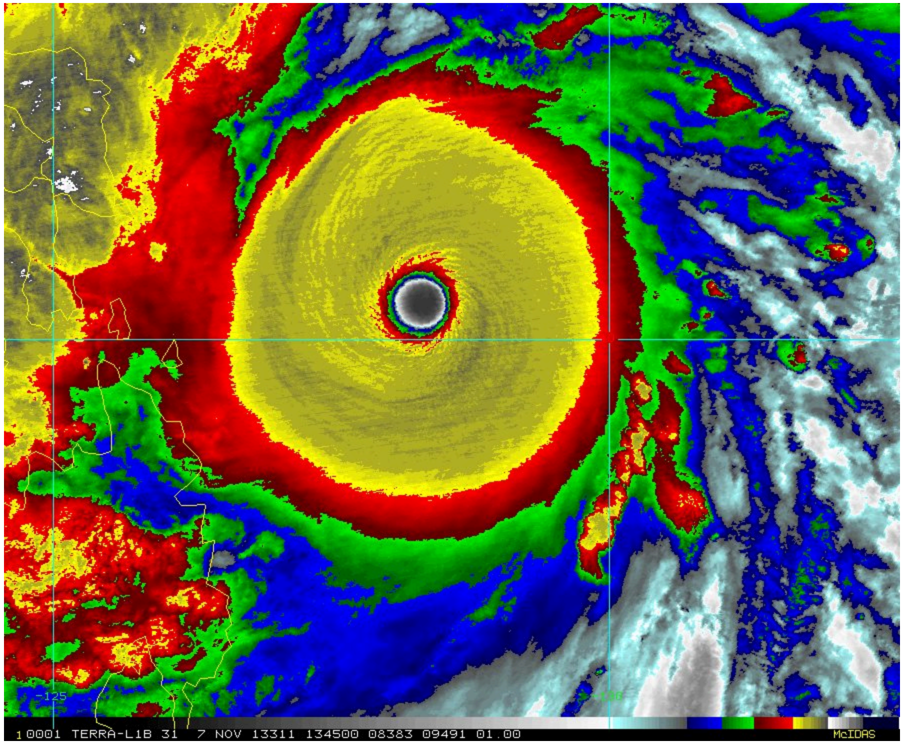
Tropical cyclones and climate change: an update focusing on the NW Pacific basin



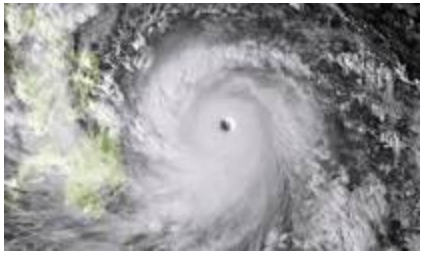
Super Typhoon Haiyan, 2013

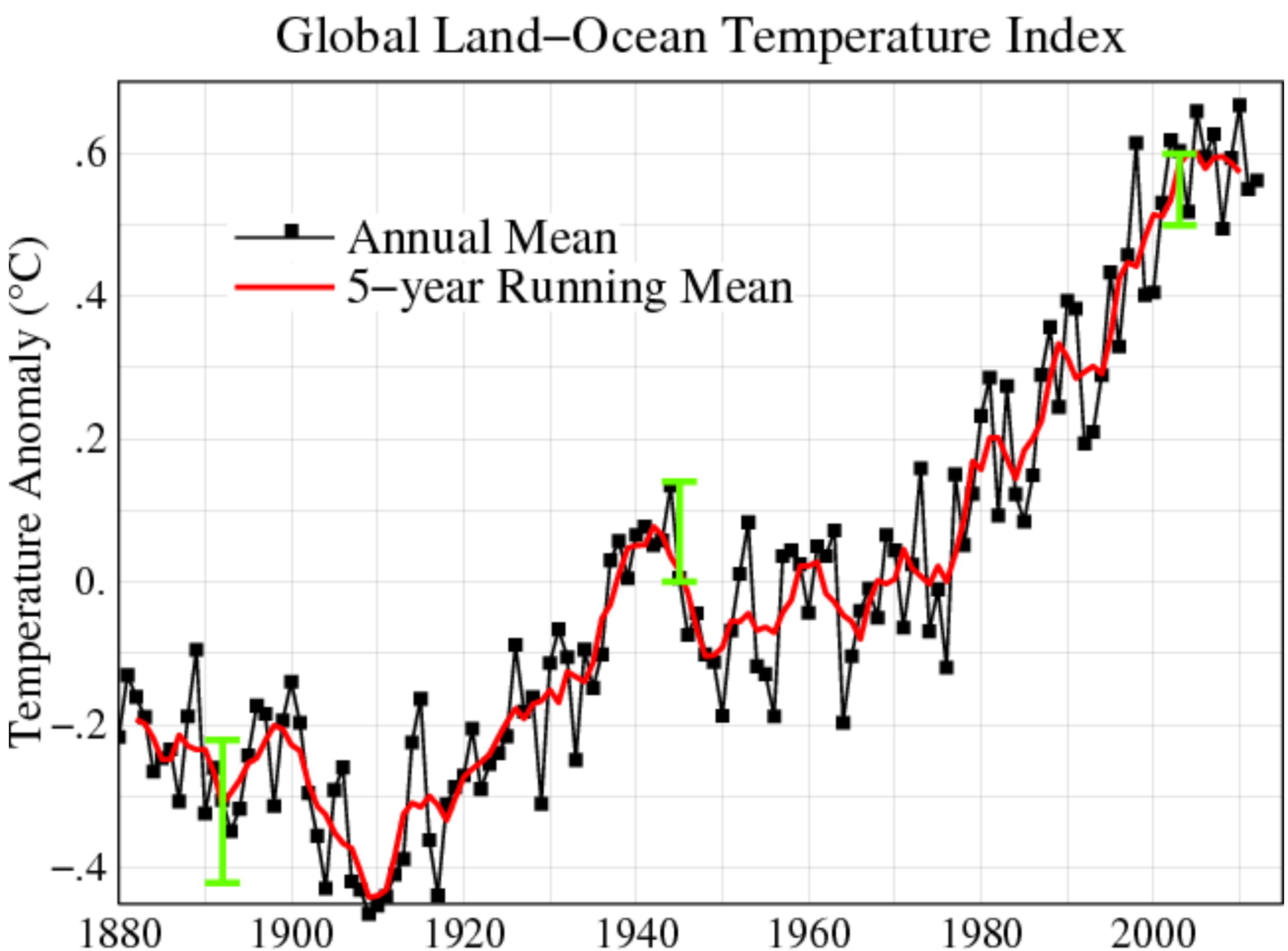
Tom Knutson

Geophysical Fluid Dynamics Lab/NOAA
Princeton, New Jersey, USA

December 2013

http://www.gfdl.noaa.gov/~tk





Source: NASA/GISS; Apr 2013

A strategy for obtaining more confident future projections of tropical cyclone activity

1. Is there a detectable past human influence on tropical cyclone activity? If so → confidence increases in projections…

2. Can our models simulate characteristics of present-day tropical cyclone activity and its variability?

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TROPICAL CYCLONES SUMMARY ASSESSMENT:

Detection and Attribution:

It remains uncertain whether past changes in any tropical cyclone activity (frequency, intensity, rainfall, etc.) exceed the variability expected through natural causes, after accounting for changes over time in observing capabilities.

Source: WMO Expert Team on Climate Change Impacts on Tropical Cyclones. February 2010

IPCC AR5 Summary for Policymakers (Sept. 2013)
[Statements related to TCs and climate change]

<u>Phenomenon:</u>
- Increase in intense tropical cyclone activity

<u>Assessment that changes occurred:</u>
- Low confidence in long-term (centennial) changes
- Virtually certain in North Atlantic since 1970

<u>Assessment of a human contribution to observed changes:</u>
- Low confidence
- "There is medium confidence that a reduction in aerosol forcing over the North Atlantic has contributed at least in part in the observed increase in tropical cyclone activity since the 1970s in this region."

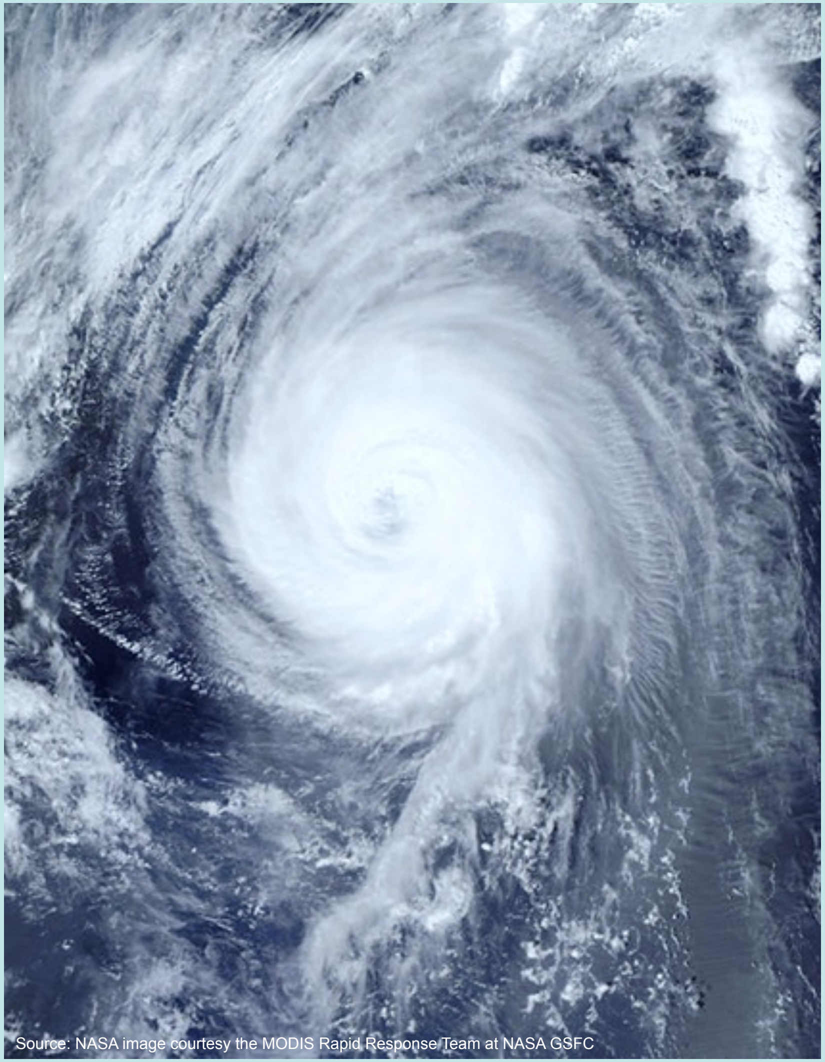
<u>Likelihood of further changes (late 21st century):</u>
- More likely than not (Western North Pacific and N. Atlantic)

Second Assessment Report on Impacts of Climate Change on Tropical Cyclones in the Typhoon Committee Region

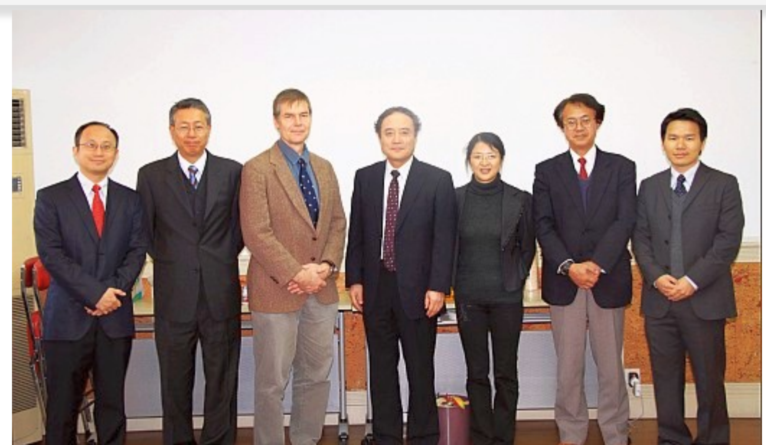
By :

Ming YING (China),
Thomas. R. KNUTSON (USA),
Tsz-Cheung LEE (Hong Kong, China)
Hirotaka KAMAHORI (Japan)
Weng-Kun LEONG* (Macao, China)

*Expert team coordinator



Source: NASA image courtesy the MODIS Rapid Response Team at NASA GSFC



Also in picture: Leong Kai Hong and Koji Kuroiwa

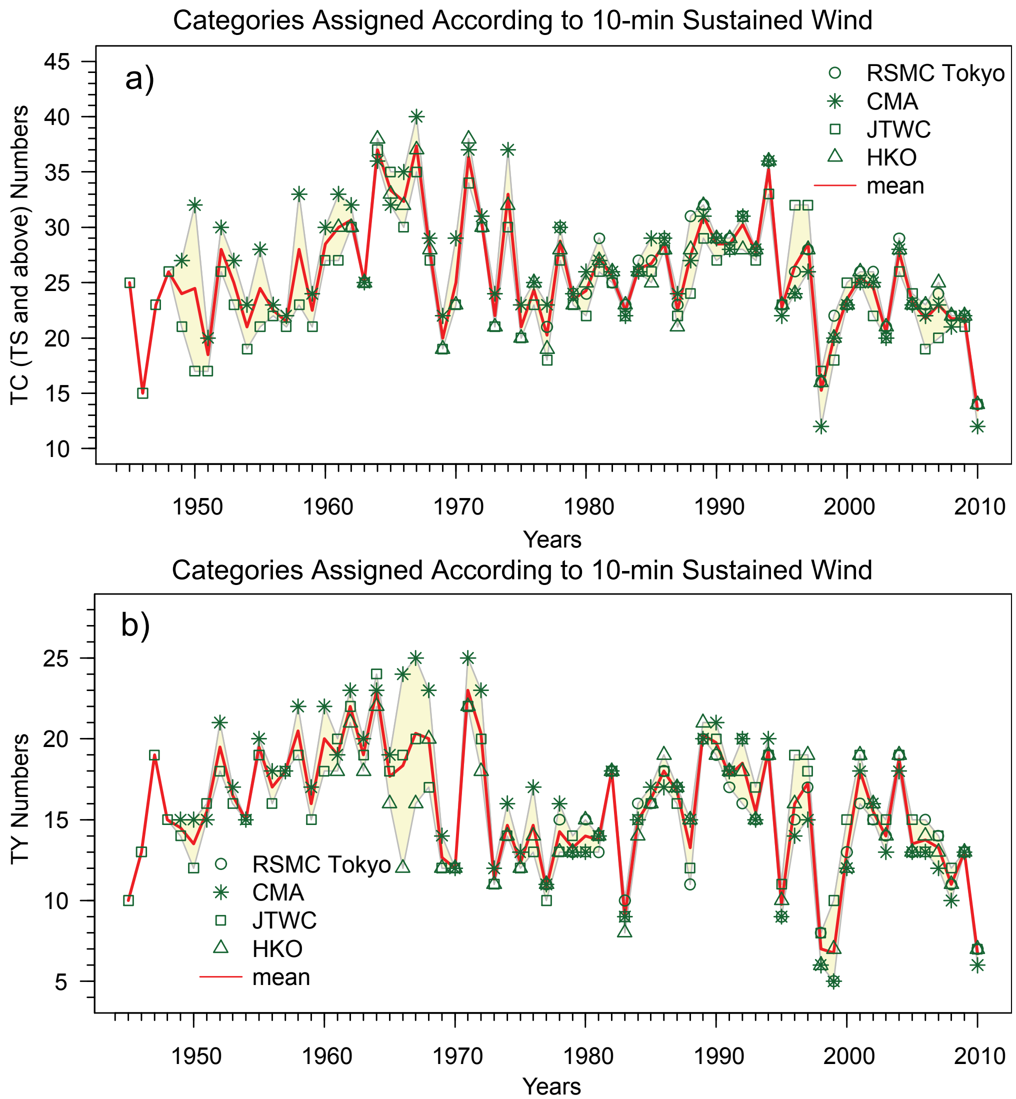
Past changes in NW Pacific basin-wide TC activity

Tropical cyclone frequency

- Significant inter-annual and inter-decadal variations in the annual storm count in WNP

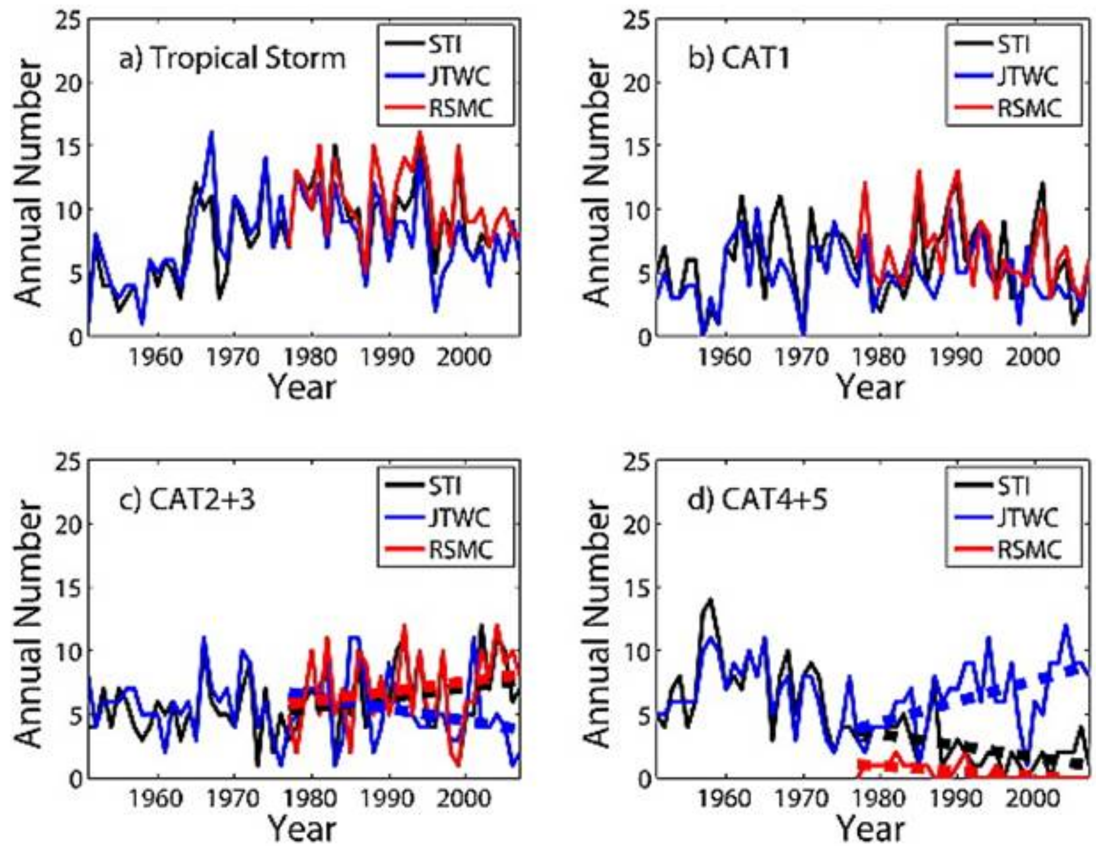
TCs (Tropical storms or above)

Typhoons



NW Pacific basin Tropical cyclone intensity

- Significant inter-decadal variations
- Notable discrepancies between data sets from different centers for the WNP basin, in particular for intense typhoons
- After 1987, the RMSC data has less Cat. 4-5 storms, while JTWC data set has more over the same time period.
- None of the available WNP Cat. 4-5 time series from any of the centers shows a pronounced positive trend over time

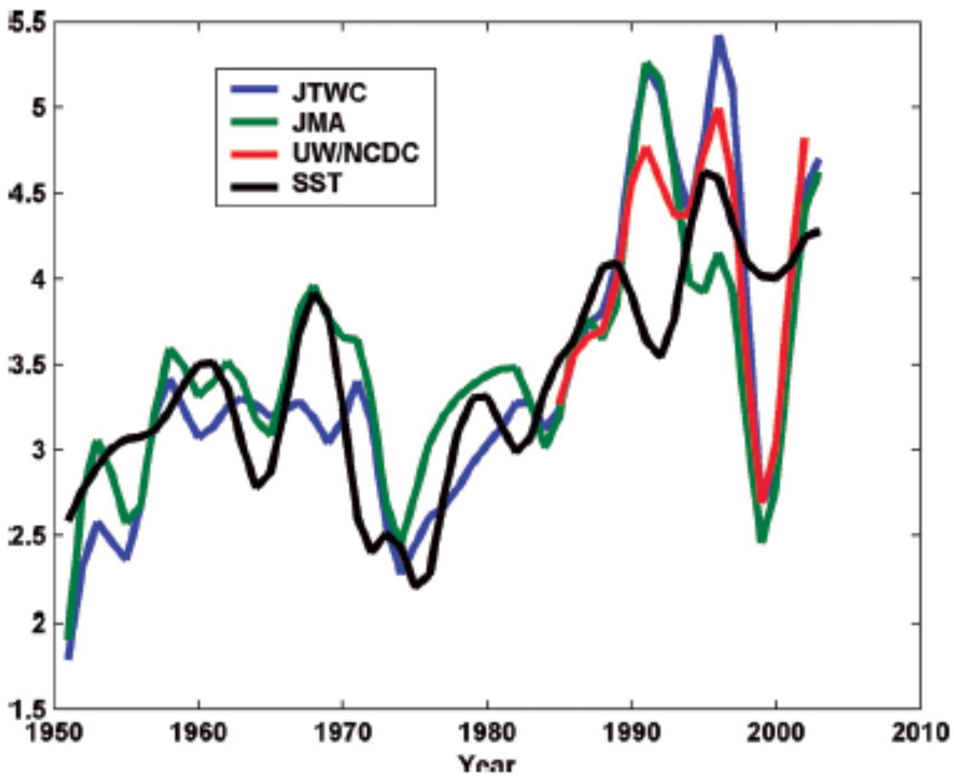


Annual numbers and linear trends of:
a)TS;
b)Cat. 1;
c)Cat. 2-3; and
d)Cat. 4-5 storms for the WNP basin according to data from the STI (black), the U.S. JTWC (blue), and the RSMC-Tokyo (red).

From Song et al. 2010.

NW Pacific Integrated Storm Activity Metrics (ACE and PDI)

- Significant inter-decadal variations
- The PDI curves extending from the late 1940s show some evidence for a rise over time, although Emanuel presents no formal trend analyses of these data.
- In addition, the low-frequency variations show some correlation to low frequency variations of the WNP SST index, although this relationship appears to degrade in the years following discontinuation of the aircraft reconnaissance.

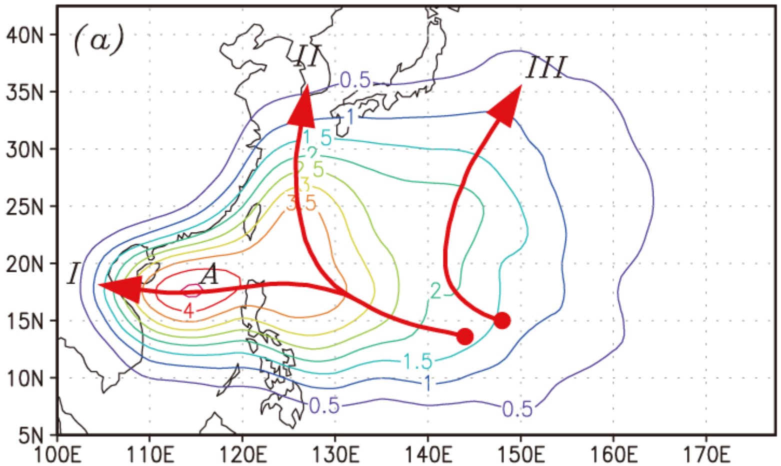


"PDI in WNP according to data from JTWC (blue) as adjusted by Emanuel (2005), unadjusted data from the RSMC-Tokyo (green), and reanalyzed satellite data from Kossin et al. (2007) (red).

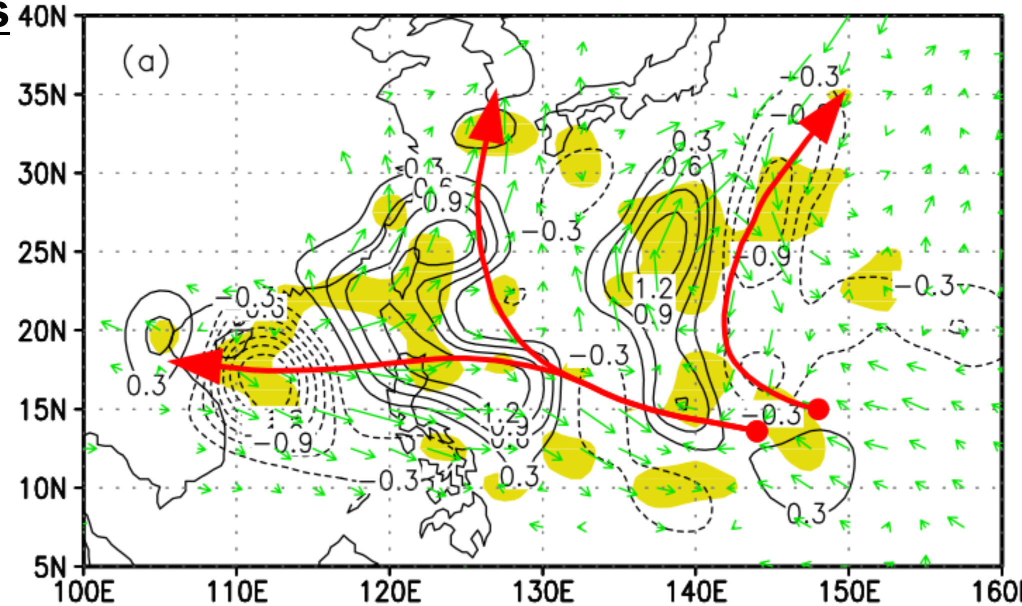
The black curve represents a scaled Jul–Oct SST in the tropical WNP region.
All quantities have been smoothed using a 1-3-4-3-1 filter."

From Emanuel, 2008.

NW Pacific Tropical cyclone tracks



Distribution of June-October mean frequency of TC occurrence (unit per year) derived from the JTWC Best Track data from 1963 to 2003 (Wu et al., 2005)



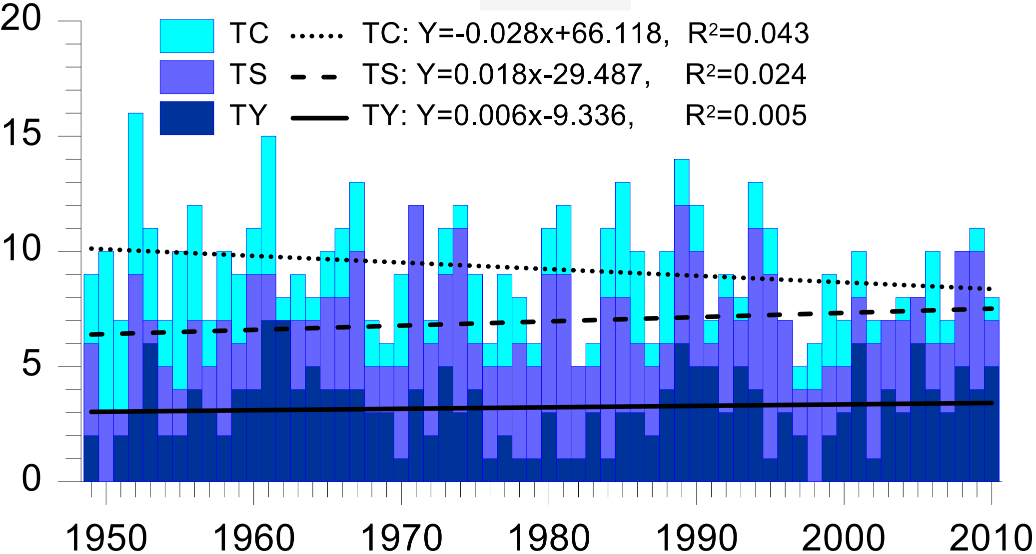
Linear trends in the June-October mean frequency of TC occurrence and in the TC motion vectors. The areas with confidence level exceeding 95% for the changes are shaded. (Wu et al., 2005)

- Negative trend values over the central South China Sea depict a decrease in the number of the TCs that follow track I
- Positive trends extending from the Philippine Sea to the eastern coast of China and the eastern part of the basin indicate a westward shift of prevailing tracks II and III, respectively.
- A decrease in westward-moving TCs and an increase in recurving TCs—including those taking tracks toward Japan or the Korean Peninsula.

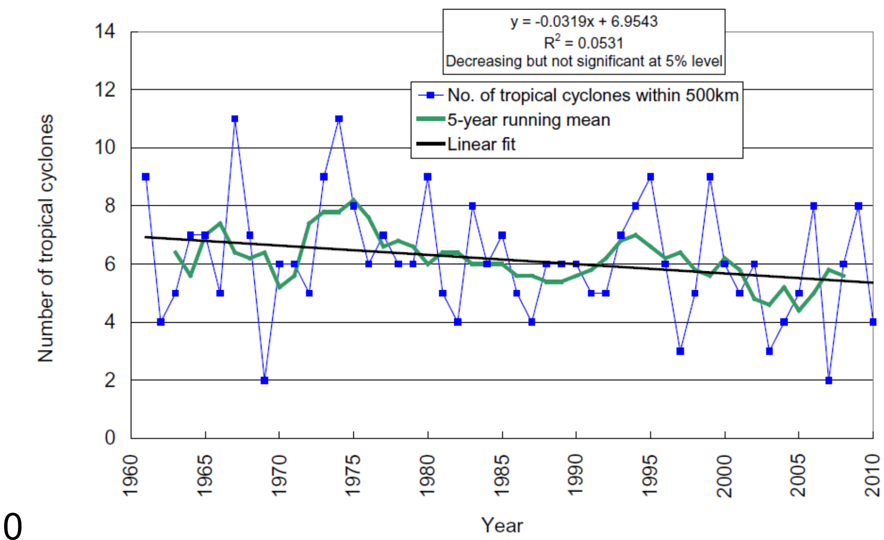
NW Pacific Trends of landfalling tropical cyclones

- No significant trend for China, Japan (tropical storm or above), the Philippines, the Korean peninsula and in the vicinity of Hong Kong and Macao.
- Although not statistically significant, the trends are negative for China and in the vicinity of Hong Kong and positive for the Korean peninsula.

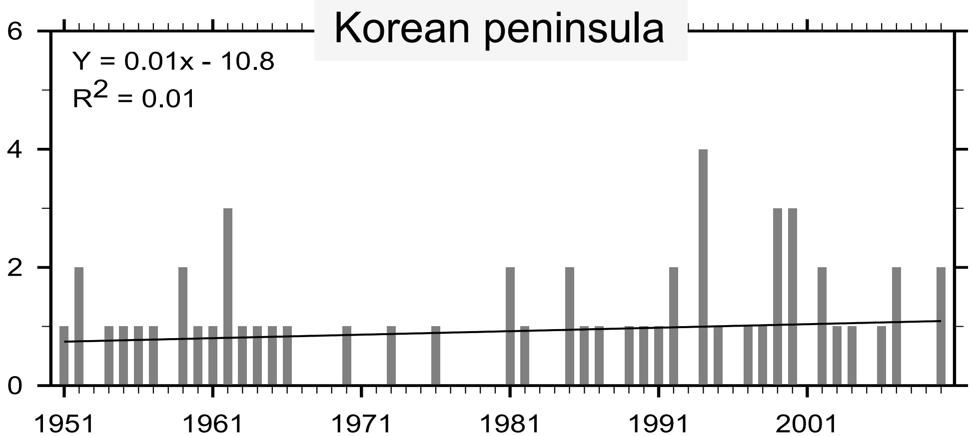
China



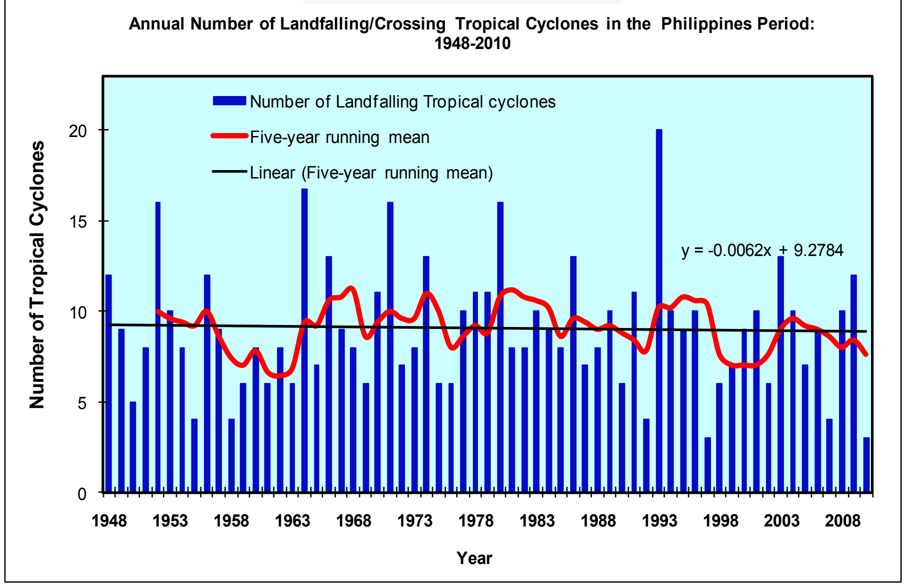
Vicinity of Hong Kong, China



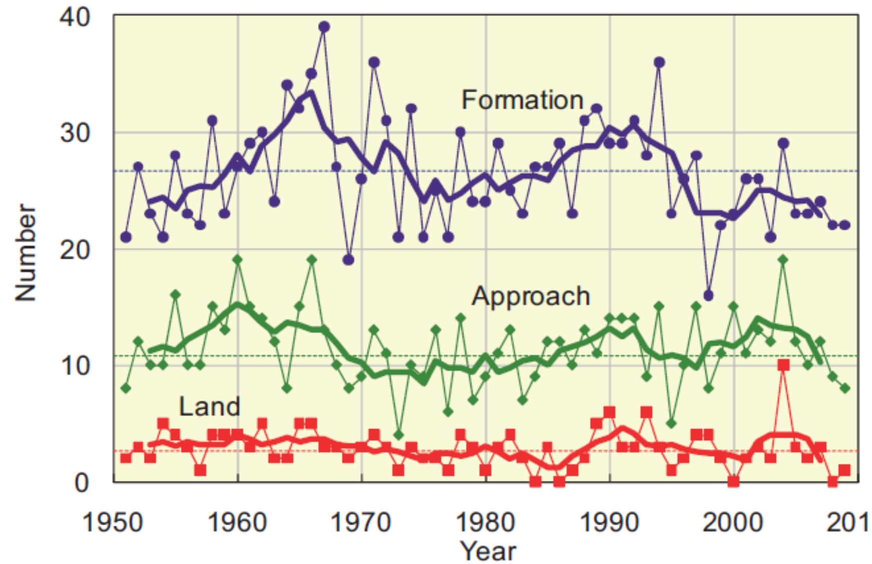
Korean peninsula



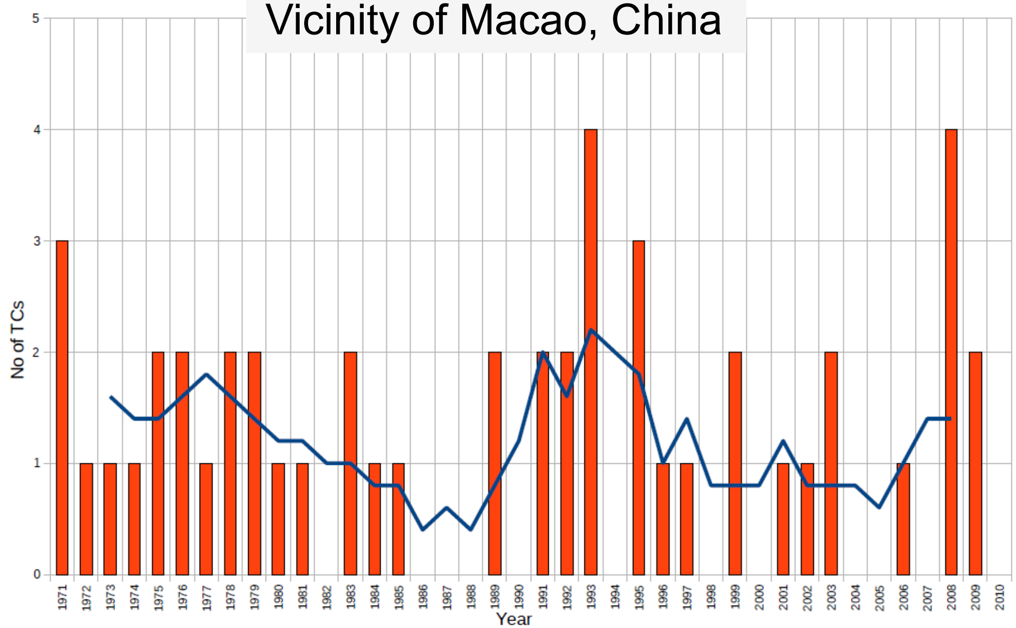
the Philippines



Japan

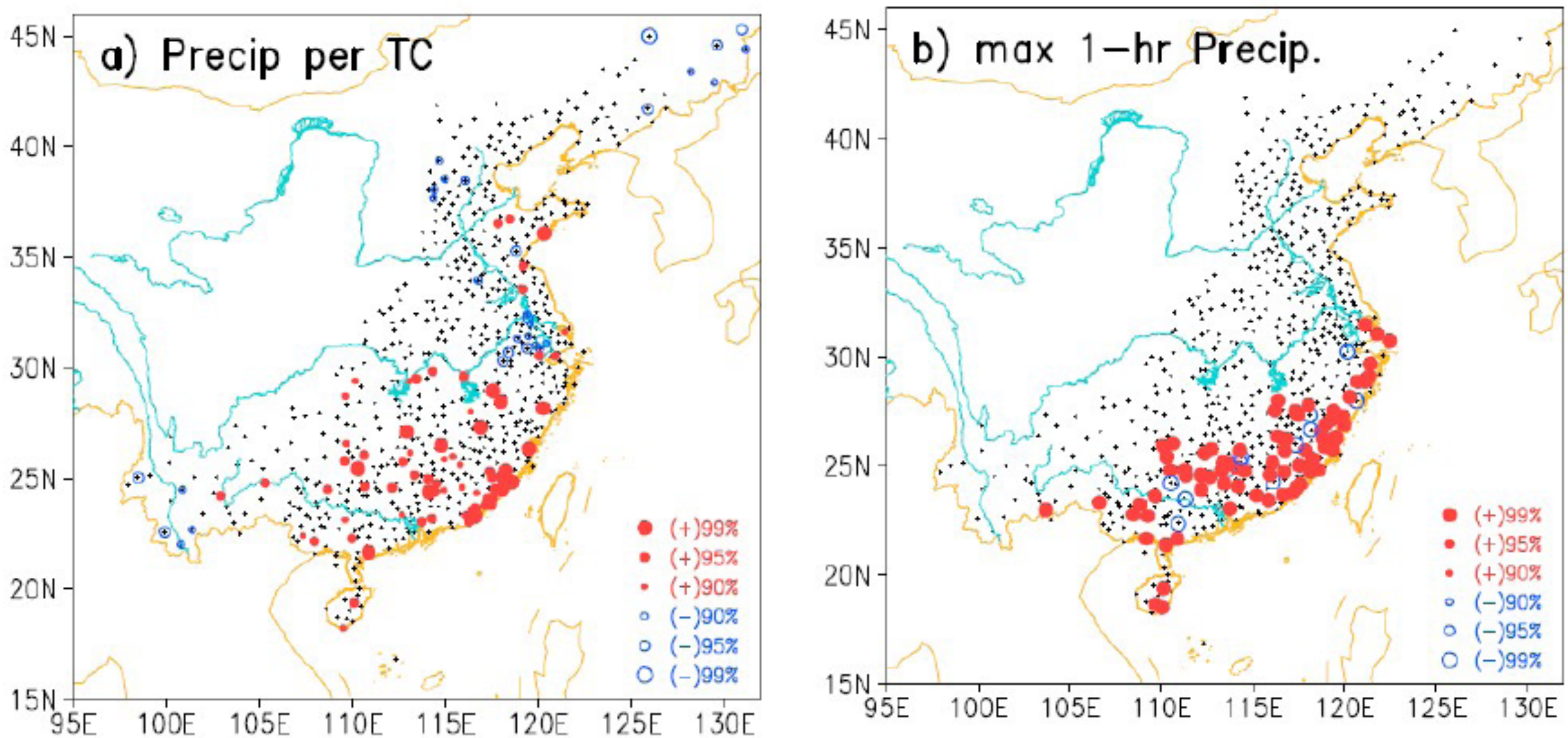


Vicinity of Macao, China



Observational study of TC rainfall changes (Ying et al. 2011)

In China, changes in TC induced precipitation per TC and maximum 1-hour precipitation have substantial spatial variations in China with significant increasing trends at a number of stations, mainly over coastal and near-coastal areas of southeastern China. However, the majority of stations over central and northeastern China in their analysis did not have statistically significant trends (Ying et al. 2011)



Significant climatic trends (red and blue dots) for the median of (a) precipitation per TC and (b) maximum 1-hour precipitation in China (1955 to 2006).

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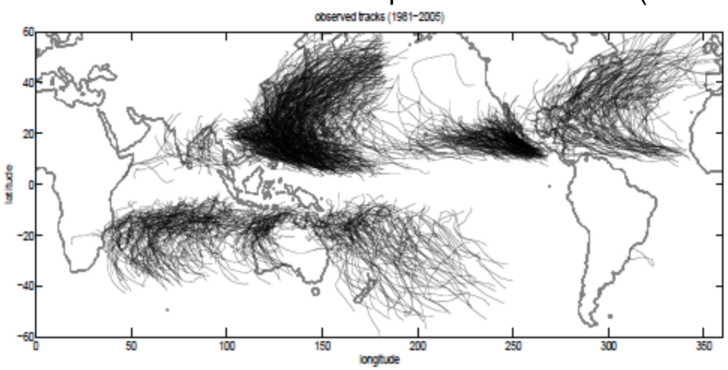
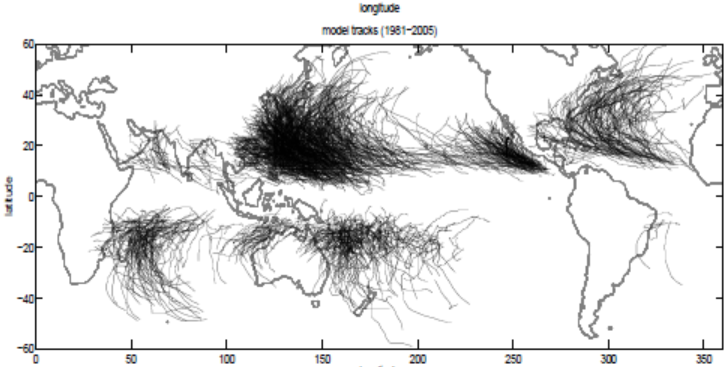
GFDL HIRAM 50 km grid model TC simulations

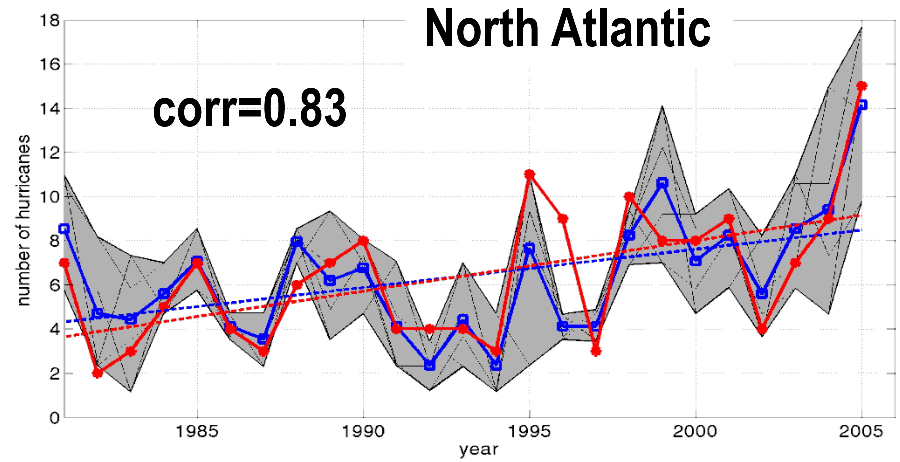
red: observations
blue: HiRAM ensemble mean
shading: model uncertainty

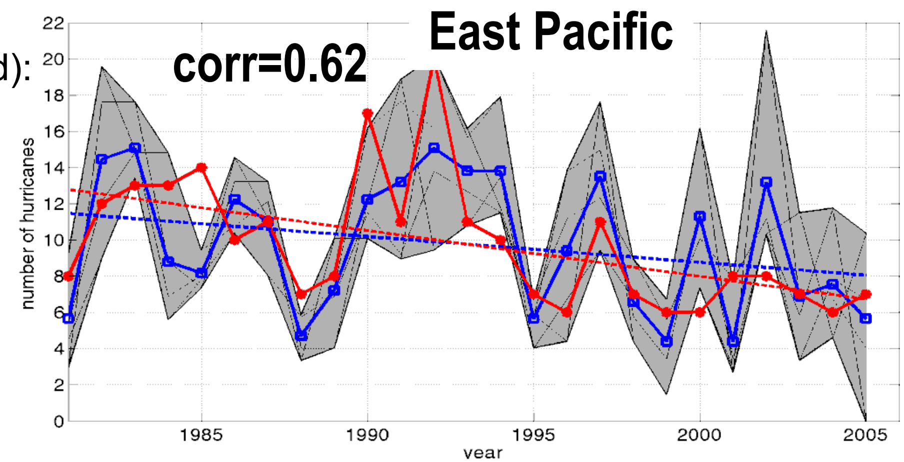
GFDL HIRAM 50km grid global model (SST-forced):
Simulated vs Observed Tropical Storm Tracks (1981-2005)

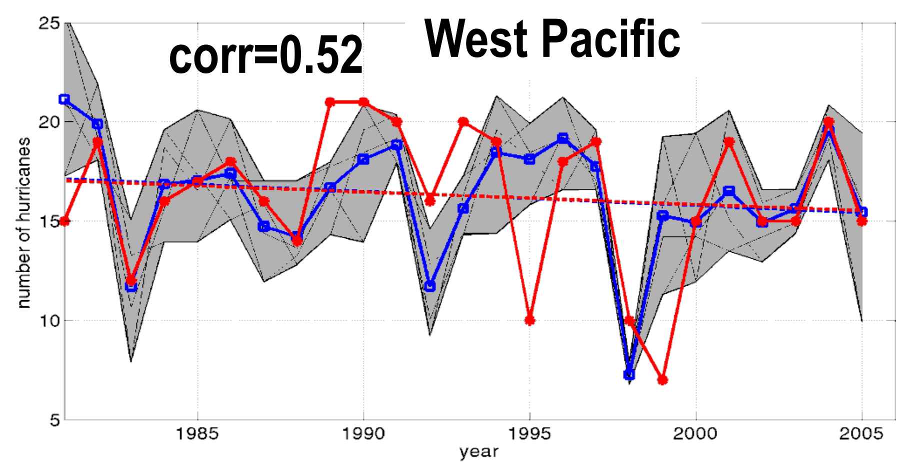




Source: Zhao, Held, Lin, and Vecchi (J. Climate, 2009

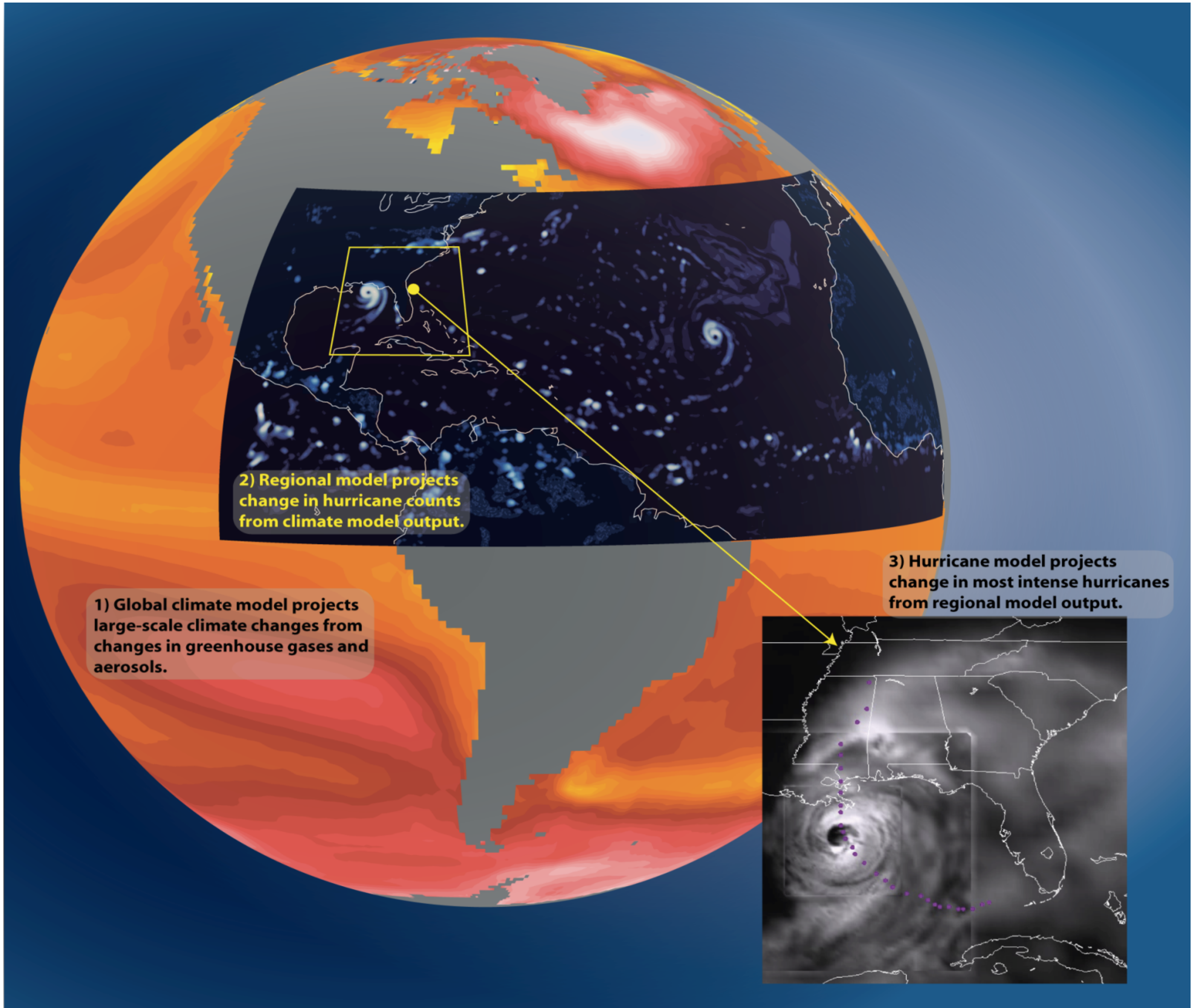




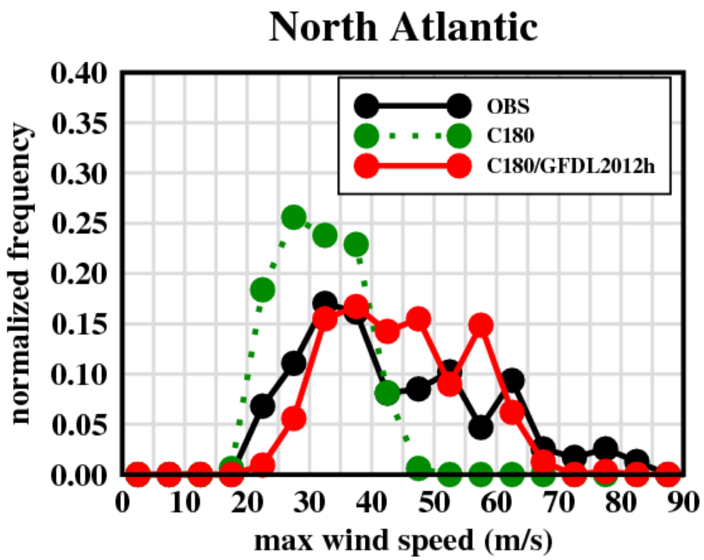


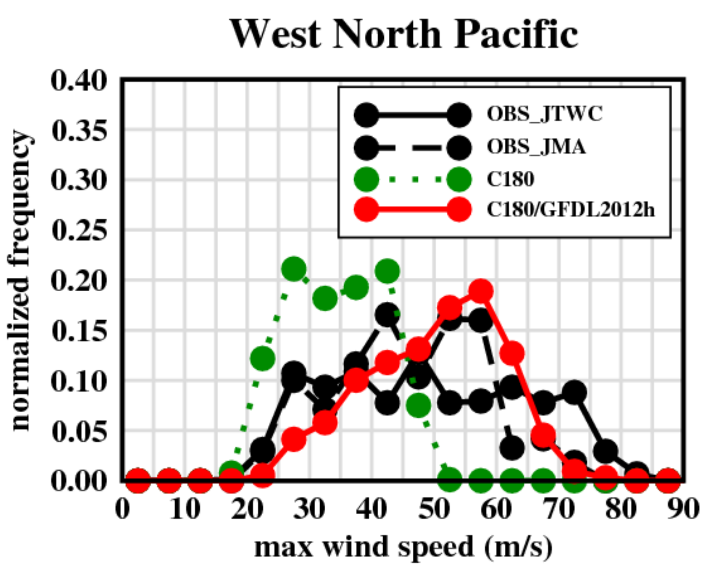
A “double-downscaling” approach for modeling the frequency of intense Atlantic hurricanes.

Bender et al., *Science,* 2010.



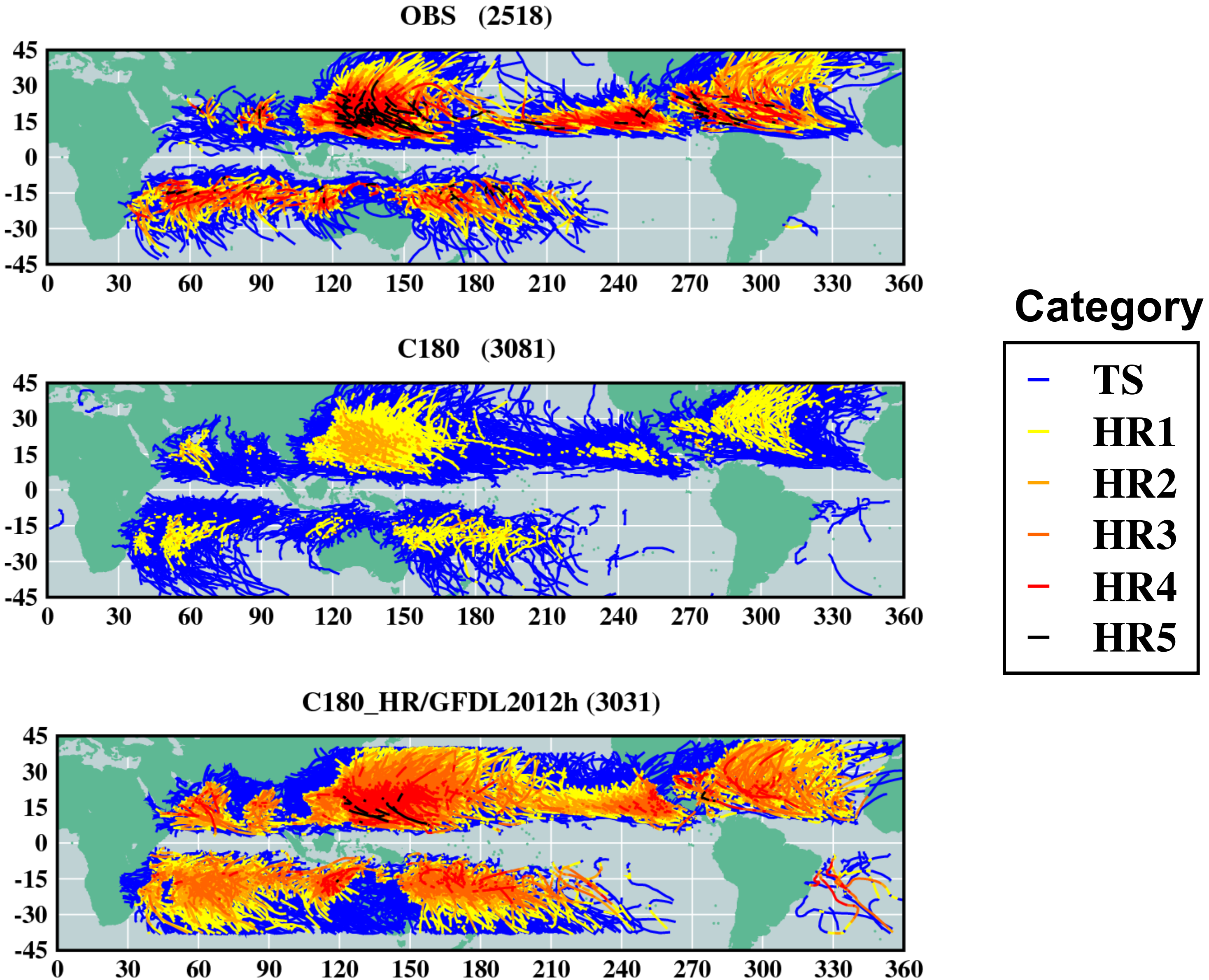
Normalized histogram of maximum winds (1980-2008 SSTs)





GFDL dynamical downscaling to 6 km grid model; preliminary results 2013.

Tropical Storms (1980-2008)



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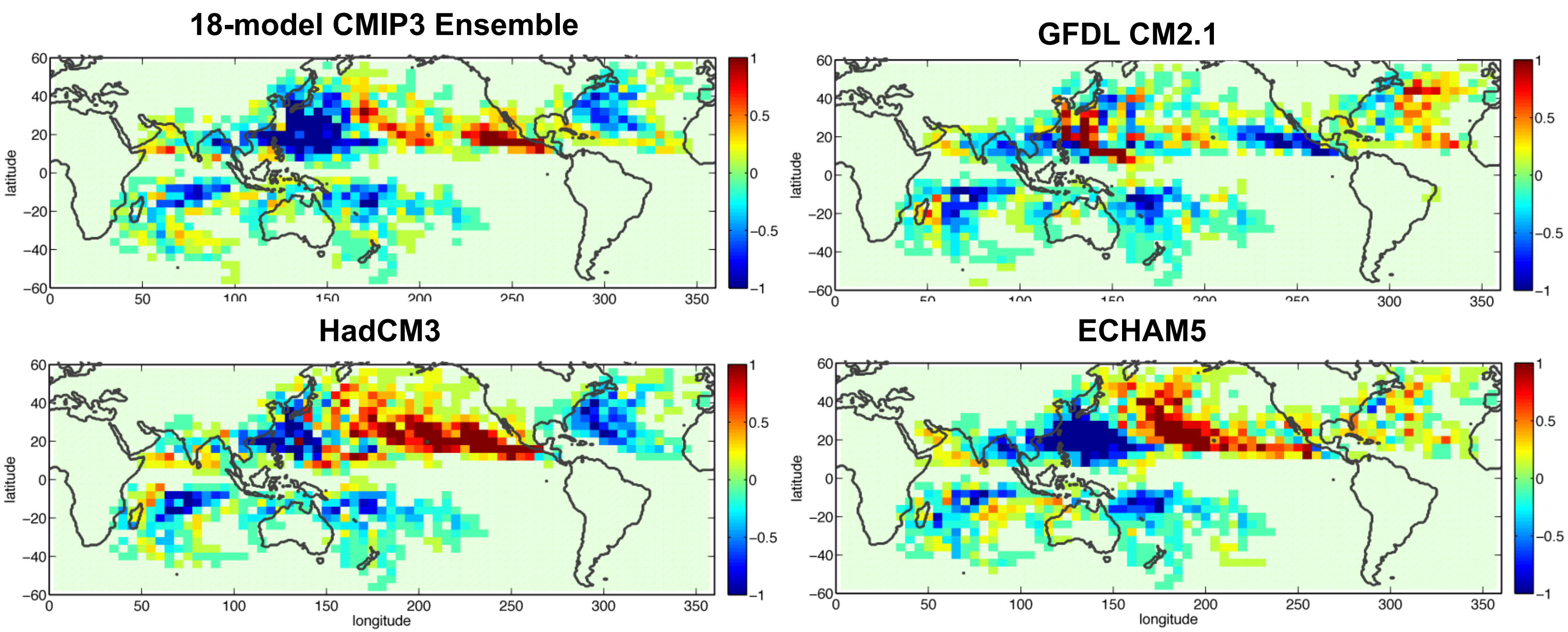
Global tropical cyclone activity: Late 21st century projected changes based on CMIP3

GFDL 50-km HIRAM, using four CMIP3-based projections of SSTs.



Red/yellow = increase
Blue/green = decrease

Unit: Number per year

- Regional increases/decreases much larger than global-mean changes.
- Pattern depends on details of SST change.

Source: Auxiliary figure from Zhao, Held, Lin and Vecchi (J. Climate, 2009)

Summary of projections results of the twelve available studies on the WNP tropical storm frequency projections from dynamical models having a grid spacing finer than about T106 or 120 km

(Extracted and simplified based on Table 5.1 of the 2nd Assessment Report)

Study reference	**Model details**	**WNP** (changes: %, significance in bold)
Sugi et al. (2002)#	JMA , T106 L21 (~120 km)	**-66**
McDonald et al. (2005) * #	HadAM3, N144 L30 (~100 km)	**-30**
Hasegawa and Emori (2005) #	CCSR/NIES/FRC GC T106 L56 (~120 km)	-4
Oouchi et al. (2006) #	MRI/JMA, T106 L21 (~120 km)	**-38**
Stowasser et al. (2007) #	NCAR CCSM2 IPRC regional model (downscaling)	+19
Bengtsson et al. (2007) #	ECHAM5 T213 (~60 km) T319 (~40 km)	-20 (T213) -28 (T319)
Gualdi et al. (2008) #	SINTEX-G coupled model T106 (~120 km)	-20
Zhao et al. (2009)	GFDL AM2.1, (~ 50 km)	**-29** (CMIP3 Ensemble), -5 (CM2.1), **-12** (HADCM3), **-52** (ECHAM5)
Sugi et al. (2009) #	JMA/MRI AGCM, (~20km, ~60 km)	**-36** (MRI CGCM2.3, 20km), **-29** (MRI CGCM2.3, 20km), **+28** (MIROC-H,20km), **-26** (CMIP3, 18 ens. mean, 20km), **-36** (MRI CGCM2.3, 60km), **+64** (MIROC-H, 60km), -14 (CMIP3, 18 ens. mean, 60km), +13 (CSIRO, 60km)
Murakami and Sugi (2010)	MRI/JMA-AGCM TL95 (180 km), TL159 (120 km), TL319 (60 km), TL959 (20 km)	**-18.5** (TL95), **-26.0** (TL159), -11.7 (TL319), **-26.8** (TL959)
Murakami et al. (2011b)	MRI□AGCM, (60 km)	+8, -1, -5, -22, -22, **-25**, **-28**, **-30**, **-35**, **-35**, **-40**, **-45**
Murakami et al. (2011c)	MRI□AGCM v3.2 and v3.1, (20 and 60 km)	**-27** (v3.1 20km), **-23** (v3.2 20km), -20 (v3.1 60km), **-28** (v3.2 60km)

Cited in the first assessment report (Lee et al., 2010).

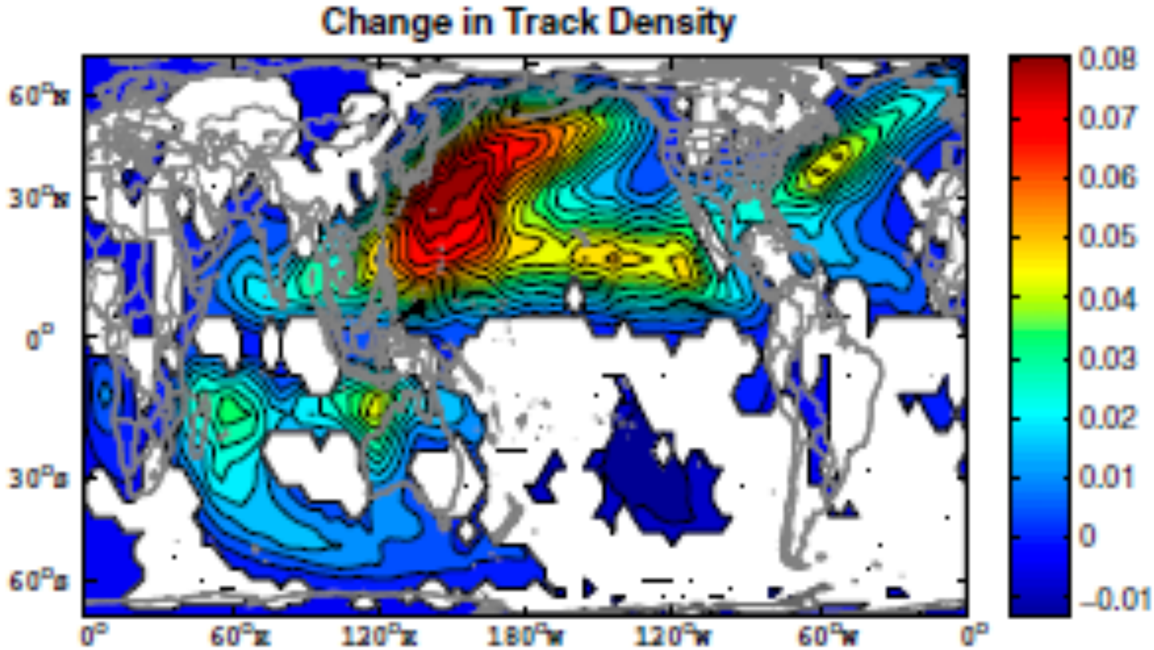
Summary of projections results of the nine available studies on the WNP TC intensity

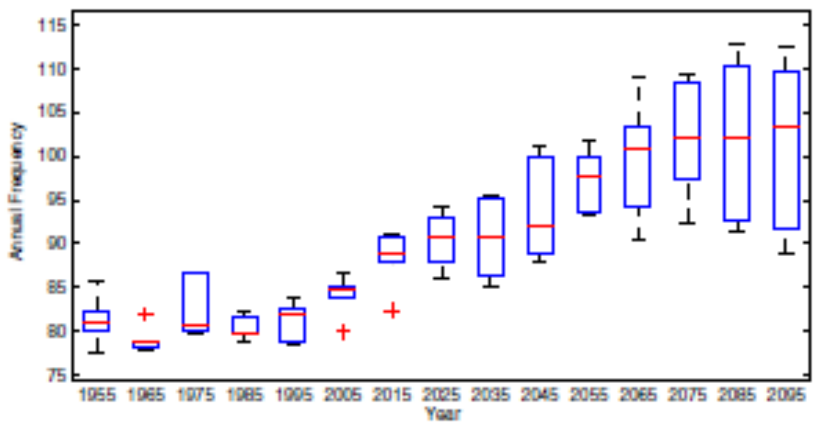
(Extracted and simplified based on Table 5.2 of the 2nd Assessment Report)

Study reference	**Model details**	**WNP** (changes: %, significance in bold)
Knutson and Tuleya (2004)#	Regional model downscale (~9km grid) of TCs in idealized (e.g., no shear) environments	+7.0 (-1.0, 19.6) in MCP**, +8.5 (2.8, 25.2) in MCP, +17.3 (9.4, 30.6) in MCP, +5.4 (3.3, 6.7) in MSW +13.6 (8.0, 16.5) in MCP
Hasegawa and Emori (2005)#	JMA, T106 L21 (~120 km)	Decrease (all intensity)
Oochi et al. (2006)#	MRI/JMA TL959 L60 (~20km)	+4.2 (average lifetime MSW) -2.0 (average annual max MSW)
Stowasser et al. (2007)#	NCAR CCSM2 IPRC Reg. Model downscale (~50km)	+50 (PDI and intensity in July to October)
Vecchi and Soden (2007)	CMIP3 18 models	+2.9 (-3.1, 12.6) PI
Emanuel et al. (2008)	(CCSM3, CNRM-Mk3.0, CSIRO-Mk3.0, ECHAM5, GFDL-CM2.0, MIROC3.2, MRI-CGCM2.3.2a)	+4.1 (MSW, PDI)
Yu et al. (2009)	CMIP3	PI: +1.3 ms^{-1} (-0.1 to 2.4 ms^{-1}), i.e., +2.0% (-0.2 to 3.9%). DPI: +2.3% (13 out of 15 models show an increase).
Murakami et al. (2011a)	MRI/JMA-AGCM (20 km mesh)	**+7.4** (East Japan, 95% confidence) **+7.2** (West Japan, 95% confidence) +1.8 (Korea), +4.4 (North China), +1.1 (Central China) **+7.4** (South China, 99% confidence), +1.0 (Taiwan) **+5.8** (Southeast Asia, 90% confidence), **+8.7** (Philippines, 95% confidence)
Murakami et al. (2011c)	MRI-AGCM v3.2 and v3.1 (20 km)	**+18.1** (v3.1, mean MSW, 99% confidence) **+7.1** (v3.2, mean MSW, 99% confidence) **+15.5** (v3.1, lifetime max MSW, 99% confidence) **+6.2** (v3.2 lifetime max MSW, 95% confidence)

Cited in the first assessment report (Lee et al., 2010). ** MSW: mean sustained wind speed; MCP: minimum central pressure.

CMIP5 (**RCP8.5)** 6-model average: 2006-2100 minus 1950-2005





Global average TC frequency (increase contrasts with other models reported in WMO expert team assessment; Knutson et al. 2010)

Source: K. Emanuel, *Proc. Nat. Acad. Sci.*, 2013

Emanuel reports a much larger projected increase in TC activity using CMIP5 models than CMIP3 models.

Table 2. Comparison between CMIP3 and CMIP5 changes in downscaled tropical cyclone frequency and power dissipation

Institute ID	CMIP3 model	CMIP5 model	CMIP3 change in global frequency, %	CMIP5 change in global frequency, %	CMIP3 change in global power dissipation, %	CMIP5 change in global power dissipation, %
NCAR	CCSM3	CCSM4	−3	+11	+5	+8
GFDL	CM2.0	CM3	−13	+41	+2	+72
MOHC		HADGEM2-ES		+22		+31
MPI	ECHAM5	MPI-ESM-MR	−11	+29	+4	+57
MIROC	MIROC3.2	MIROC5	−12	+38	+8	+80
MRI	MRI-CGCM2.3.2a	MRI-CGCM3	+2	+13	+22	+26

For CMIP3 models, the listed numbers are percentage changes from the 20-y period 1981–2000 to the 20-y period 2181–2200 under emissions scenario A1b. For the CMIP5 models, the listed numbers represent percentage changes from 1981–2000 to 2081–2100 under radiative forcing scenario RCP8.5.

Source: K. Emanuel, PNAS, 2013.

The GFDL HIRAM C180 global model TC downscaling projection does not show a strong dependence on CMIP5 vs. CMIP3

(Very preliminary analysis courtesy Ming Zhao)

Downscaled Global Tropical Cyclone Frequency Change (Late 21st century or late 22nd century):

GFDL C180 global model (Zhao)		Emanuel stat./dyn. model
GFDL CM2.1/A1B	-20%	-13% (CM2.0/A1B)* (CMIP3 class)
GFDL ESM2M/RCP4.5:	-34%	
GFDL CM3/RCP4.5:	-40%	+41% (CM3/RCP8.5)* (CMIP5 class)

*Rough comparison, as model configurations, emission scenarios, and years analyzed are different.

Tropical Cyclones and Climate Change: NW Pacific Focus

Detection/Attribution:

- It remains uncertain whether past changes in any tropical cyclone activity (frequency, intensity, rainfall, etc.) exceed the variability expected through natural causes.

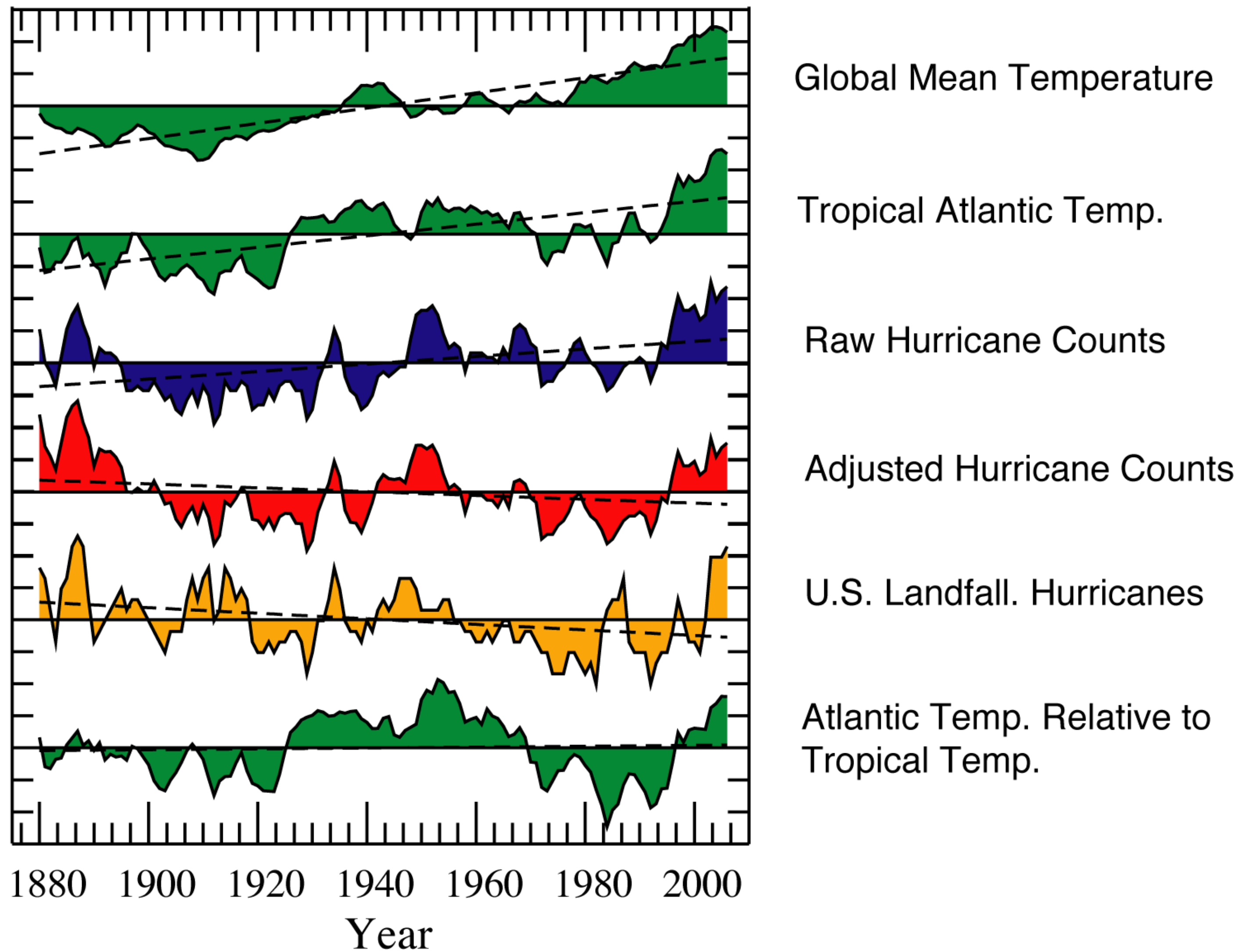
TC Projections for NW Pacific: (with caveat of no detection at present)

- TC frequency: Large uncertainty for 21st century TC frequency projections (-70% to +60%). More models indicate a decrease than an increase. Emanuel (PNAS 2013): Much stronger increase globally (and NW Pac) for CMIP5 (RCP8.5) projections than CMIP3 (A1B); but no indication yet from GFDL global model of a fundamentally different sensitivity for CMIP5 (RCP4.5) vs. CMIP3.

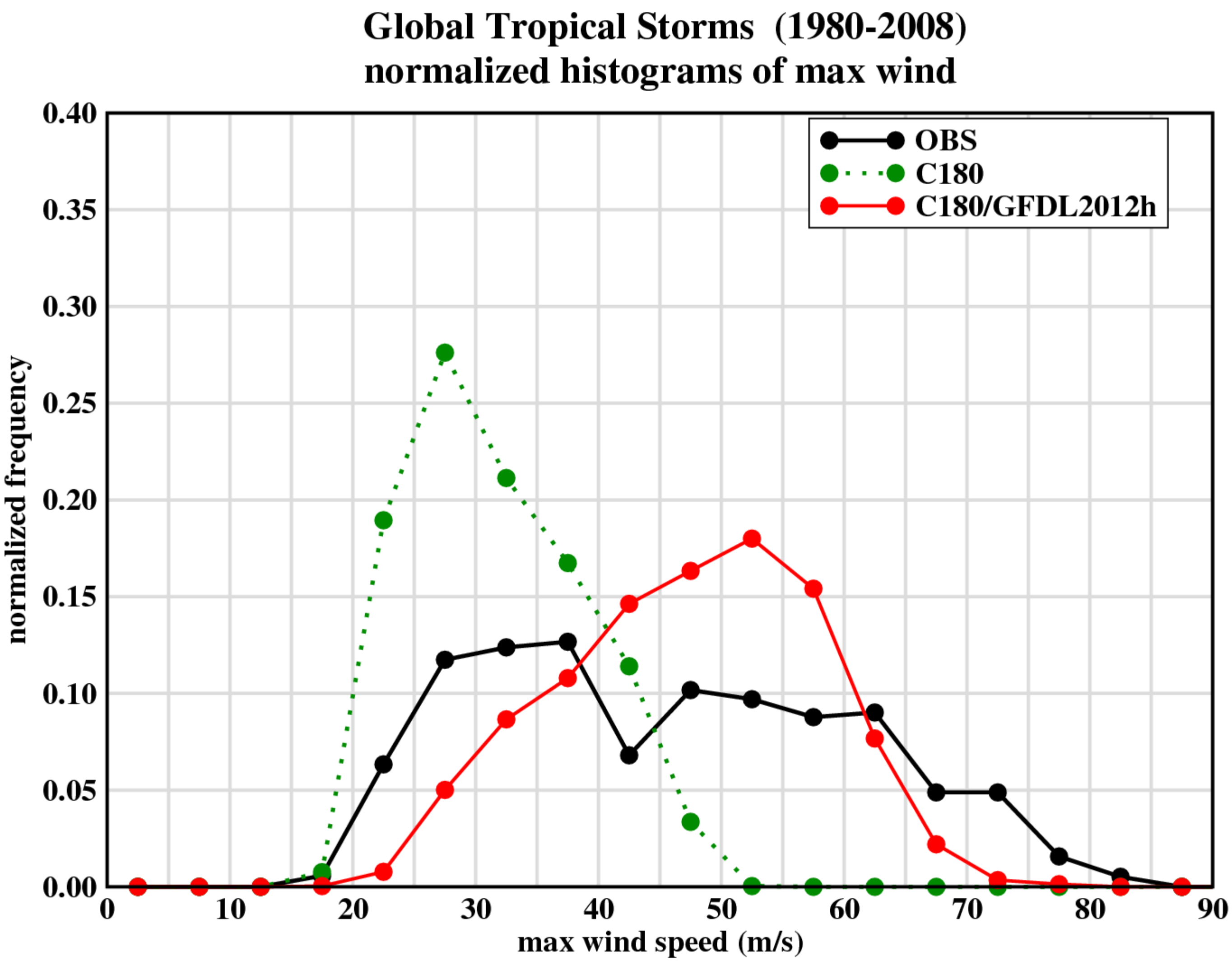
- TC intensity: most available studies indicate a modest increase of intensity (~5%) over the 21st century for the NW Pacific. Range among high resolution/PI studies was -3 to +18%.

- TC precipitation rate: available studies for the NW Pacific suggest an increase (~15%; magnitude depending on averaging radius).

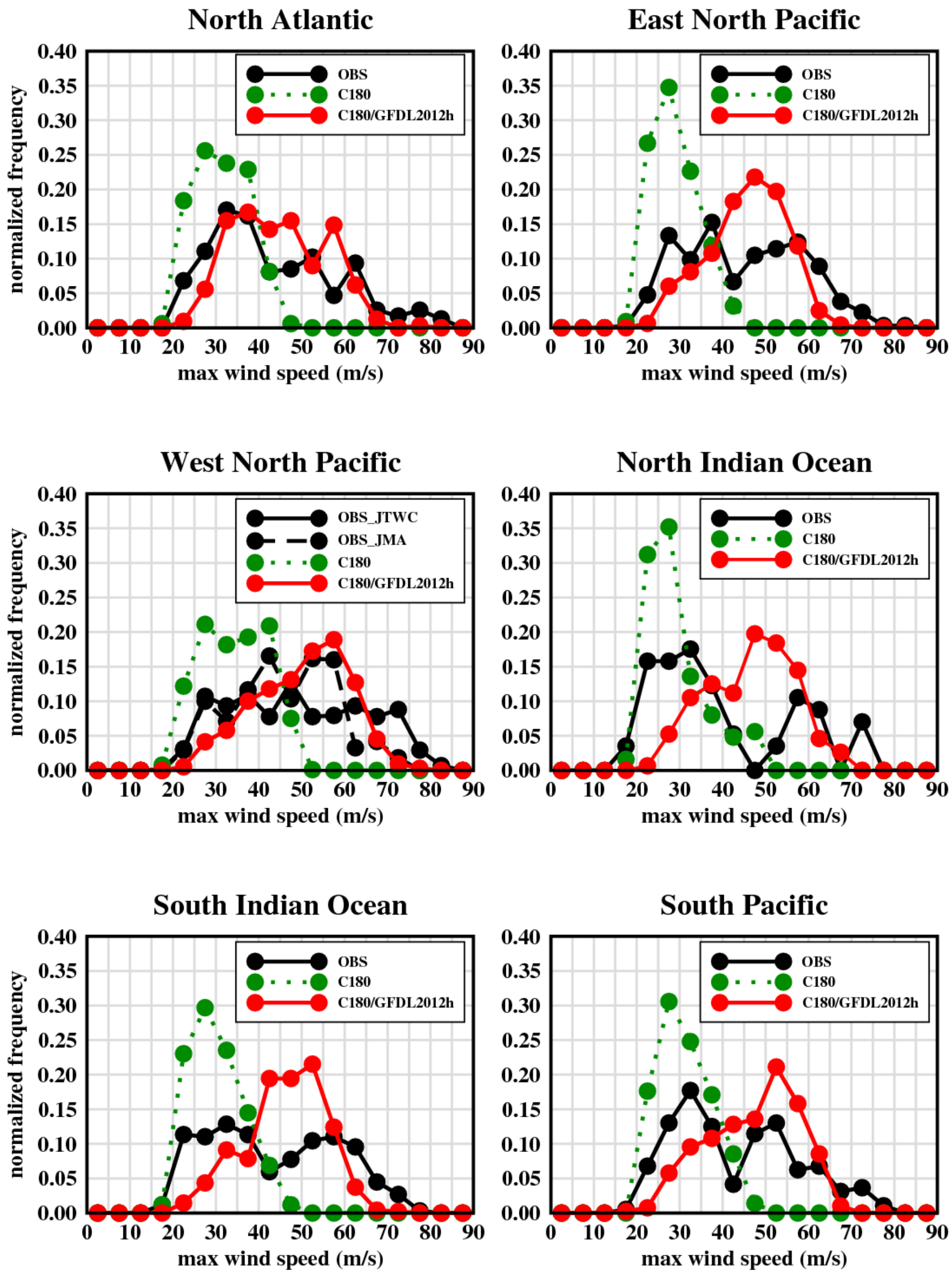
Normalized Tropical Atlantic Indices - Hurricane Focus



Source: Vecchi and Knutson (2011).

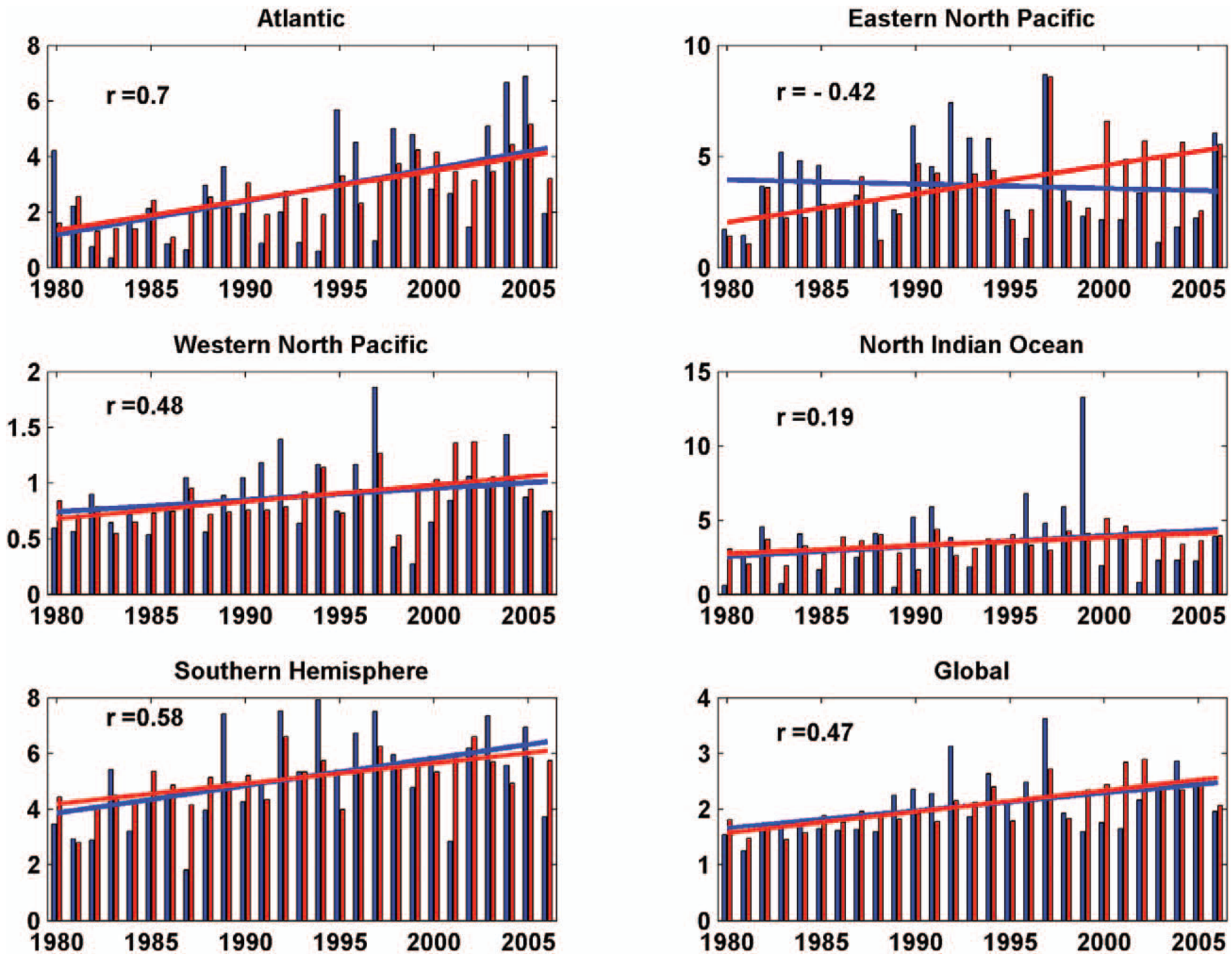

Global Tropical Storms (1980-2008)
normalized histograms of max wind
OBS
C180
C180/GFDL2012h
normalized frequency
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0
10
20
30
40
50
60
70
80
90
max wind speed (m/s)

Normalized histograms of max wind tropical storms (1980-2008)



Emanuel's Statistical-Dynamical Downscaling: Simulating Past PDI Variations

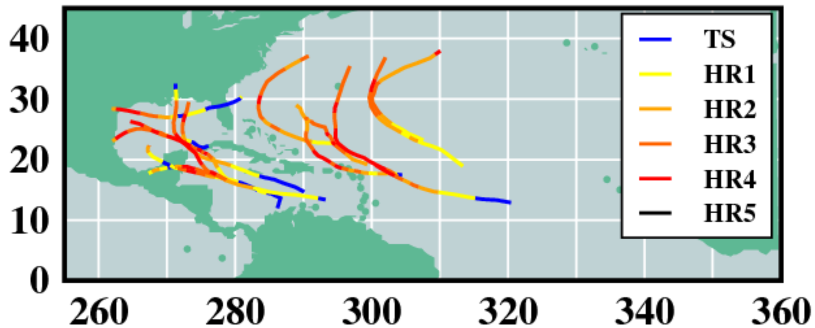
Model hindcast (red) uses NCEP Reanalysis. Best track is blue.



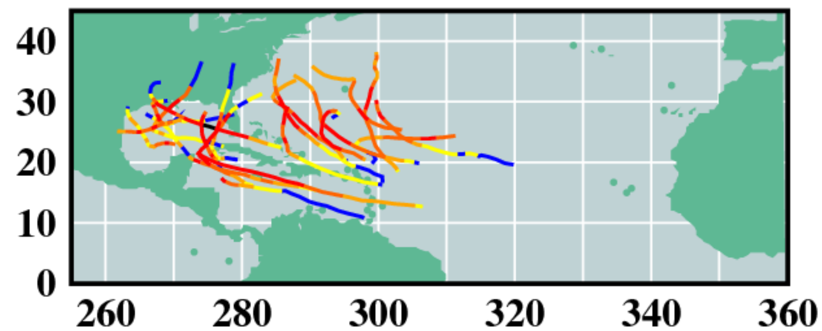
Source: Emanual et al. (2008) Bull. Amer. Meteor. Soc.

GFDL Hurricane Model: Category 4 & 5 Atlantic Hurricane Tracks (27 simulation years)

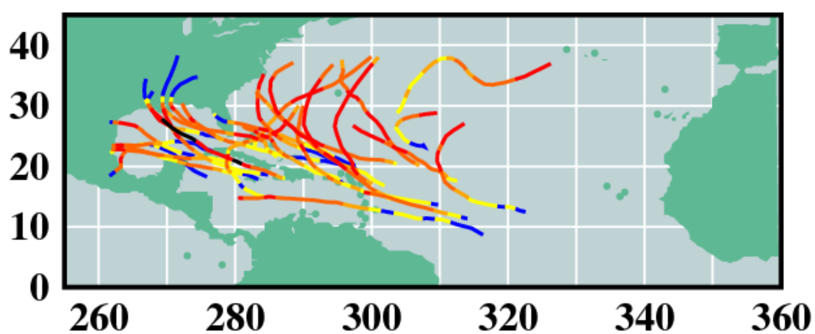
Present-Day (1980-2006): 14 storms



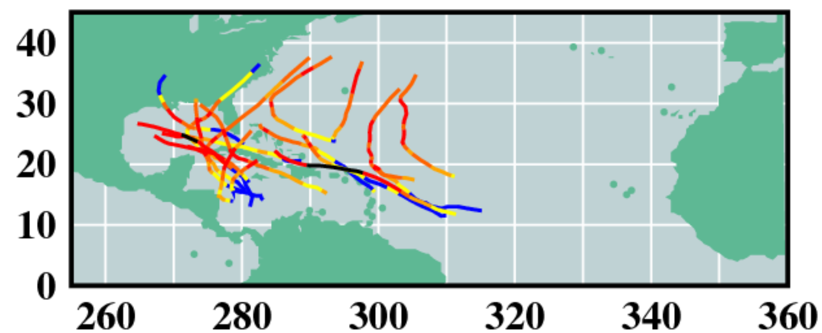
CMIP5 (Early 21st Century): 20 storms



CMIP3 (Late 21st Century): 28 storms

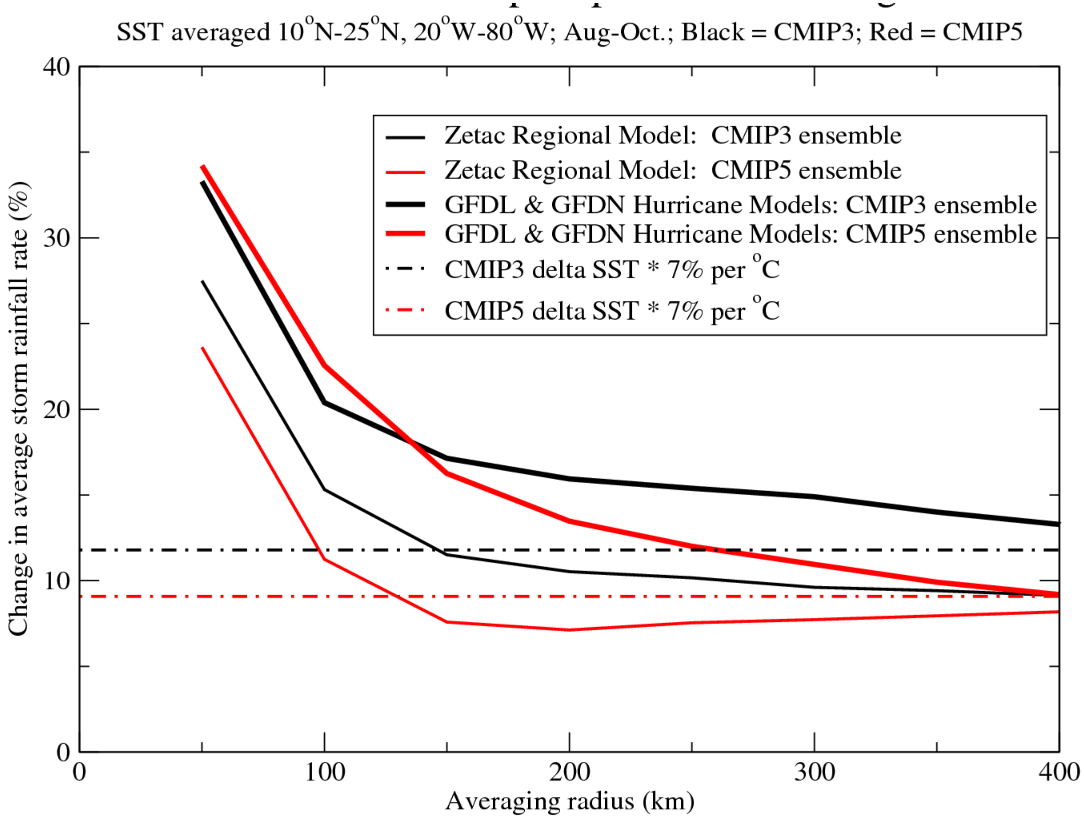


CMIP5 (Late 21st Century): 19 storms



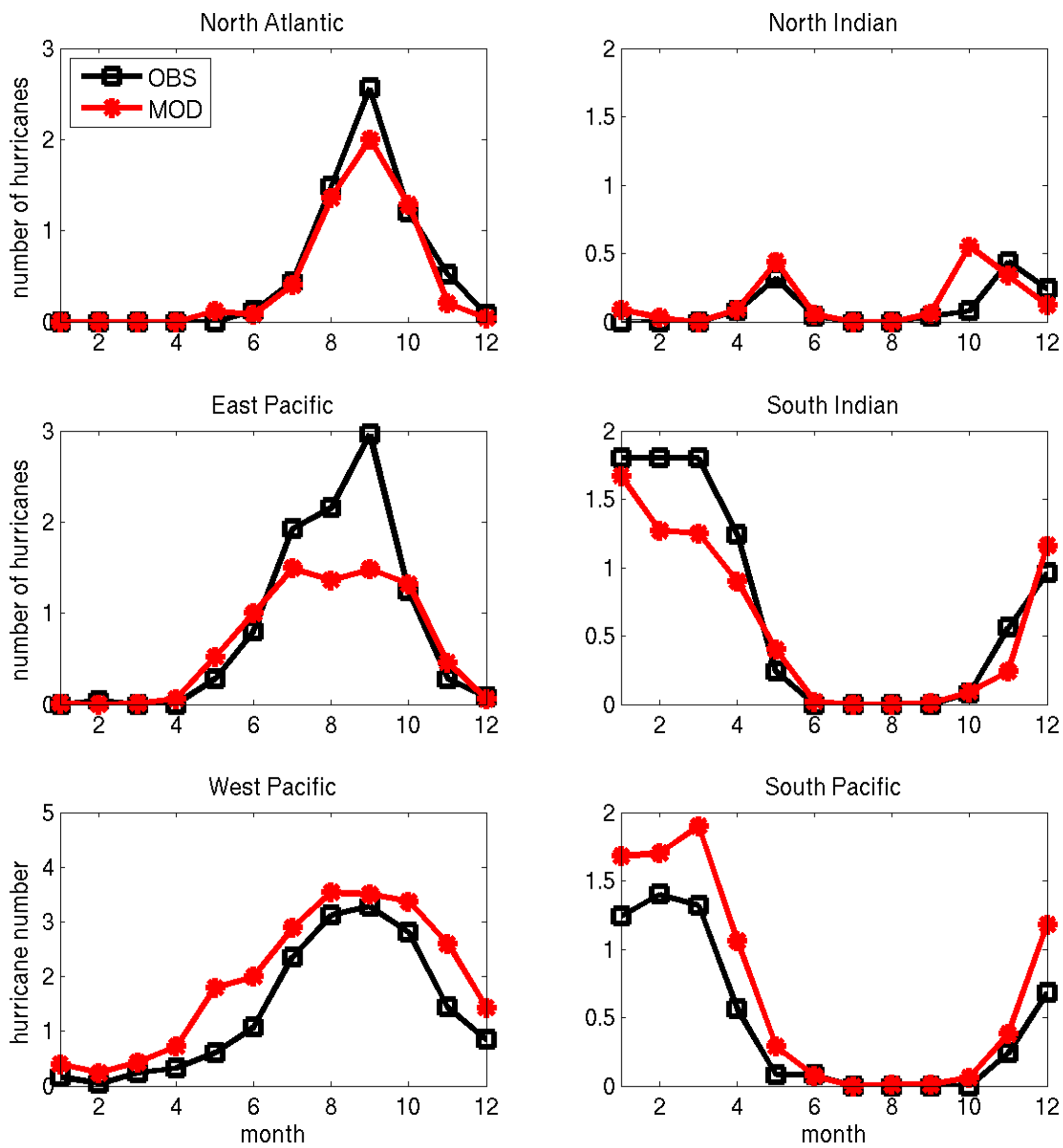
Source: Knutson et al. (J. Climate, in press, 2013).

Atlantic Basin Hurricane-related precipitation changes



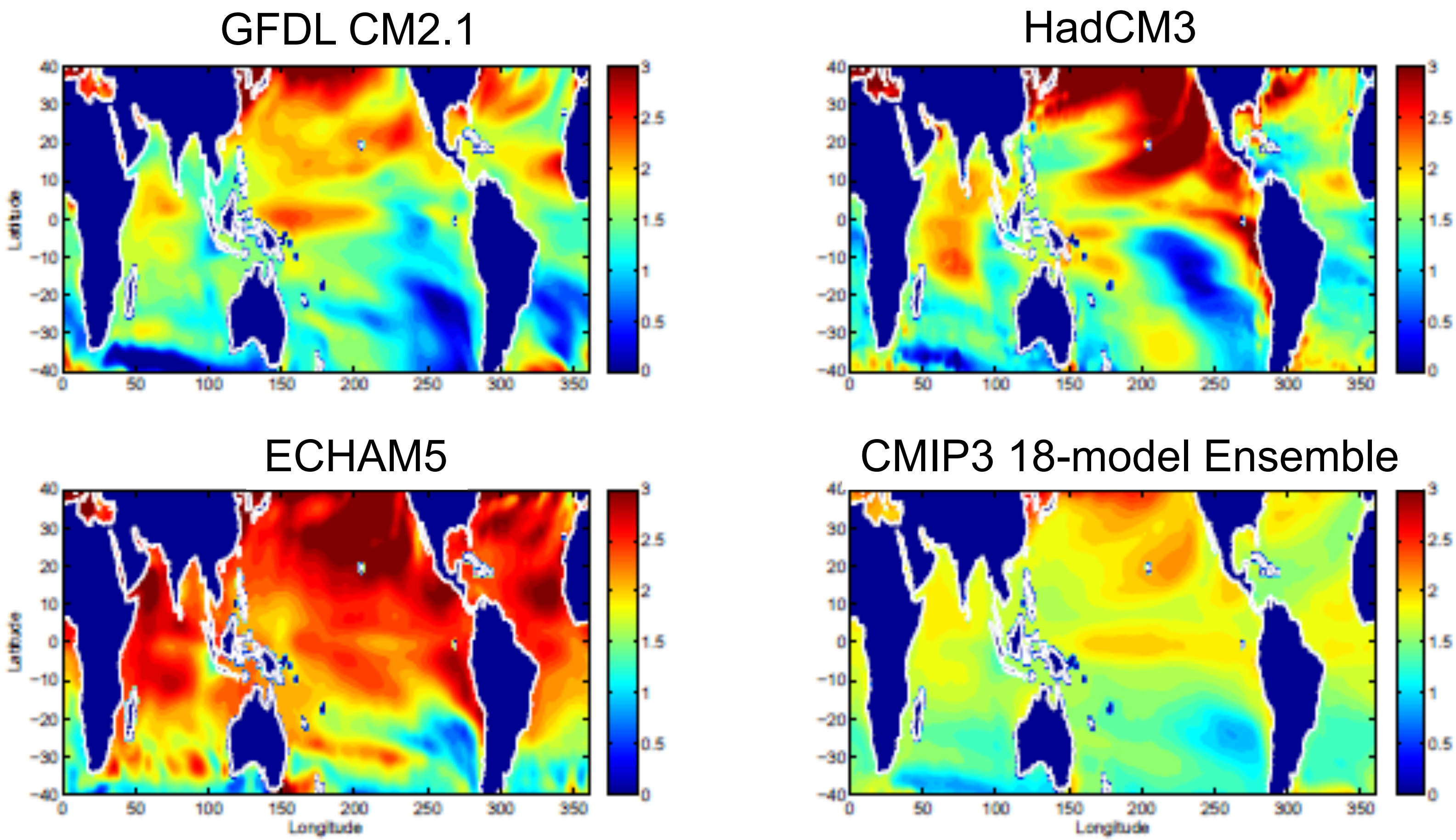
Source: Knutson et al. J. Climate, in press, 2013.

GFDL HIRAM 50-km grid model: realistic seasonal cycles of TCs in most basins



Source: Zhao, Held, Lin, and Vecchi (J. Climate, 2009)

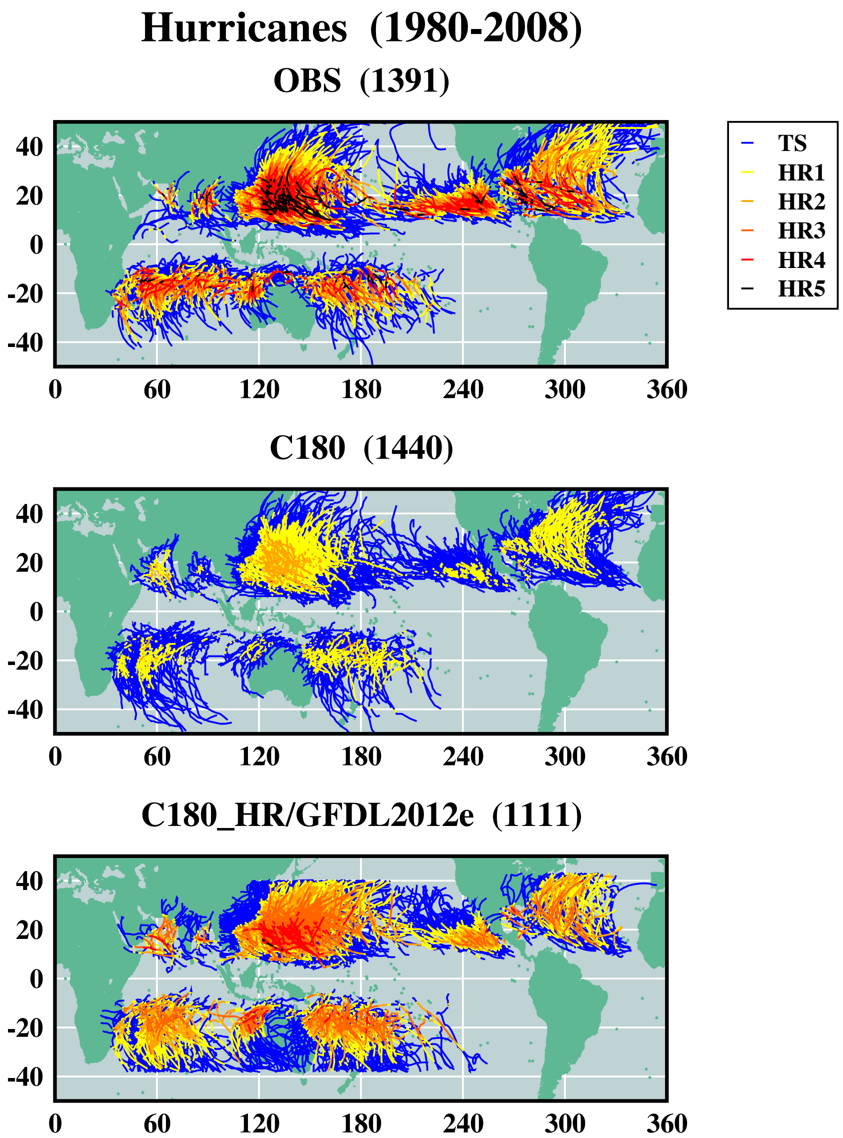
Global Model Tropical Cyclone Climate Change Experiments: Use A1B Scenario late 21st century projected SST changes from several CMIP3 models



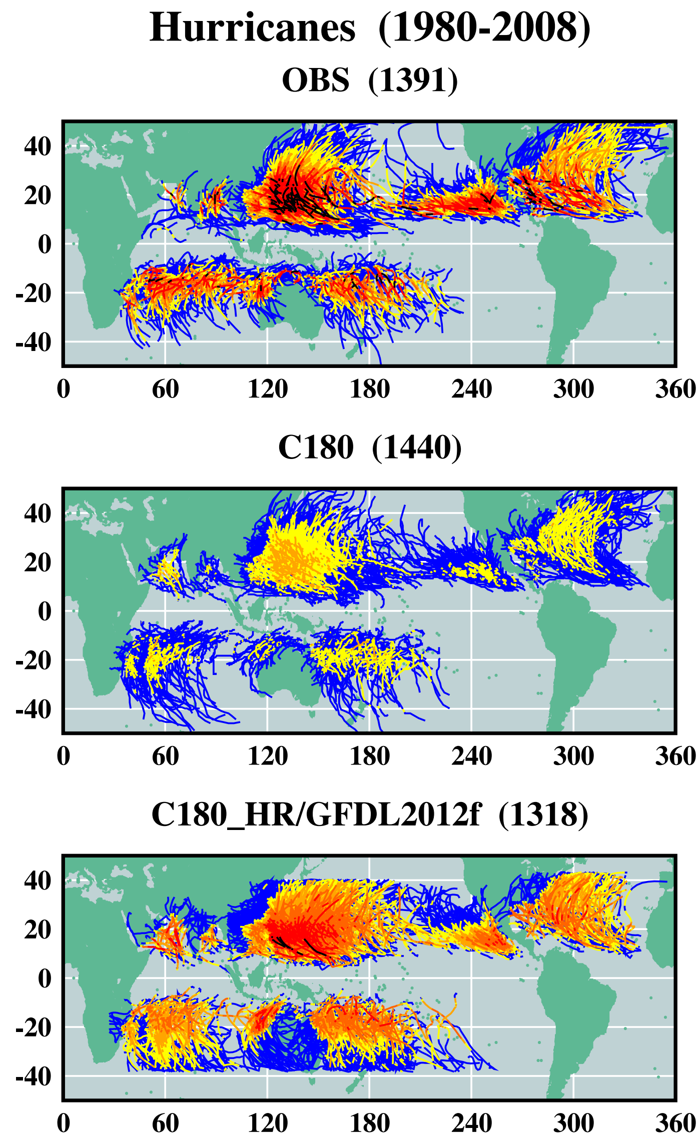
Source: Zhao, Held, Lin, and Vecchi (J. Climate, 2009)

Unit: Deg C

GFDL2012e

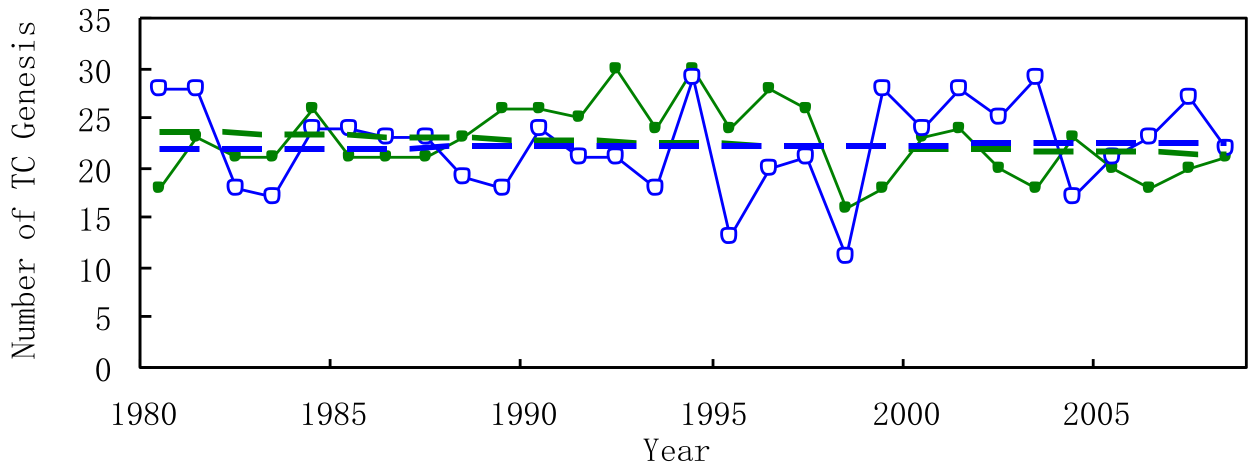


GFDL2012f

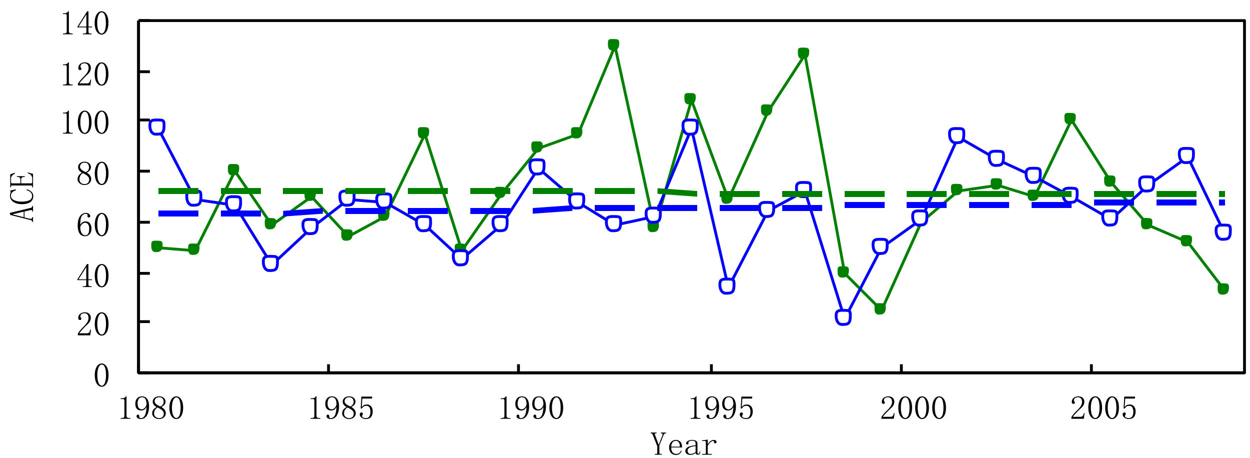


GFDL2012e (with synthetic vortex replacement)
GFDL2012f (no replacement; uses C180 vortex)

GFDL Zetac Model: NW Pac simulations:
TC genesis frequency and Accumulated Cyclone Energy (ACE):



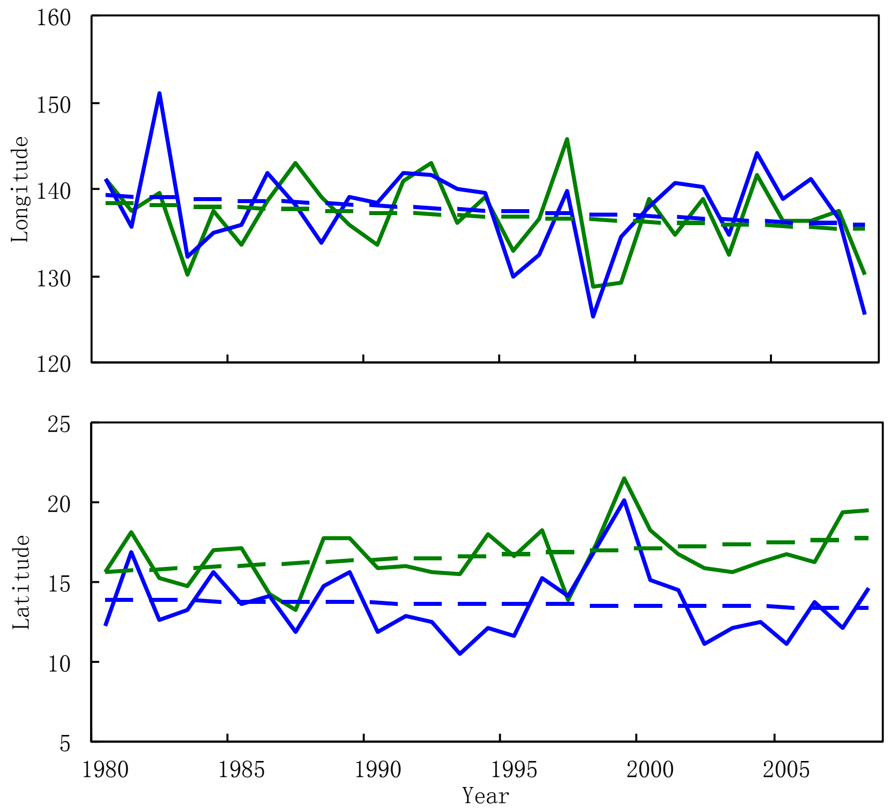
TC frequency
r = -0.02



ACE
r = 0.28

Source: Liang Wu et al., *J. Climate*, submitted, 2013. Green = obs; Blue = model

GFDL Zetac Model NW Pac simulations: Mean longitude and latitude of genesis:

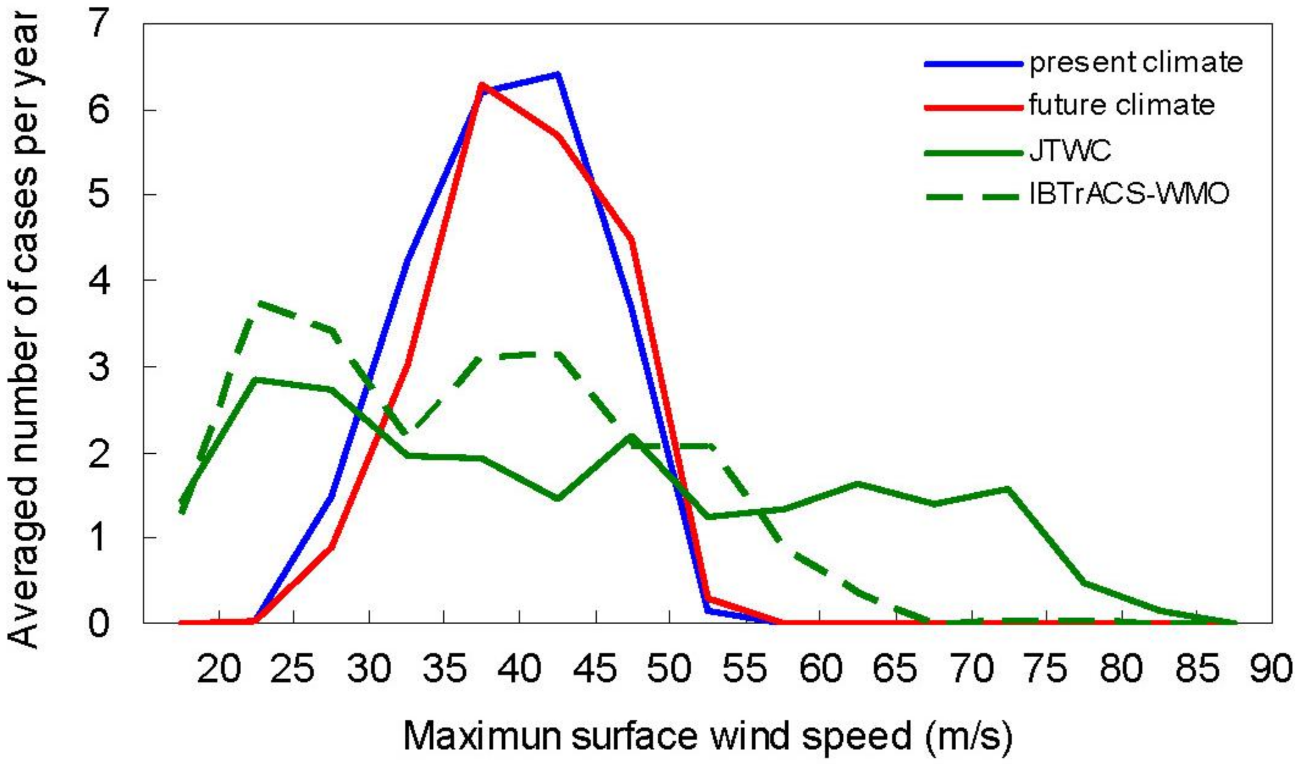


Mean Longitude
r = 0.67

Mean Latitude
r = 0.59

Source: Liang Wu et al., *J. Climate*, submitted, 2013

GFDL Zetac Model, NW Pac. Basin: Simulated vs. Observed TC intensities



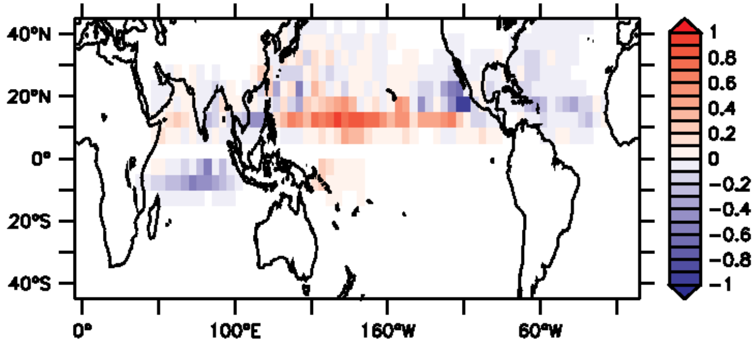
Source: Liang Wu et al., *J. Climate*, submitted, 2013

Relationship of TC activity to ENSO

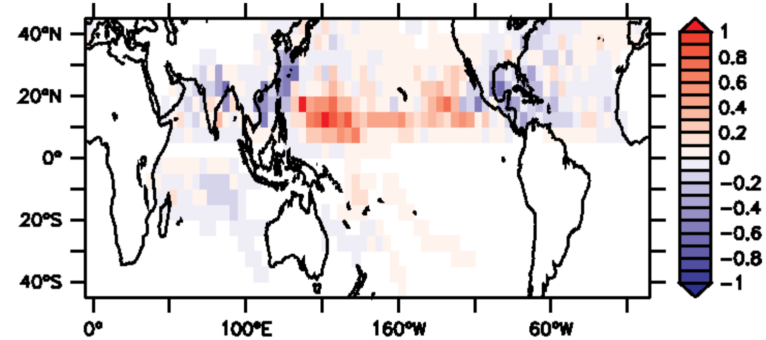
TC occurrences (5°x5°) Regressed on the NINO 3.4 Index

JASO

Simulated (CM2.5)

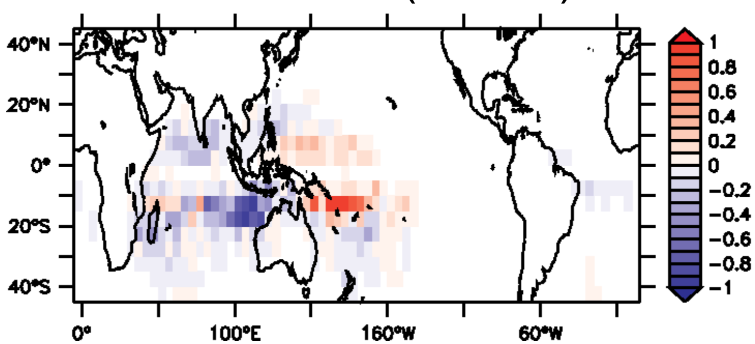


Observed (IBTRACS)

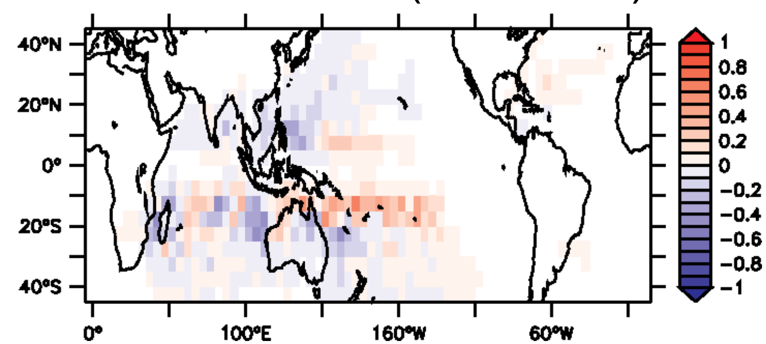


JFMA

Simulated (CM2.5)



Observed (IBTRACS)



Source: H.-S. Kim et al. (in preparation, 2013).