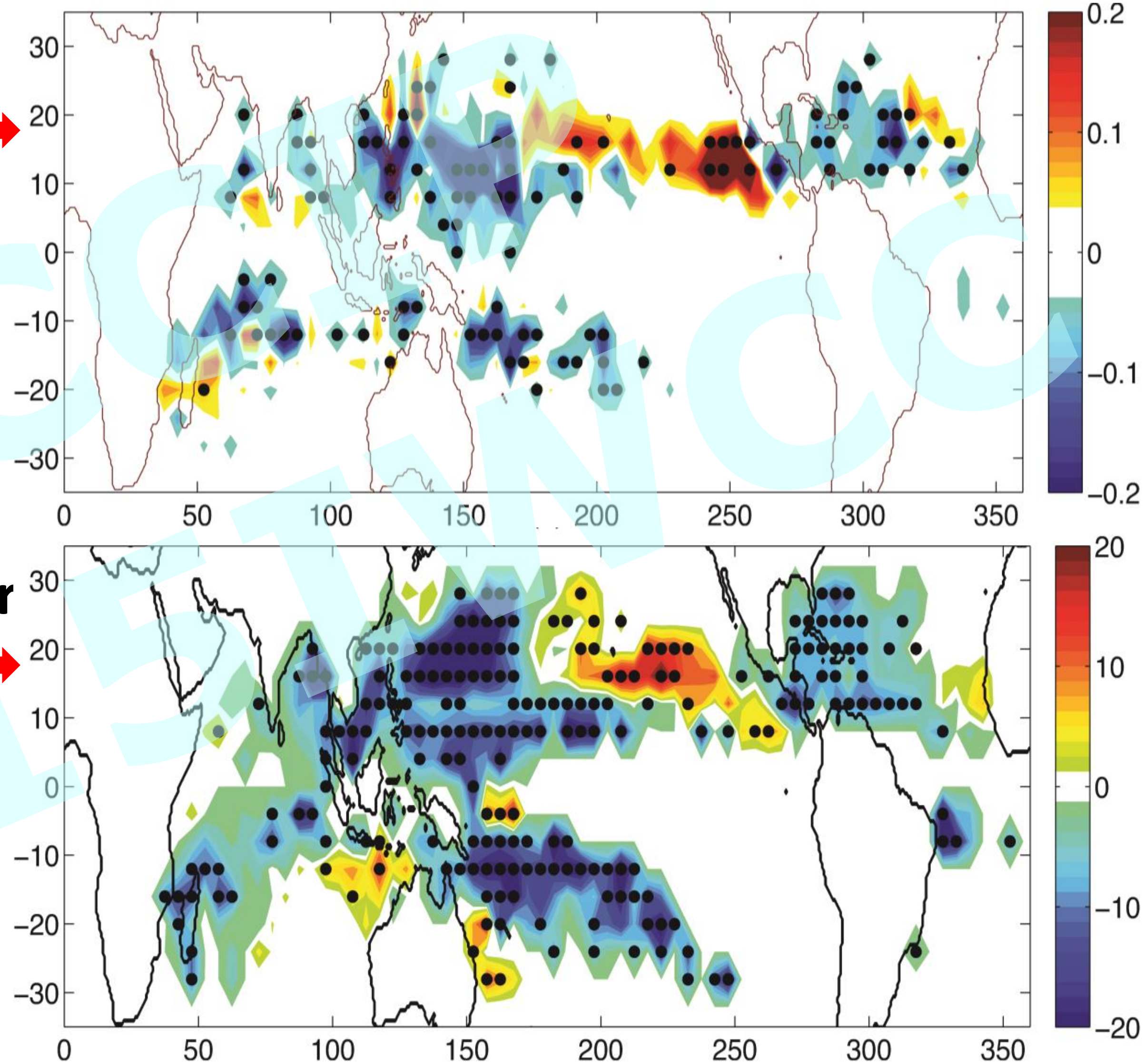
The eastward migration of TC genesis frequency can be explained by changes in mid-troposphere vertical velocity

change in hurricane genesis frequency

(unit: #/year/4°x5°)

change in mid-tropospher vertical velocity

Color: average from 8 individual models; stipple: area where 6 out of the 8 models agree on the sign of change. (unit: hPa/day)



Summary

A 50km HiRAM forced by the observed SSTs appears to realistically simulate many aspects of TC frequency variability. The advanced dynamical core and convection representation are key toward the success. The results further suggest:

- decoupling between simulations of TC frequency and intensity
- strong relationship between SST and TC frequency variability
- justifying time-slice method for studying future change in TC frequency

For future TC change, it is useful to decompose total response into 3 components: changes due to 1) GHG increase, 2) global mean SST increase, 3) changes in spatial pattern of SSTs. Results suggest:

- Robust reduction in global mean frequncy to GHG increase
- Less robust reduction in global TC count to global mean SST warming
- Large uncertainties at basin scale due to different SST pattern change.

All 3 aspects of the response suggest the importance of changes in large-scale convective overturning motion in predicting TC responses.

End

HIRAM performs well in the GCMs participating in the US CLIVAR Hurricane Working Group (Figure: TC genesis density)

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."