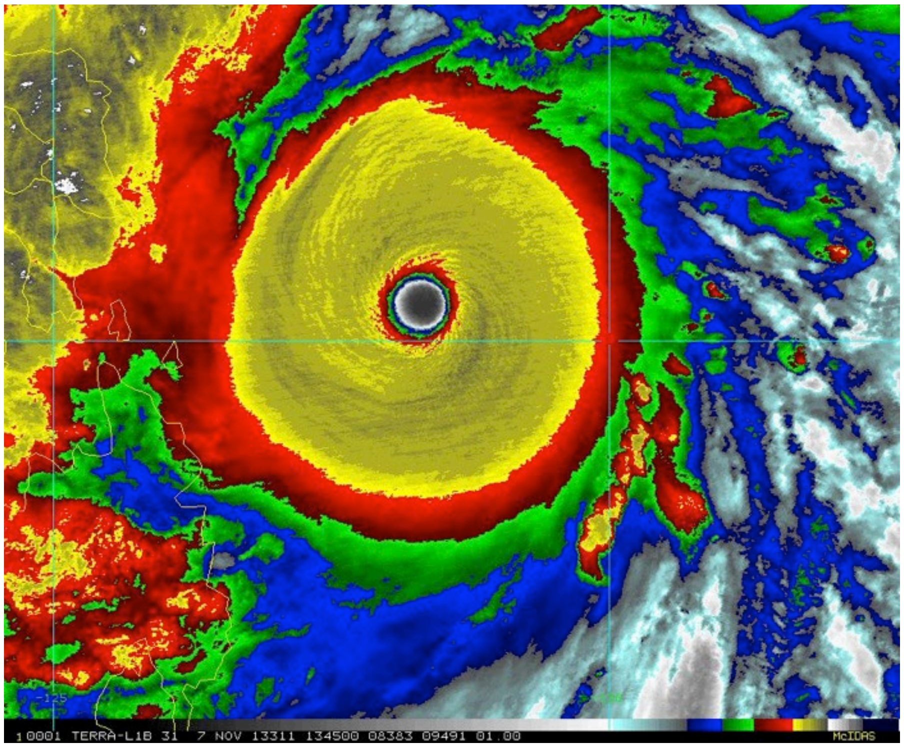
Assessing Climate Change in the Tropics



Super Typhoon Haiyan, 2013

Tom Knutson
NOAA/GFDL
Climate Impacts and Extremes Group

Princeton, New Jersey
November 2014

<u>Collaborators (partial listing):</u>
Andrew Wittenberg,
Fanrong Zeng, Joe Sirutis,
Ming Zhao, Gabe Vecchi,
Morris Bender, Bob Tuleya

Figure Credits: John Dunne,
Andrew Wittenberg

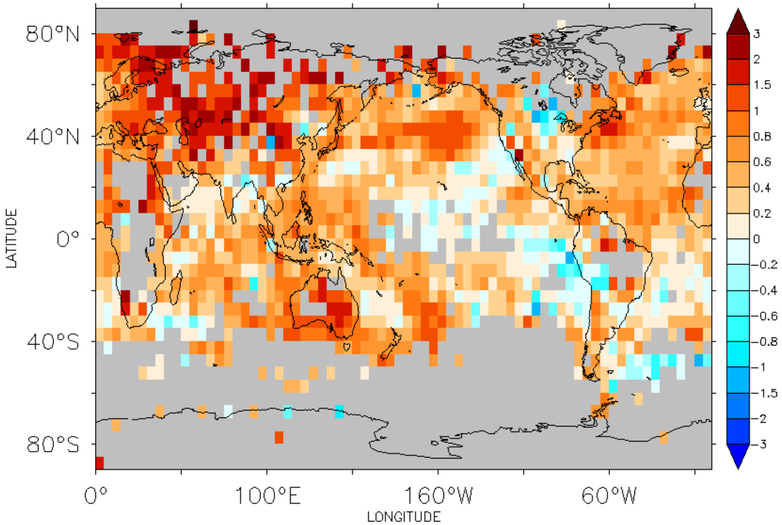
Main Points – with Recent GFDL Work as Examples

1. Anthropogenic climate change is affecting tropical climate (detection/attribution)
   - Especially evident in century scale surface temperature trends and recent extremes (examples)
2. Tropical cyclones and climate change – impact not as clear
   - Anthropogenic influence on tropical cyclones (hurricanes, typhoons, etc.) is difficult to detect.
   - Projections for late 21st century include increased intensity (~4%); decreased overall frequency (-16%); increased rain rates (+14%); sea level rise
3. ENSO and climate change: difficult to detect or project anthro. changes due to likely large internal variability fluctuations of amplitude, etc.
4. Heat stress increases – tropical temperatures are ‘expanding’ poleward

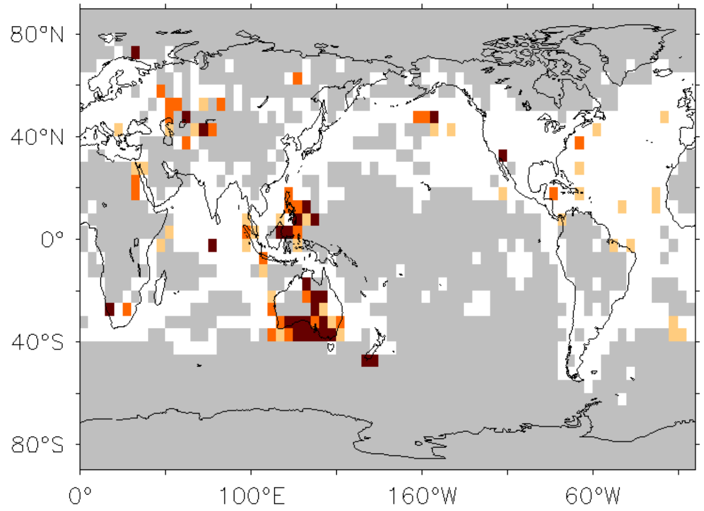
Explaining Extreme Events from a Climate Perspective…

Surface temperature: annual-mean extremes for 2013

Annual 2013 anomalies



Annual means: 2013 extremes



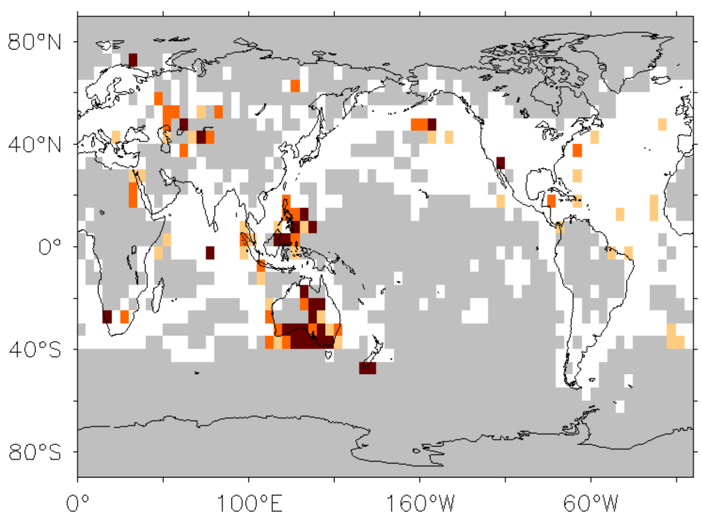
Map Legend: (and percent coverage by category)

Highest	(3.0%)
2nd highest	(3.1%)
3rd highest	(4.3%)
3rd lowest	(0%)
2nd lowest	(0%)
Lowest	(0%)

Source: Knutson, Zeng, and Wittenberg, *BAMS,* accepted (2014)

Surface temperature annual-mean extremes for 2013: historical context

Annual mean surface temperature: 2013 extremes



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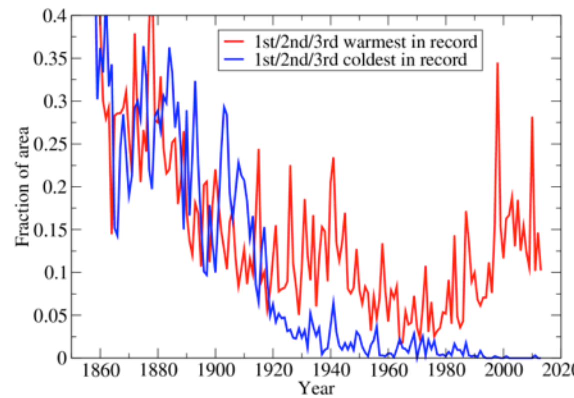
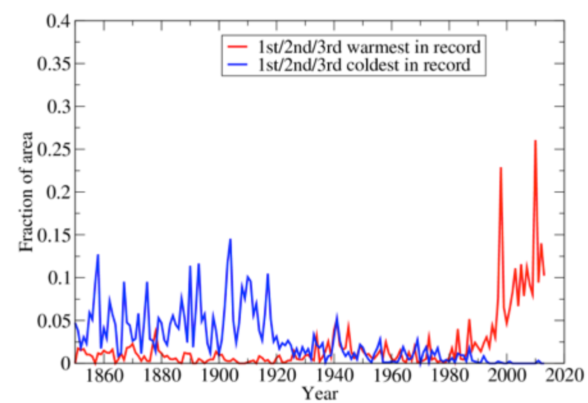
Lowest	(0%)

Area with warm vs cold annual-mean extremes (record to date)



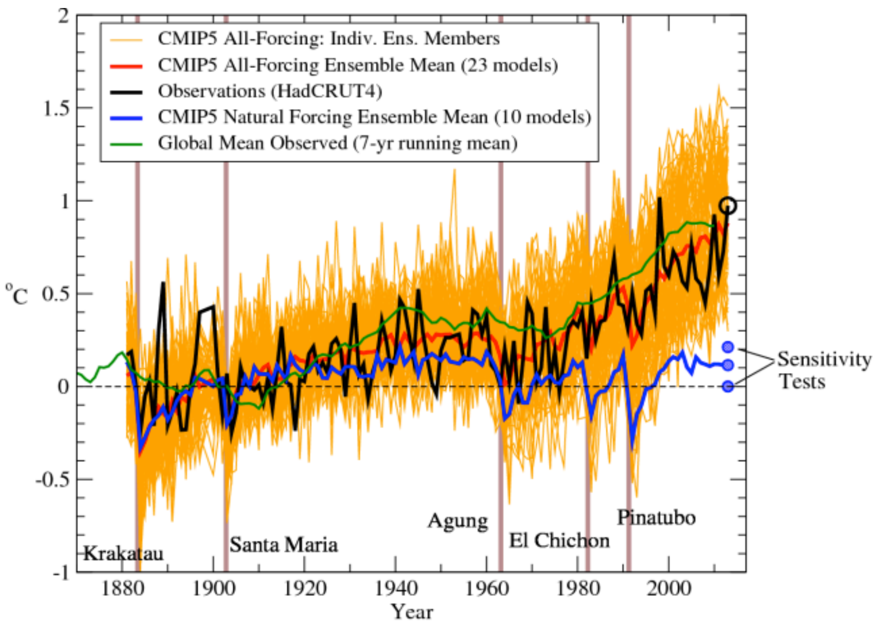
Area with warm vs cold annual-mean extremes (full record)

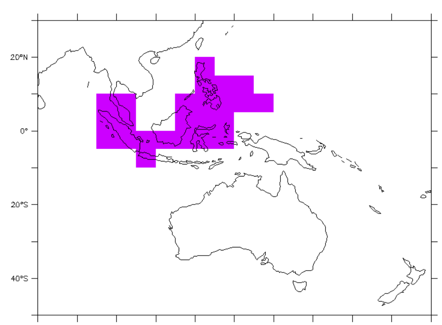


Source: Knutson, Zeng, and Wittenberg, *BAMS,* accepted (2014)

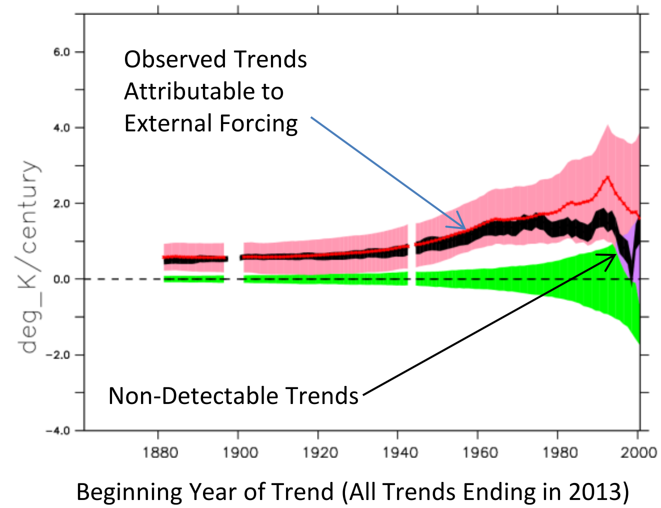
Western Pacific/Indonesia Region:

Annual Temperatures

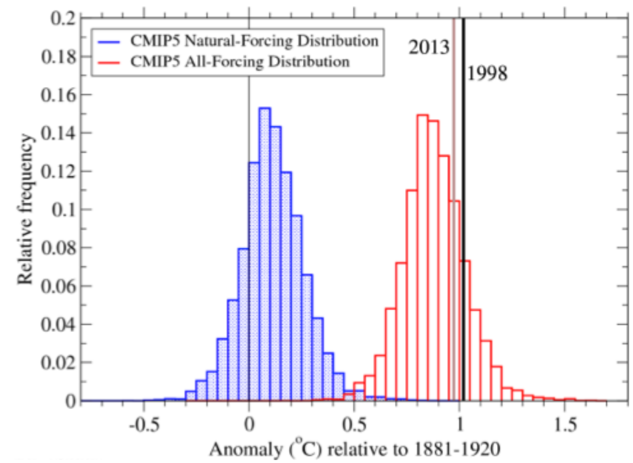




Sliding Trend Analysis

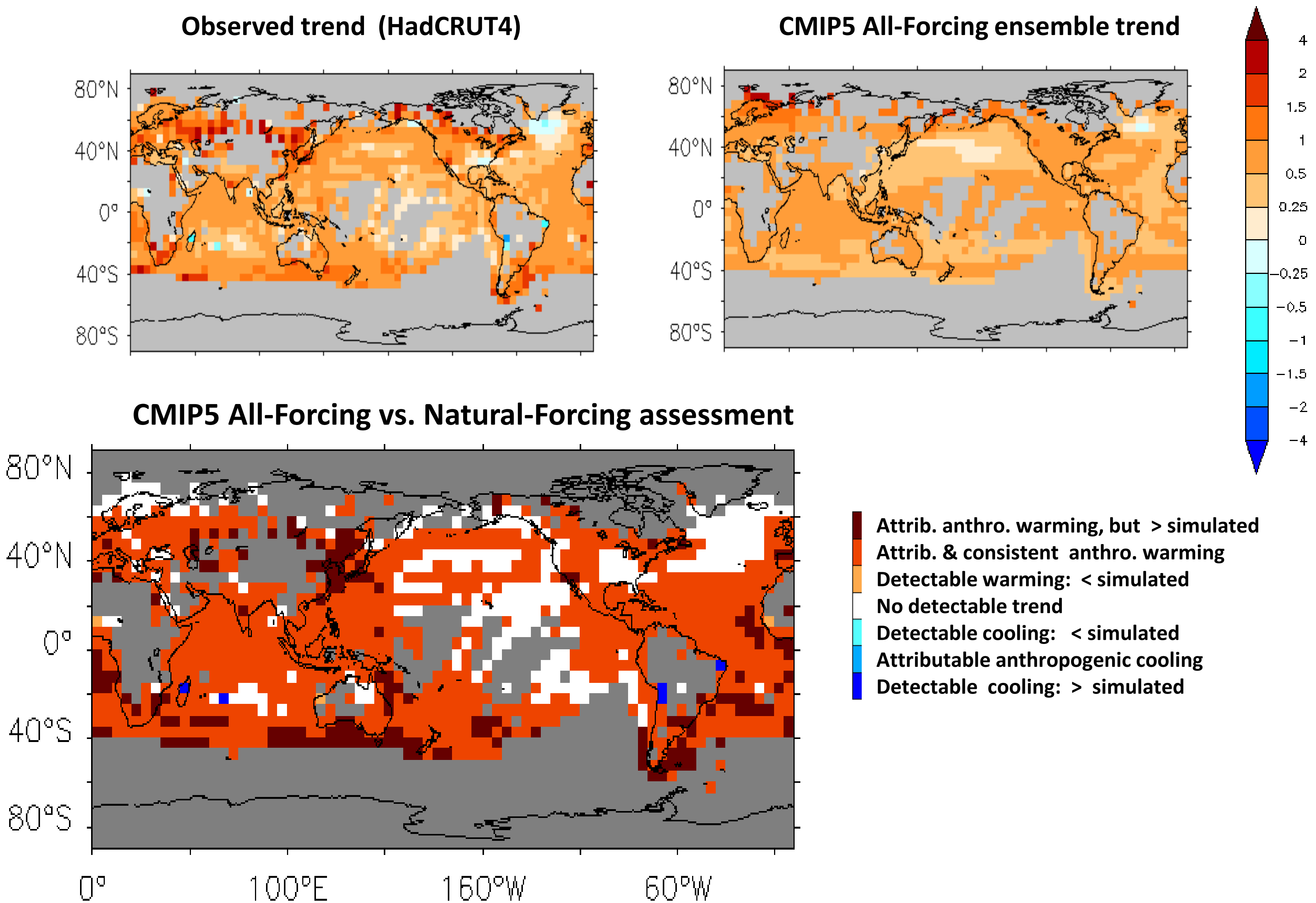


Attributable Risk Analysis



Source: Knutson, Zeng, and Wittenberg, *BAMS* (2014)

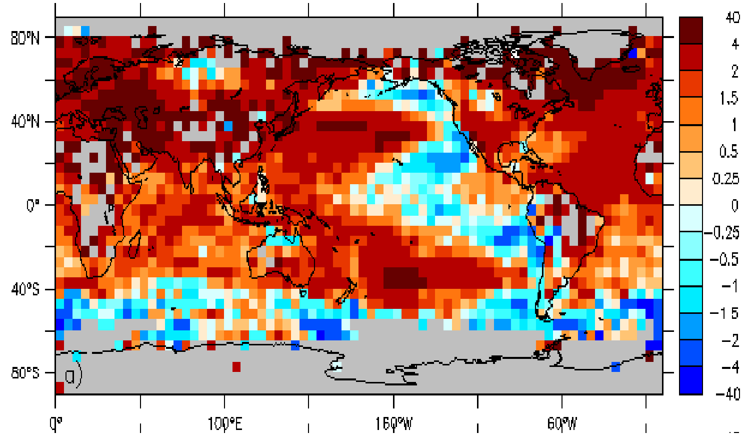
1901-2010 Surface Temperature Trend Assessment



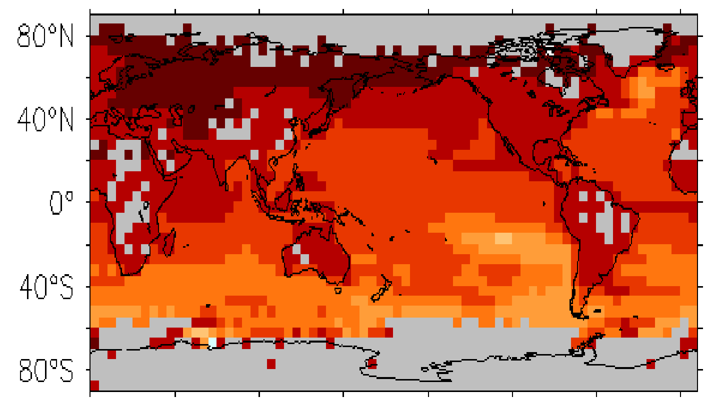
Source: Knutson, Zeng, and Wittenberg, *J. Climate* (2013)

1981-2010 Surface Temperature Trend Assessment*

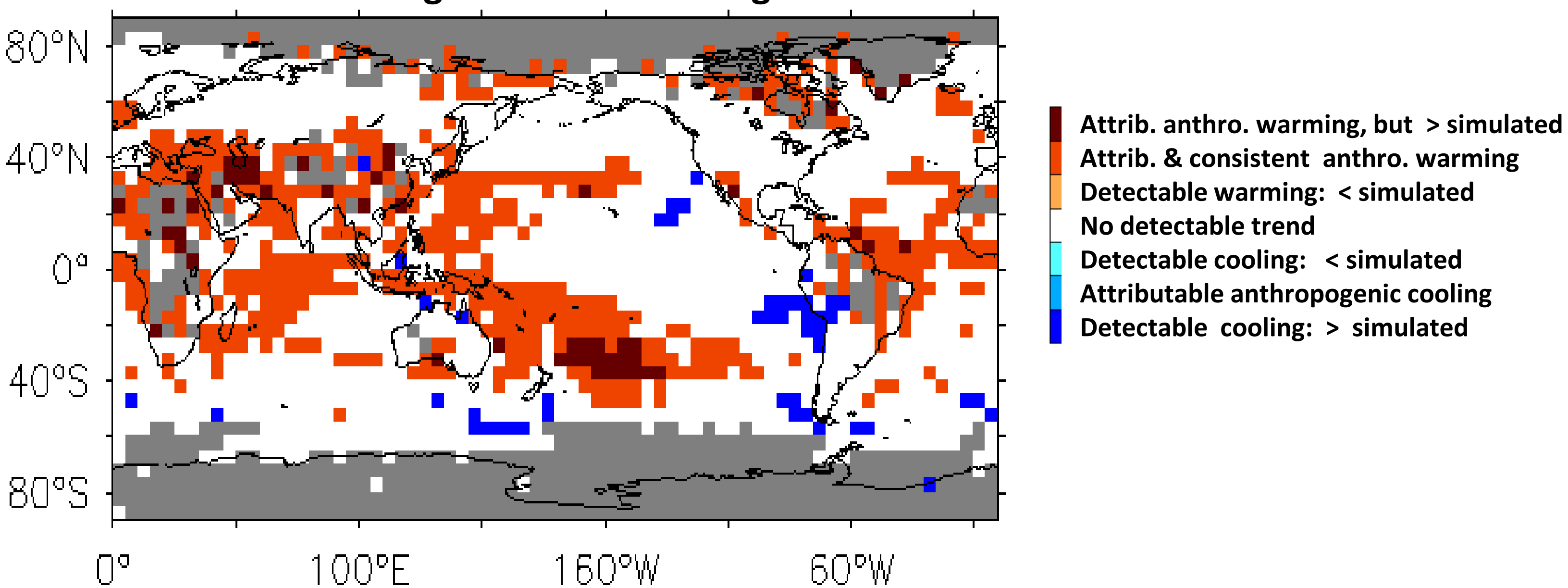
Observed trend (HadCRUT4)



CMIP5 All-Forcing ensemble trend

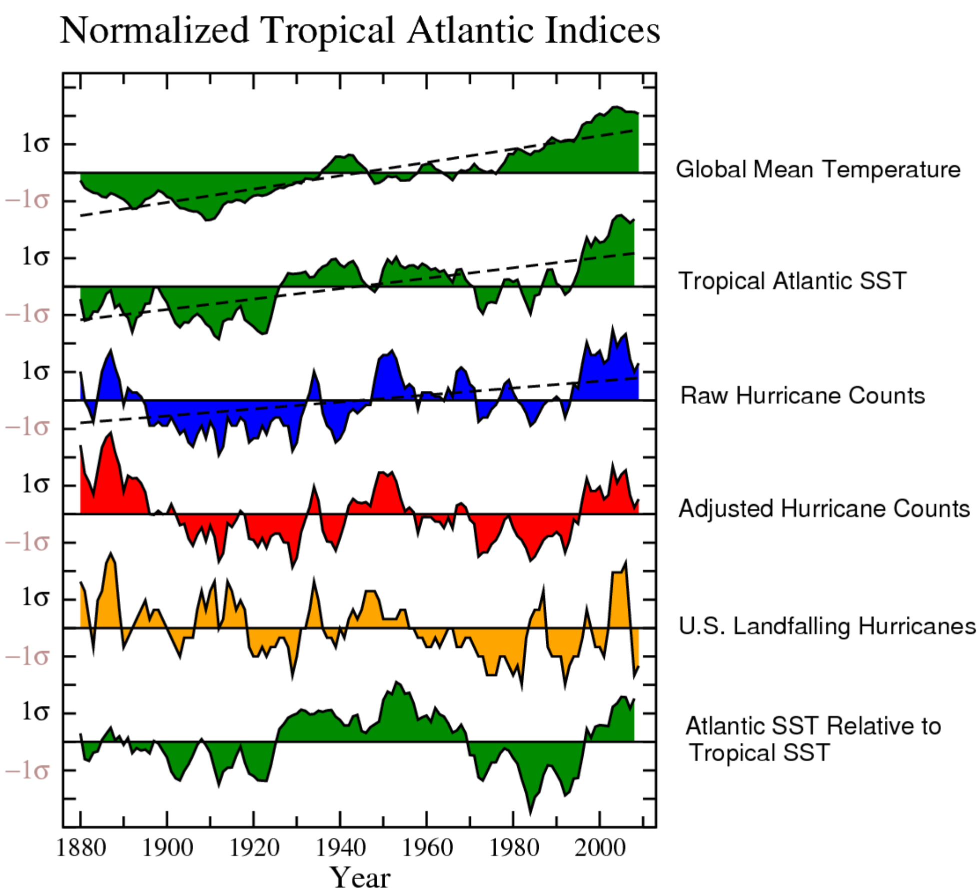


CMIP5 All-Forcing vs. Natural-Forcing assessment

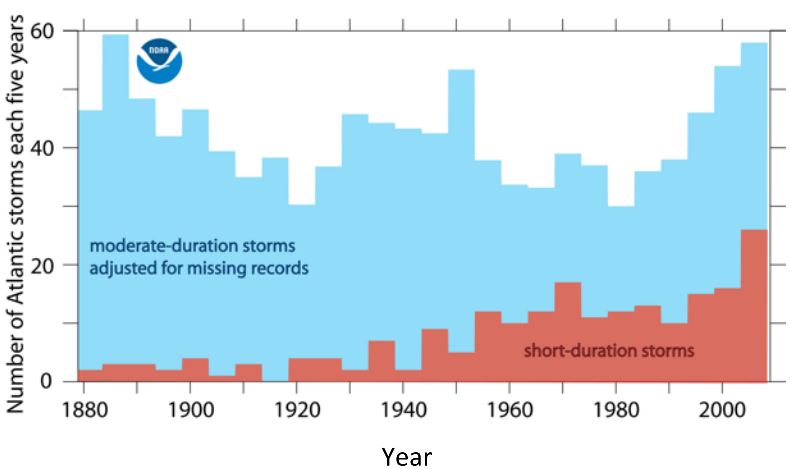


Source: Knutson, Zeng, and Wittenberg, *J. Climate* (2013)

Low confidence in long-term (centennial-scale) changes in TCs

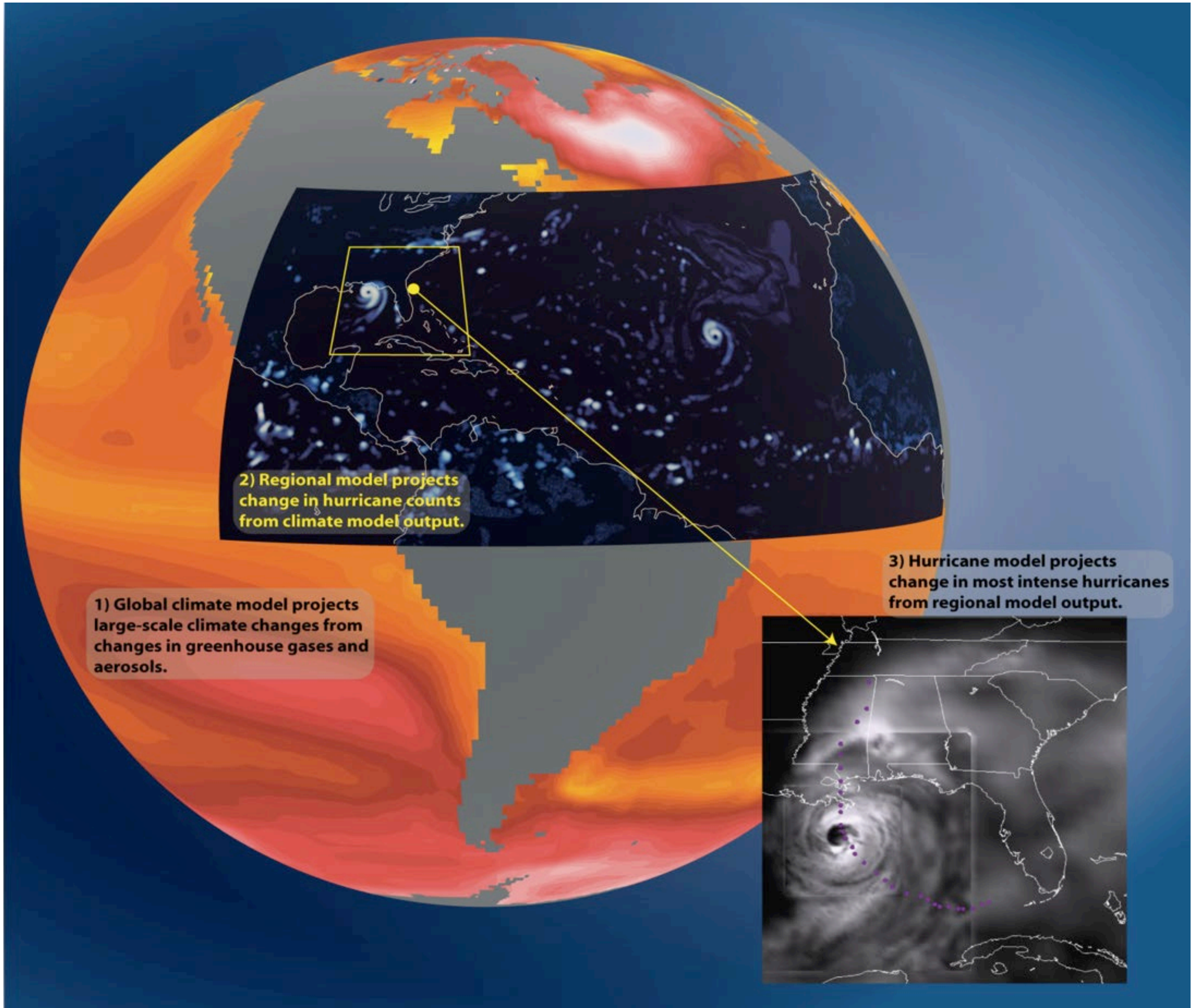


Moderate-duration tropical storms do not show a trend.



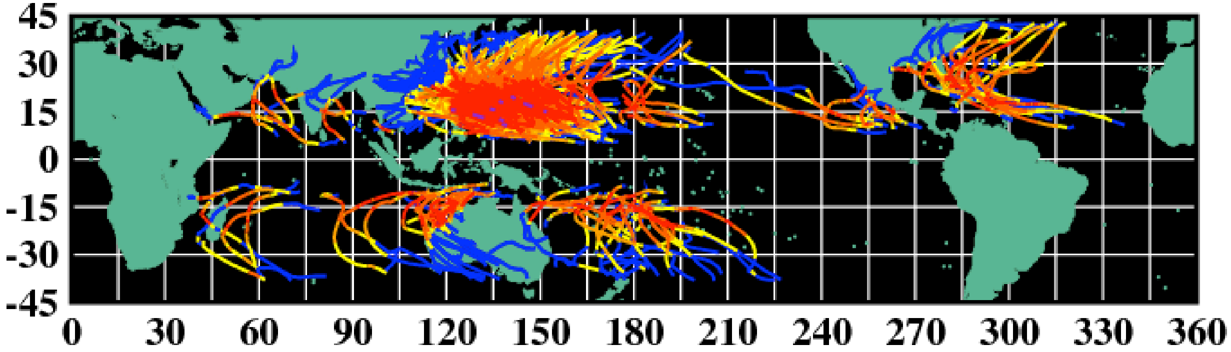
Sources: Vecchi and Knutson, *J. Climate* (2011); Landsea , Vecchi, Bengtsson, Knutson. *J. Climate* (2010).

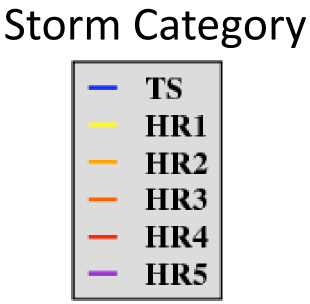
A “double-downscaling” approach for modeling the frequency of intense Atlantic hurricanes.



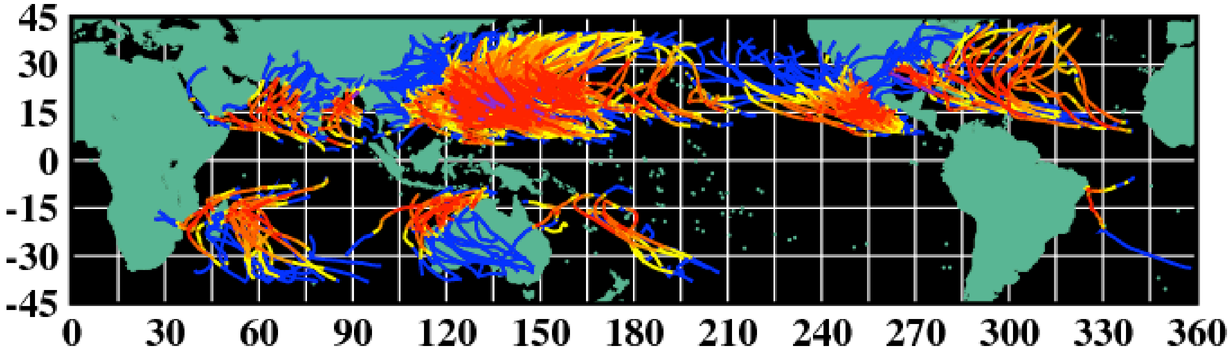
Simulating intense (Category 4&5) hurricanes for present-day and late 21st century

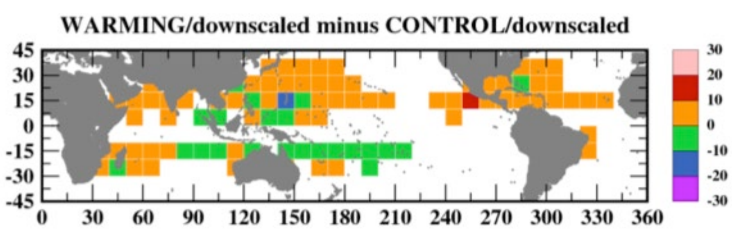
a) Present-Day Simulation: 244 Cat 4-5 storms



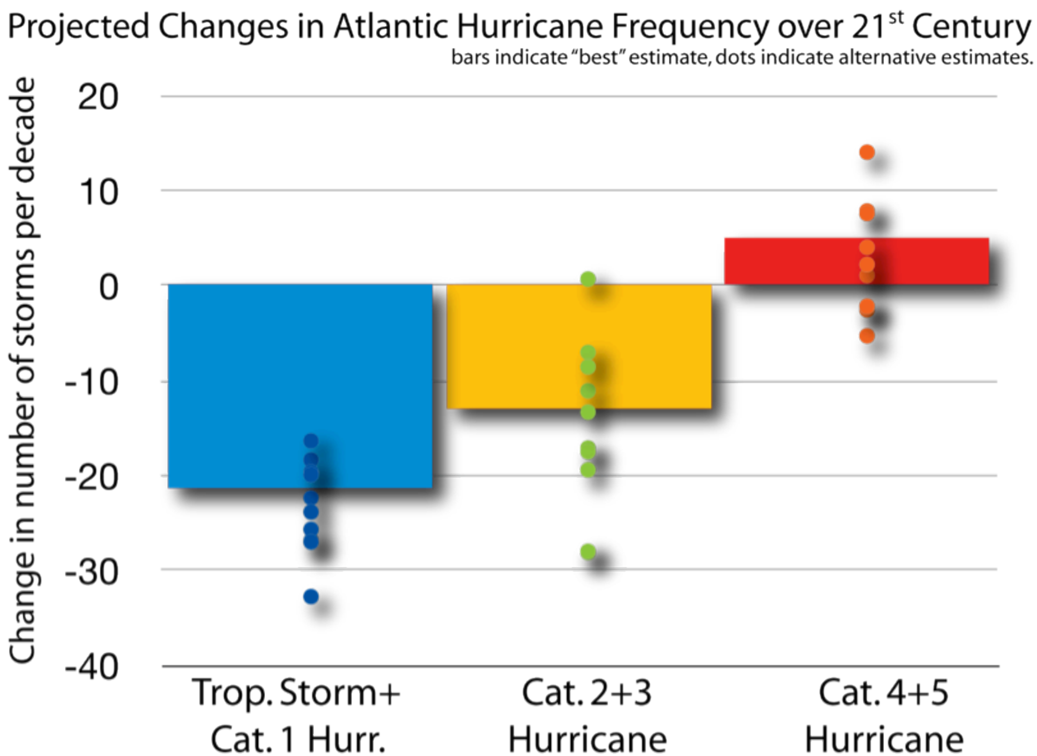


b) RCP4.5 Late 21st Century: 313 Cat 4-5 storms





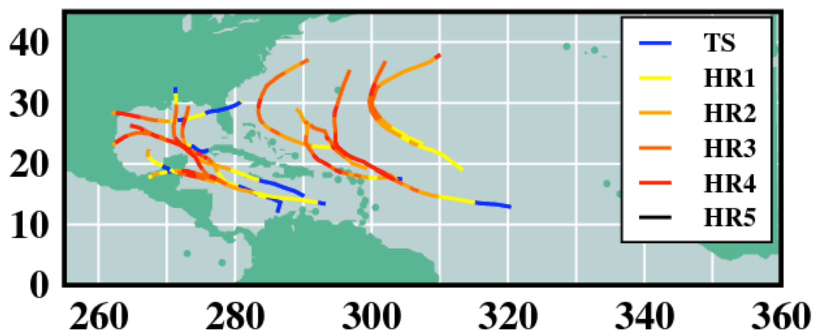
Summary of Atlantic Tropical Cyclone Projections over the 21st Century



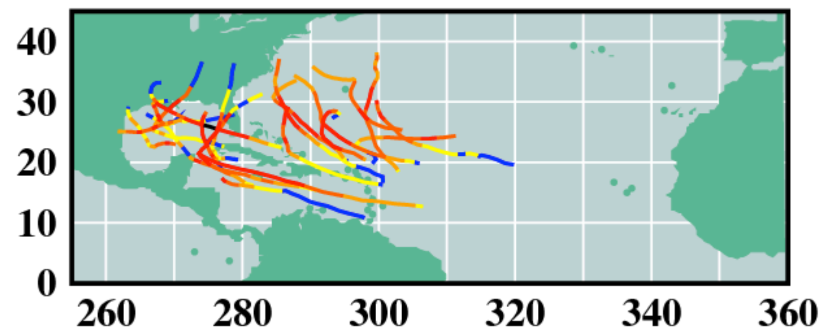
Adapted from Knutson et al. (2013, J. Clim.). See also: Knutson et al. (2009), Zhao et al. (2009), Bender et al. (2010), Villarini et al. (2011), Villarini and Vecchi (2012, 2013)

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

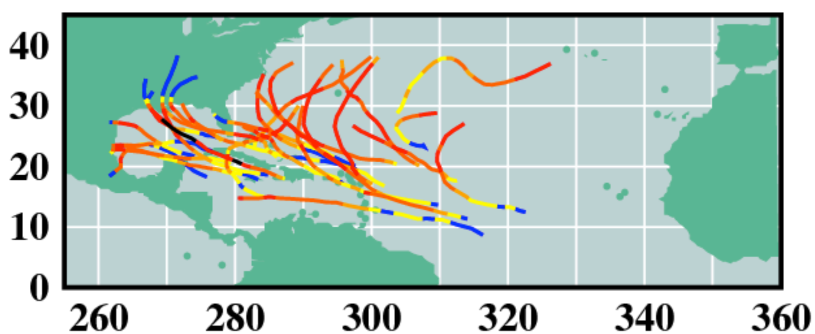
Present-Day (1980-2006): 14 storms



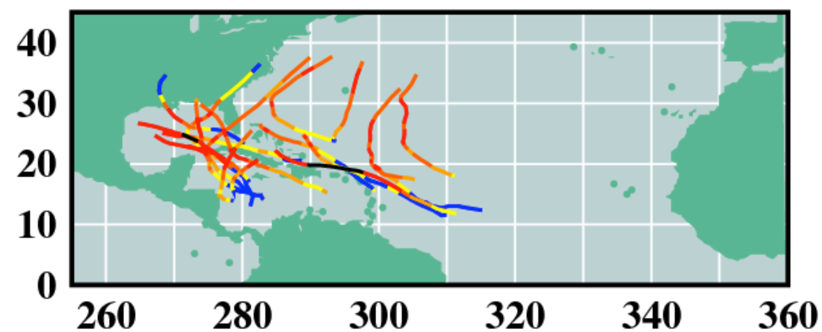
CMIP5 (Early 21st Century): 20 storms



CMIP3 (Late 21st Century): 28 storms



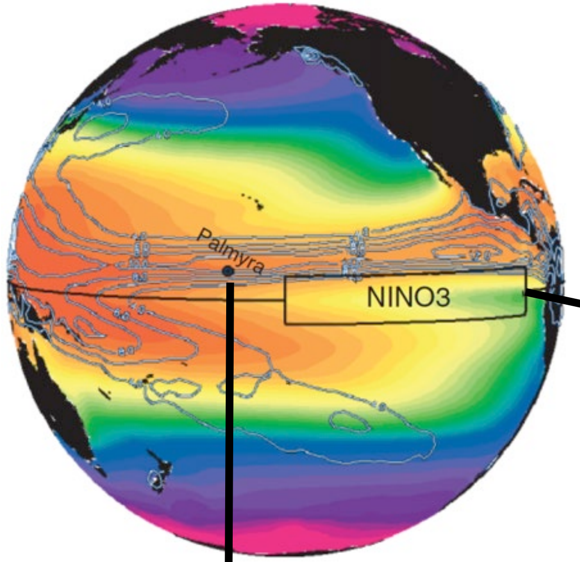
CMIP5 (Late 21st Century): 19 storms

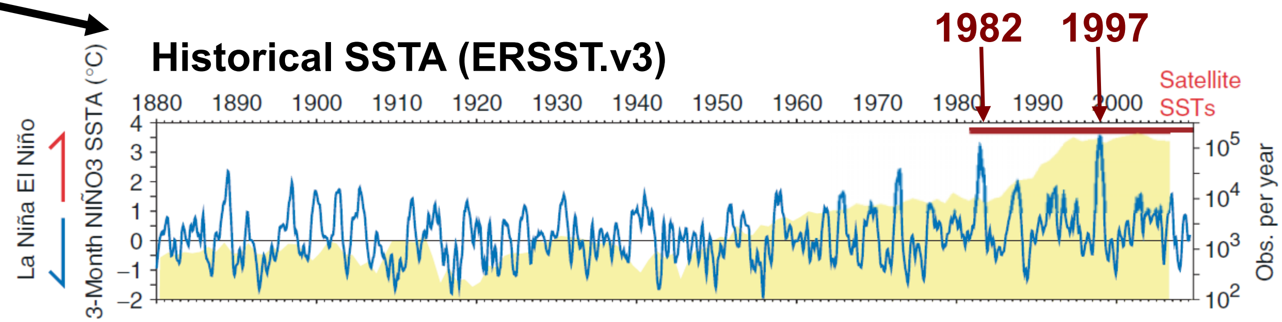


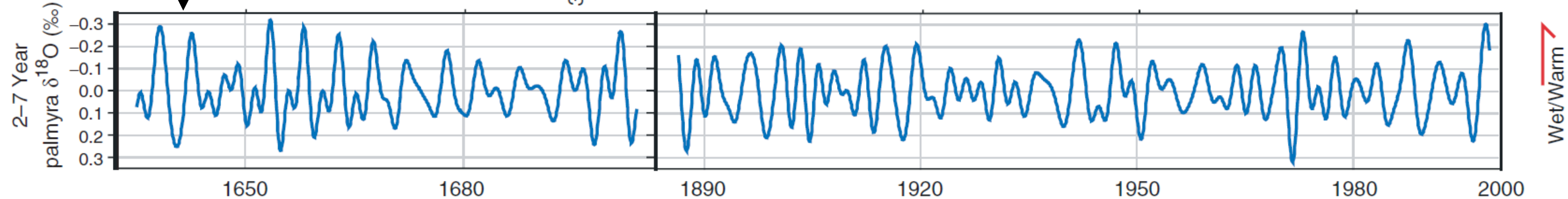
Source: Knutson et al. (J. Climate, 2013).

Both historical & paleo records suggest past modulation of ENSO

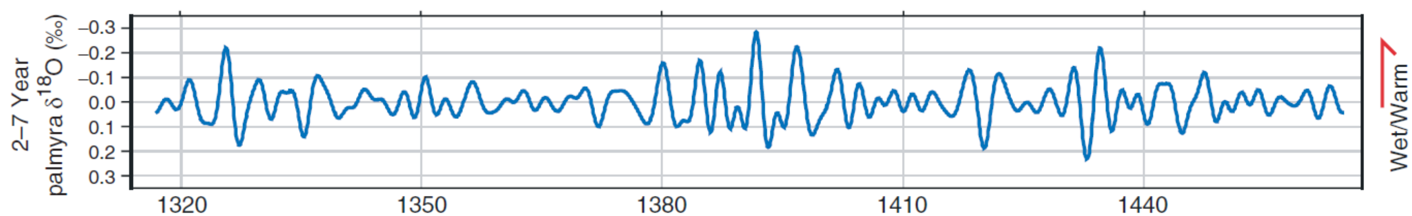
Vecchi & Wittenberg (WIREsCC 2010)



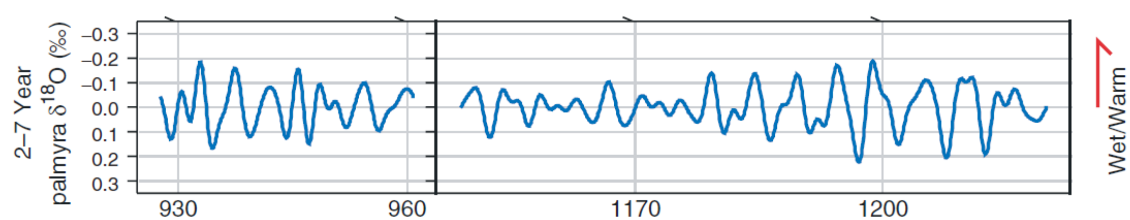




Palmyra corals (Cobb et al., Nature 2003)

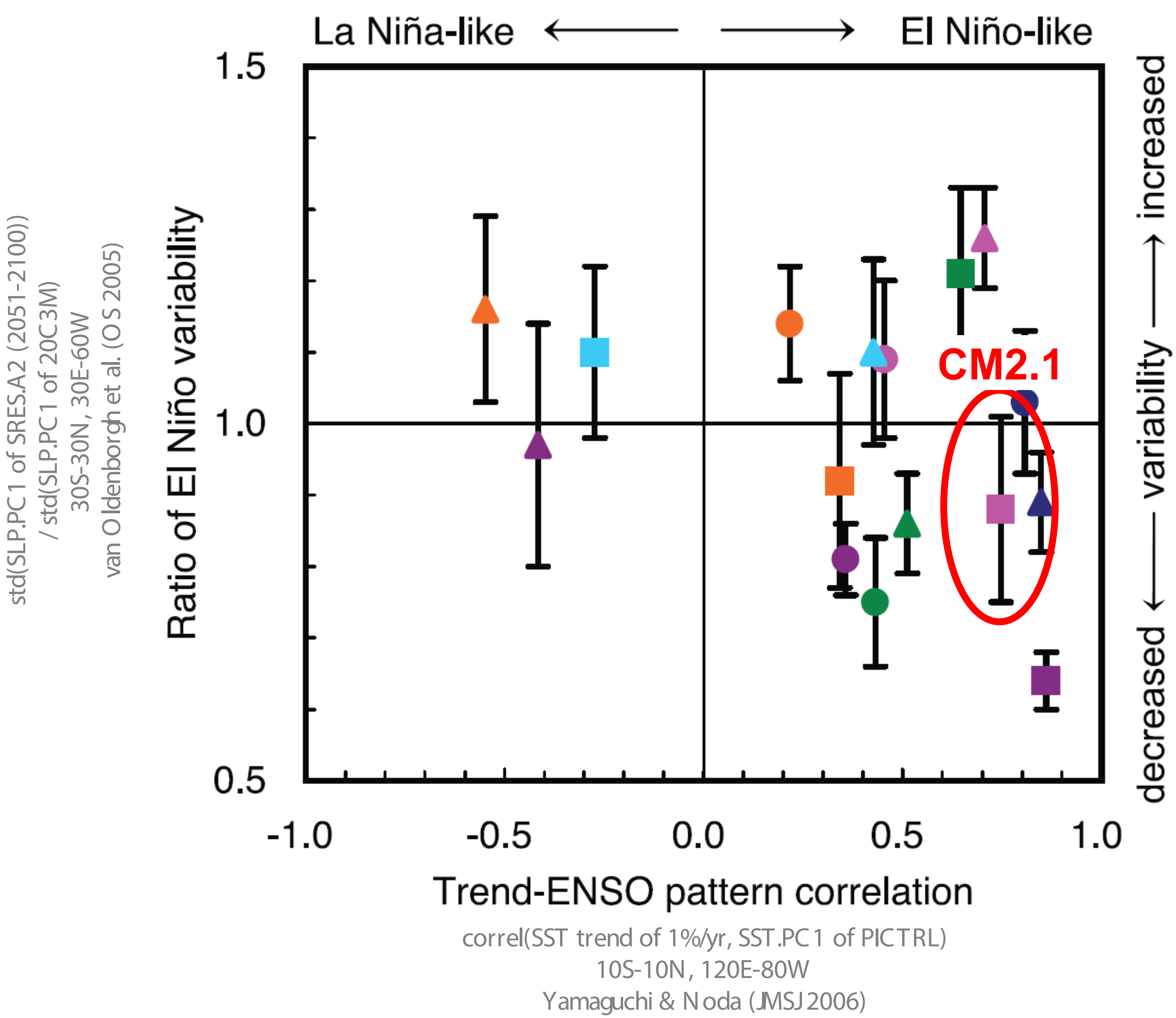


Multiproxy reconstructions:
e.g. Li et al. (NCC 2011);
Emile-Geay et al.
(J. Climate, 2013ab);
McGregor et al. (subm.)



ENSO has existed for thousands, perhaps millions, of years.
Obscures detection of slower climate changes (decadal, global warming).

Projected ENSO changes (CMIP3/AR4)



Weak/ambiguous *near-term* anthropogenic impacts on ENSO

Intrinsic modulation

Reviews:

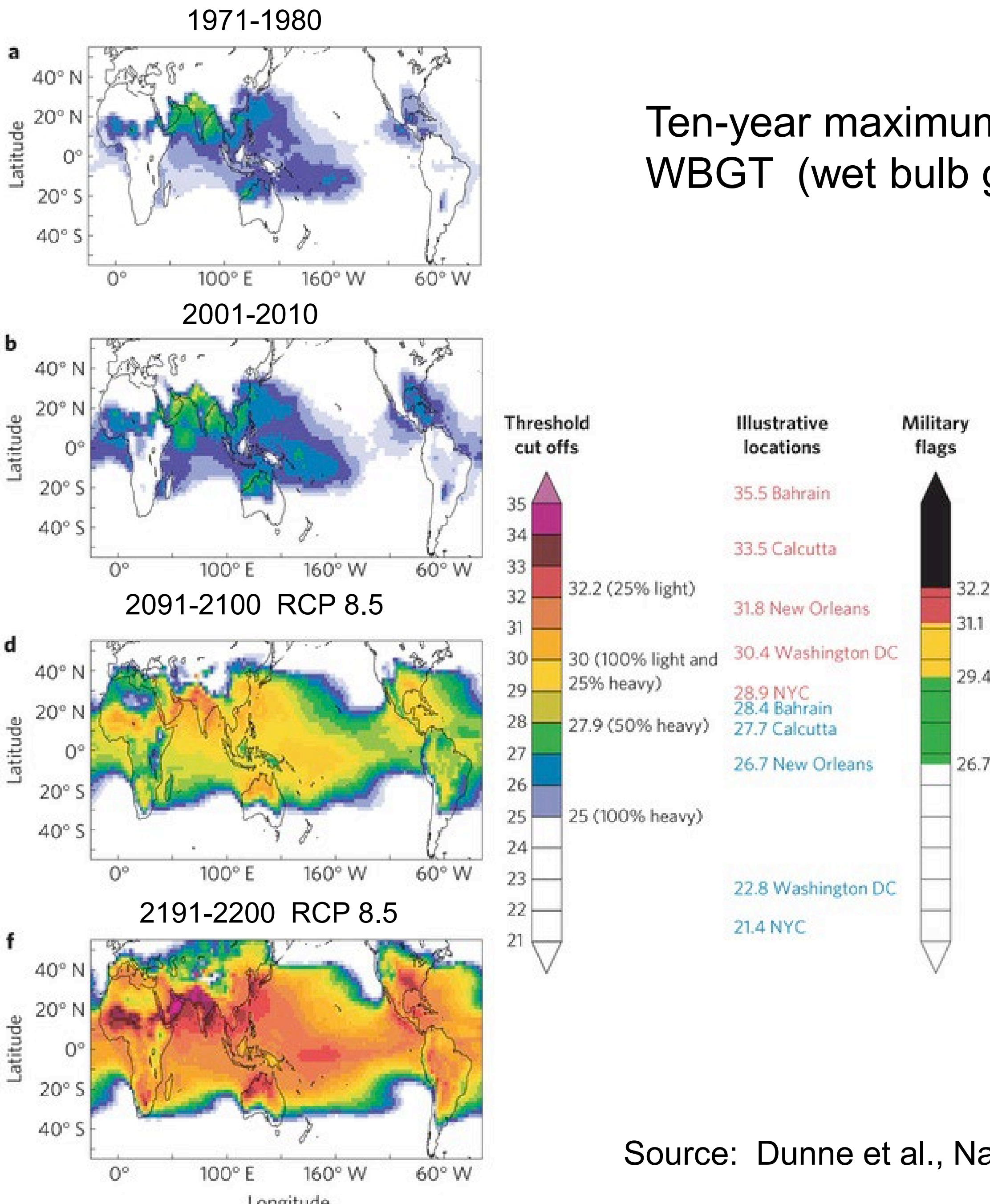
Meehl et al. (IPCC-AR4 2007)

Guilyardi et al. (BAMS 2009)

Vecchi & Wittenberg (WIREs CC 2010)

Collins et al. (Nature Geosci. 2010)

Ten-year maximum monthly mean WBGT (wet bulb globe temperature)



Source: Dunne et al., Nature Geoscience, 2013.

Main Points – with Recent GFDL Work as Examples

1. Anthropogenic climate change is affecting tropical climate (detection/attribution)
    - Especially evident in century scale surface temperature trends and recent extremes (examples)
2. Tropical cyclones and climate change – impact not as clear
    - Anthropogenic influence on tropical cyclones (hurricanes, typhoons, etc.) is difficult to detect.
    - Projections for late 21st century include increased intensity (~4%); decreased overall frequency (-16%); increased rain rates (+14%); sea level rise
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4. Heat stress increases – tropical temperatures are 'expanding' poleward

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

Phenomenon:

- Increase in intense tropical cyclone activity

Assessment that changes occurred:

- Low confidence in long-term (centennial) changes
- Virtually certain in North Atlantic since 1970

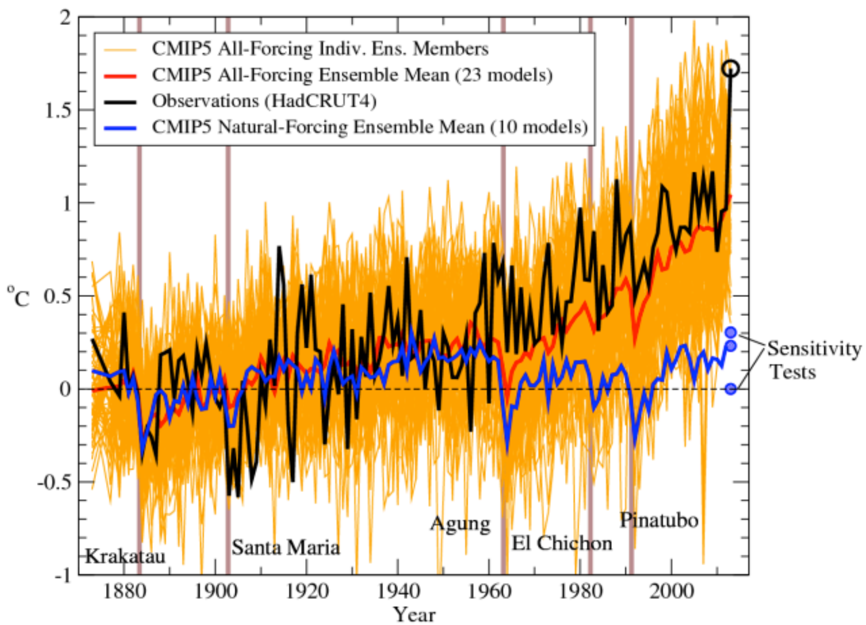
Assessment of a human contribution to observed changes:

- 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.”

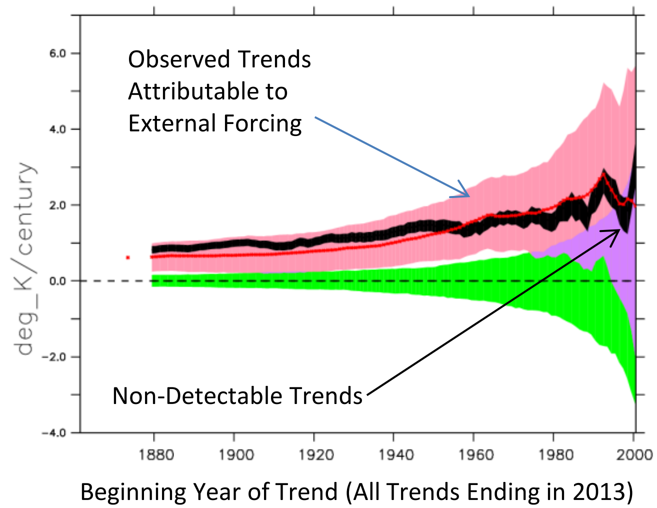
Likelihood of further changes (late 21st century):

- More likely than not (Western North Pacific and N. Atlantic)

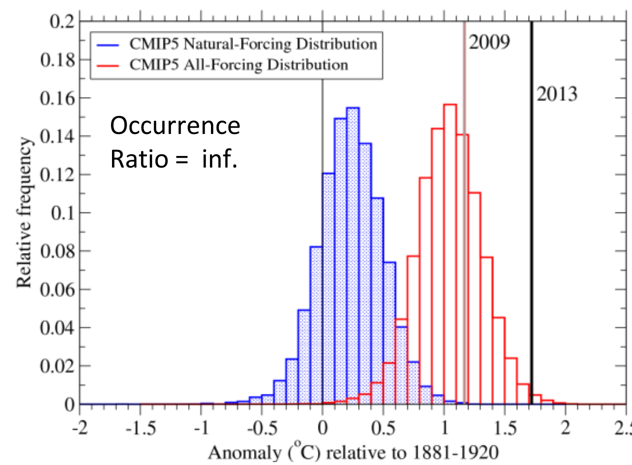
Australia Region: Annual Temperatures

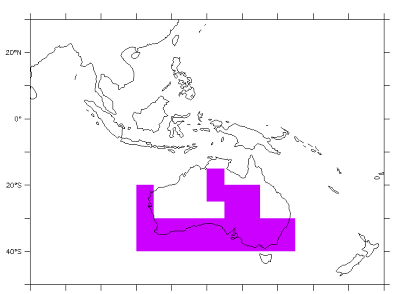


Sliding Trend Analysis



Attributable Risk Analysis





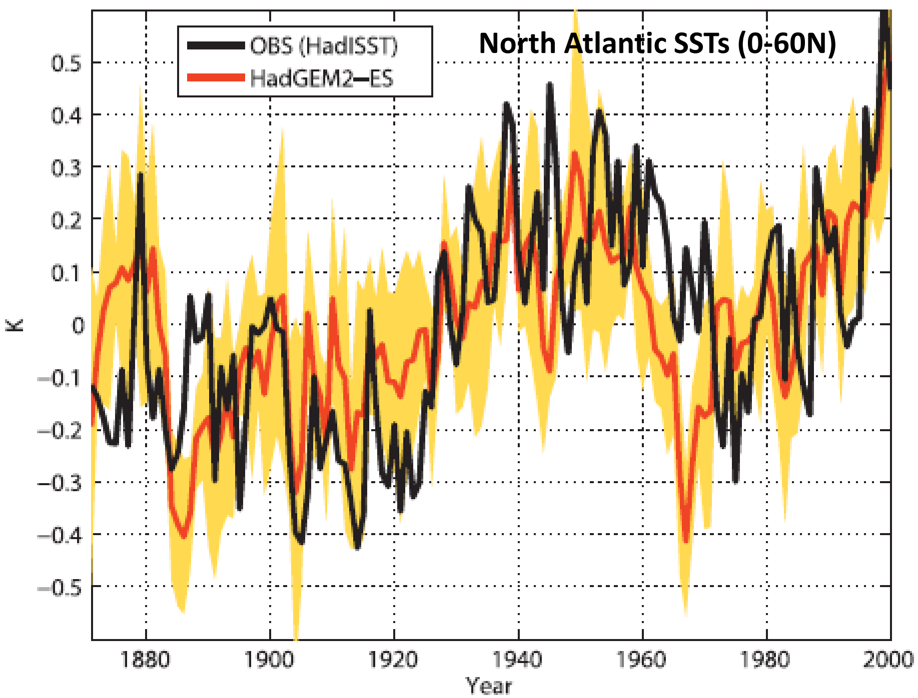
$$\text{Ratio} = \frac{p_{ALL}}{p_{NAT}}$$

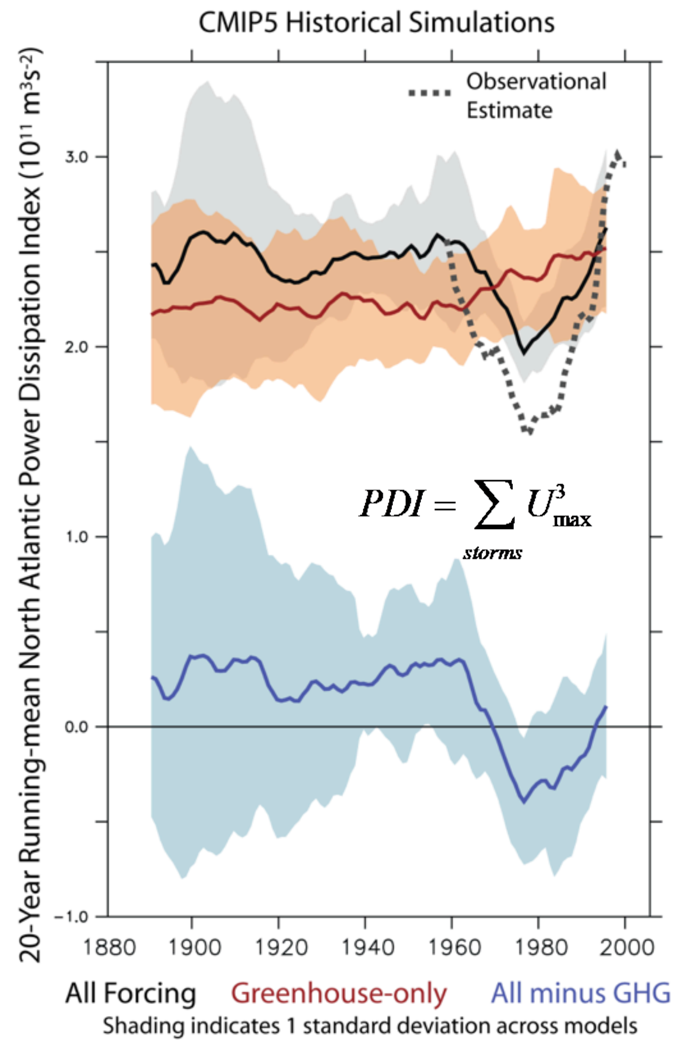
p_{ALL} and p_{NAT} : probabilities of exceeding the threshold in the All Forcing and Natural distributions.

Source: Knutson, Zeng, and Wittenberg, *BAMS,* accepted (2014)

What caused the rise in Atlantic hurricane activity since the 1970s?

Booth et al. (2012) attribute North Atlantic multidecadal SST variations primarily to aerosol forcing. Villarini and Vecchi (2013) attribute part of the multidecadal 'lull' in Atlantic hurricanes (70s and 80s) to aerosol forcing.

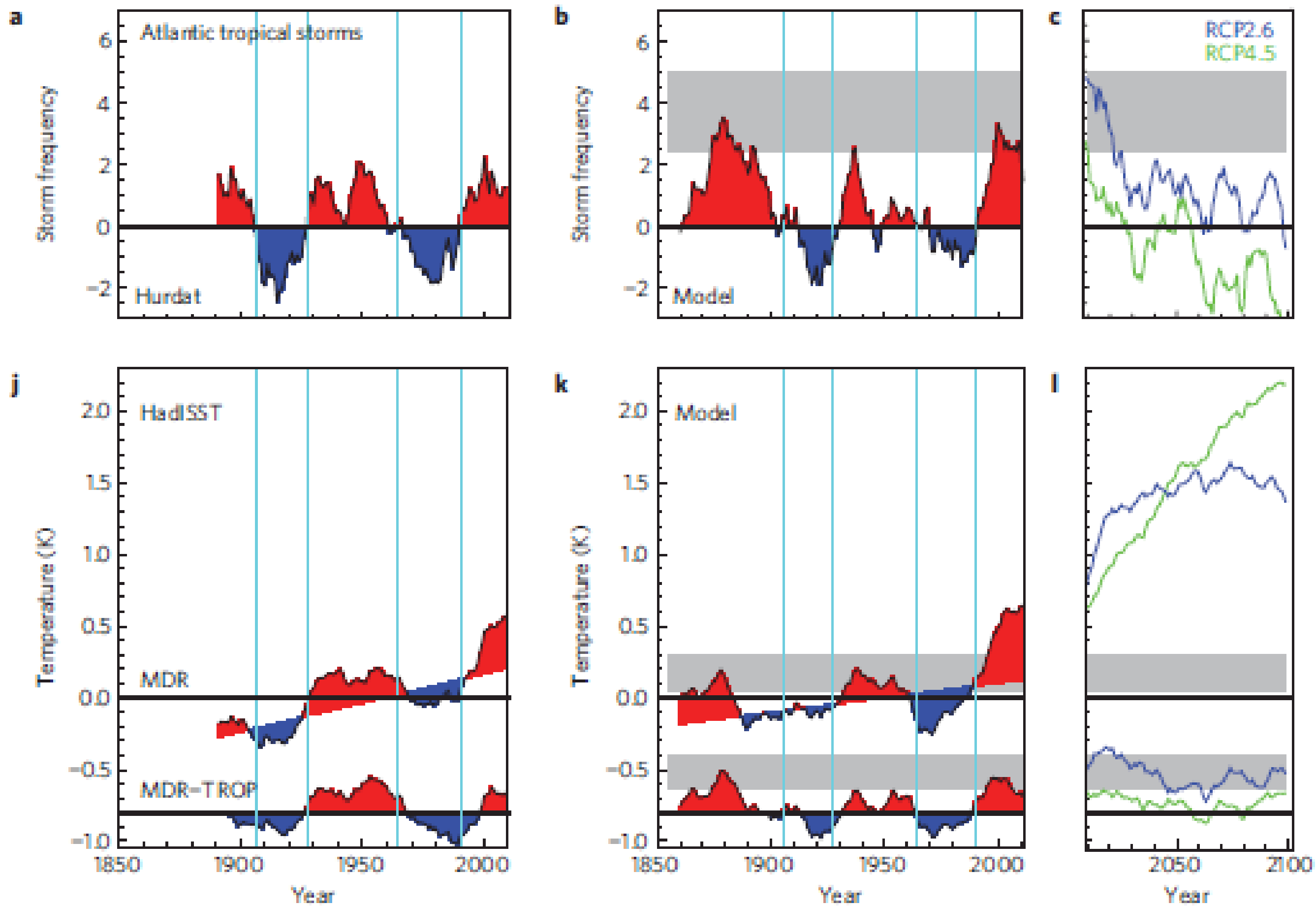




Sources: Left: Fig. 1 adapted from Booth et al., *Nature*, 2012 (Zhang et al. JAS, 2013); right: Villarini and Vecchi (J. Climate 2013).

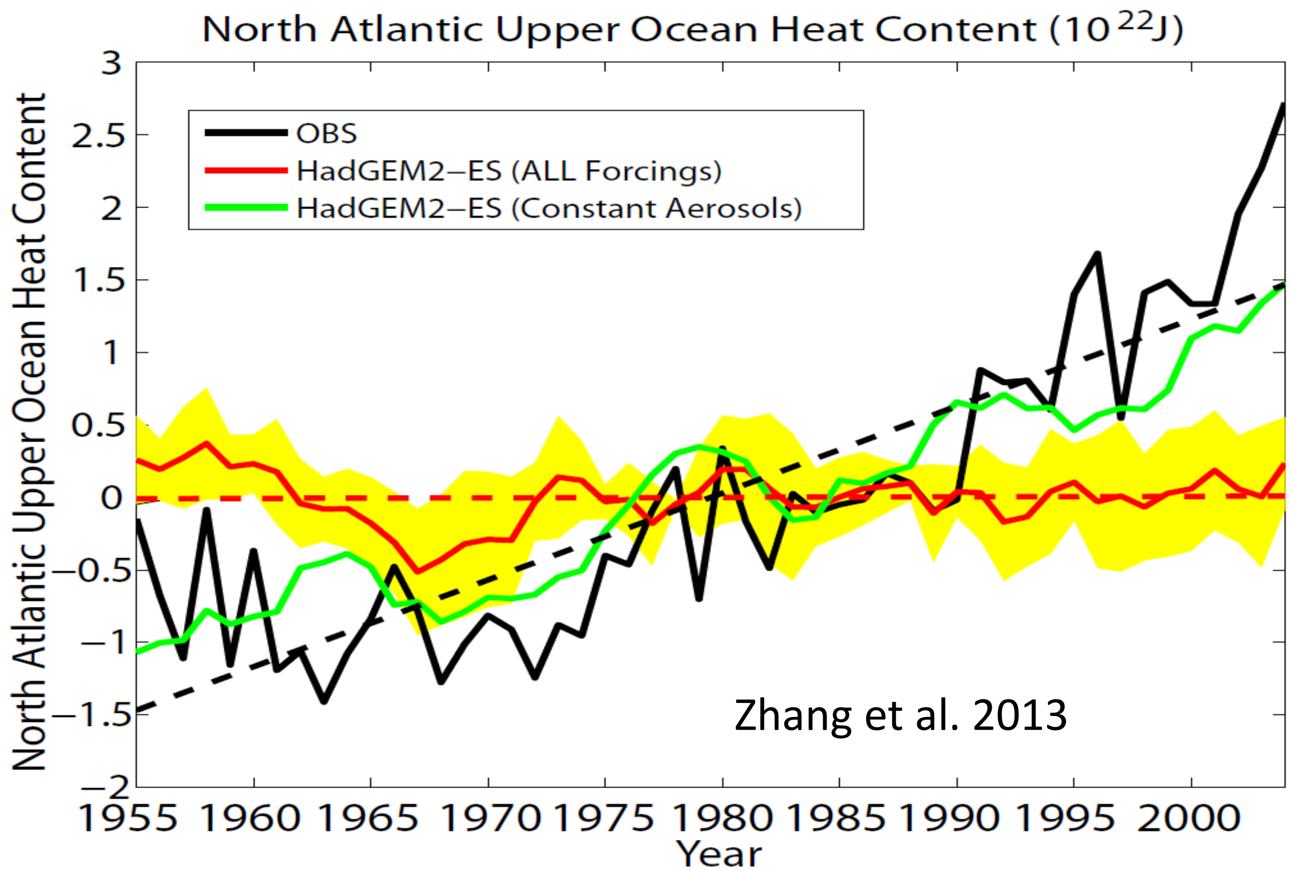
- Did Aerosols force 20th century multi-decadal changes in Atlantic tropical storm frequency?

  - Hadley Centre model (HadGEM2-ES) suggests a strong aerosol forcing/SST/TC frequency link.
  - Their future projections (RCP2.5, RCP4.5) show a decline in TCs over the coming century…



Reference: Dunstone et al., Nature Geoscience (2013).

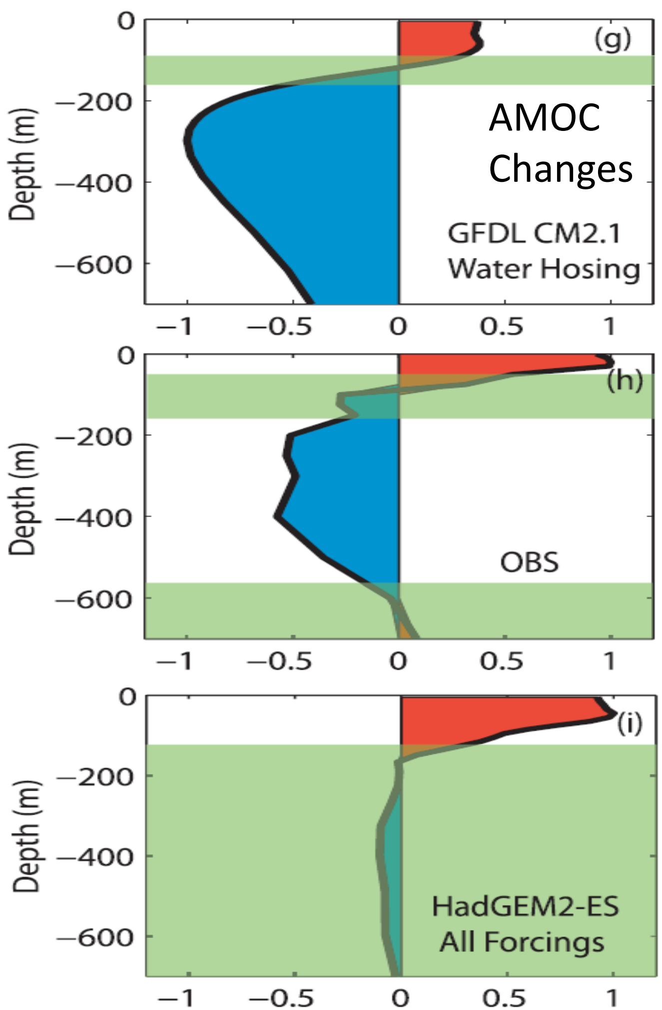
Aerosol Effects and Upper Ocean Heat Content



- Observations show substantial warming trend in the North Atlantic upper ocean heat content
- All-forcing simulations used in Booth et al. (2012) show no warming trend
- The discrepancy is mainly due to anthropogenic sulfate aerosols and the indirect effects of sulfate aerosols are strongly overestimated

Reference: Rong Zhang et al., J. Atm. Sci., 2013.

Anti-Correlated Multidecadal Variations in Tropical North Atlantic (TNA)

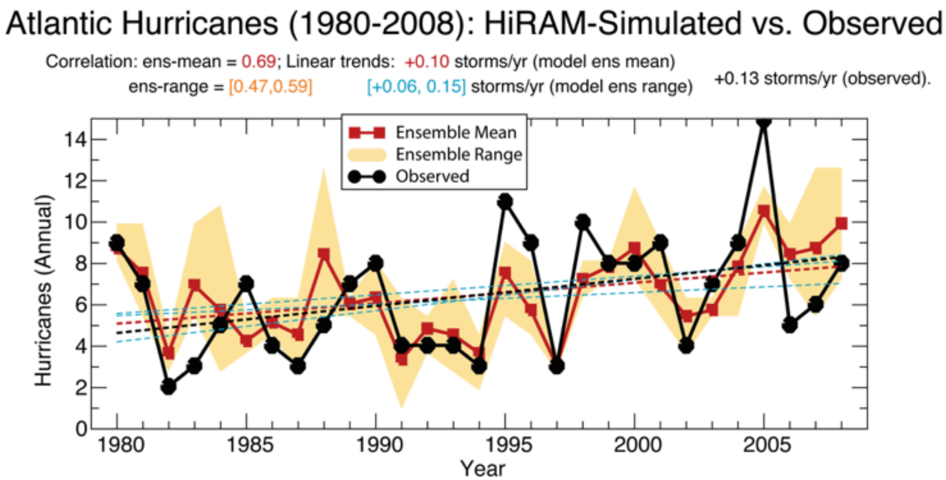


- The anti-correlated variations are seen for both observations and in model simulations of AMOC changes, but not in the simulation (HadGEM2-ES) used in Booth et al. 2012

- The aerosol mechanism cannot account for the observed anticorrelated multidecadal TNA SST and subsurface temperature variations

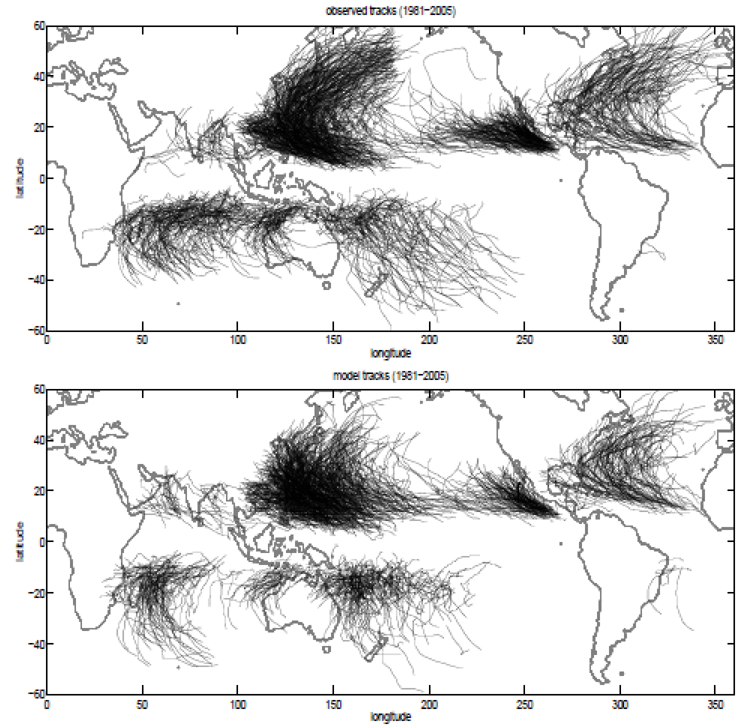
Reference: Rong Zhang et al., J. Atm. Sci., 2013

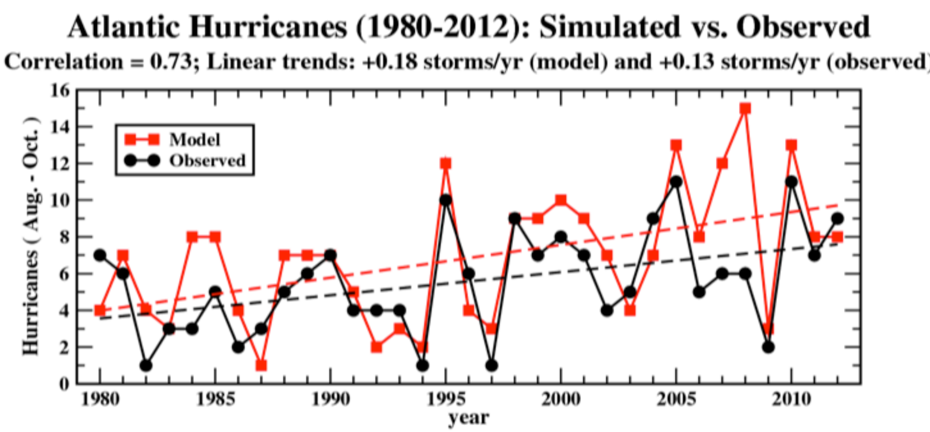
Two GFDL models reproduce the interannual variability of Atlantic hurricane counts; trend in NCEP reanalysis-forced ZETAC model is too large



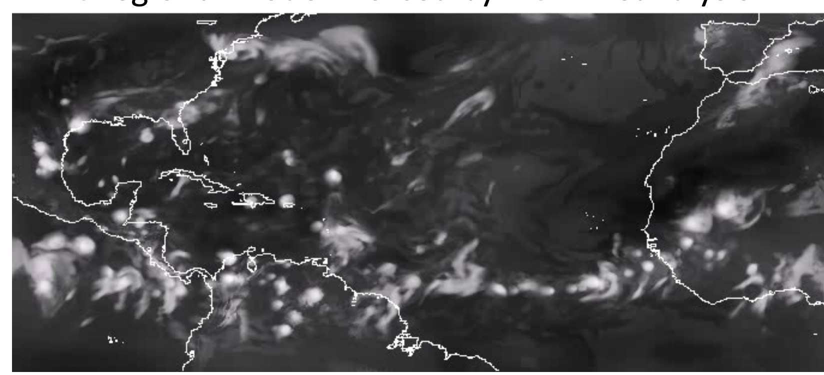
GFDL HIRAM 50km grid global model (SST-forced)

Simulated vs Observed Tropical Storm Tracks (1981-2005)



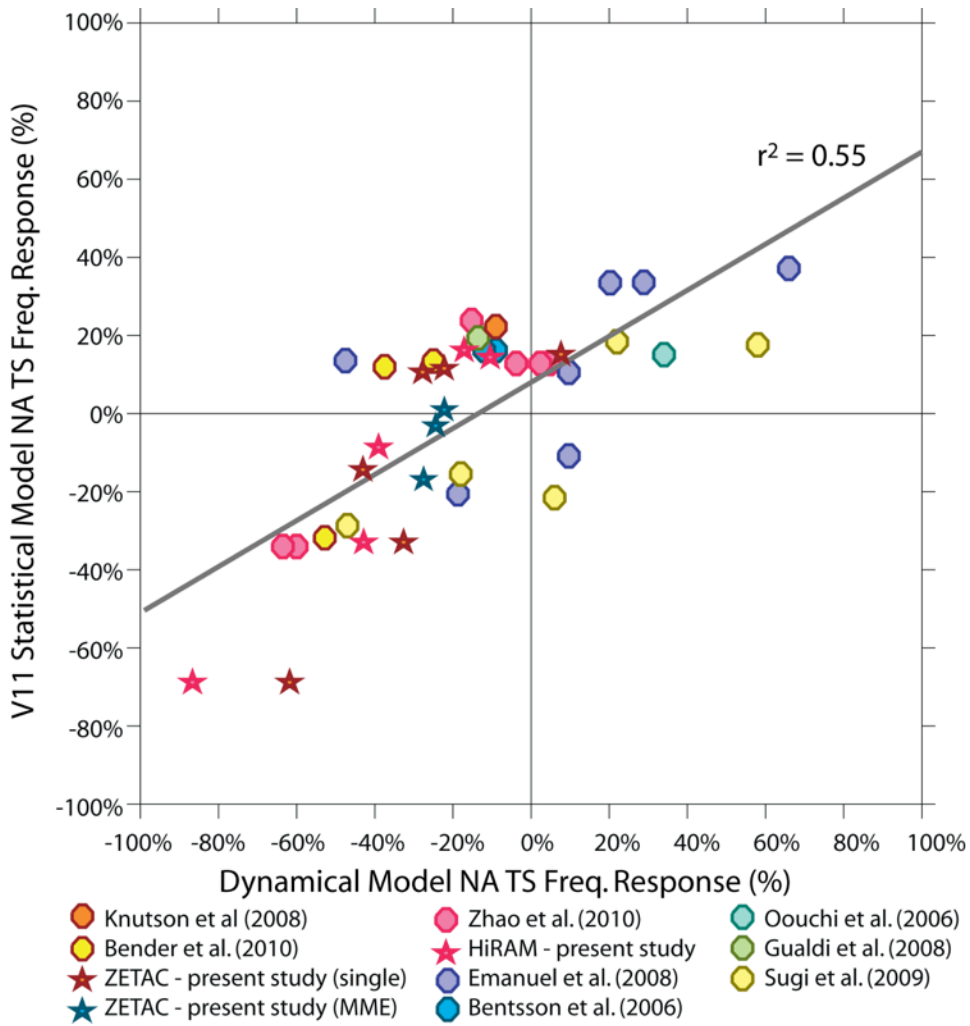


ZETAC regional model: forced by NCEP Reanalysis



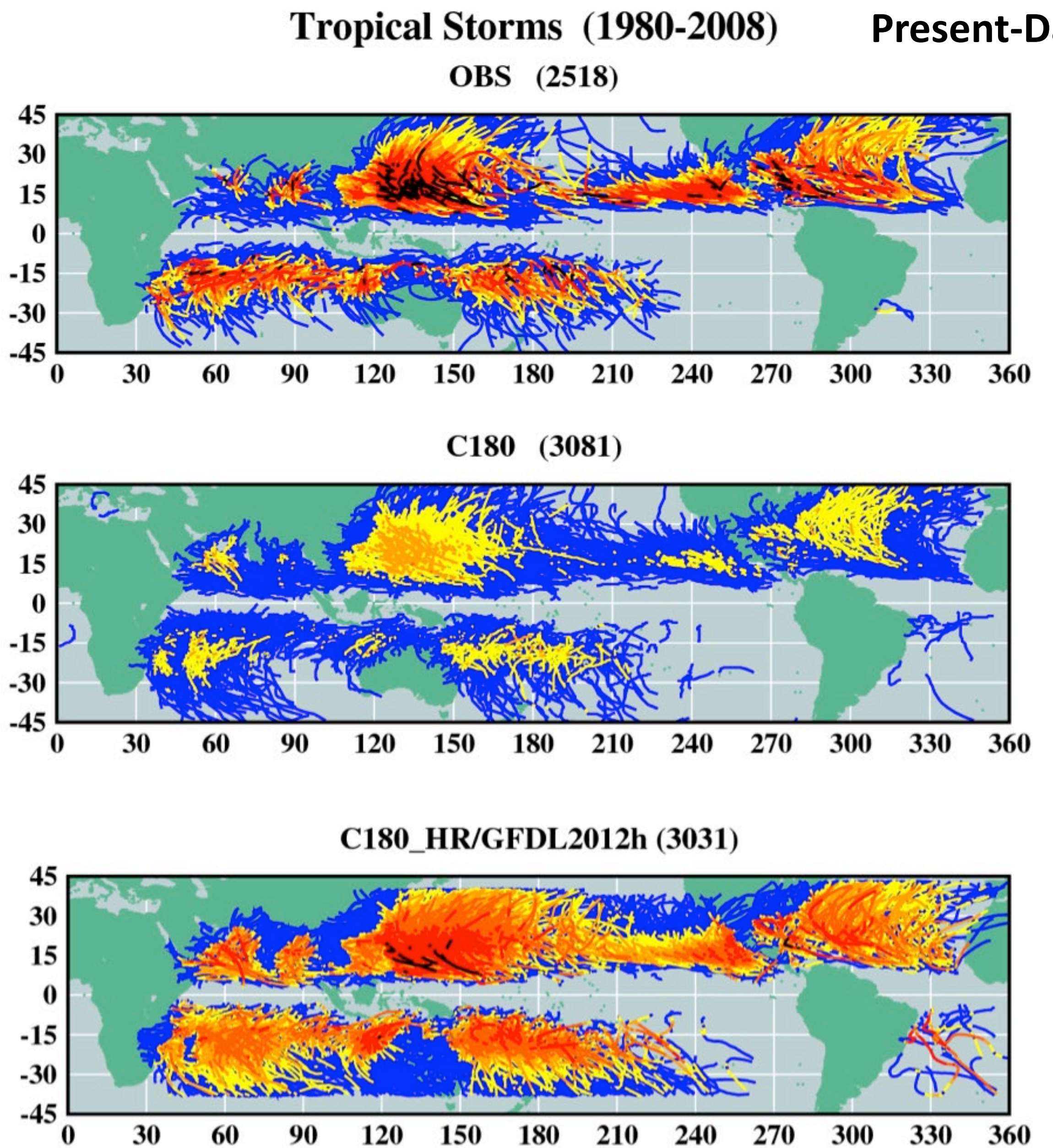
Sources: Knutson et al., *2007*, Bull. Amer. Meteor. Soc.; Zhao et al., 2009, J. Climate

Relative SST-based statistical model describes Atlantic basin projected tropical storm changes fairly well:



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

Present-Day Climate



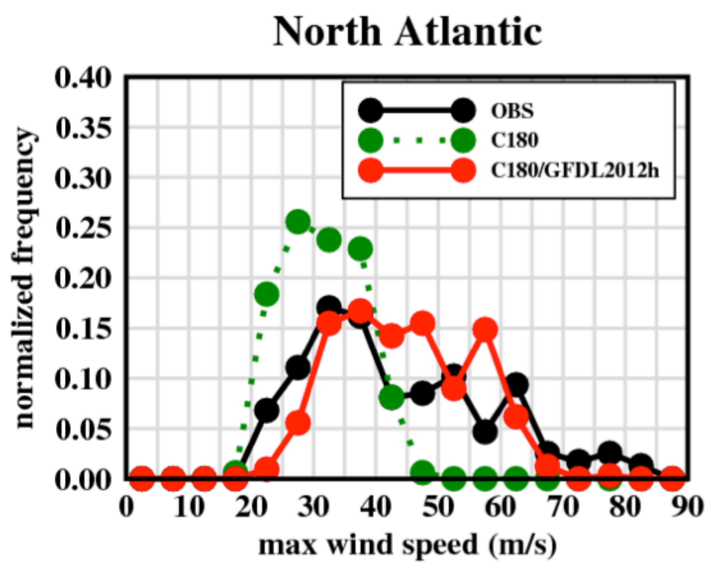
Storm Category:

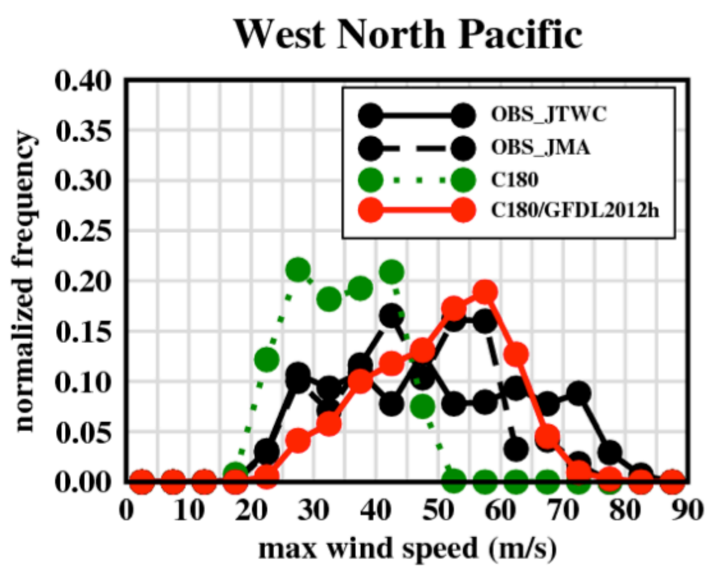
—	TS
—	HR1
—	HR2
—	HR3
—	HR4
—	HR5

GFDL dynamical downscaling to 6 km grid model; preliminary results, 2014.

Normalized histogram of maximum winds (1980-2008 Obs. SSTs)

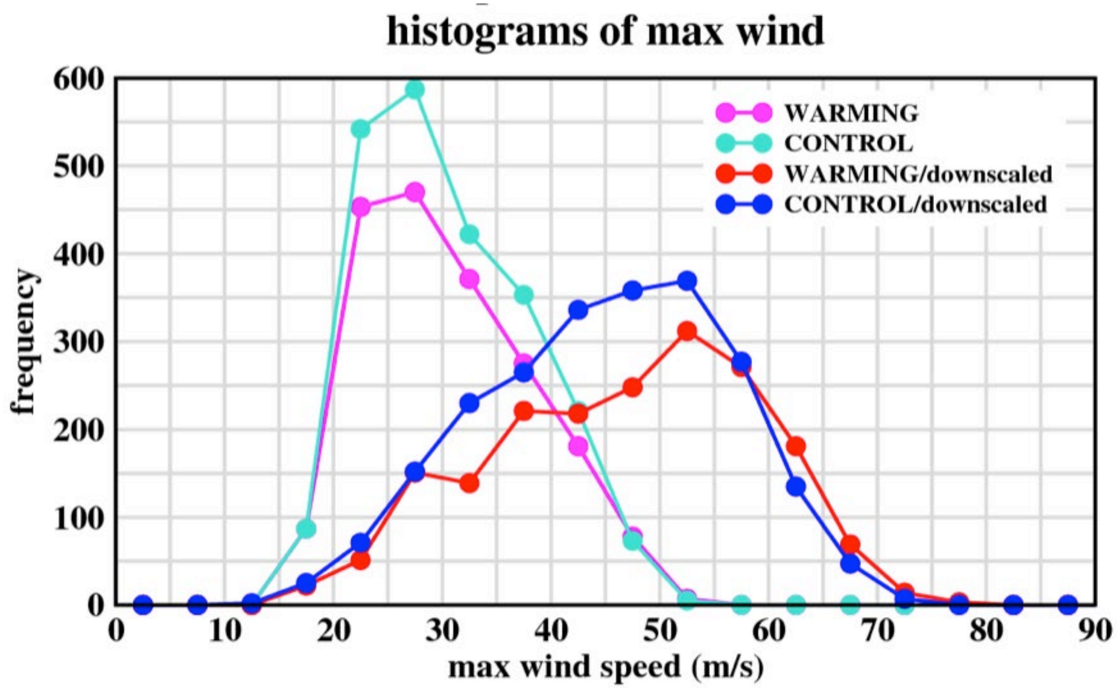
Present-Day Climate





GFDL dynamical downscaling to 6 km grid model; preliminary results, 2014.

CMIP5/RCP4.5 Late 21st Century Projections



Mean maximum windspeed changes for storm intensity of at least:

Tropical storms: Global: **+3.6%** [range: -5.6% (Southwest Pac) to +8.2% (NE Pac.)]

Hurricanes: Global: **+4.1%** [range: -3.1% (Southwest Pac.) to +7.8% (NE Pac.)]

Aggregate activity:

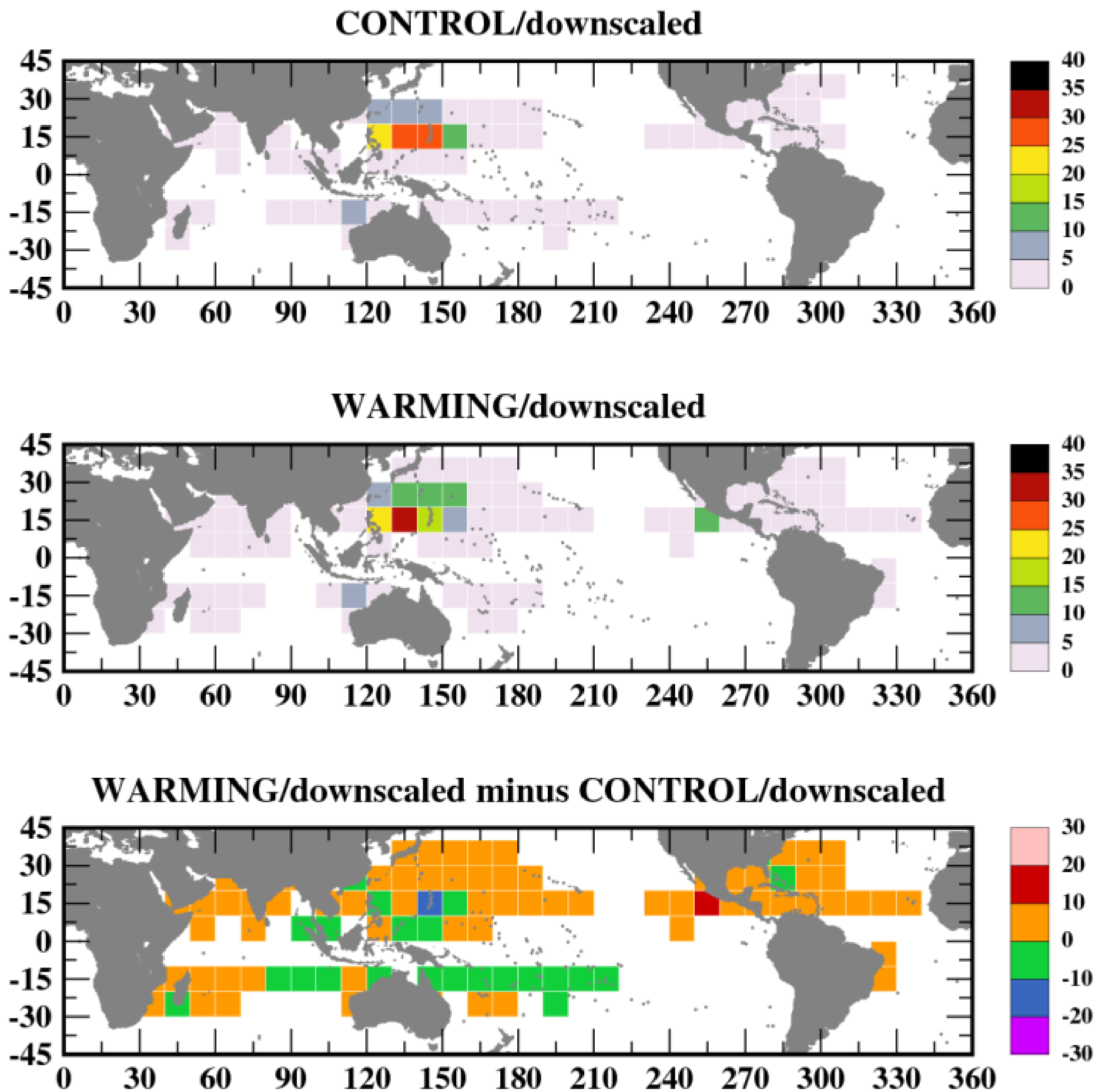
Power Dissipation Index: Global: **-9.7%**

Cat 4-5 storm days: Global: **+34.5%**

Global Frequency: Tropical storms: **-16%** [range: -37% (Southwest Pac) to +27% (N. Ind.)]

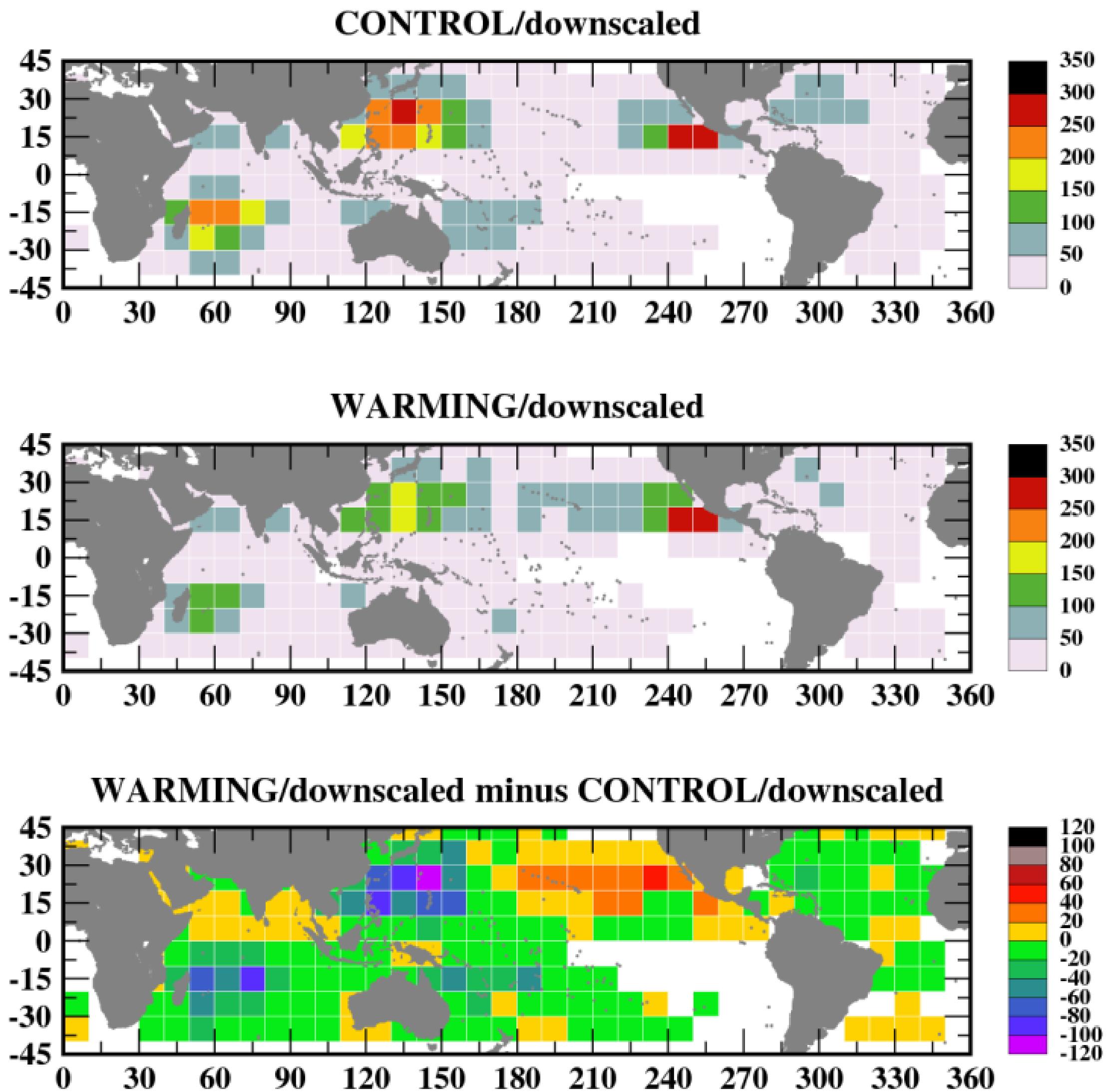
Cat 4-5 storms: **+24%** [range: -58% (Southwest Pac) to +340% (NE Pac.)]

CMIP5/RCP4.5 Late 21st Century Projection: Cat 4-5 Occurrence



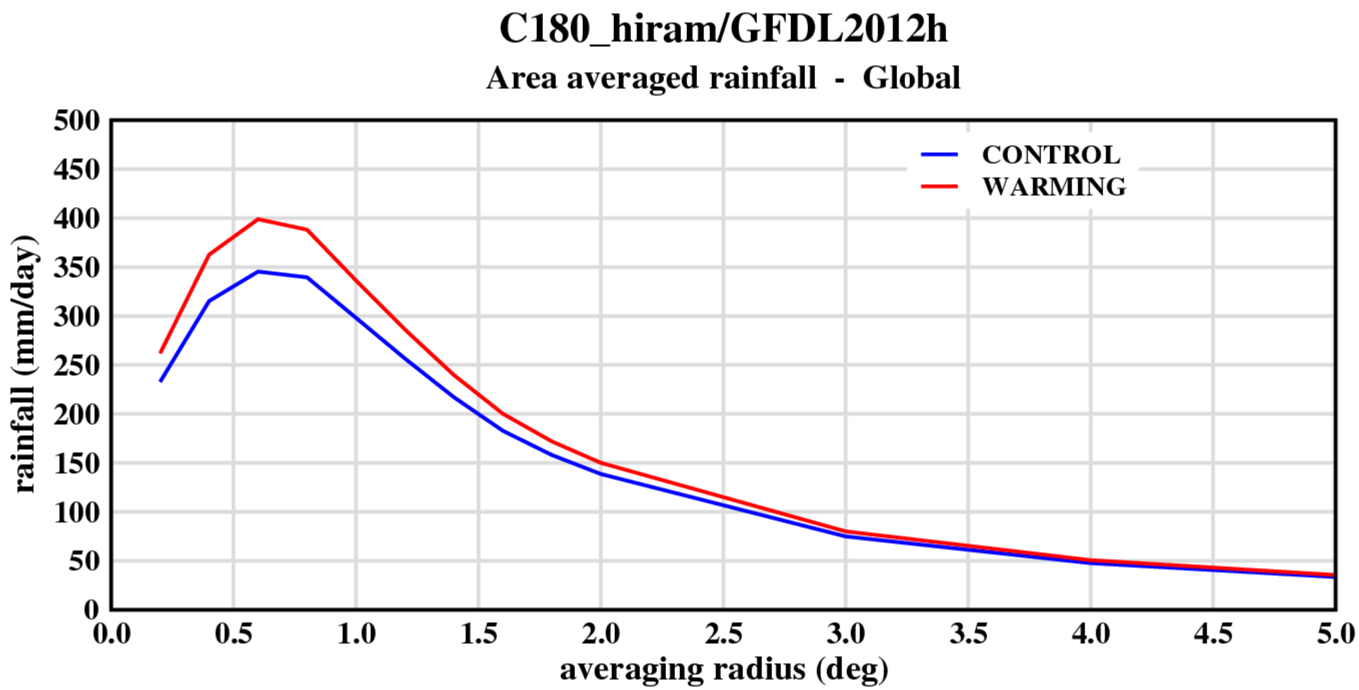
GFDL dynamical downscaling to 6 km grid model; preliminary results, 2014.

CMIP5/RCP4.5 Late 21st Century Projection: Tropical Storm Occurrence



GFDL dynamical downscaling to 6 km grid model; preliminary results, 2014.

CMIP5/RCP4.5 Late 21st Century Projection



Mean rain rate within 100 km radius of storm center:

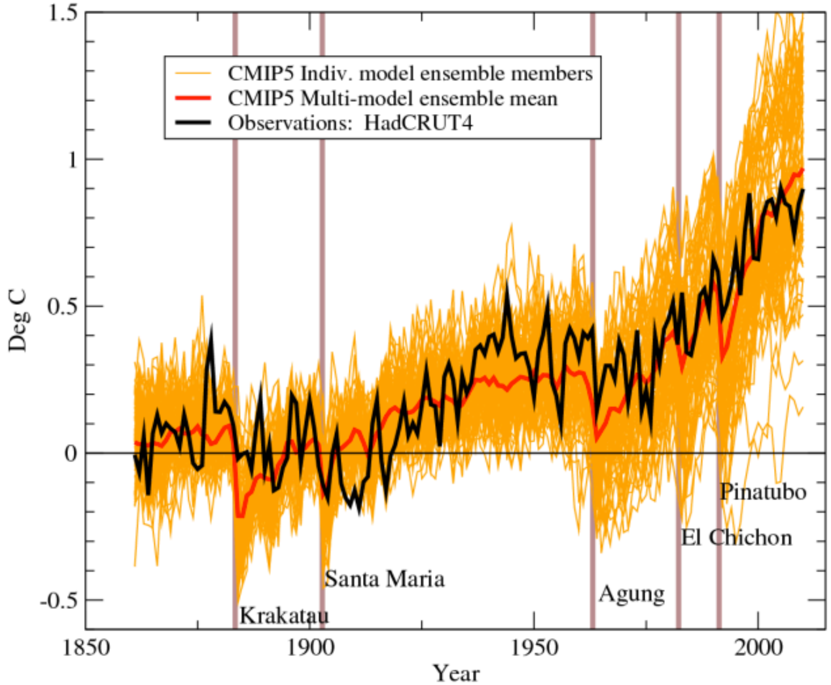
Tropical storms: Global: +14 % [range: -1.2% (Southwest Pac) to +21% (NW Pac.)]

Hurricanes: Global: +13 % [range: +3.4% (Southwest Pac.) to +20% (N. Atl.)]

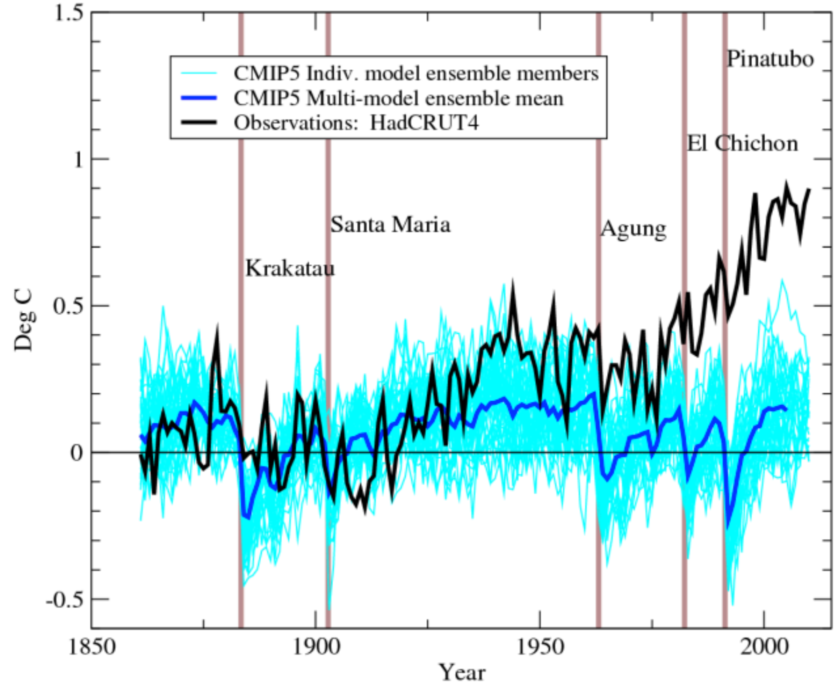
GFDL dynamical downscaling to 6 km grid model;
preliminary results, 2014.

Global Mean Surface Temperature Anomalies

a) CMIP5: All Forcings (Anthro. + Natural)



b) CMIP5: Natural forcing only (solar & volcanic)

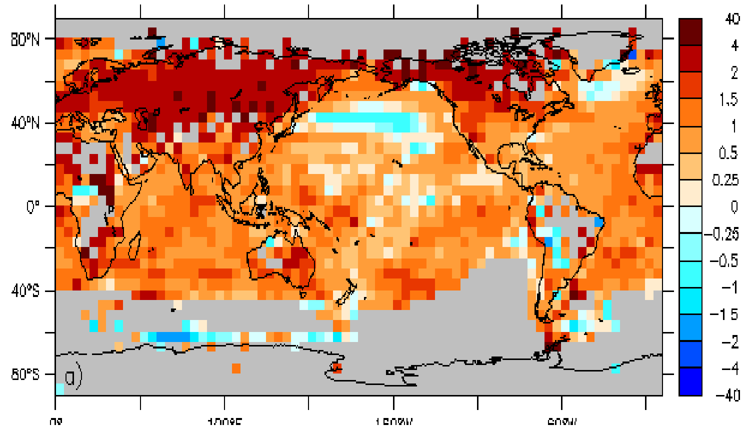


All Forcing: Anthropogenic (well-mixed GHGs, ozone, aerosols, land use change) + Natural Forcing
Natural Forcing: Solar variability; volcanic aerosols

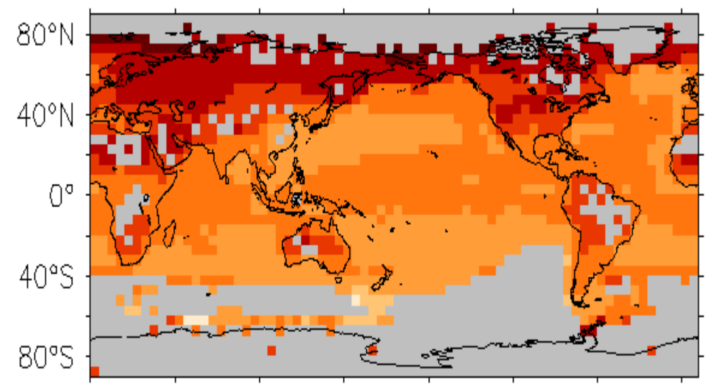
Source: Knutson, Zeng, and Wittenberg; J. Climate 2013.

1951-2010 Surface Temperature Trend Assessment *

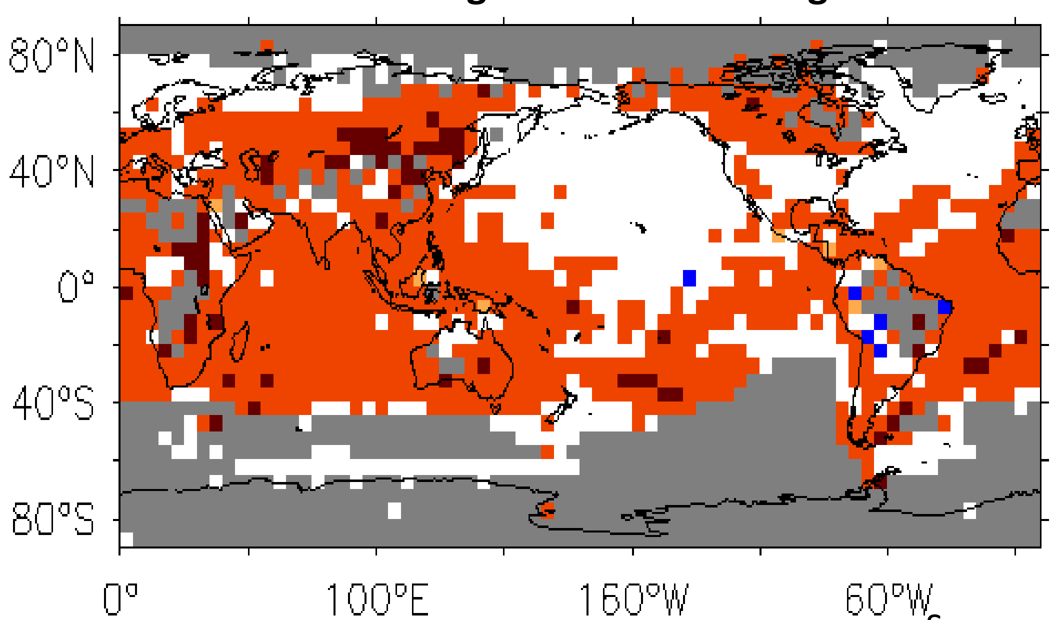
Observed trend (HadCRUT4)



CMIP5 All-Forcing ensemble trend



CMIP5 All-Forcing vs. Natural-Forcing assessment



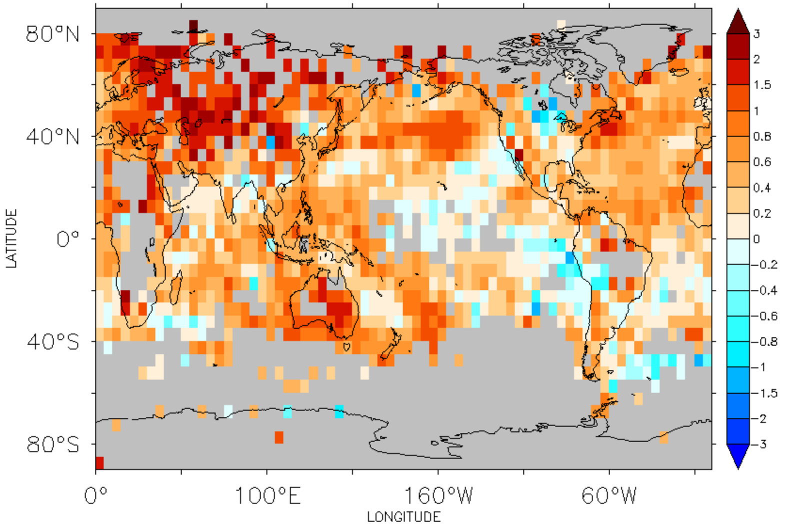
Attrib. anthro. warming, but > simulated
Attrib. & consistent anthro. warming
Detectable warming: < simulated
No detectable trend
Detectable cooling: < simulated
Attributable anthropogenic cooling
Detectable cooling: > simulated

Source: Knutson, Zeng, and Wittenberg, *J. Climate* (2013)

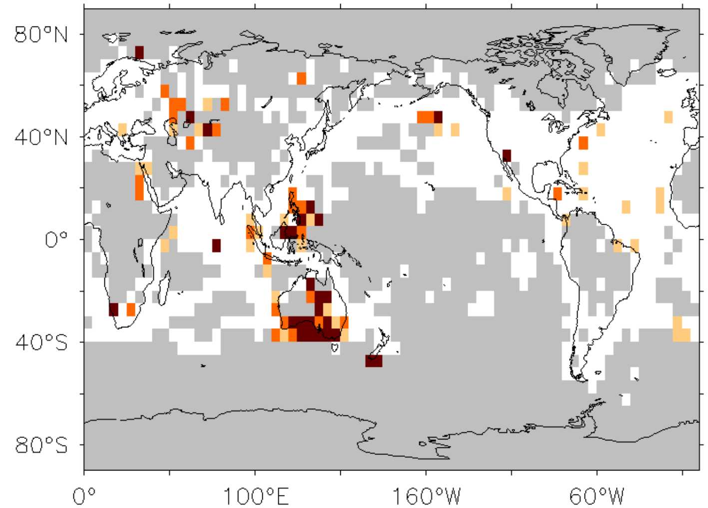
Explaining Extreme Events from a Climate Perspective…

Surface temperature: annual-mean extremes for 2013

Annual 2013 anomalies



Annual means: 2013 extremes



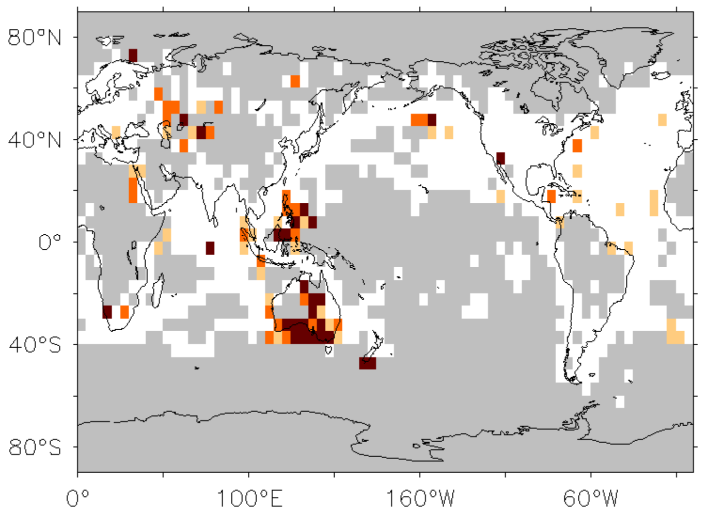
Map Legend:
(and percent coverage by category)

Highest	(3.0%)
2nd highest	(3.1%)
3rd highest	(4.3%)
3rd lowest	(0%)
2nd lowest	(0%)
Lowest	(0%)

Source: Knutson, Zeng, and Wittenberg, *BAMS,* accepted (2014)

Surface temperature annual-mean extremes for 2013: historical context

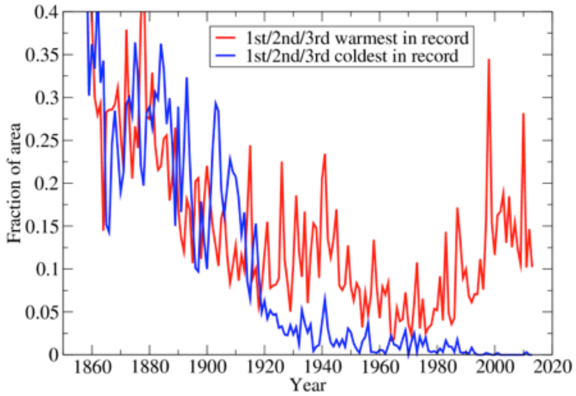
Annual mean surface temperature: 2013 extremes



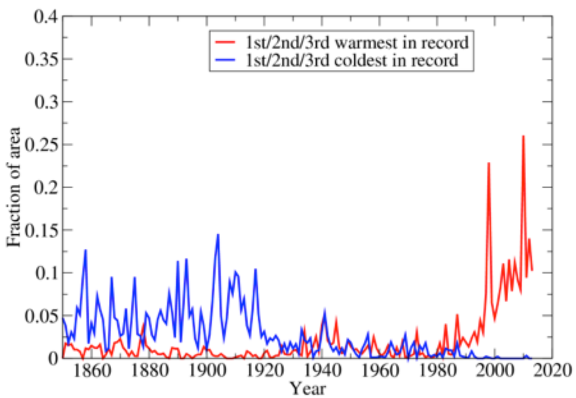
Map Legend:
(and percent coverage by category)

Highest	(3.0%)
2nd highest	(3.1%)
3rd highest	(4.3%)
3rd lowest	(0%)
2nd lowest	(0%)
Lowest	(0%)

Area with warm vs cold annual-mean extremes (record to date)

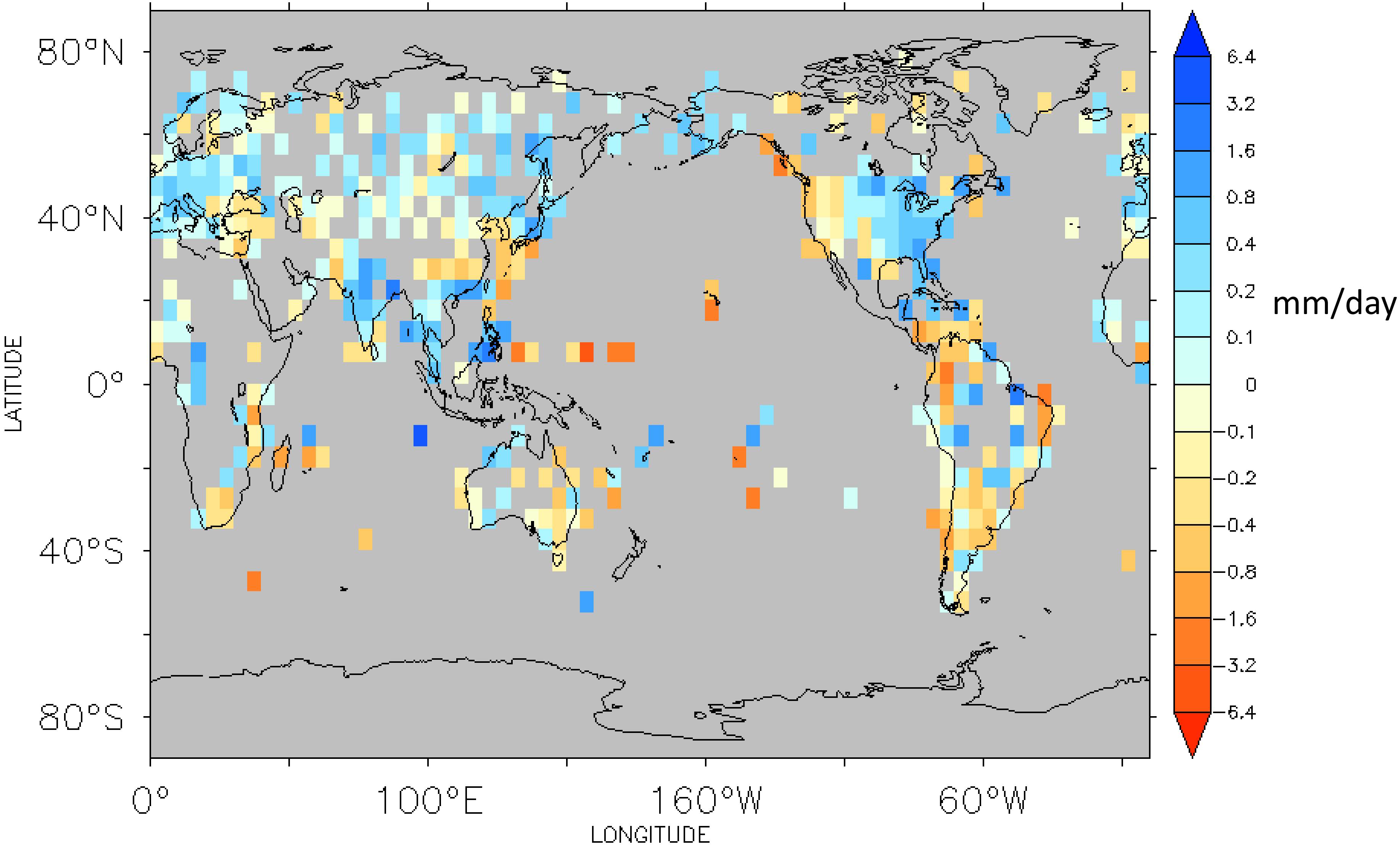


Area with warm vs cold annual-mean extremes (full record)

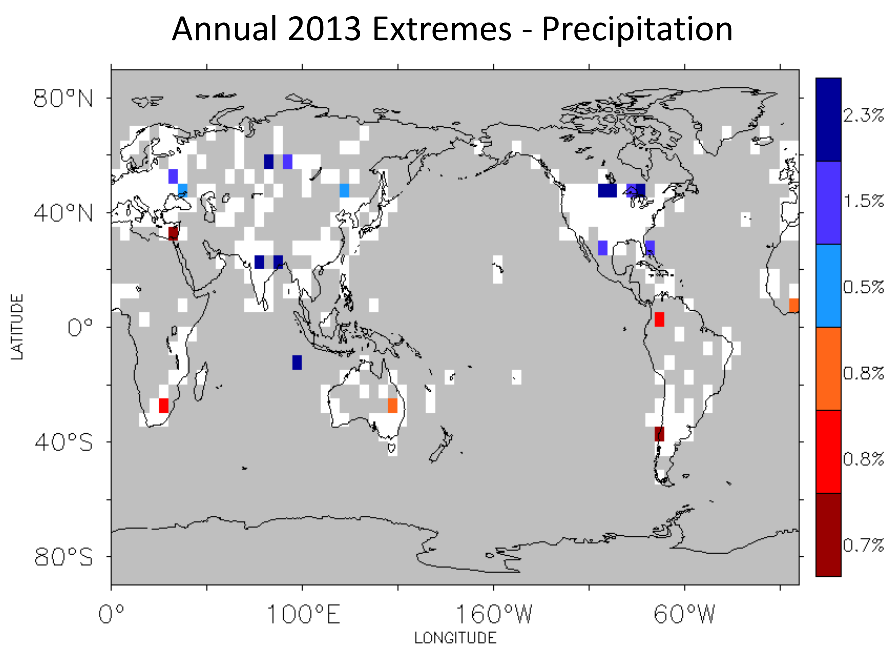


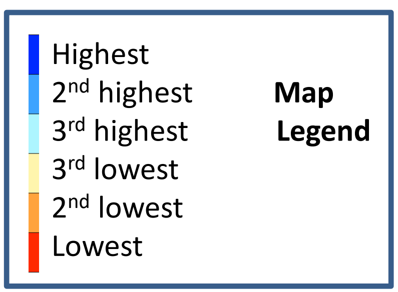
Source: Knutson, Zeng, and Wittenberg, *BAMS,* accepted (2014)

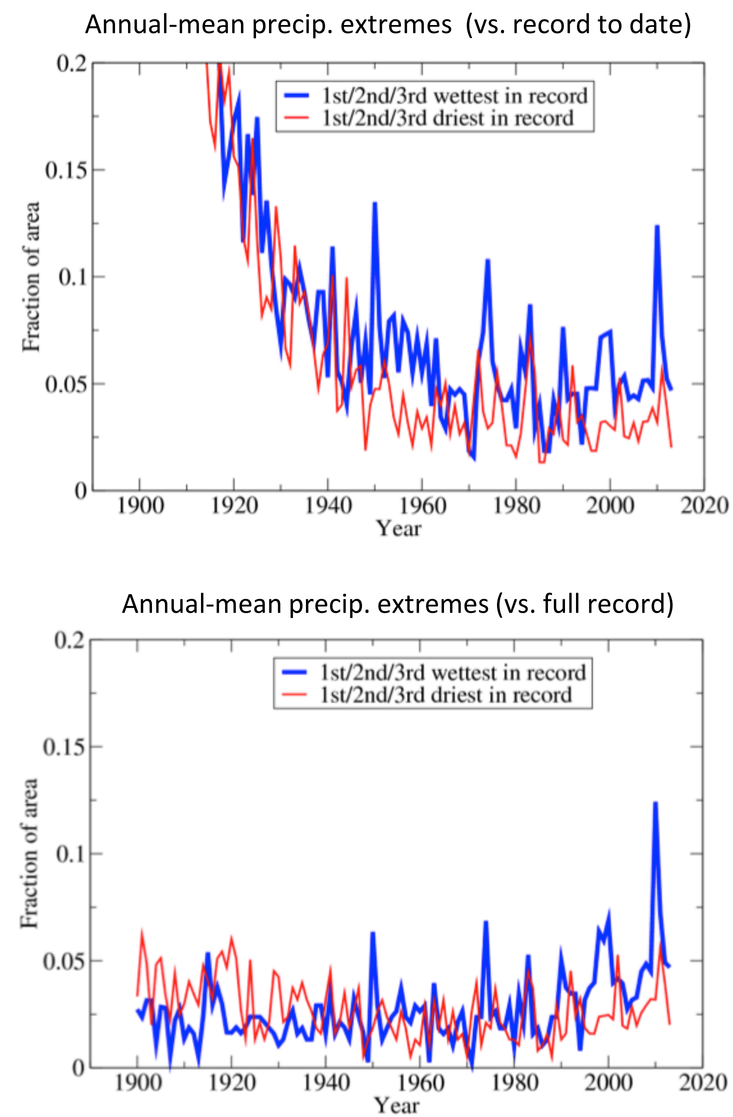
Annual Mean Precipitation Extremes for 2013 (100 yrs+ of record)



Source: Knutson, Zeng, and Wittenberg, *BAMS* accepted (2014)



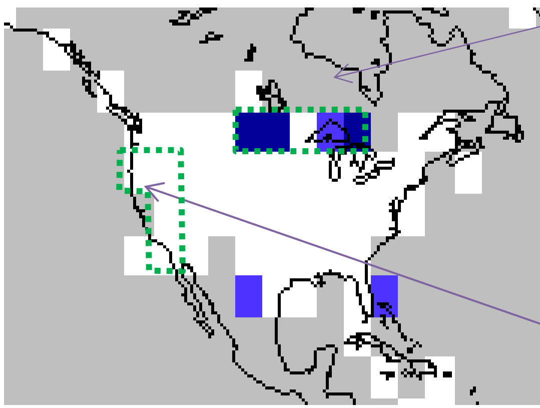




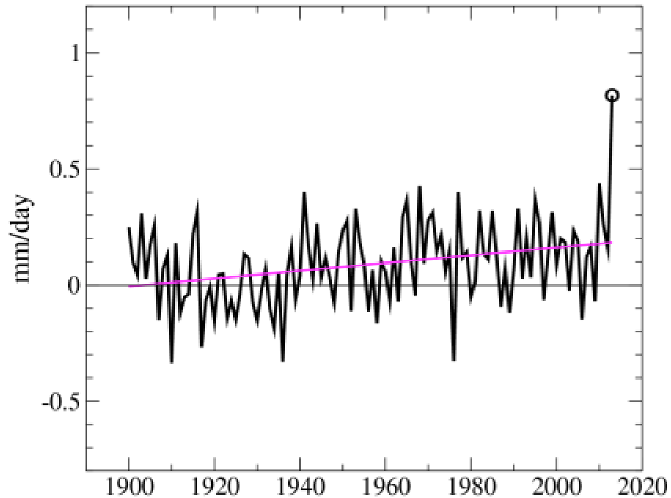
Source: Knutson, Zeng, and Wittenberg, *BAMS* accepted (2014)

2013 Annual Mean Precipitation Extremes: Climate Perspective

Annual 2013 Extremes - Precipitation

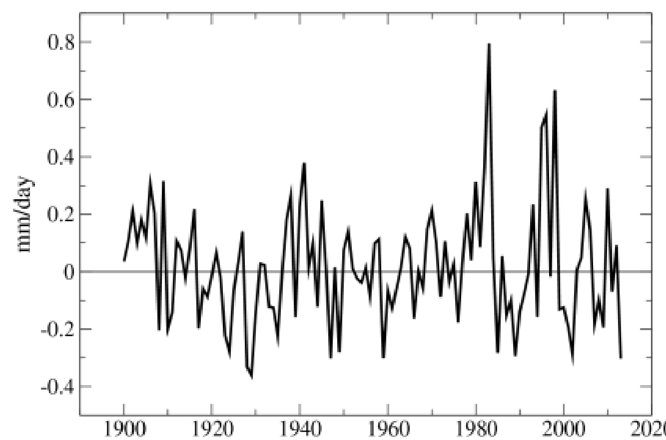


U.S./Canadian border region: annual means



U.S./Canadian border region —ANN:
Significant increasing trend;
Trend attributable to Anthro. + Natural

California region: annual means



California region -- ANN:
Non-significant trend

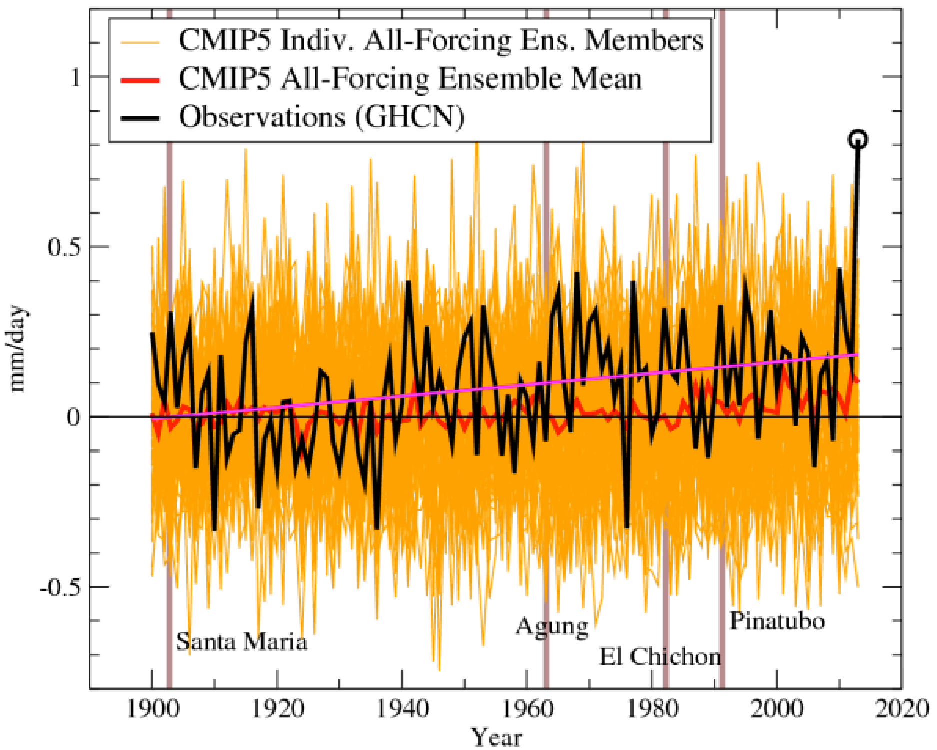
Map Legend

- Highest
- 2nd highest
- 3rd highest
- 3rd lowest
- 2nd lowest
- Lowest

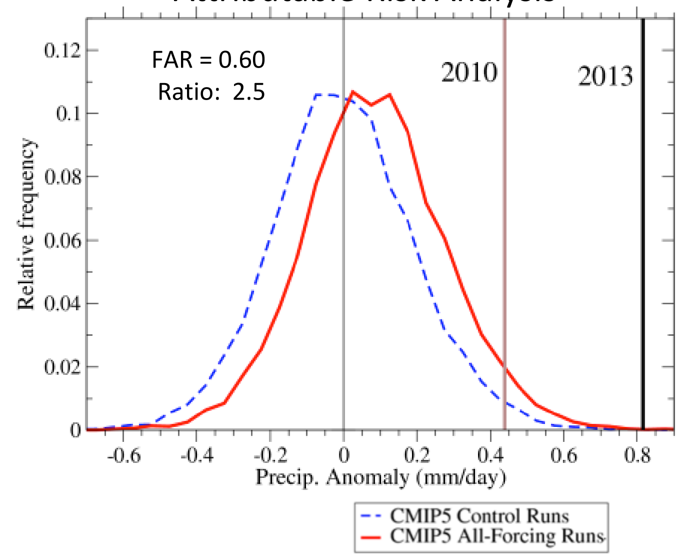
Source: Knutson, Zeng, and Wittenberg, *BAMS* accepted (2014)

2013 Annual Mean Precipitation Extremes: Climate Perspective

U.S./Canadian Border Region – Annual-mean Precipitation



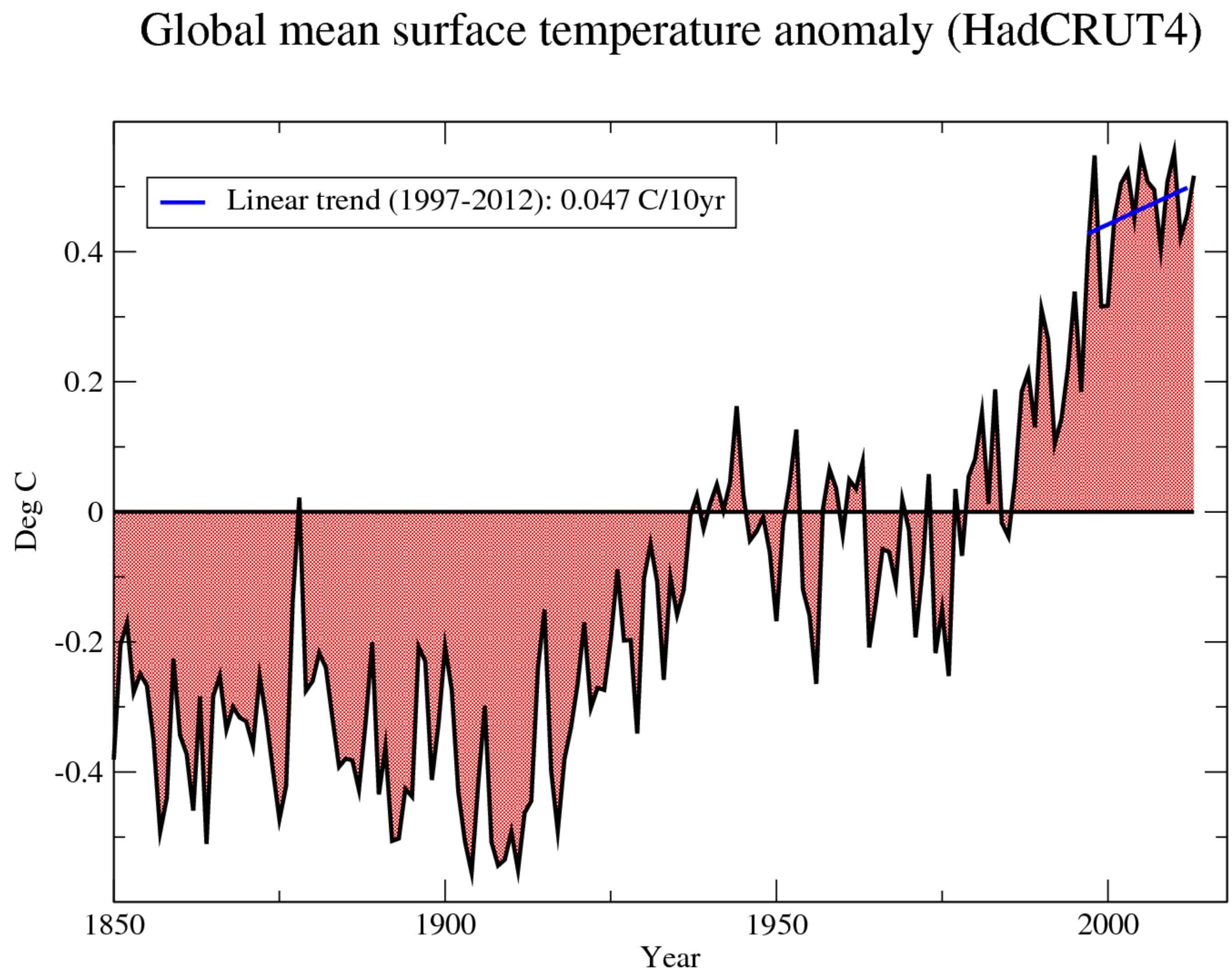
Attributable Risk Analysis



$$\text{Ratio} = \frac{p_{ALL}}{p_{CON}}$$

p_{ALL} and p_{CON} : probabilities of exceeding the 2013 or 2010 thresholds in the All Forcing and Control distributions.

Source: Knutson, Zeng, and Wittenberg, *BAMS* accepted (2014)

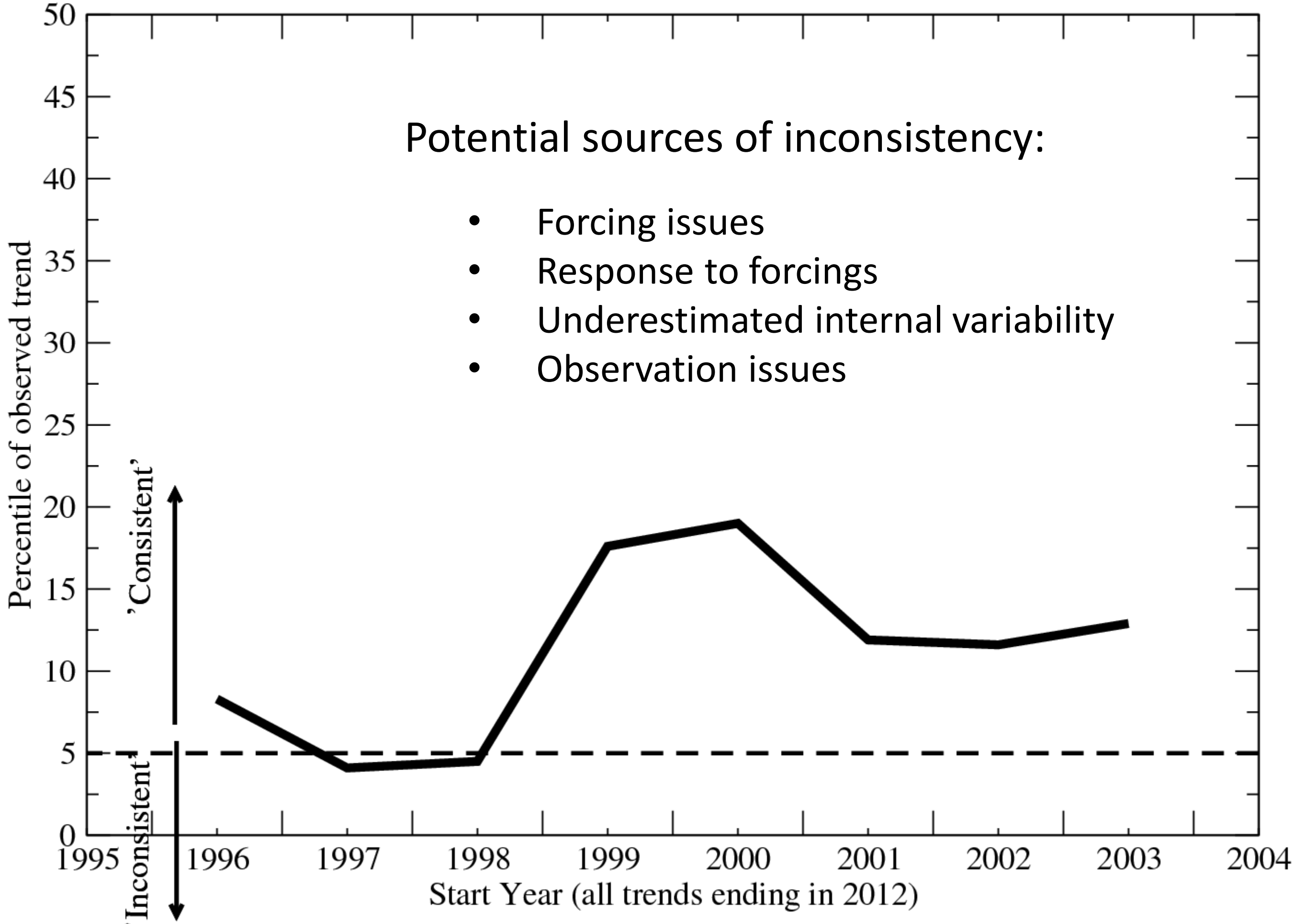


Note: Trend using previous year's version of HadCRUT4 was 0.0446 C/10yr.

Wed Jan 29 17:14:37 2014

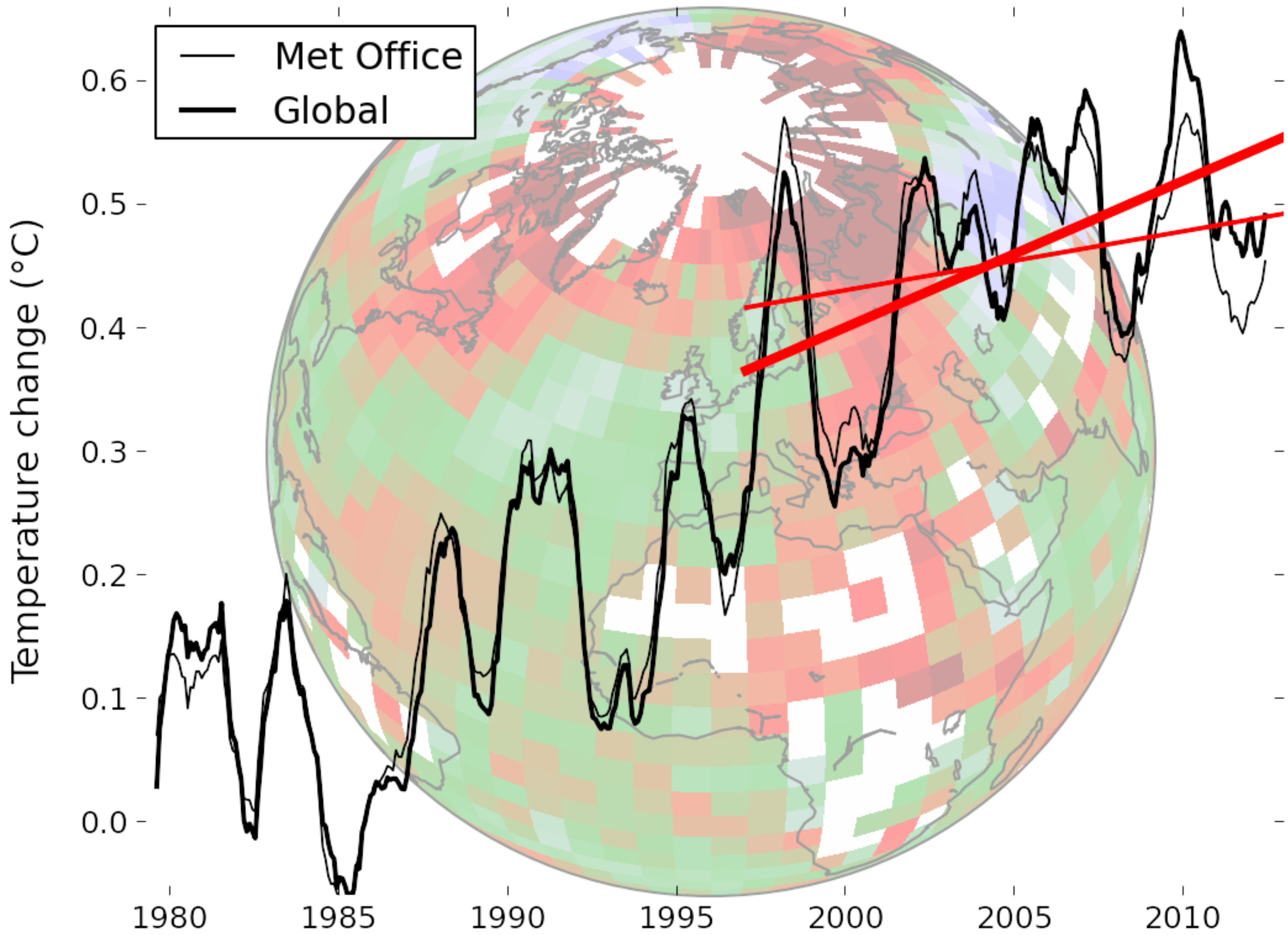
Assessment of Global Surface Temperature Trends (1997-2012)

CMIP5 Historical/Control Runs; Base case: HadCRUT4 (available area only);

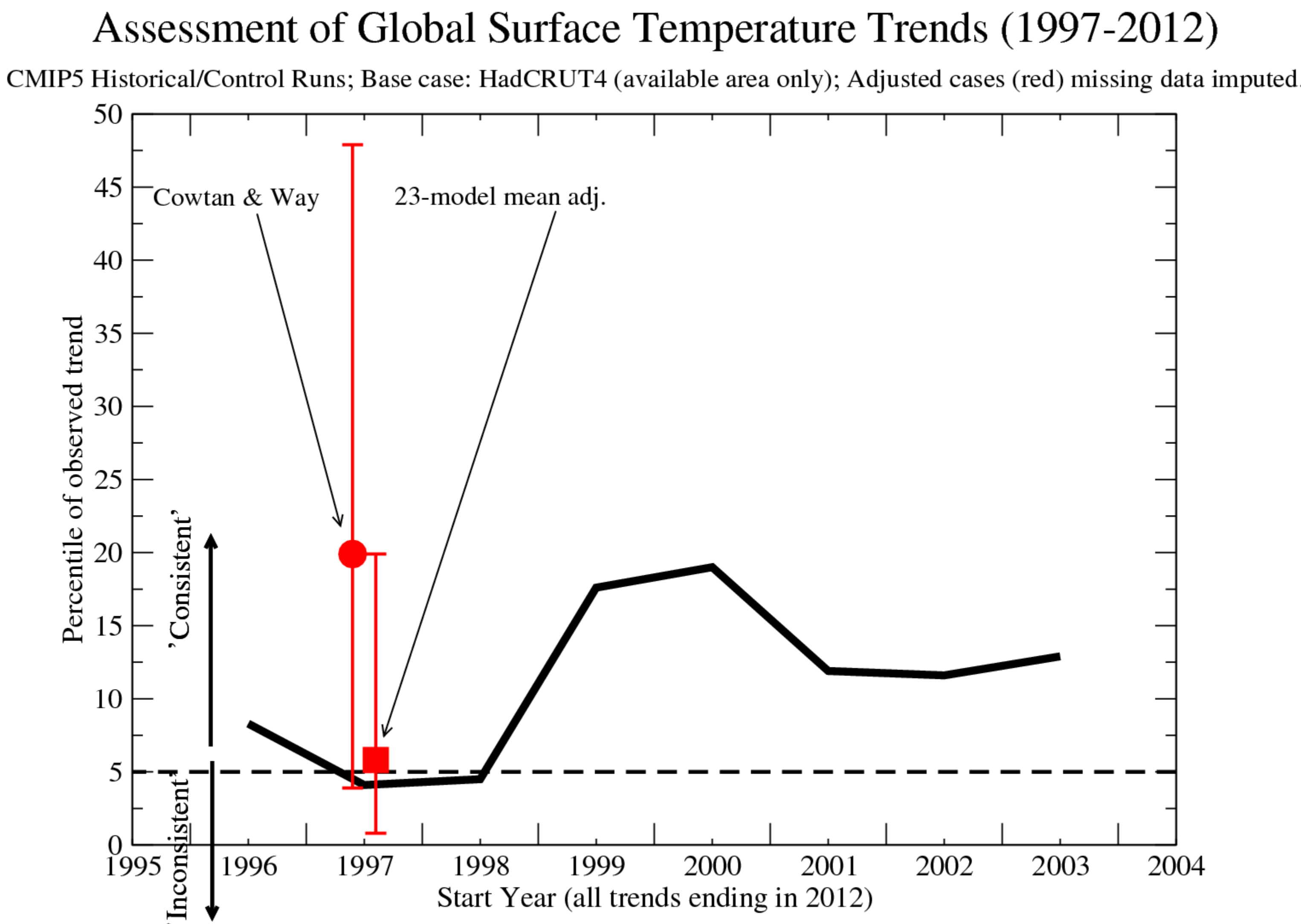


Thu Apr 10 13:38:34 2014

Are missing temperature observations in the Arctic causing the hiatus?



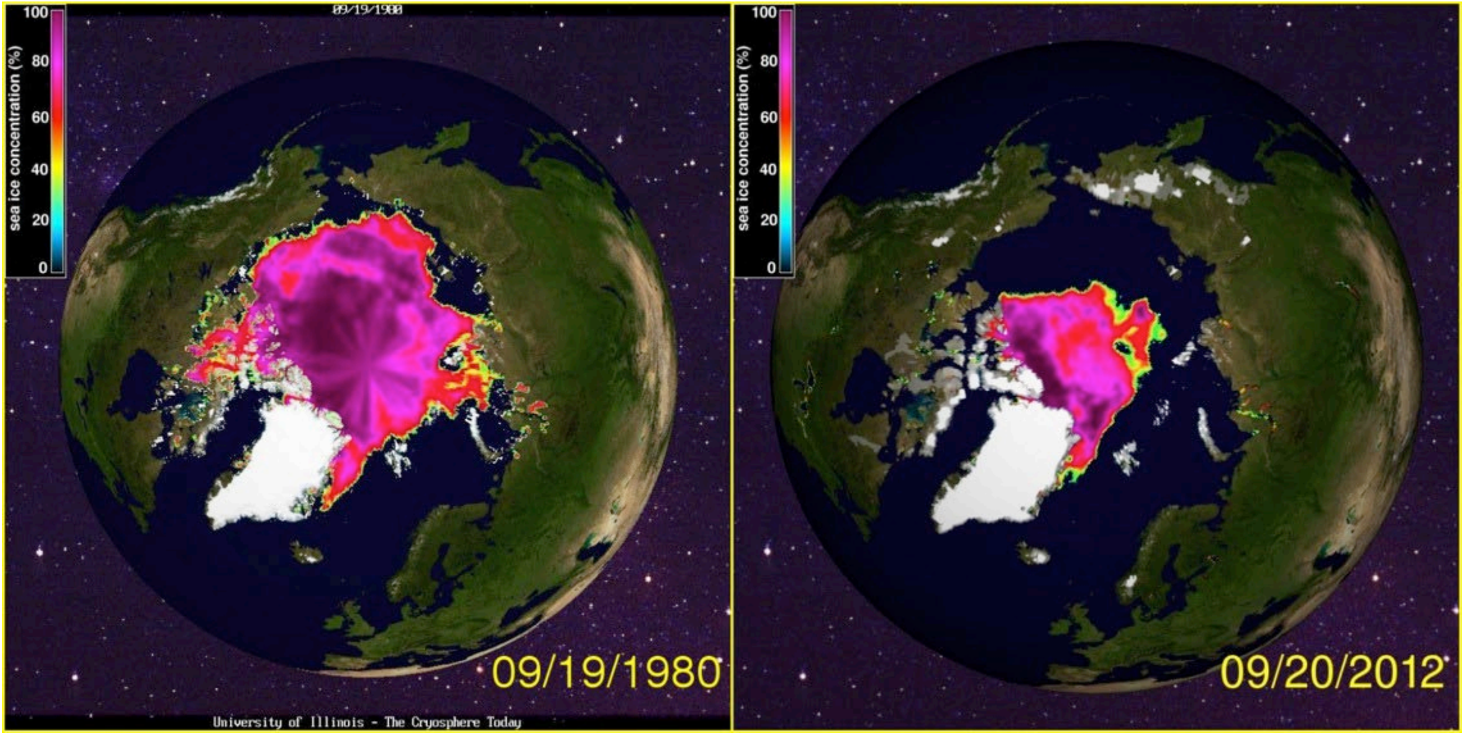
Source: Realclimate.org (Rahmsdorf, Nov. 13, 2013, after Cowtan and Way, QJRMS, 2014.).



Note: Filled circle / error bar is percentile within 23-model combined distribution of Cowtan and Way's adjusted trend (and trend +/- 1 sigma).

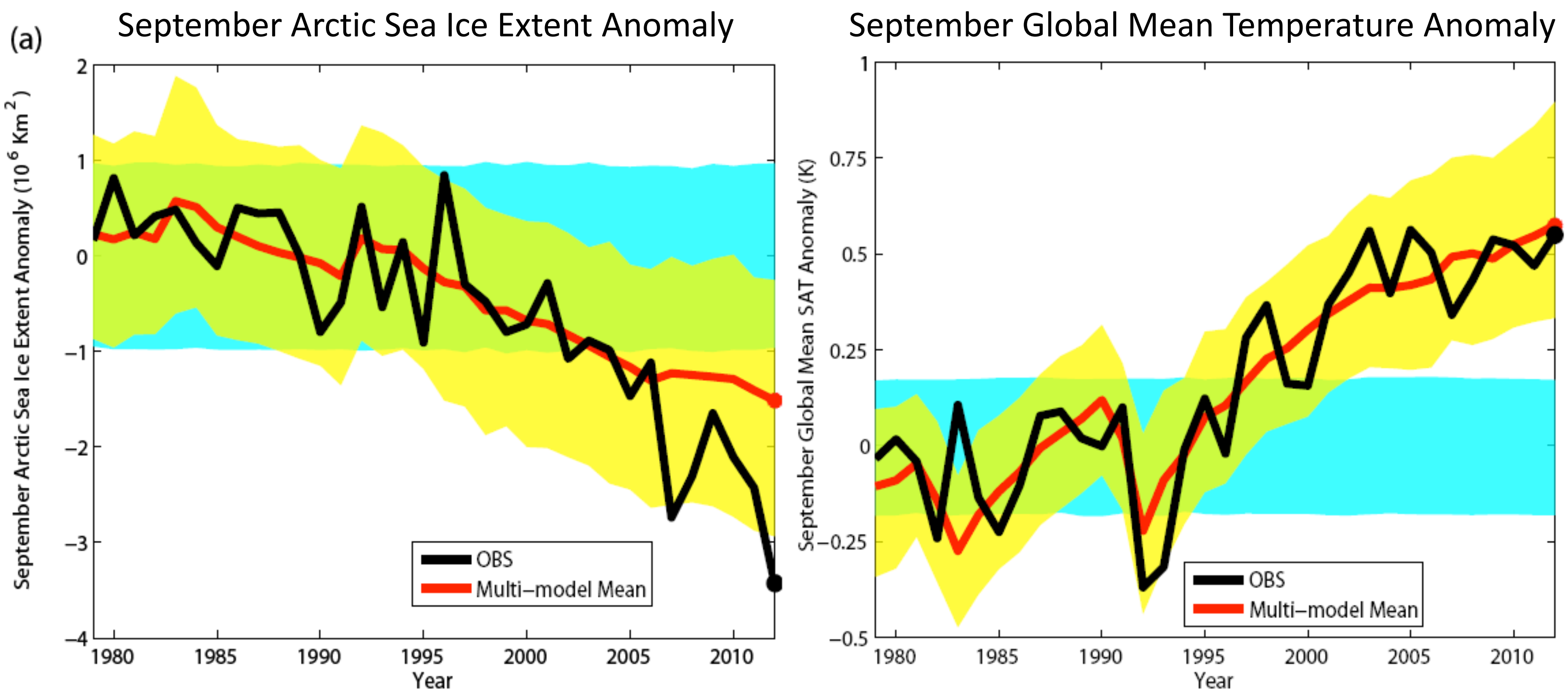
Fri Jan 31 11:43:37 2014

Arctic Sea Ice Is Decreasing…



Source: University of Illinois – The Cryosphere Today

Arctic Sea Ice Extent Anomalies During 2012: An Extreme Year

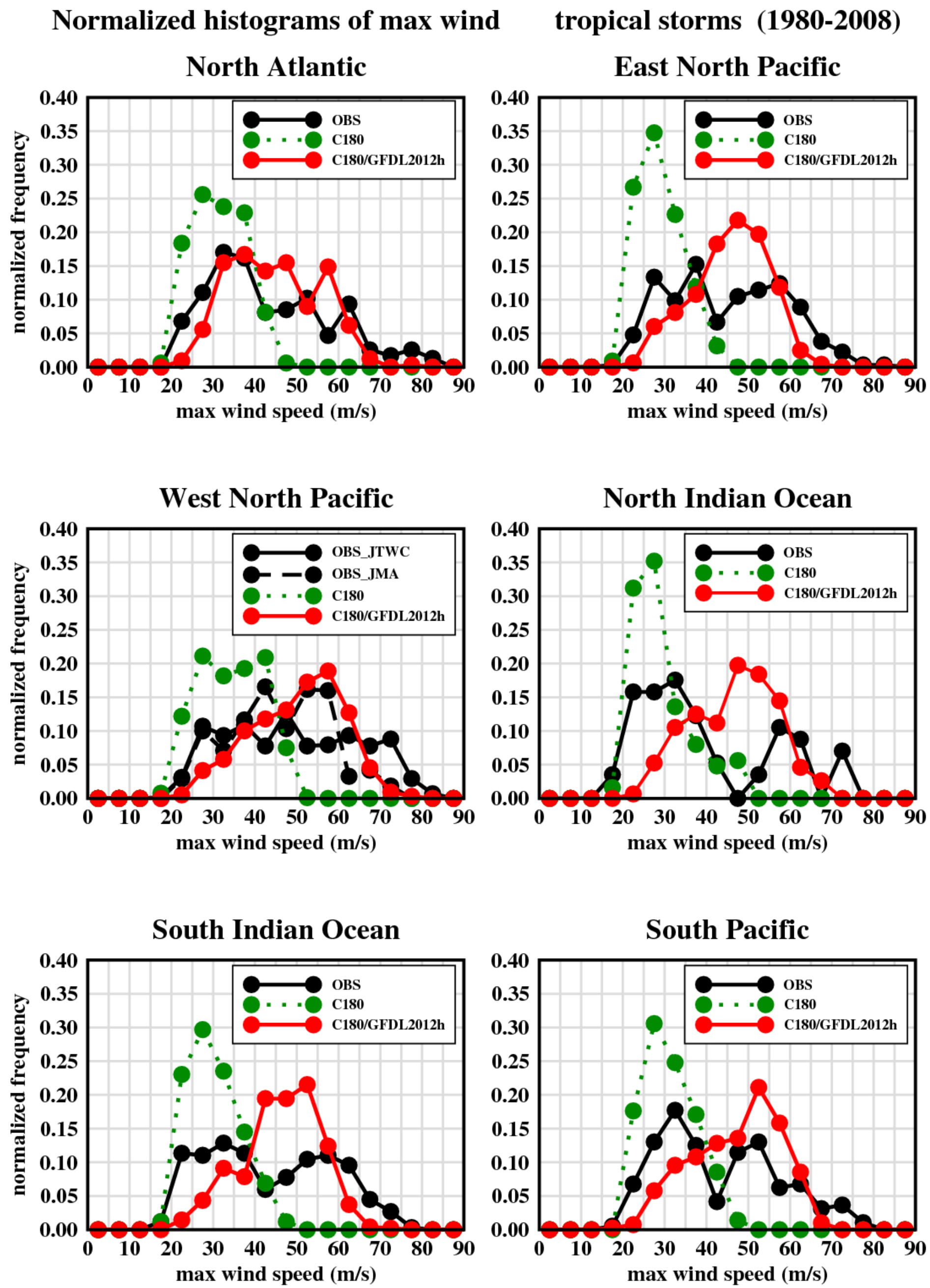


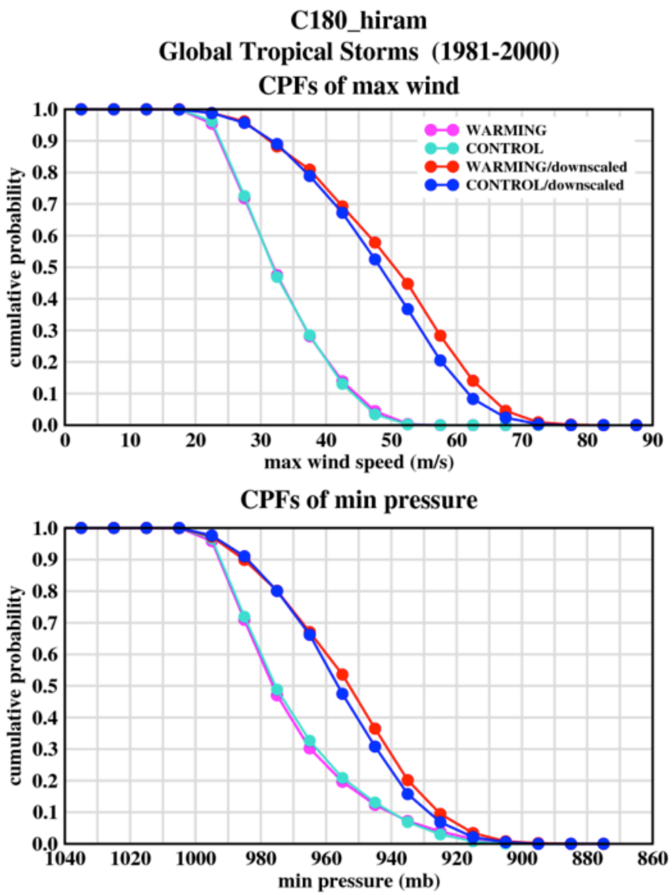
Source: Rong Zhang and Thomas Knutson, BAMS, 2013.

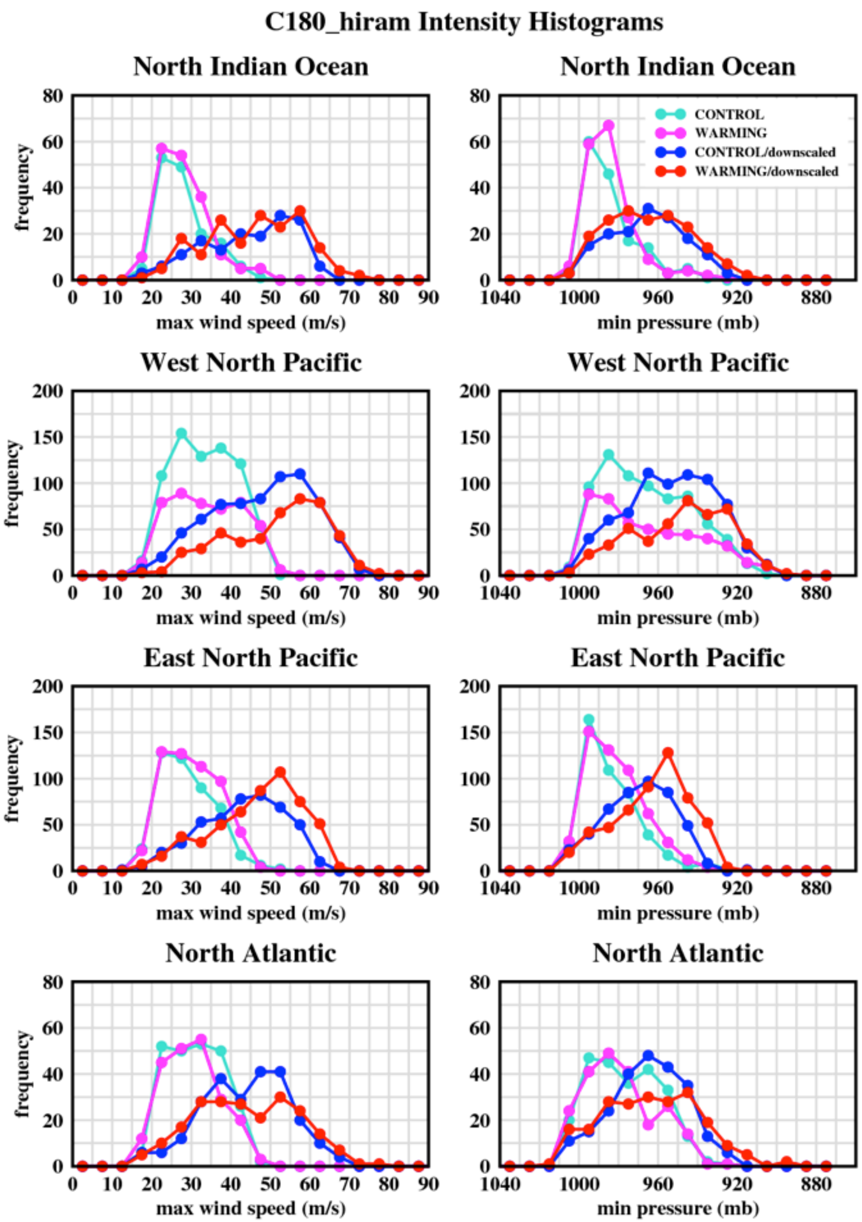
Summary – Some Recent GFDL Work on Extremes

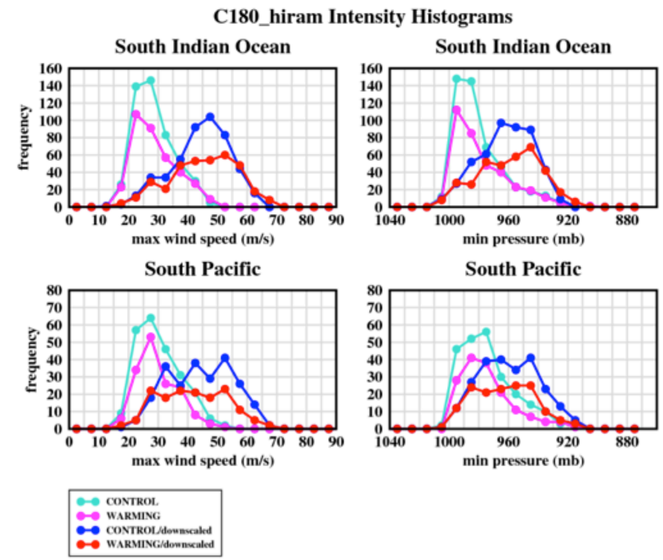
1. Hurricanes and Climate Change:
   - No detectable human influence on hurricanes yet.
   - Late 21st century projections: increased average intensity and precipitation rates; decreased overall tropical storm frequency. Sea level?
2. Examples of attribution for recent climate extremes
   - Temperatures (seasonal- or annual-mean warm extremes)
     - Australia region (2013) – risk increase fully attributable to anthro. forcing, according to CMIP5 models
     - Eastern U.S. (Spring 2012) - risk increased 10x by anthro. + natural forcing
   - Precipitation (seasonal- or annual-mean extremes)
     - U.S./Can. border (2013) – risk increased 2-3x by anthro. + nat. forcing combined, according to CMIP5 models
   - Arctic sea ice: 2012 extreme loss – difficult for models to capture
3. The "global warming hiatus"
   - CMIP5 models are inconsistent with observations (data-available regions)
   - lack of observations in Arctic may affect this conclusion for global mean

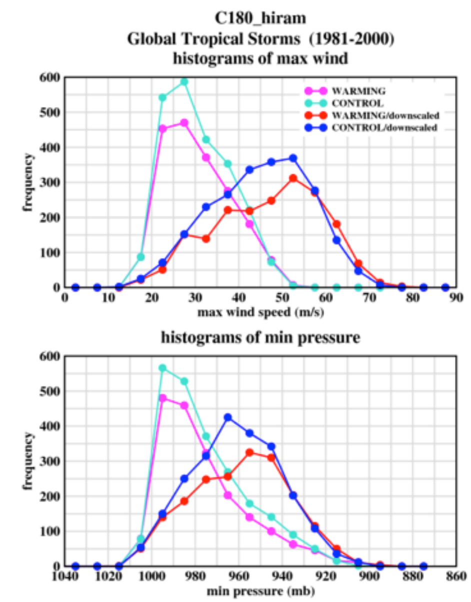
Present-Day Climate

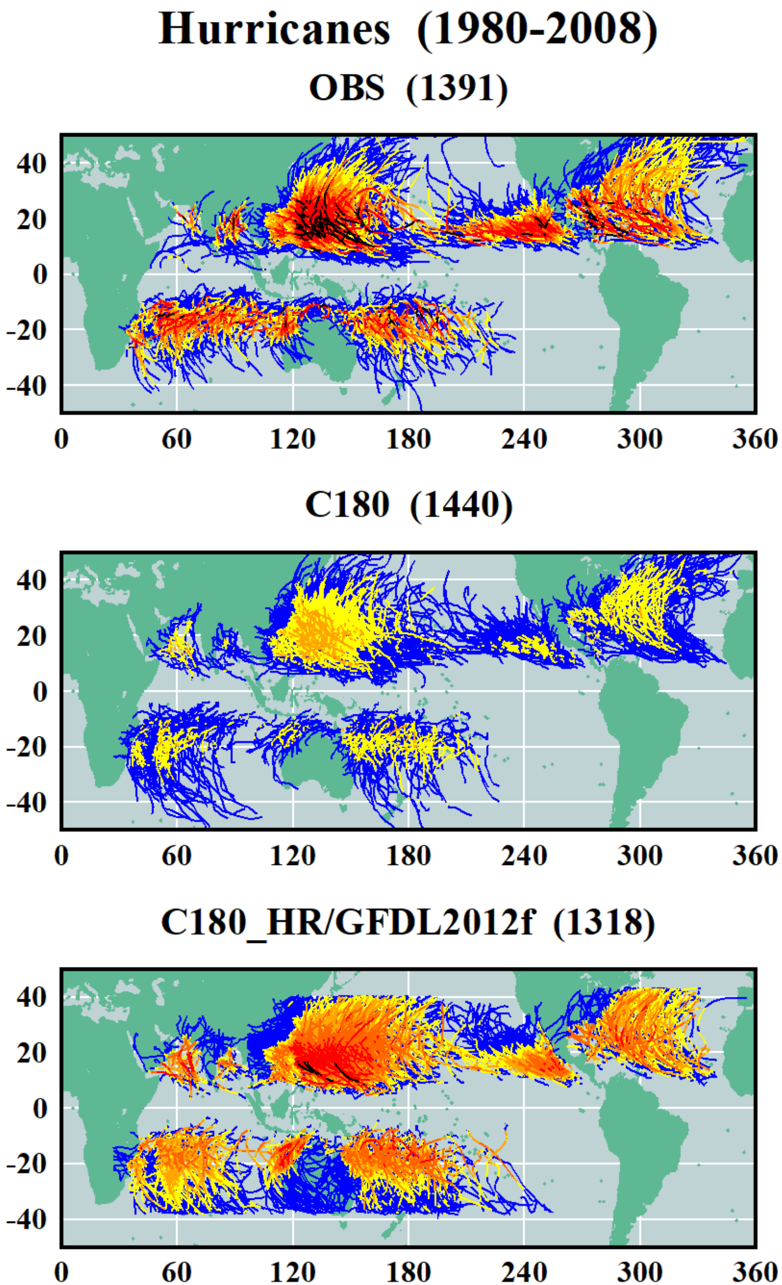



C180_hiram
Global Tropical Storms (1981-2000)
CPFs of max wind
cumulative probability
max wind speed (m/s)
WARMING
CONTROL
WARMING/downscaled
CONTROL/downscaled
C180_hiram
Global Tropical Storms (1981-2000)
Cumulative Histograms of max wind
cumulative frequency
max wind speed (m/s)
WARMING
CONTROL
WARMING/downscaled
CONTROL/downscaled
CPFs of min pressure
cumulative probability
min pressure (mb)
Cumulative histograms of min pressure
cumulative frequency
min pressure (mb)


C180_hiram Intensity Histograms
North Indian Ocean
West North Pacific
East North Pacific
North Atlantic
frequency
max wind speed (m/s)
min pressure (mb)
CONTROL
WARMING
CONTROL/downscaled
WARMING/downscaled

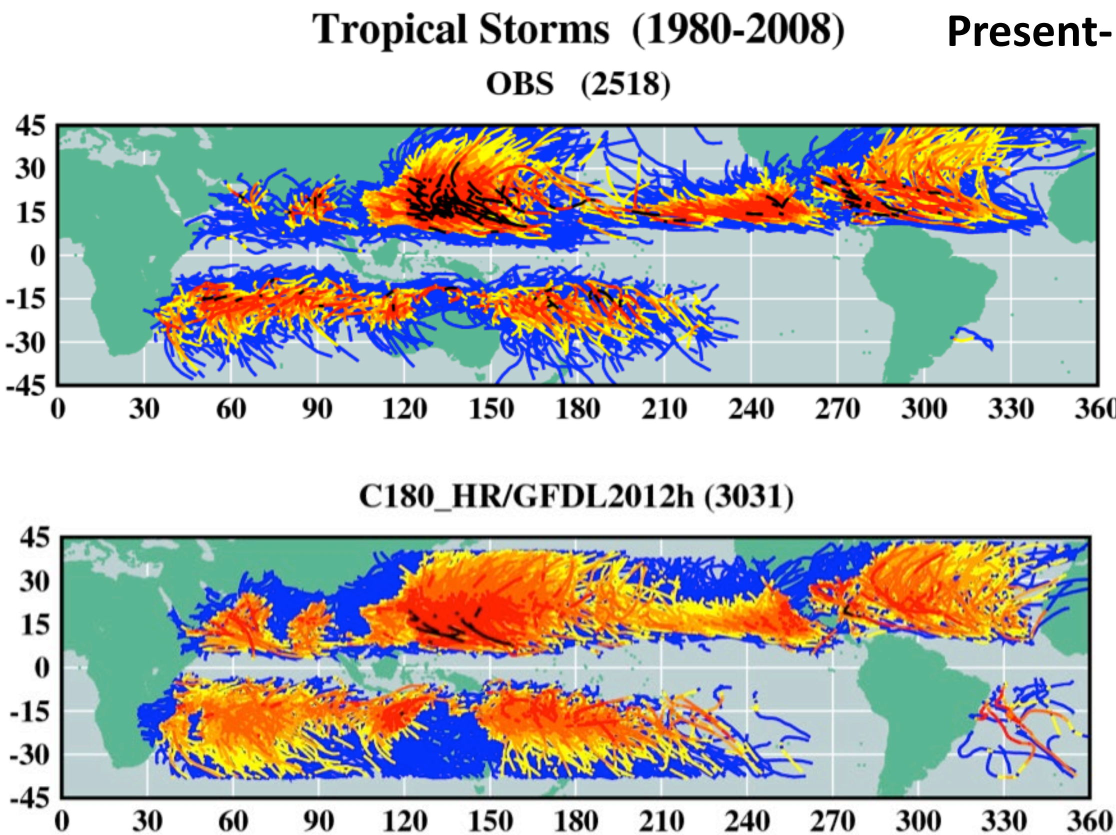

C180_hiram Intensity Histograms
South Indian Ocean
South Pacific
frequency
max wind speed (m/s)
min pressure (mb)
CONTROL
WARMING
CONTROL/downscaled
WARMING/downscaled


C180_hiram
Global Tropical Storms (1981-2000)
histograms of max wind
WARMING
CONTROL
WARMING/downscaled
CONTROL/downscaled
frequency
max wind speed (m/s)
histograms of min pressure
min pressure (mb)



GFDL2012f (9 km grid, no vortex replacement)

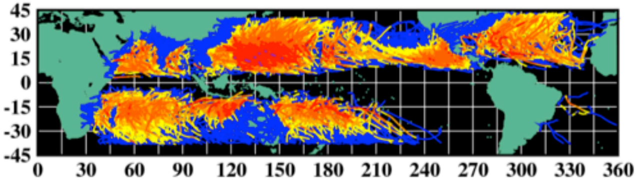
Present-Day Climate



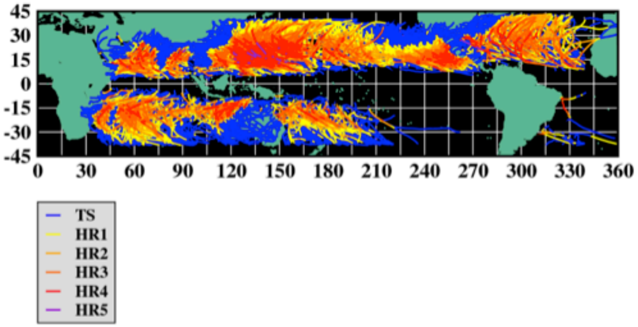
Storm Category:

CMIP5/RCP4.5 Late 21st Century Projection

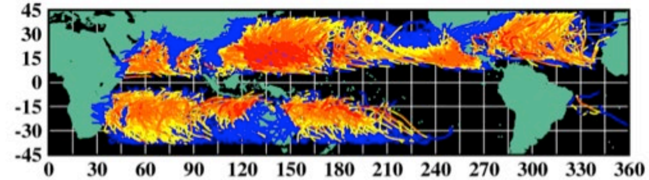
C180_hiram - Global
Tropical Storms (1981-2000)
CONTROL/downscaled - 2274 storms



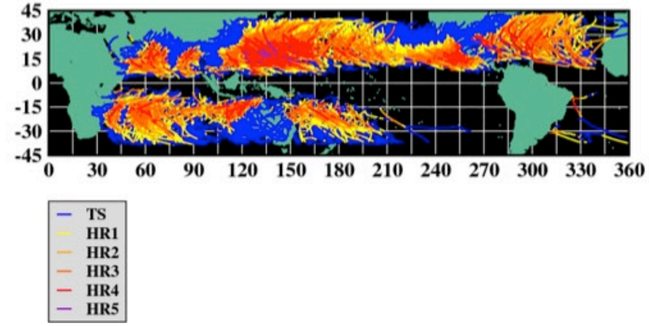
WARMING/downscaled - 1900 storms



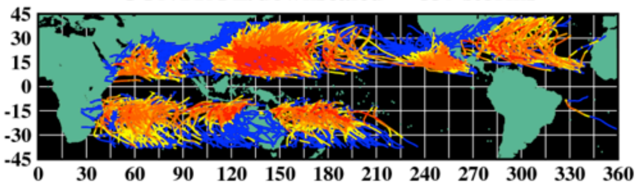
C180_hiram - Global
Hurricanes (1981-2000)
CONTROL/downscaled - 1905 storms



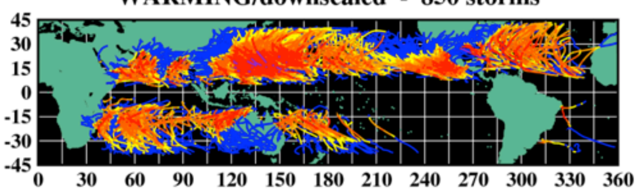
WARMING/downscaled - 1589 storms



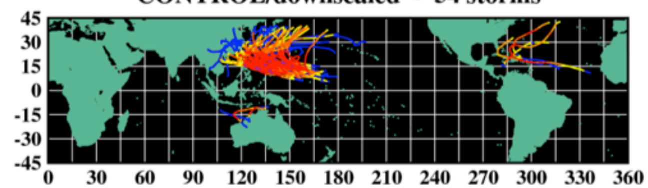
C180_hiram - Global
Major Hurricanes (1981-2000)
CONTROL/downscaled - 835 storms



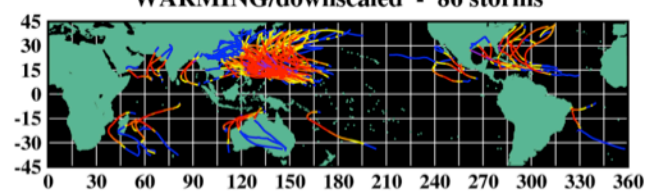
WARMING/downscaled - 850 storms



C180_hiram - Global
Hurricanes with w >= 65 m/s (1981-2000)
CONTROL/downscaled - 54 storms



WARMING/downscaled - 86 storms



Atlantic TC projections for late 21st century:

Tropical storm frequency: In the Atlantic, GFDL downscaling approaches support a reduced frequency (~-25%, range 0 to -50%)), but the projected range is even wider across a range of studies (-70% to +40%). Relative SST statistically describes this variation across dynamical model projections fairly well (r^2=0.55).

Hurricane intensity: Our models simulate about 5% increase in lifetime maximum intensity (range -4 to +11%).

Frequency of intense hurricanes: does not behave like overall TC frequency. Our model projects +87% for CMIP3 (range -90 to +240%); for CMIP5 it projects +45% (Early 21st) and +39% (Late 21st) though only marginally significant.

Tropical cyclone precipitation: robust increase in rate in model projections. Simulated increase is at a rate expected from Clausius-Clapeyron (total water vapor) or about +11% at 200-400 km radius, but with higher percentage increase (~+30%) closer to the storm center (50-150km). For 100 km radius the range of changes across the models was: -3 to +38%.

Tropical Cyclones and Climate Change

- Tropical cyclones can be extremely damaging
  - Cyclone Nargis (2008; Myanmar; 138,000 deaths)
  - Hurricanes Katrina ($130B), Sandy (NY/NJ), Iniki (Hawaii)
  - SuperTyphoon Haiyan (2013; Philippines; 6200+ deaths)
- Sea-level rise a concern; here we focus on changes in storm characteristics with climate warming
- No detectable influence yet of greenhouse warming on TC (e.g., long-term trends).
- Atlantic Basin projections study: see Journal of Climate (Sept. 2013)
- Today's talk: Preliminary results of new global study

TROPICAL CYCLONES SUMMARY ASSESSMENT:

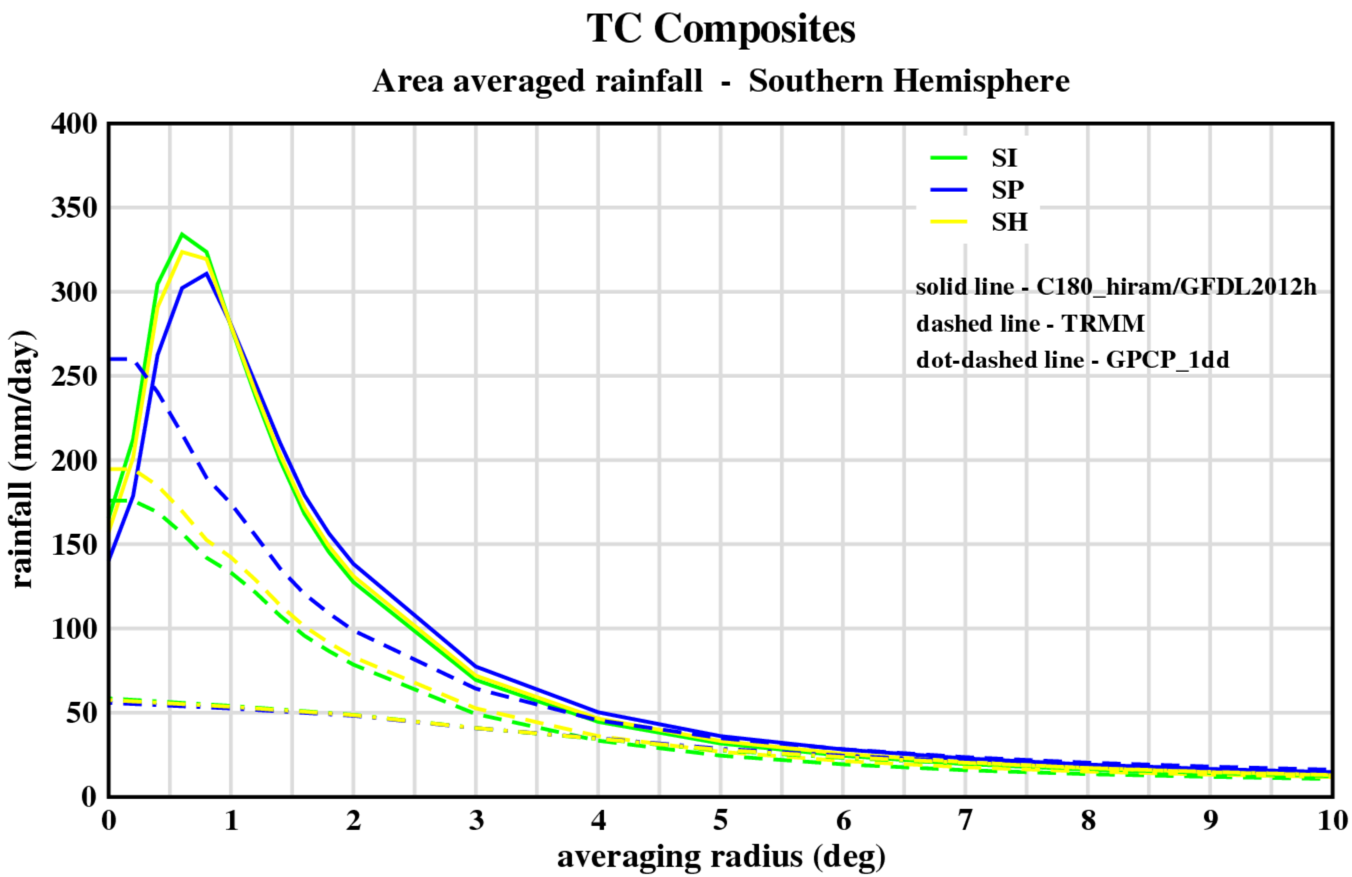
Detection and Attribution:

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

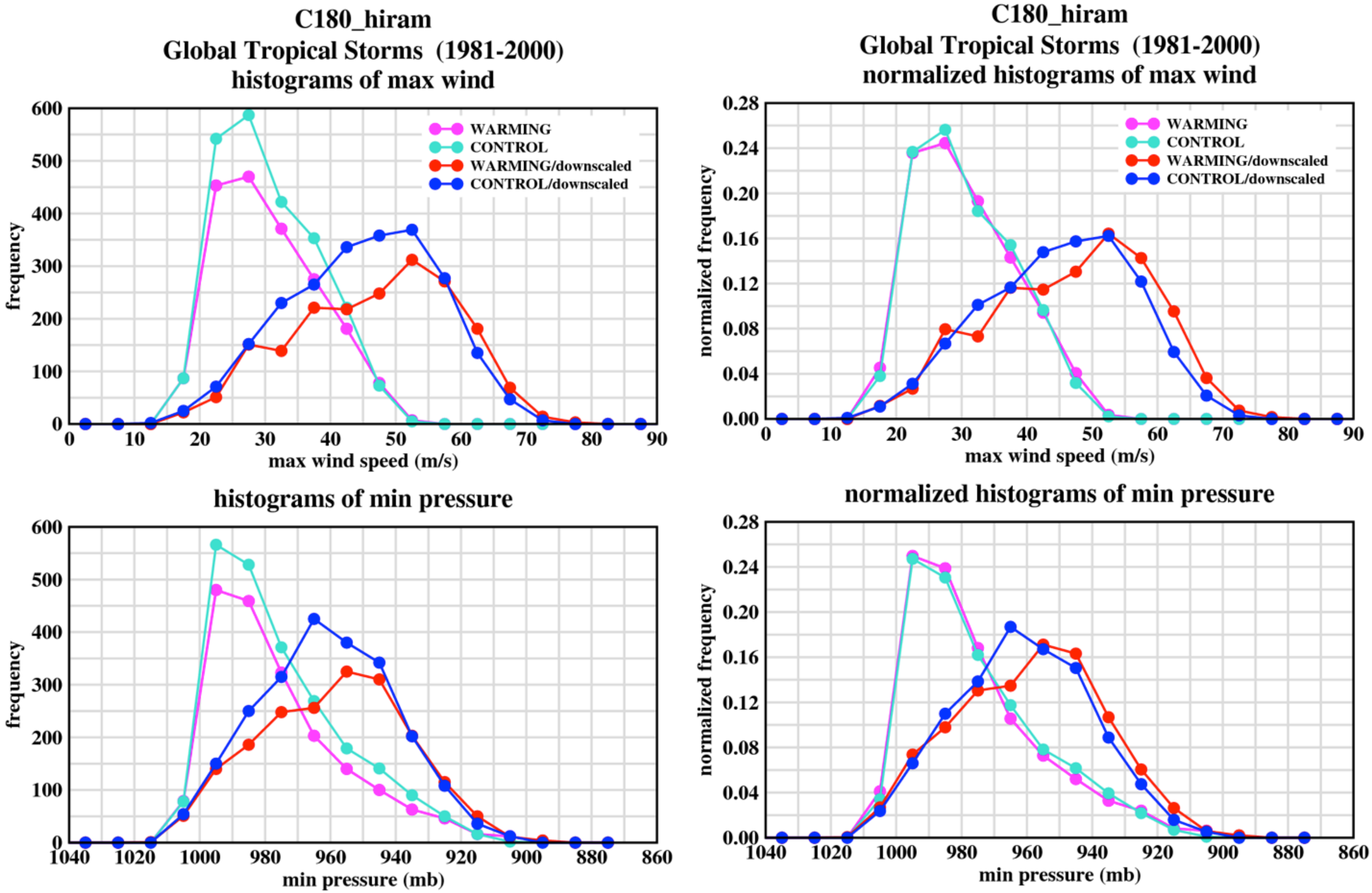
Future Climate Projections- Some notes on ocean coupling

- GFDL hurricane model includes a three-dimensional ocean component to simulate cool wakes and their interaction with the storm. We are one of just a few groups that attempt to incorporate this effect in our TC/climate change studies for high-resolution (intense TC) simulations.
- Knutson, Tuleya, Shen, and Ginis (J. Climate 2001) found that while ocean coupling reduces storm intensity, the percent increase is TC intensity with climate warming is about the same with or without ocean coupling. Based on CO2-warming experiment with GFDL R30 coupled model.
- Vertical structure of ocean temperature change: Ensemble mean SST change from CMIP5 climate models is initially applied uniformly over the observed climatological ocean mixed layer depth (MLD, where SST-T_{ocn} reaches 0.5^{o}C). The change tapers to zero below the MLD. The tapering also affects temperatures in the mixed layer, reducing the MLD compared to control conditions. {CHECK ON THIS PROCEDURE TO CONFIRM DETAILS}

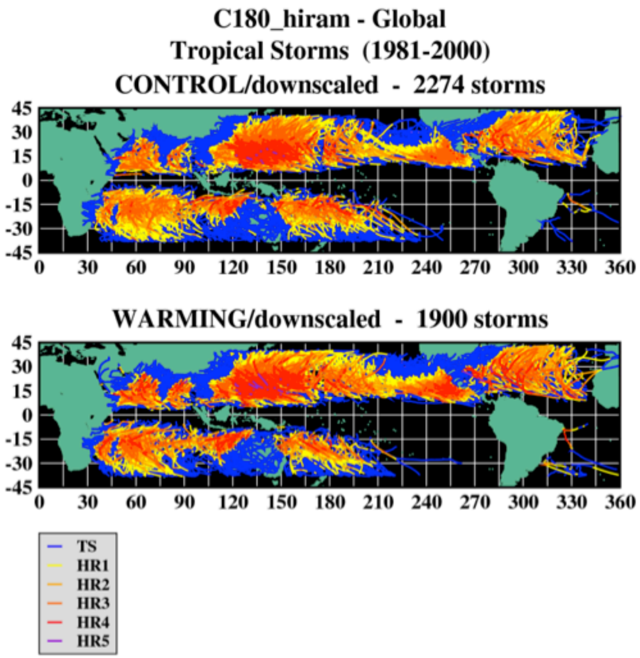


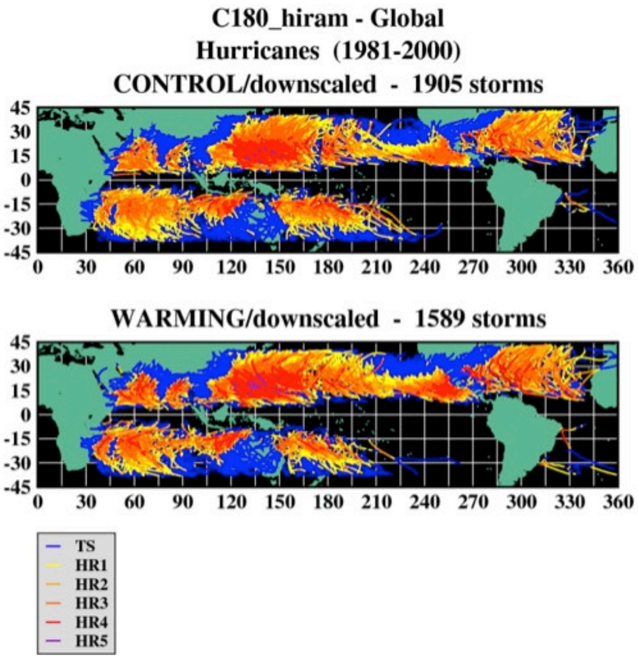
TC Composites
Area averaged rainfall - Southern Hemisphere
SI
SP
SH
solid line - C180_hiram/GFDL2012h
dashed line - TRMM
dot-dashed line - GPCP_1dd
rainfall (mm/day)
averaging radius (deg)
0
50
100
150
200
250
300
350
400
0
1
2
3
4
5
6
7
8
9
10

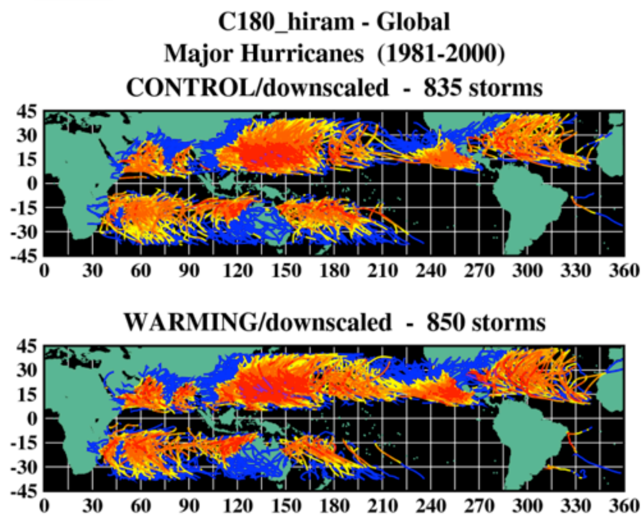
CMIP5/RCP4.5 Late 21st Century Projection

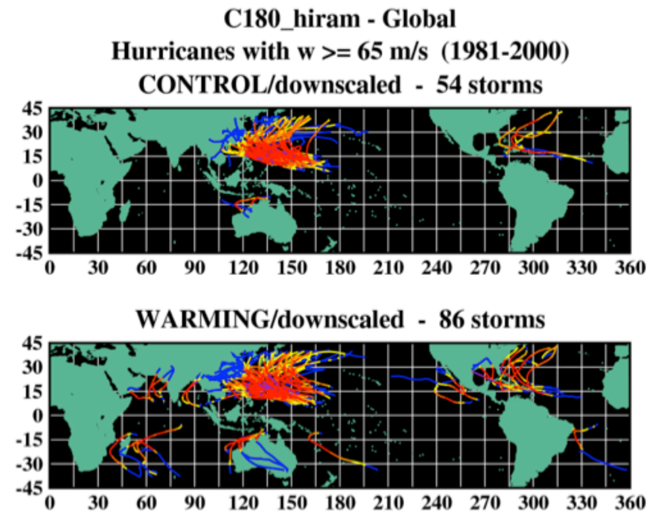


CMIP5/RCP4.5 Late 21st Century Projection

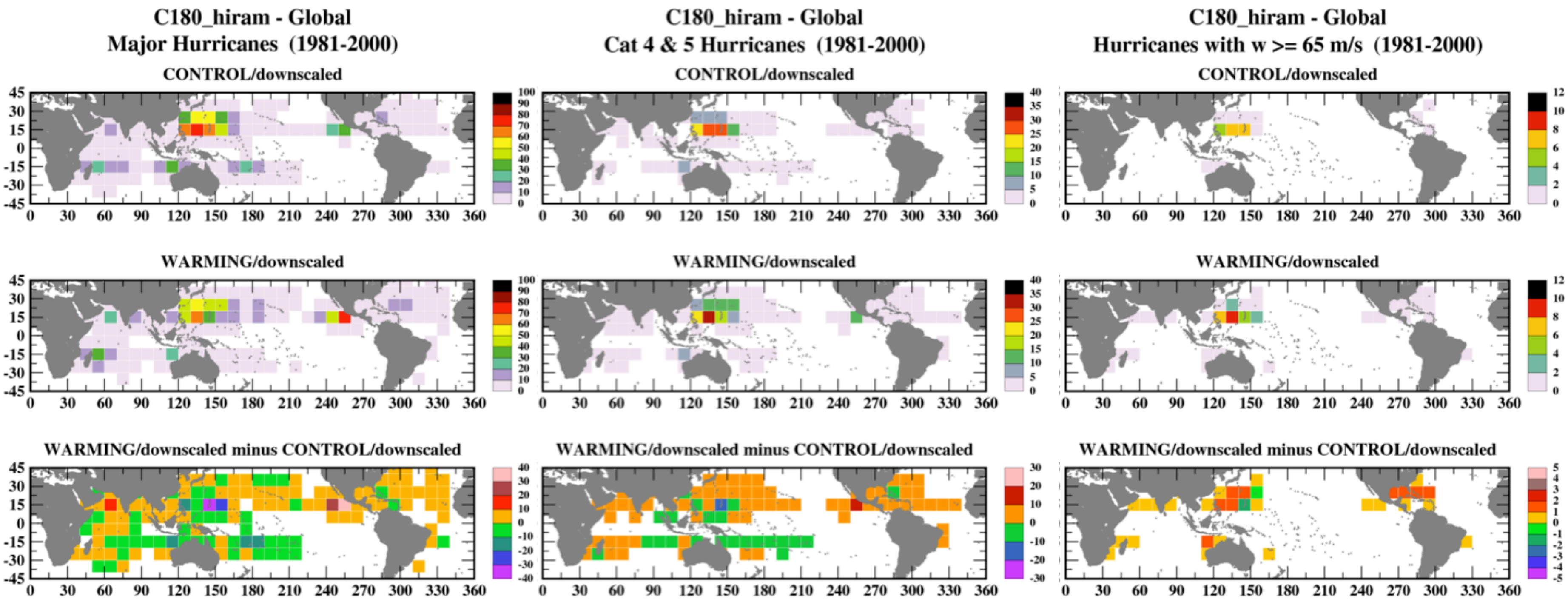




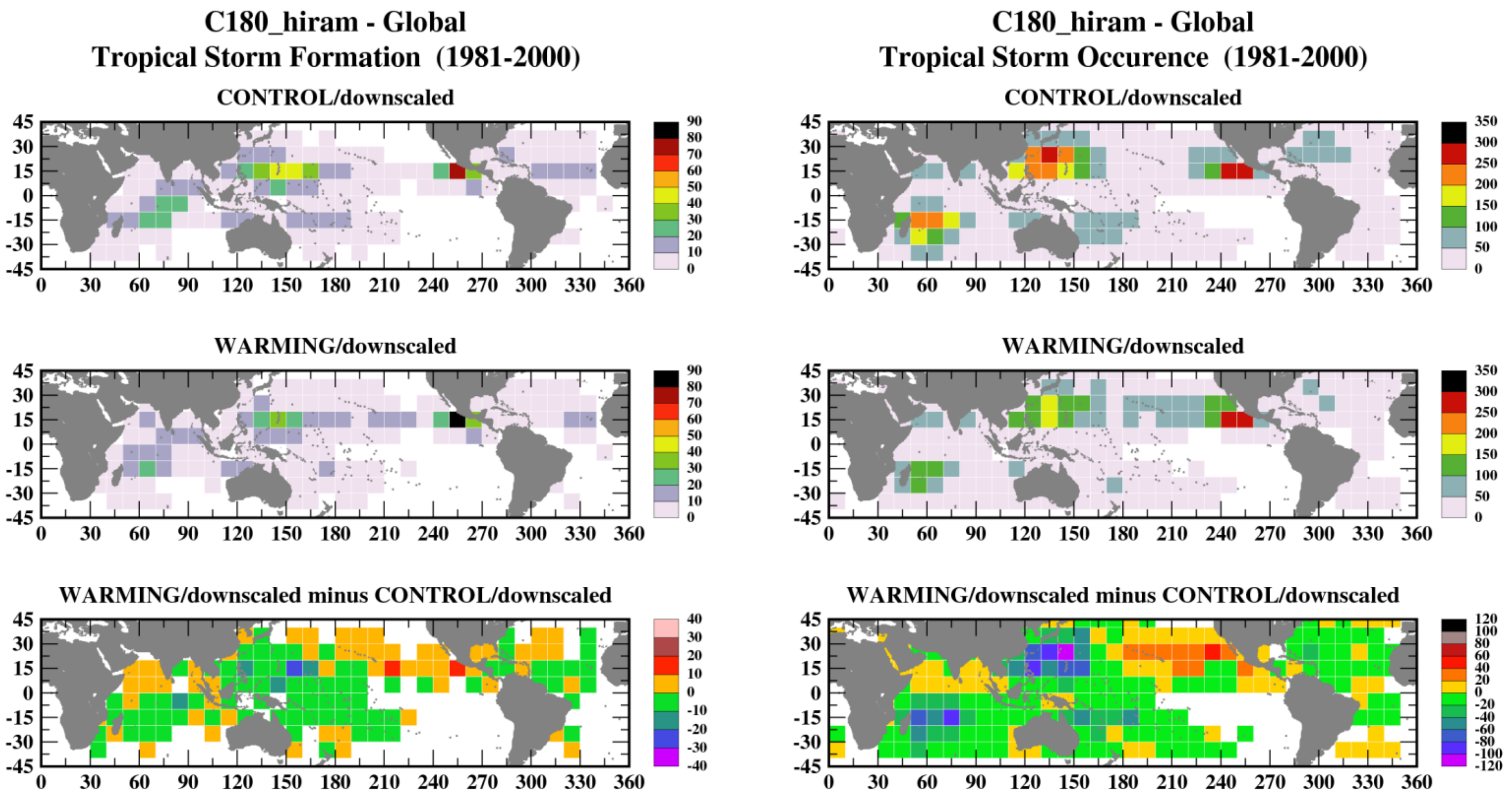




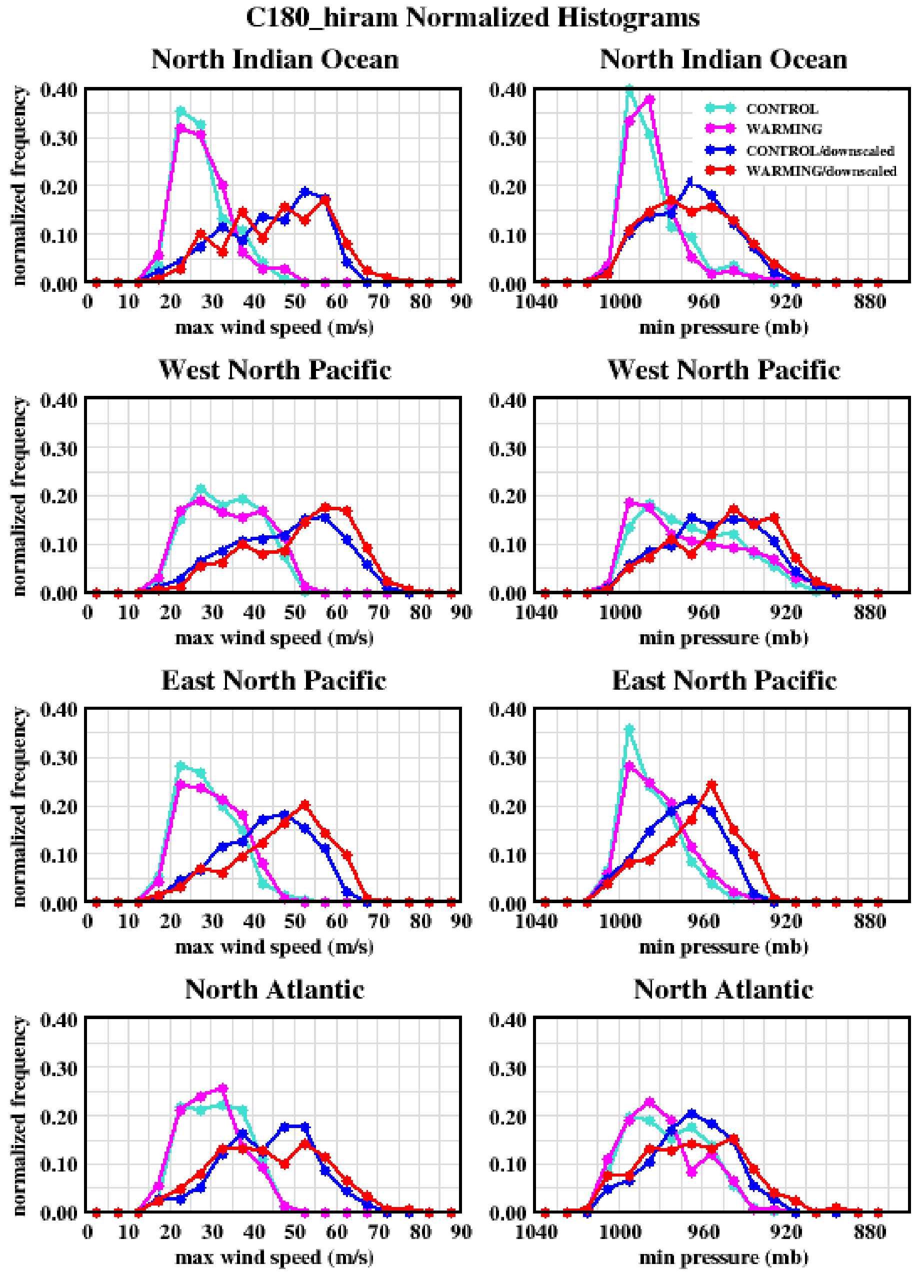
CMIP5/RCP4.5 Late 21st Century Projection: TC Occurrence



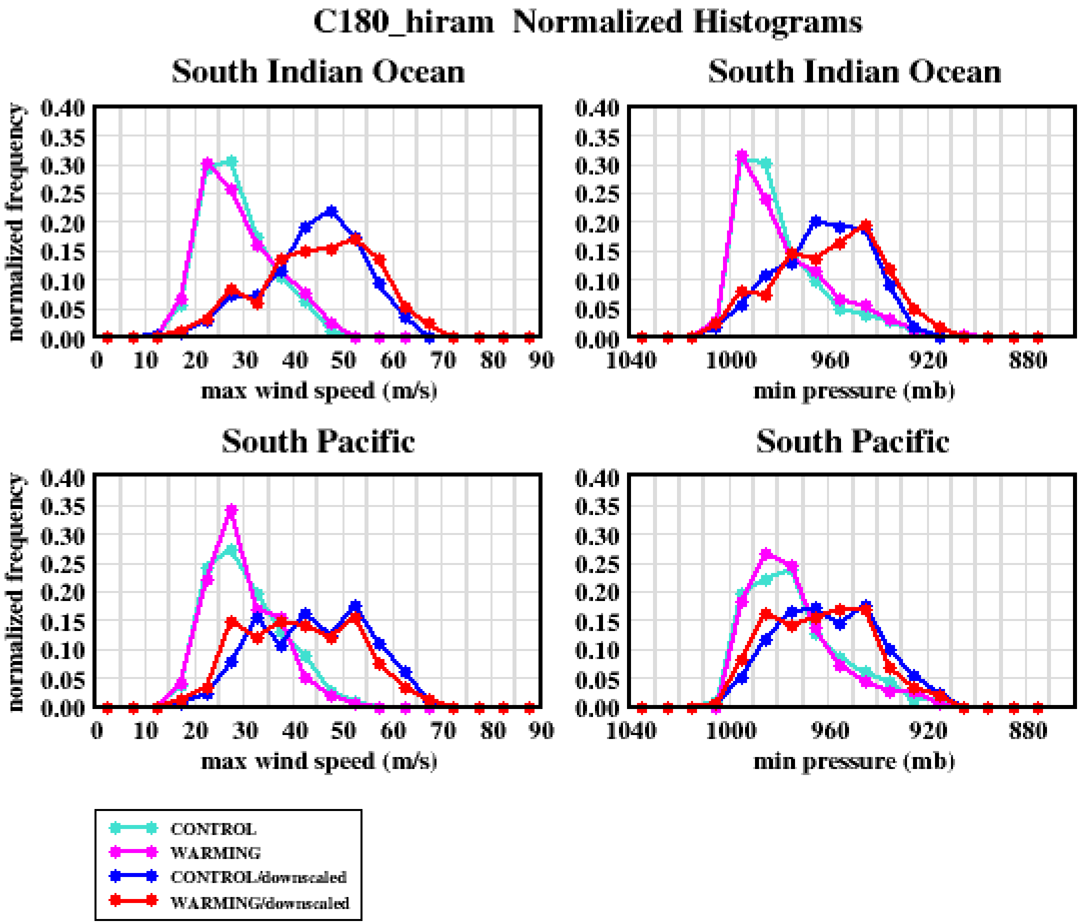
CMIP5/RCP4.5 Late 21st Century Projection: Tropical Storm Formation vs. Occurrence



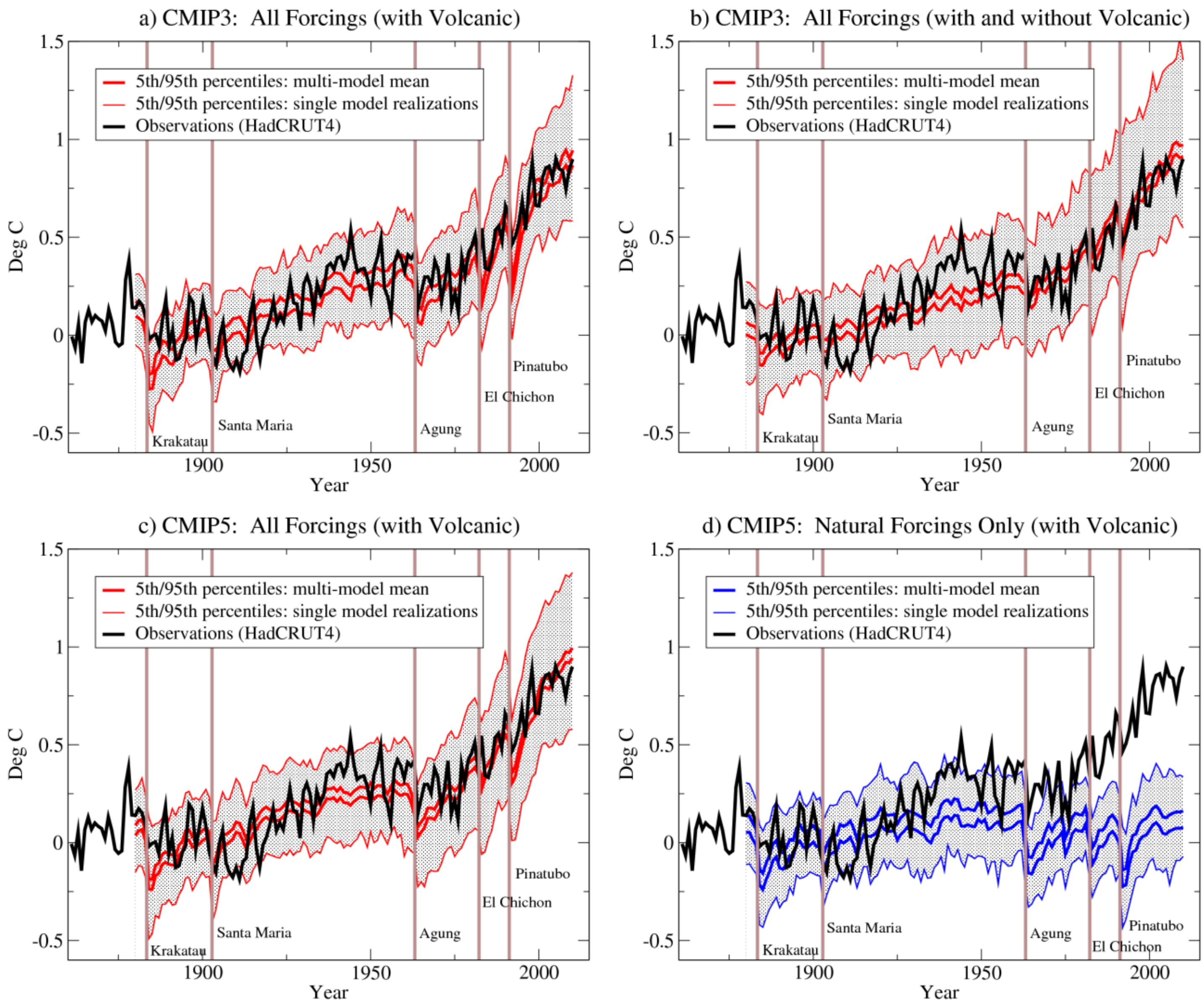
CMIP5/RCP4.5 Late 21st Century Projection



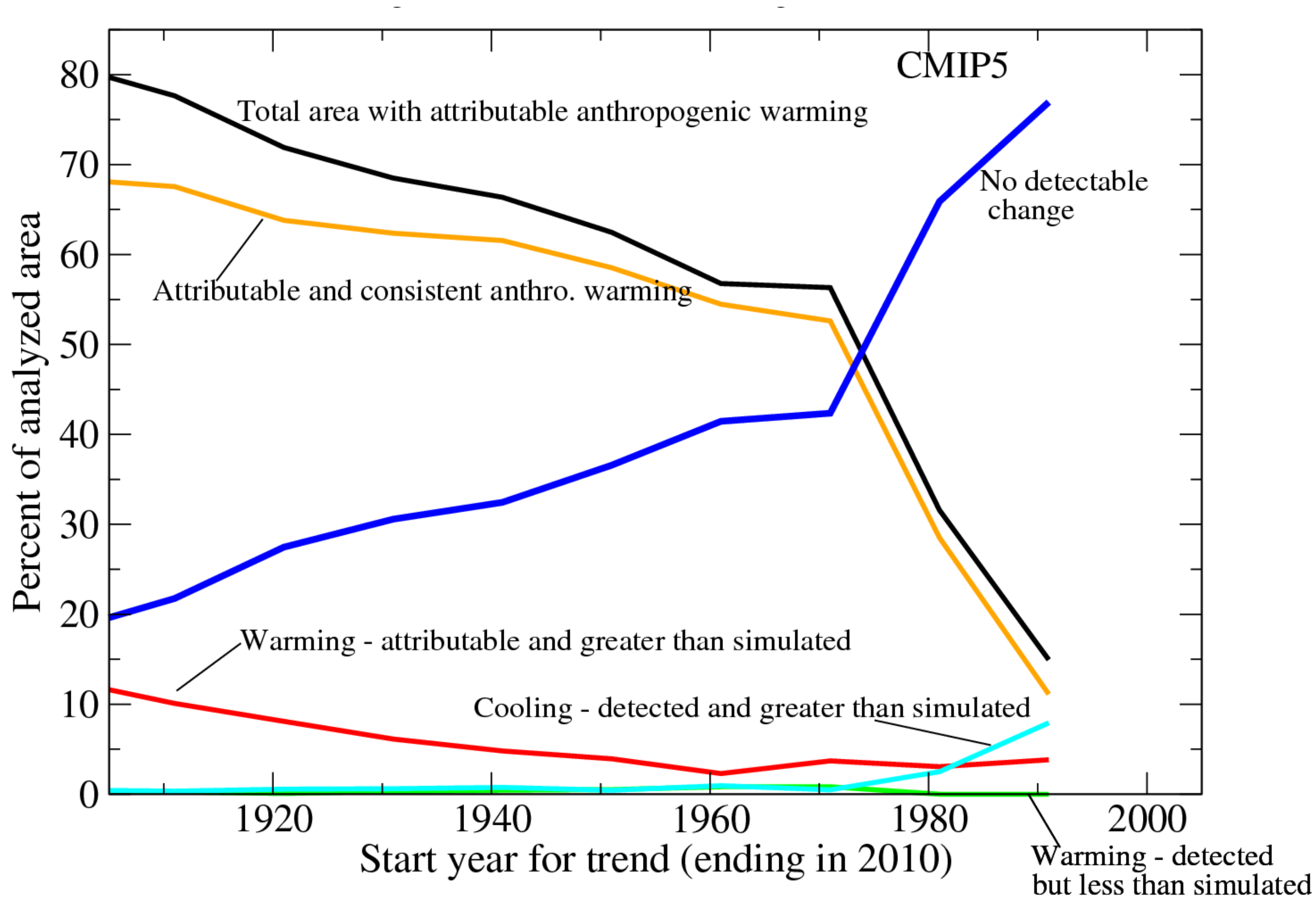
CMIP5/RCP4.5 Late 21st Century Projection



Global Mean Surface Temperature Anomalies

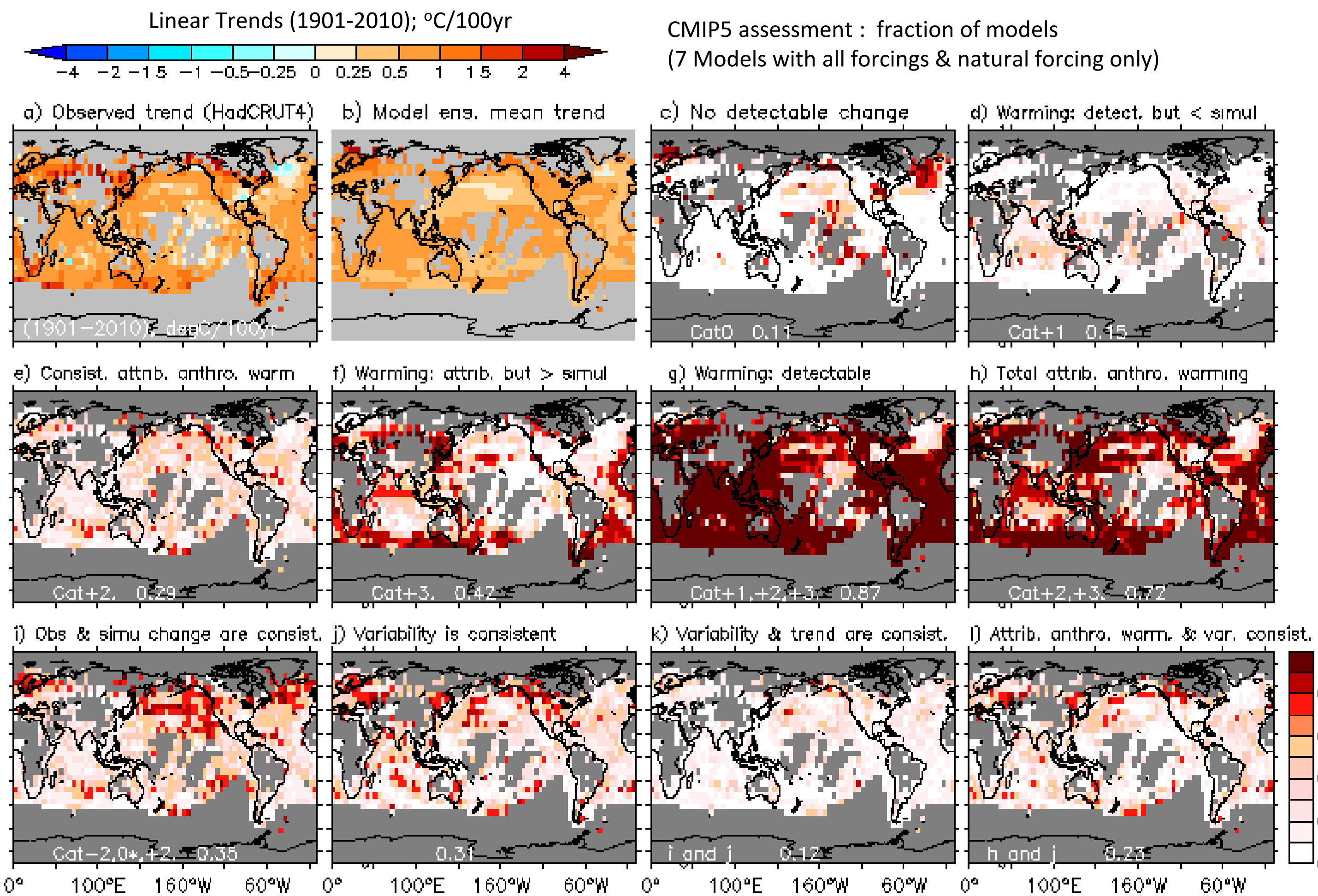


Comparison of CMIP5 ensemble mean trend (7-model subset) vs. Observations

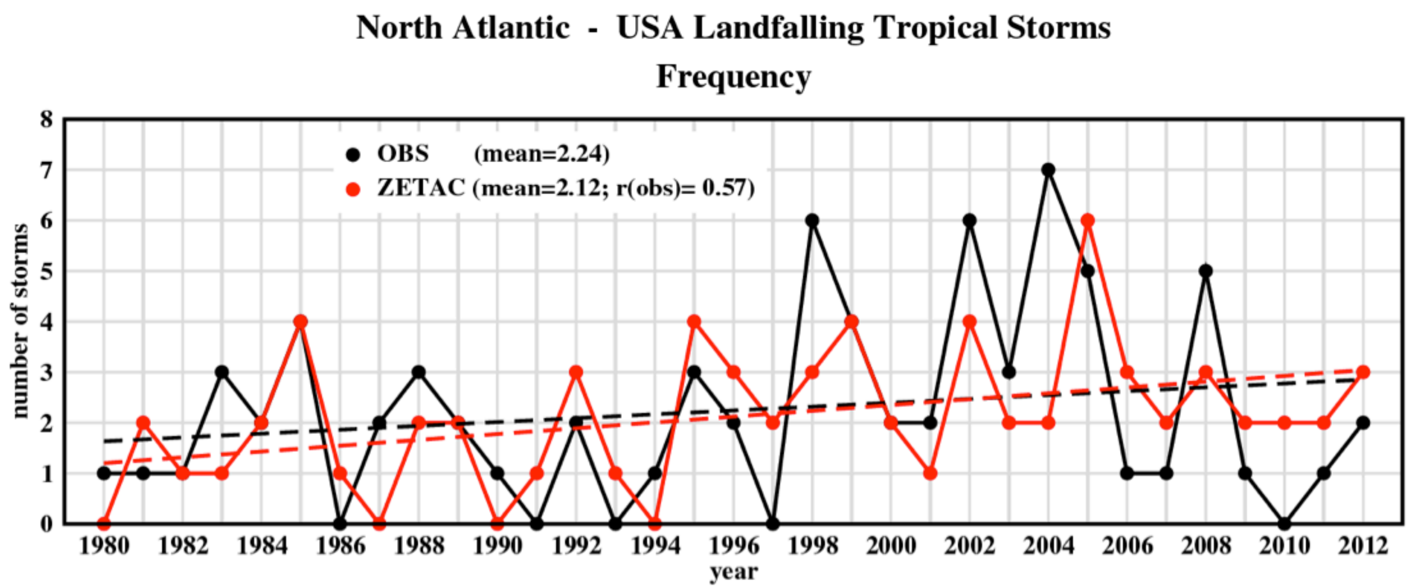


Fraction of CMIP5 models meeting certain detection/attribution criteria

(7 CMIP5 Models with All-forcing runs & Natural Forcing Only runs)

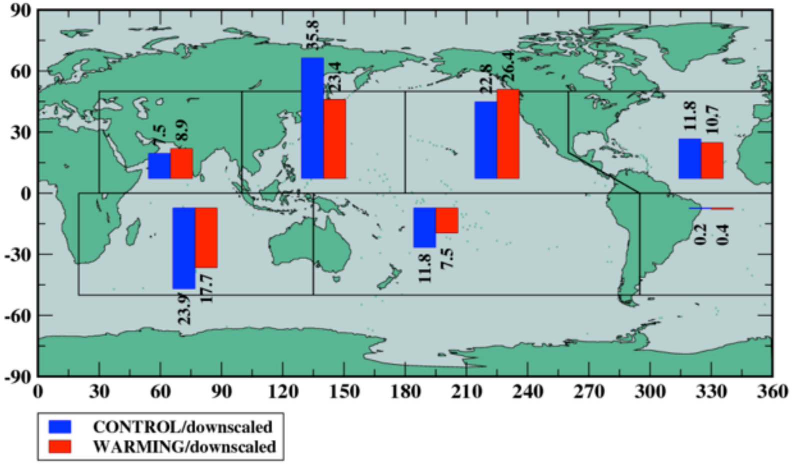


Future work: Simulations of US landfalling tropical storms

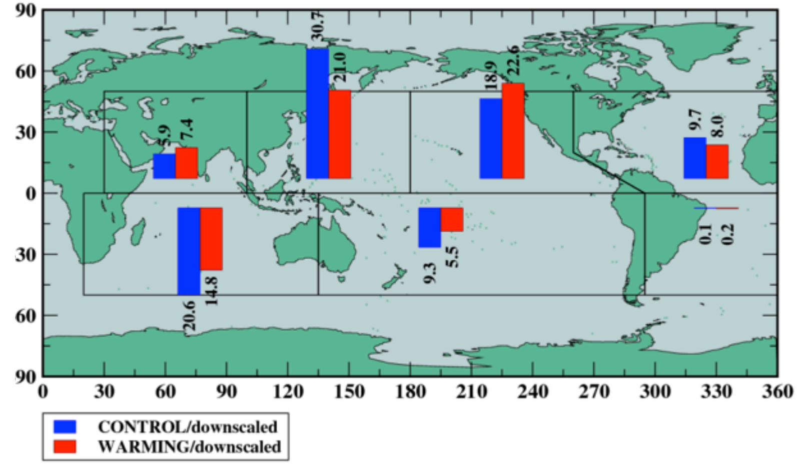


CMIP5/RCP4.5 Late 21st Century Projection

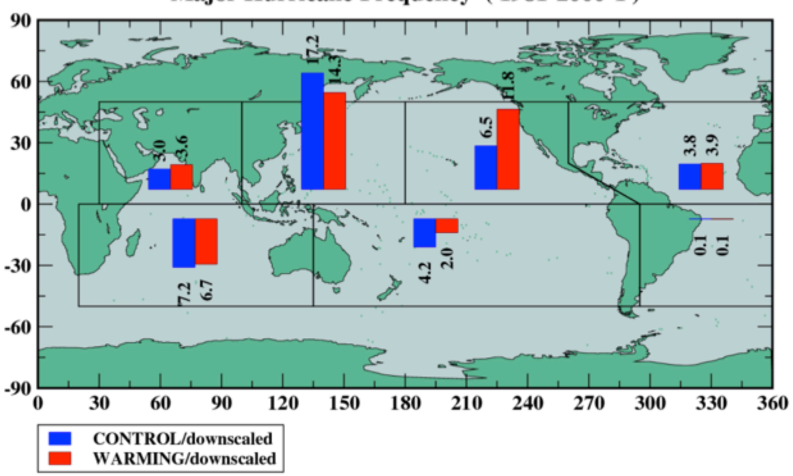
c180_hiram
Tropical Storm Frequency (1981-2000)



c180_hiram
Hurricane Frequency (1981-2000-1)

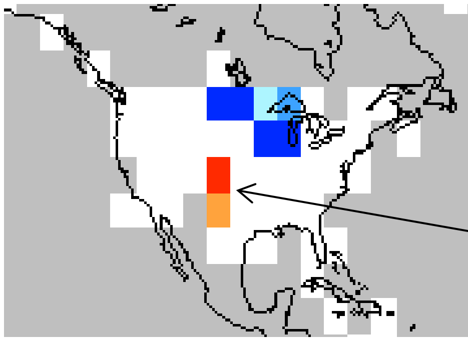


c180_hiram
Major Hurricane Frequency (1981-2000-1)

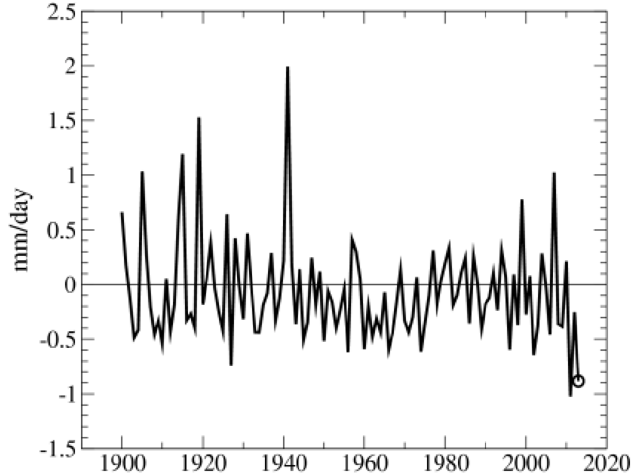


2013 Seasonal-Mean Precipitation Extremes: Climate Perspective

Mar.-May 2013 Extremes - Precipitation

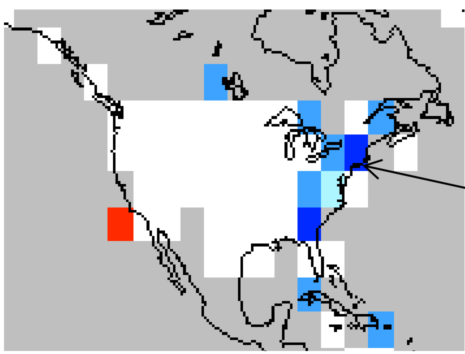


U.S. Southern Plains—Mar.-May

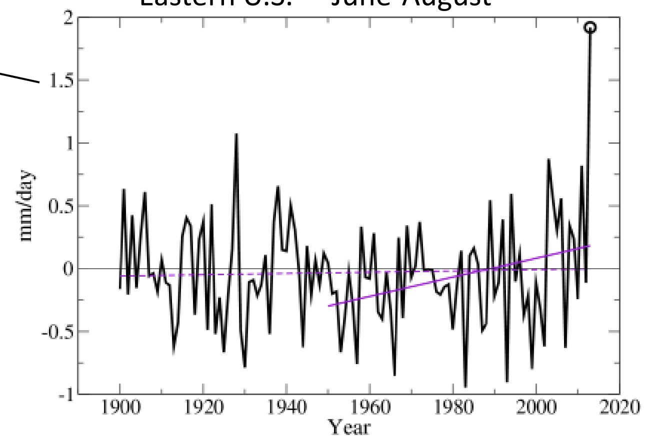


U.S. Southern Plains region—Mar.-May:
- Non-significant trend;
- Data inhomogeneities?

June-Aug. 2013 Extremes - Precipitation



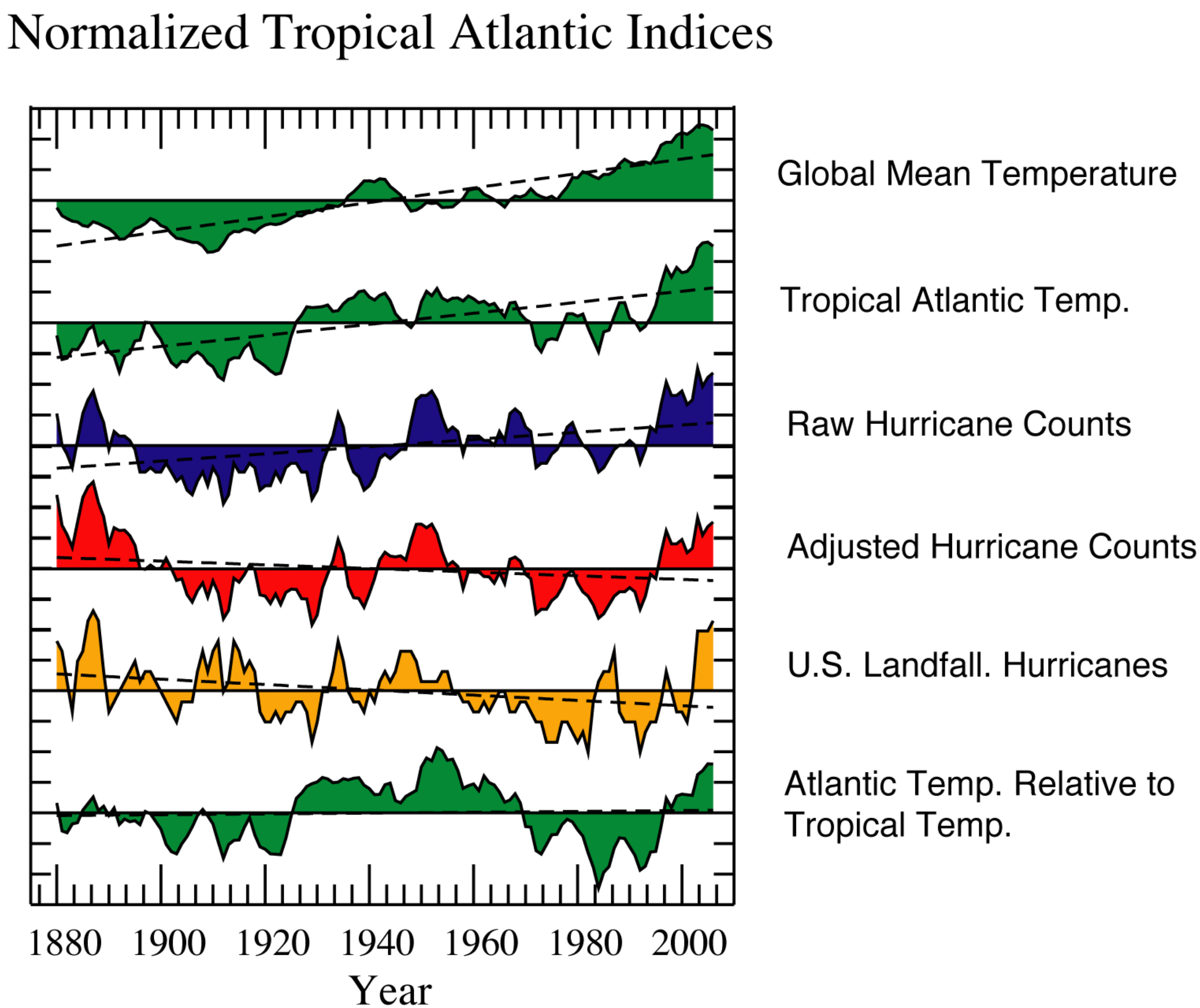
Eastern U.S. – June-August



Eastern U.S. region -- JJA:
- Non-significant trend from 1900;
- Detectable trend from 1950 or later;
- Detection not robust to excluding 2013
- Trend attributable to Anthro. + Natural
- Occurrence Ratio = 1.7 or undefined

Map Legend
- Highest
- 2nd highest
- 3rd highest
- 3rd lowest
- 2nd lowest
- Lowest

Low confidence in long-term (centennial-scale) changes in TCs



Source: Vecchi and Knutson, *J. Climate* (2011)

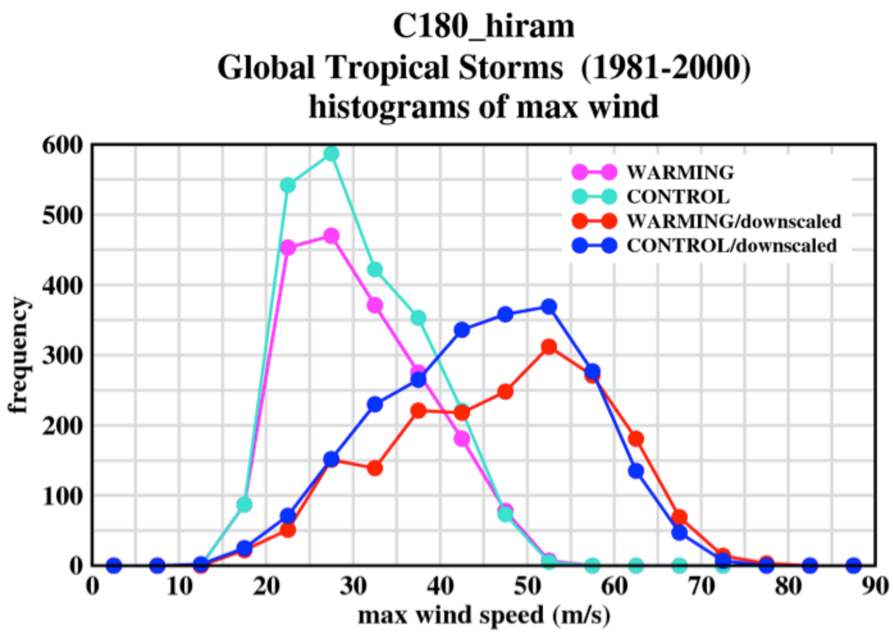
Future TC Projections: Atlantic Basin Methodology

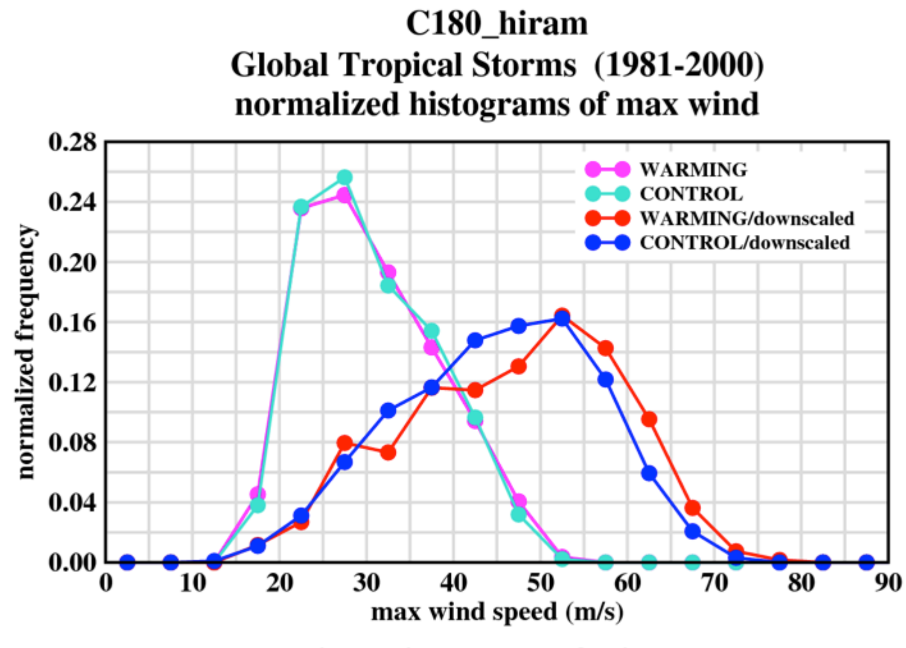
- Simulate Atlantic tropical cyclone activity with 18 km grid regional atmospheric model (Zetac)
  - Observed SSTs and NCEP Reanalyses (1980-2008)
  - Control boundary conditions + CMIP3 or CMIP5/RCP4.5 Early and Late 21st century climate changes
- Downscale all individual storm cases into GFDL hurricane model (9-km grid, moveable mesh, with ocean coupling)

Future TC Projections: Global Methodology

- Simulate global tropical cyclone activity with 50 km grid atmospheric model (HiRAM C180)
  - Observed SSTs (1980-2008)
  - Climatological SSTs
  - Climatological SSTs + CMIP5/RCP4.5 Late 21st century climate change
- Downscale all individual storm cases into GFDL hurricane model (6-km grid, moveable mesh, with ocean coupling)

CMIP5/RCP4.5 Late 21st Century Projections





Mean maximum windspeed changes for storm intensity of at least:

Tropical storms: Global: **+3.6%** [range: -5.6% (Southwest Pac) to +8.2% (NE Pac.)]

Hurricanes: Global: **+4.1%** [range: -3.1% (Southwest Pac.) to +7.8% (NE Pac.)]

Aggregate activity:

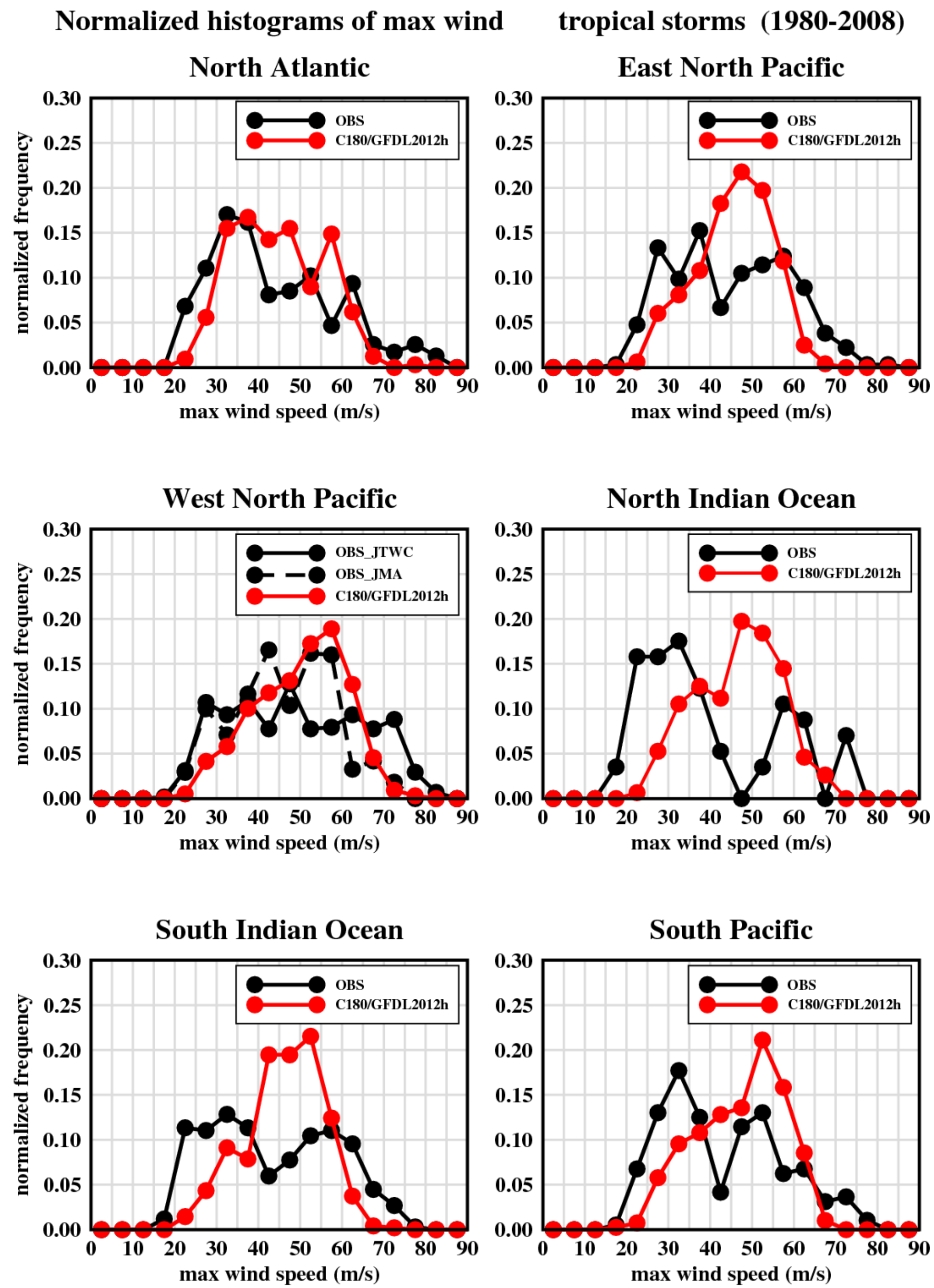
Power Dissipation Index: Global: **-9.7%**

Cat 4-5 storm days: Global: **+34.5%**

Global Frequency: Tropical storms: **-16%** [range: -37% (Southwest Pac) to +27% (N. Ind.)]

Cat 4-5 storms: **+24%** [range: -58% (Southwest Pac) to +340% (NE Pac.)]

Present-Day Climate



GFDL dynamical downscaling to 6 km grid model; preliminary results, 2014.

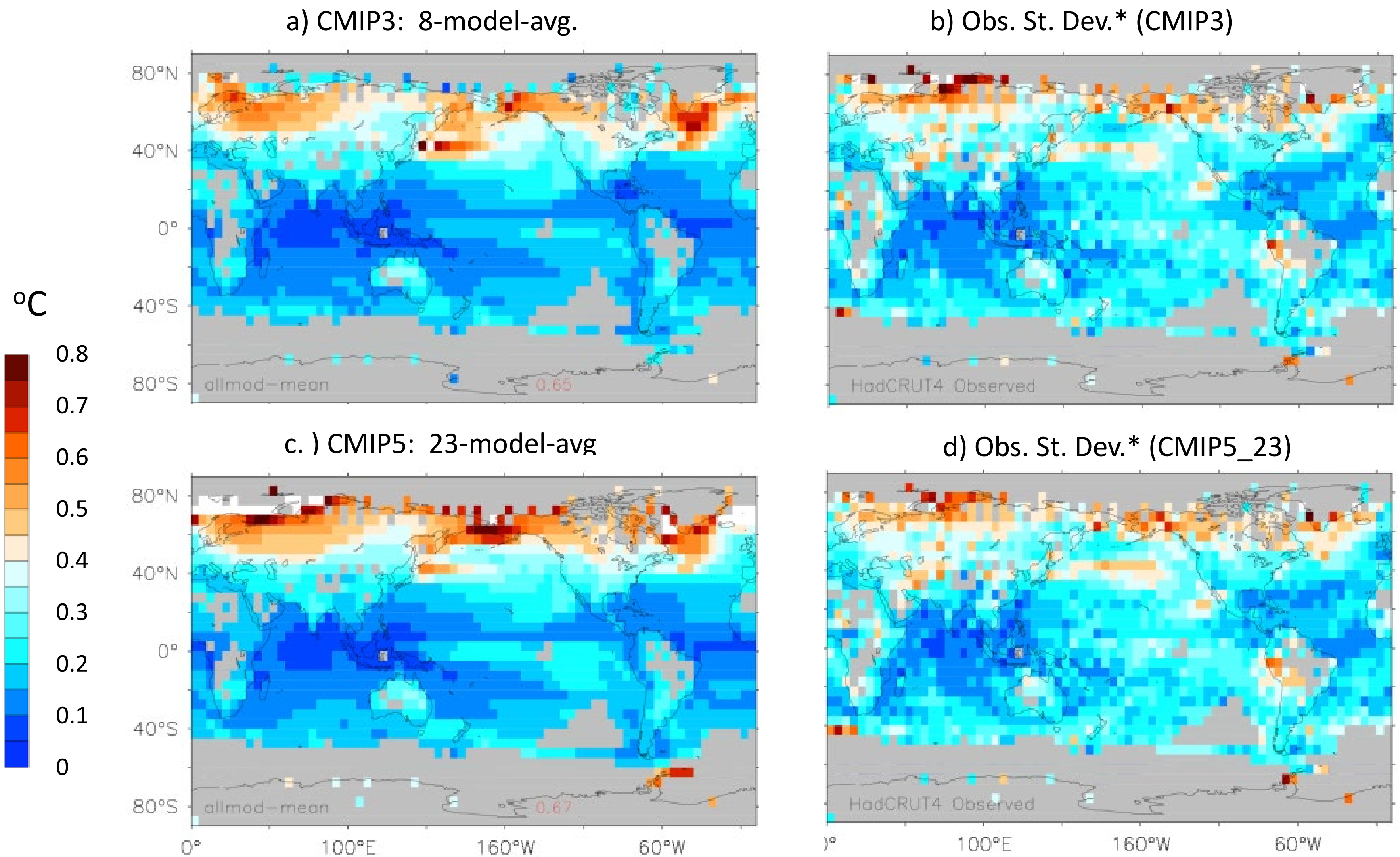
Preliminary Conclusions: Global TC Projections

1. GFDL downscaling models continues to project:

- decrease in global tropical cyclone frequency: -16%
- increase in the occurrence of the most intense tropical cyclones (cat 4-5): +24%
- increase in the average maximum intensity of tropical cyclones: +4%
- increase in the precipitation rates (100 km radius) near tropical cyclones: +14%

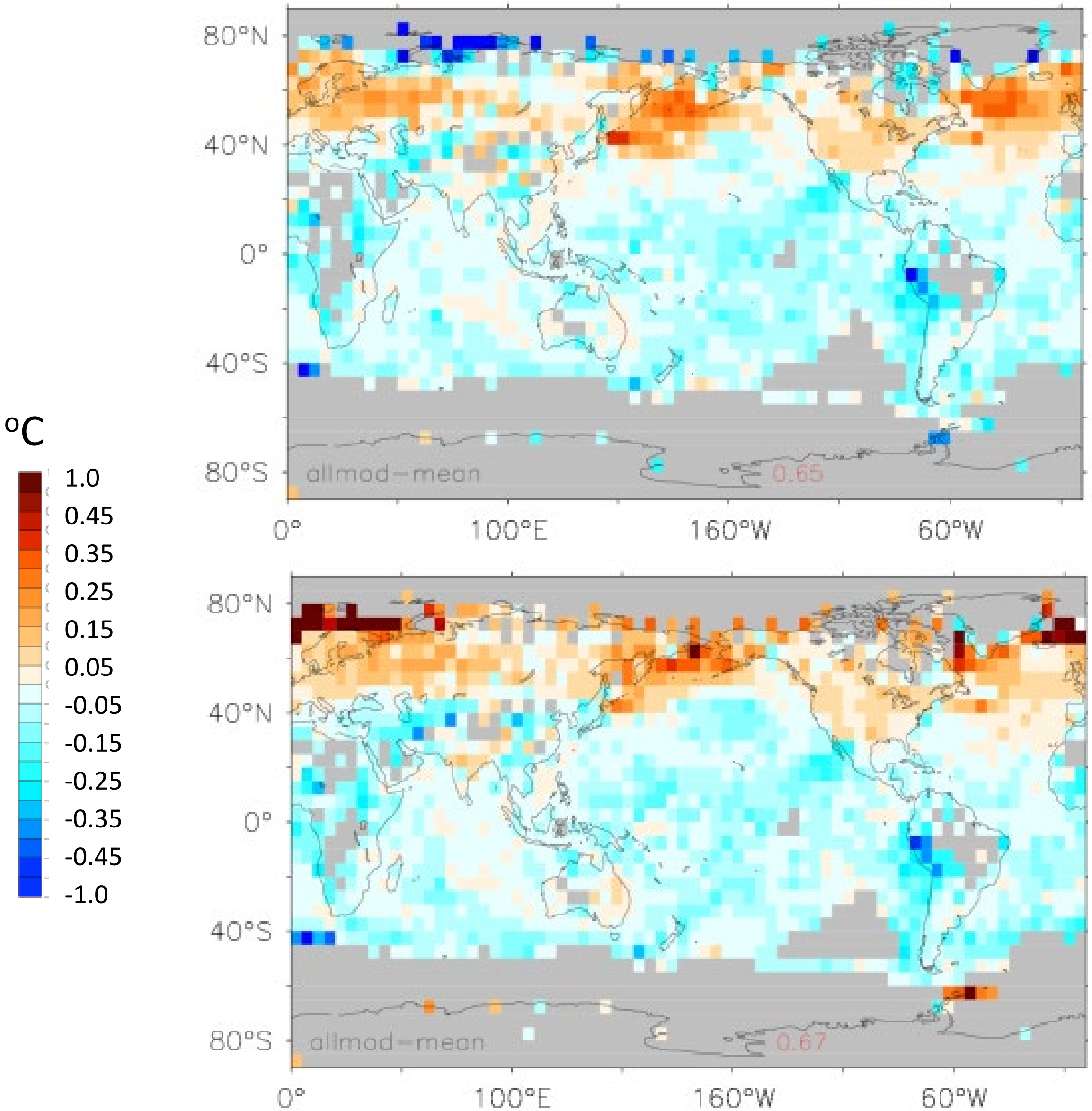
2. These projections vary considerably by basin: Cat 4-5 frequency increases +24% globally; +42 in North Atlantic; +340% in NE Pacific; +200% in N. Indian Ocean; but decreases by -6% in NW Pacific and -59% in SW Pacific.

St. Deviation of low-freq. (>10 yr) variability: Model vs. Observed*



Notes: Model estimate is from control runs; observed estimate is based on the residual with All-Forcing ensemble mean subtracted. An additional adjustment was made to reduce the systematic error due to the computation method for creating the residual. We let each ensemble member substitute for observations in the computation procedure. Source: Knutson, Zeng, and Wittenberg; J. Climate 2013.

St. Deviation of low-freq. (>10 yr) variability: Model – Observed*

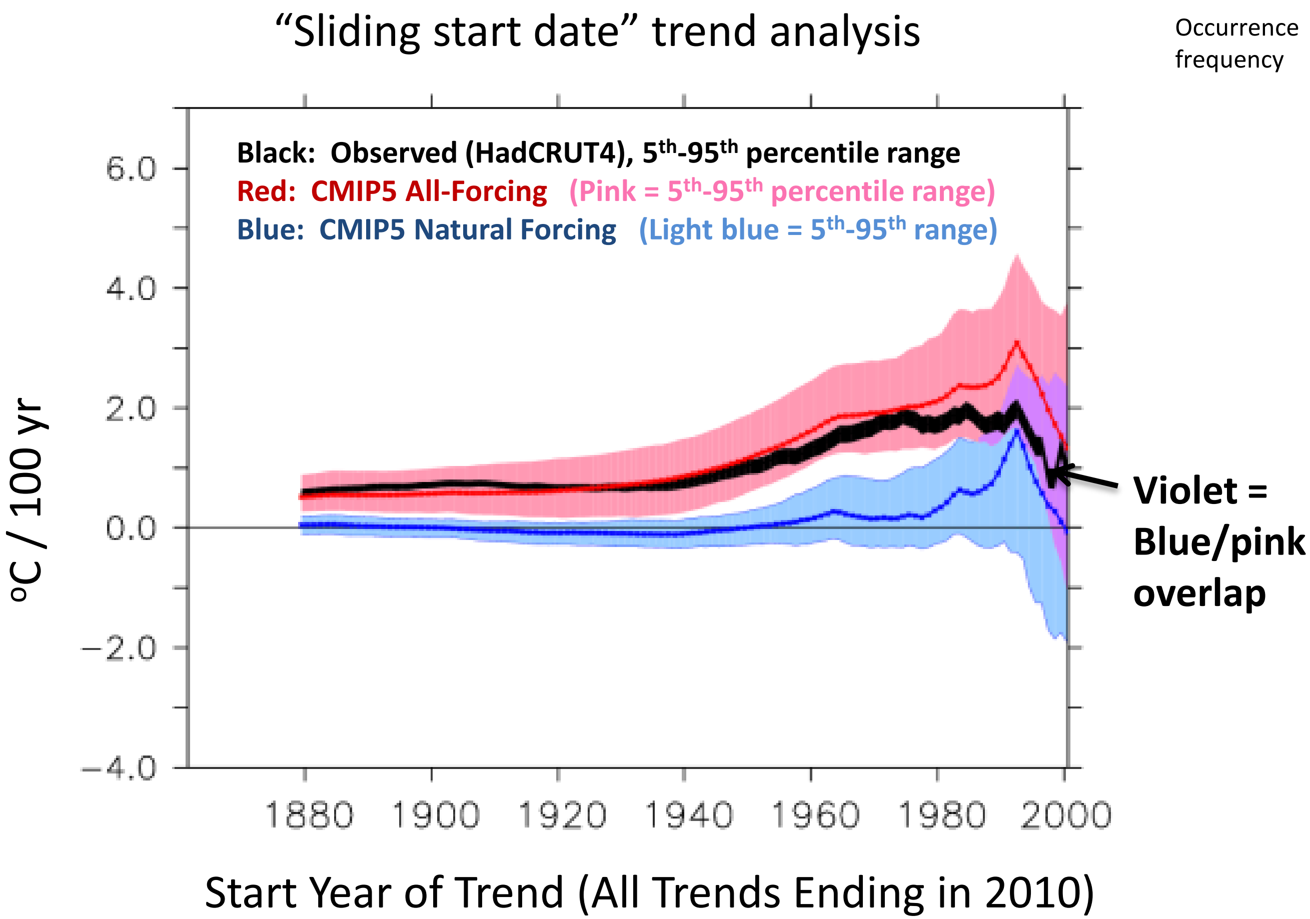


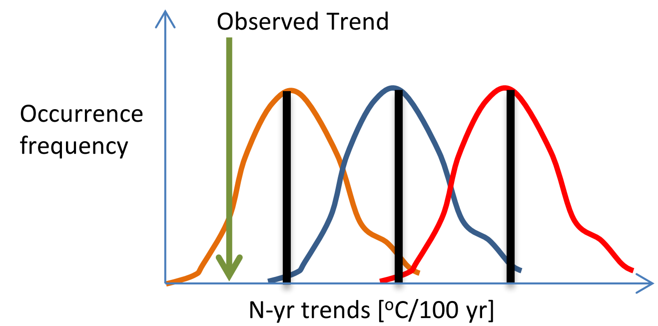
CMIP3: 8 models

CMIP5: 23 models

Source: Knutson, Zeng, and Wittenberg; J. Climate 2013.

Global temperature attribution analysis: CMIP5 7-model ensemble

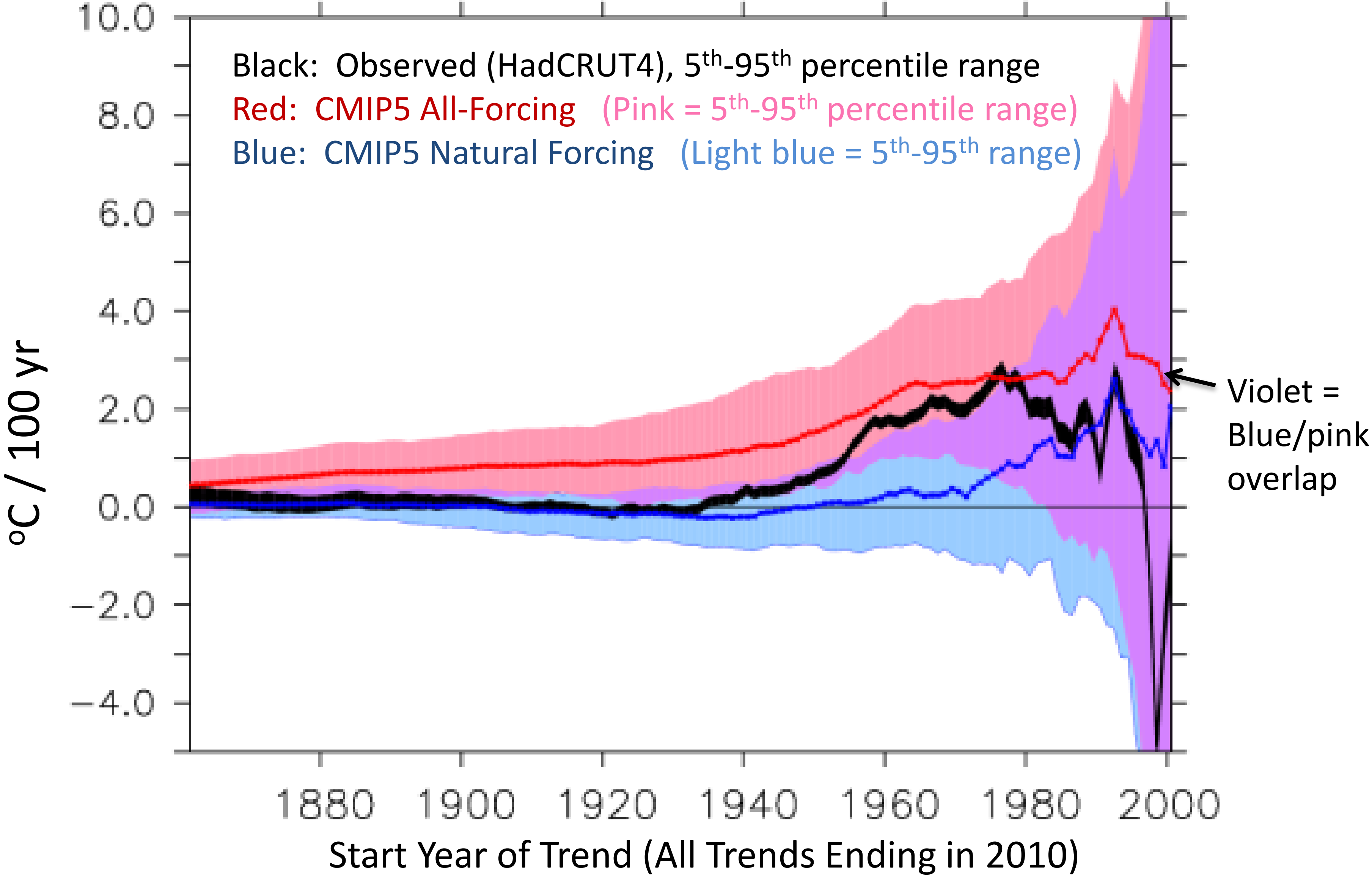




Note: Shaded regions are multi-model combined trend distributions and not formal 90% confidence intervals.

Source: Knutson, Zeng, and Wittenberg, *J. Climate* (2013)

Southeast United States: Sliding Trend Analysis

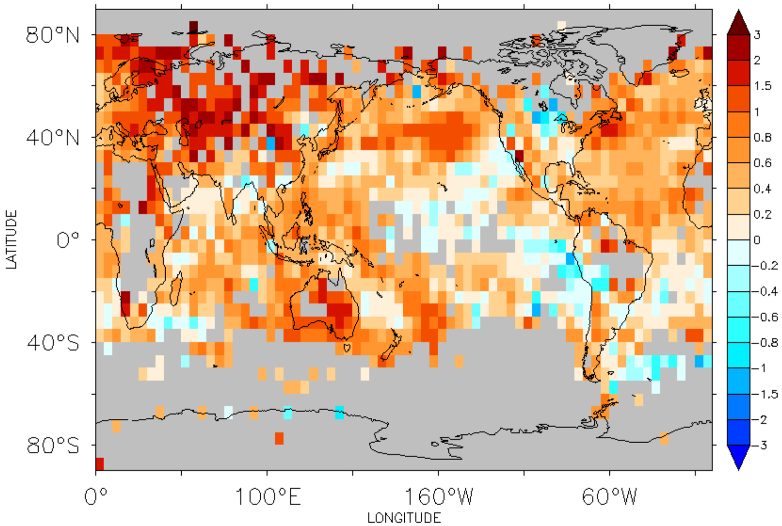


Source: Knutson, Zeng, and Wittenberg, *J. Climate* (2013)

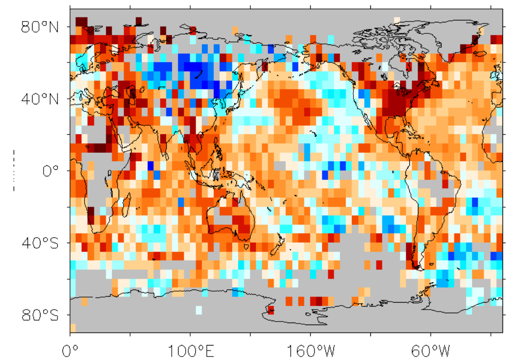
Explaining Extreme Events from a Climate Perspective…

Regional Surface Temperature anomalies for 2013

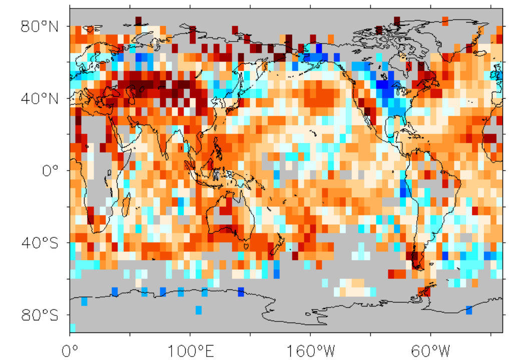
Annual 2013 anomalies



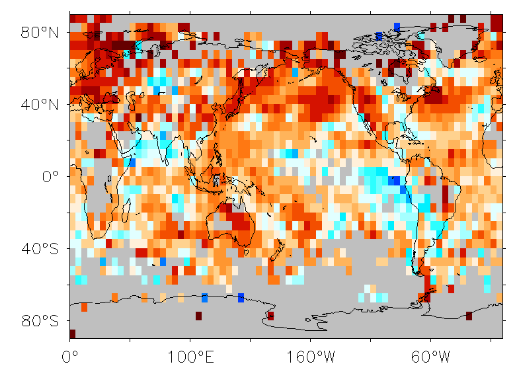
Dec.-Feb. 2013 anomalies



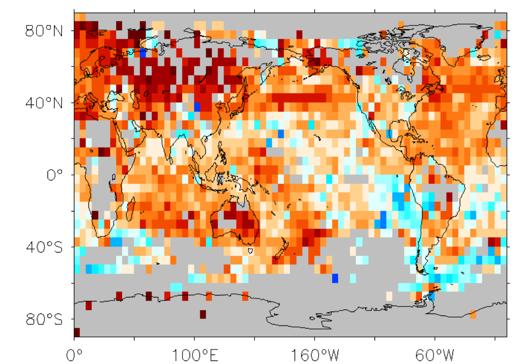
Mar.-May 2013 anomalies



June-Aug. 2013 anomalies



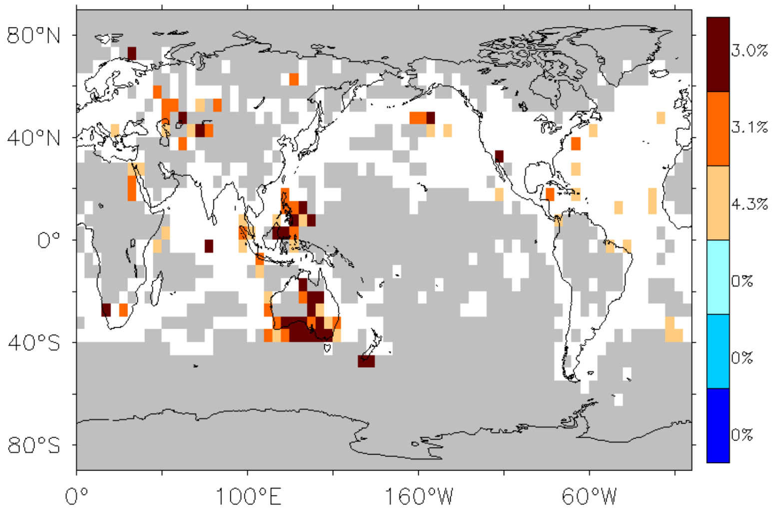
Sept.-Nov. 2013 anomalies



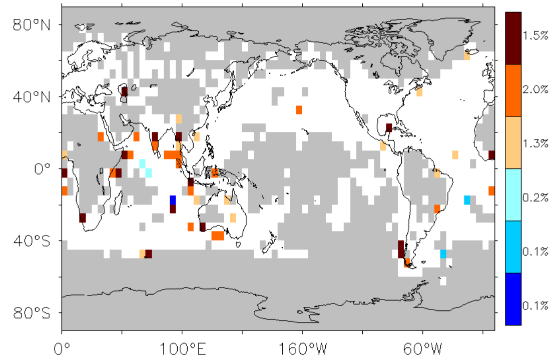
Source: Knutson, Zeng, and Wittenberg, *BAMS,* accepted (2014)

Surface temperature seasonal- or annual-mean extremes for 2013

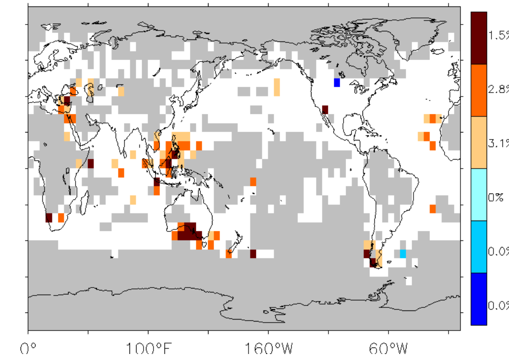
Annual means: 2013 extremes



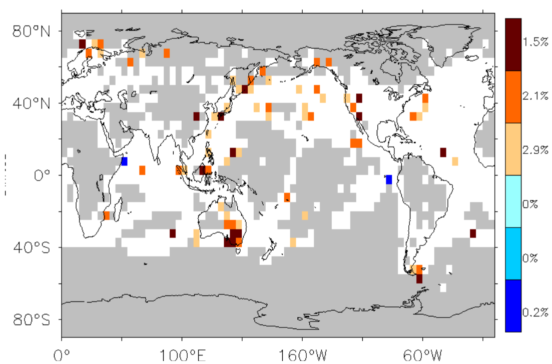
Dec.-Feb. 2013 seasonal extremes



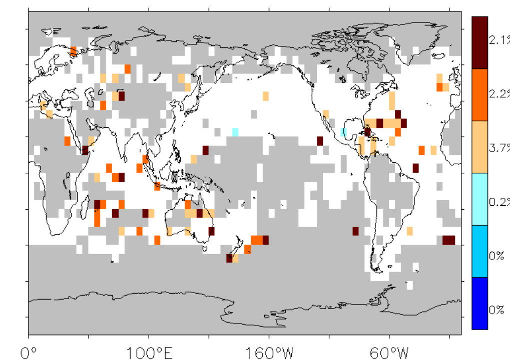
Mar.-May 2013 seasonal extremes



June-Aug. 2013 seasonal extremes



Sept.-Nov. 2013 seasonal extremes



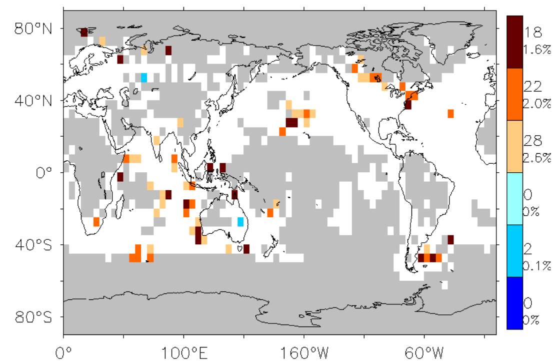
Highest
2nd highest
3rd highest
3rd lowest
2nd lowest
Lowest

Map Legend

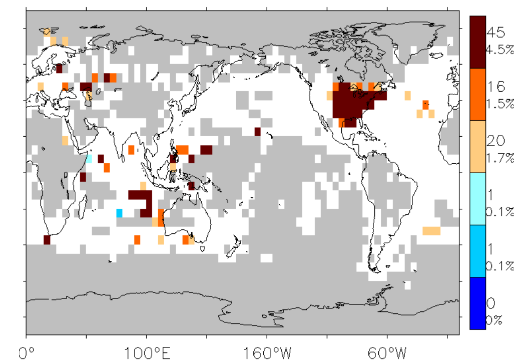
Source: Knutson, Zeng, and Wittenberg, *BAMS,* accepted (2014)

Where were the 2012 anomalies ranked 1st, 2nd, 3rd warmest or coldest?

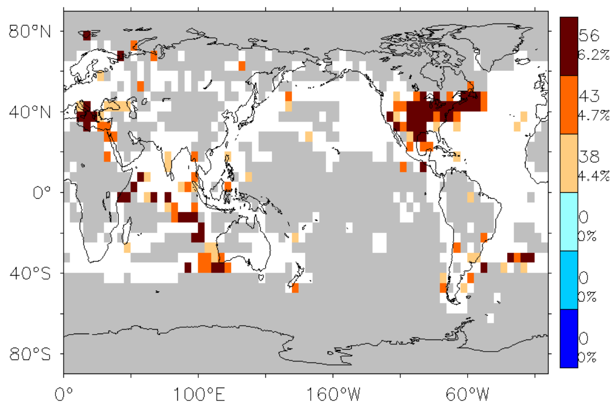
DJF 2012 extremes



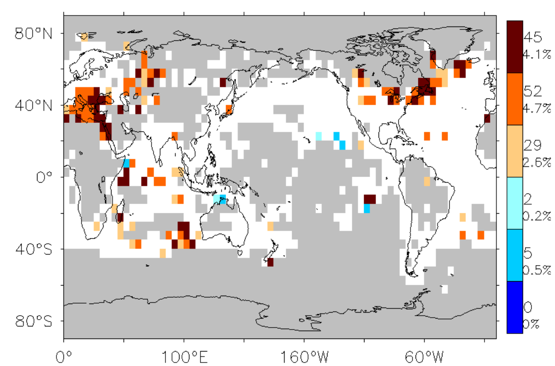
MAM 2012 extremes



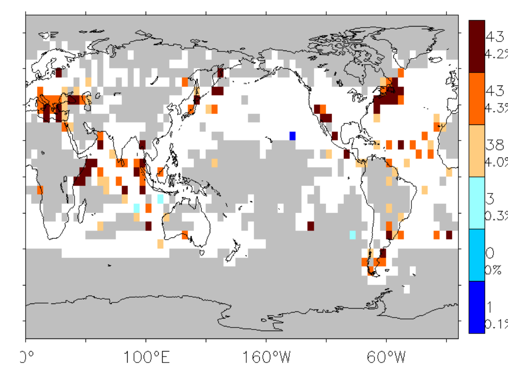
Annual 2012 extremes



JJA 2012 extremes



SON 2012 extremes

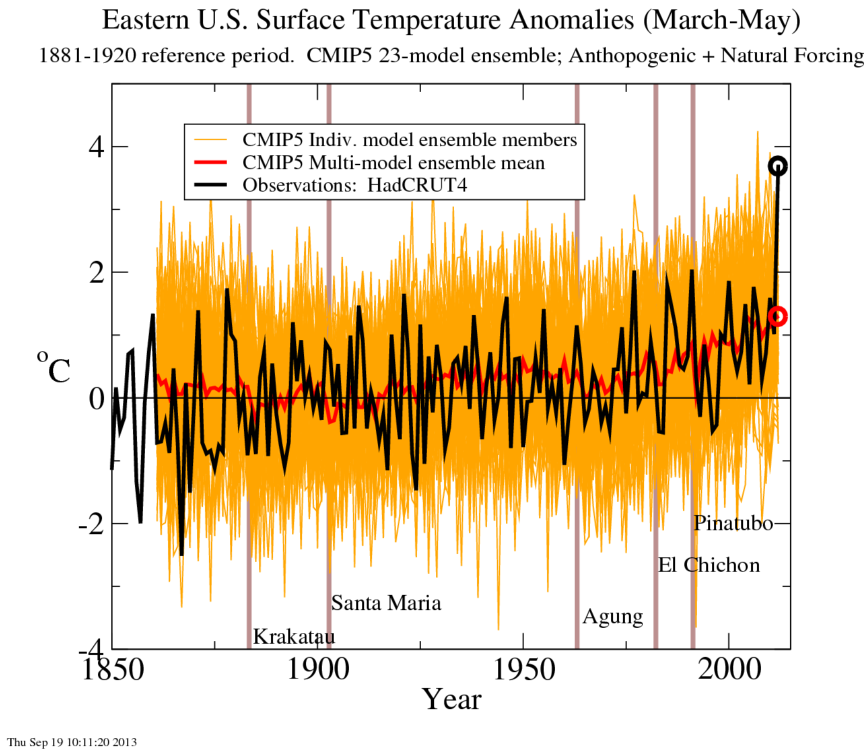


Map Legend

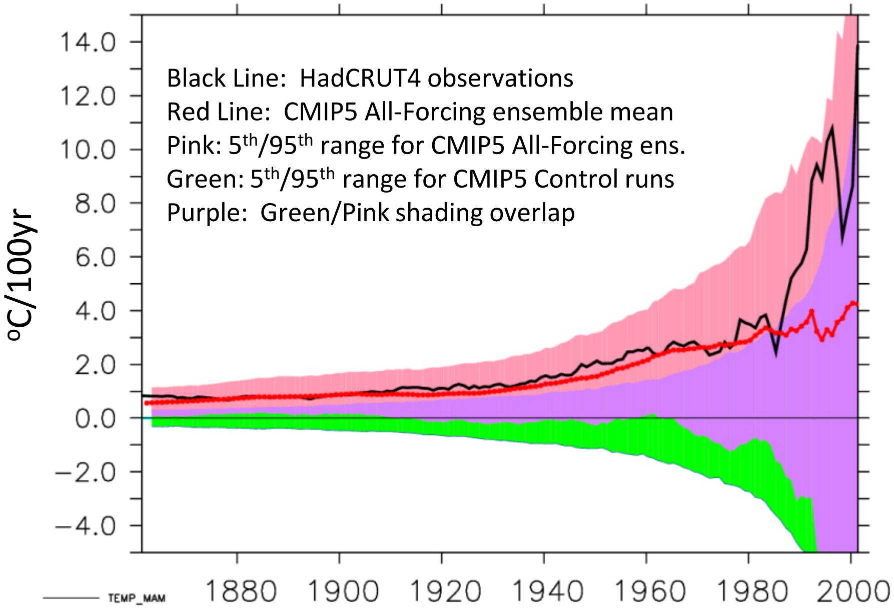
- Highest
- 2nd highest
- 3rd highest
- 3rd lowest
- 2nd lowest
- Lowest

Source: Knutson, Zeng, and Wittenberg, *BAMS* (2013)

An assessment of the extreme March-May 2012 temperatures over the eastern U.S.



b) Trend assessment



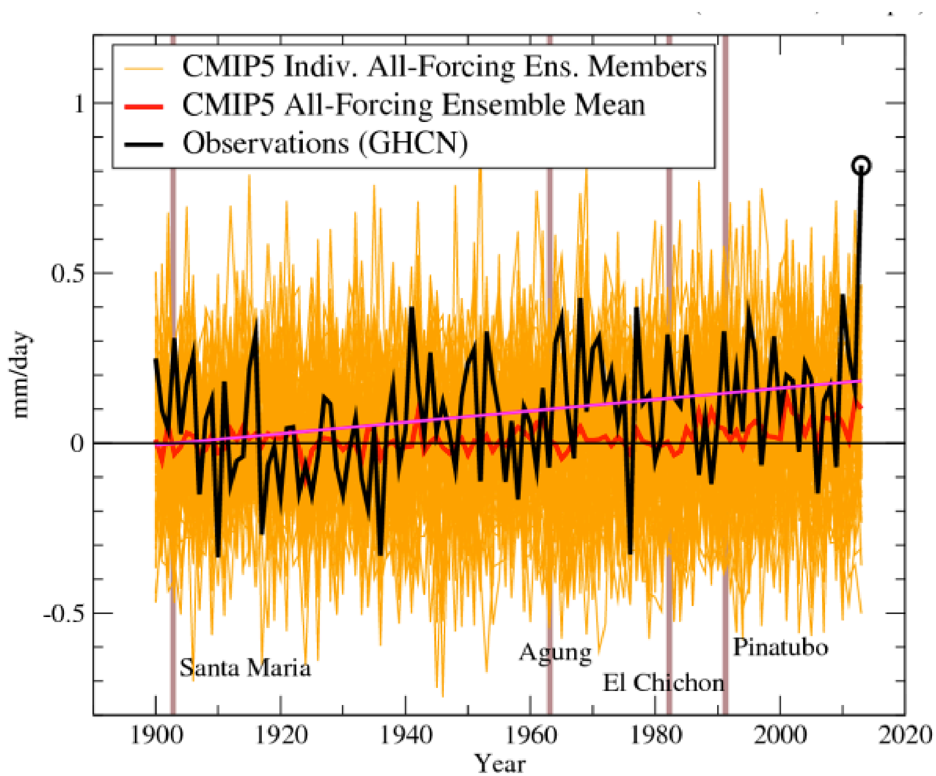
Trend start year (all trends ending in 2012)

$$\text{Ratio} = \frac{p_{ALL}}{p_{CON}} = 11 \text{ to } 12$$

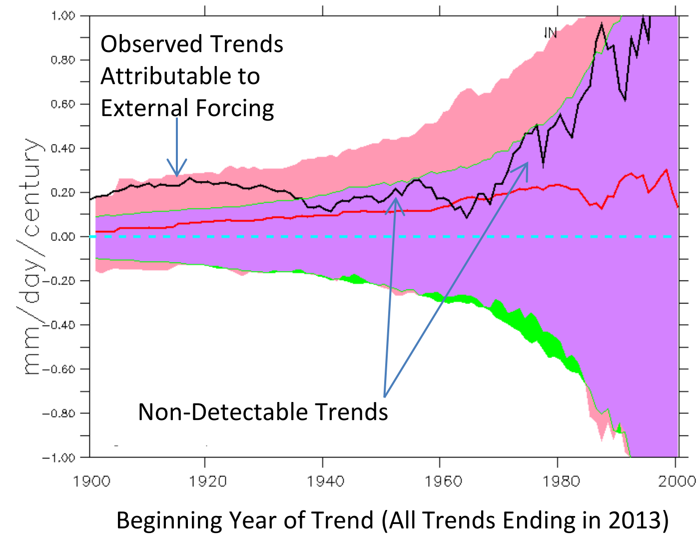
p_{ALL} and p_{CON} : probabilities of exceeding the 2012 or 1991 thresholds in the All Forcing and Control distributions.
Source: Knutson, Zeng, and Wittenberg, *BAMS* (2013)

2013 Annual Mean Precipitation Extremes: Climate Perspective

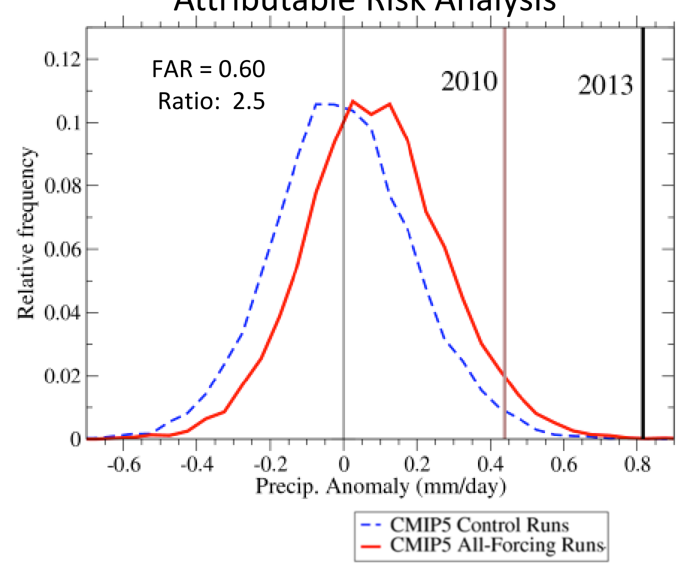
U.S./Canadian Border Region – Annual-mean Precipitation



Sliding Trend Analysis



Attributable Risk Analysis

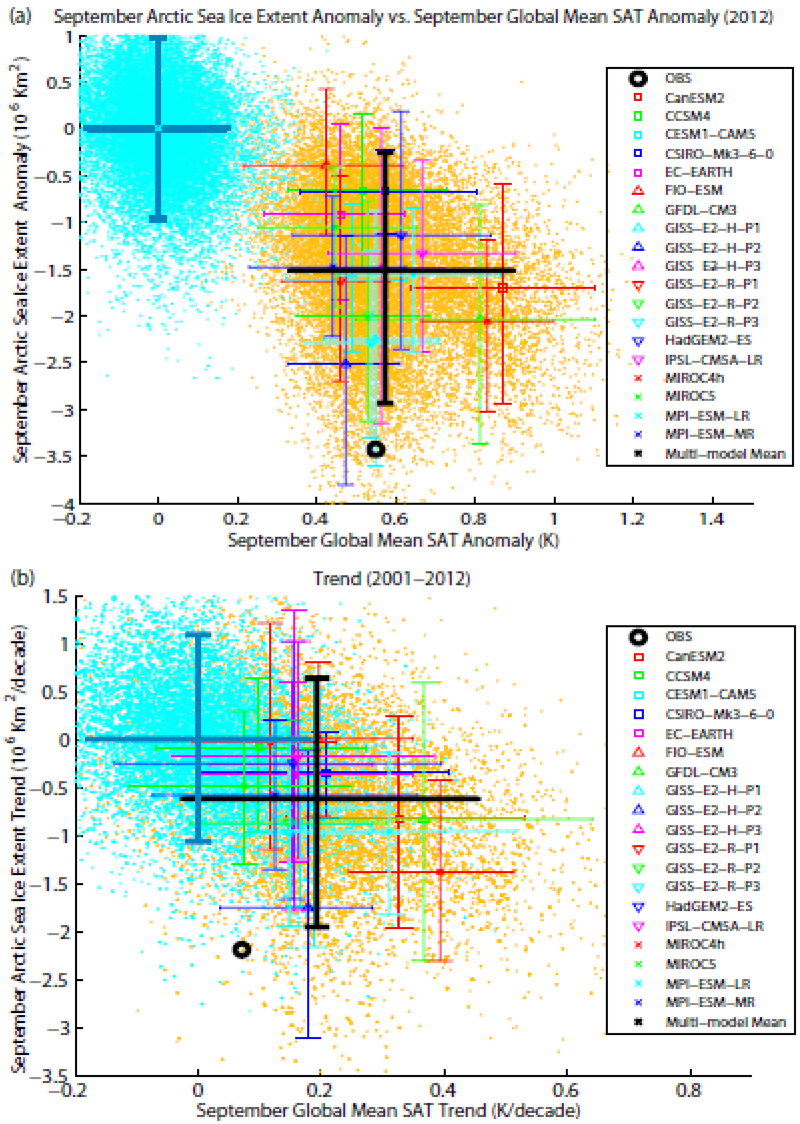


$$\text{Ratio} = \frac{p_{ALL}}{p_{CON}}$$

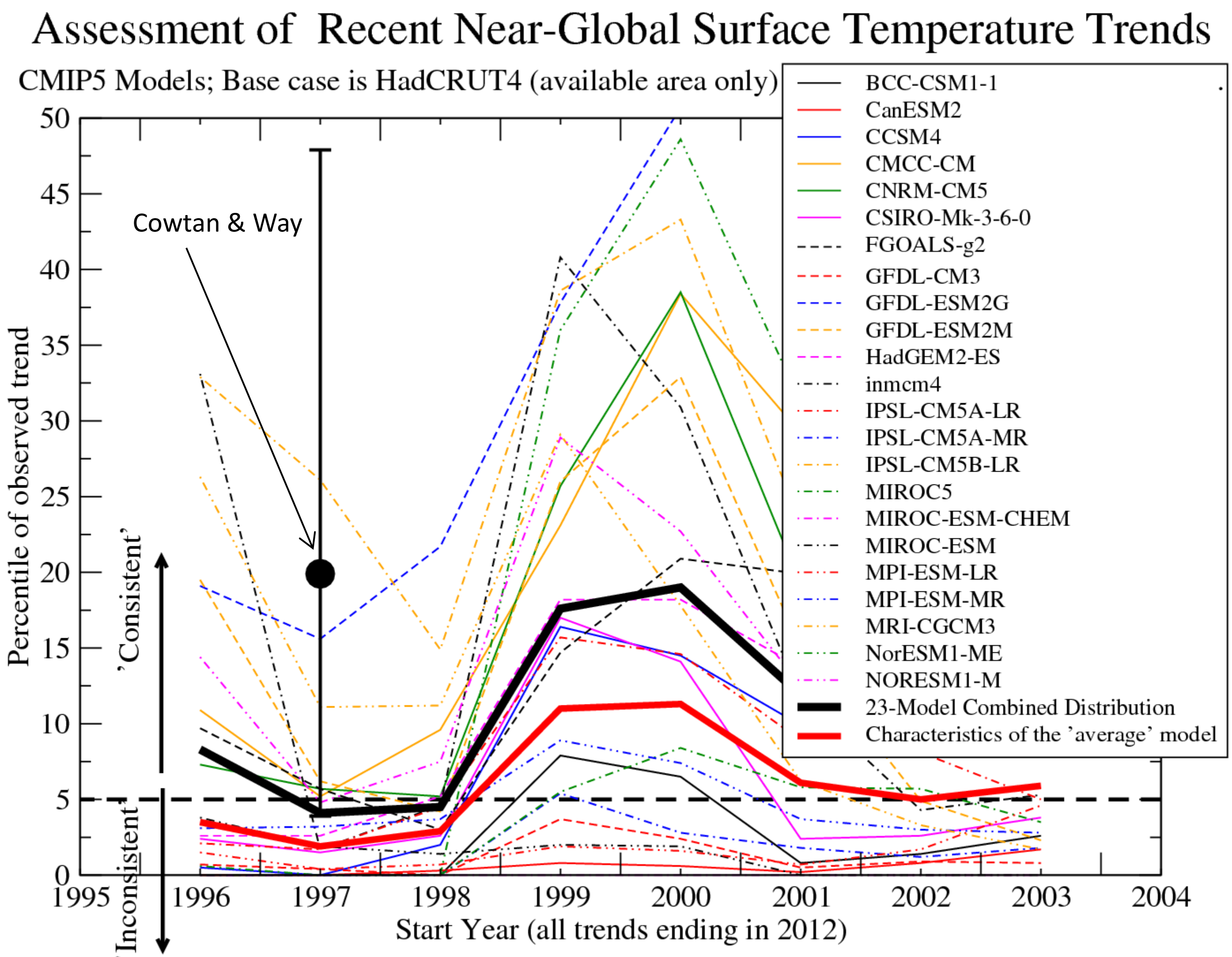
p_{ALL} and p_{CON} : probabilities of exceeding the 2013 or 2010 thresholds in the All Forcing and Control distributions.

Source: Knutson, Zeng, and Wittenberg, *BAMS* accepted (2014)

September 2012: Arctic Sea Ice Extent Anomaly vs. Global SAT Anomaly



Source: R. Zhang and T. Knutson, BAMS, 2013.

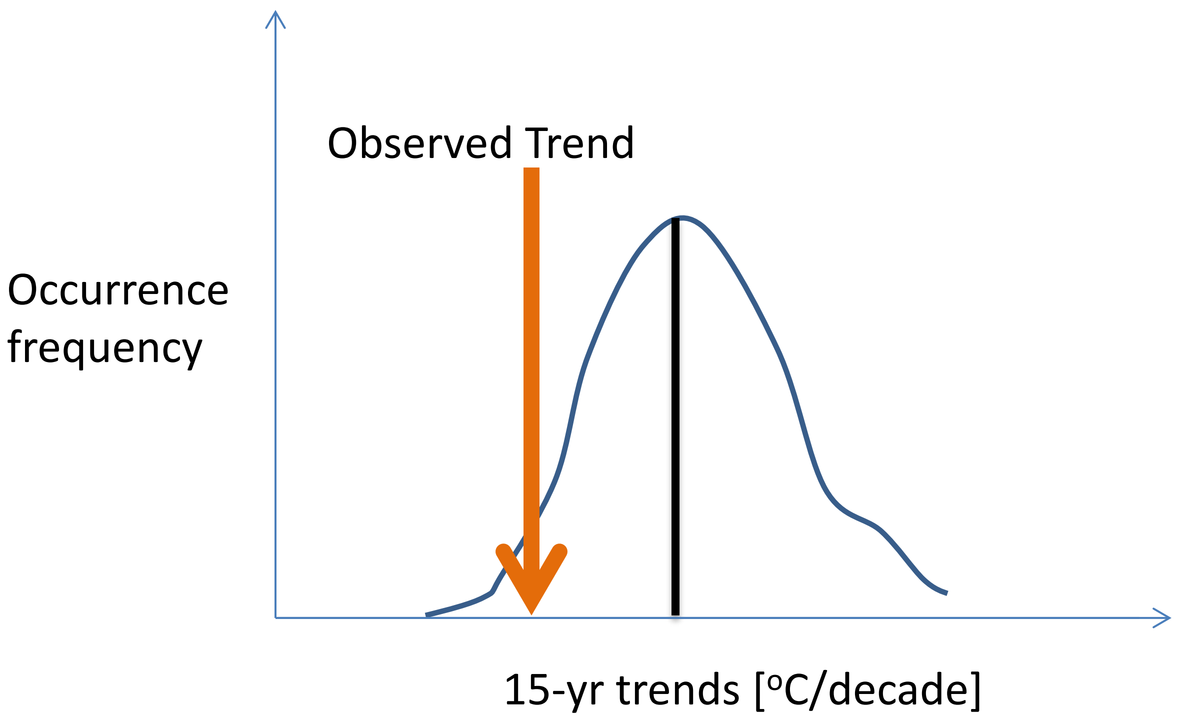


Note: Filled circle / error bar is percentile within 23-model combined distribution of Cowtan and Way's adjusted trend (and trend +/- 1 sigma).

Thu Jan 30 18:44:41 2014

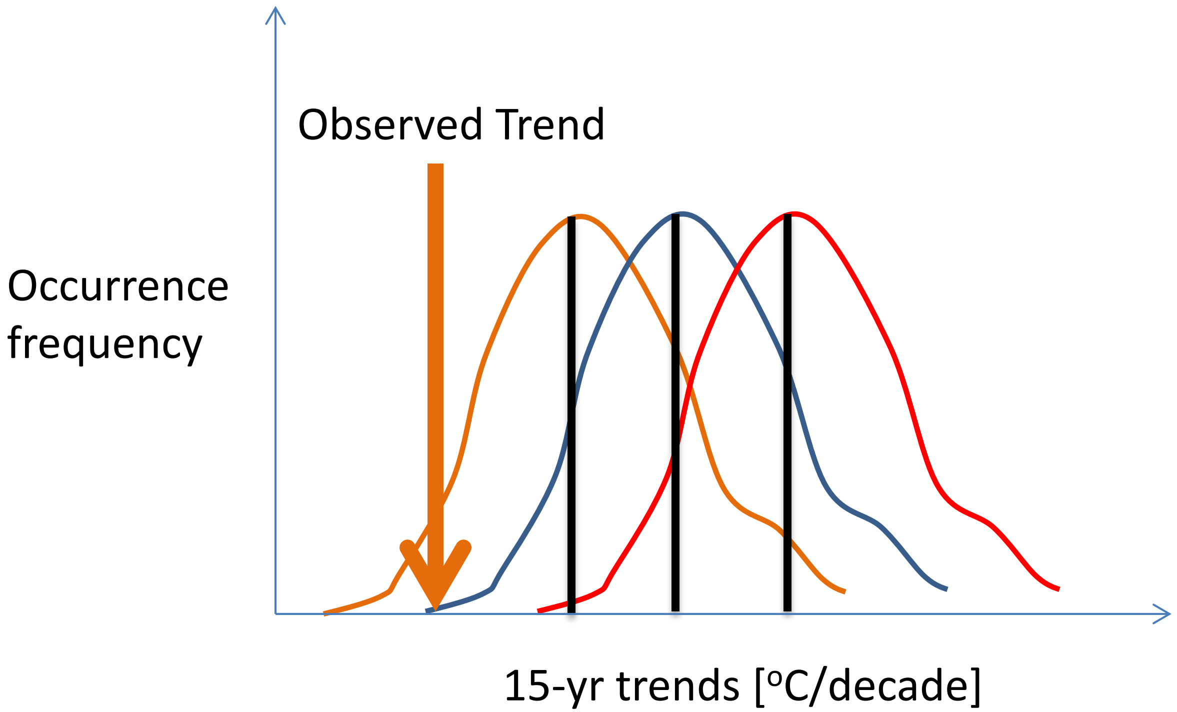
Consider the distributions of 15-yr trends from a climate model for the period 1997-2012.

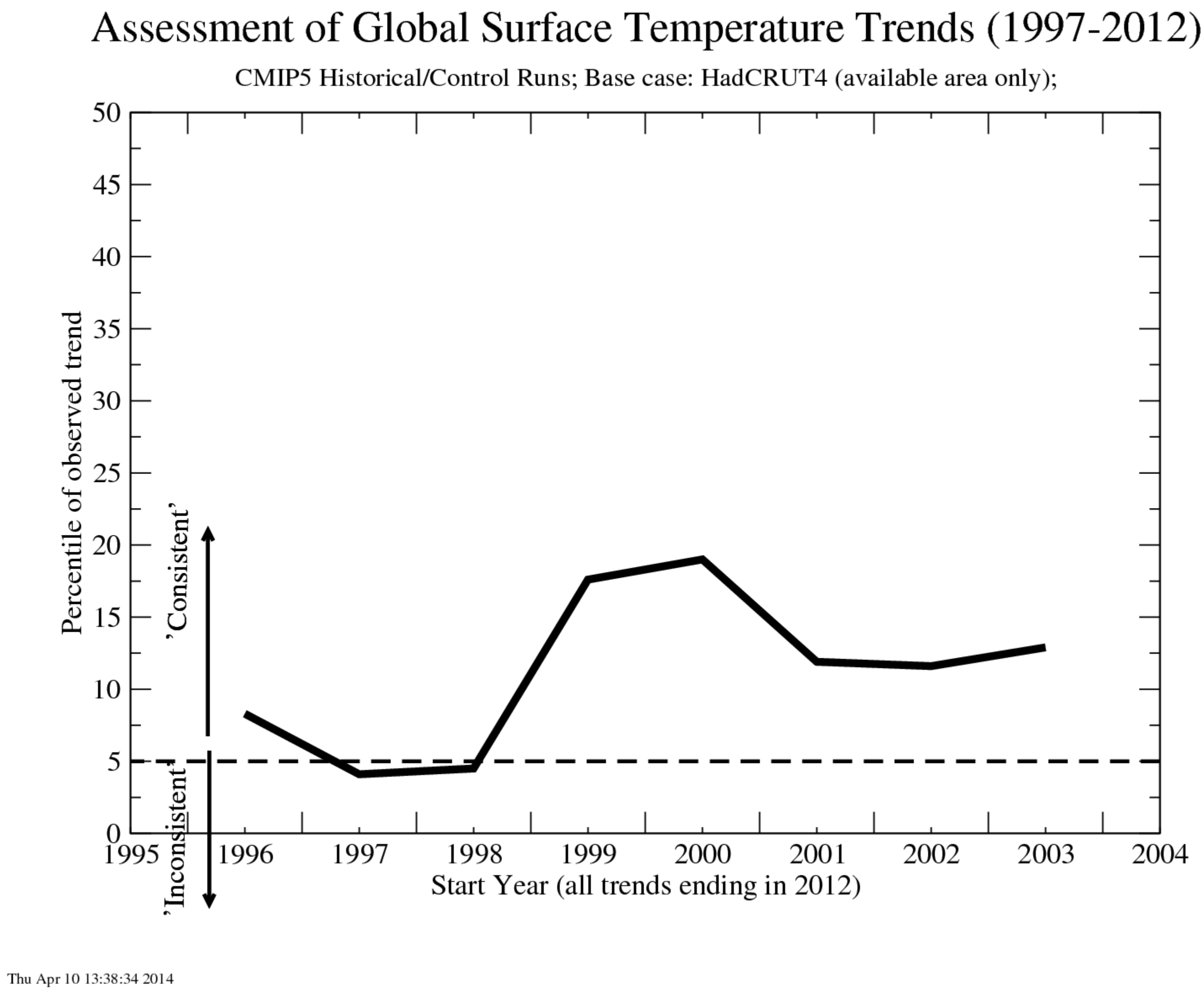
- The mean of the model's distribution is the ensemble mean of the model's historical run ensemble over the period in question.
- The spread about the mean for the model is the distribution of 15-year trends from the model's control run.

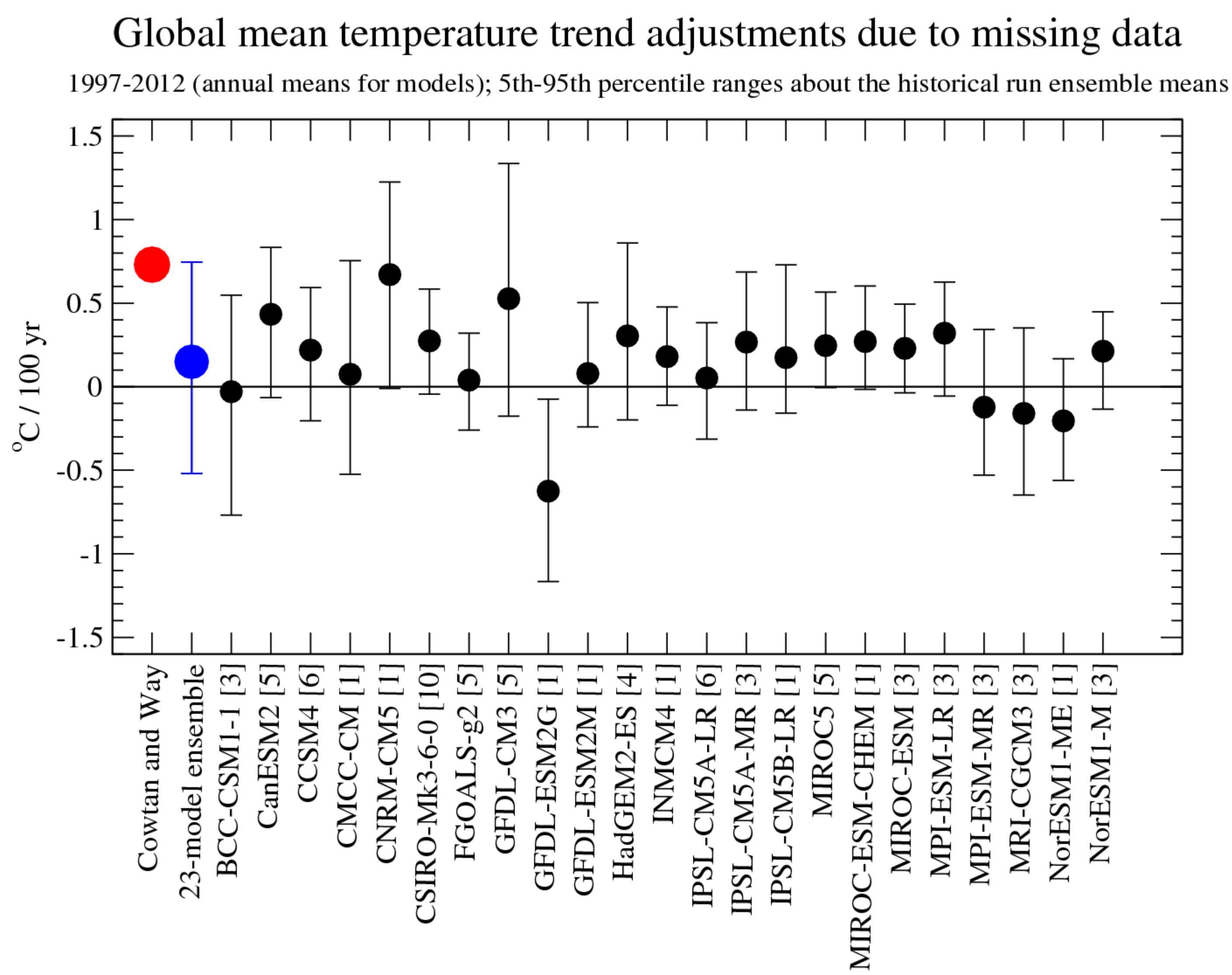


Consider three distributions of 15-yr trends from three different models for the period 1997-2012.

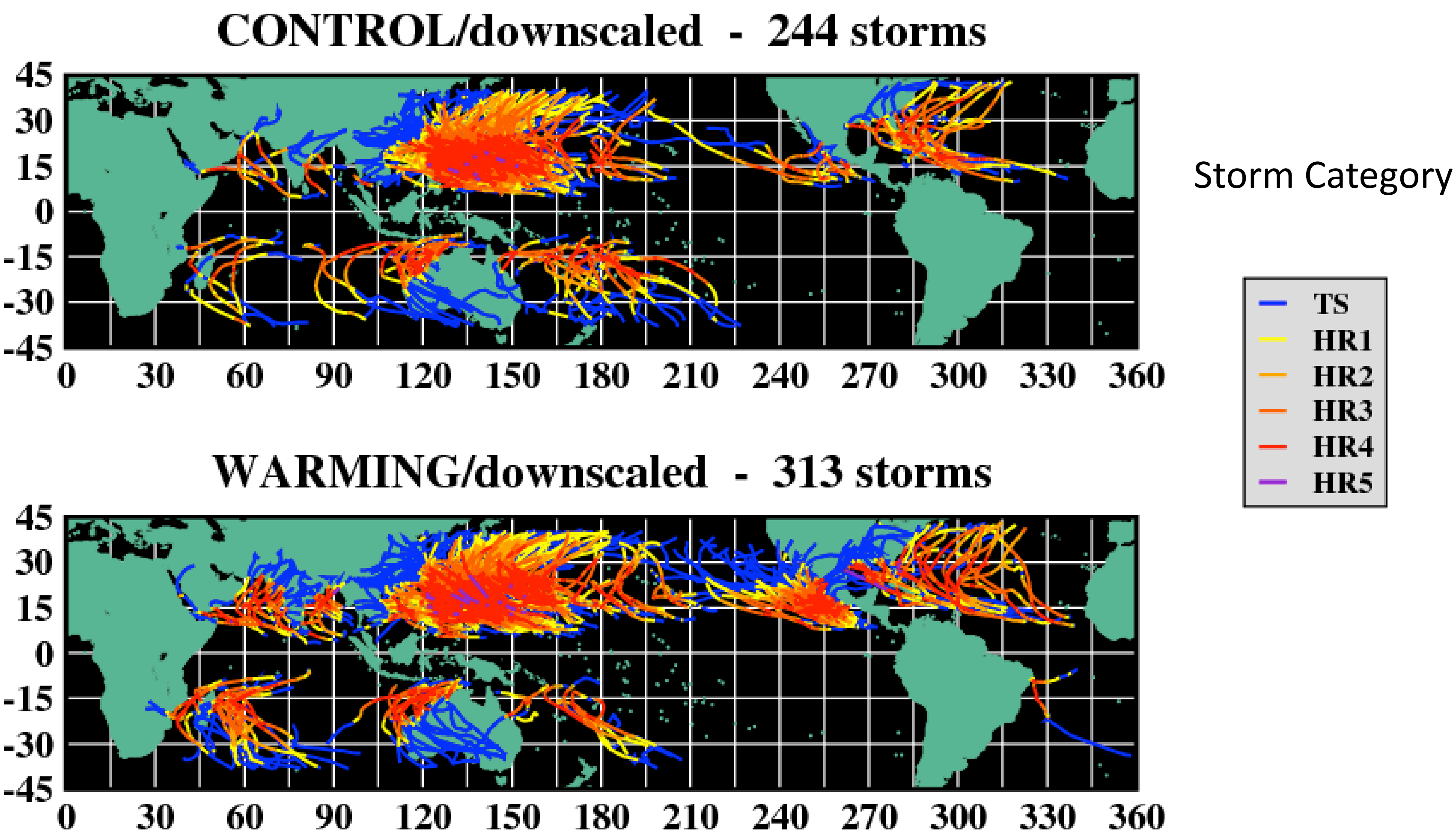
- The mean of each model's distribution is the ensemble mean of that model's historical run ensemble over the period in question.
- The spread about the mean for each model is the distribution of 15-year trends from the control run of that model.




Assessment of Global Surface Temperature Trends (1997-2012)
CMIP5 Historical/Control Runs; Base case: HadCRUT4 (available area only);
Percentile of observed trend
50
45
40
35
30
25
20
15
10
5
0
'Consistent'
'Inconsistent'
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
Start Year (all trends ending in 2012)
Thu Apr 10 13:38:34 2014

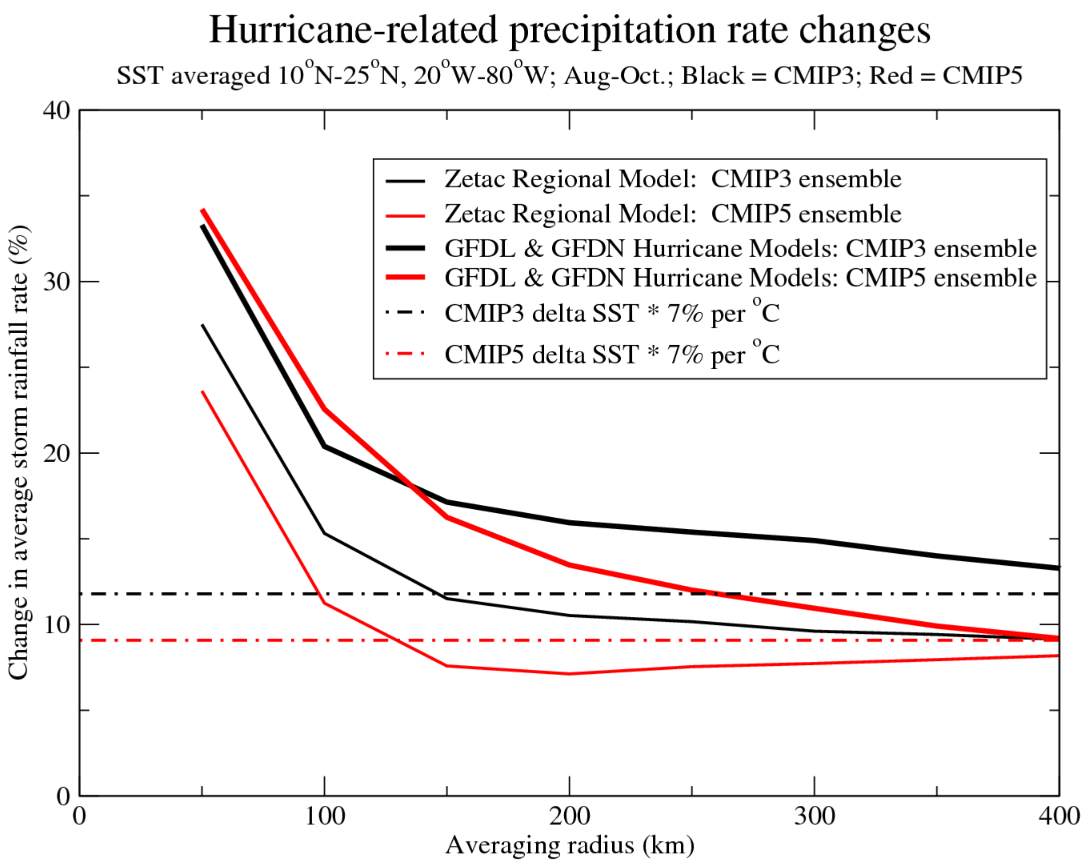

Global mean temperature trend adjustments due to missing data
1997-2012 (annual means for models); 5th-95th percentile ranges about the historical run ensemble means
°C / 100 yr
1.5
1
0.5
0
-0.5
-1
-1.5
Cowtan and Way
23-model ensemble
BCC-CSM1-1 [3]
CanESM2 [5]
CCSM4 [6]
CMCC-CM [1]
CNRM-CM5 [1]
CSIRO-Mk3-6-0 [10]
FGOALS-g2 [5]
GFDL-CM3 [5]
GFDL-ESM2G [1]
GFDL-ESM2M [1]
HadGEM2-ES [4]
INMCM4 [1]
IPSL-CM5A-LR [6]
IPSL-CM5A-MR [3]
IPSL-CM5B-LR [1]
MIROC5 [5]
MIROC-ESM-CHEM [1]
MIROC-ESM [3]
MPI-ESM-LR [3]
MPI-ESM-MR [3]
MRI-CGCM3 [3]
NorESM1-ME [1]
NorESM1-M [3]

Category 4-5 Tropical Cyclones: 20 yr simulations
CMIP5/RCP4.5 Late 21st Century vs. Present Day



24% increase in Cat 4-5 frequency globally

GFDL dynamical downscaling to 6 km grid model; preliminary results, 2014.



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