Prediction, Projection, and Attribution Study for Tropical Cyclones Using GFDL Global Climate Model

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GFDL/Princeton AOS

Topics

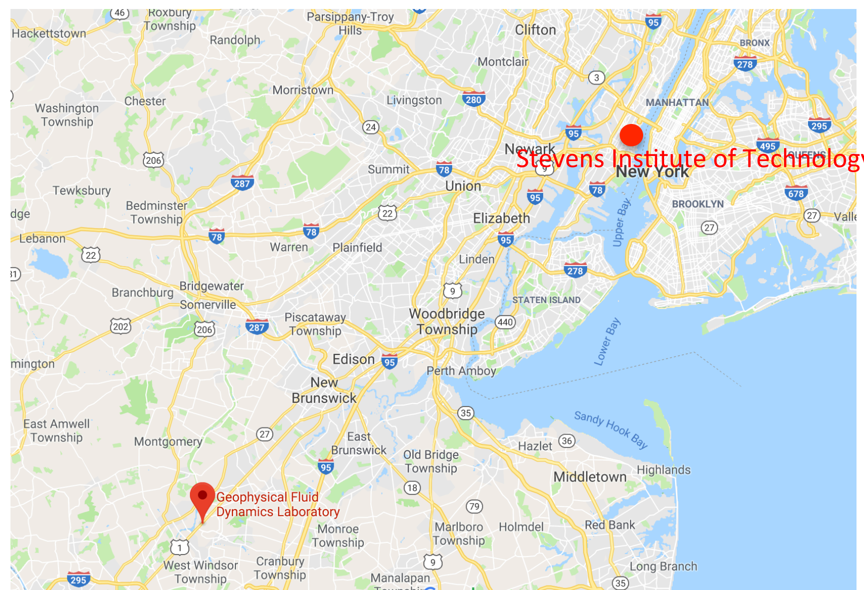
- About GFDL
- Part 1. Model Performance and Future Projections for Tropical Cyclones (TCs)
  - ➢ Interannual variations, TC Intensity — *Murakami et al. (2015, J. Climate)*
  - ➢ Sensitivities of TCs to 2xCO2 — *Vecchi et al. (in revision, Clim. Dyn.)*

    Bhatia et al. (2018, J. Climate)

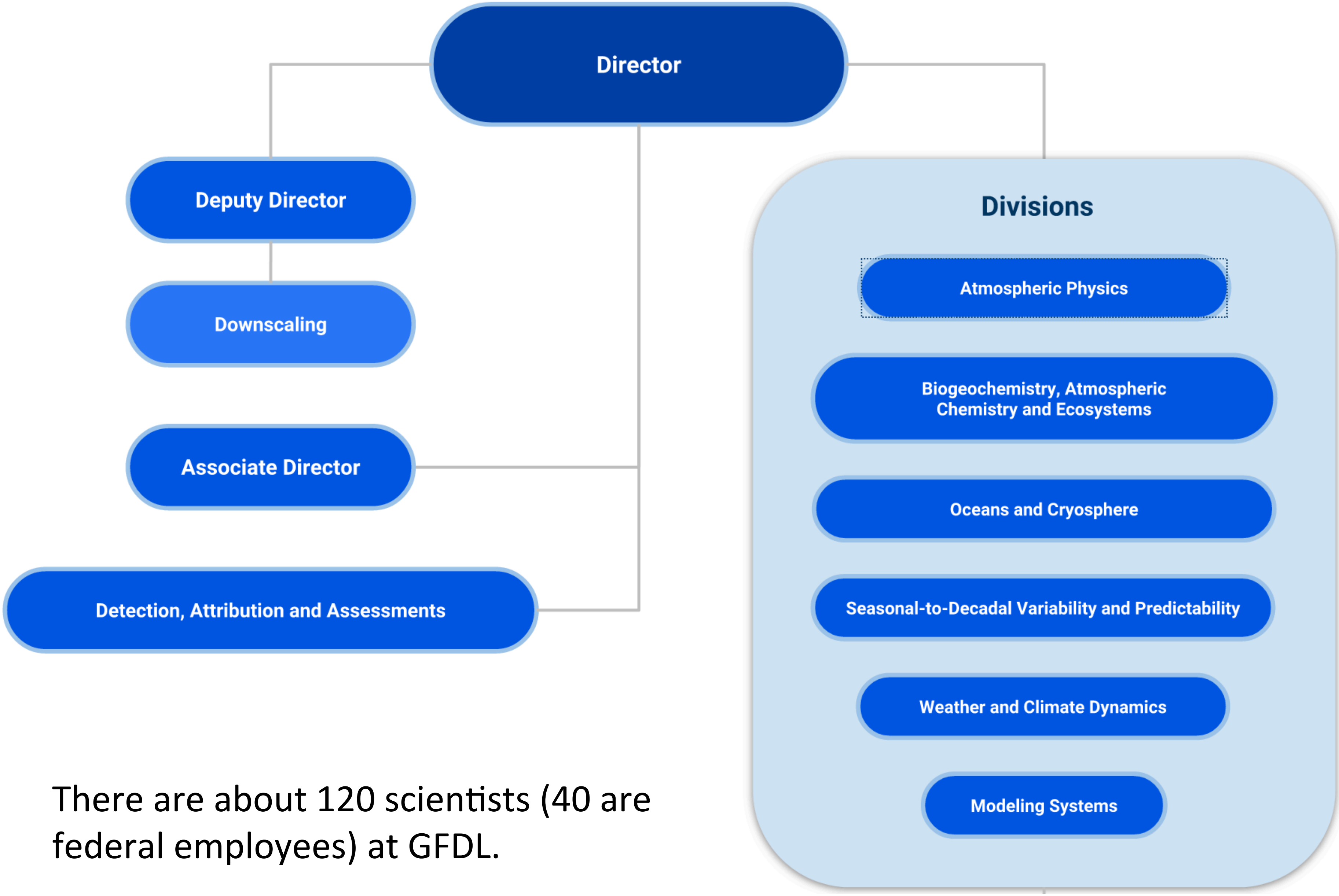
    Murakami et al. (2017, Nat. Climate Change)
- Part 2. Seasonal Prediction of TCs
  - ➢ Prediction skill for major hurricanes — *Murakami et al. (2015, 2016, J. Climate)*
  - ➢ Attribution Study for the 2017 active major hurricane season — *Murakami et al. (2018, Science)*
  - ➢ A new model under development

About GFDL

- Geophysical Fluid Dynamics Laboratory
- Office of Oceanic and Atmospheric Research (OAR), National Oceanic and Atmospheric Administration (NOAA)
- Location: Princeton, New Jersey
- Mission: To develop and use earth system models and computer simulations to improve our understanding and prediction of all aspects of the weather and climate system.

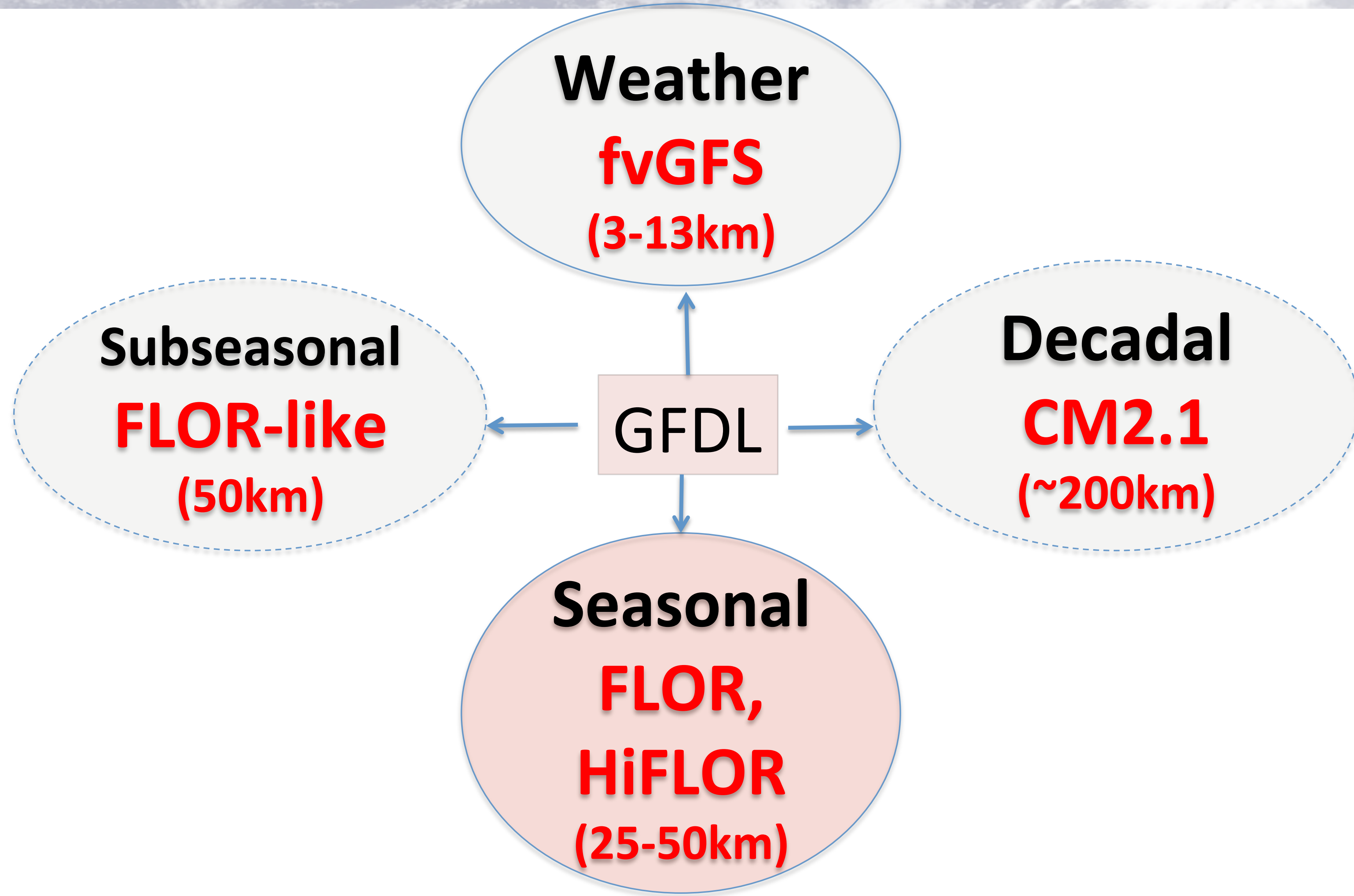


GFDL Organization



There are about 120 scientists (40 are federal employees) at GFDL.

GFDL Dynamical Models for Predictions



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Motivation

- Tropical cyclones (TCs) have large societal and economic impacts on the United States (and many other countries)

Disaster Type	Number of Events	Percent Frequency	CPI-adjusted Losses ($ billions)	Percent of Total Loss	Average Event Cost ($ billions)
Drought	21	12.4	199	19.1	9.5
Flooding	19	11.2	86	8.3	4.5
Freeze	7	4.1	25	2.4	3.6
Severe Storm	65	38.2	143	13.7	2.2
Tropical Cyclone	34	20.0	530	50.9	15.6
Wildfire	12	7.1	26	2.5	2.2
Winter Storm	12	7.1	35	3.4	2.9

Table: Damage cost from U.S. Billion-dollar disaster events (1980-2013)

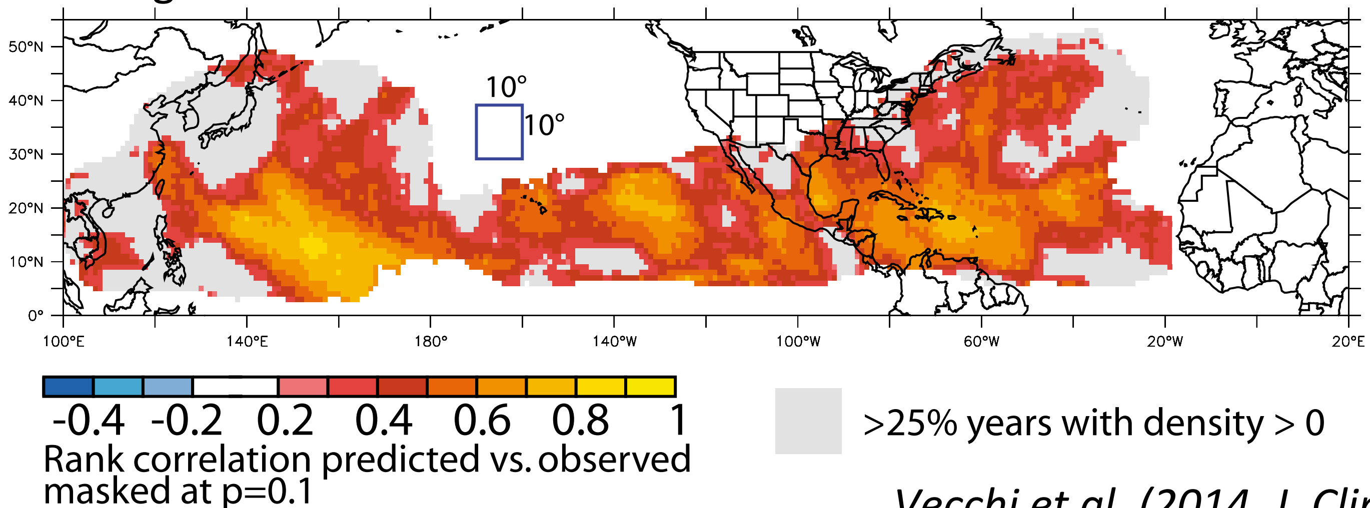
Smith and Matthes (2015, Natural Hazards)

- About **85%** of the total TC damage has been caused by the intense hurricanes (Saffir-Simpson Categories 4 and 5; hereafter C45)

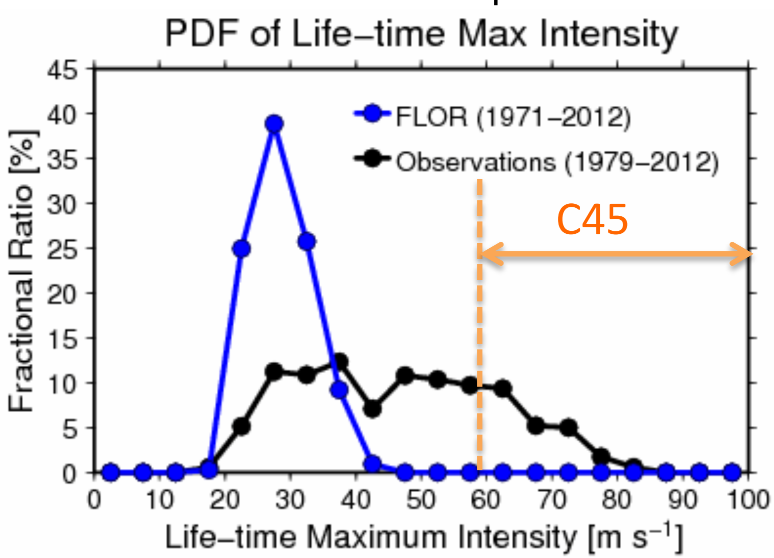
<u>C45 Hurricane</u>: Hurricane with lifetime maximum surface wind ≥60m/s (113kt)

GFDL FLOR: Forecast-oriented Low Ocean Resolution version of CM2.5

- CM2.5: Fully coupled model with 50km-mesh atmosphere and 0.25° ocean/sea ice
  FLOR : Fully coupled model with **50km**-mesh atmosphere and **1°** ocean/sea ice
- FLOR is a TC-permitting model



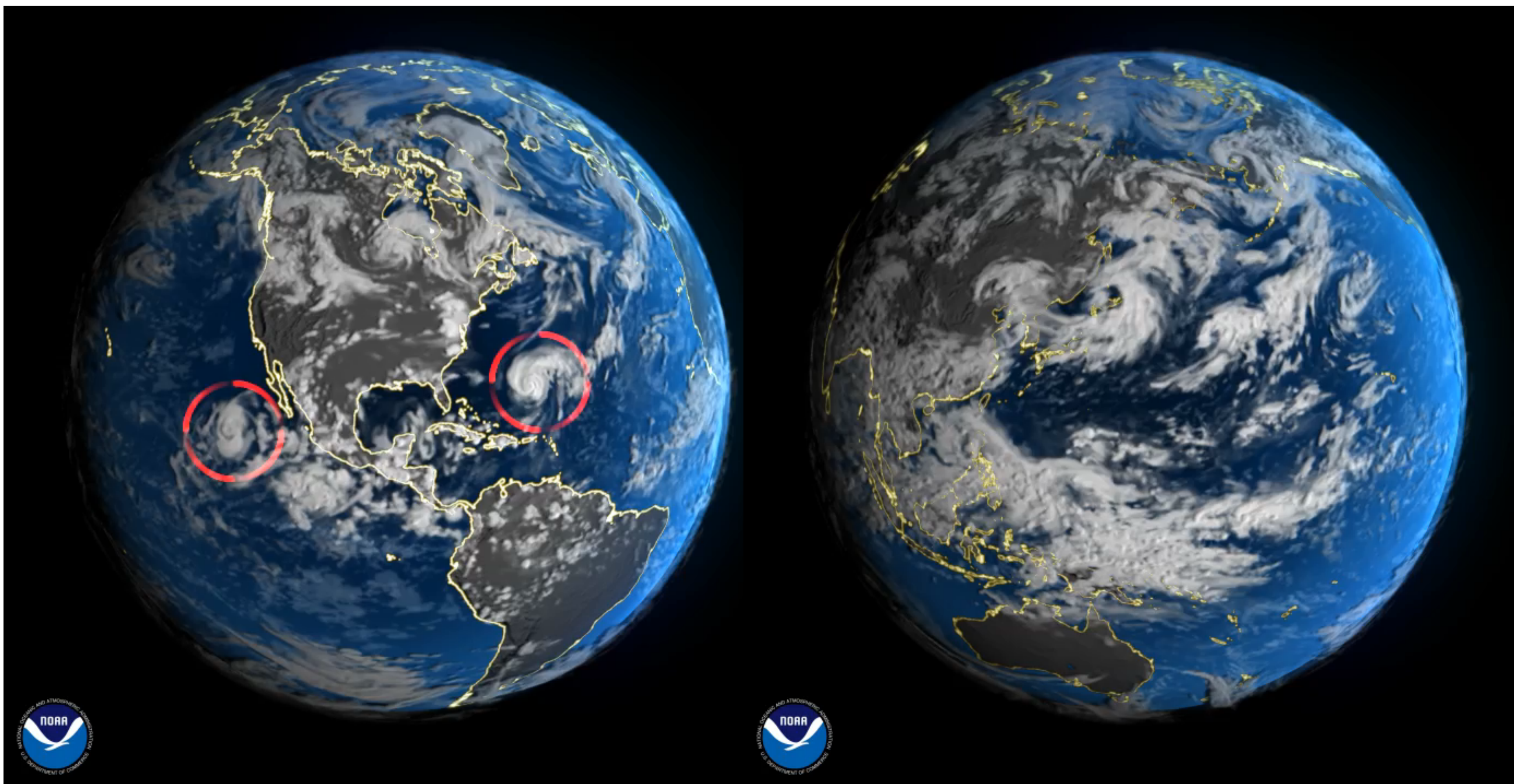
Vecchi et al. (2014, J. Climate)



FLOR critically underestimates frequency of C45 hurricanes.

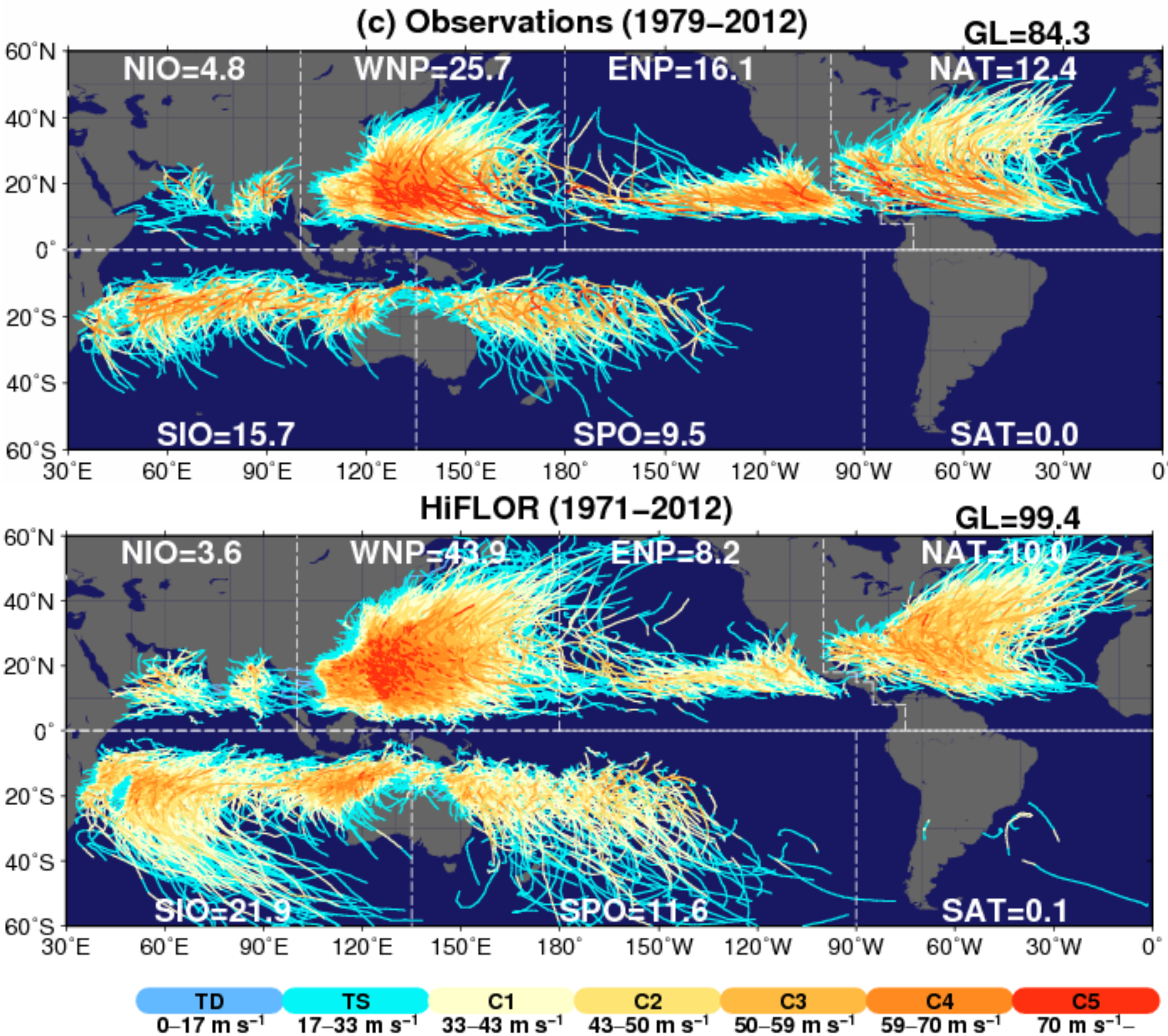
GFDL Coupled Models (FLOR and HiFLOR)

	FLOR	HiFLOR
Base Model	AM2.5 (Atmosphere model of CM2.5), MOM4 (Ocean model of CM2.1)	
Resolution	Atmosphere : **50 km**, L32 Ocean: 100 km, L50	Atmosphere : **25 km**, L32 Ocean: 100 km, L50



SST Restoring Experiments by FLOR and HiFLOR

Murakami et al. (2015, J. Climate)



Restoring Experiment:

Observed time-varying SST is restored at 5-day timescale for the period 1971–2012.

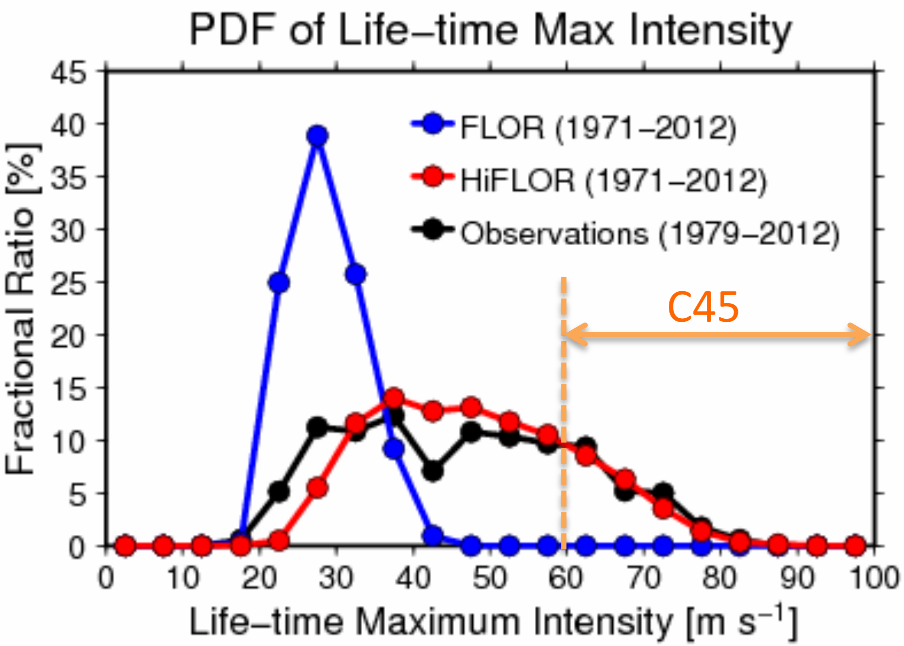
FLOR underestimates TC intensity

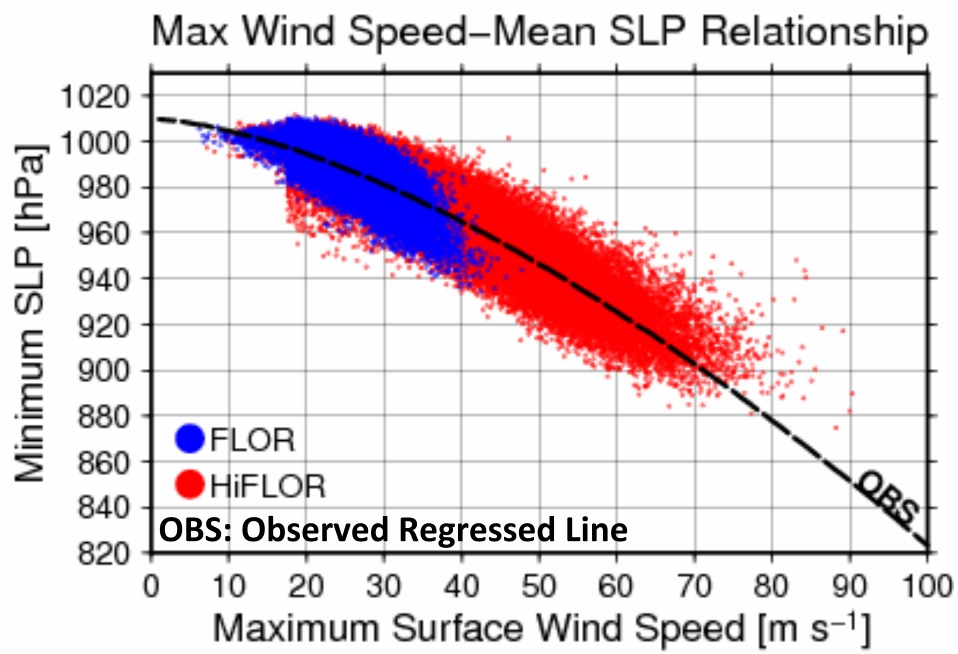
HiFLOR improved TC intensity

Number: Annual mean TC frequency

Simulated TC Intensity

Murakami et al. (2015, J. Climate)

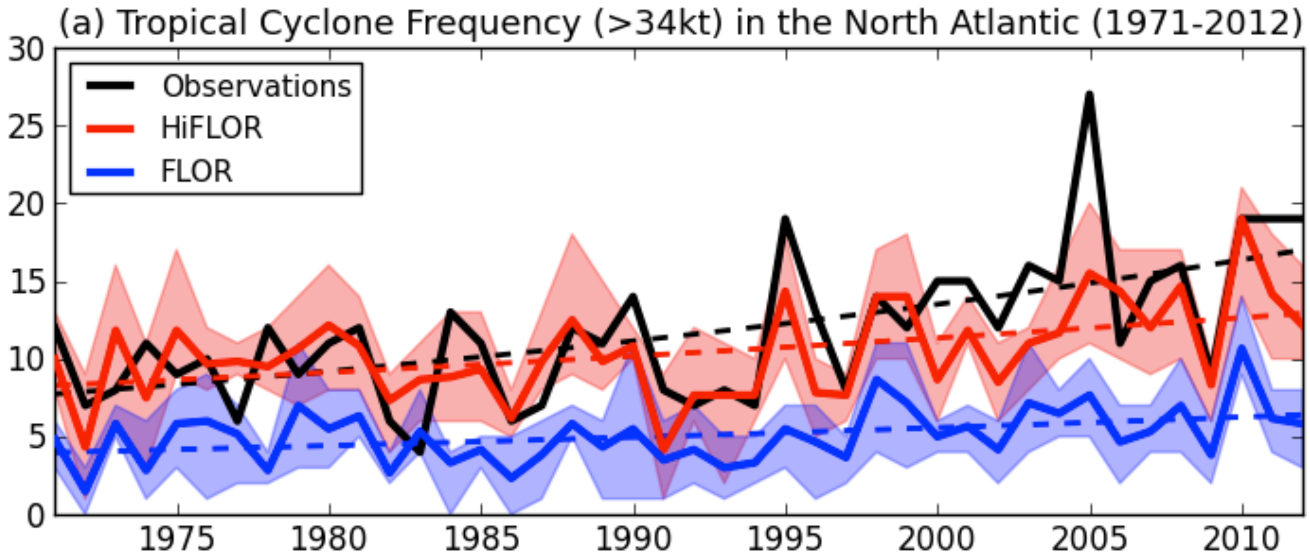




- HiFLOR can simulate C45 hurricanes.
- TC structure is reasonably simulated in terms of Maximum Wind Speed– Mean SLP relationship.

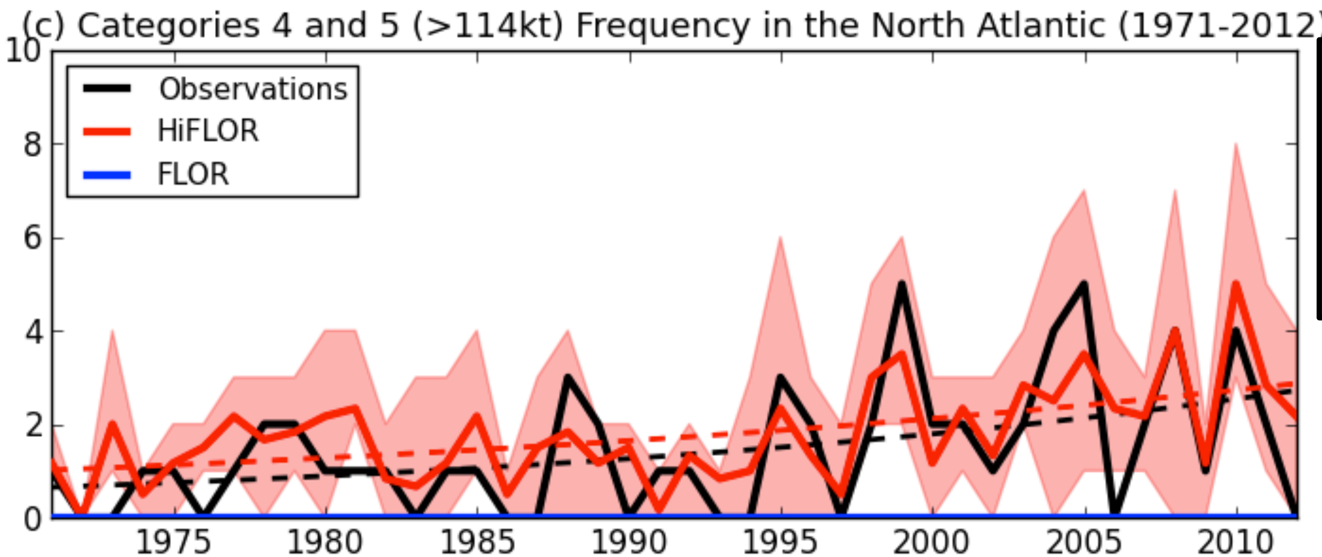
Interannual Variation of North Atlantic Storms

Murakami et al. (2015, J. Climate)



r=0.68 (HiFLOR vs Obs)

r=0.59 (FLOR vs Obs)



It is for the first time that a global coupled model could simulate observed interannual variation of C45 hurricanes.

r=0.64 (HiFLOR vs Obs)

r=N/A (FLOR vs Obs)

Interannual Variation for Global Ocean Basins

Murakami et al. (2015, J. Climate)

Correlation Coefficients (Observed vs Model, 1971–2012)

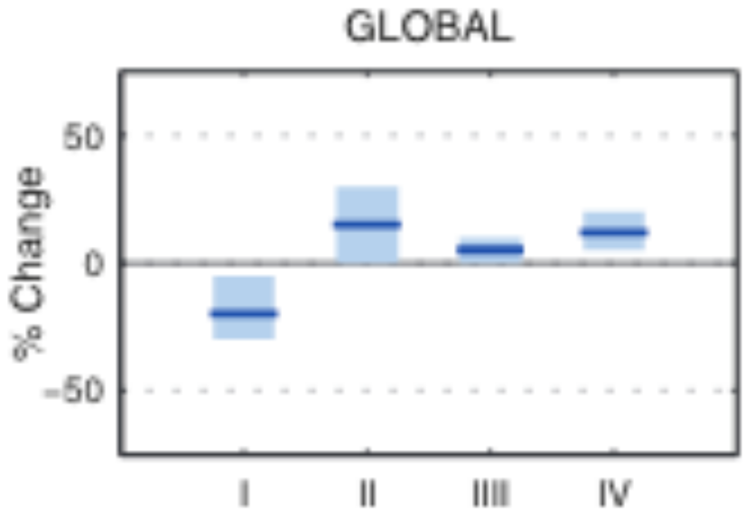
Model	N.Indian	WN.Pacific	EN.Pacific	N.Atlantic	S.Indian	S.Pacific
(a) All TSs (>34kt, 1971-2012)						
HiFLOR	−0.27	**+0.35**	**+0.49**	**+0.68**	**+0.38**	**+0.31**
FLOR	+0.01	**+0.55**	**+0.41**	**+0.59**	+0.02	+0.23
(b) Hurricanes (>64kt, 1971-2012)						
HiFLOR	+0.04	+0.17	**+0.51**	**+0.77**	**+0.51**	+0.23
FLOR	+0.01	**+0.55**	+0.27	**+0.68**	+0.11	+0.02
(c) Categories 4 and 5 (>114kt, 1971-2012)						
HiFLOR	**+0.38**	+0.24	**+0.31**	**+0.64**	**+0.32**	+0.18
FLOR	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*

95% Significant

HiFLOR shows higher skill than FLOR in all the ocean basins, except for WNP

Previous Studies on Future Changes in Global TC Frequency

Expected percent change in the average over period 2081–2100 relative to 2000–2019



I. **Global TC Frequency (decrease)**
II. Mean TC Intensity (increase)
III. Mean TC Precipitation (increase)
IV. Global C45 Frequency (increase)

IPCC AR5 Chapter 14

IPCC AR5 Assessment Summary

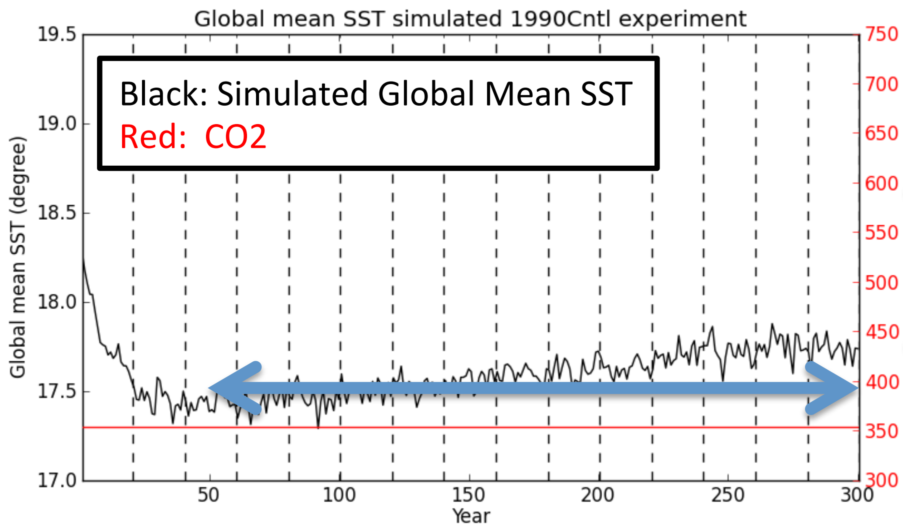
It is ***likely*** that the global frequency of tropical cyclones will either **decrease** or remain essentially **unchanged**.

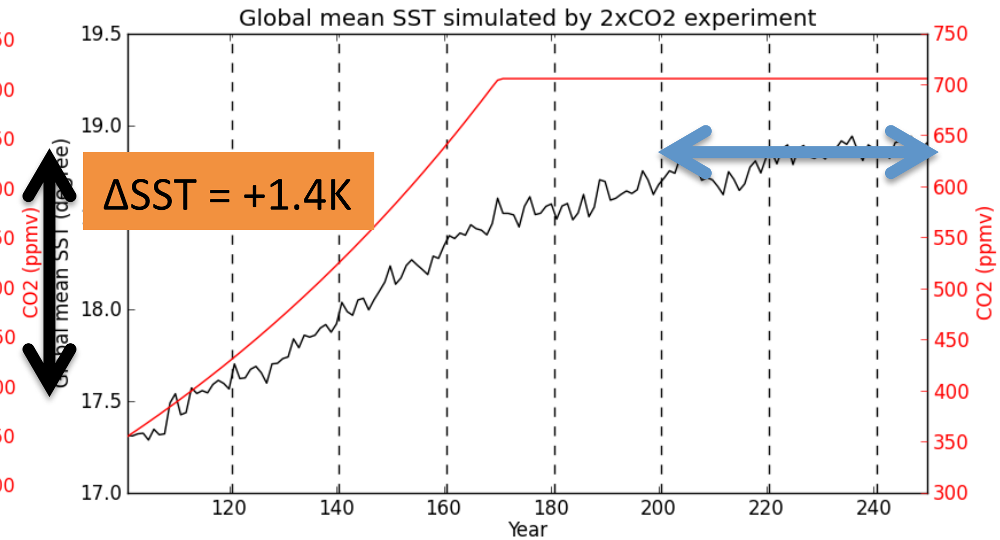
However, most of the models considered for this assessment were with 50–100 km mesh (medium or low resolution).

It is necessary to revisit this possible future change using a high resolution model like HiFLOR.

TC Sensitivities to 2xCO2 (Fully Coupled Simulations)

Vecchi et al. (Climate Dynamics, in revision)





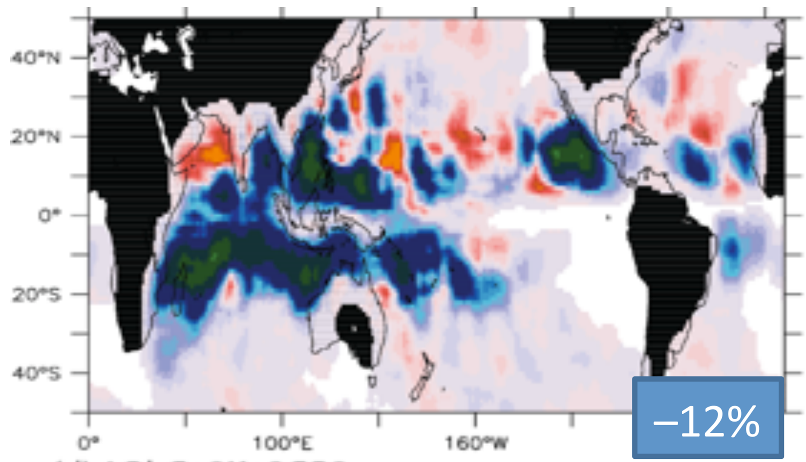
1990Cntl Experiment (300-yr simulation)

- Fully Coupled
- Fixed Forcing at 1990 level (CO_2=350ppmv)

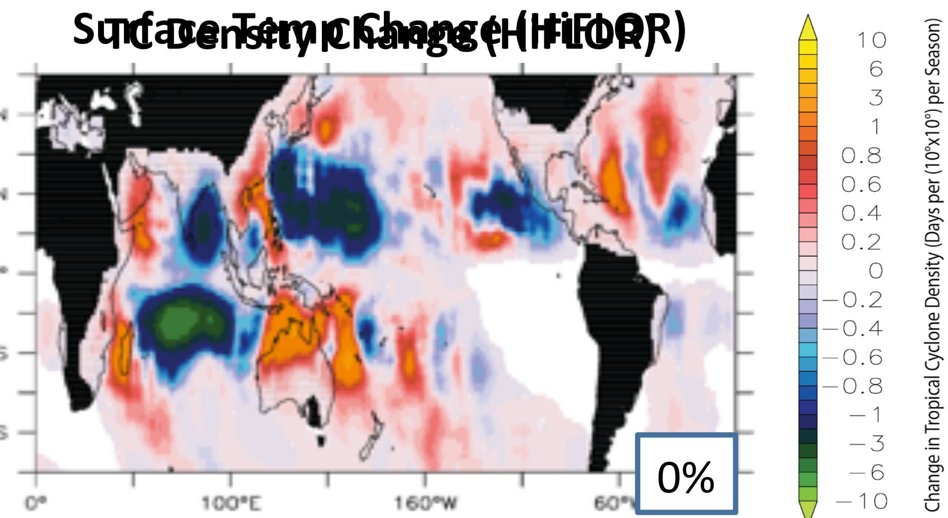
Transient +1%/yr CO2 Experiment

- Fully Coupled
- +1% CO_2 increase up to 2xCO_2 (at year 171) then fixed

Surface Temp Change (FLOR) / TC Density Change (FLOR)



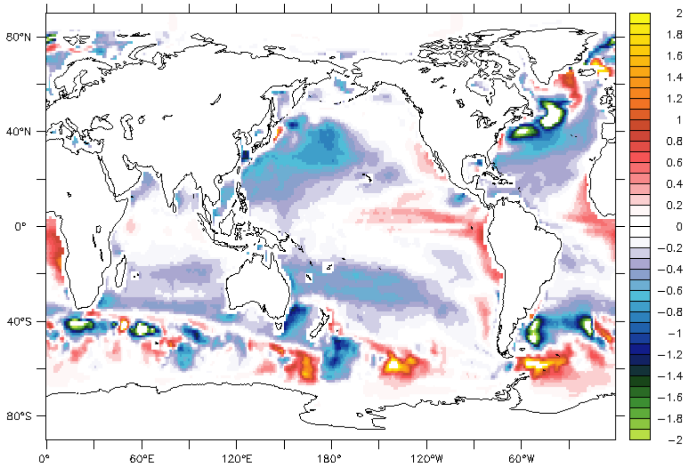
Surface Temp Change (HiFLOR) / TC Density Change (HiFLOR)



TC Sensitivities to 2xCO2 (SST Nudging Experiments)

Vecchi et al. (Climate Dynamics, in revision)

SST Bias in 1990 Cntl (reference:. HadISST)



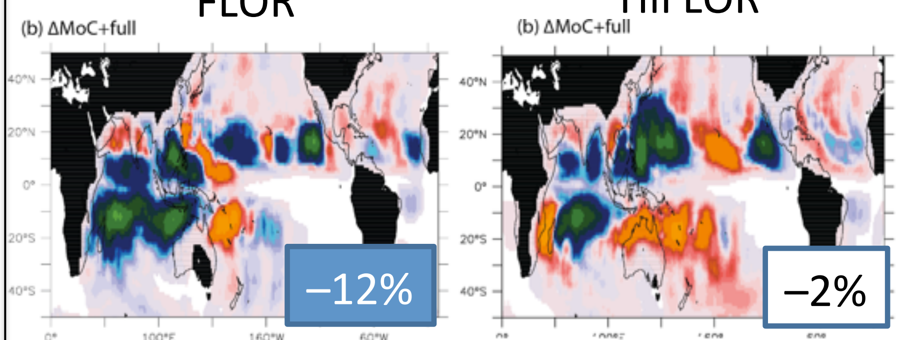
SST Nudging Experiment

SSTs are nudged to reference SSTs at 5-day time scale
(Similar to AMIP but still air-sea coupling is allowed at < 5-day scale)

Experiment	Prescribed SST	CO2 Forcing
MoC	Model Climate from 1990Cntl	352.7 ppm
MoC + Full	MoC + ΔSST	705.4 ppm
ObC	HadISST (1986-2005) Mean	352.7 ppm
ObC + Full	ObC + ΔSST	705.4 ppm

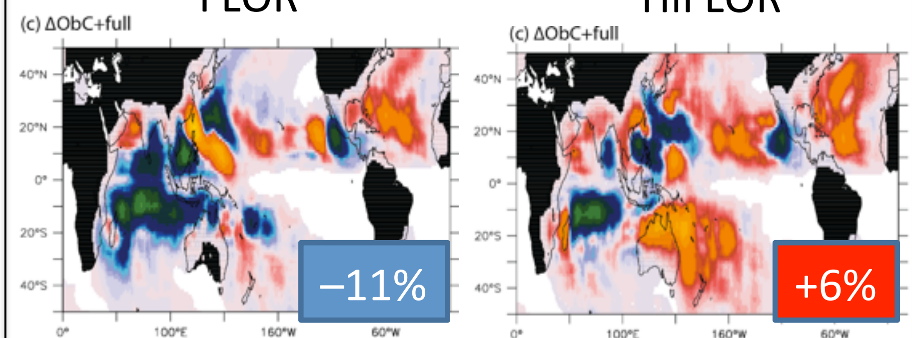
TC Density Change (ΔMoC)

FLOR HiFLOR



TC Density Change (ΔObC)

FLOR HiFLOR



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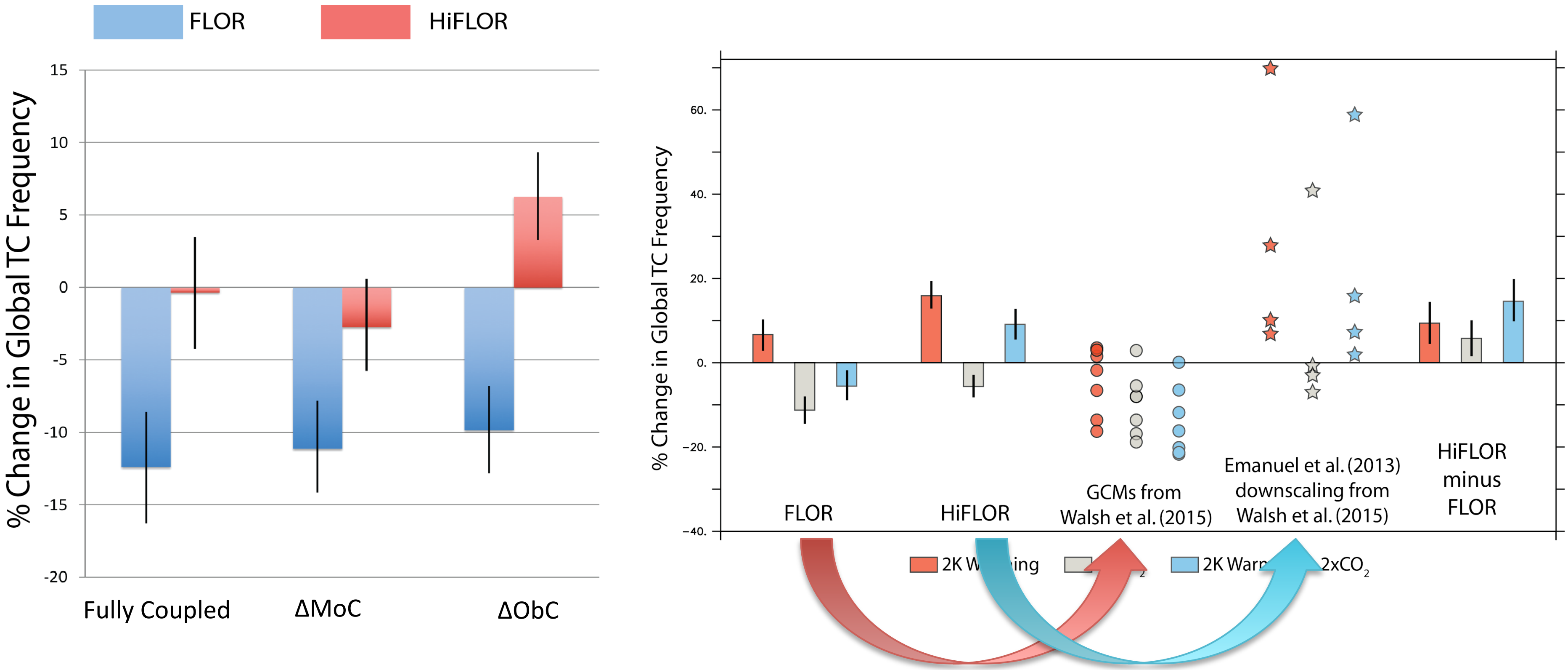
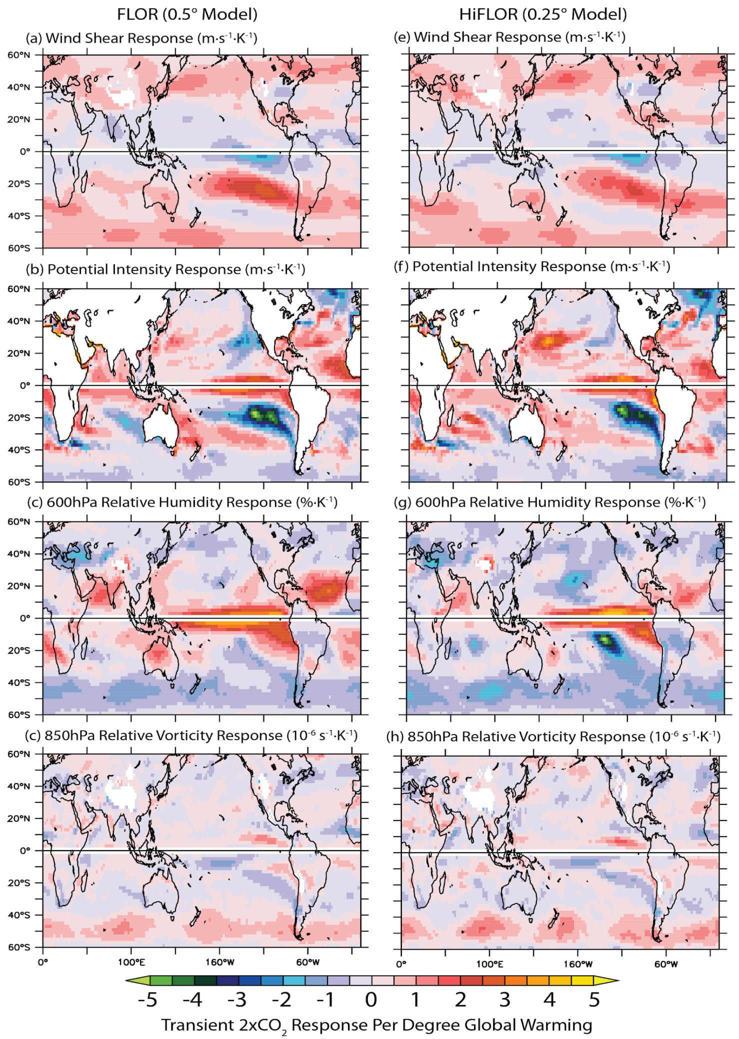


HiFLOR projects to increase (or no change) global mean TC frequency that is similar to the statistical-dynamical downscaling by Emanuel et al. (2013, 2015).

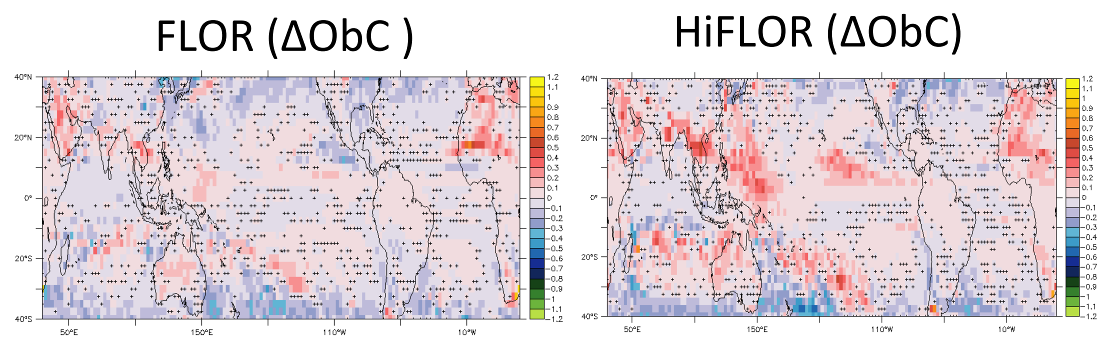
Why does HiFLOR project increases in global TCs?

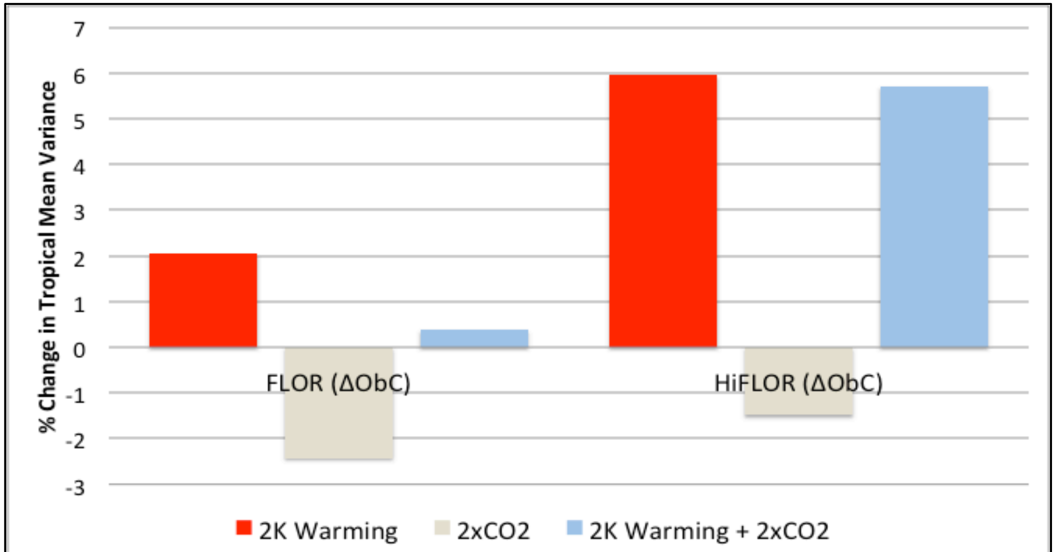
Vecchi et al. (Climate Dynamics, in revision)



Large-scale parameter cannot explain the difference in projected changes in TC frequency between FLOR and HiFLOR

Difference in Variance of 3-10-day vort850





Increase in synoptic-scale disturbances (i.e., seeds) may be relevant to the increase in TC frequency in HiFLOR

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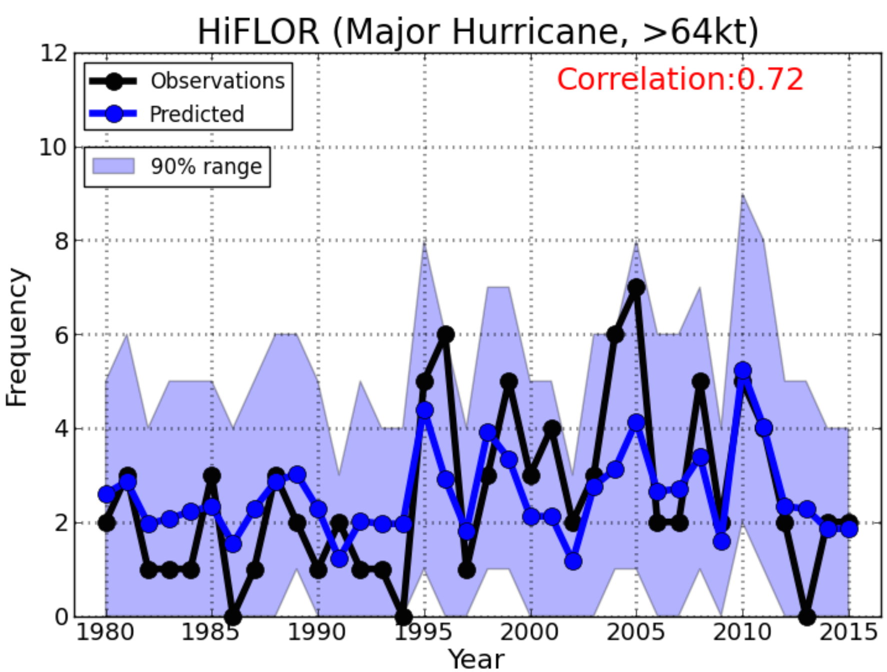
Retrospective Seasonal Prediction by HiFLOR (Major Hurricanes)

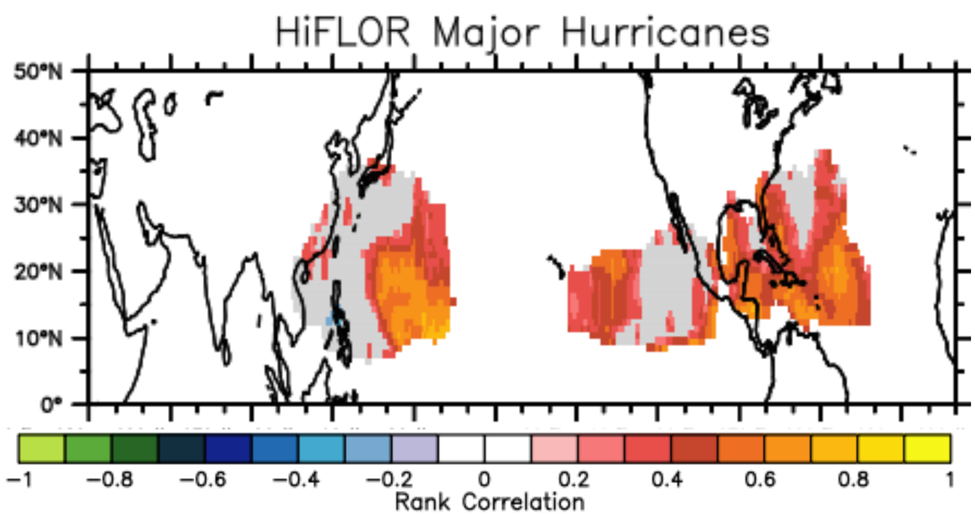
Murakami et al. (2016, J. Climate)

Model	HiFLOR
Period	1980–2015, mainly focus on TC prediction for July–November
Initial	July (Leal Month=0–4), Ocean is initialized, but atmosphere is not initialized.
Ensemble	24 Ensemble Members

Major Hurricanes in the North Atlantic



Skill in Predicting Major Hurricane Density

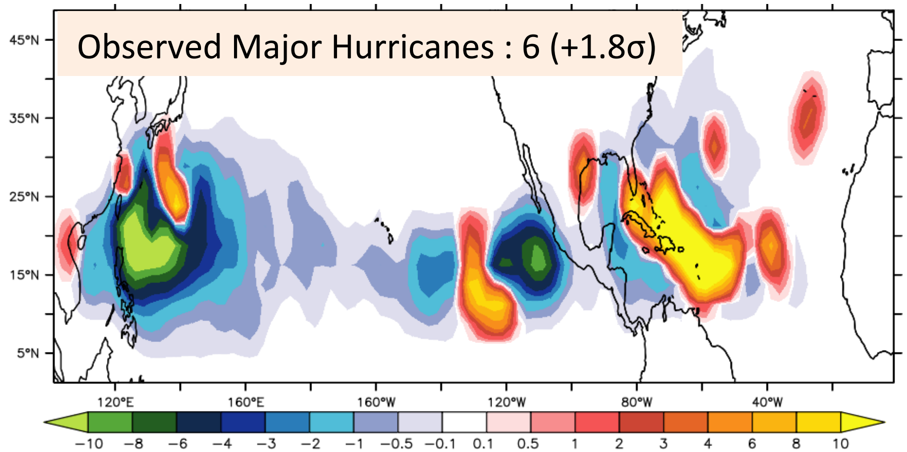


HiFLOR shows skillful prediction for major hurricanes

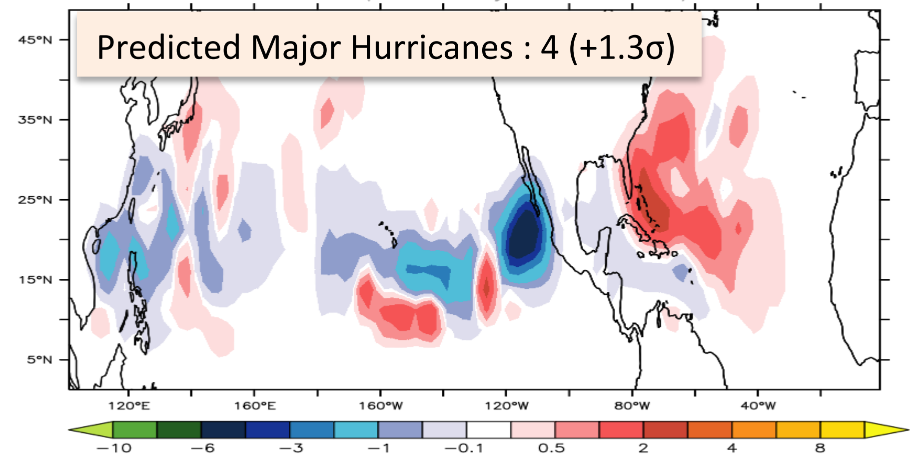
Real-Time Prediction for the 2017 Summer Season

Murakami et al. (2018, Science)

Observed MH Density Anomaly in 2017

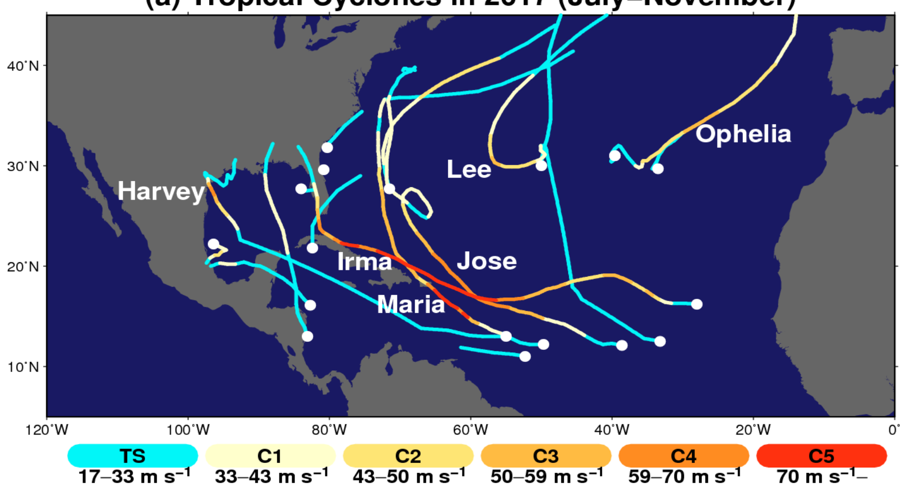


Predicted MH Density Anomaly in 2017



Observed Storm Tracks in 2017

(a) Tropical Cyclones in 2017 (July–November)



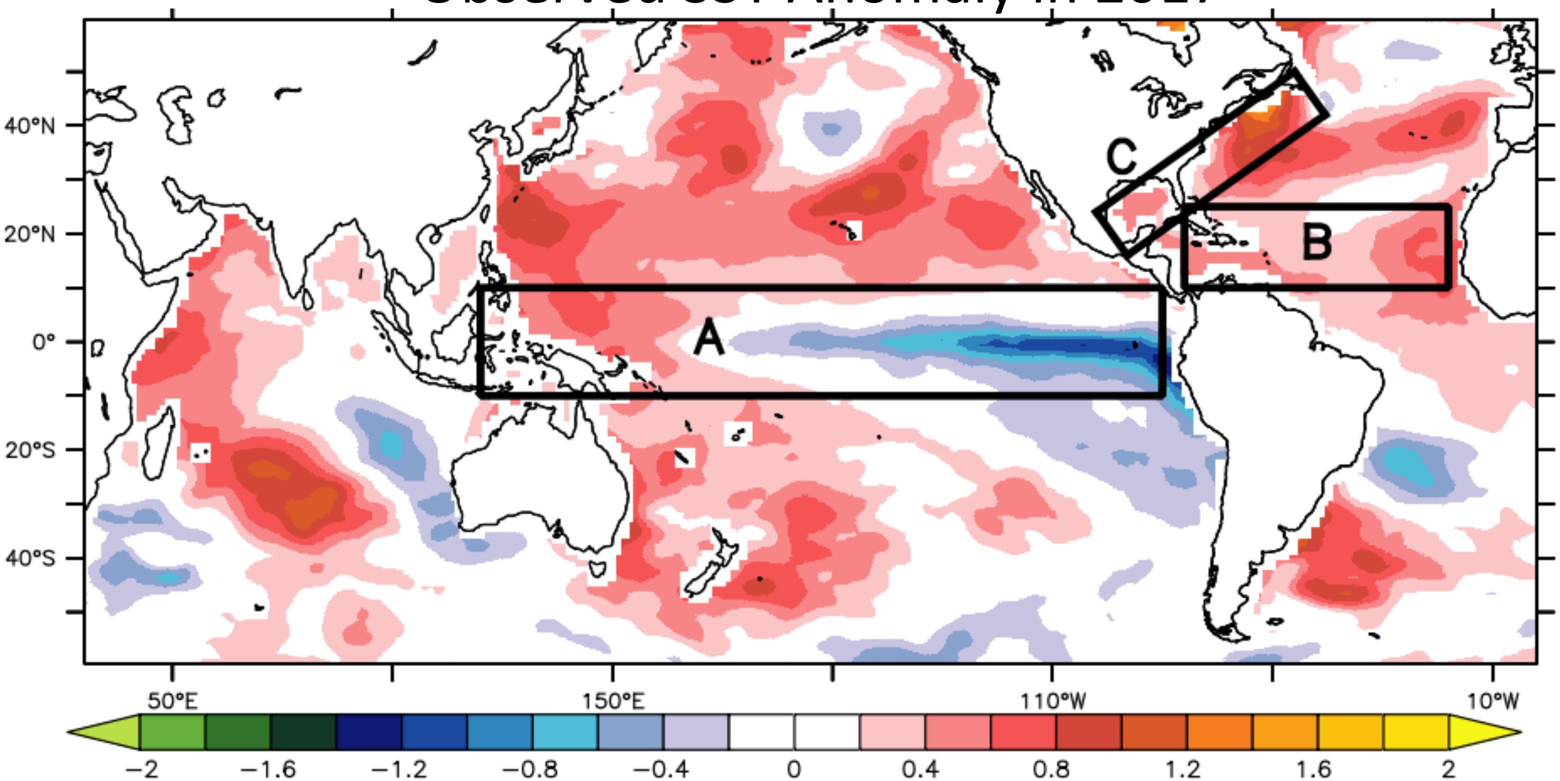
Example of HiFLOR prediction for the 2017 Summer

HiFLOR could predict the locations of MHs as well as above normal frequency of MHs a few months in advance for the 2017 summer.

What caused the active 2017 MH season?

Murakami et al. (2018, Science)

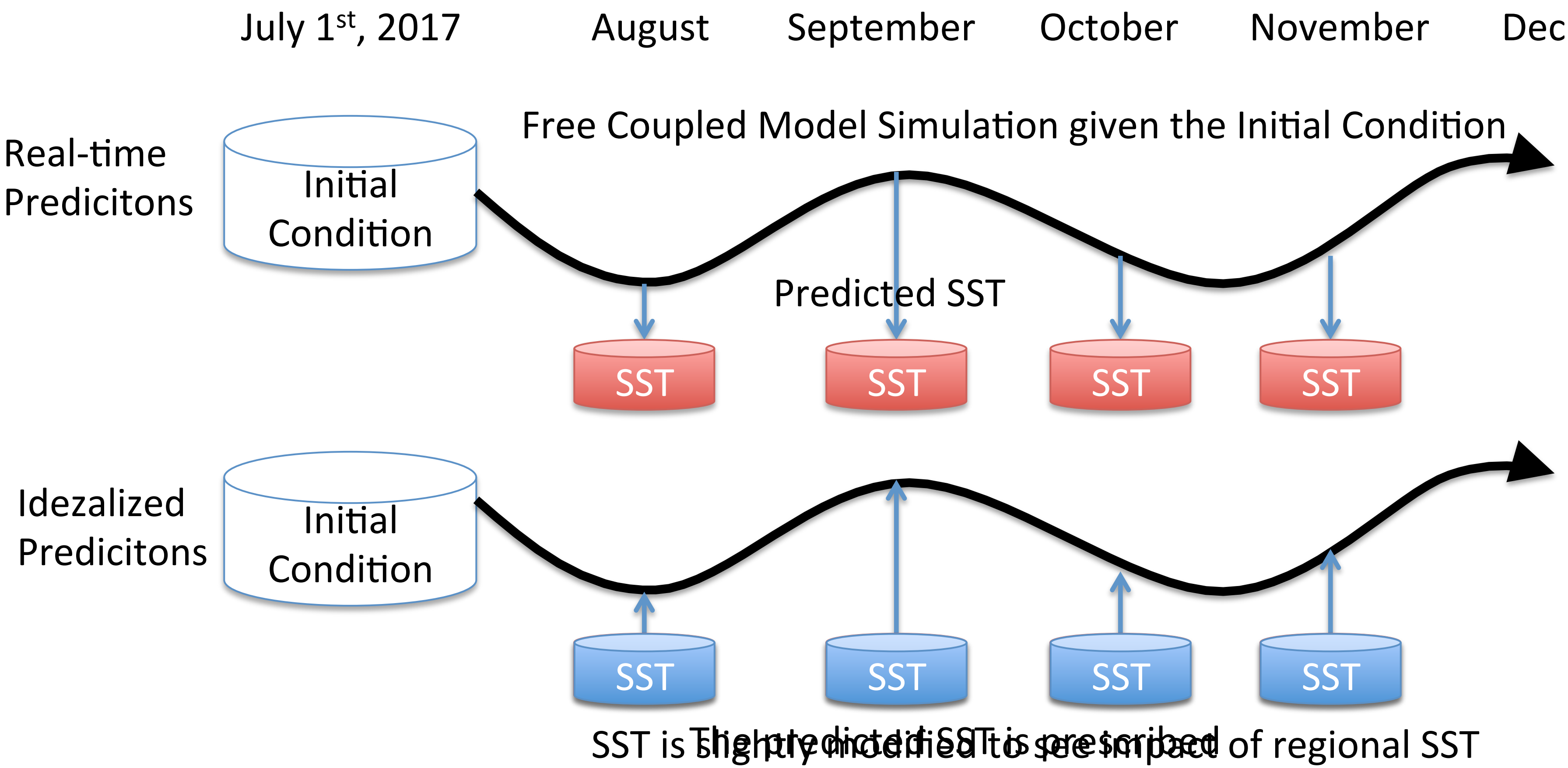
Observed SST Anomaly in 2017



A. Moderate La Niña?
B. Warmer Tropical Atlantic?
C. Warmer off the coast of North America?

Idealized Seasonal Predictions

Murakami et al. (2018, Science)

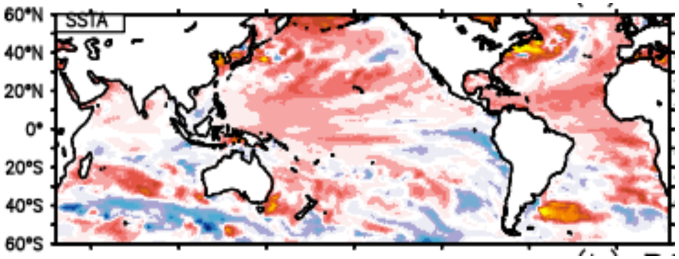


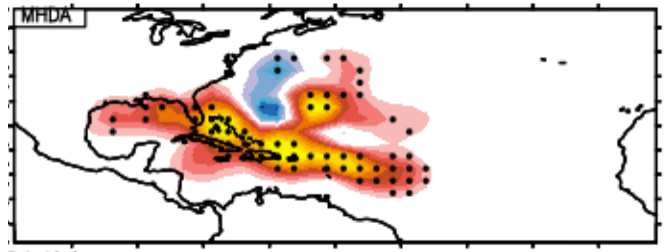
We call this type of experiments as "real-time attribution" because we can examine causes for active hurricane season even as hurricane season is underway.

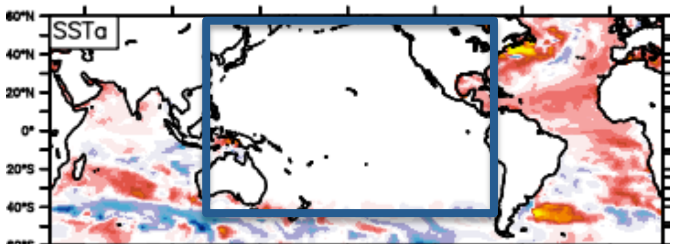
Idealized SST-Prescribed Seasonal Prediction

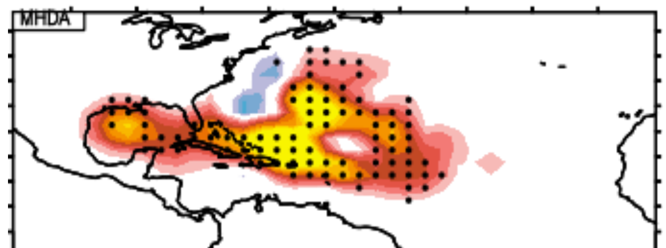
Murakami et al. (2018, Science)

Prescribed SST Anomaly | Predicted Major Hurricane Density Anomaly





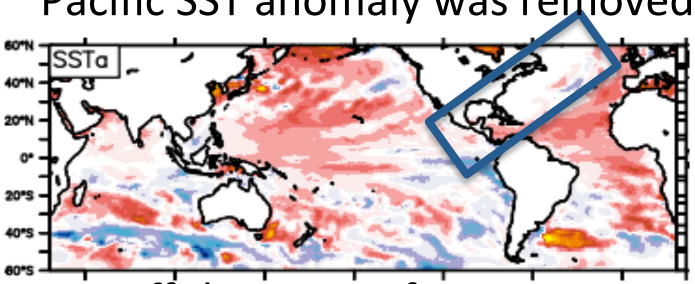


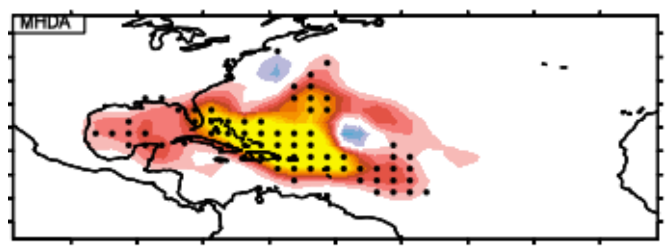


A. Moderate La Niña? ✗

Pacific SST anomaly was removed.

MHs are still active.

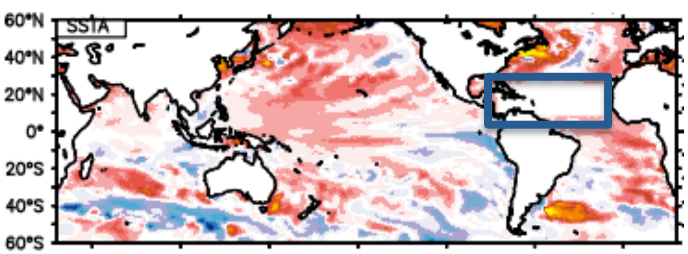


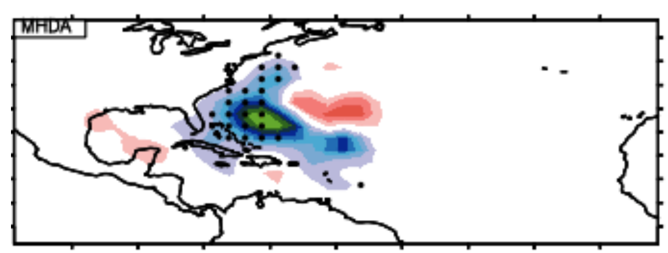


C. Warmer off the coast of North America? ✗

SSTa off the coast of US was removed.

MHs are still active.





B. Warmer Tropical Atlantic? ○

SSTa in the tropical Atlantic was removed.

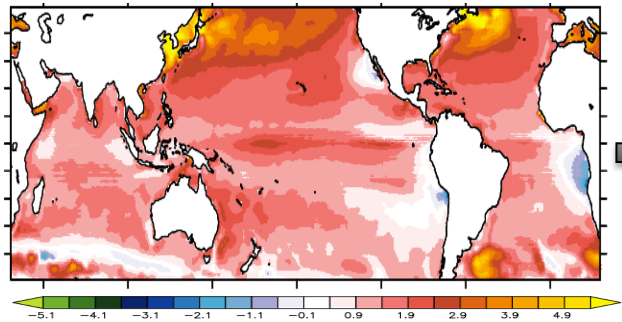
MHs reduced.

Idealized Prescribed SST Experiments in the Future

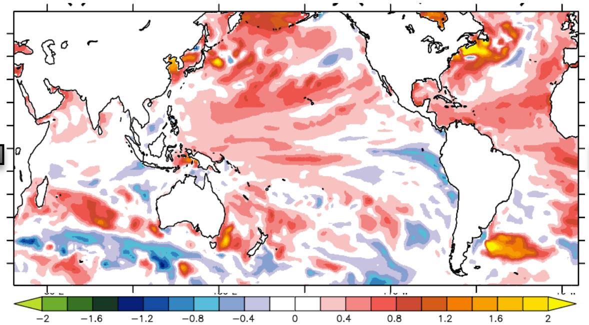
Murakami et al. (2018, Science)

RCP4.5

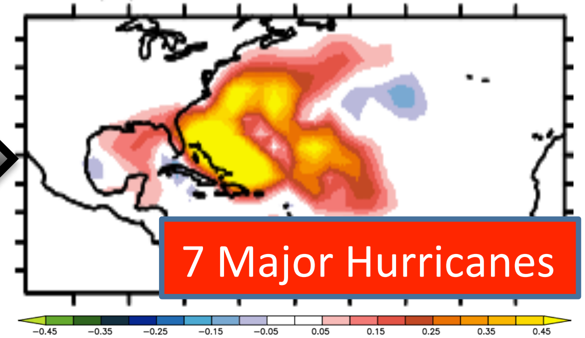
(2080-2099 minus 2015-2025)



2017 SST Anomaly



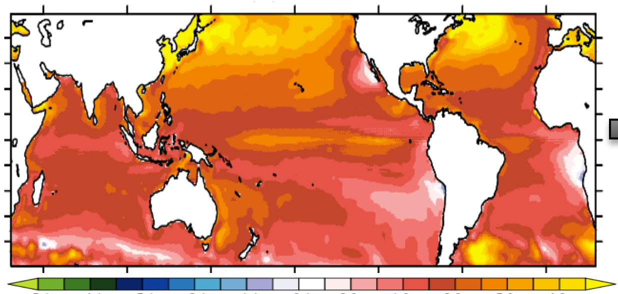
Projected MH Density Anomaly



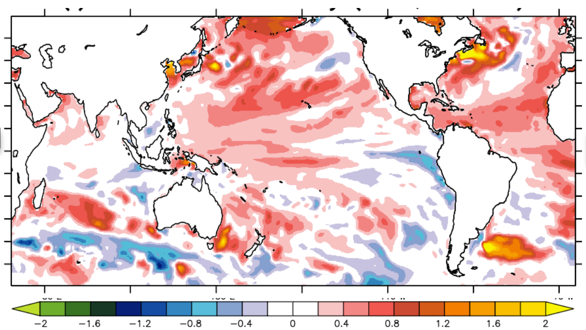
& CO_2 = 533 ppm

RCP8.5

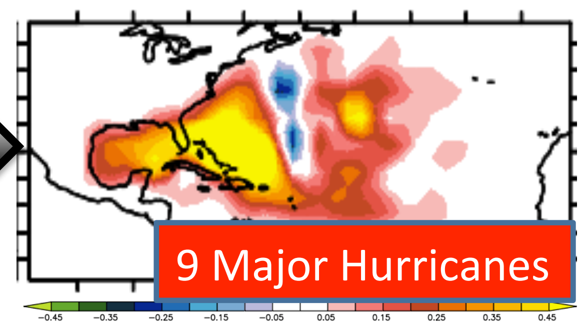
(2080-2099 minus 2015-2025)



2017 SST Anomaly



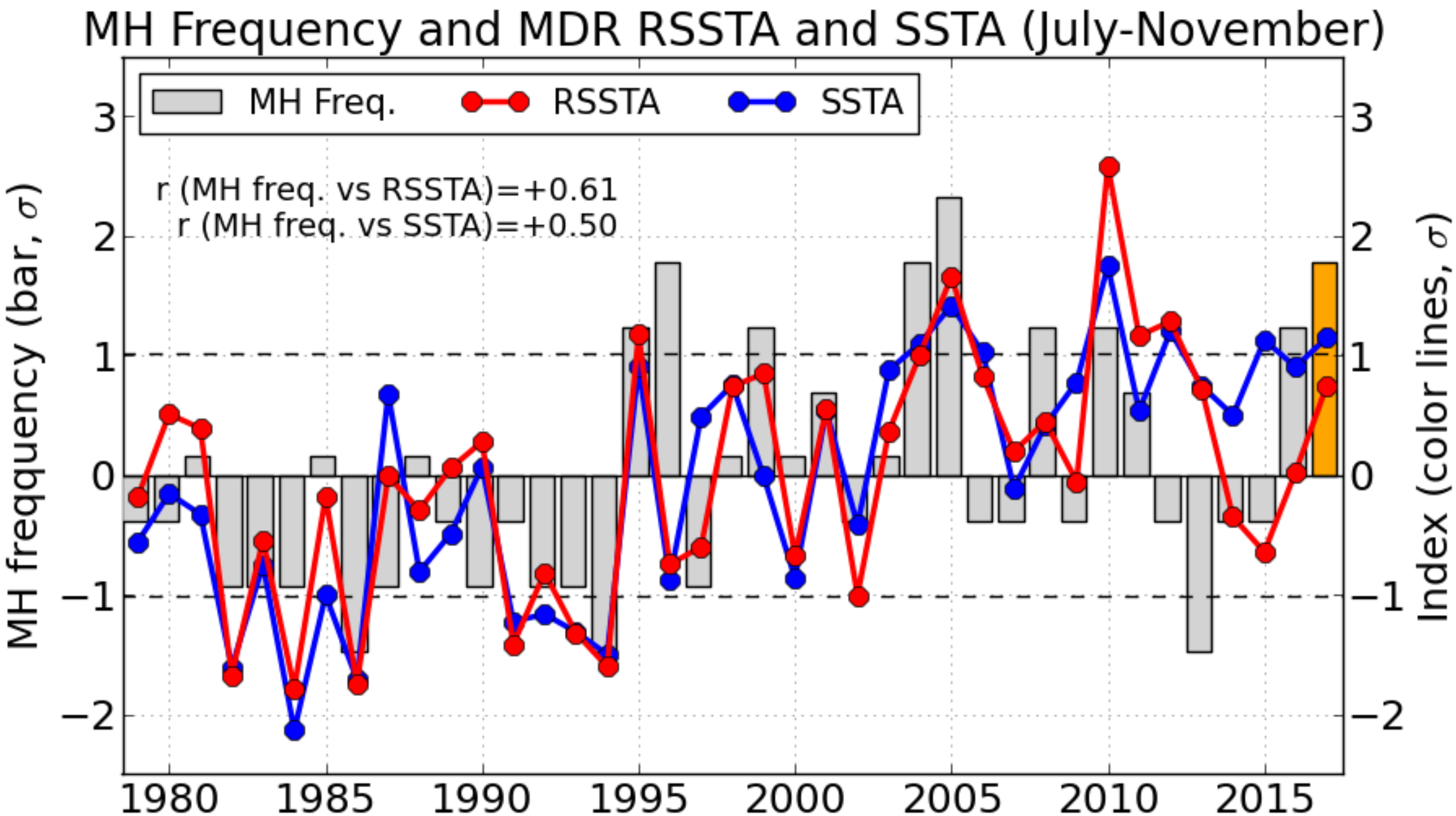
Projected MH Density Anomaly



& CO_2 = 840 ppm

More active MH season than the 2017 summer is projected in the future even with the same spatial patterns of 2017 SST anomaly, resulting in **amplifying the risk of MHs**.

Which of local SST anomaly or relative SST anomaly is important for frequency of MHs in the North Atlantic?

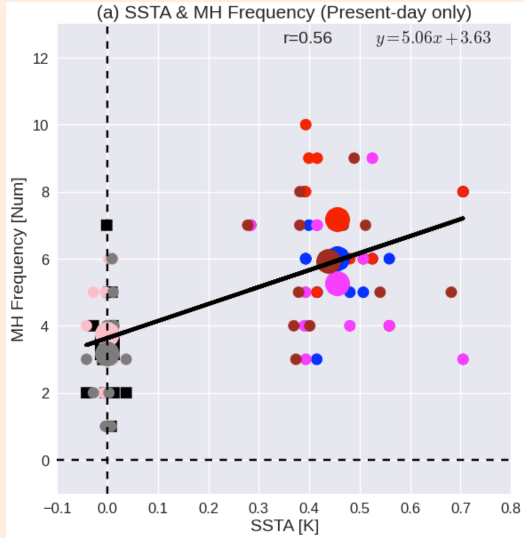


Observed number of MHs (gray bars) is correlated with both
tropical Atlantic (10–25°N, 80–20°W) SST anomaly (SSTA, r=+0.50) and
tropical Atlantic SST relative to tropical mean (*30°S–30°N*) (RSSTA, r=+0.61)

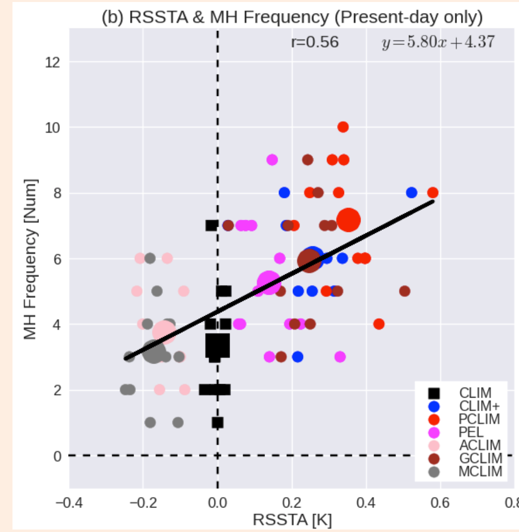
Murakami et al. (2018, Science)

Which of local SST anomaly or relative SST anomaly is important for frequency of MHs in the North Atlantic?

2017 Experiments only

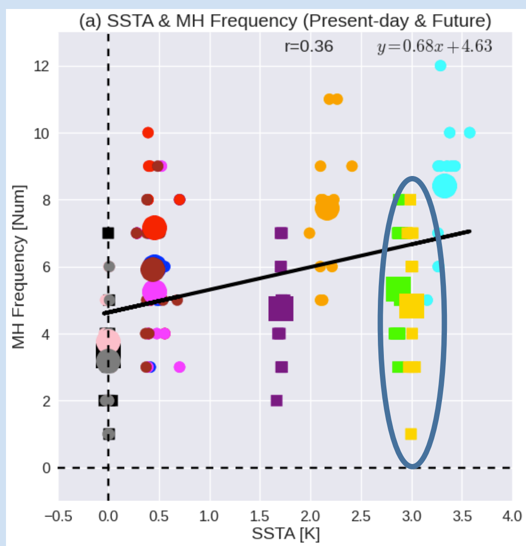


SSTA vs MHs (r=+0.56, Slope=+5.1)

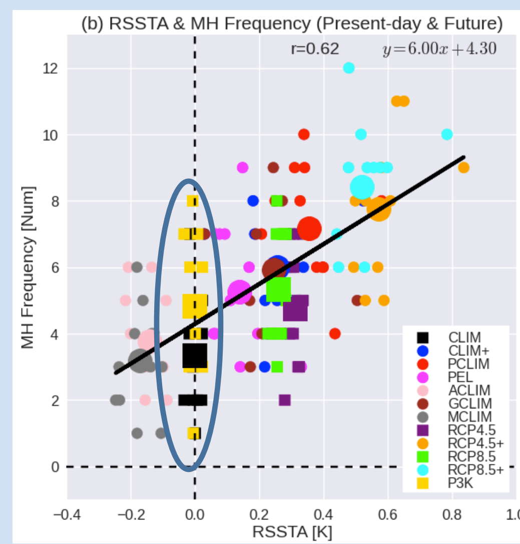


RSSTA vs MHs (r=+0.56, Slope=+5.8)

2017 Experiments & Future Experiments



SSTA vs MHs (r=+0.36, Slope=+0.7)

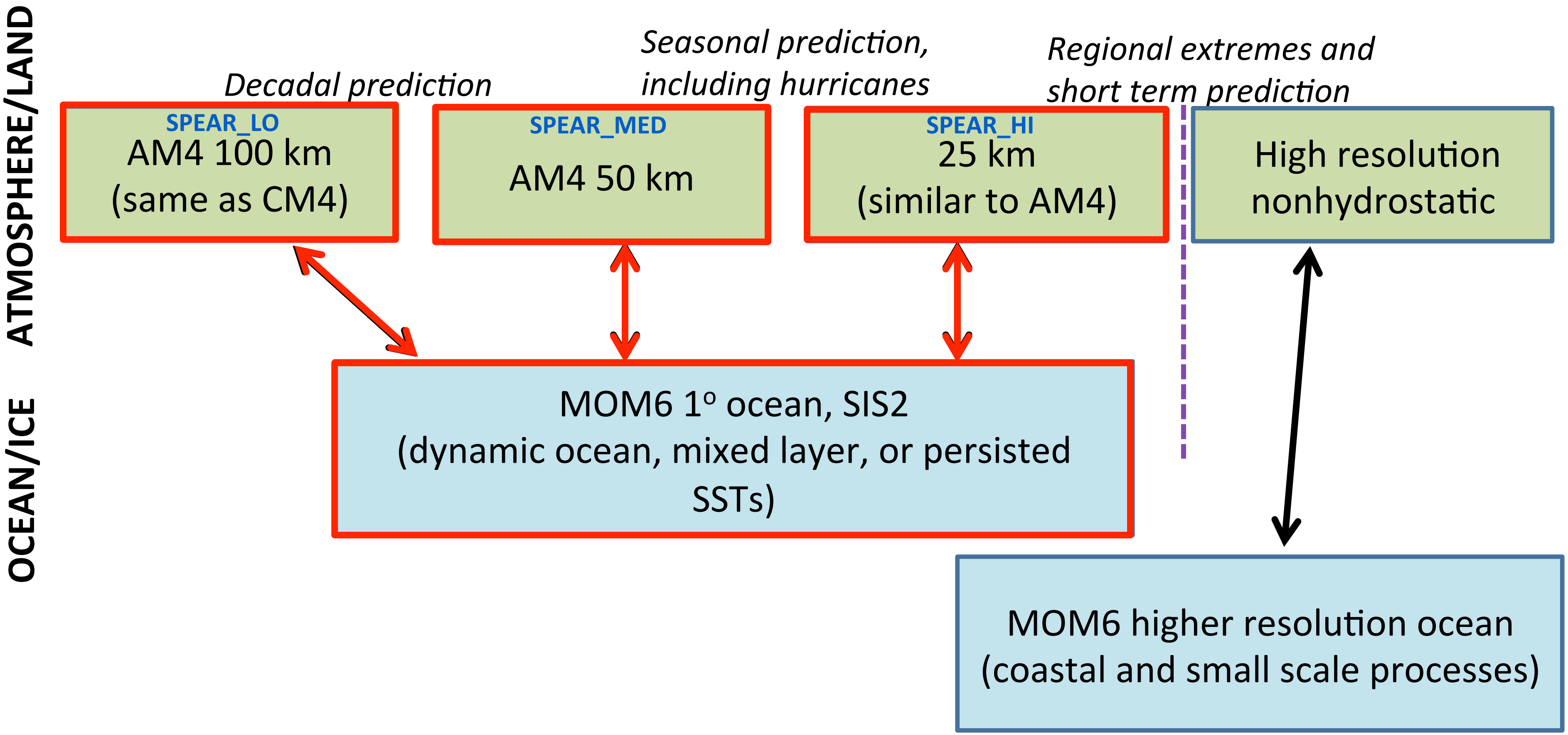


RSSTA vs MHs (r=+0.62, Slope=+6.0)

Developing a New Coupled Model (SPEAR)

Delworth et al. (in prep)

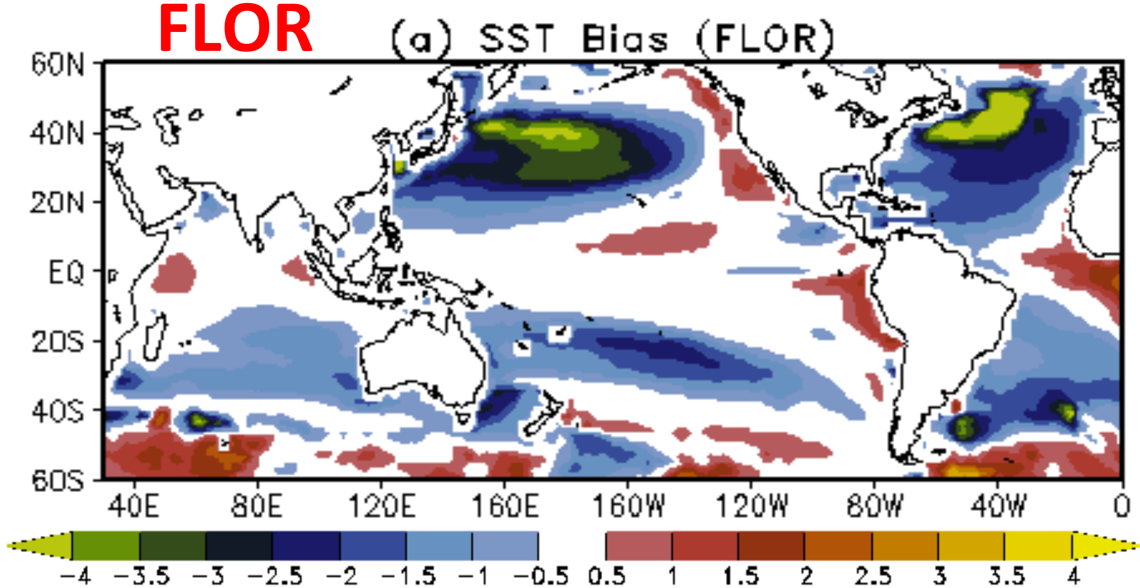
Towards a **S**eamless System for **P**rediction and **EA**rth System **R**esearch
"SPEAR"

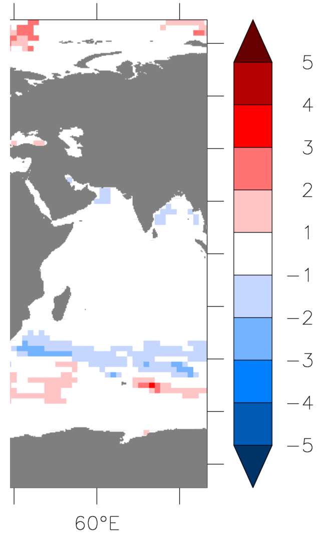


Developing a new coupled model (SPEAR)

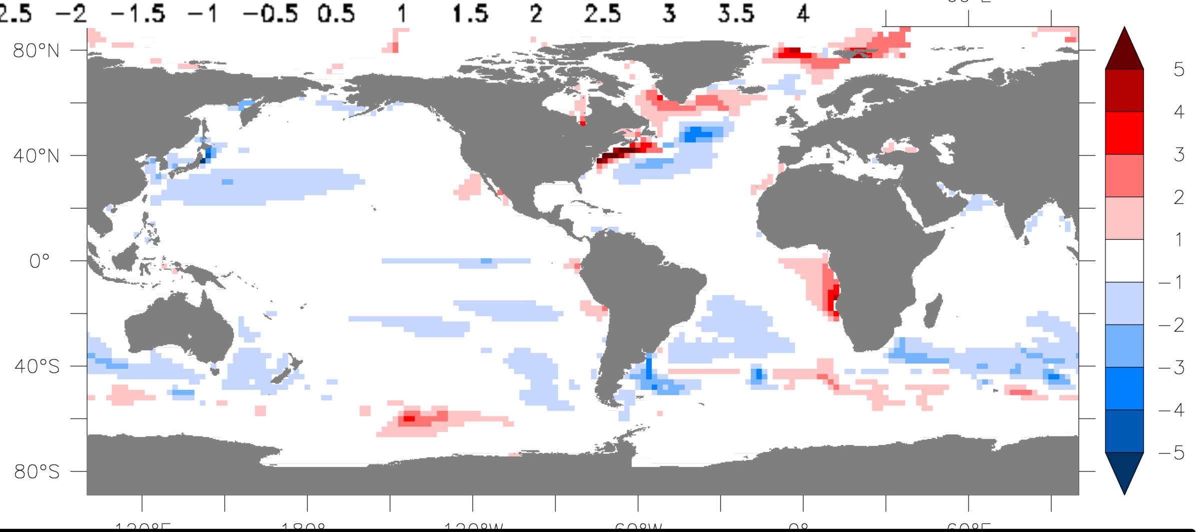
Delworth et al. (in prep)

Control, 2010 forcing





SPEAR_LO
RMSE = 0.84

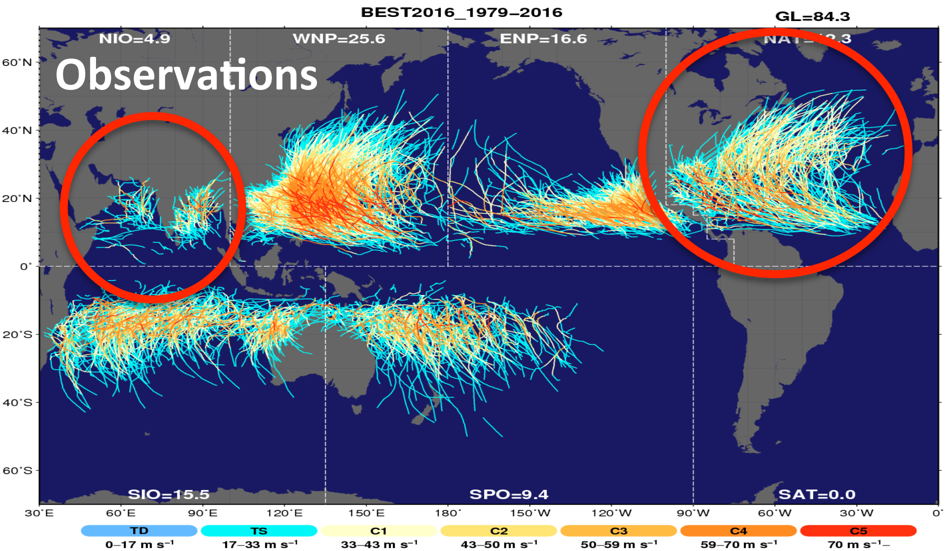


SPEAR_MED
RMSE= 0.86

SPEAR model shows smaller SST bias compared with FLOR

Simulated TCs in SPEAR

Delworth et al. (in prep)



Tropical cyclone statistics

RMSE

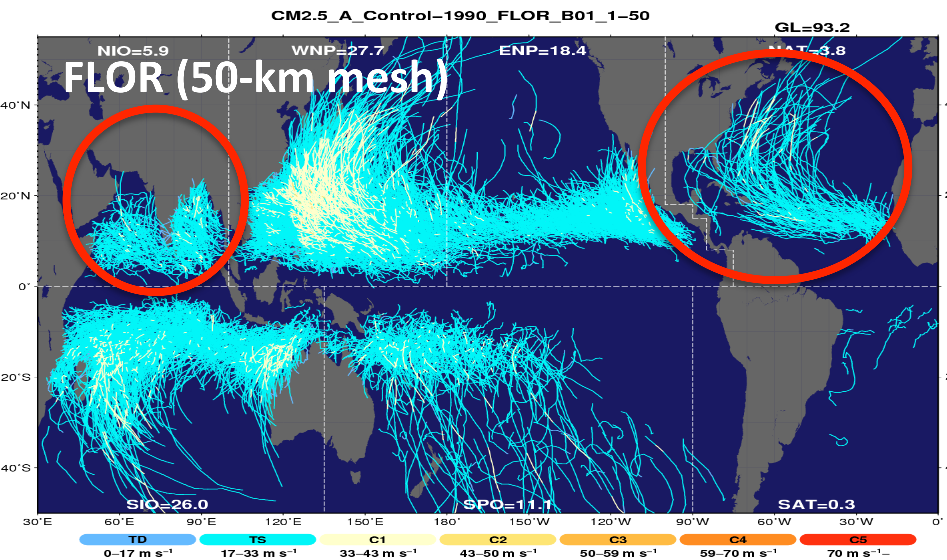
FLOR: 0.58

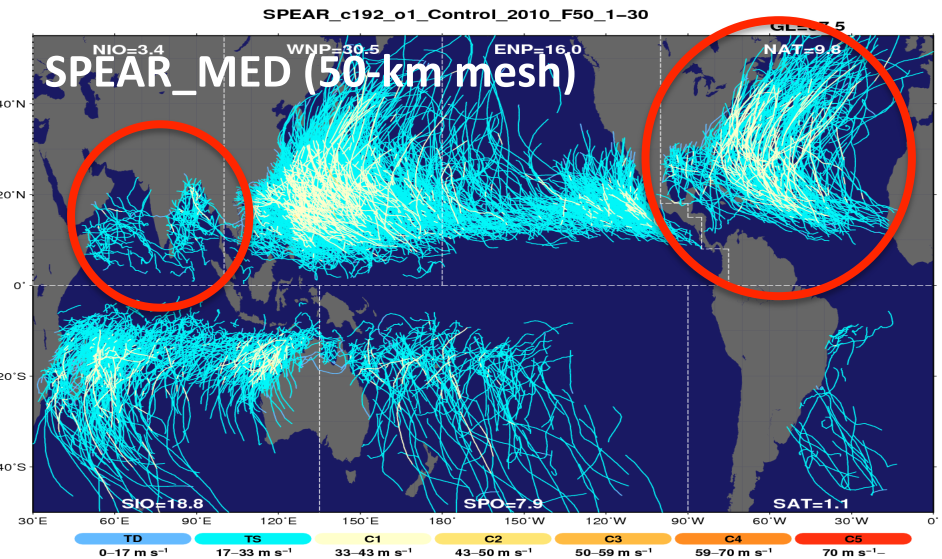
SPEAR_MED: 0.41

Spatial Correlations

FLOR: 0.80

SPEAR_MED: 0.86





Delworth et al. (in prep)

Summary

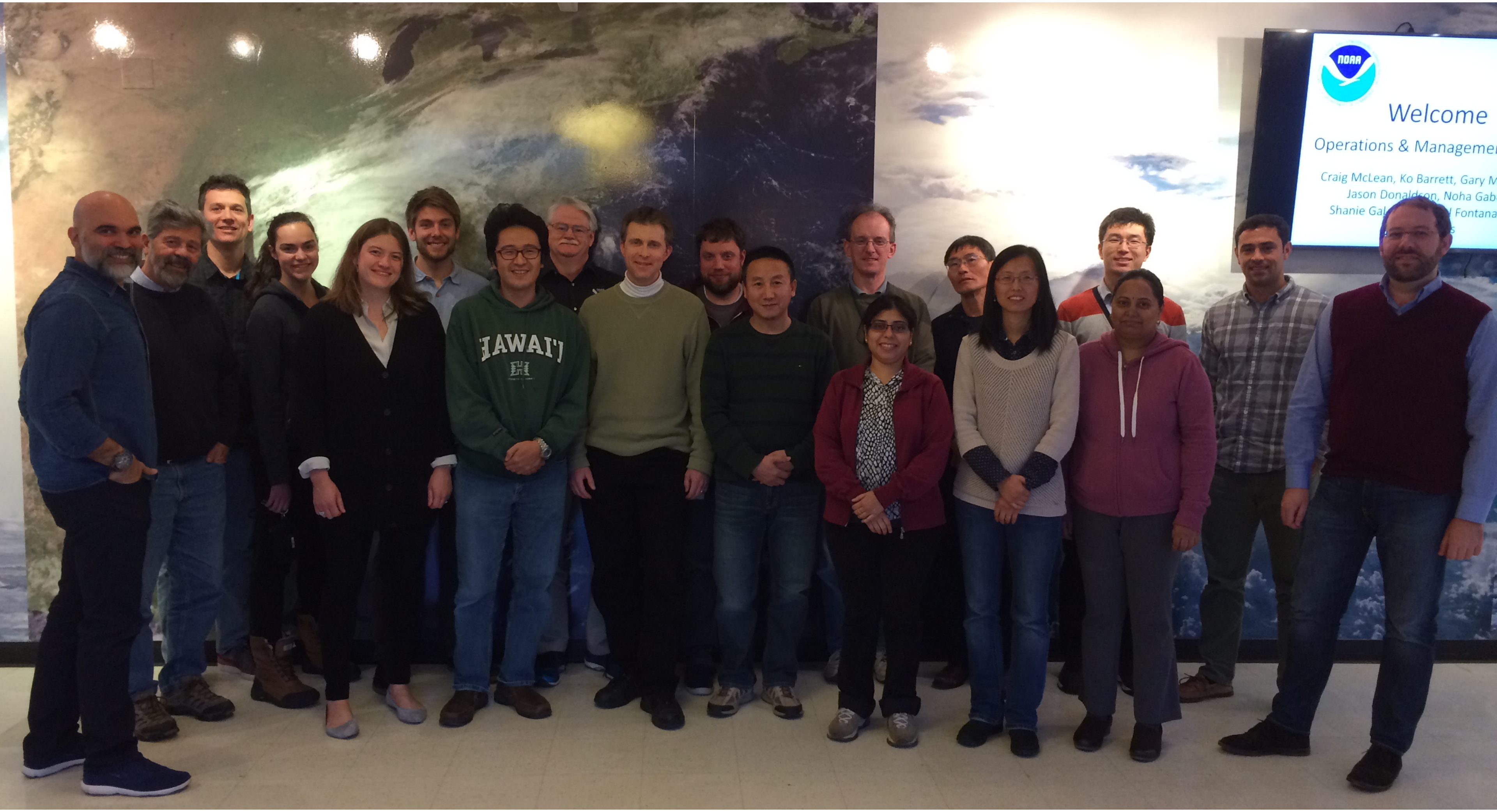
Part 1. Model Performance and Future Projections by HiFLOR

- HiFLOR can simulate C45 hurricanes as observed.
- HiFLOR projects an increase in frequency of global tropical storms, whereas FLOR projects a decrease in global frequency.
- Large-scale parameters do not account for the increase of storms. But changes in frequency of seeds may be a key for the increase.

Part 2. Seasonal Prediction of Tropical Cyclones

- HiFLOR has potential to predict major hurricanes a few months in advance.
- The active 2017 major hurricanes were controlled by the tropical ocean surface warming in the North Atlantic.
- Relative SST anomaly is a key for prediction of major hurricanes in the near future.
- A new seamless model (SPEAR) is under development.

Thank You!



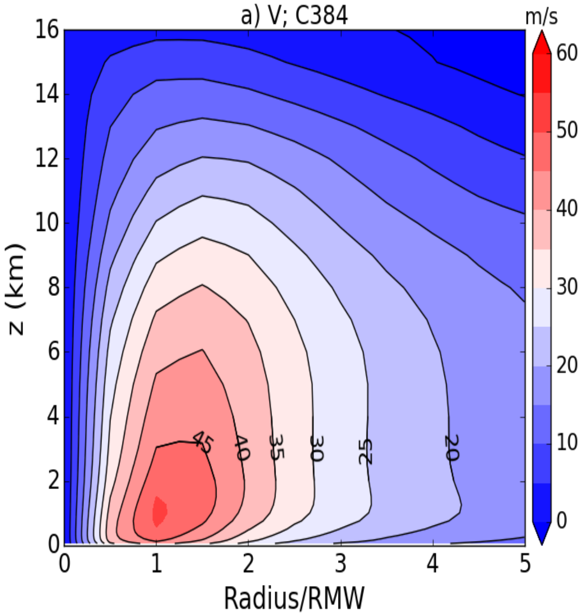
Members at Seasonal to Decadal Variability and Predictability Division

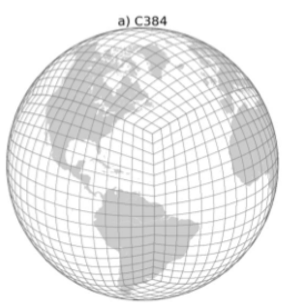
Azimuthal Mean of Tangential Wind Speed

Gao et al. submitted

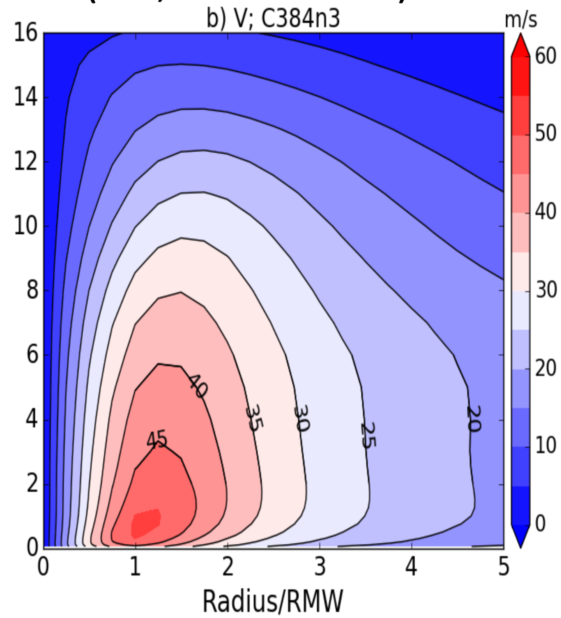
Radius-vertical cross sections of the composite tangential winds

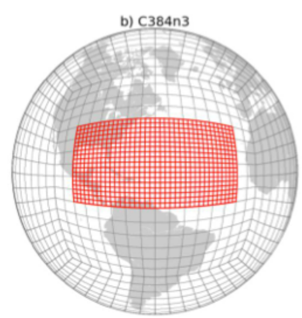
C384 (25-km mesh, HiFLOR)



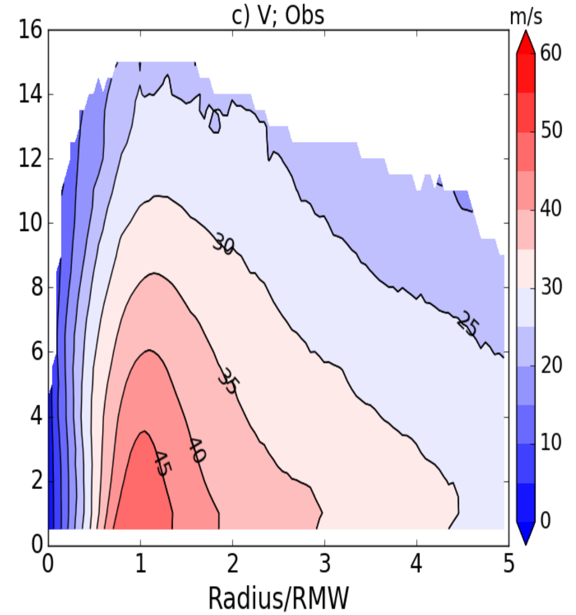


C384n3 configuration (i.e., 7-km mesh)



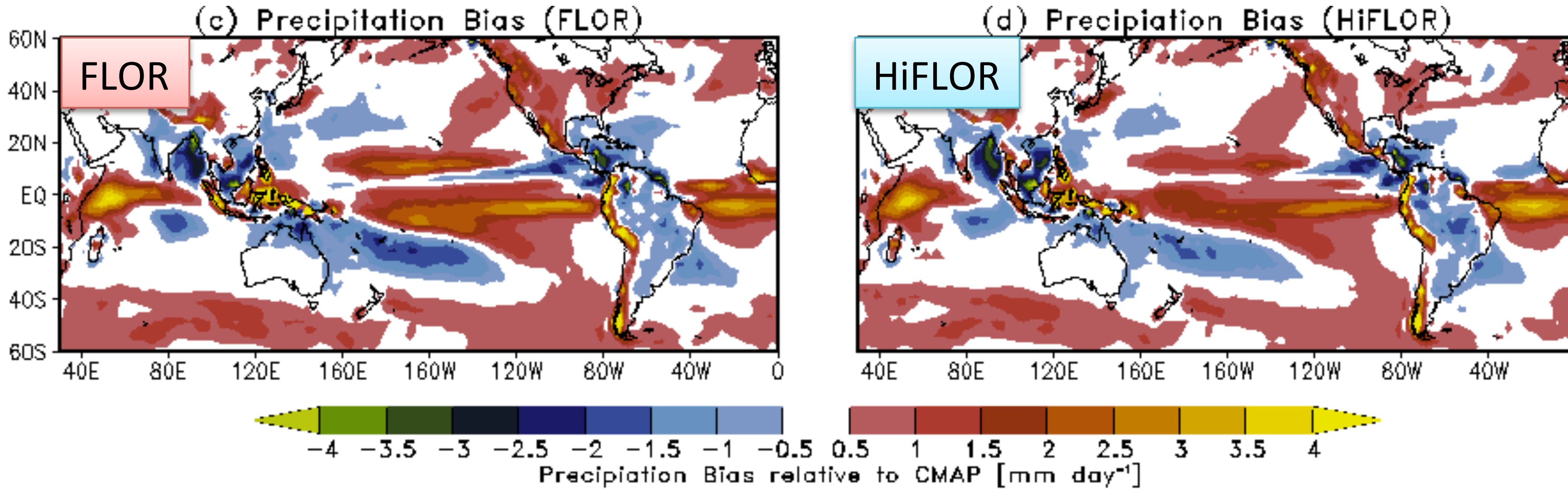


Observations (Doppler Radar)

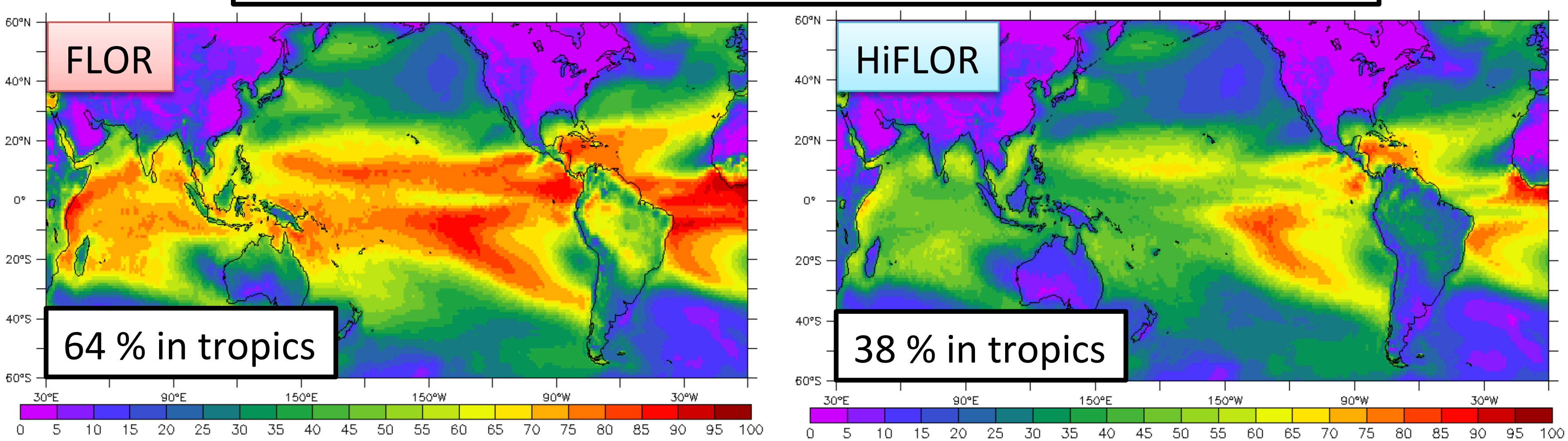


Precipitation Biases & Fraction of Deep Convection

Precipitation Biases [mm/day]

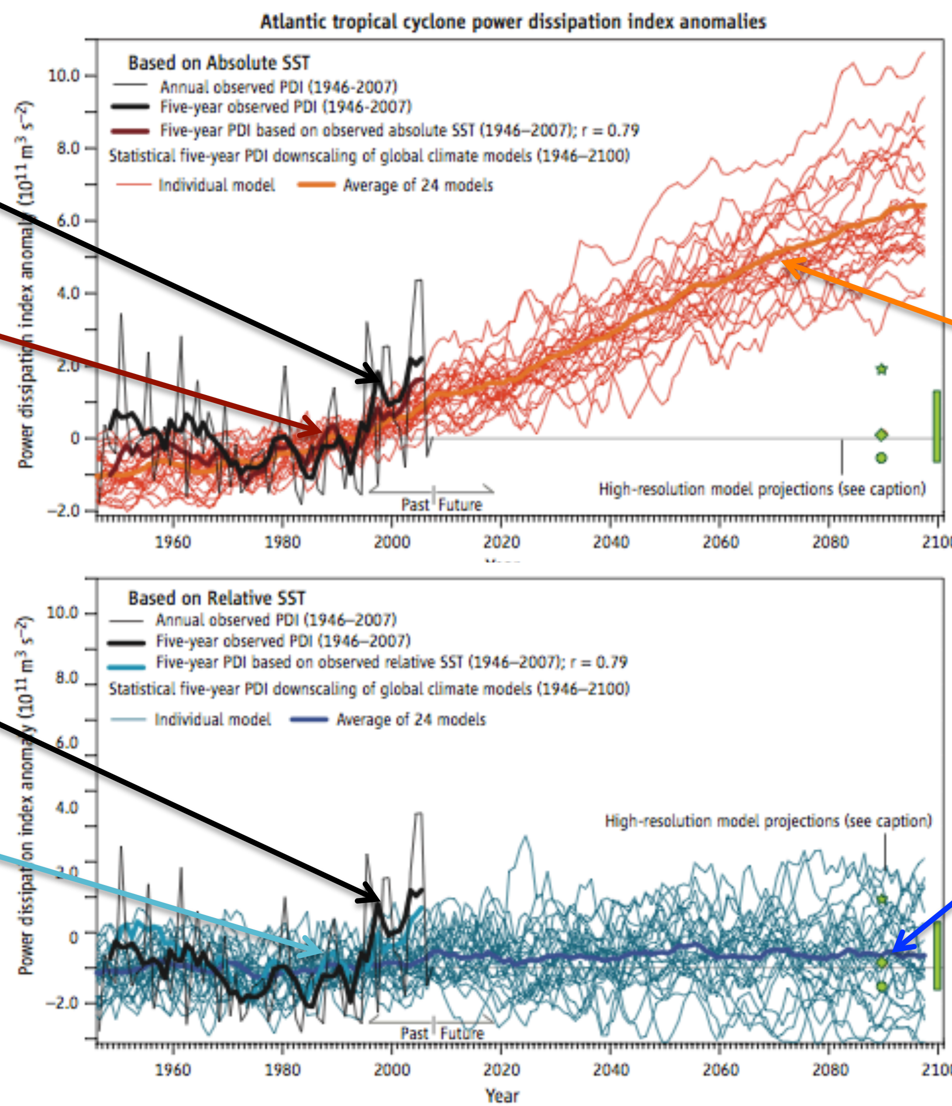


Fraction of Deep Convection Relative to Total Precipitation [%]



Which of local SST anomaly or relative SST anomaly is important for frequency of MHs in the North Atlantic?

PDI (Power Dissipation Index = $\sum V^3$)



Vecchi et al (2007)