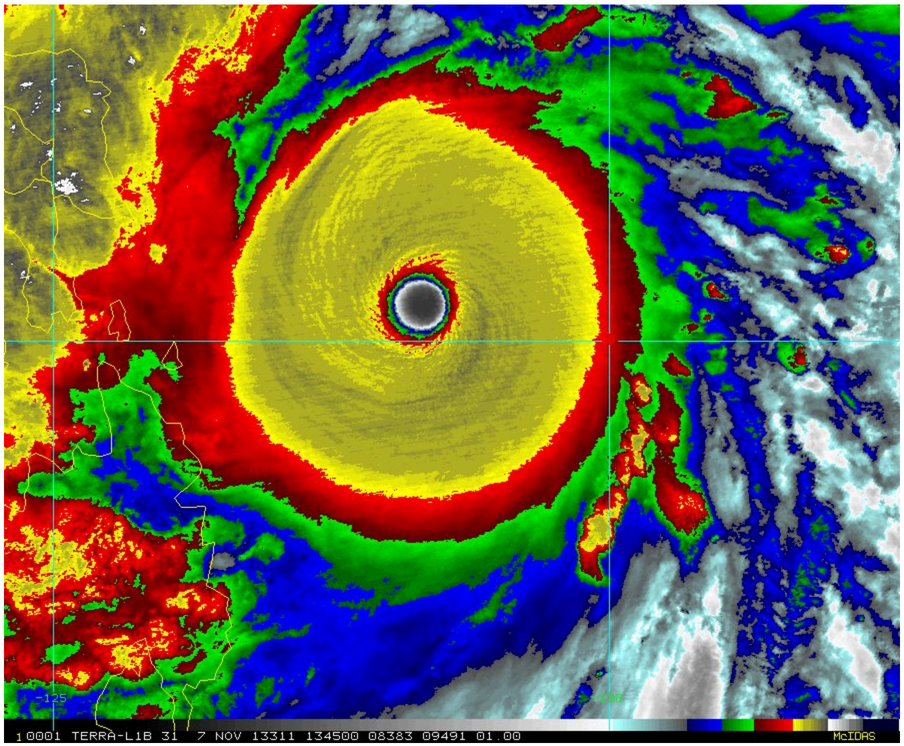
Changes in Frequency and Intensity of Extremes



Super Typhoon Haiyan, 2013

Tom Knutson
NOAA/GFDL
Climate Impacts and Extremes Group

Princeton, New Jersey
September 2014

<u>Collaborators (partial listing):</u>
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Ming Zhao, Rong Zhang,
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Bob Tuleya, Phil Duffy, Daithi
Stone, Michael Wehner, Matt
Morin

Climate Extremes: Challenges in Estimating and Understanding Recent Changes in the Frequency and Intensity of Extreme Climate and Weather Events

Francis W. Zwiers, Lisa V. Alexander, Gabriele C. Hegerl, Thomas R. Knutson, James P. Kossin, Phillippe Naveau, Neville Nicholls, Christoph Schär, Sonia I. Seneviratne, and Xuebin Zhang

Abstract This paper focuses primarily on extremes in the historical instrumental period. We consider a range of phenomena, including temperature and precipitation extremes, tropical and extra-tropical storms, hydrological extremes, and transient extreme sea-level events. We also discuss the extent to which detection and attribution research has been able to link observed changes to external forcing of the climate system. Robust results are available that detect and often attribute changes in frequency and intensity of temperature extremes to external forcing. There is also some evidence that on a global scale, precipitation extremes have intensified due

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G.R. Asrar and J.W. Hurrell (eds.), *Climate Science for Serving Society: Research, Modeling and Prediction Priorities*, DOI 10.1007/978-94-007-6692-1_13,

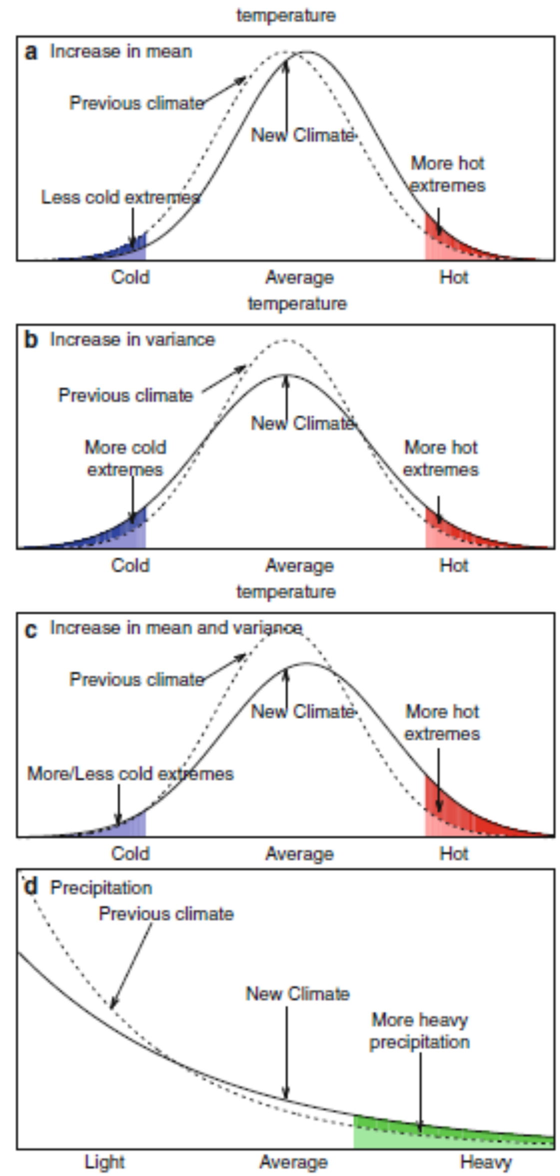


Fig. 1 Schematic representations of the probability distributions of daily temperature, which tends to be approximately Gaussian (exceptions can be caused by soil freezing, feedbacks, or energy balance constraints, see text), and daily precipitation, which has a skewed distribution.

Source: Zwiers et al. 2013

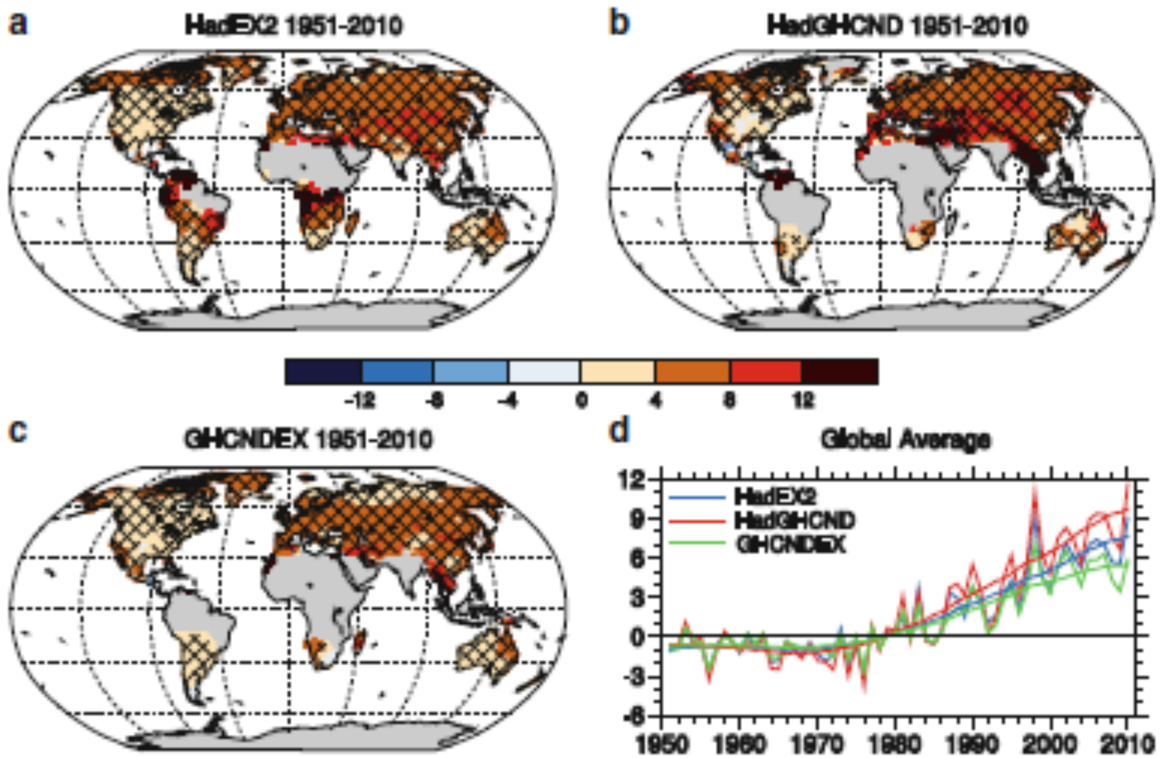


Fig. 2 Annual trends in warm nights (TN90p) using different datasets for the period 1951–2010 where at least 40 years are available. The datasets are (**a**) HadEX2 (Alexander and Donat 2011), (**b**) HadGHCNDEX (ETCCDI indices calculated from an updated version of HadGHCND (Caesar et al. 2006)) and (**c**) GHCNDEX (Donat and Alexander 2011). *Panel* (**d**) represents the global average time series plots for each of the three datasets presented as anomalies relative to the 1961–1990 with associated 21-year Gaussian filters

Source: Zwiers et al. 2013

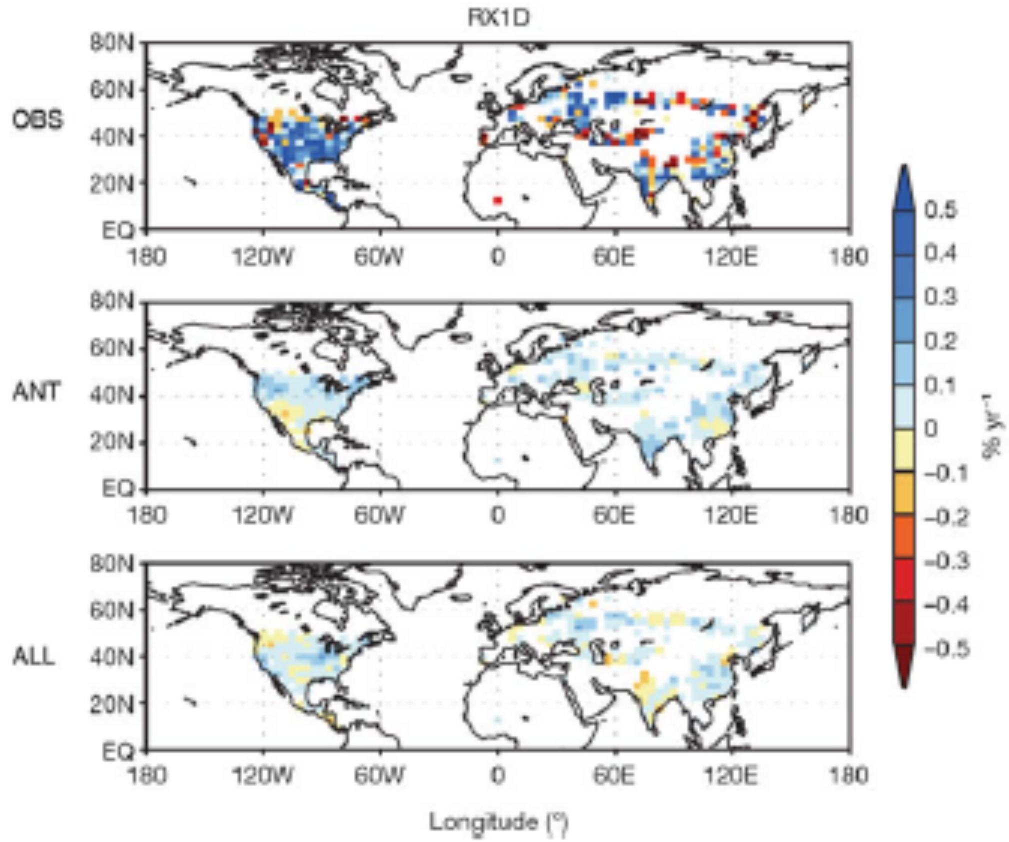
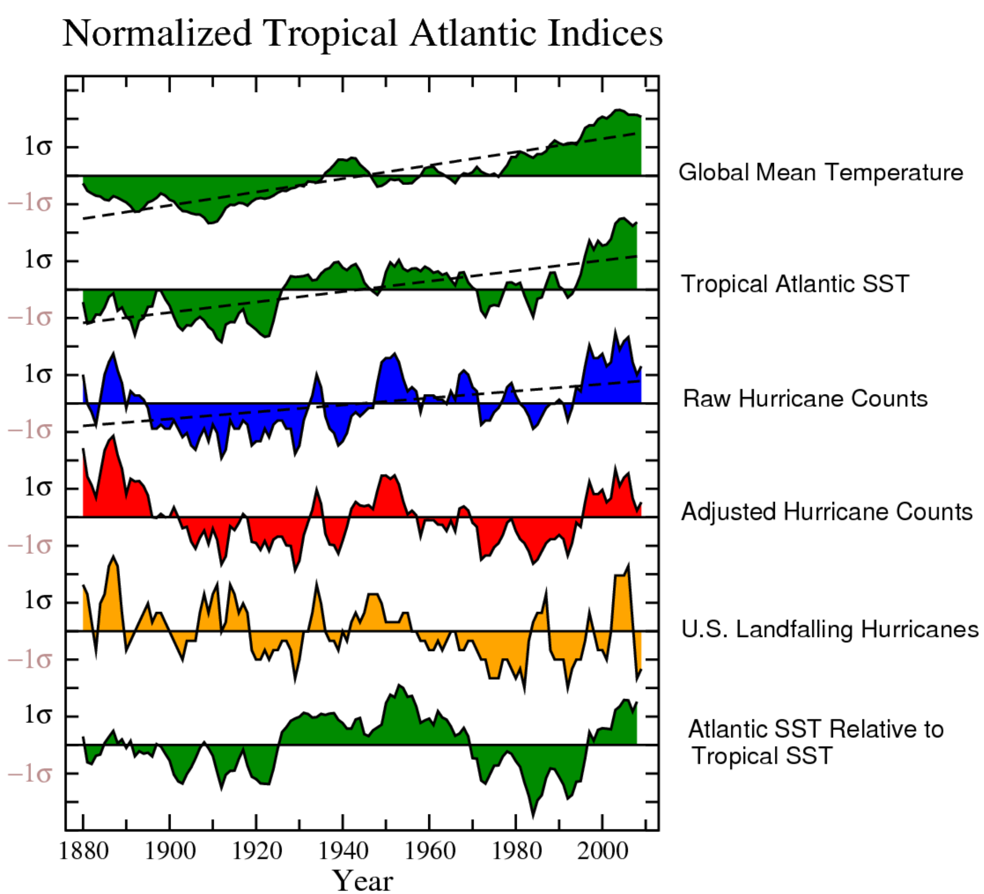


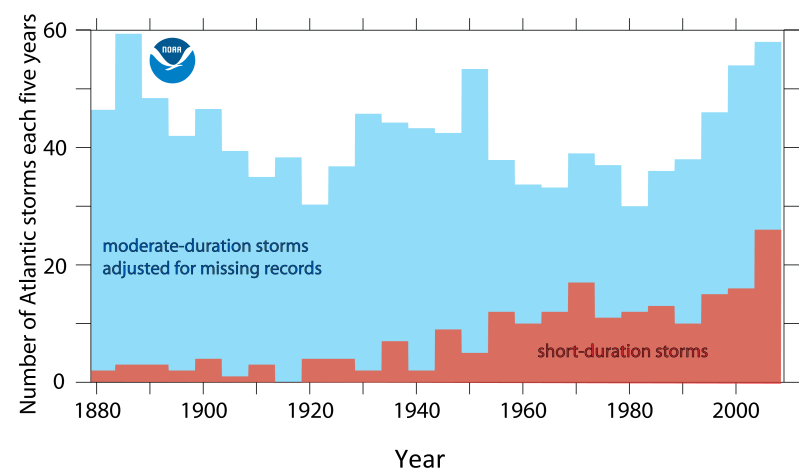
Fig. 4 Geographical distribution of trends of extreme precipitation indices (*PI*) for annual maximum daily precipitation amounts (*RX1D*) during 1951–1999. Observations (*OBS*); model simulations with anthropogenic (*ANT*) forcing; model simulations with anthropogenic plus natural (*ALL*) forcing. For models, ensemble means of trends from individual simulations are displayed. Units: per cent probability per year (From Min et al. (2011; see paper for details))

Source: Zwiers et al. 2013

IPCC AR5: Low confidence in long-term (centennial-scale) changes in tropical cyclones



Moderate-duration tropical storms do not show a trend.



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

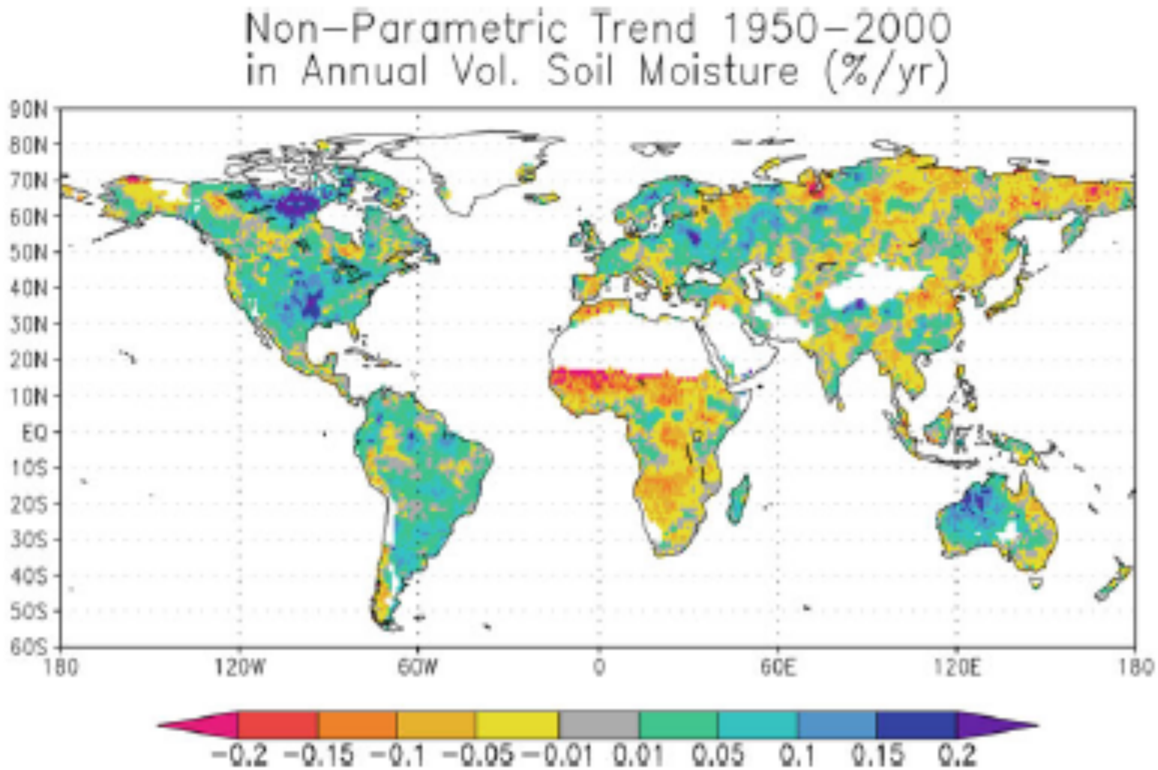


Fig. 7 Global distribution of linear trends in annual mean volumetric soil moisture for 1950–2000 obtained from the Variable Infiltration Capacity (*VIC*) hydrologic model when driven with observationally based forcing. The trends are calculated using the Theil-Sen estimator and evaluated with the Mann–Kendall nonparametric trend test. Regions with mean annual precipitation less than 0.5 mm day^{-1} have been masked out because the VIC model simulates small drying trends in desert regions that, despite being essentially zero, are identified by the nonparametric test (From Sheffield and Wood (2008; Fig. 1)) Source: Zwiers et al. 2013

IPCC AR5: "The frequency and intensity of drought has likely increased in the Mediterranean and West Africa, and likely decreased in central North America and north-west Australia."

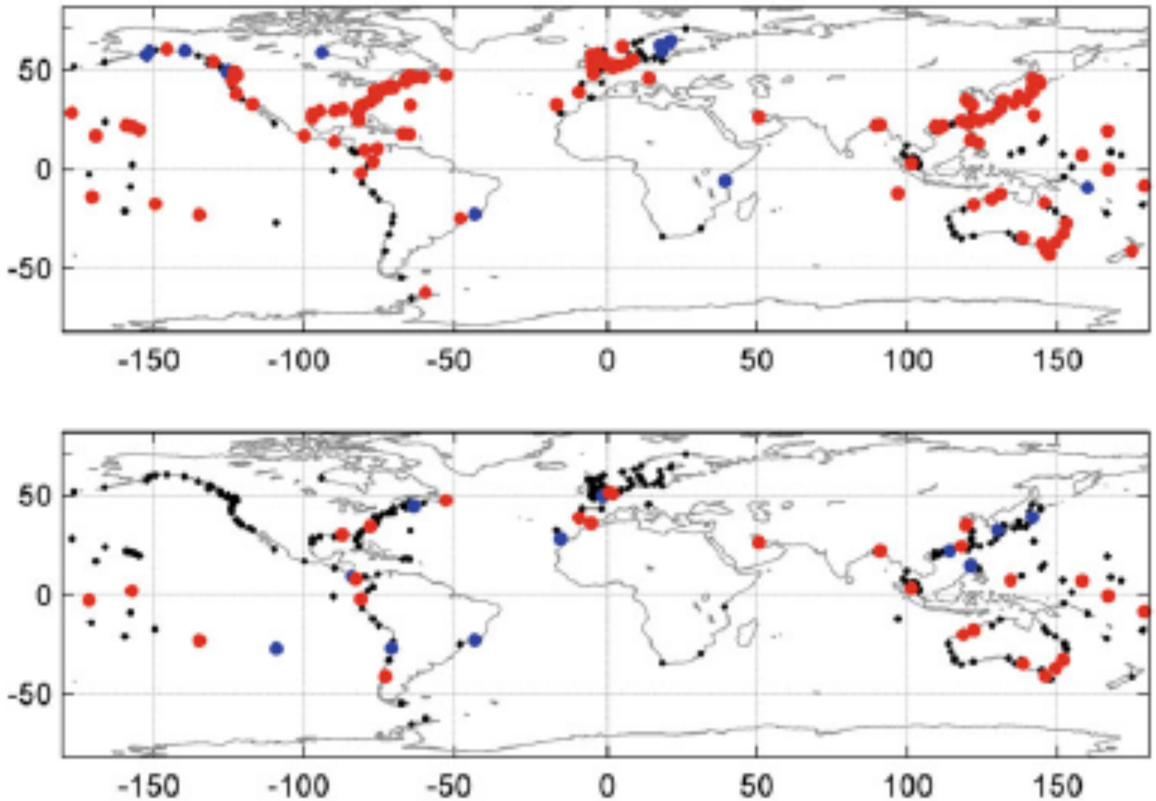


Fig. 8 Estimated trends in (*upper*) annual 99th percentile of sea level based on monthly maxima of hourly tide gauge readings from 1970 onwards, and (*lower*) 99th percentile after removal of the annual medians of hourly readings. Only trends significant at the 5 % level are shown in color: *red* for positive trends and *blue* for negative trends. Linear trends were estimated via least-squares regression taking the interannual perigean tidal influence into account (From Menéndez and Woodworth 2010). The figure shows that extreme sea levels have risen broadly, and that the dominate influence on that rise is from the increase in mean sea level

Source: Zwiers et al. 2013

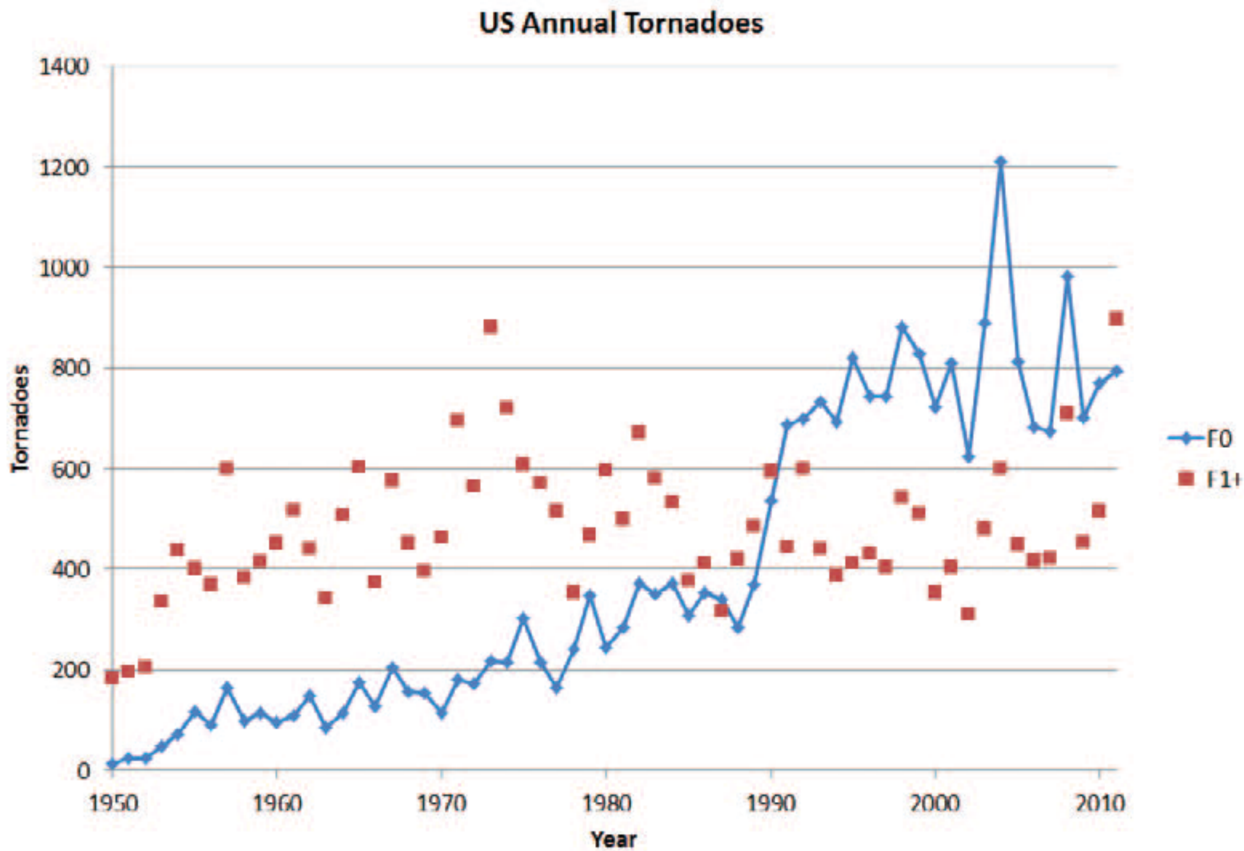
MONITORING AND UNDERSTANDING TRENDS IN EXTREME STORMS

State of Knowledge

BY KENNETH E. KUNKEL, THOMAS R. KARL, HAROLD BROOKS, JAMES KOSSIN, JAY H. LAWRIMORE, DEREK ARNDT, LANCE BOSART, DAVID CHANGNON, SUSAN L. CUTTER, NOLAN DOESKEN, KERRY EMANUEL, PAVEL YA. GROISMAN, RICHARD W. KATZ, THOMAS KNUTSON, JAMES O'BRIEN, CHRISTOPHER J. PACIOREK, THOMAS C. PETERSON, KELLY REDMOND, DAVID ROBINSON, JEFF TRAPP, RUSSELL VOSE, SCOTT WEAVER, MICHAEL WEHNER, KLAUS WOLTER, AND DONALD WUEBBLES

Review of the climate science for severe convective storms, extreme precipitation, hurricanes and typhoons, and severe snowstorms and ice storms shows that the ability to detect and attribute trends varies, depending on the phenomenon.

SOURCE: *Bull. Amer. Meteor. Soc.,* April 2013.



Reported tornadoes in US NWS database (1950-2011). Red is F1 and stronger.

SOURCE: Kunkel et al. BAMS 2013.

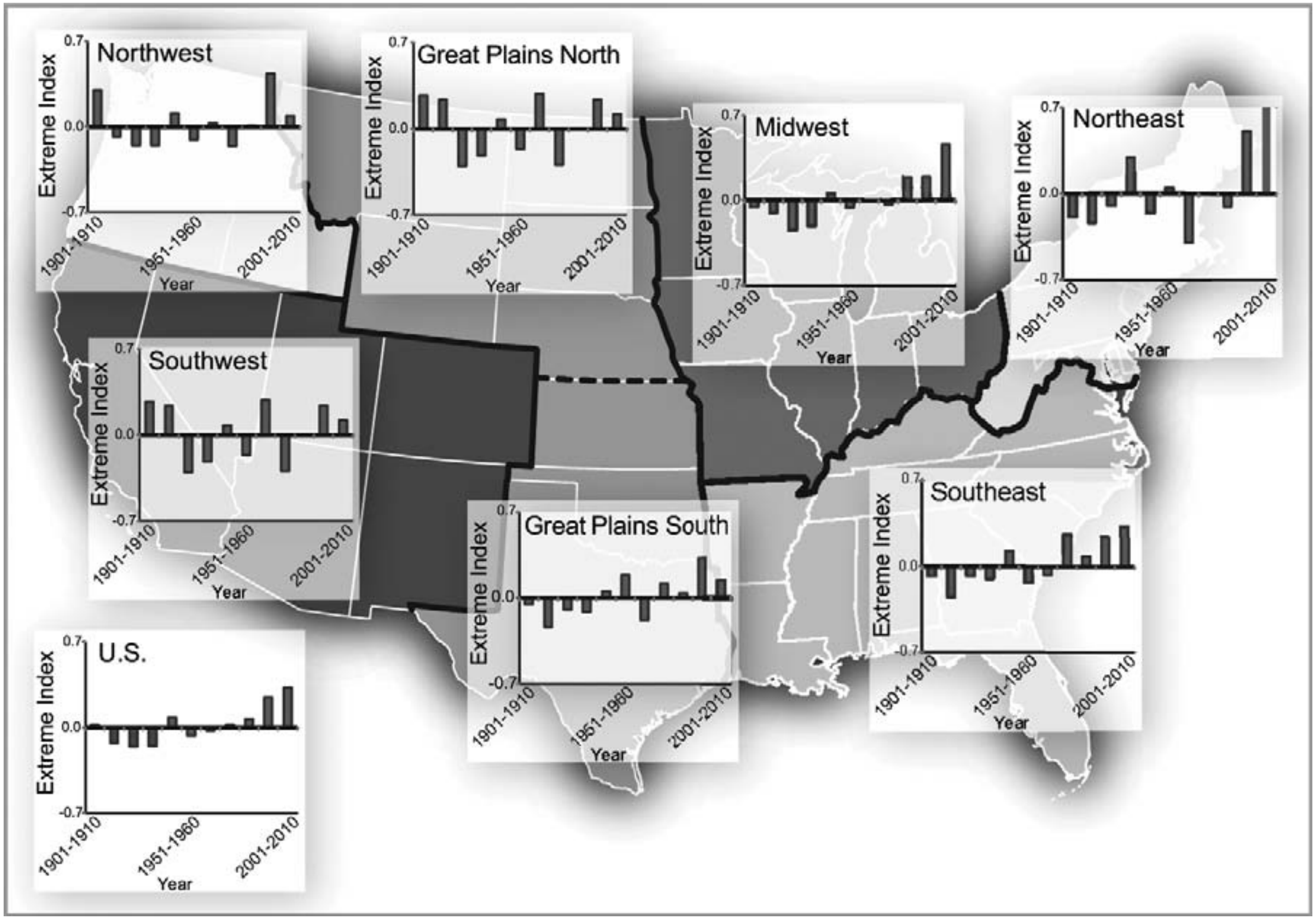


Fig. 3. Time series of decadal values of an index (standardized to 1) of the number of 2-day precipitation totals exceeding a threshold for a 1-in-5-yr occurrence for seven regions and the United States as a whole. This was based on an individual analysis of 930 long-term stations. Station time series of the annual number of events were gridded and then regional annual values were determined by averaging grid points within the region. Finally, the results were averaged over decadal periods. SOURCE: Kunkel et al. BAMS 2013.

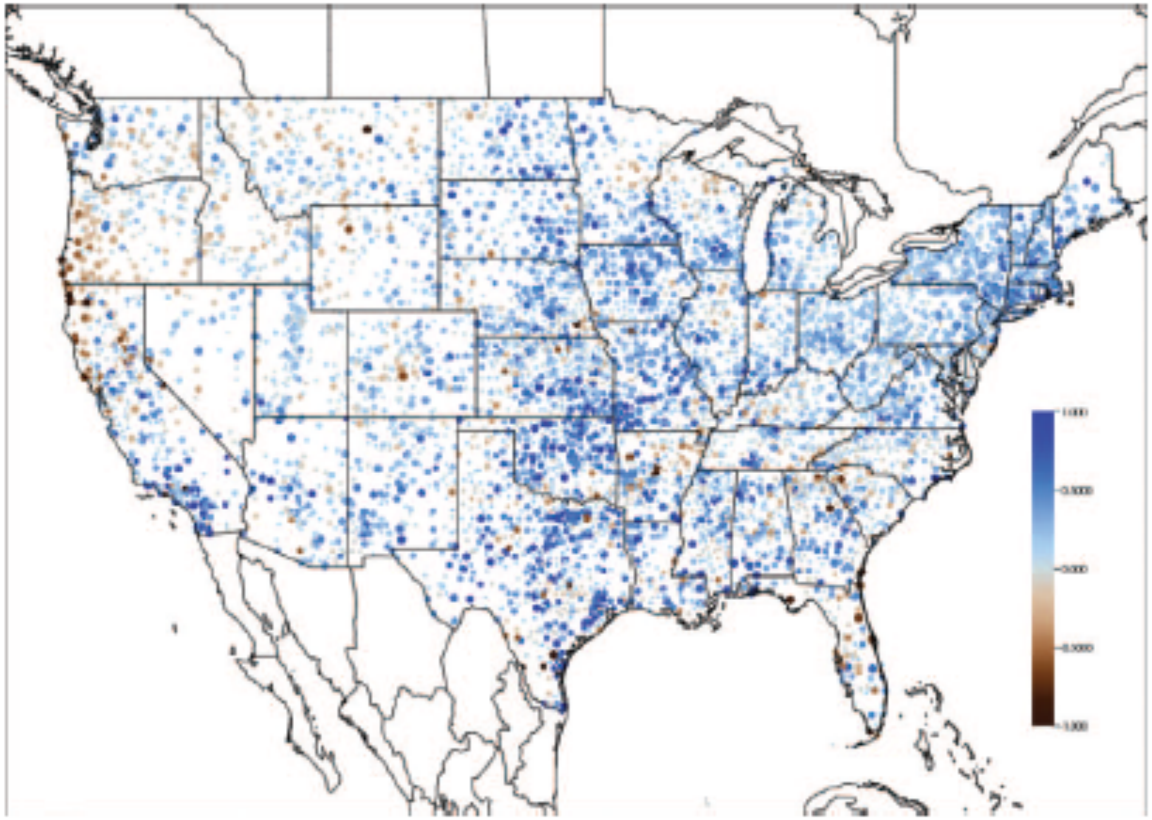
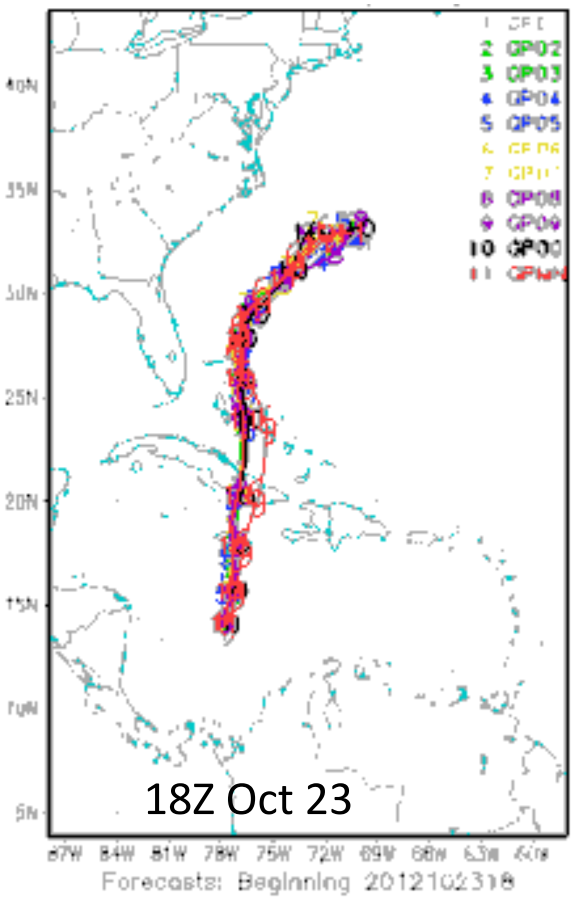


FIG. 4. Changes in observed 20-yr return value of the daily accumulated precipitation (in.) from 1948 to 2010. Only locations for which data from at least two-thirds of the days in the 1948–2010 period were recorded are included in this analysis. The change in the return value at each station is shown by a circle whose relative size portrays its statistical significance: the large circles indicate the z score (estimated change in the return value divided by its standard error) is greater than two in magnitude, medium circles indicate the z score is between one and two in magnitude, and the small circles indicate the z score is less than one in magnitude.

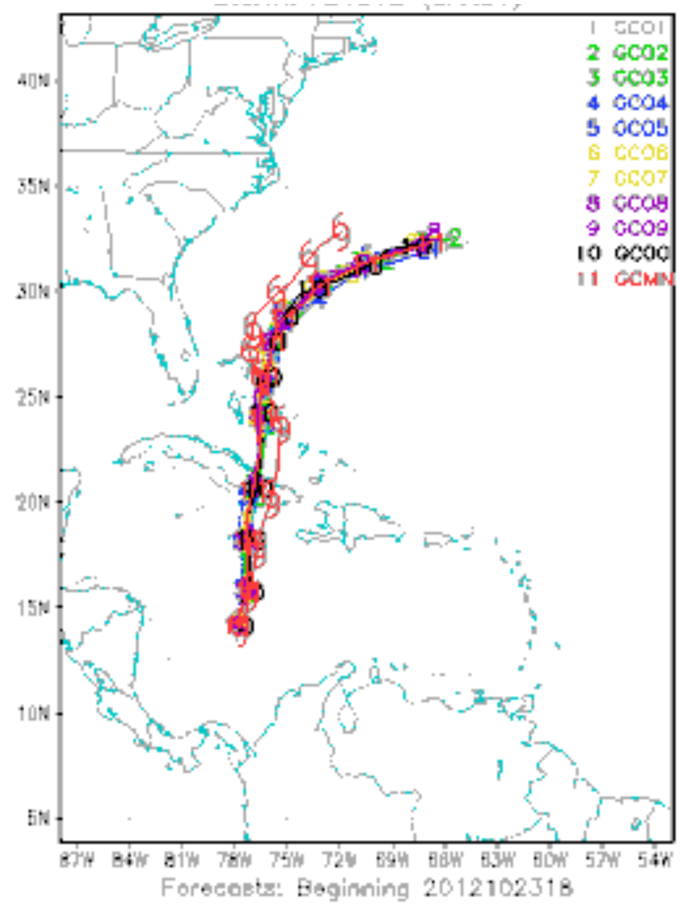
Source: Kunkel et al., BAMS, 2013

Climate Change Influence on Track of ‘Sandy-like’ storms

Present-Day

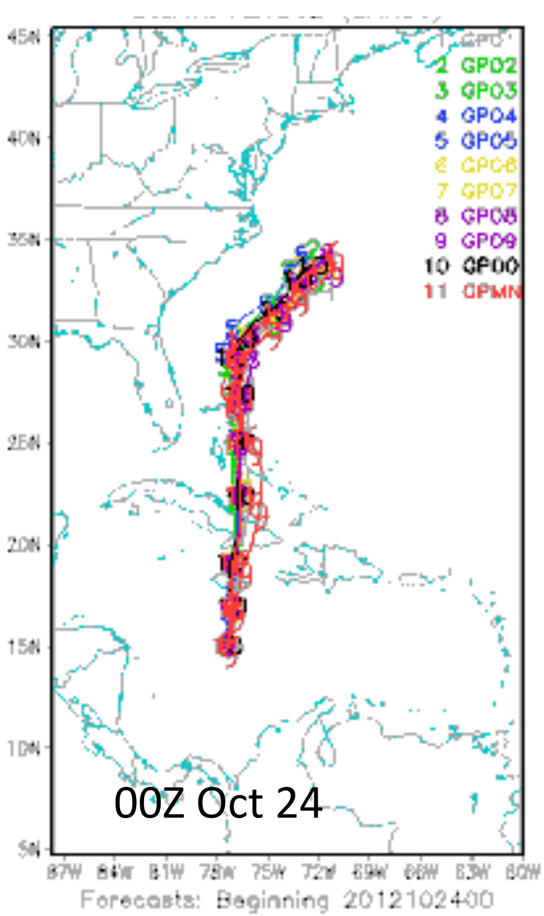


Pre-Industrial



Climate Change Influence on Track of 'Sandy-like' storms

Present-Day



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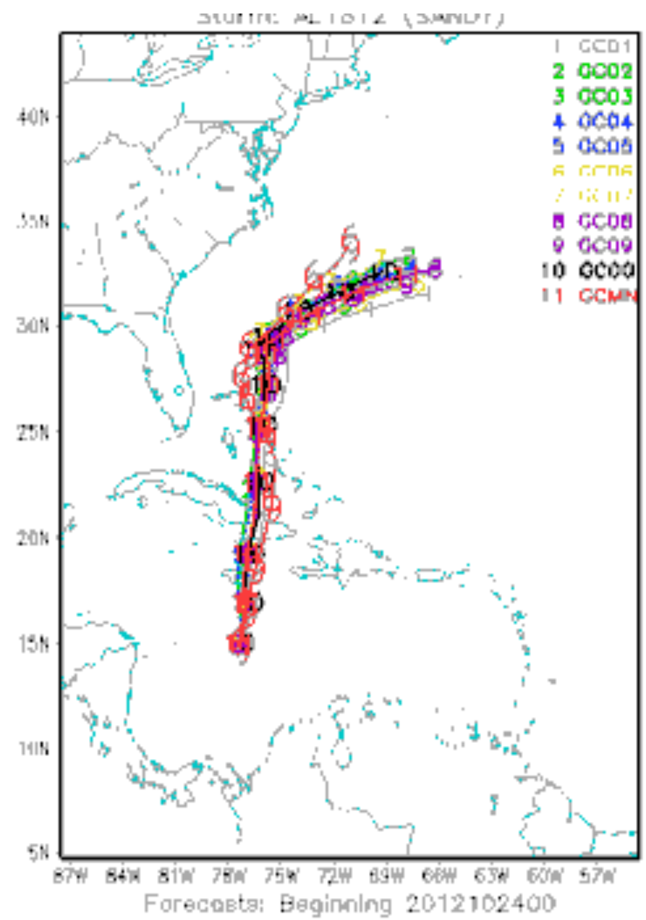
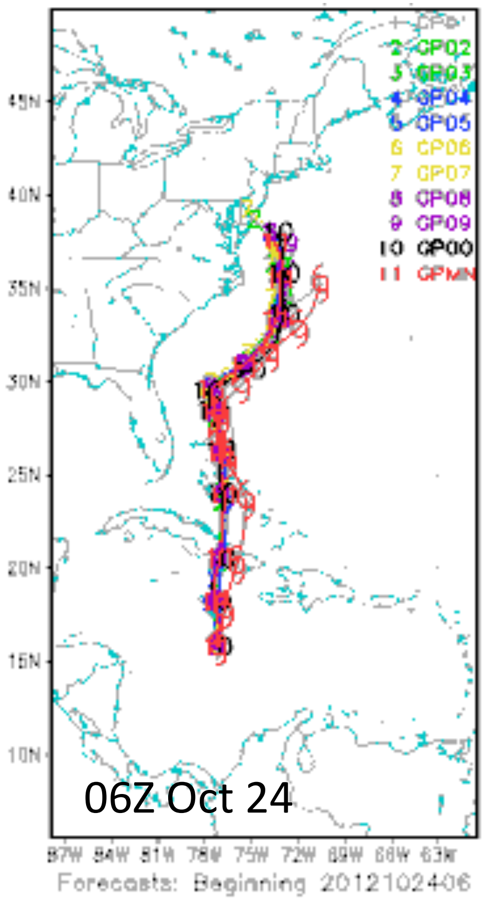


Climate Change Influence on Track of ‘Sandy-like’ storms

Present-Day



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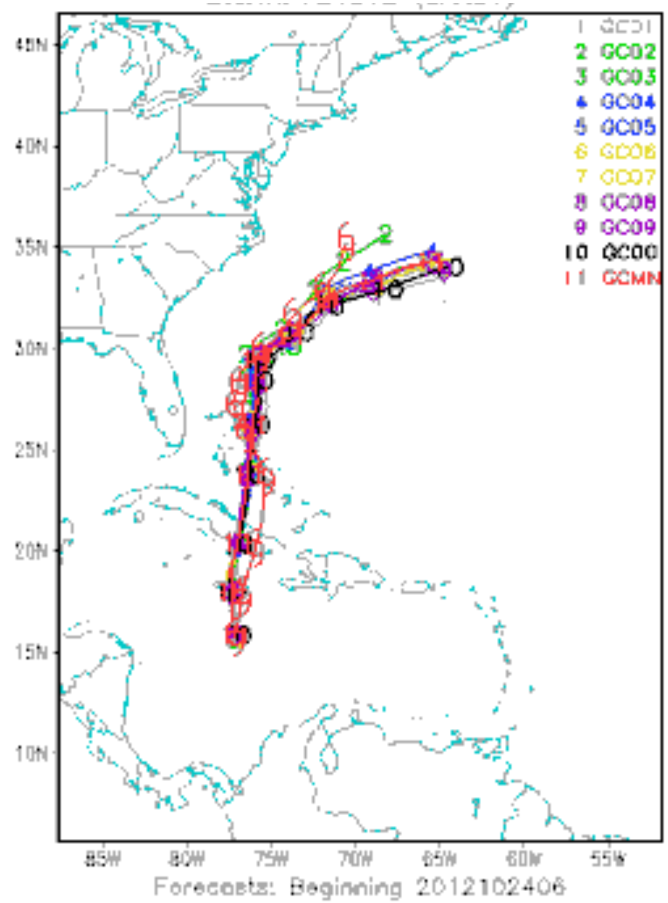
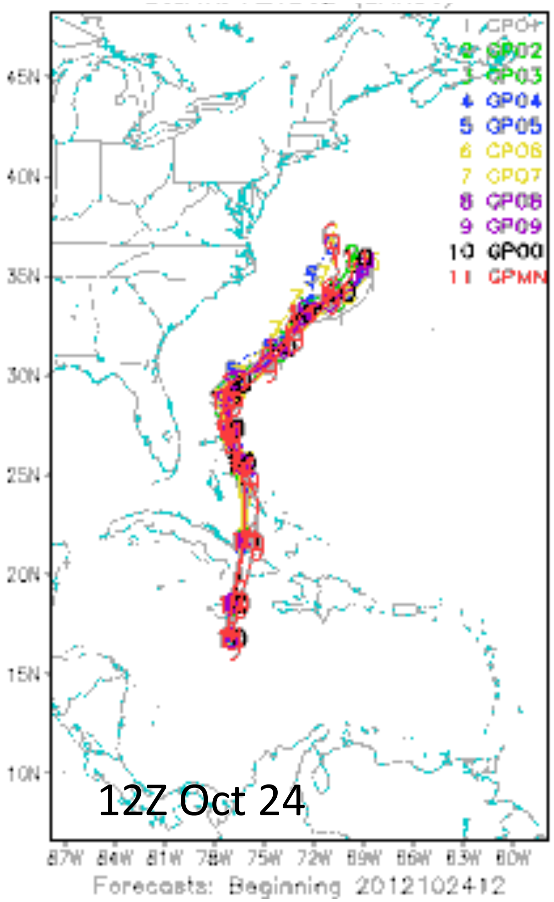
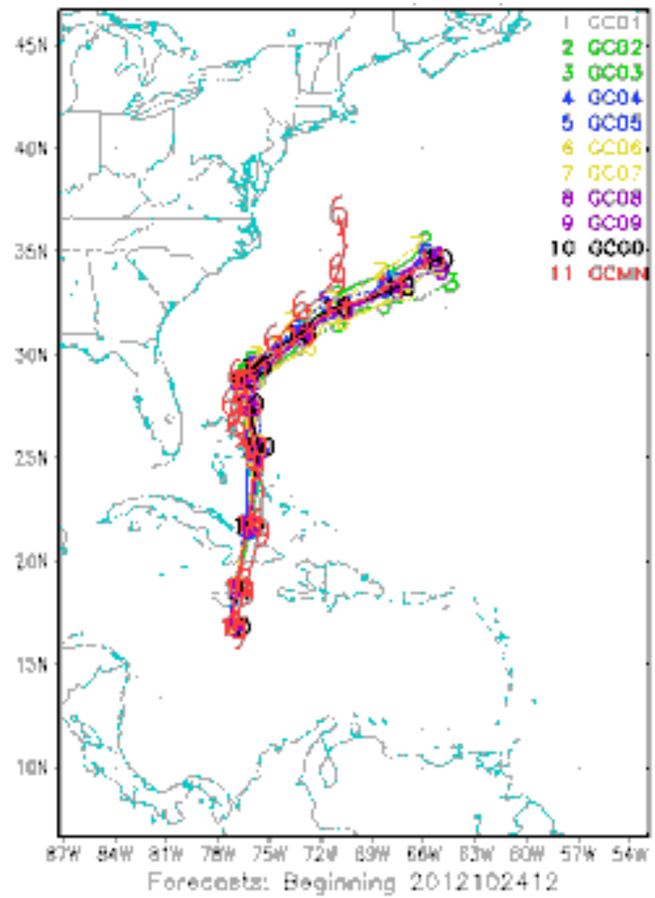


Climate Change Influence on Track of 'Sandy-like' storms

Present-Day

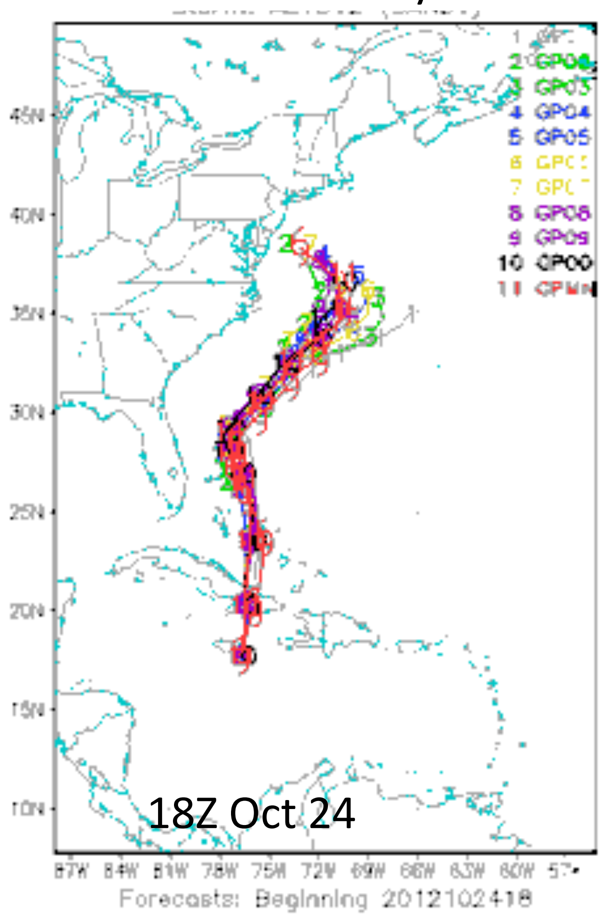


Pre-Industrial

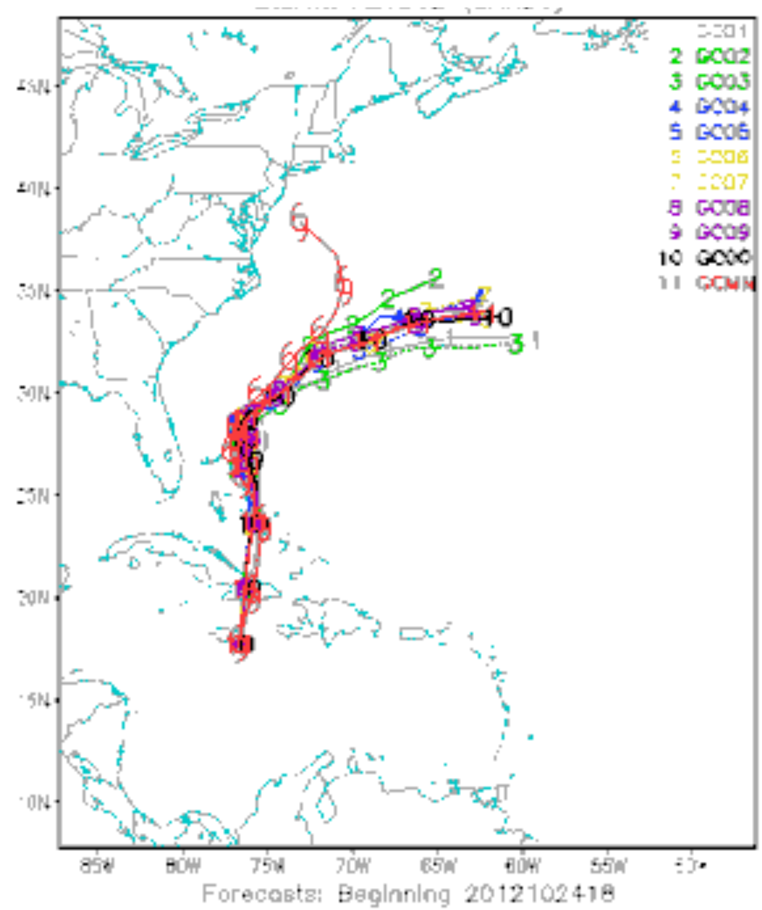


Climate Change Influence on Track of 'Sandy-like' storms

Present-Day

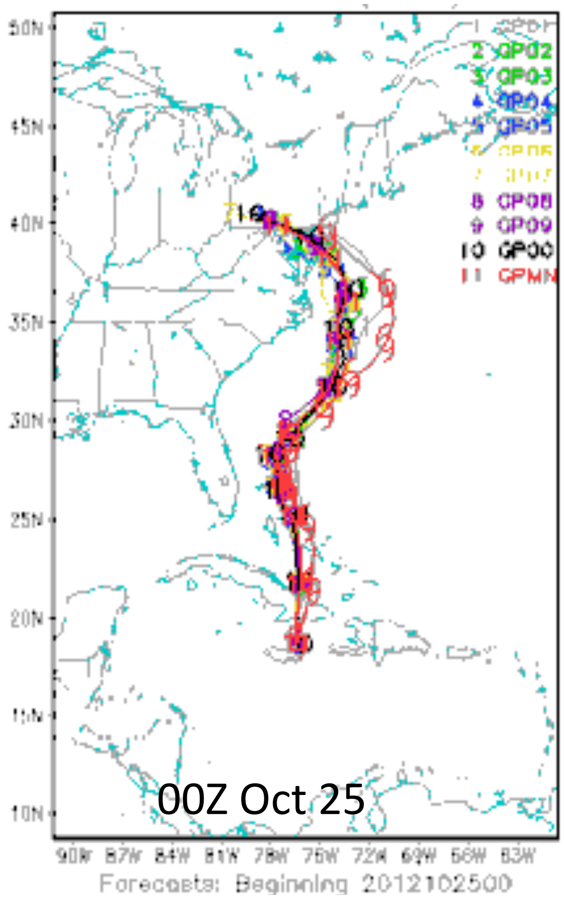


Pre-Industrial



Climate Change Influence on Track of 'Sandy-like' storms

Present-Day



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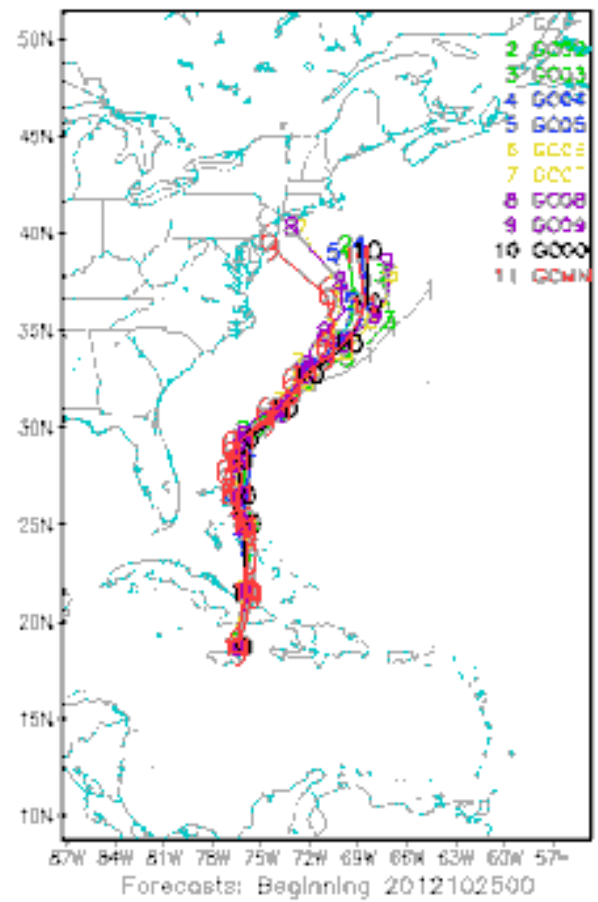
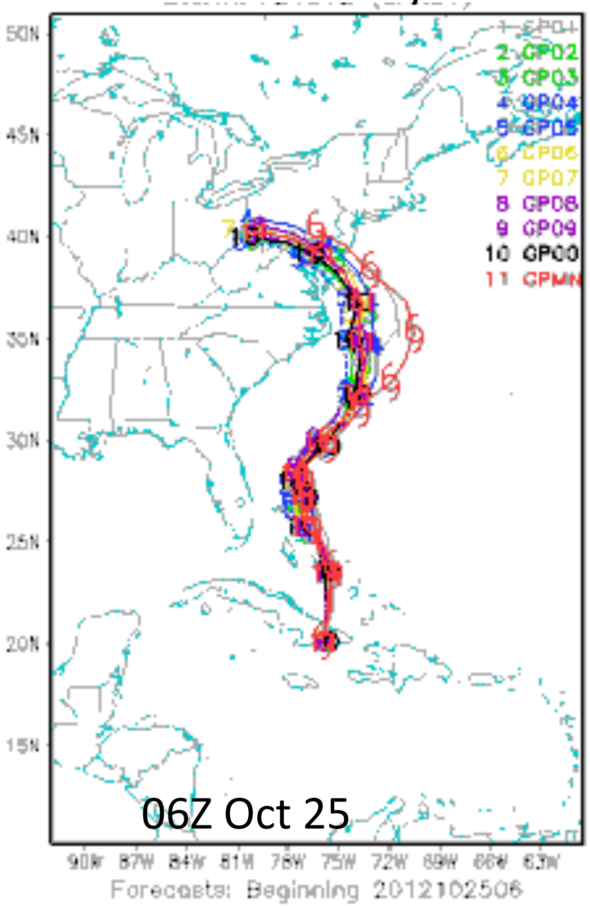


Climate Change Influence on Track of 'Sandy-like' storms

Present-Day



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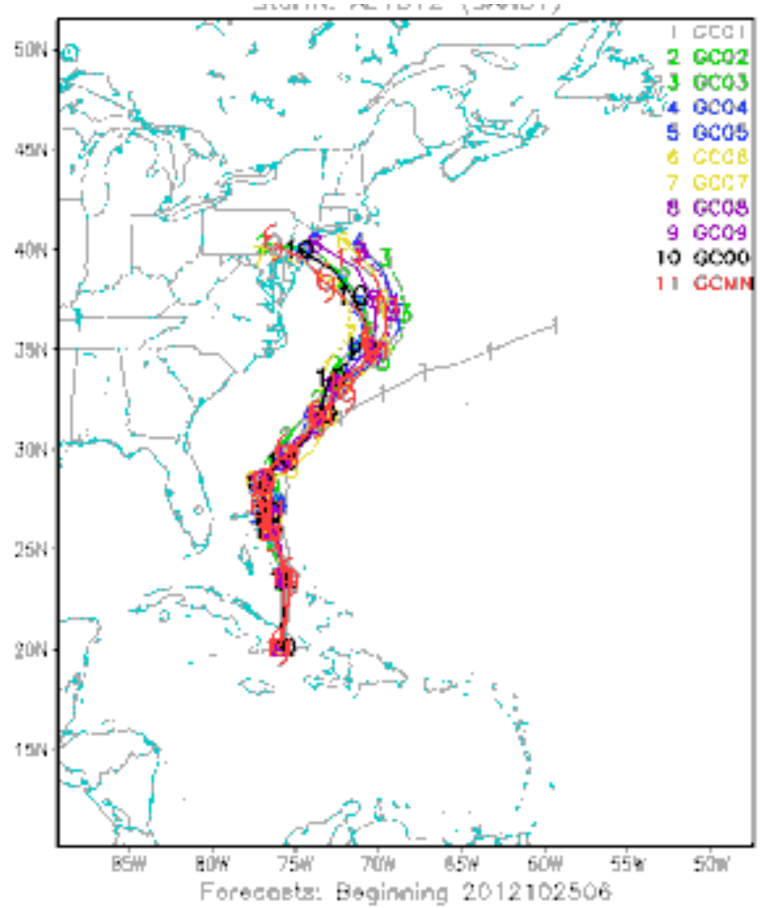
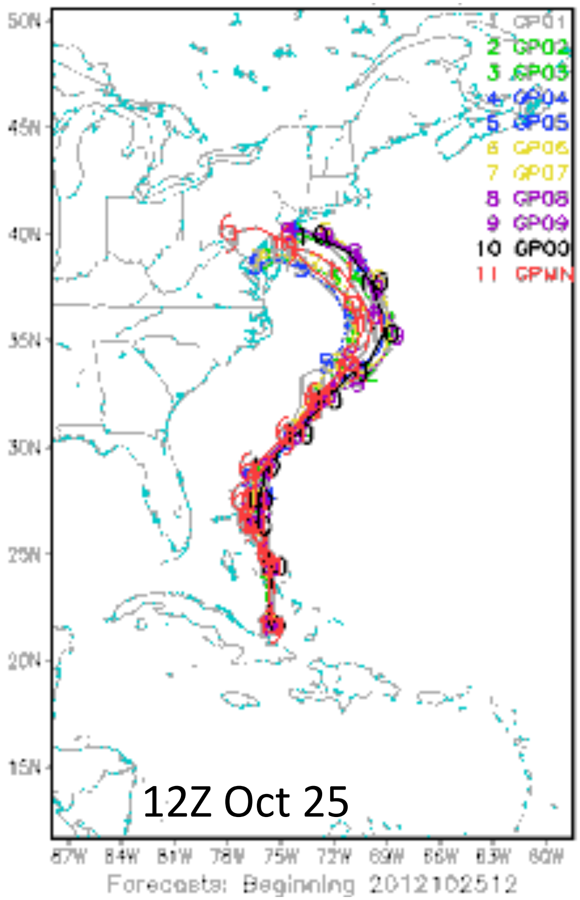


Climate Change Influence on Track of 'Sandy-like' storms

Present-Day



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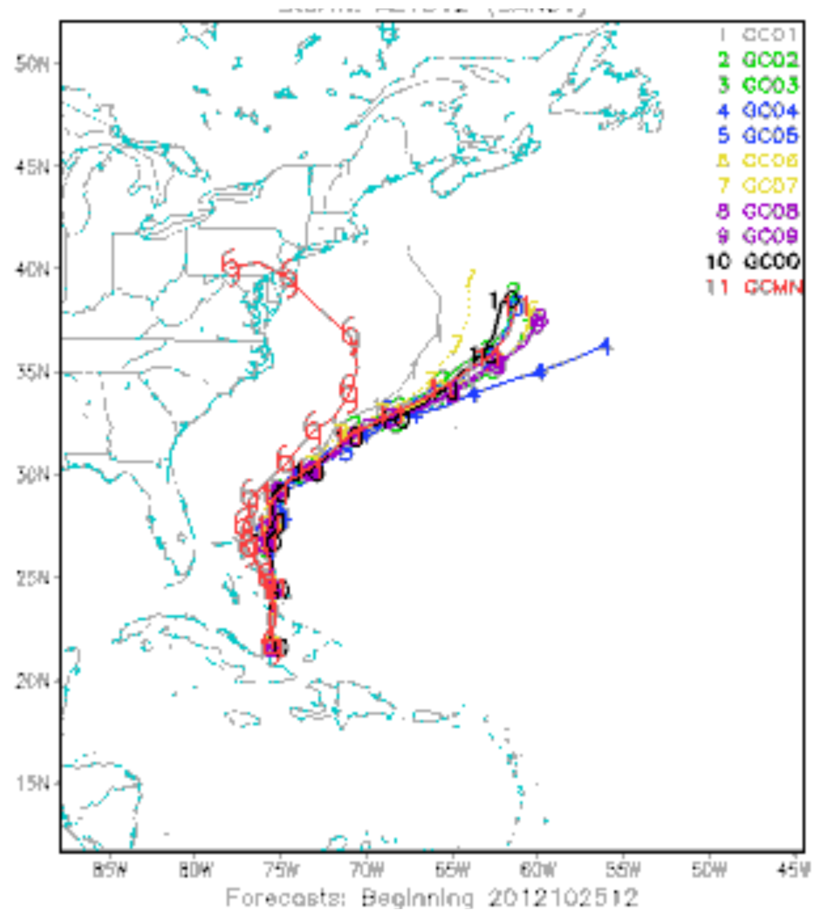
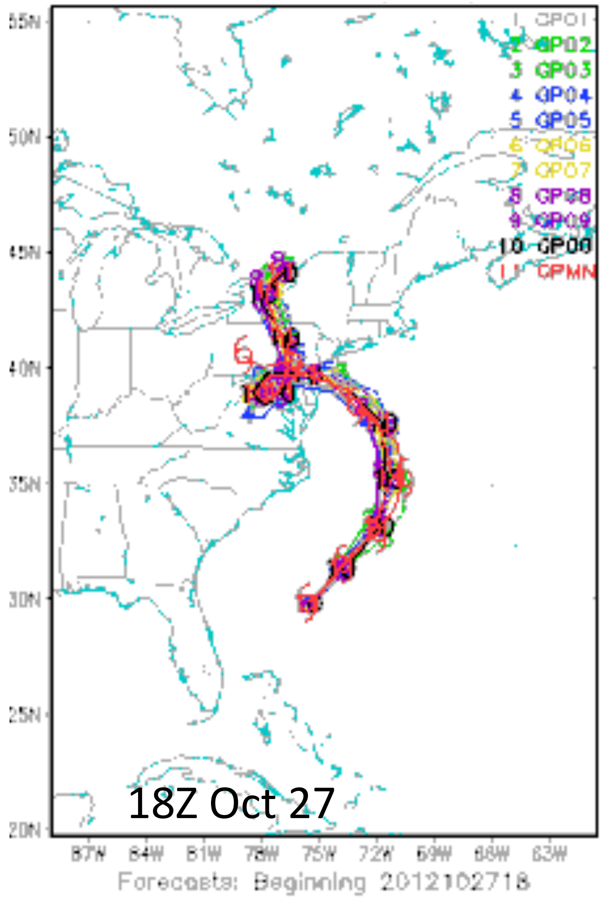


Climate Change Influence on Track of 'Sandy-like' storms

Present-Day



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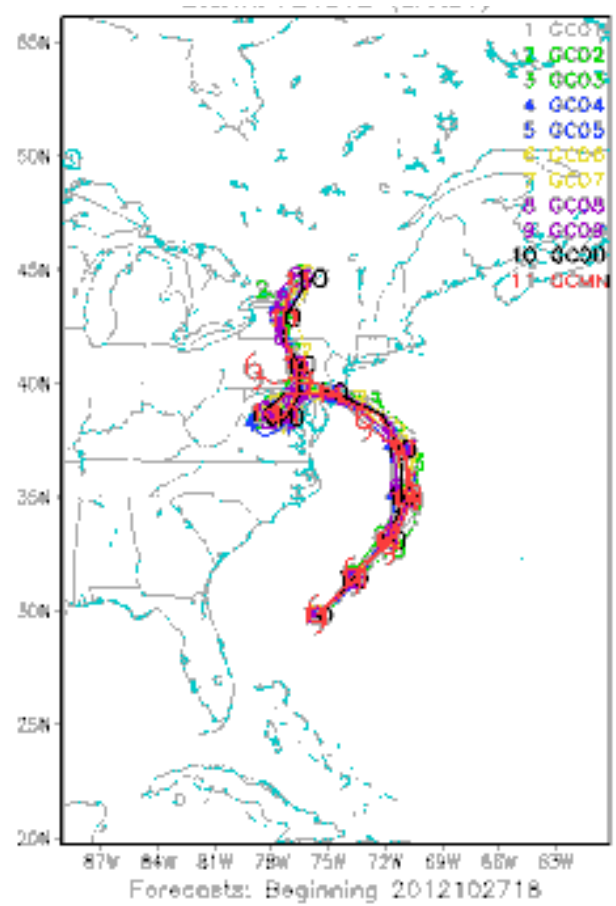

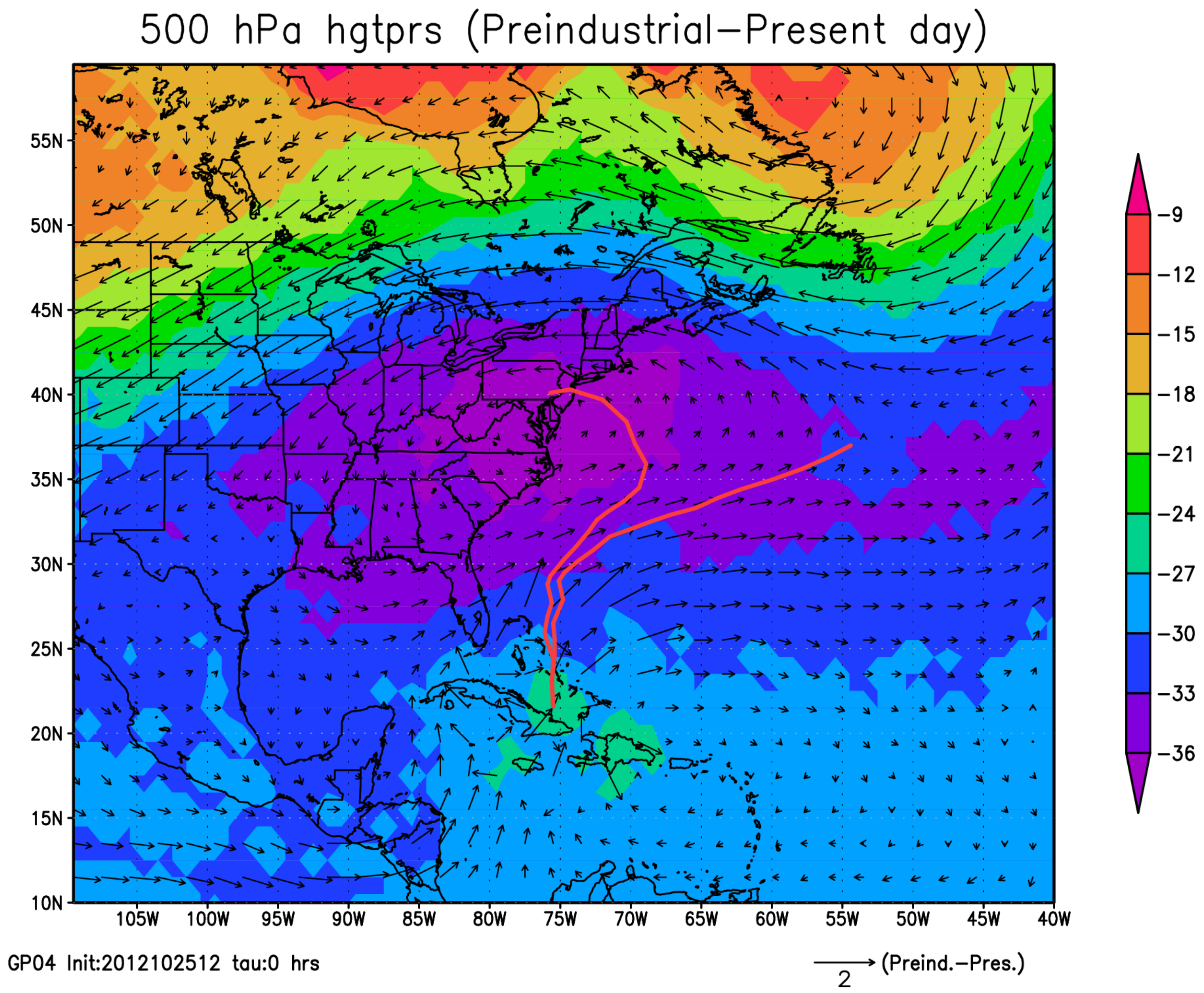
500 hPa hgtprs (Preindustrial−Present day)
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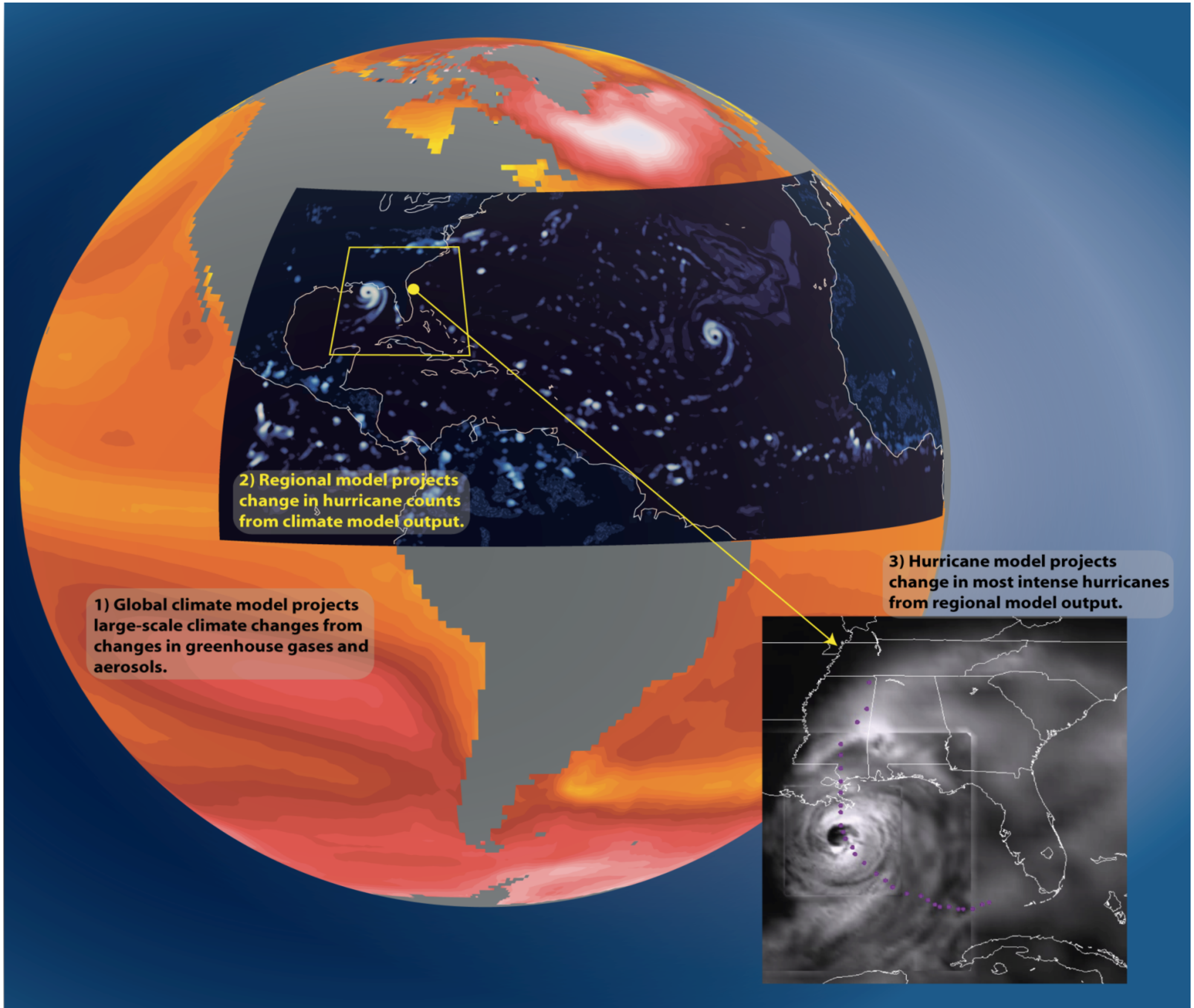
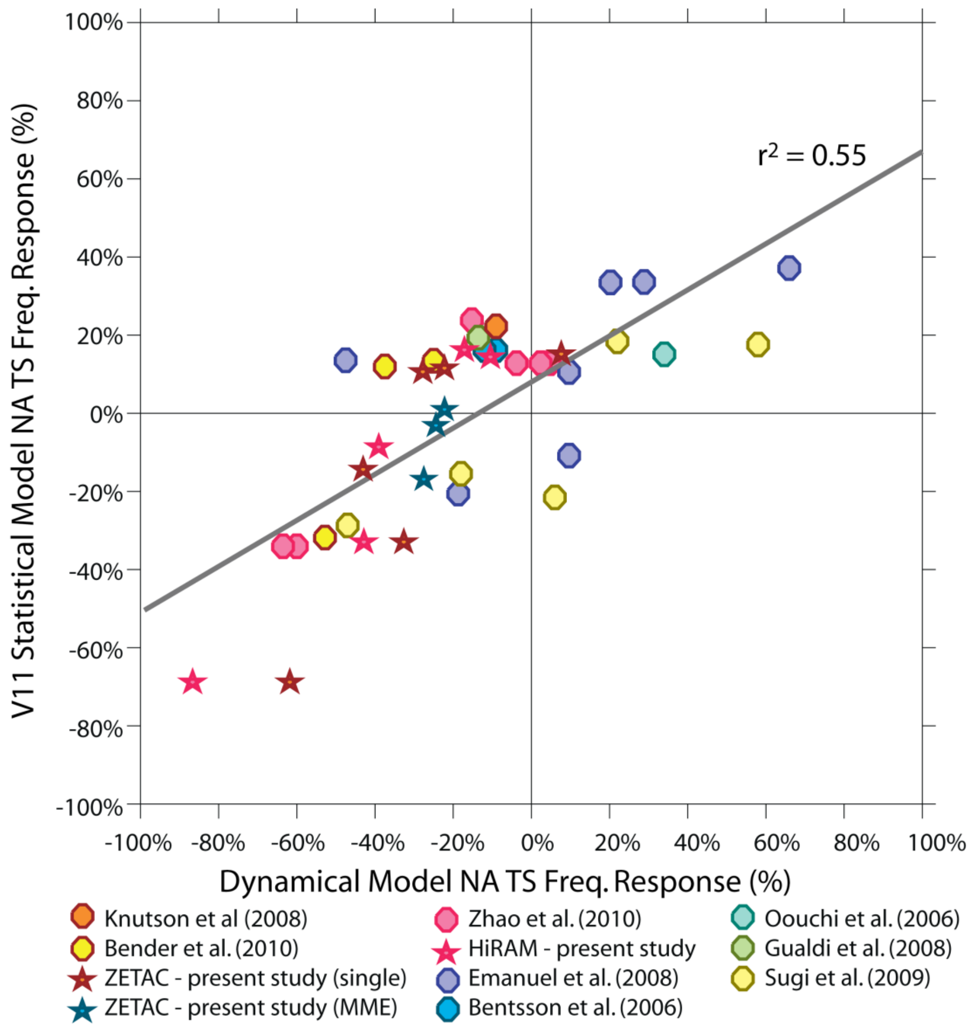
(Preind.−Pres.)

A “double-downscaling” approach for modeling the frequency of intense Atlantic hurricanes under late 21st century climate conditions.

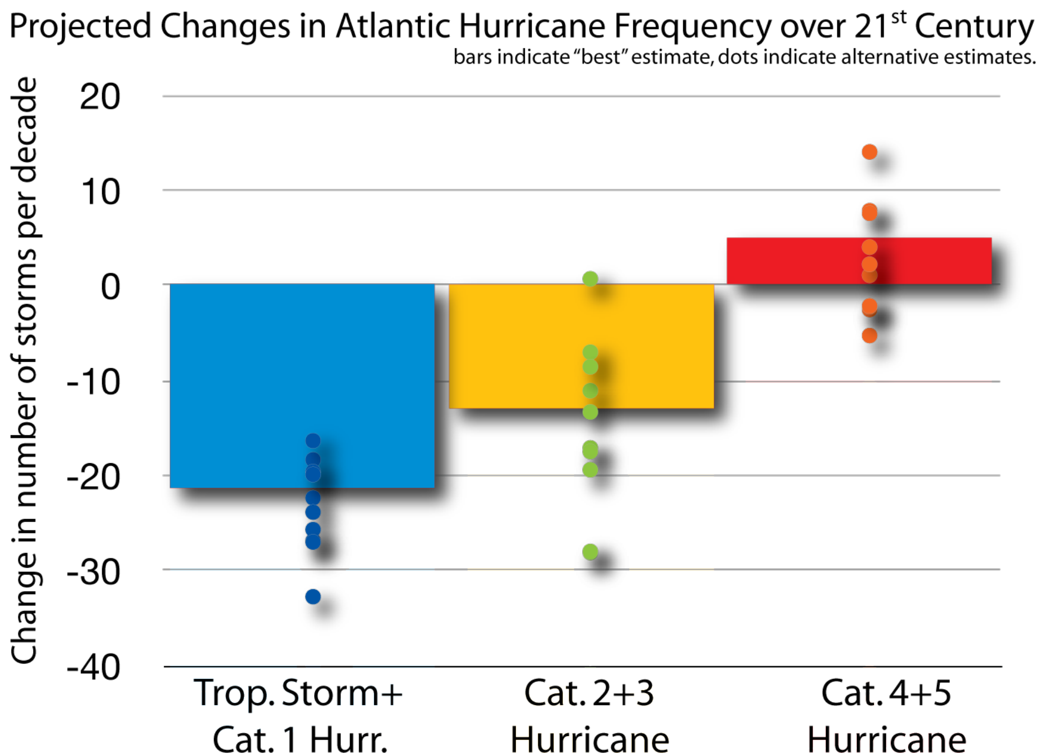


Relative SST-based statistical model describes Atlantic basin projected tropical storm changes fairly well:



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

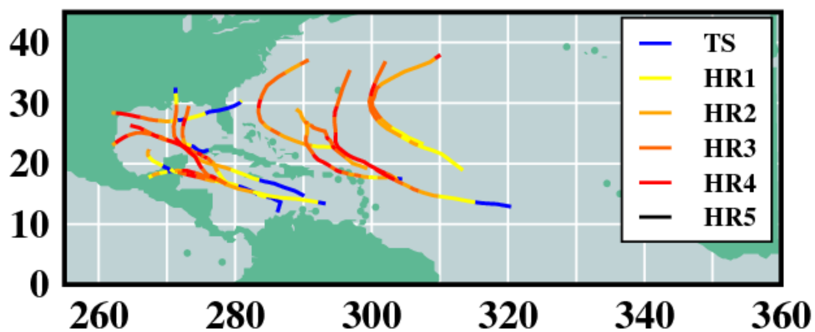
Summary of Atlantic Tropical Cyclone Projections over the 21st Century (CMIP3)



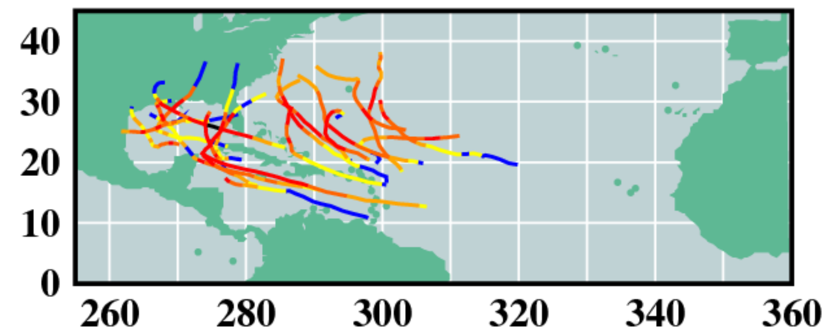
Adapted from Knutson et al. (2013, J. Clim.). See also: Knutson et al. (2009), Zhao et al. (2009), Bender et al. (2010), Villarini et al. (2011), Villarini and Vecchi (2012, 2013)

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

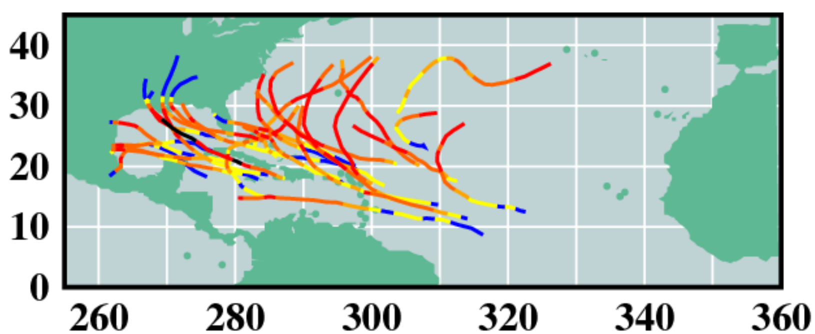
Present-Day (1980-2006): 14 storms



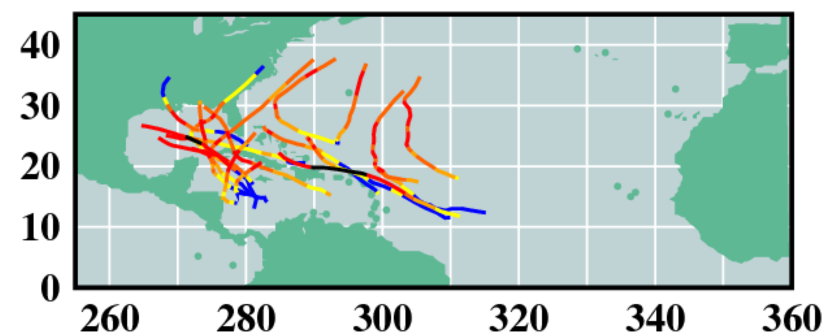
CMIP5 (Early 21st Century): 20 storms



CMIP3 (Late 21st Century): 28 storms



CMIP5 (Late 21st Century): 19 storms

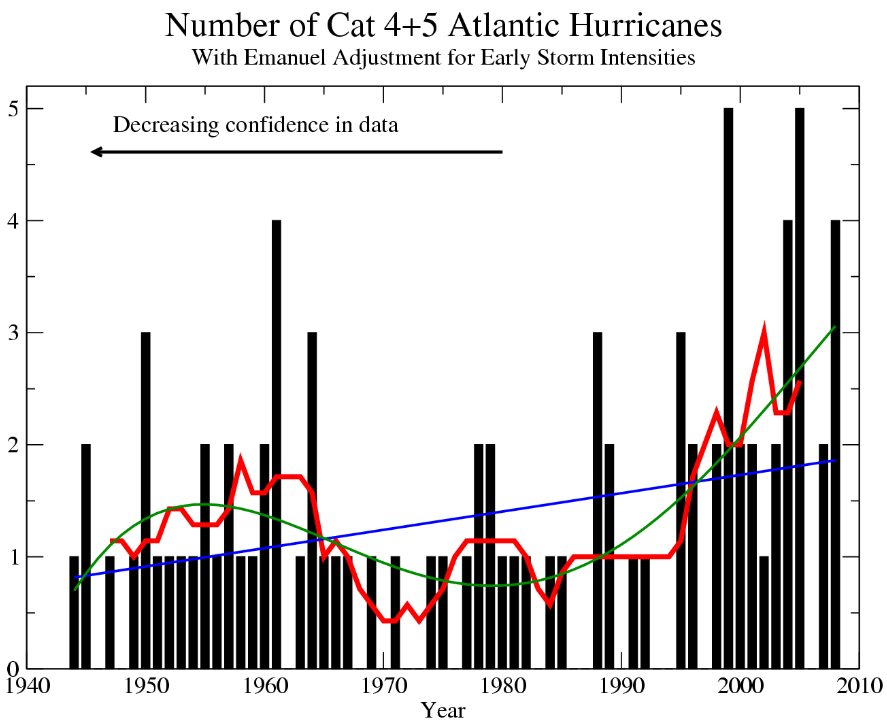


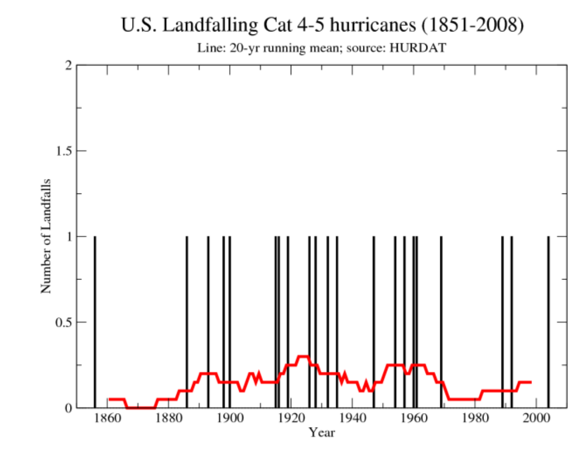
Source: Knutson et al. (J. Climate, 2013).

<u>Emergence Time Scale</u>: If the observed Cat 4+5 data since 1944 represents the noise (e.g. through bootstrap resampling), how long would it take for a trend of ~10% per decade in Cat 4+5 frequency to emerge from noise?
Answer: **~60 yr** (by then 95% of cases are positive)

Instead, assume residuals from a 4^{th} order polynomial: **55 yr**

Instead, resample chunks of length 3-7 yr: **65-70 yr**



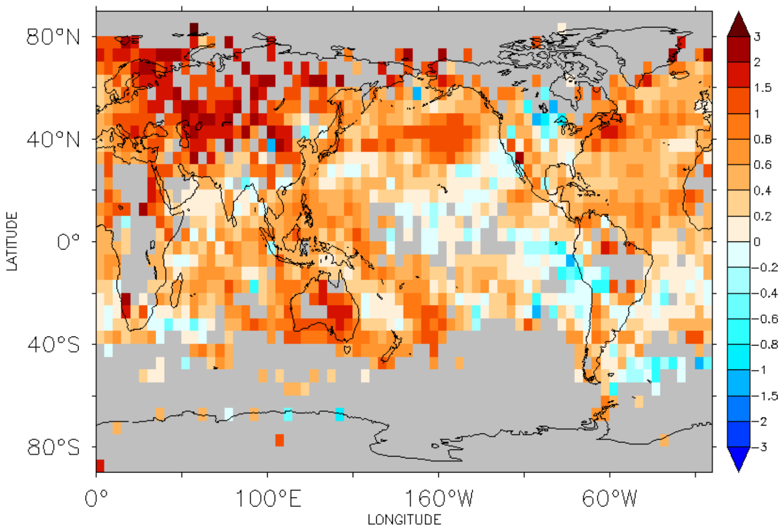


Source: Bender et al., *Science*, 2010.

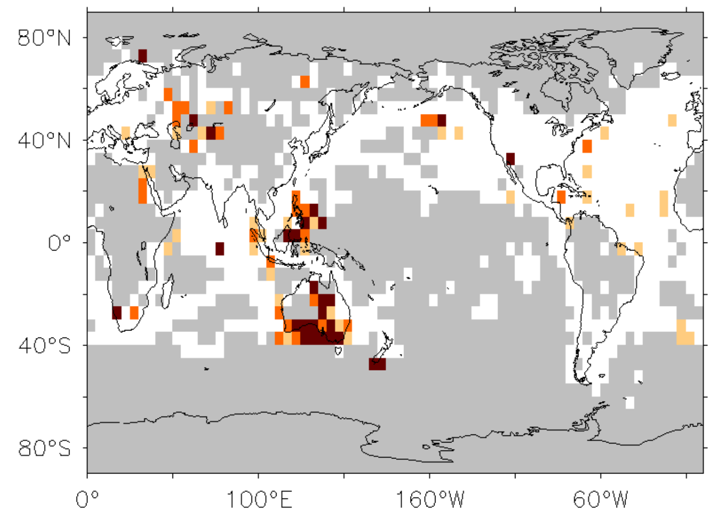
Explaining Extreme Events from a Climate Perspective…

Surface temperature: annual-mean extremes for 2013

Annual 2013 anomalies



Annual means: 2013 extremes



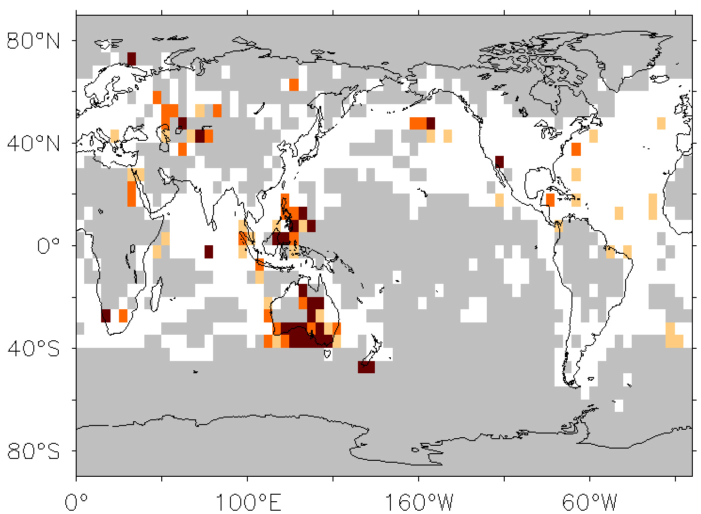
Map Legend:
(and percent coverage by category)

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:
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Highest	(3.0%)
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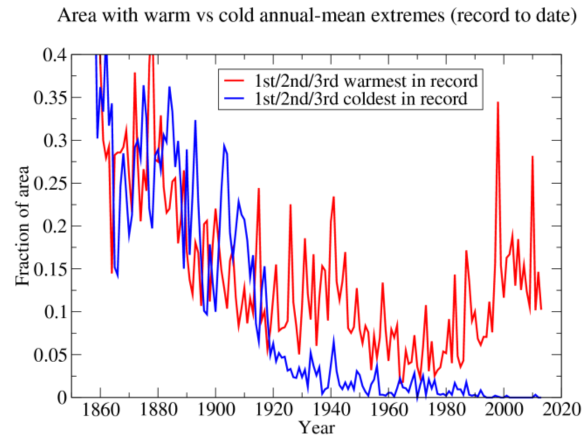
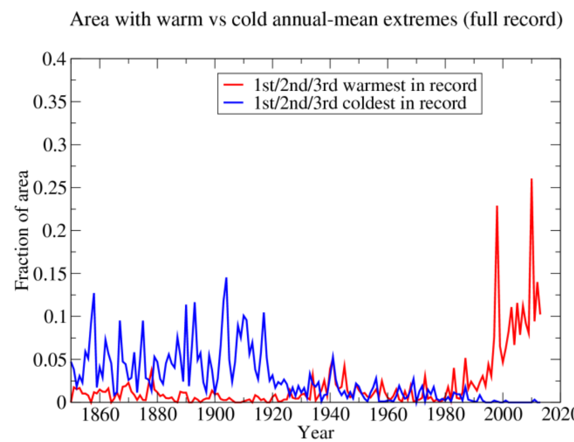
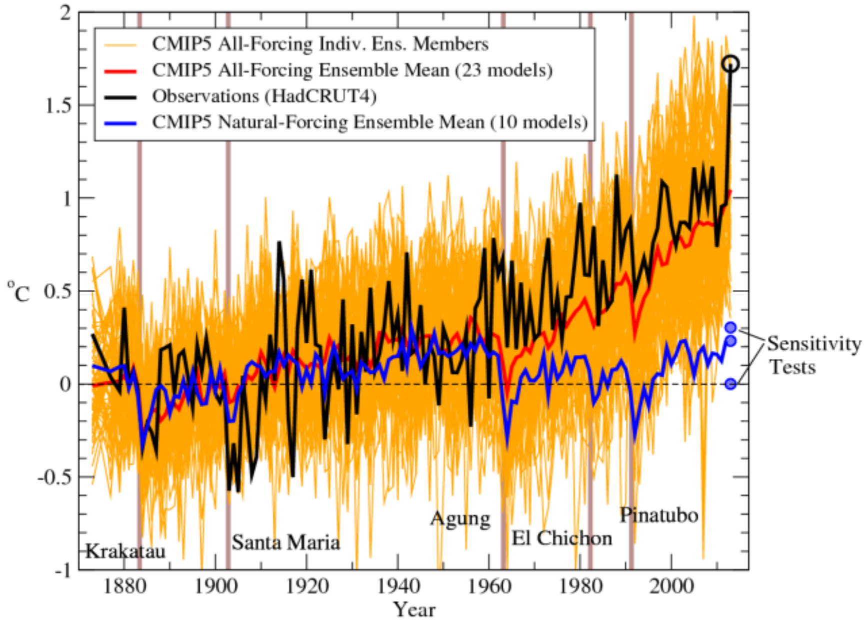


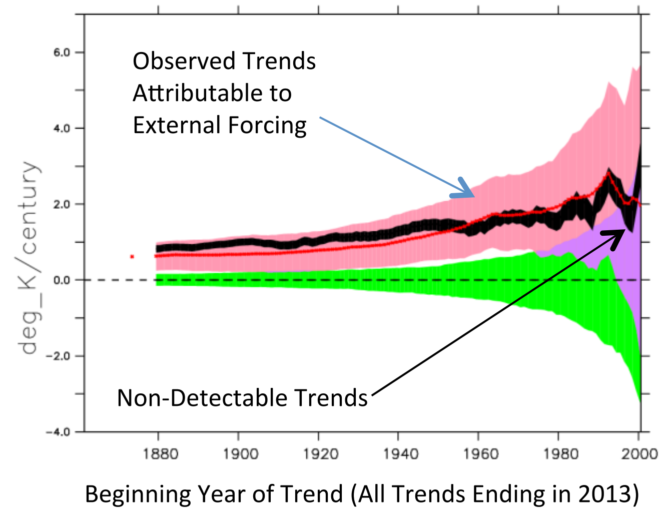


Source: Knutson, Zeng, and Wittenberg, *BAMS,* accepted (2014)

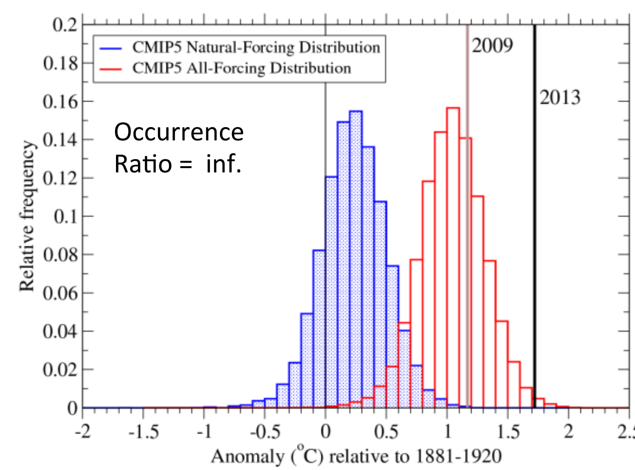
Australia Region: Annual Temperatures

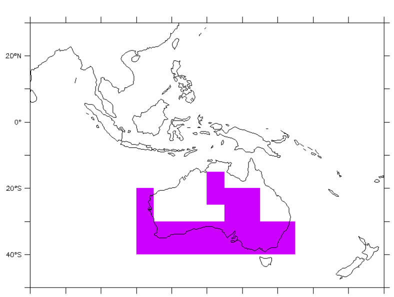


Sliding Trend Analysis



Attributable Risk Analysis

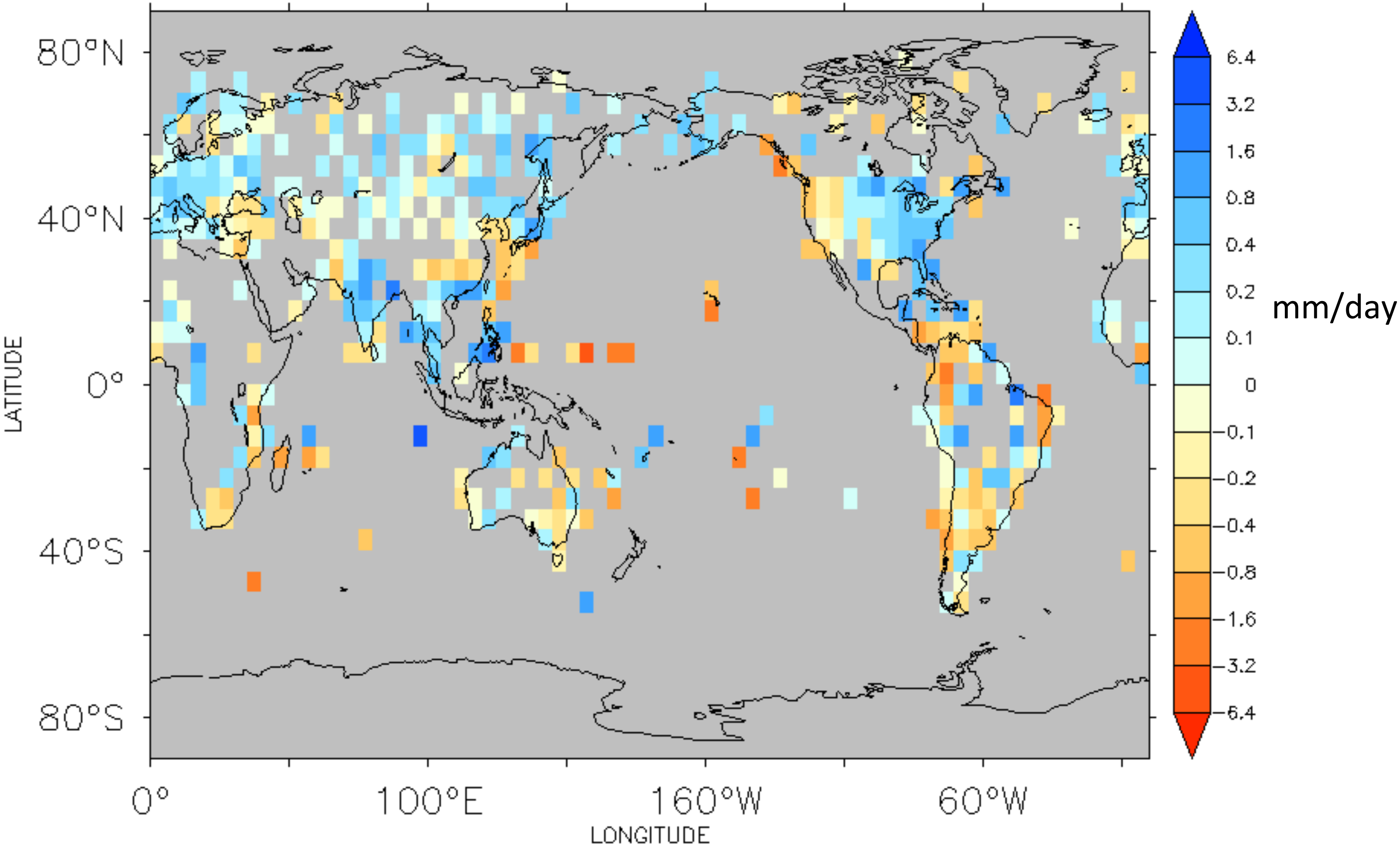




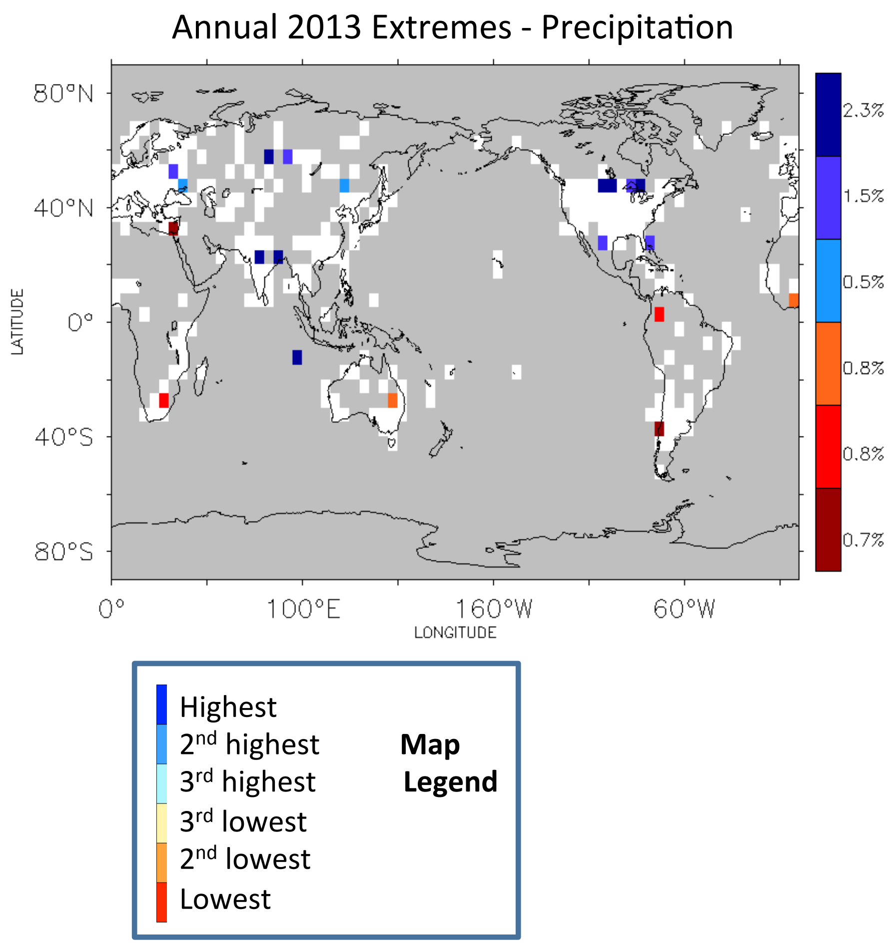
$$\text{Ratio} = \frac{p_{ALL}}{p_{NAT}}$$

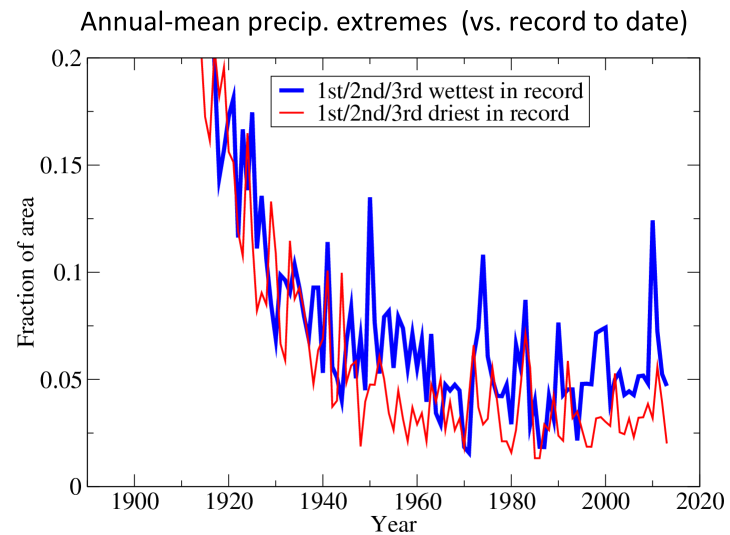
p_{ALL} and p_{NAT} : probabilities of exceeding the threshold in the All Forcing and Natural distributions.
Source: Knutson, Zeng, and Wittenberg, *BAMS,* accepted (2014)

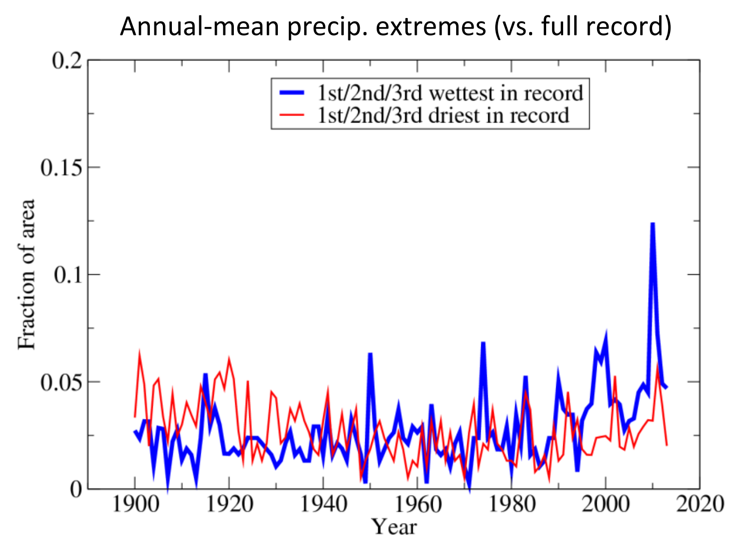
Annual Mean Precipitation Extremes for 2013 (100 yrs+ of record)



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



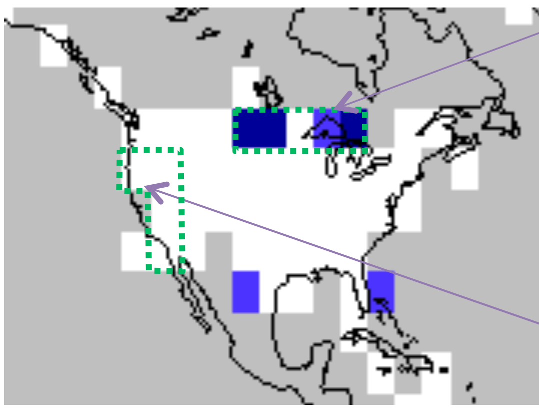




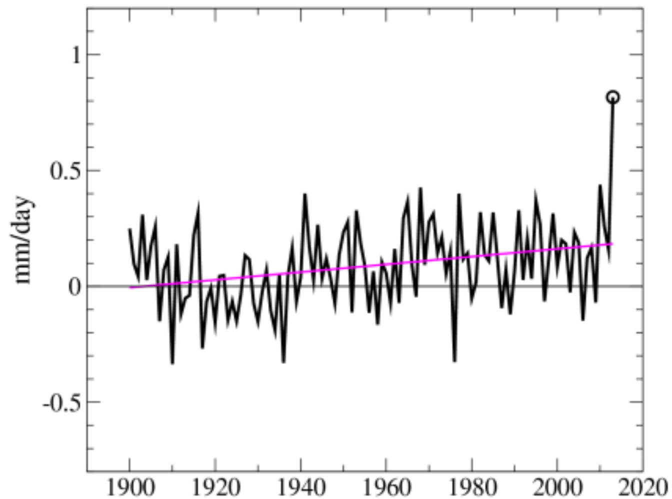
Source: Knutson, Zeng, and Wittenberg, *BAMS* accepted (2014)

2013 Annual Mean Precipitation Extremes: Climate Perspective

Annual 2013 Extremes - Precipitation

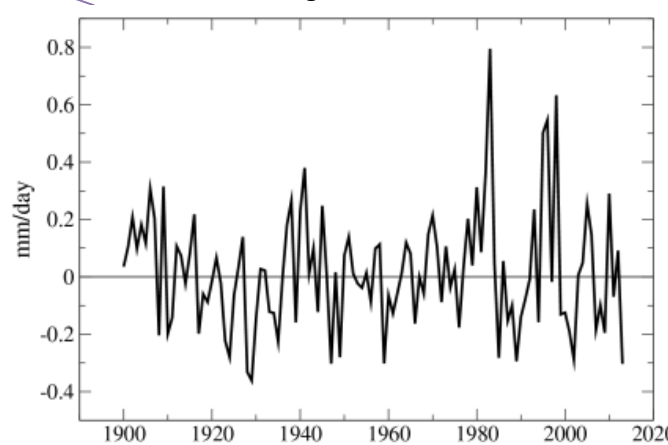


U.S./Canadian border region: annual means



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

California region: annual means



California region -- ANN:
Non-significant trend

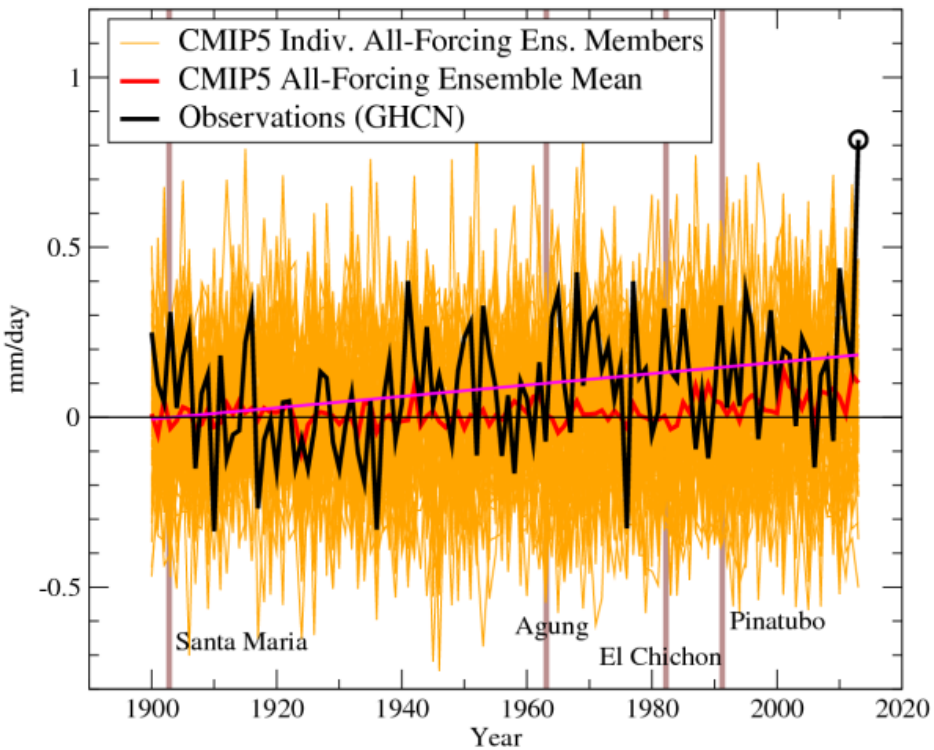
Map Legend

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

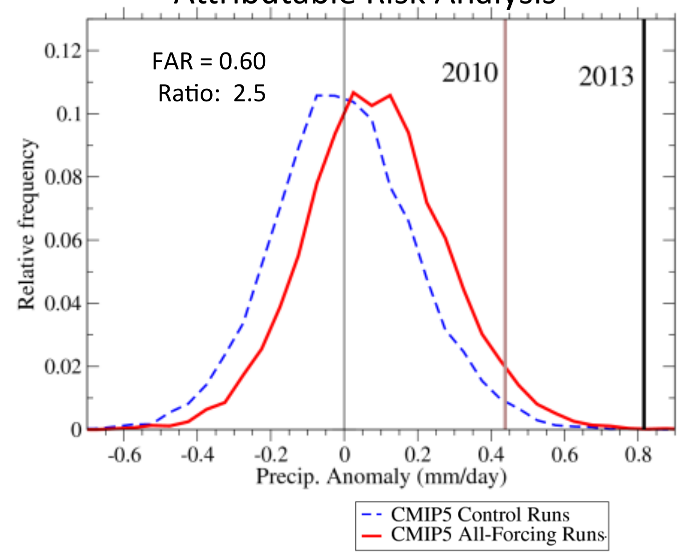
Source: Knutson, Zeng, and Wittenberg, *BAMS* accepted (2014)

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)

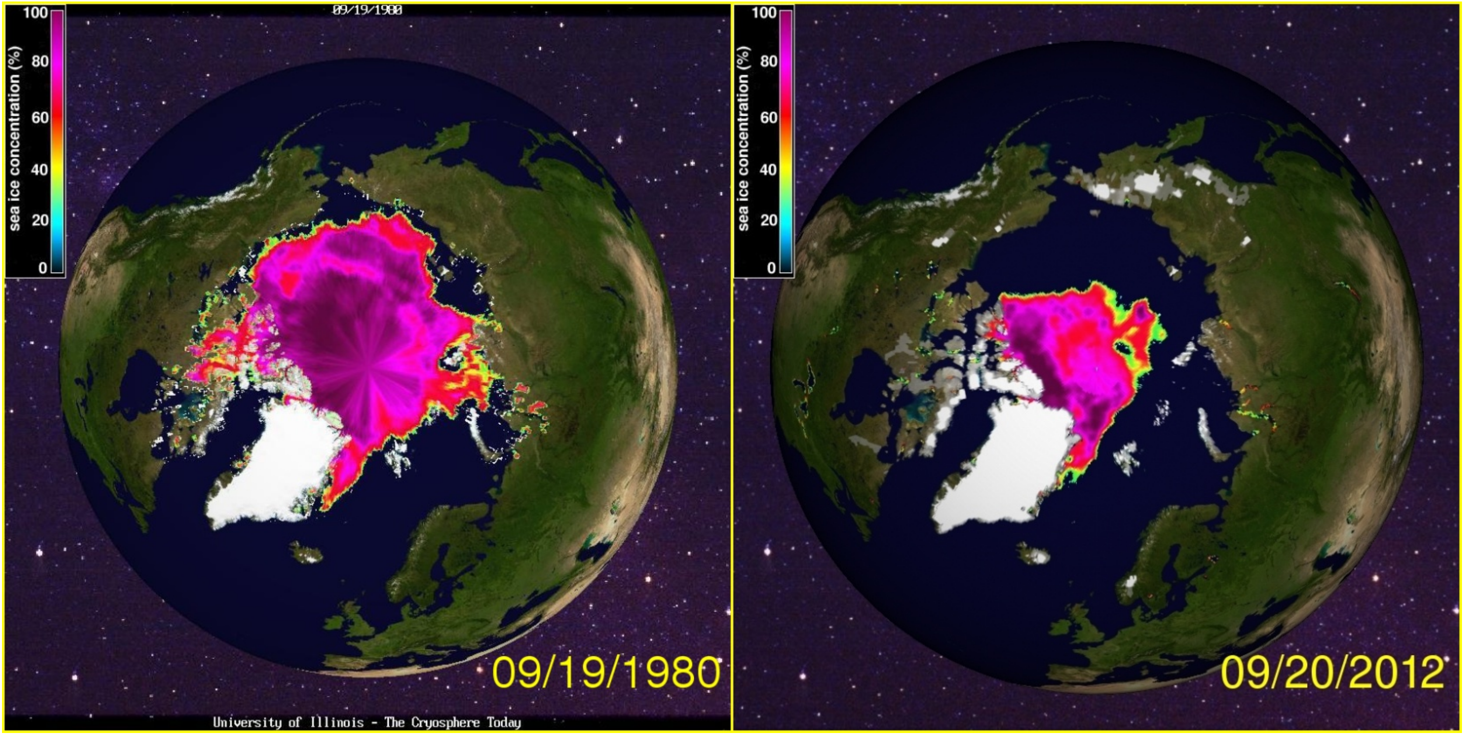
Remaining Challenges to these Analyses

- limitations to historical data length, data quality, model ensemble size, and model control run length

- important underlying question of how well current models simulate internal (intrinsic) climate variability.

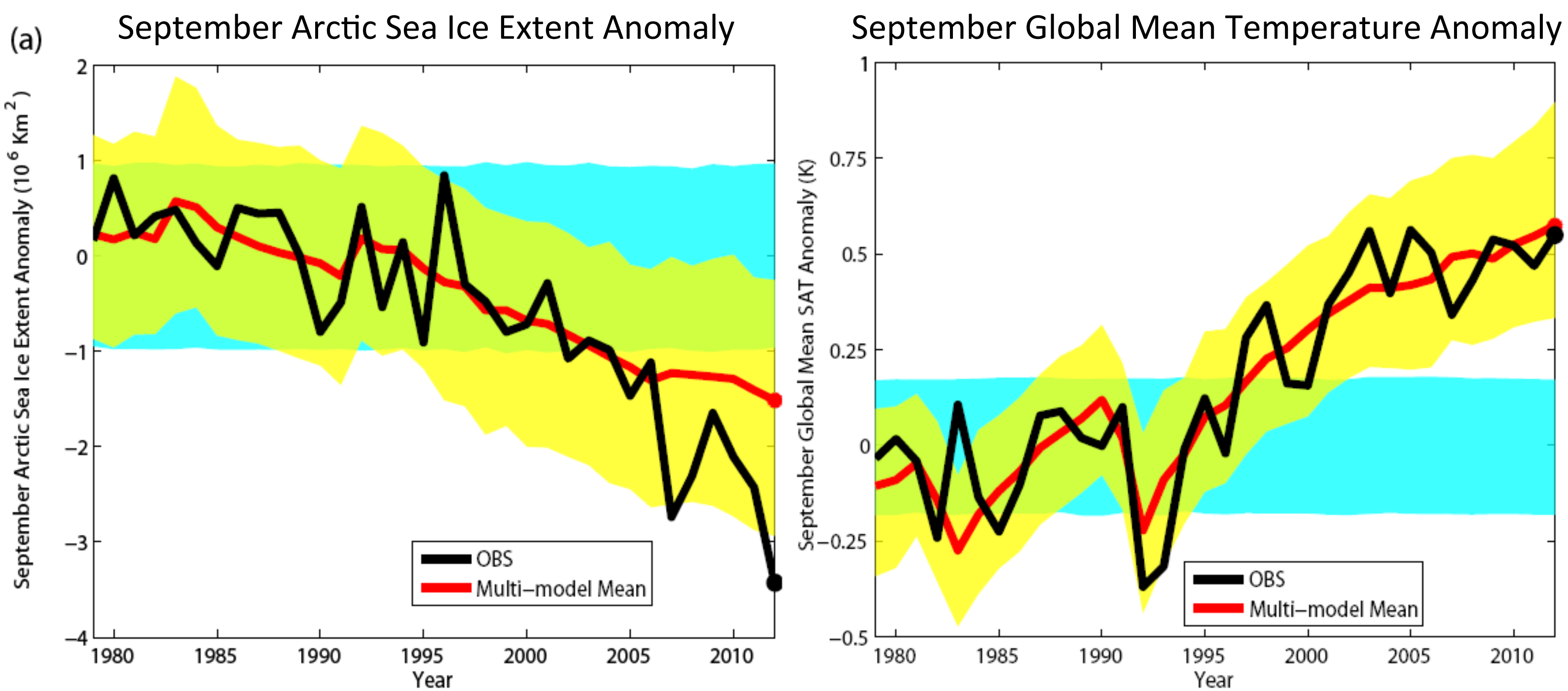
- room for improvement in addressing model biases, station/gridcell scale mismatches, and modeling the extreme ends of the distributions (e.g. with Generalized Extreme Value methods).

Arctic Sea Ice Is Decreasing…



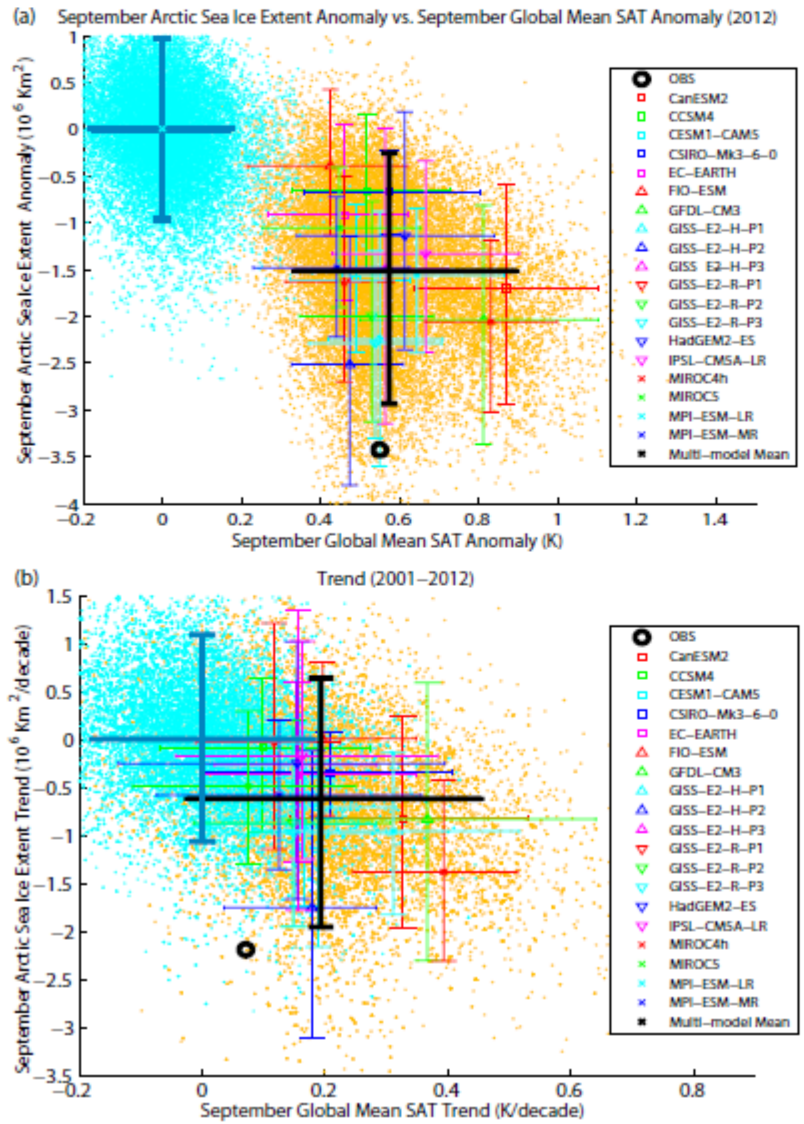
Source: University of Illinois – The Cryosphere Today

Arctic Sea Ice Extent Anomalies During 2012: An Extreme Year



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

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

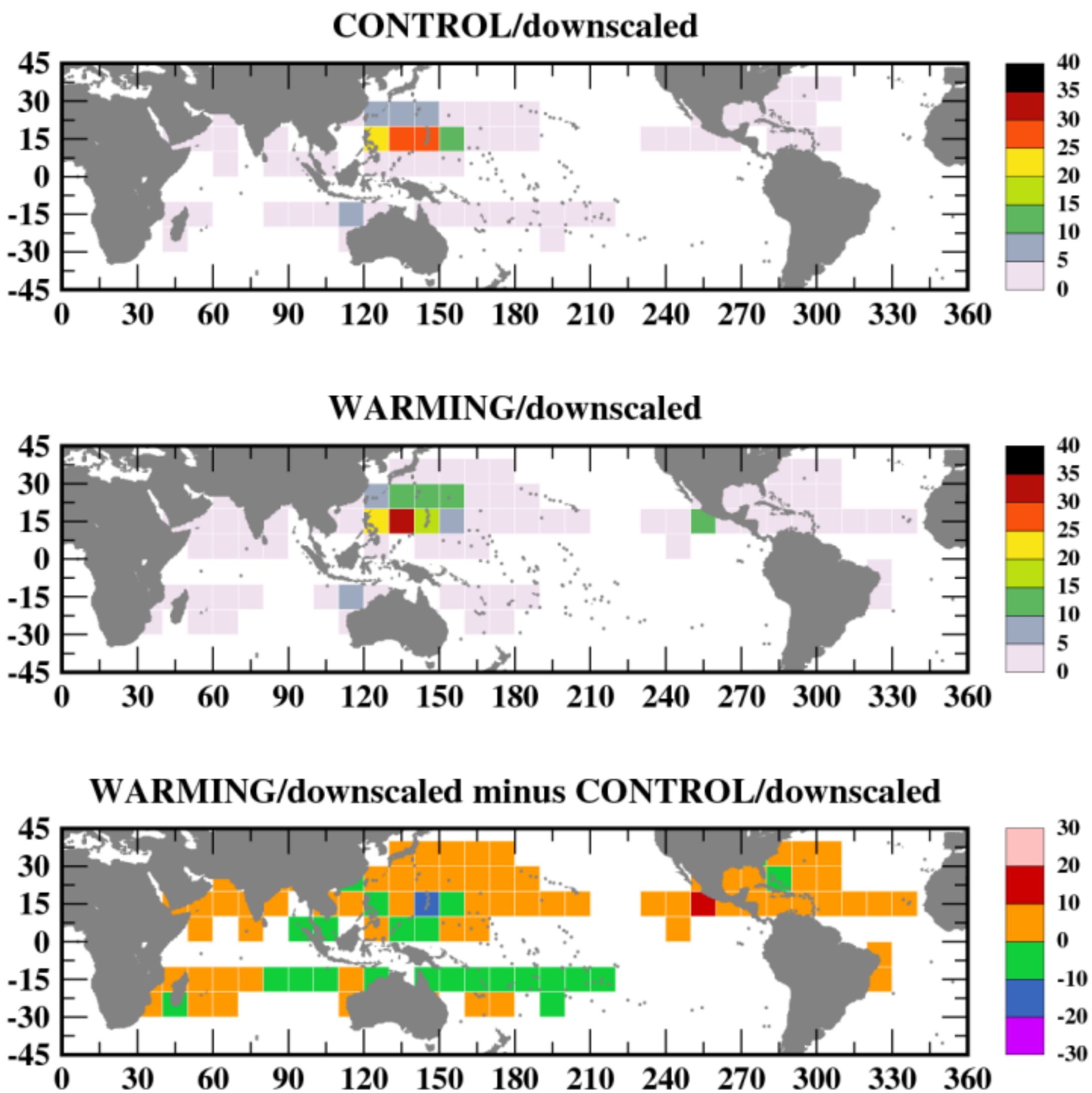


Source: R. Zhang and T. Knutson, BAMS, 2013.

Summary – Some Recent GFDL Work on Extremes

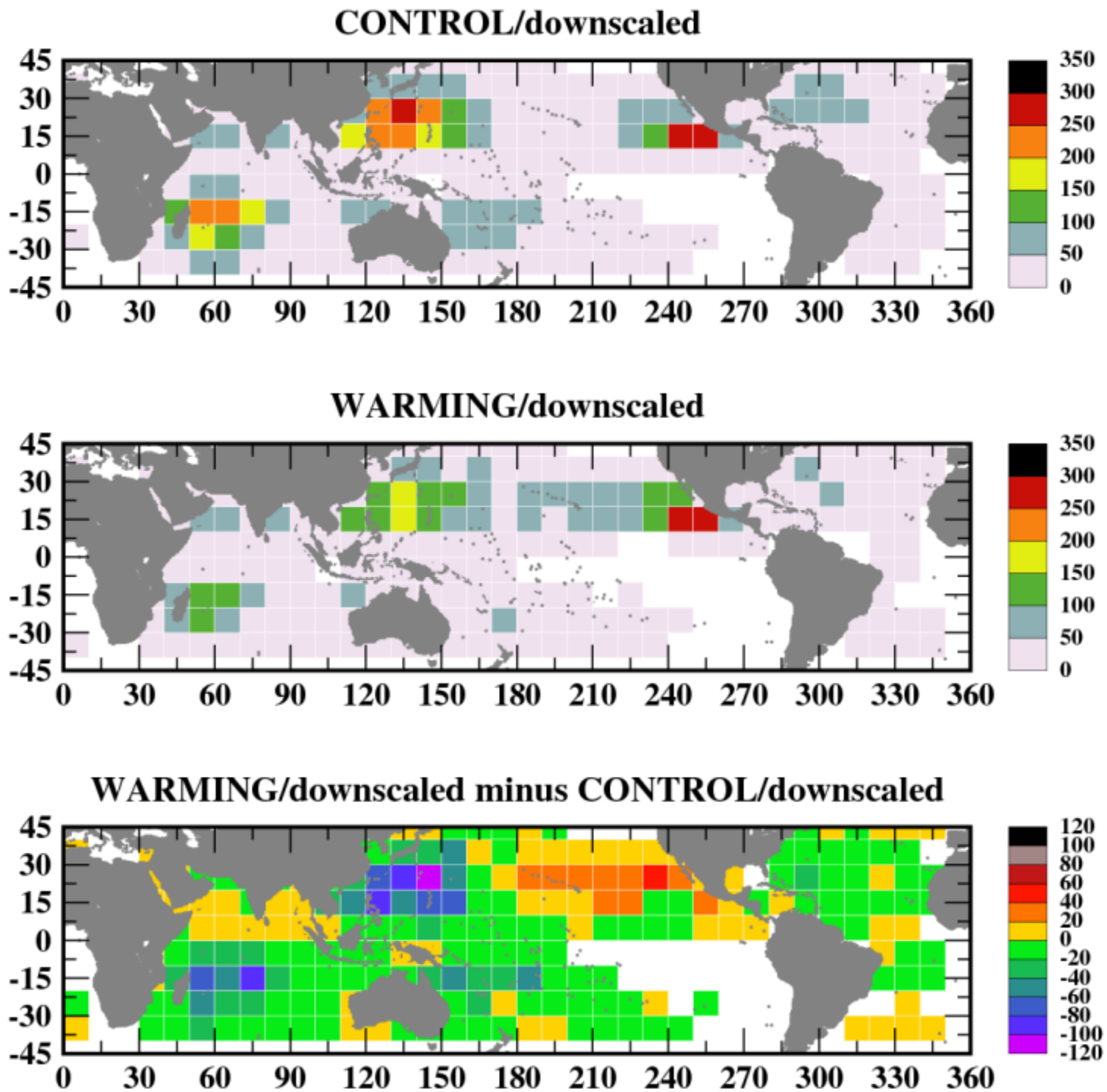
1. Hurricanes and Climate Change:
   - No detectable influence of greenhouse warming on hurricanes yet. Likely contribution of human aerosol forcing to temporary lull in Atlantic activity.
   - Late 21st century projections: increased average intensity and precipitation rates; decreased overall tropical storm frequency. Sea level?
   - Sandy's unusual left turn may have been made more likely by historical anthropogenic climate forcing since 1860.
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
   - 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

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.

Talk Outline – Some Recent GFDL Work on Extremes

1. Tropical Cyclones and Climate Change:
   - Review of IPCC AR5: detection/attribution of possible human influence on past tropical cyclone activity (open science questions).
   - Late 21st century projections:
     - Atlantic basin downscaling (Dec. 2013 J. Climate)
     - Global tropical cyclone downscaling
2. Examples of attribution for recent climate extremes
   - Temperatures (seasonal- or annual-mean warm extremes)
   - Precipitation (seasonal- or annual-mean extremes)
   - Arctic sea ice: 2012 extreme low extent
3. The "global warming hiatus"
   - Consistency of CMIP5 models with observations (data-available regions)
   - Possible impact of observing network on the consistency results

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:

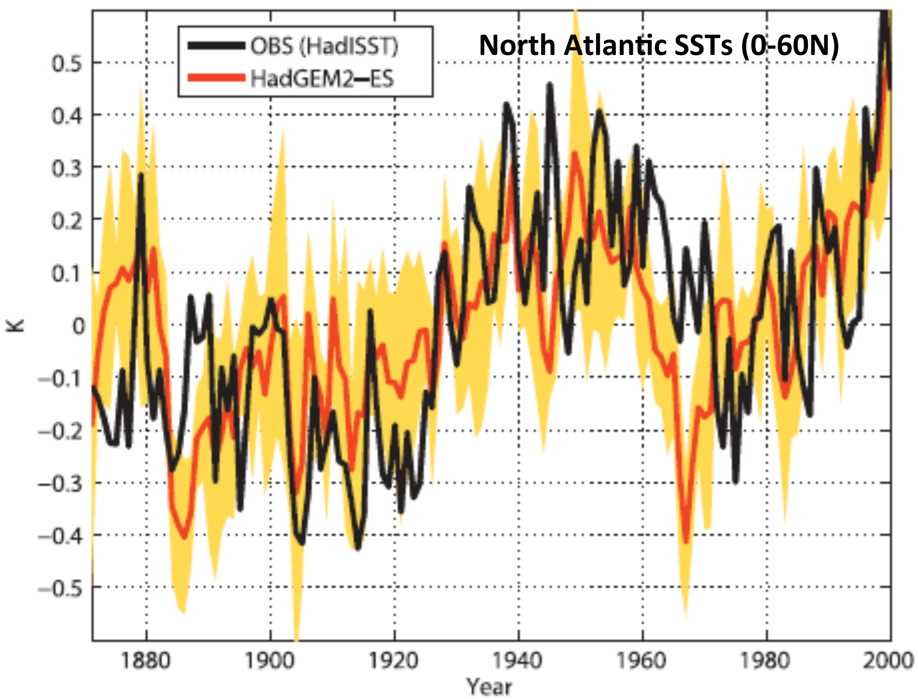
- Low confidence
- "There is medium confidence that a reduction in aerosol forcing over the North Atlantic has contributed at least in part in the observed increase in tropical cyclone activity since the 1970s in this region."

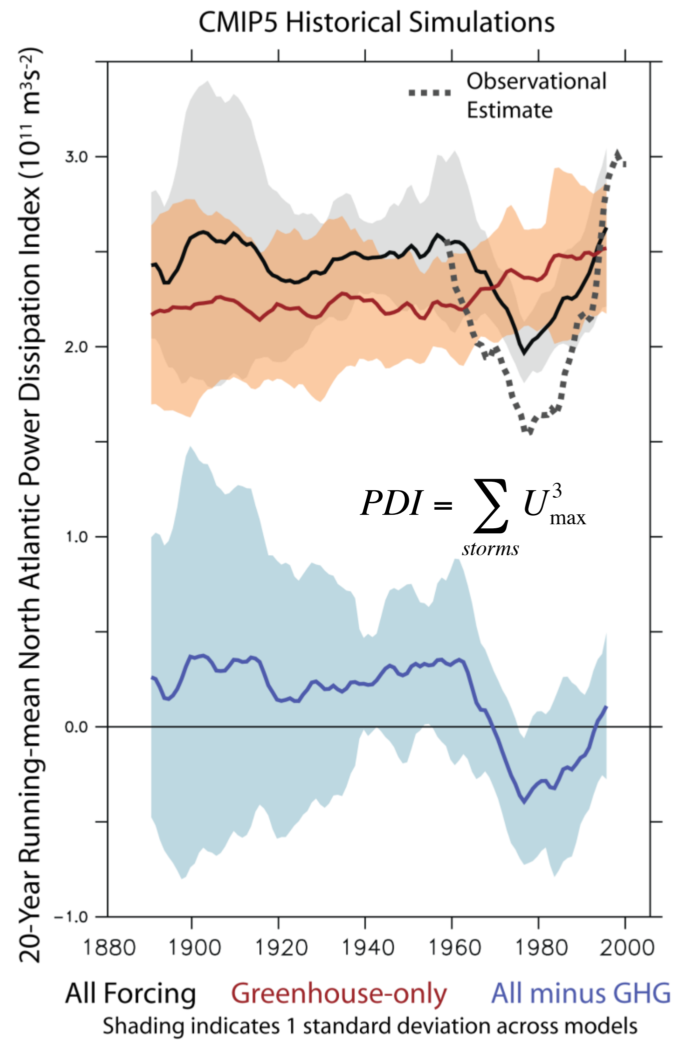
Likelihood of further changes (late 21st century):

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

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.

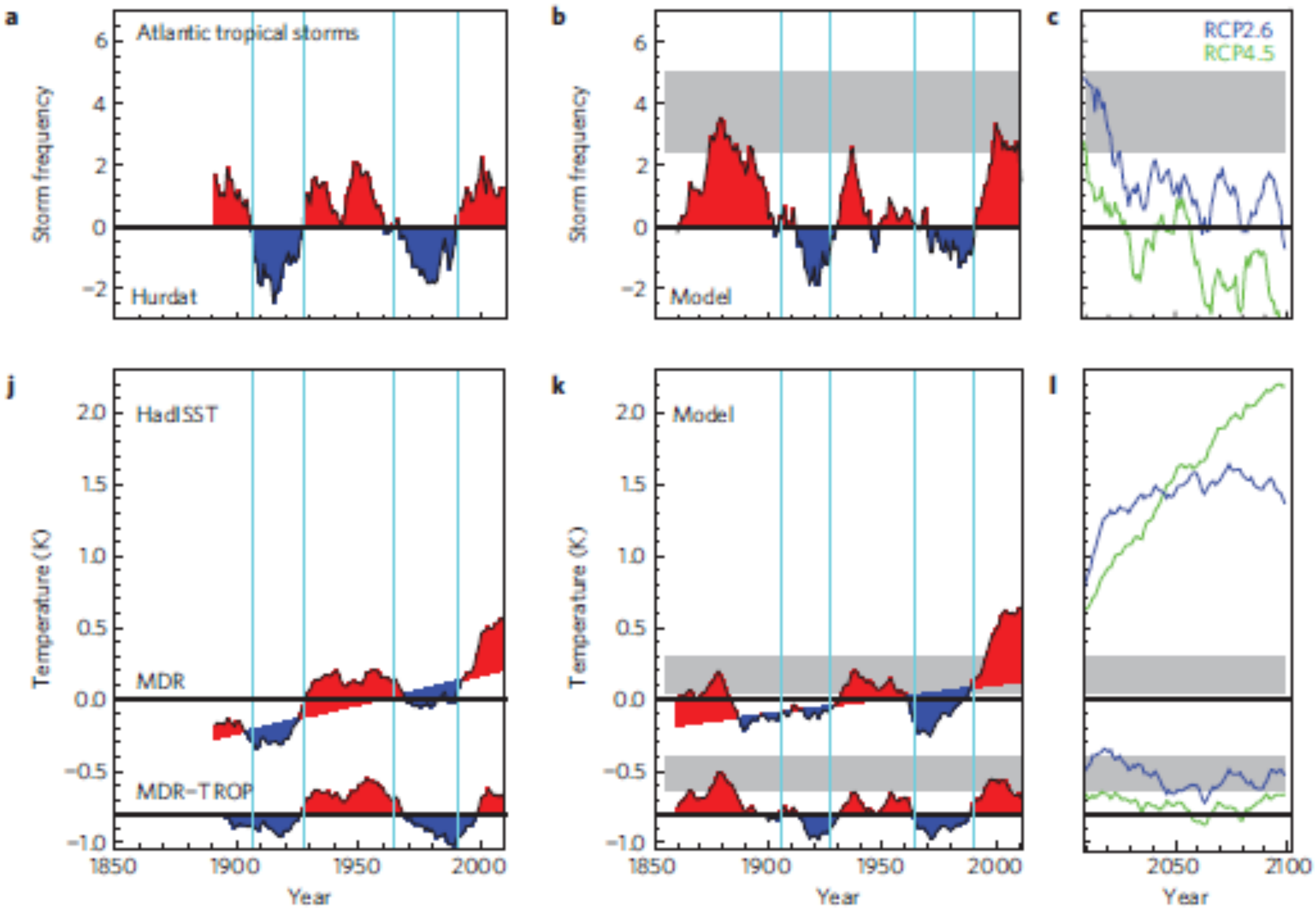




Sources: Left: Fig. 1 adapted from Booth et al., *Nature*, 2012 (Zhang et al. JAS, 2013); right: Villarini and Vecchi (J. Climate 2013).

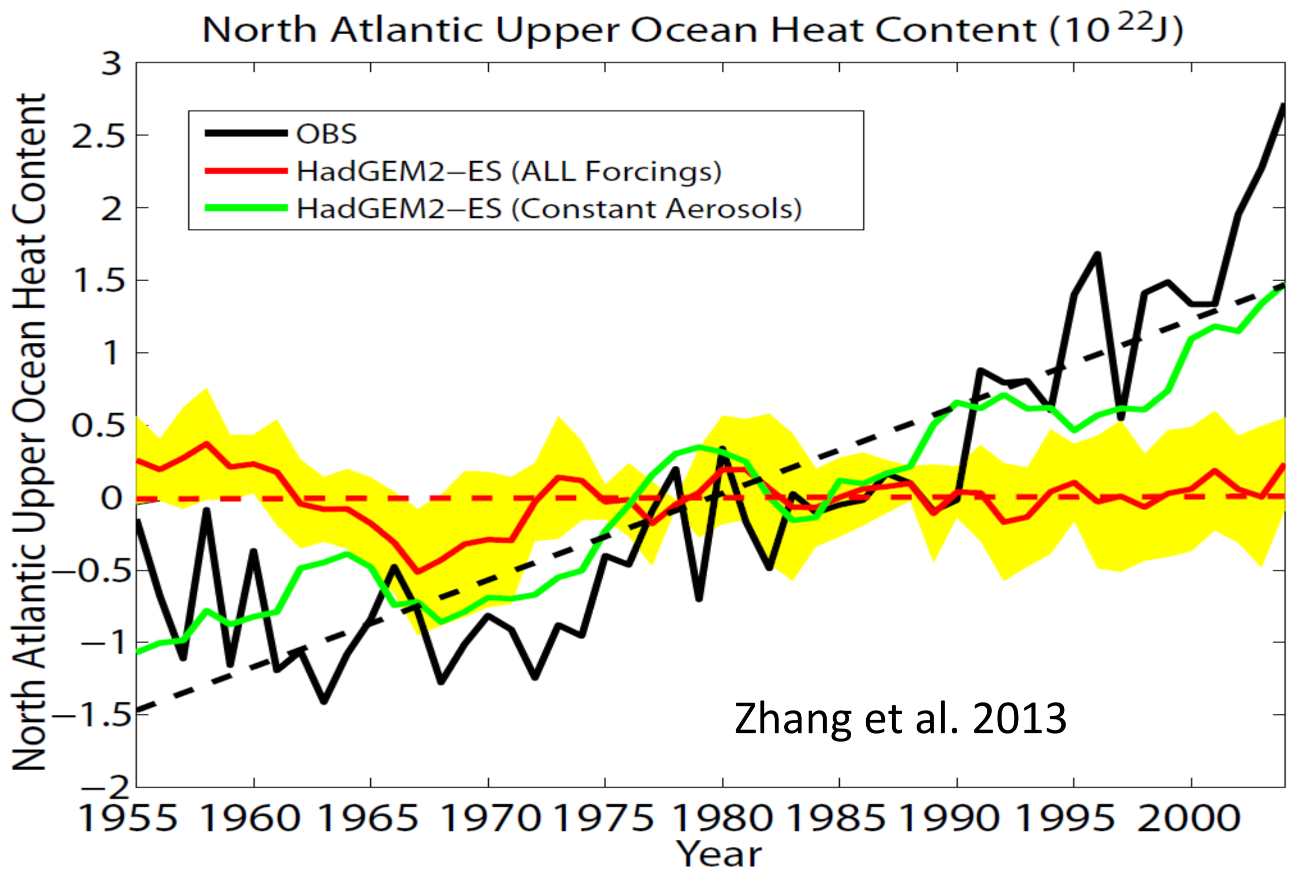
- Did Aerosols force 20th century multi-decadal changes in Atlantic tropical storm frequency?

  - 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).

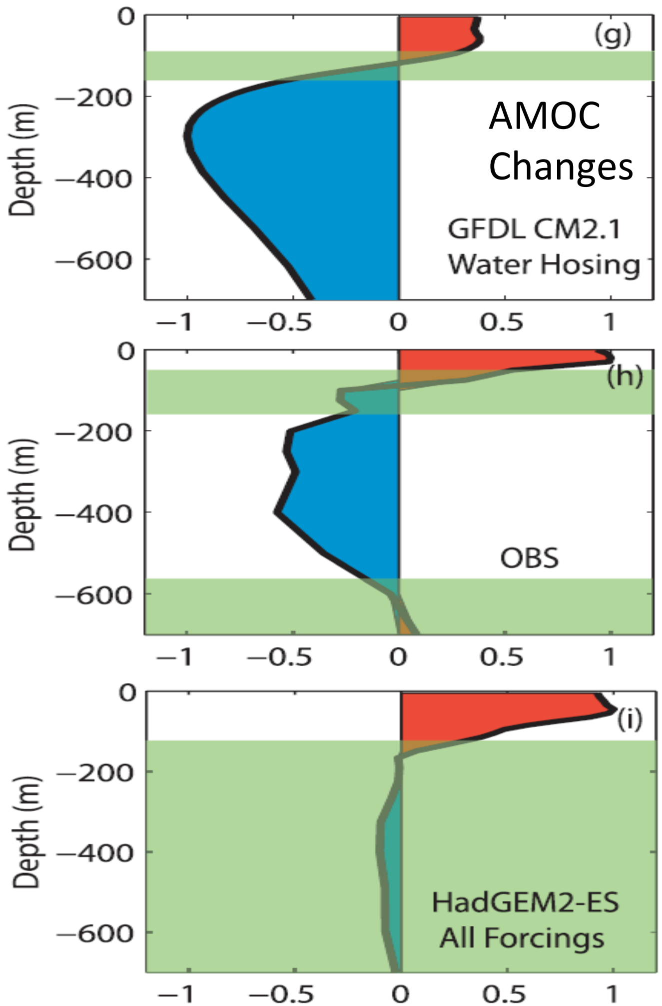
Aerosol Effects and Upper Ocean Heat Content



- 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

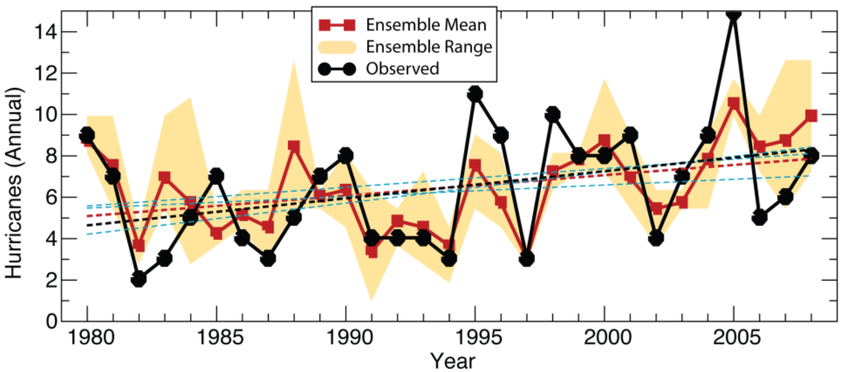
- The aerosol mechanism cannot account for the observed anticorrelated multidecadal TNA SST and subsurface temperature variations

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

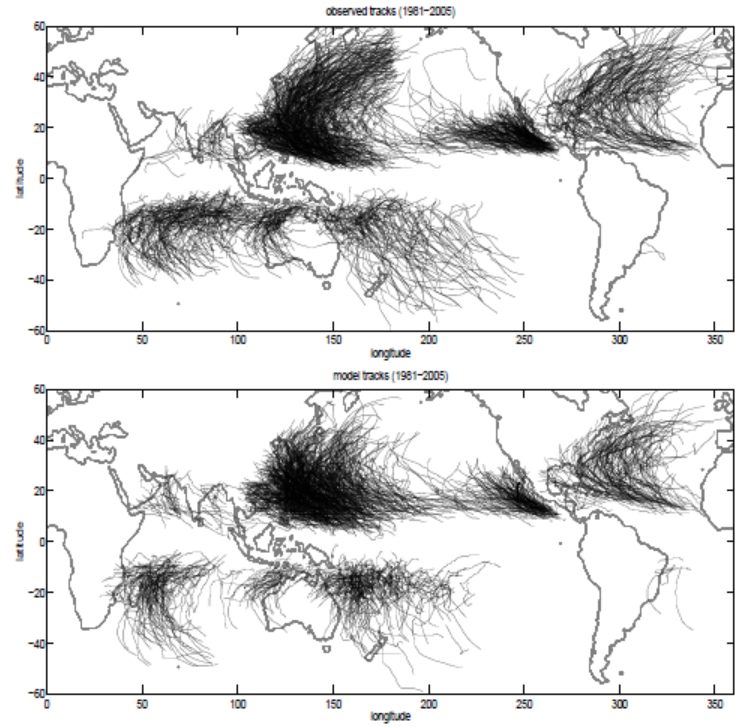
Atlantic Hurricanes (1980-2008): HiRAM-Simulated vs. Observed

Correlation: ens-mean = 0.69; Linear trends: +0.10 storms/yr (model ens mean)
ens-range = [0.47,0.59] [+0.06, 0.15] storms/yr (model ens range) +0.13 storms/yr (observed).



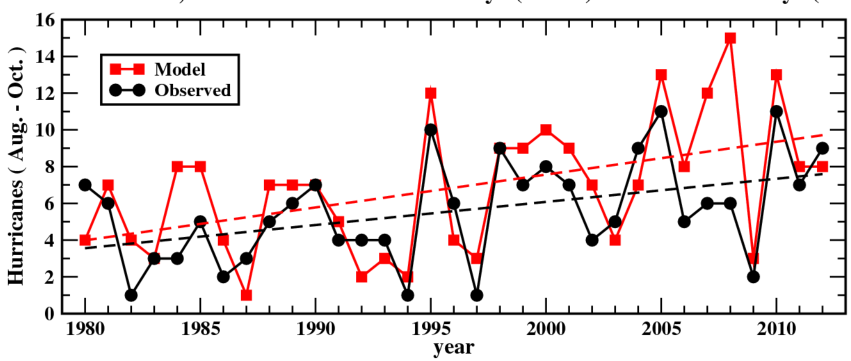
GFDL HIRAM 50km grid global model (SST-forced)

Simulated vs Observed Tropical Storm Tracks (1981-2005)

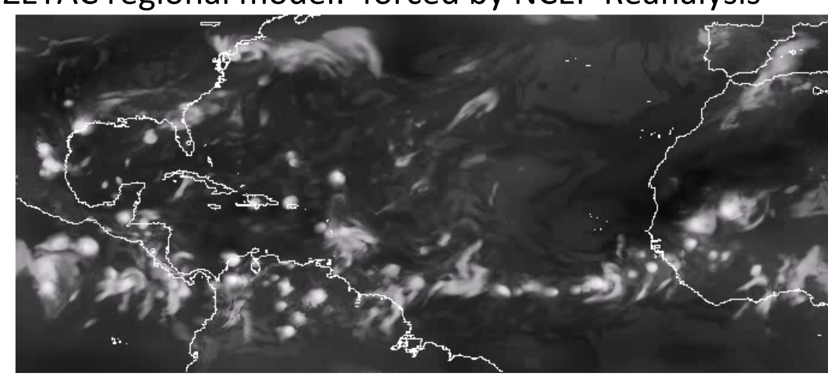


Atlantic Hurricanes (1980-2012): Simulated vs. Observed

Correlation = 0.73; Linear trends: +0.18 storms/yr (model) and +0.13 storms/yr (observed)



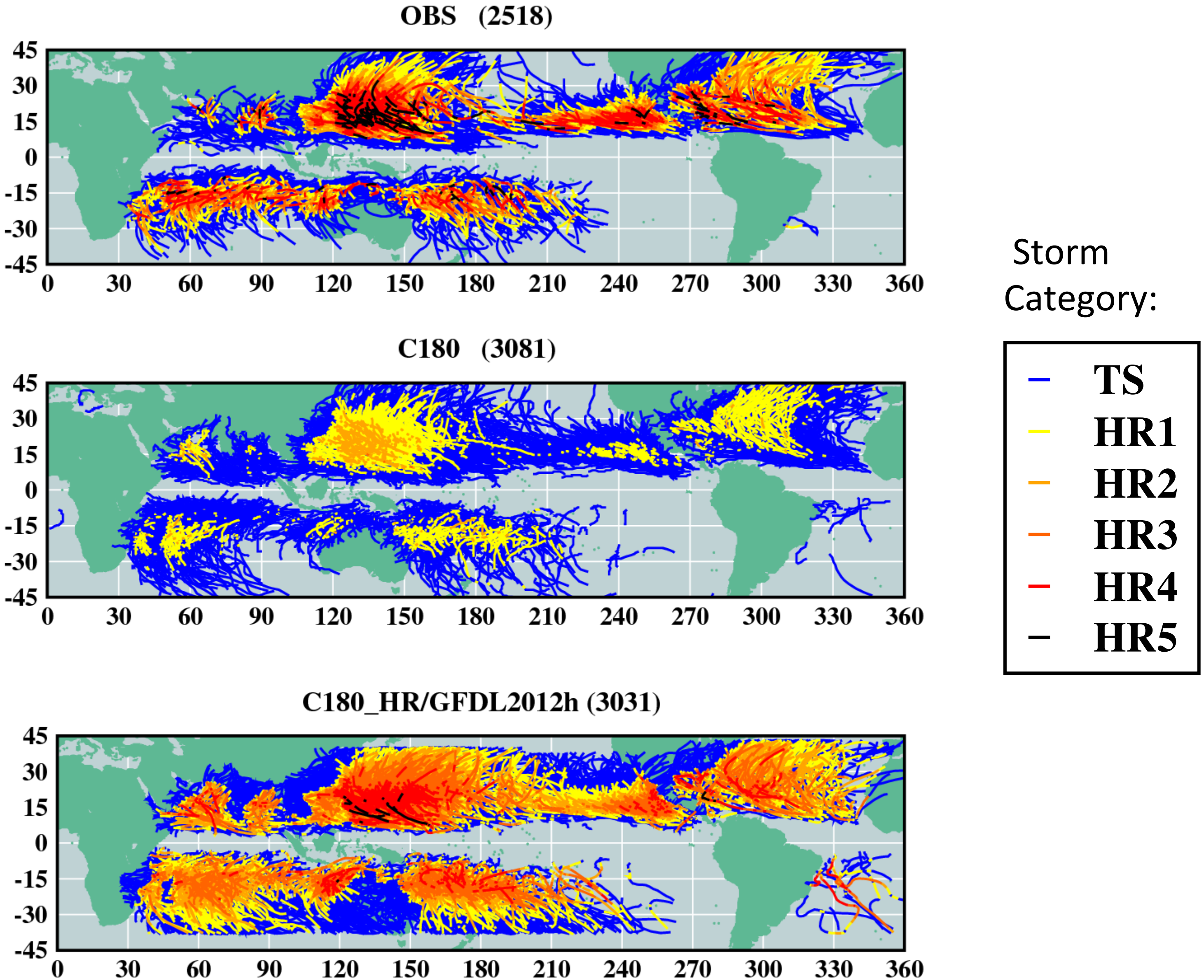
ZETAC regional model: forced by NCEP Reanalysis



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

Tropical Storms (1980-2008)

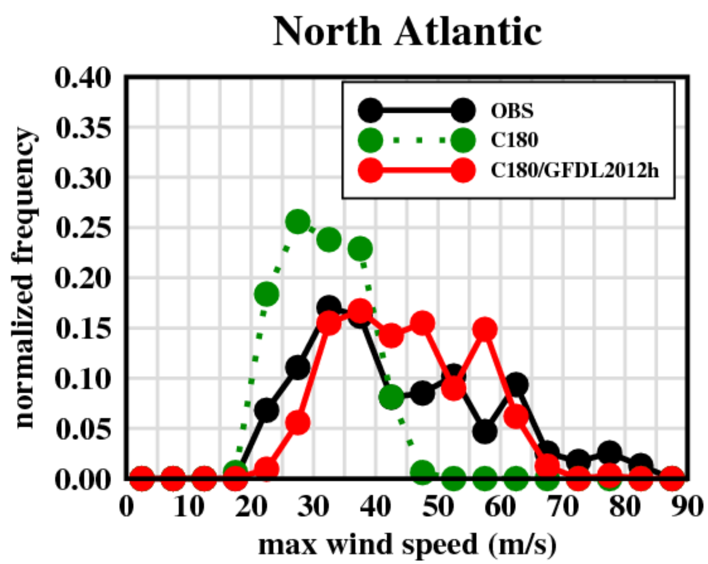
Present-Day Climate

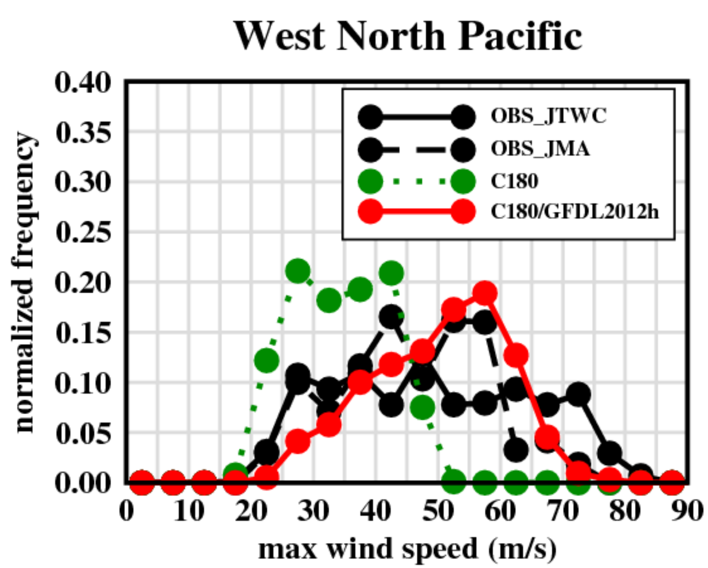


GFDL dynamical downscaling to 6 km grid model; preliminary results, 2014.

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

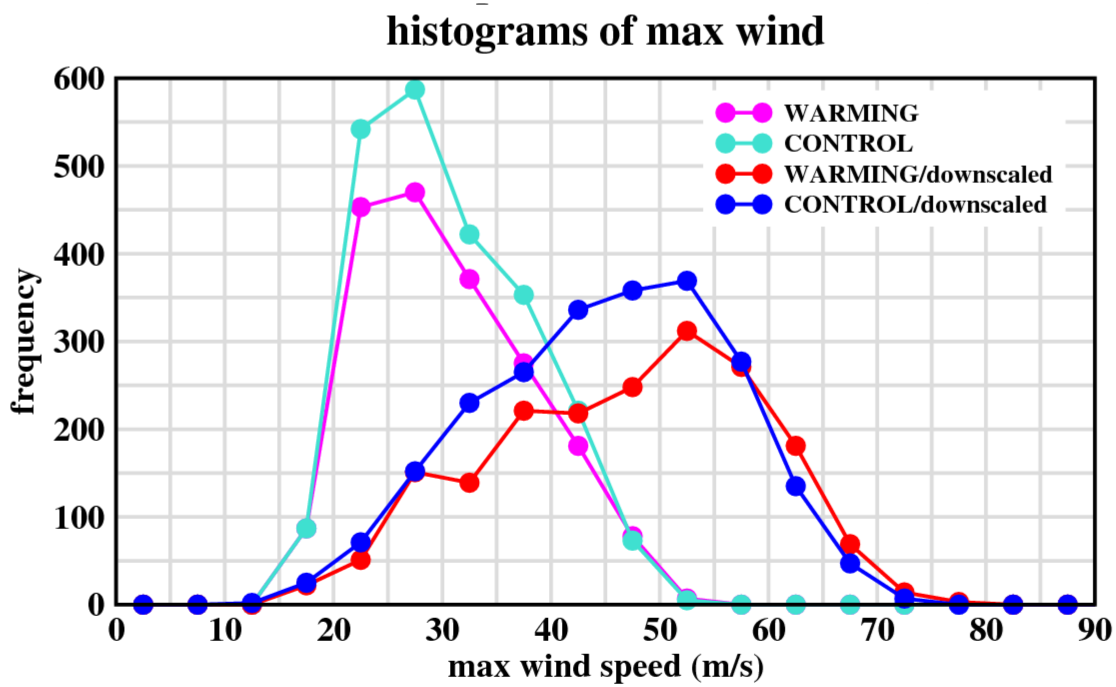
Present-Day Climate





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:

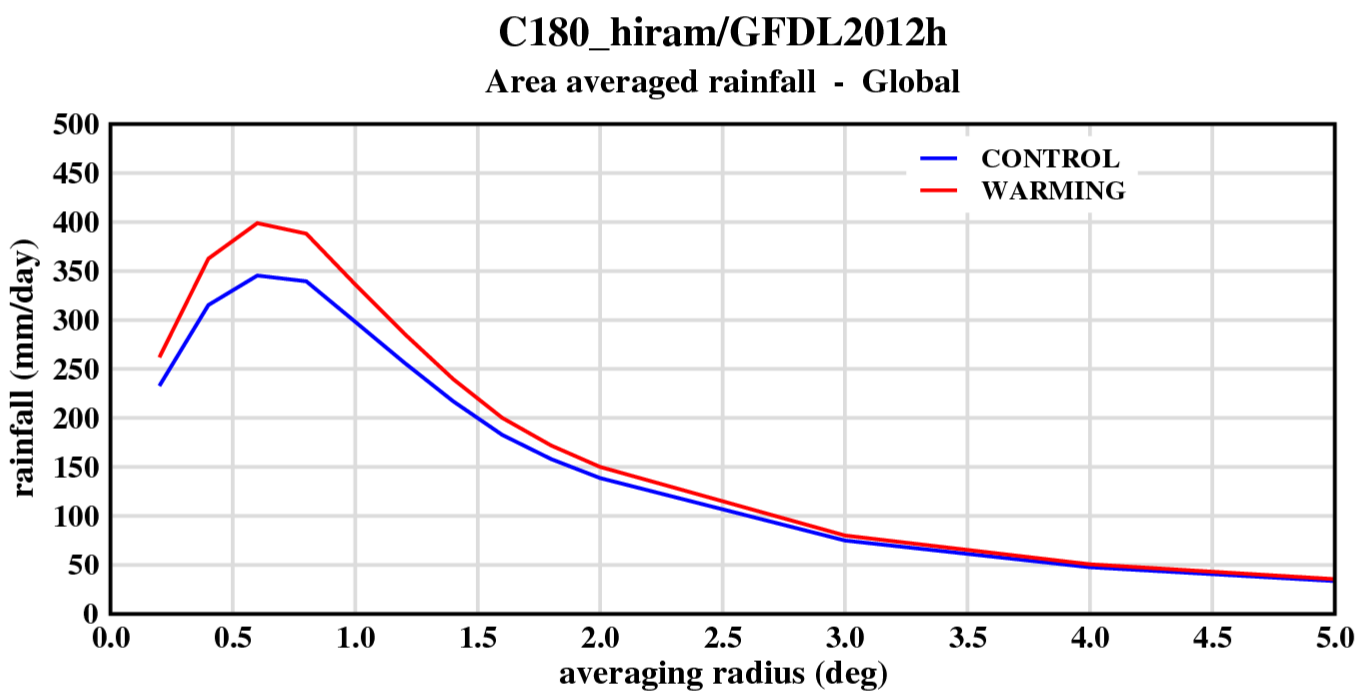
Power Dissipation Index: Global: **-9.7%**

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



Mean rain rate within 100 km radius of storm center:

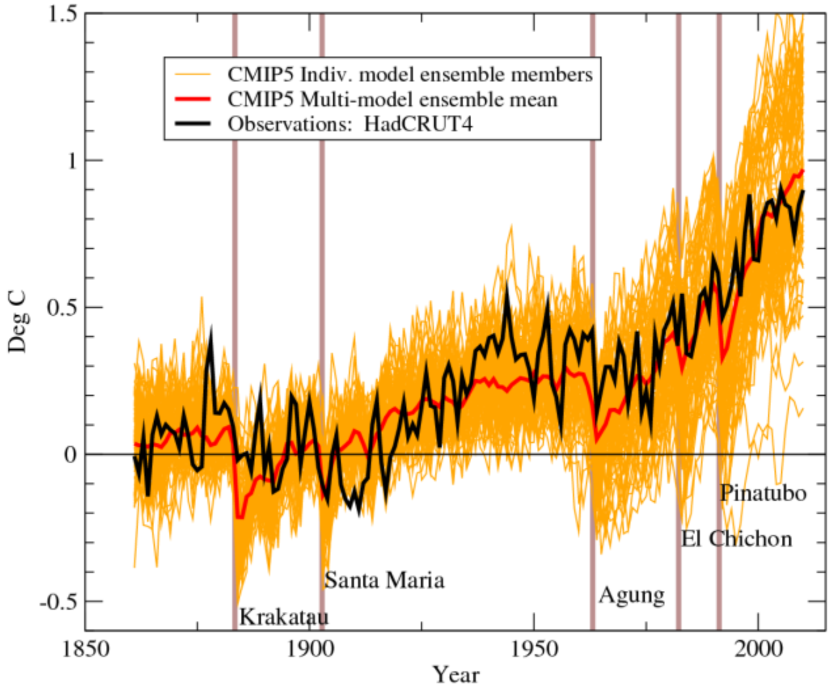
Tropical storms: Global: +14 % [range: -1.2% (Southwest Pac) to +21% (NW Pac.)]

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

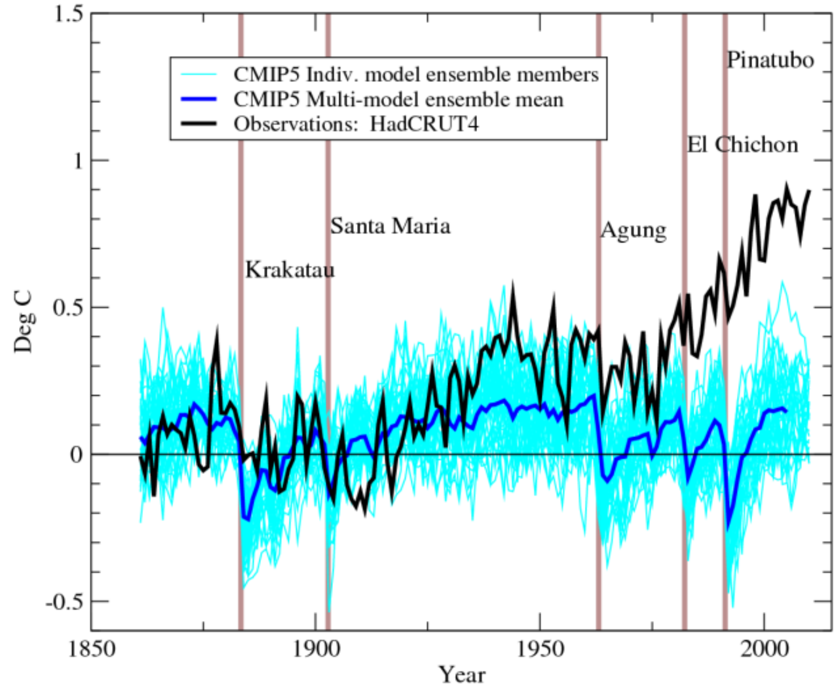
GFDL dynamical downscaling to 6 km grid model;
preliminary results, 2014.

Global Mean Surface Temperature Anomalies

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



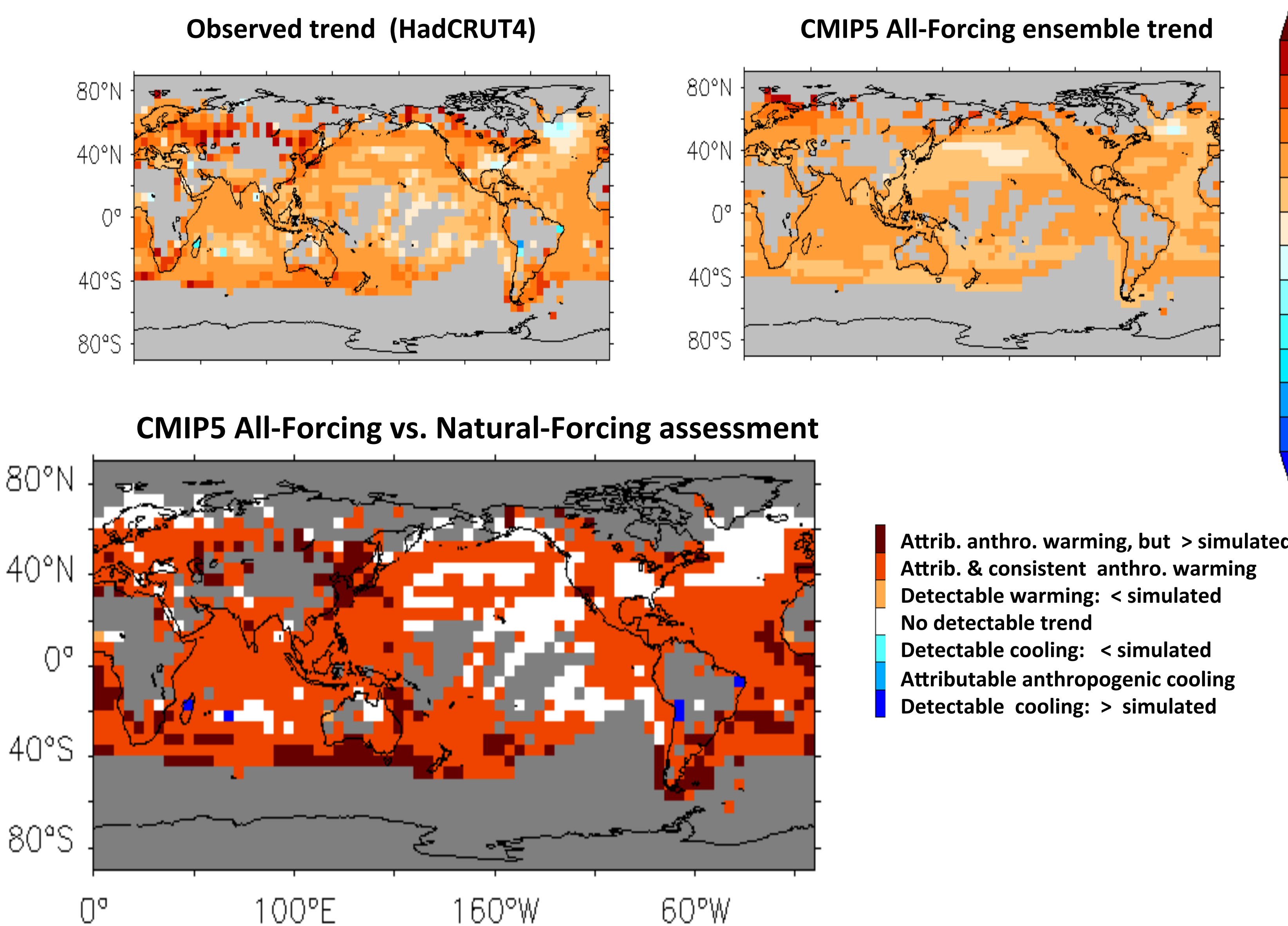
b) CMIP5: Natural forcing only (solar & volcanic)



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.

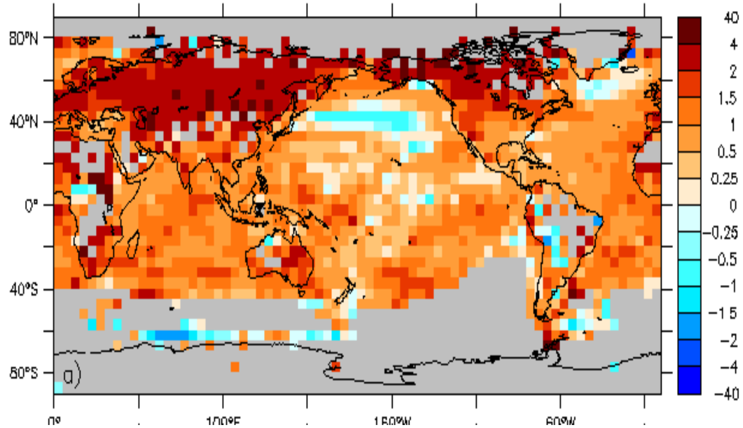
1901-2010 Surface Temperature Trend Assessment



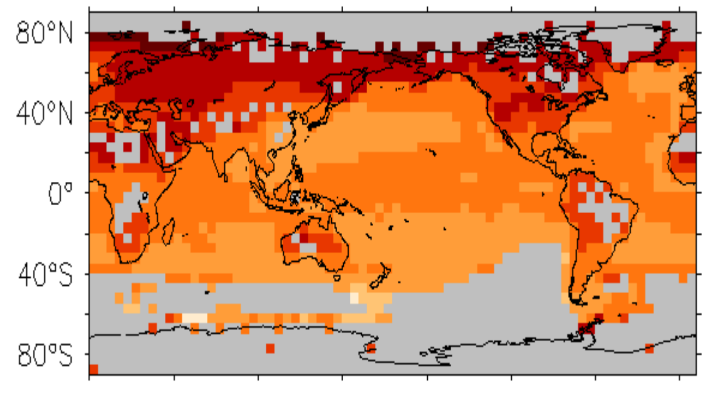
Source: Knutson, Zeng, and Wittenberg, *J. Climate* (2013)

1951-2010 Surface Temperature Trend Assessment *

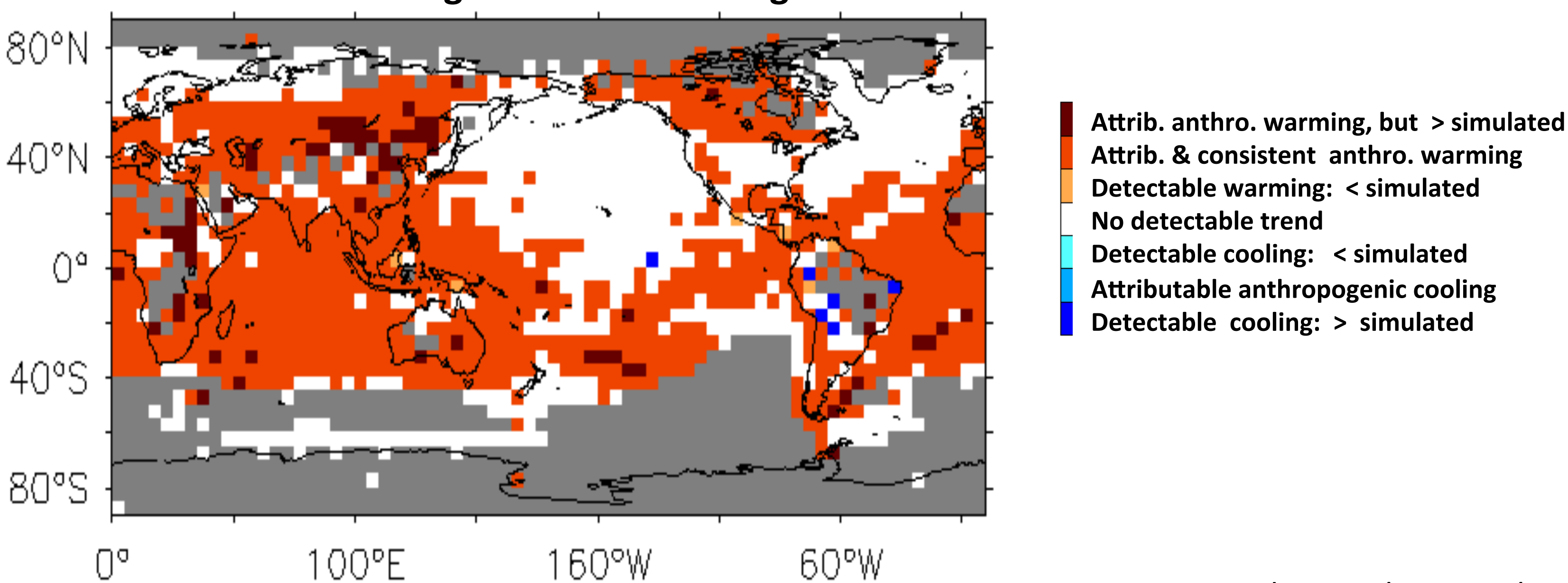
Observed trend (HadCRUT4)



CMIP5 All-Forcing ensemble trend



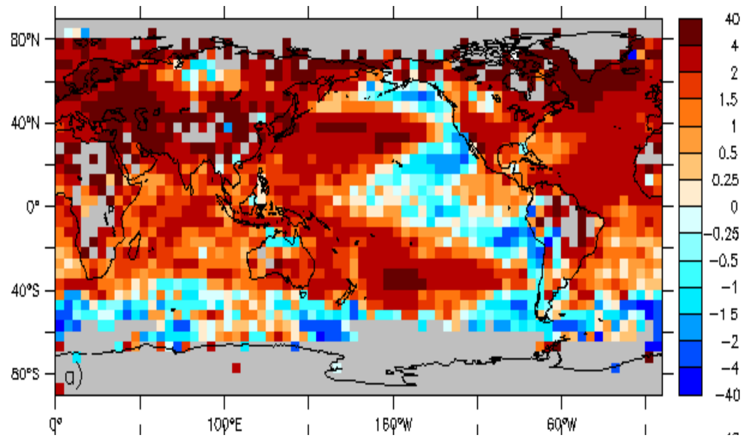
CMIP5 All-Forcing vs. Natural-Forcing assessment



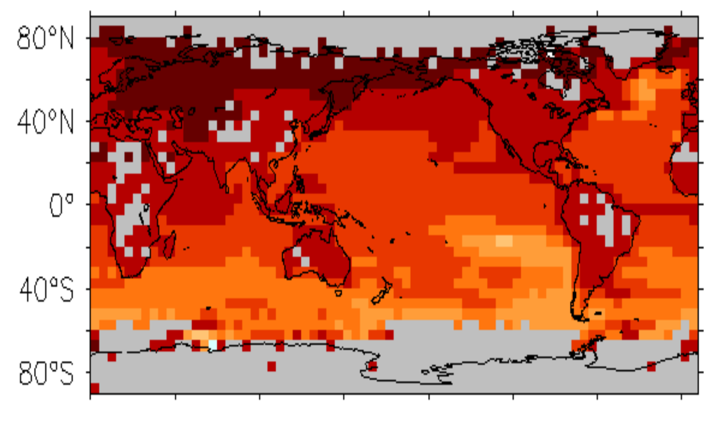
Source: Knutson, Zeng, and Wittenberg, *J. Climate* (2013)

1981-2010 Surface Temperature Trend Assessment*

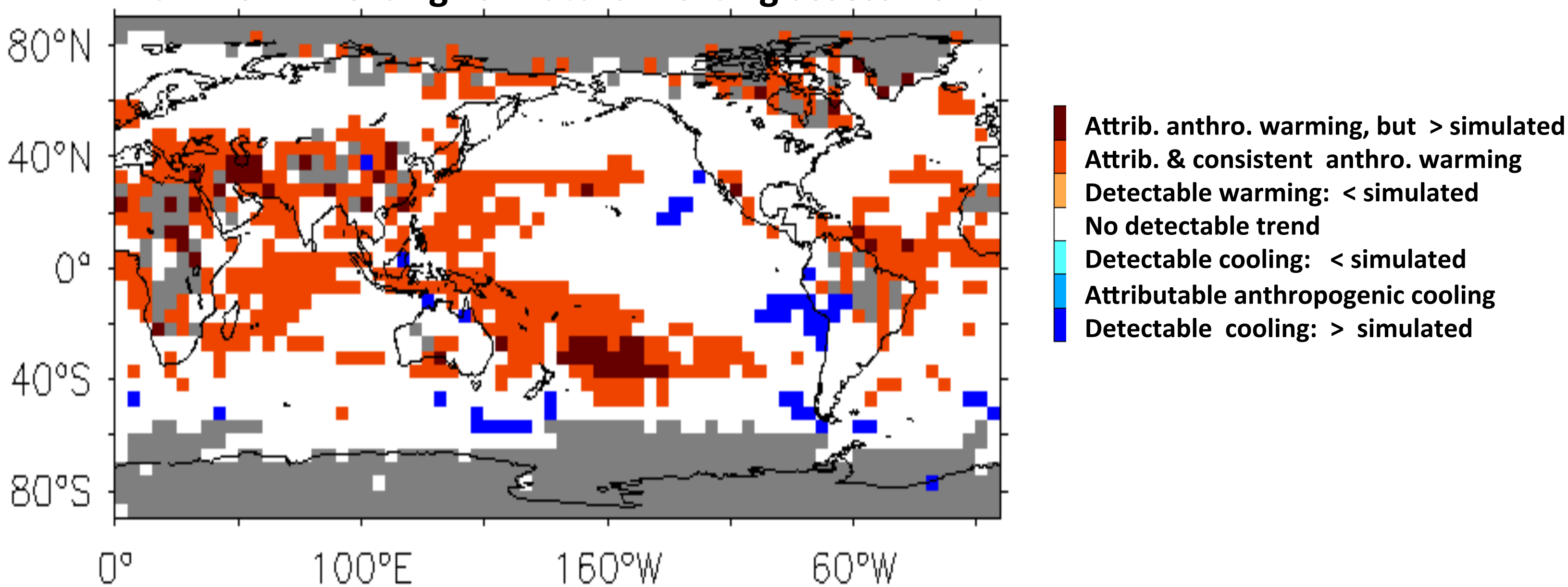
Observed trend (HadCRUT4)



CMIP5 All-Forcing ensemble trend

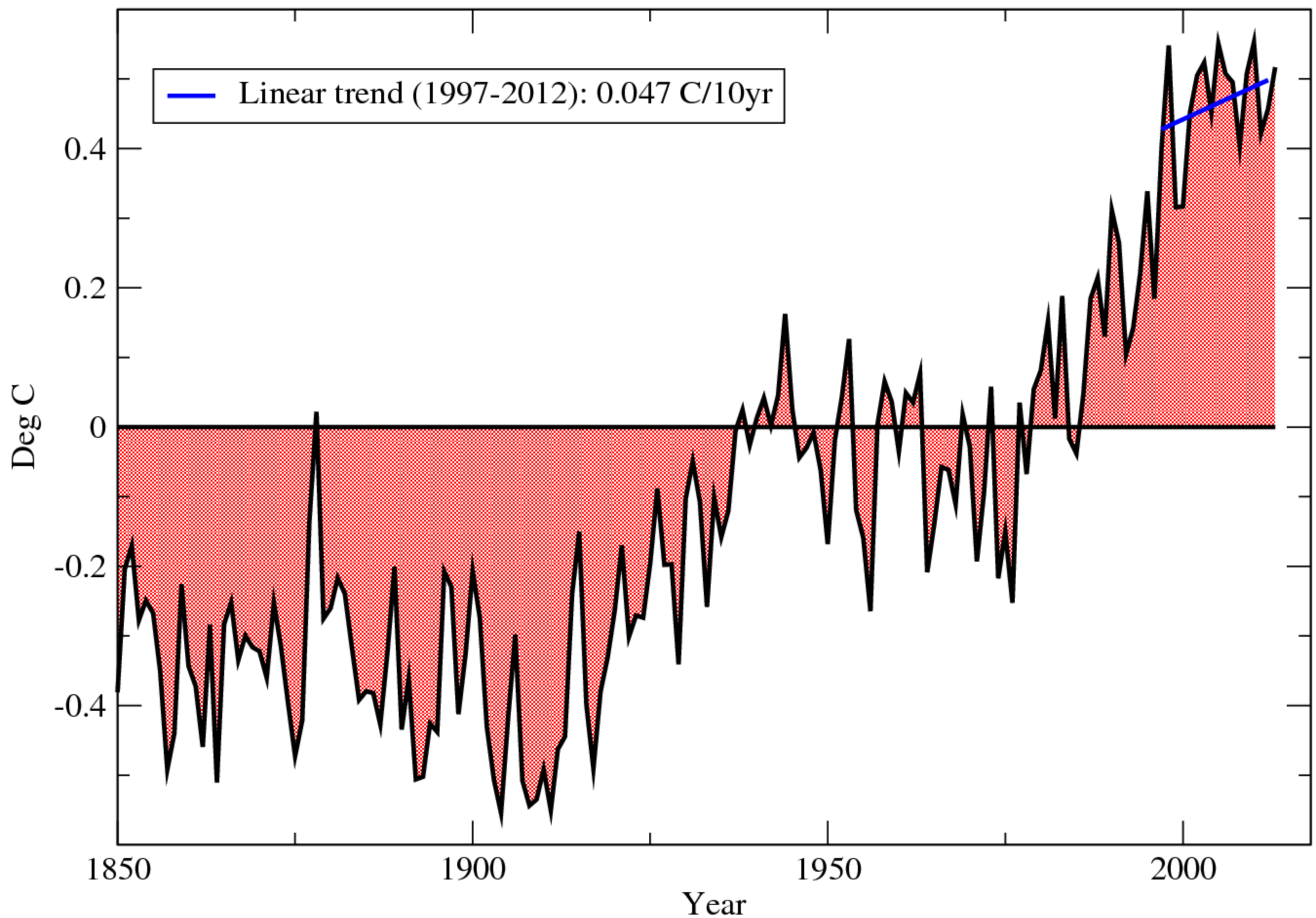


CMIP5 All-Forcing vs. Natural-Forcing assessment



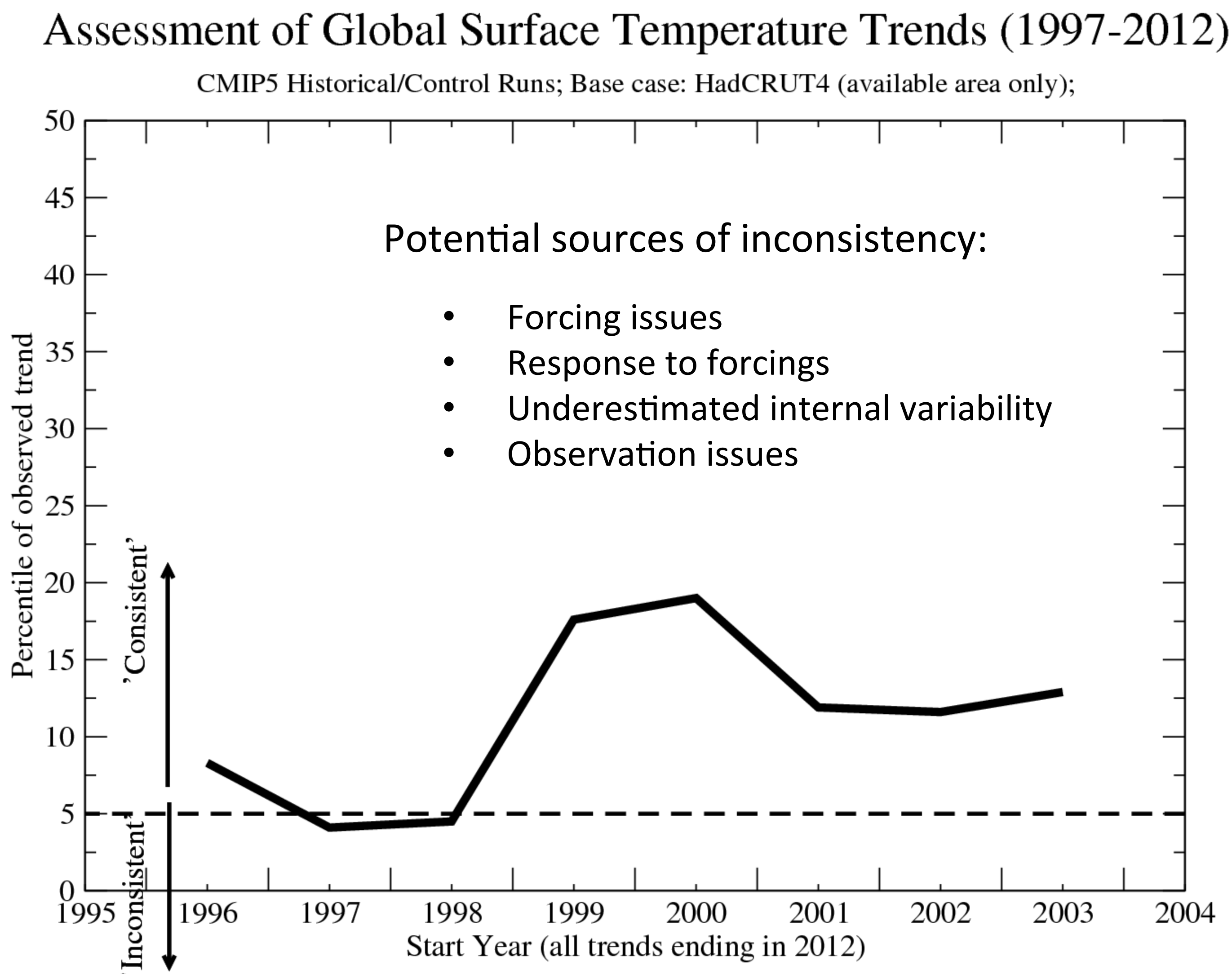
Source: Knutson, Zeng, and Wittenberg, *J. Climate* (2013)

Global mean surface temperature anomaly (HadCRUT4)



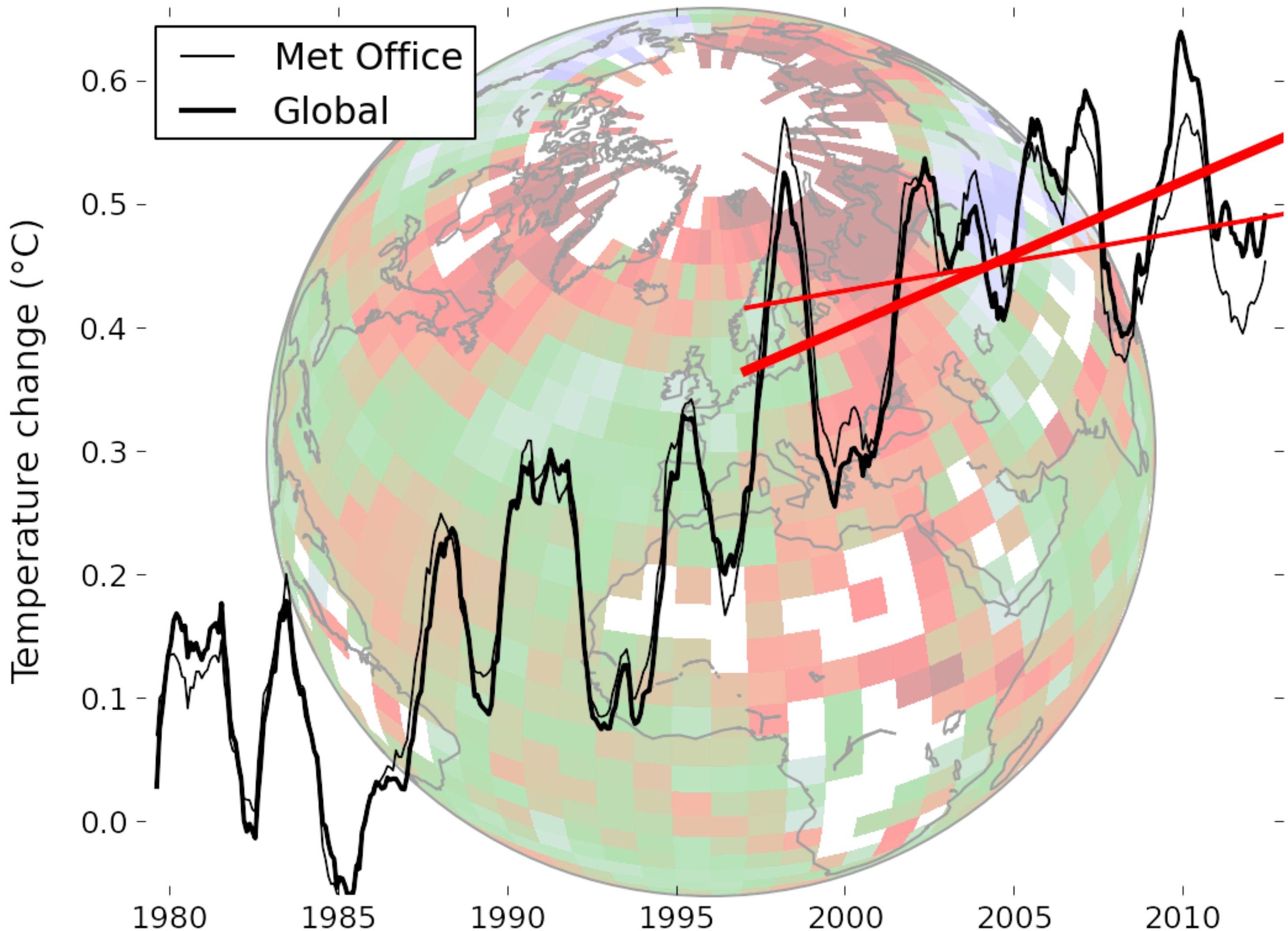
Note: Trend using previous year's version of HadCRUT4 was 0.0446 C/10yr.

Wed Jan 29 17:14:37 2014

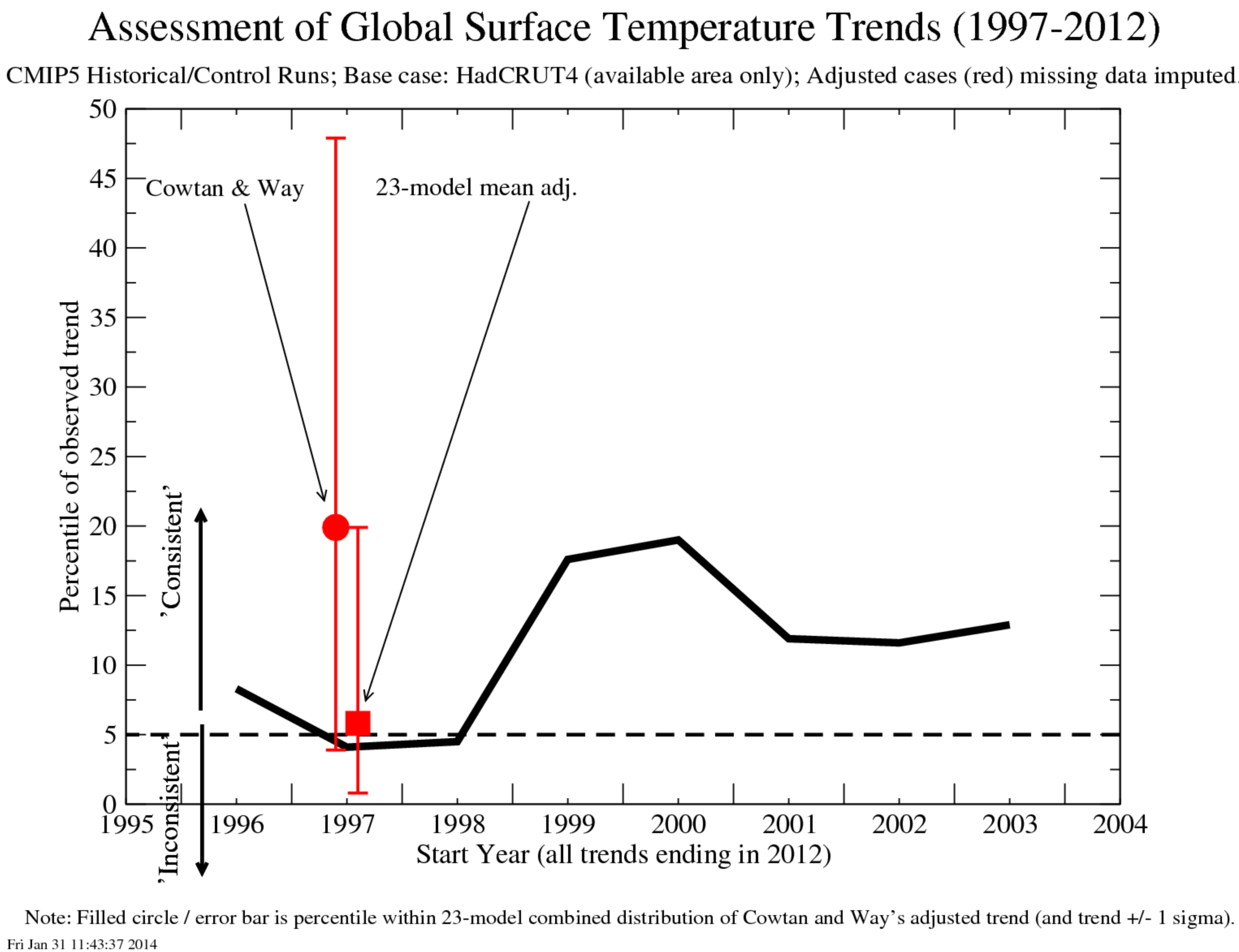


Thu Apr 10 13:38:34 2014

Are missing temperature observations in the Arctic causing the hiatus?



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



Assessment of Global Surface Temperature Trends (1997-2012)
CMIP5 Historical/Control Runs; Base case: HadCRUT4 (available area only); Adjusted cases (red) missing data imputed.
Percentile of observed trend
0
5
10
15
20
25
30
35
40
45
50
Cowtan & Way
23-model mean adj.
'Consistent'
'Inconsistent'
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
Start Year (all trends ending in 2012)
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

TABLE 1. Nonparametric test for trend in extreme precipitation based on Kendall's τ for the number of occurrences of 2-day precipitation exceeding a threshold for a 1-in-5-yr return period over the period of 1895–2010 and over the period of 1957–2010, as well as the total precipitation exceeding the 99th percentile for daily amounts over the period of 1957–2010. Kendall's τ can be used to perform a nonparametric test for trend (Hollander and Wolfe 1973, chapter 8). The statistic τ is a measure of association between the variable and time, ranging between −1 and 1 like an ordinary correlation coefficient. The P value is based on the null hypothesis of no trend (i.e., the time series is uncorrelated with time). Positive values of τ indicate indices increasing with time but not necessarily linearly. Kendall's τ is commonly used to test for trends in hydrologic time series (Helsel and Hirsch 1993, chapter 8; Villarini et al. 2009).

Region	Kendall's τ (2 days,5 years) 1895–2010	Kendall's τ (2 days,5 years) 1957–2010	Kendall's τ (99th percentile) 1957–2010
United States	0.240[a]	0.388[a]	0.340[a]
Northeast	0.065	0.266[a]	0.360[a]
Southeast	0.242[a]	0.192[b]	0.188[b]
Midwest	0.206[a]	0.224[b]	0.301[a]
Northern Great Plains	0.032	0.146	0.085[c]
Southern Great Plains	0.097	0.053	—
Northwest	−0.006	0.063	0.062
Southwest	0.012	0.121	0.048

[a] Significant at the 0.01 level.

[b] Significant at the 0.05 level.

[c] Results for combined northern and southern Great Plains.

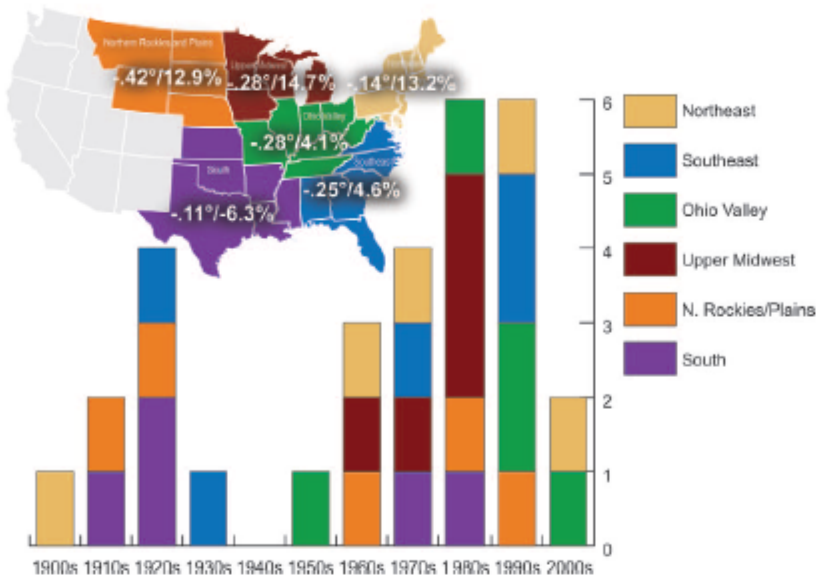


Fig. 6. Number of extreme snowstorms (upper 10th percentile) occurring each decade within the six U.S. climate regions in the eastern two-thirds of the contiguous United States (based on an analysis of the 50 strongest storms for each of the six climate regions from Oct 1900 to Apr 2010). The inset map shows the boundaries of each climate region. These regions were selected for consistency with the National Oceanic and Atmospheric Administration's (NOAA) monthly to annual operational climate monitoring activities. The map includes standardized temperature anomalies and precipitation departures from the twentieth-century mean calculated across all snow seasons in which each storm occurred. The snow season is defined as Dec–Mar for the South and Southeast regions and Nov–Apr for the other four regions.

Source: Kunkel et al., BAMS, 2013

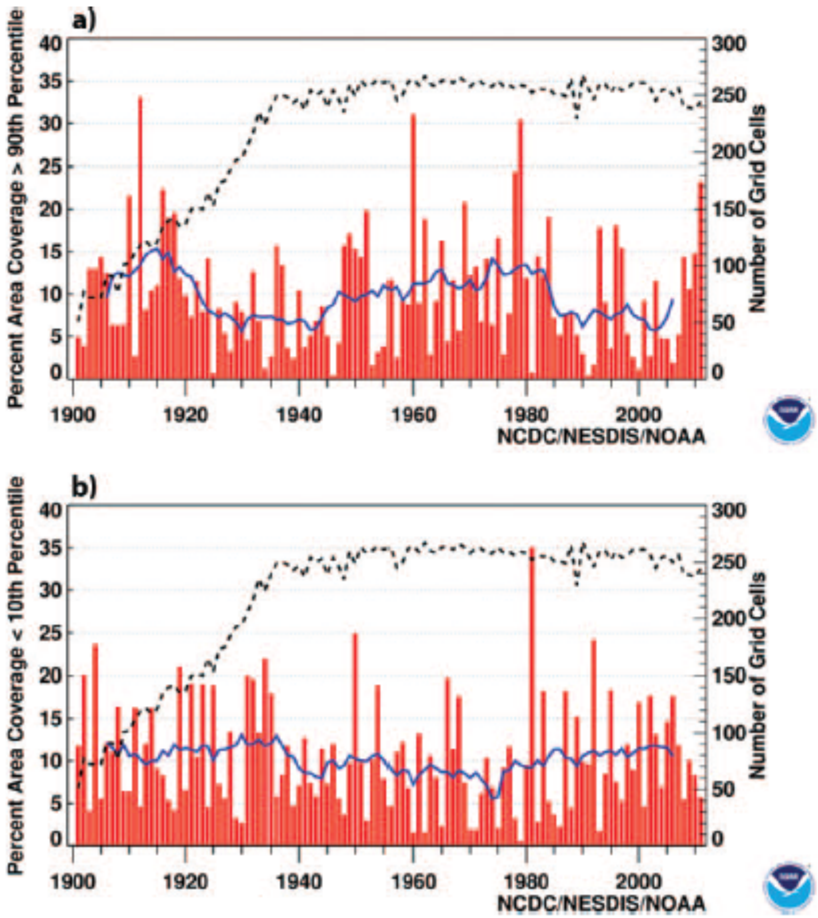
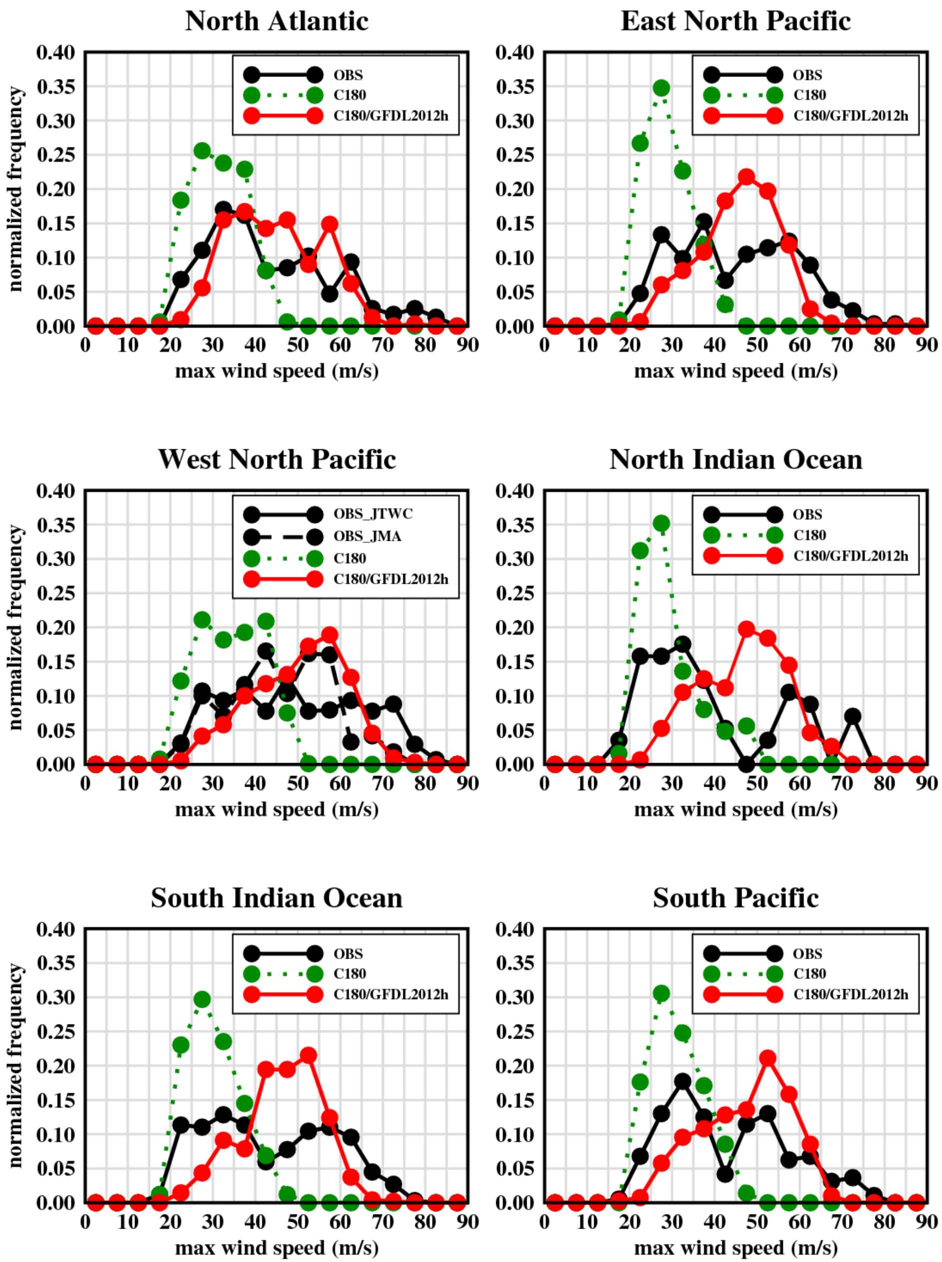


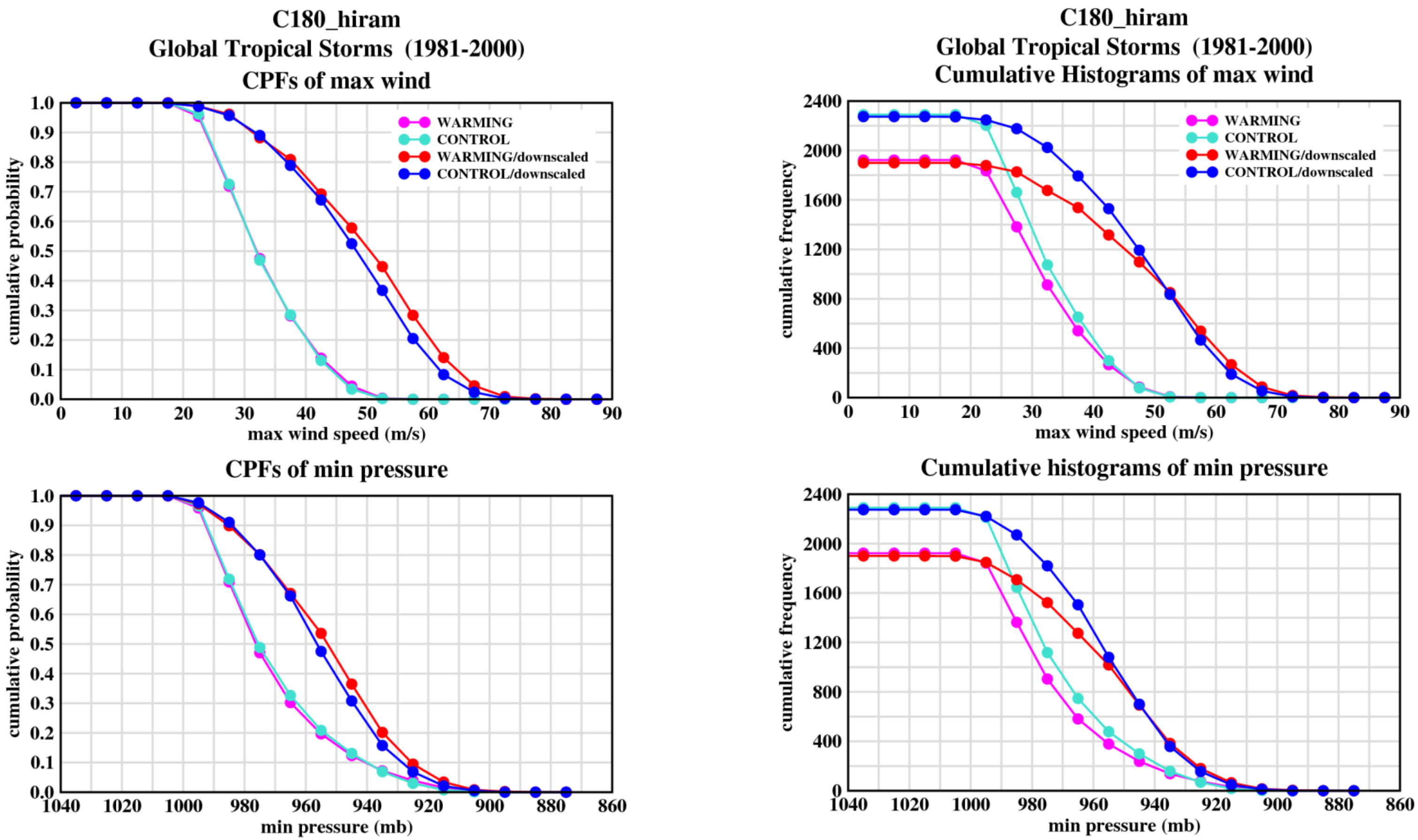
FIG. 7. (a) Area-weighted annual percentage of U.S. homogenous snowfall stations exceeding their own 90th percentile seasonal totals, from 1900–01 to 2010–11. Reference period is 1937–38 to 2006–07. (Adapted from Kunkel et al. 2009b). Thick blue line is the 11-yr running mean of the percentages. Dashed line is the number of grid cells with active stations each year. (b) As in (a), but for the percentage of the contiguous U.S. snowfall data below the 10th percentile.

Source: Kunkel et al., BAMS, 2013

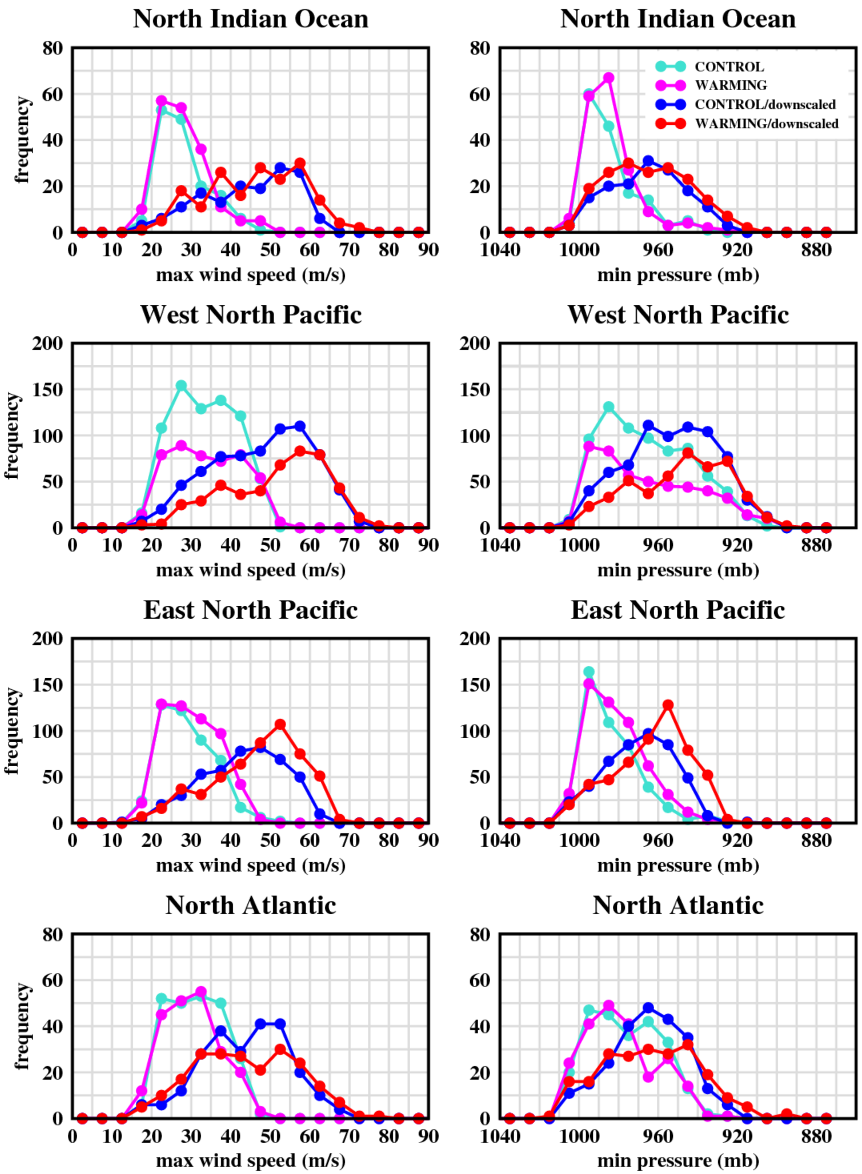
Normalized histograms of max wind tropical storms (1980-2008)



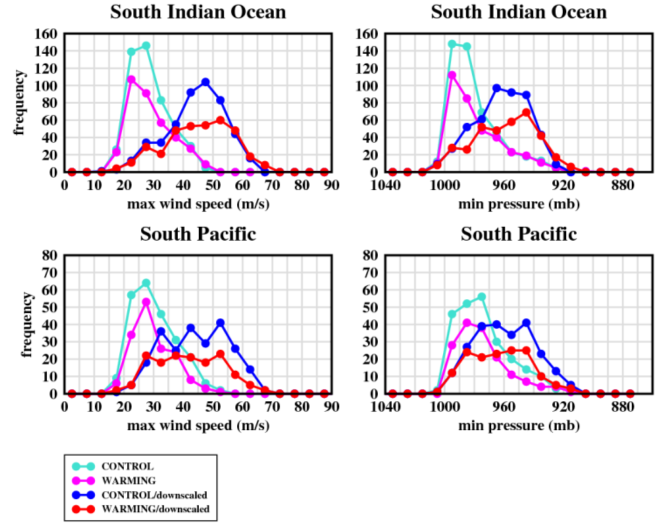
Present-Day Climate


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)
CPFs of min pressure
cumulative probability
min pressure (mb)
Cumulative histograms of min pressure
cumulative frequency
min pressure (mb)

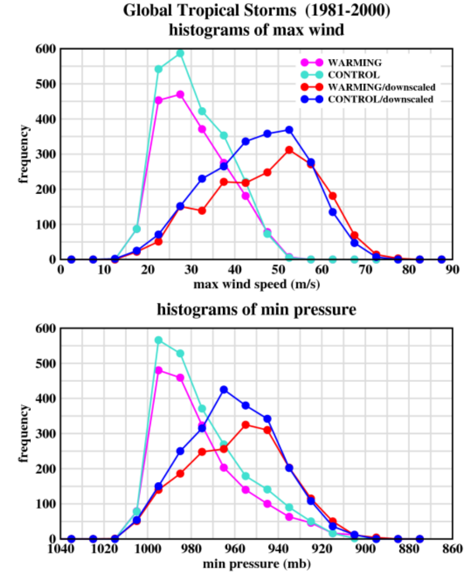
C180_hiram Intensity Histograms

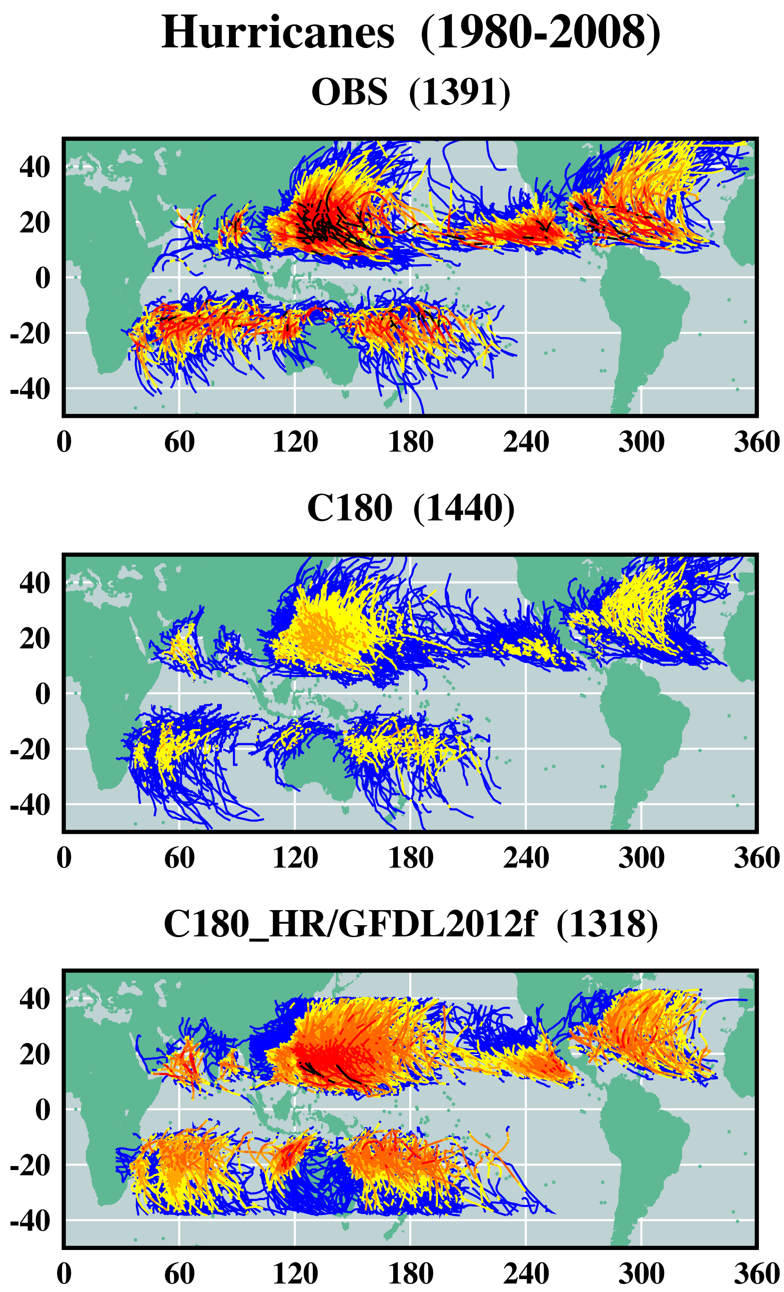


C180_hiram Intensity Histograms

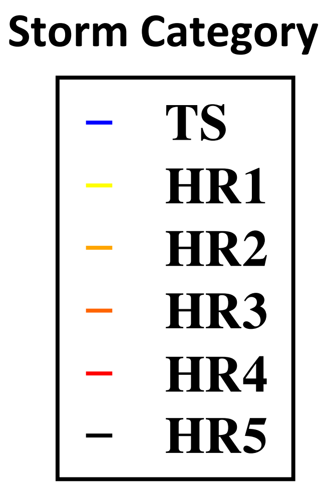


C180_hiram
Global Tropical Storms (1981-2000)

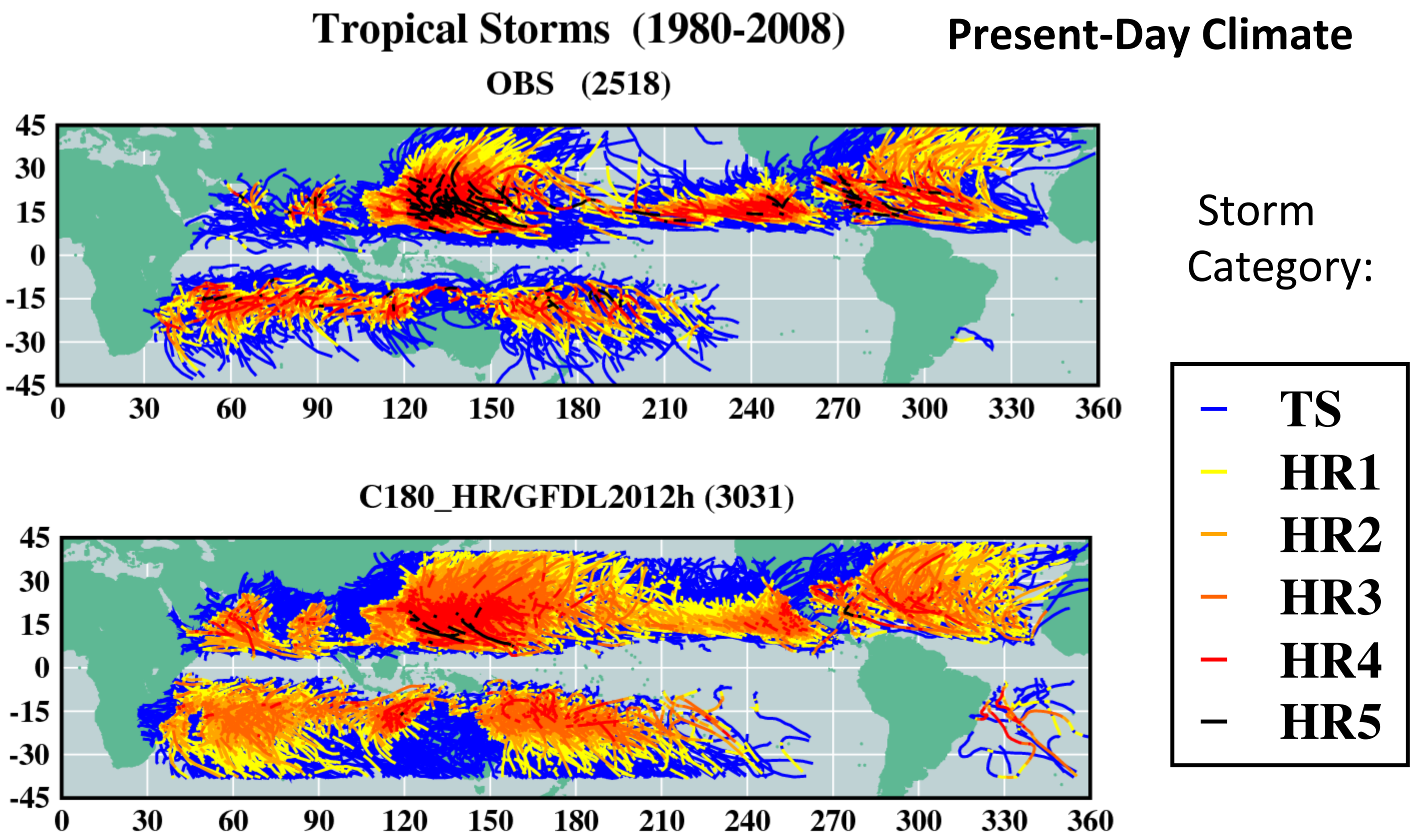




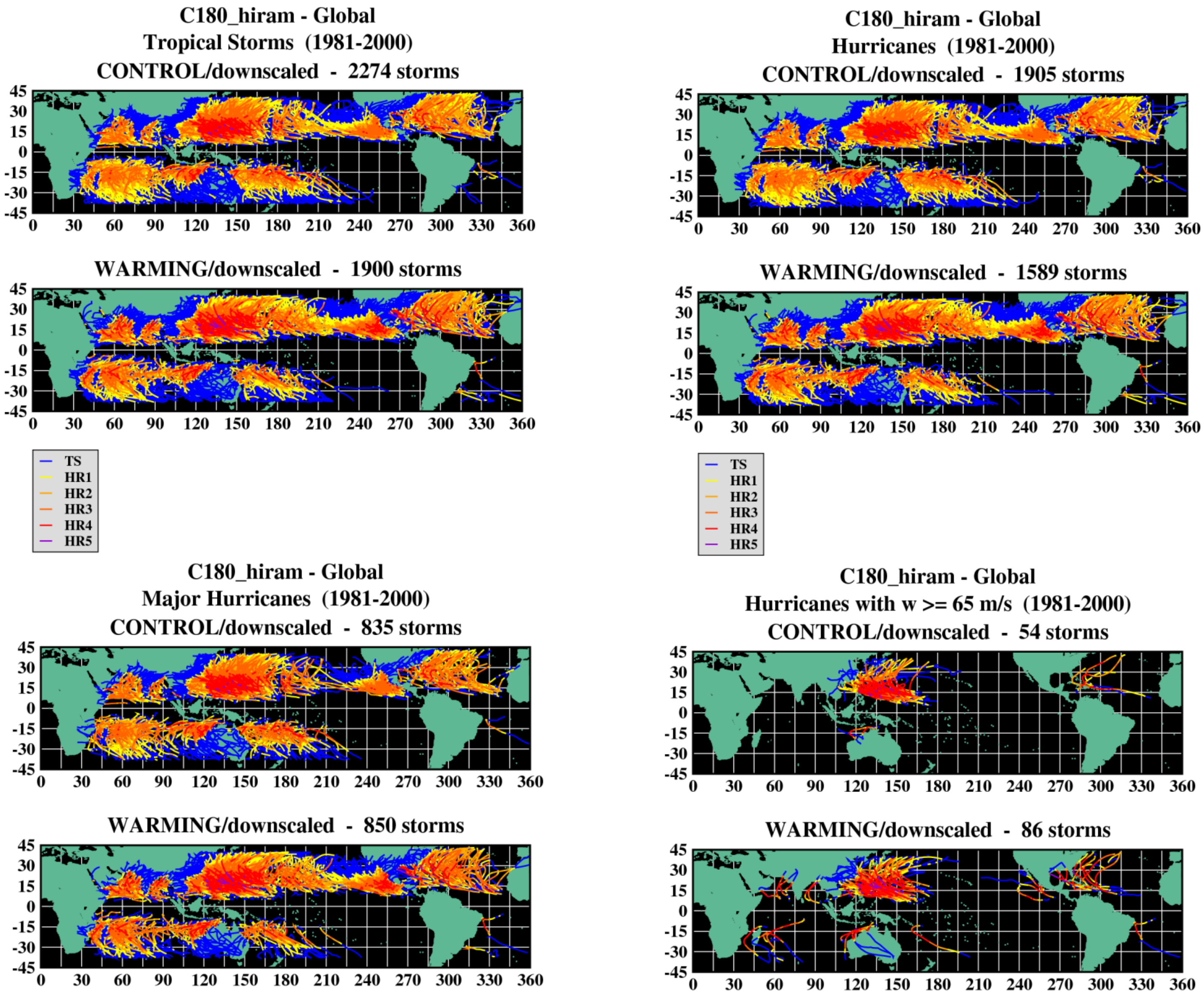
GFDL2012f (9 km grid, no vortex replacement)



Present-Day Climate



CMIP5/RCP4.5 Late 21st Century Projection



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:

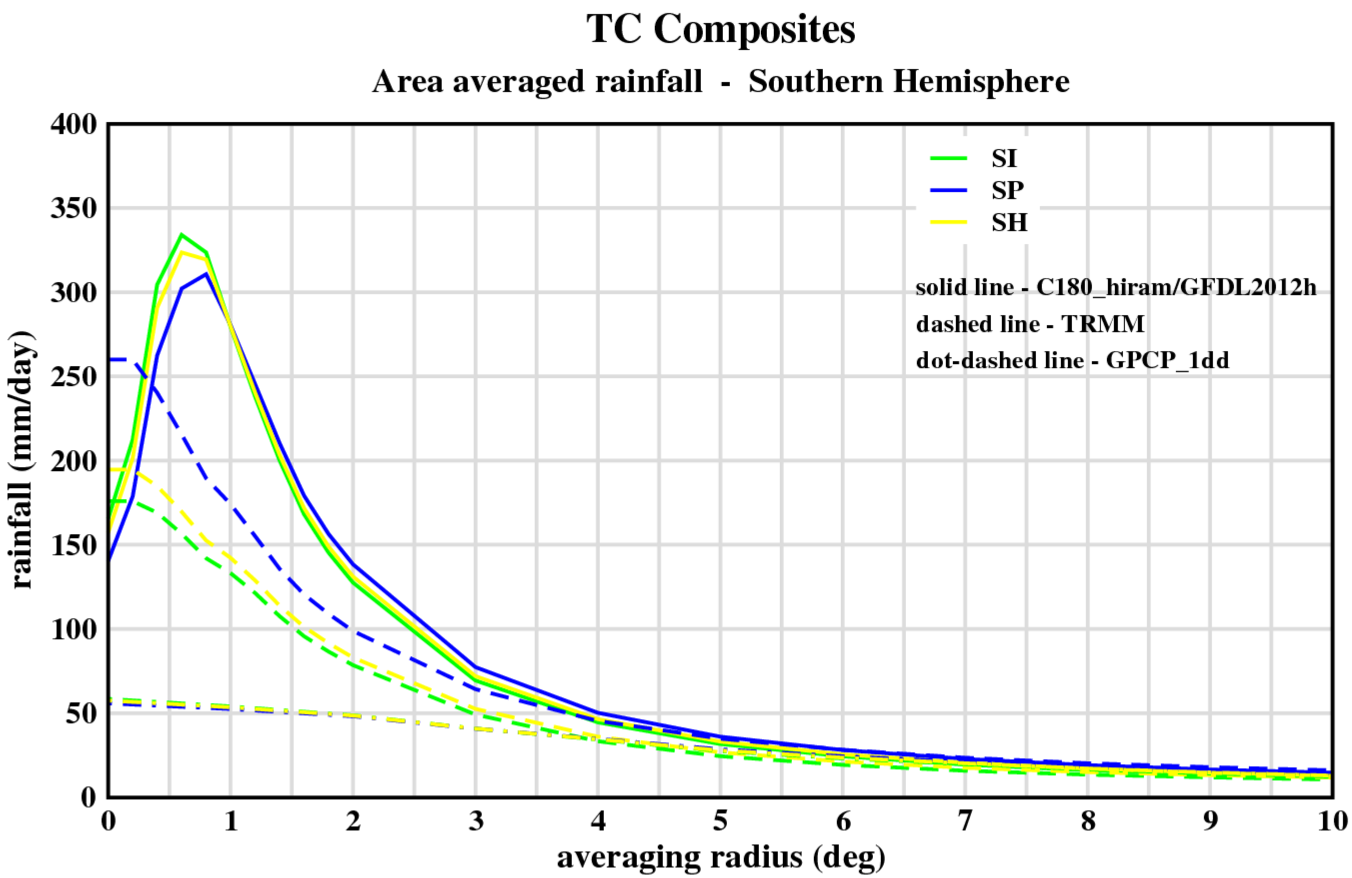
Detection and Attribution:

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.

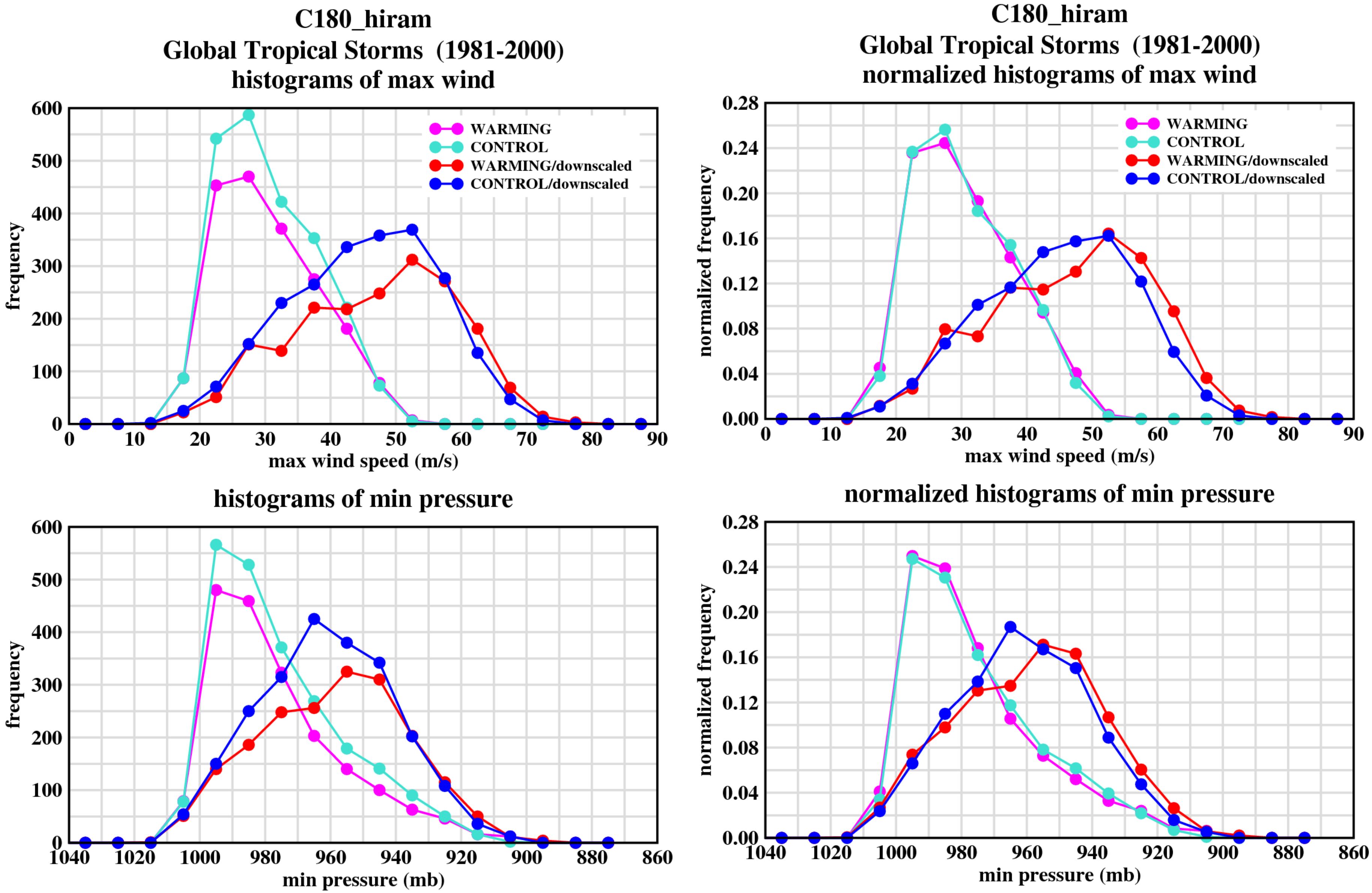
Source: WMO Expert Team on Climate Change Impacts on Tropical Cyclones. February 2010

Future Climate Projections- Some notes on ocean coupling

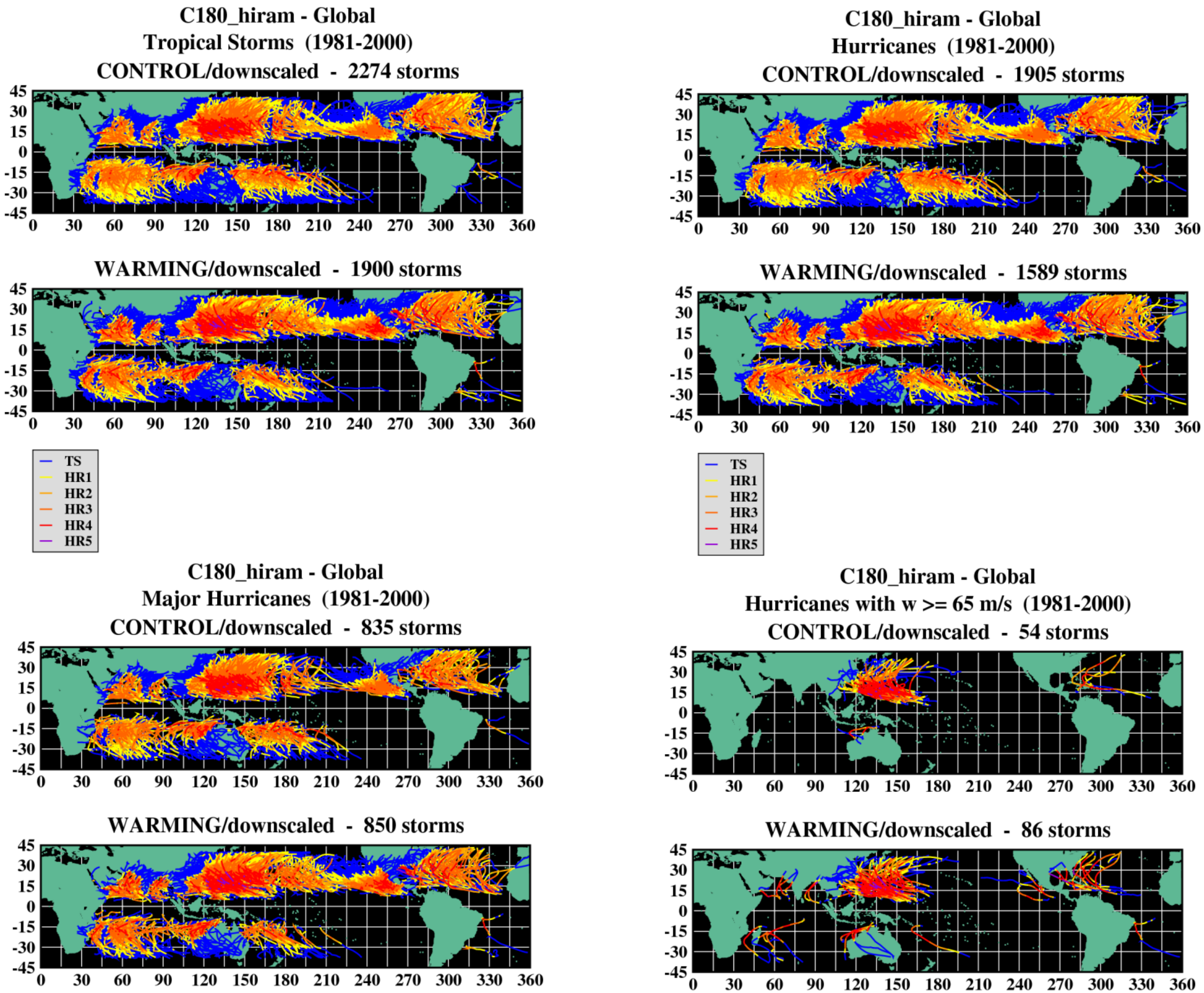
- GFDL hurricane model includes a three-dimensional ocean component to simulate cool wakes and their interaction with the storm. We are one of just a few groups that attempt to incorporate this effect in our TC/climate change studies for high-resolution (intense TC) simulations.
- Knutson, Tuleya, Shen, 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
rainfall (mm/day)
averaging radius (deg)
SI
SP
SH
solid line - C180_hiram/GFDL2012h
dashed line - TRMM
dot-dashed line - GPCP_1dd
0
50
100
150
200
250
300
350
400
0
1
2
3
4
5
6
7
8
9
10

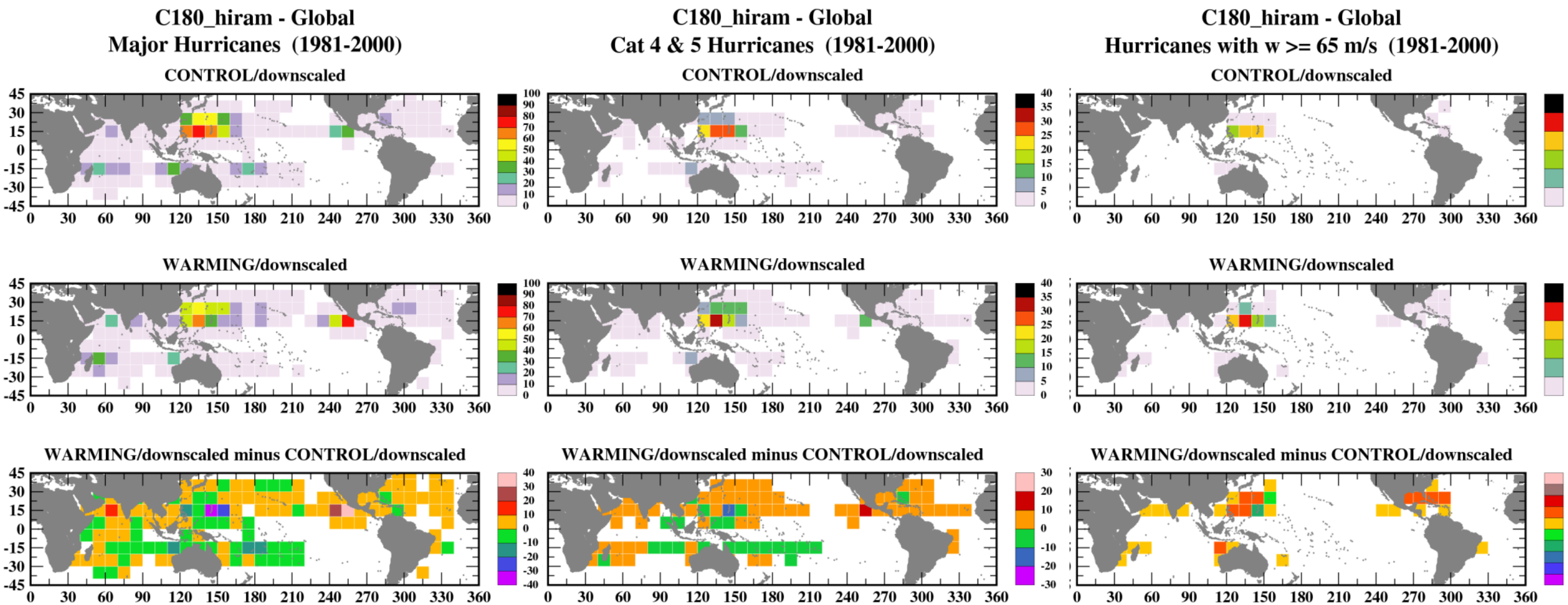
CMIP5/RCP4.5 Late 21st Century Projection



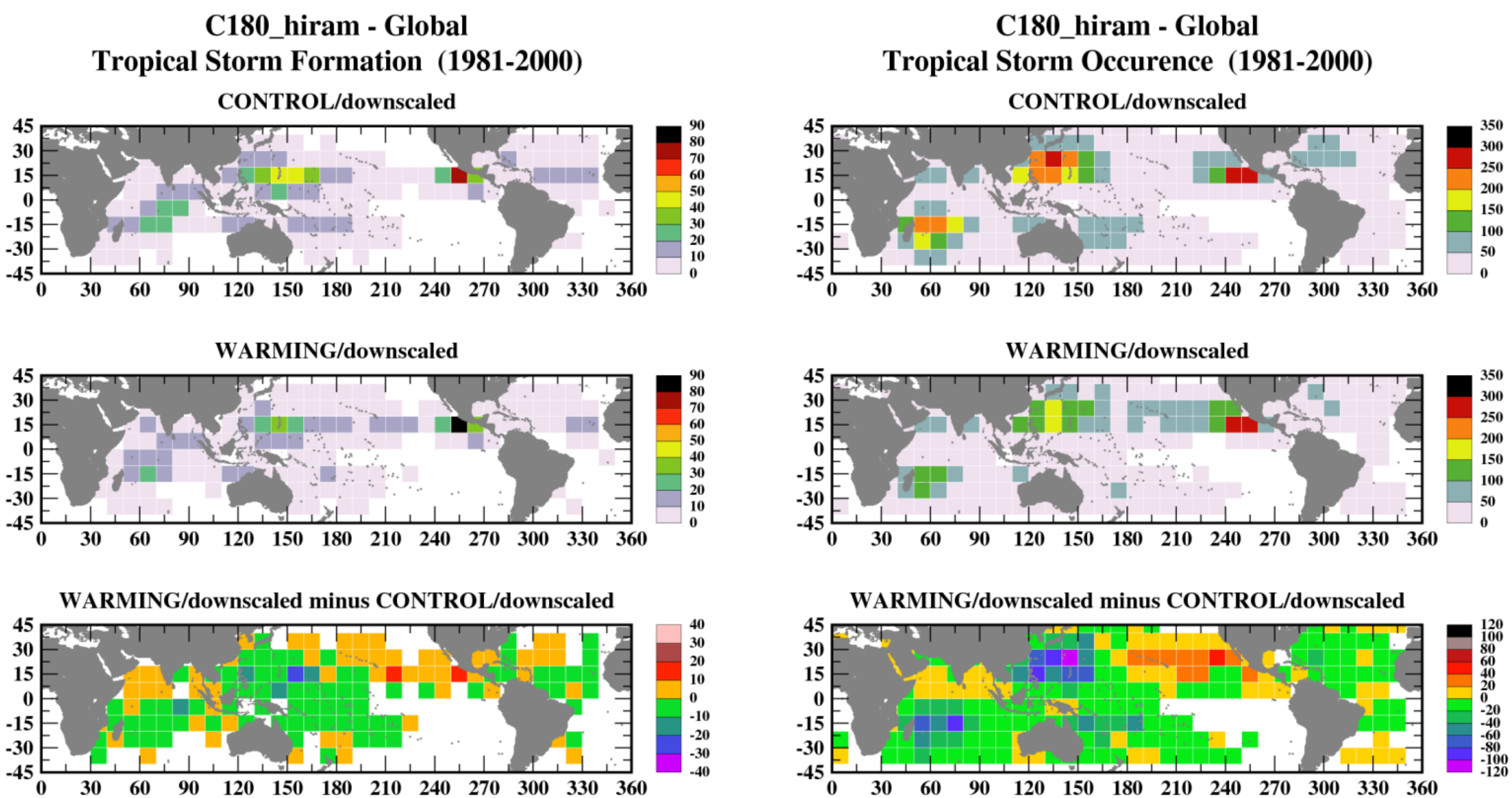
CMIP5/RCP4.5 Late 21st Century Projection



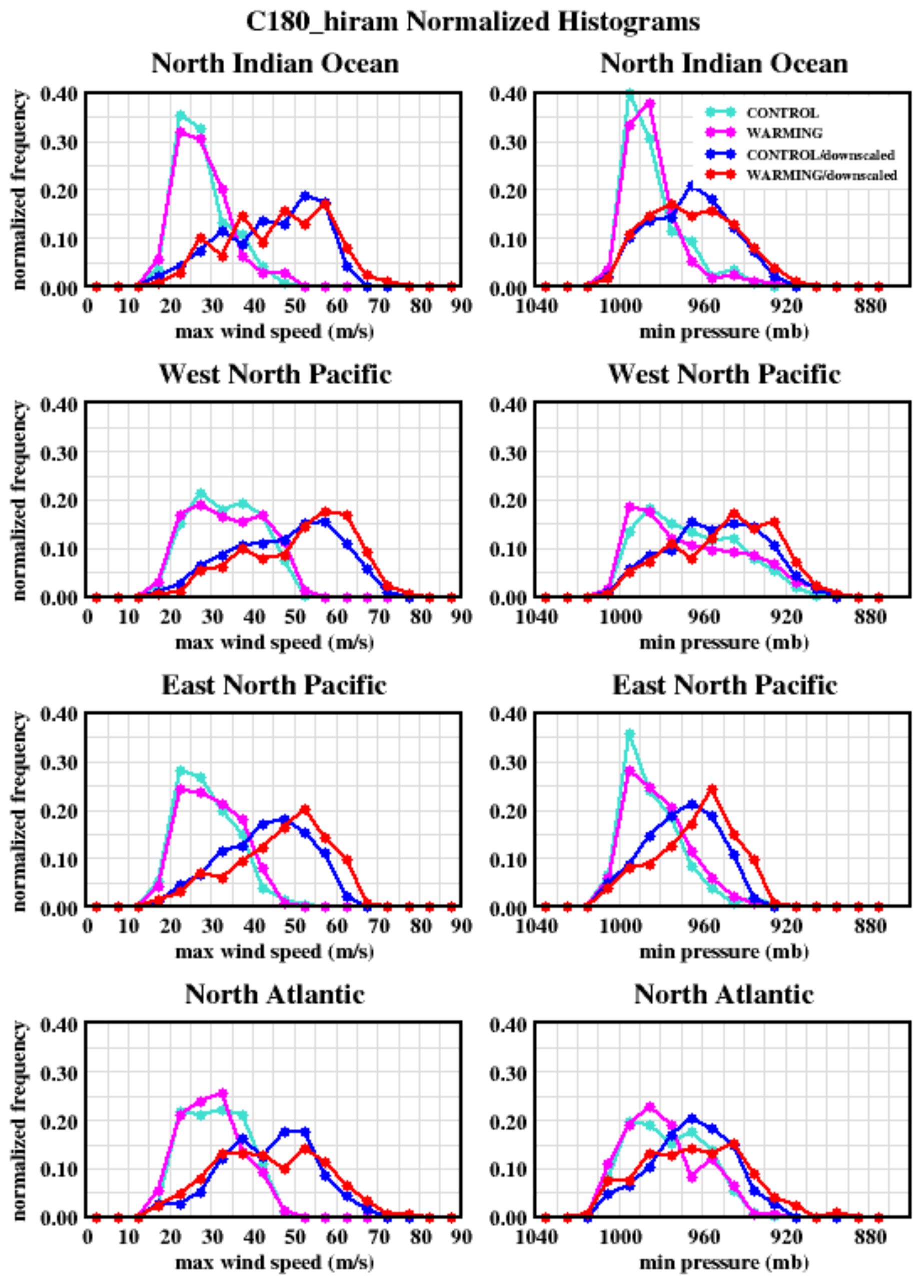
CMIP5/RCP4.5 Late 21st Century Projection: TC Occurrence



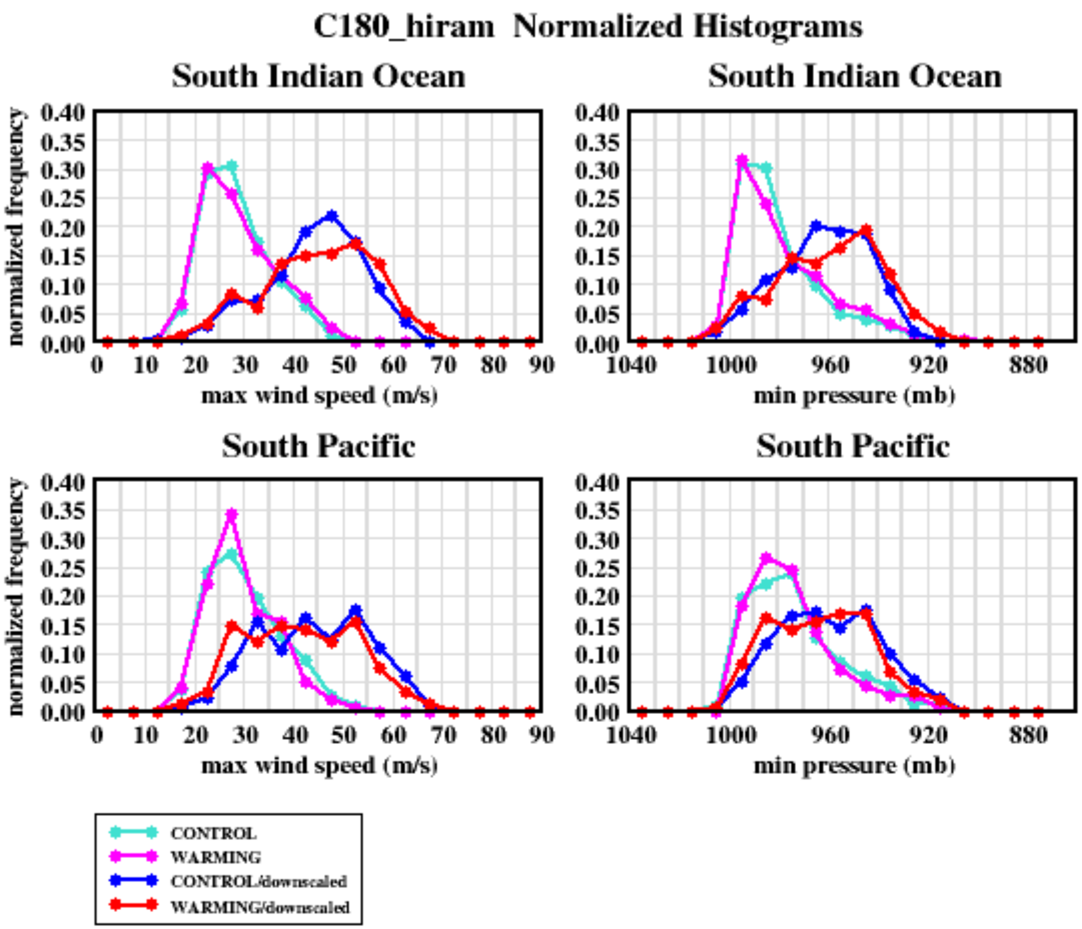
CMIP5/RCP4.5 Late 21st Century Projection: Tropical Storm Formation vs. Occurrence



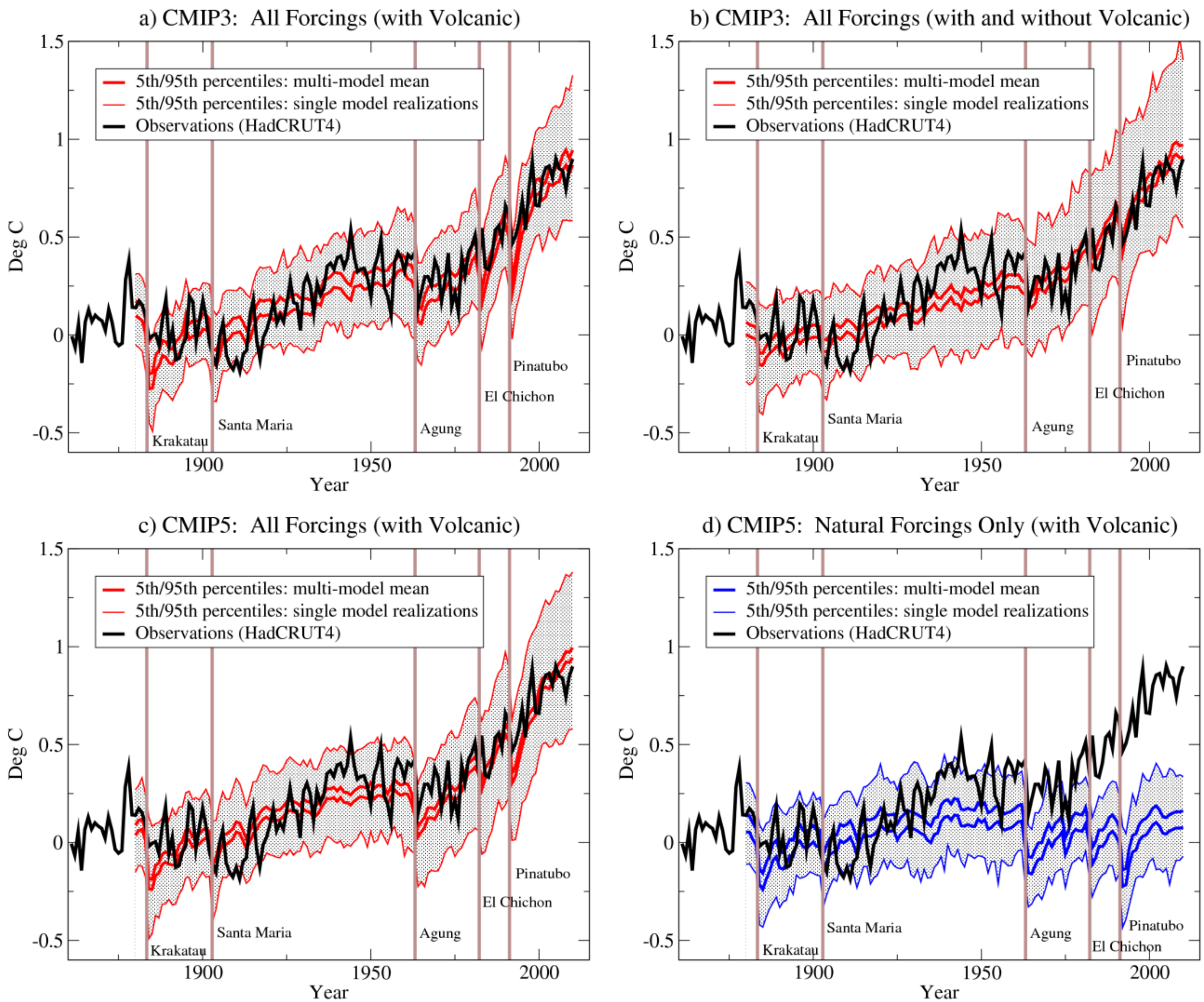
CMIP5/RCP4.5 Late 21st Century Projection



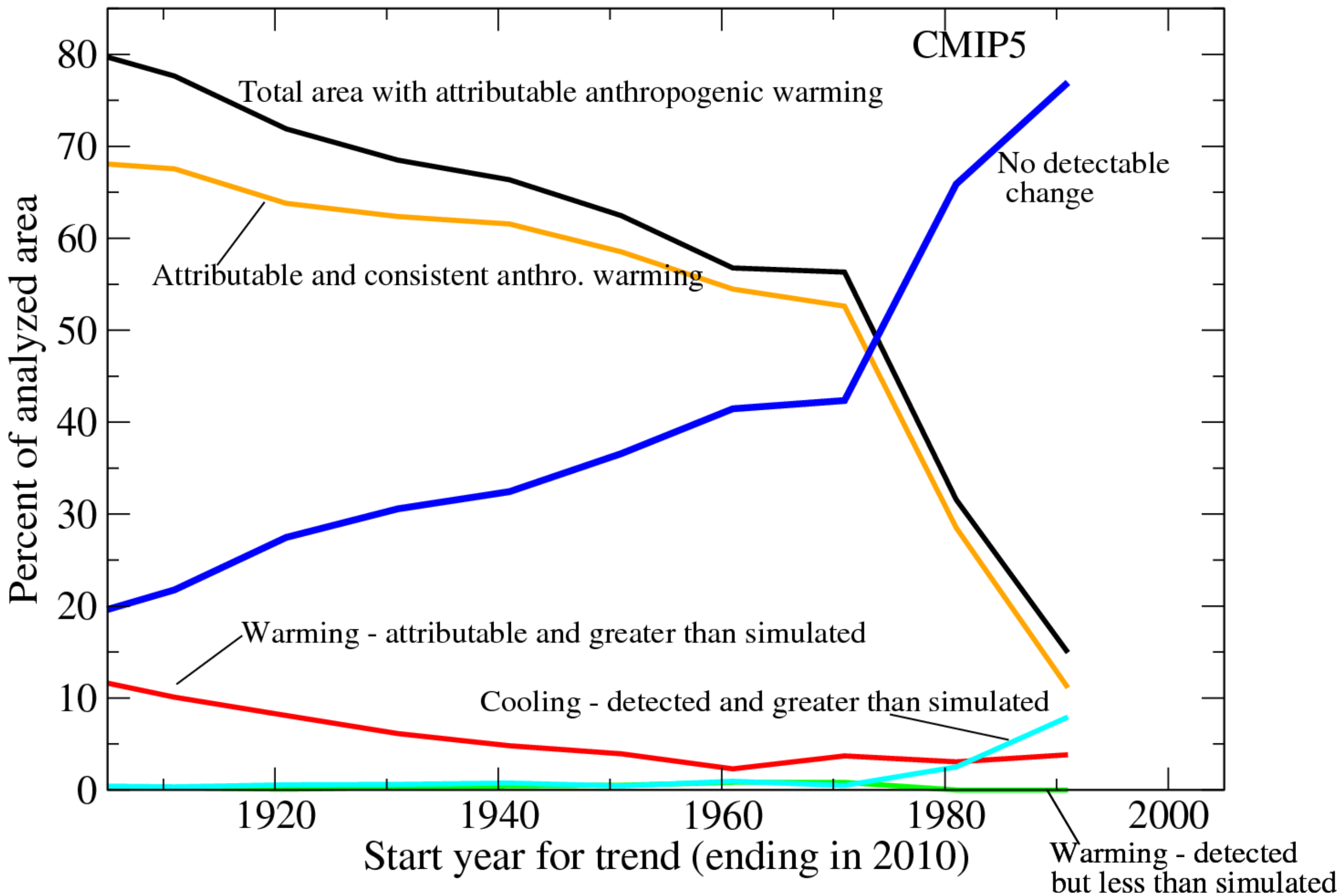
CMIP5/RCP4.5 Late 21st Century Projection



Global Mean Surface Temperature Anomalies

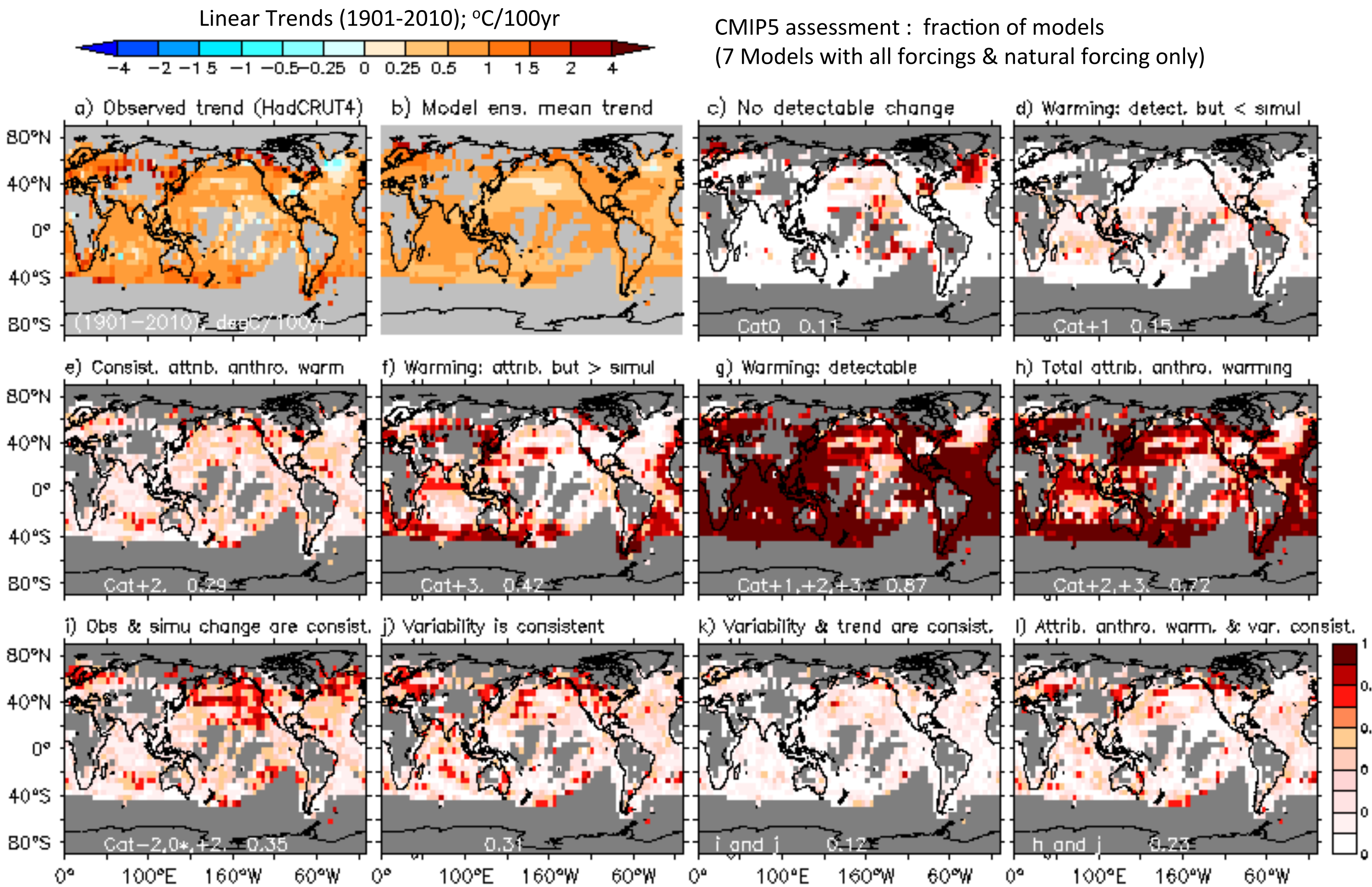


Comparison of CMIP5 ensemble mean trend (7-model subset) vs. Observations

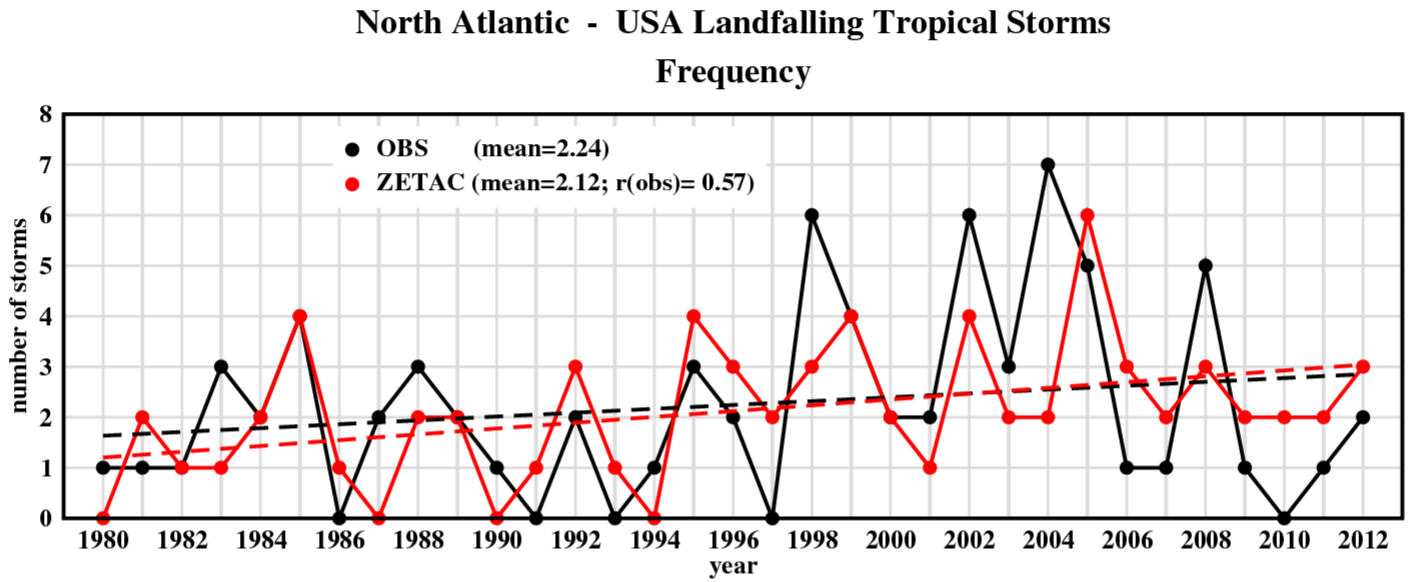


Fraction of CMIP5 models meeting certain detection/attribution criteria

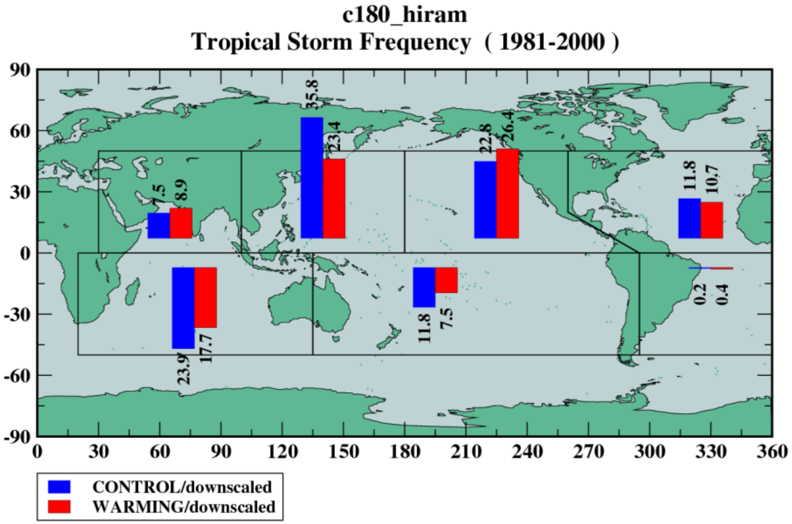
(7 CMIP5 Models with All-forcing runs & Natural Forcing Only runs)

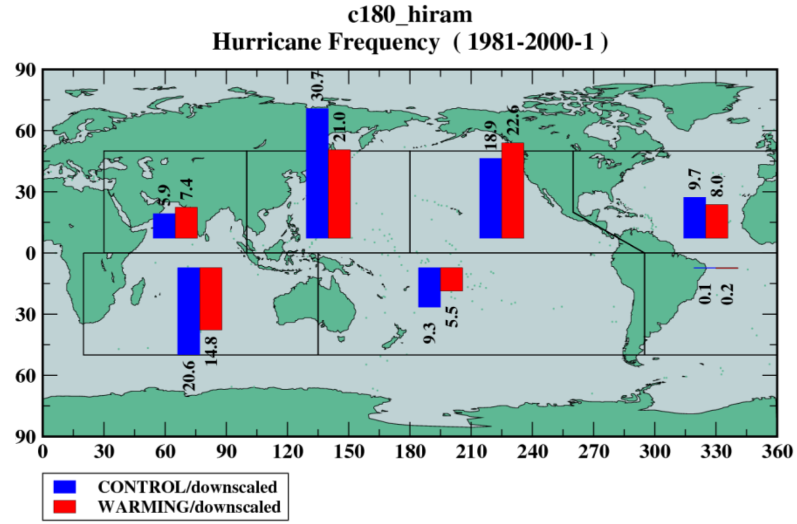


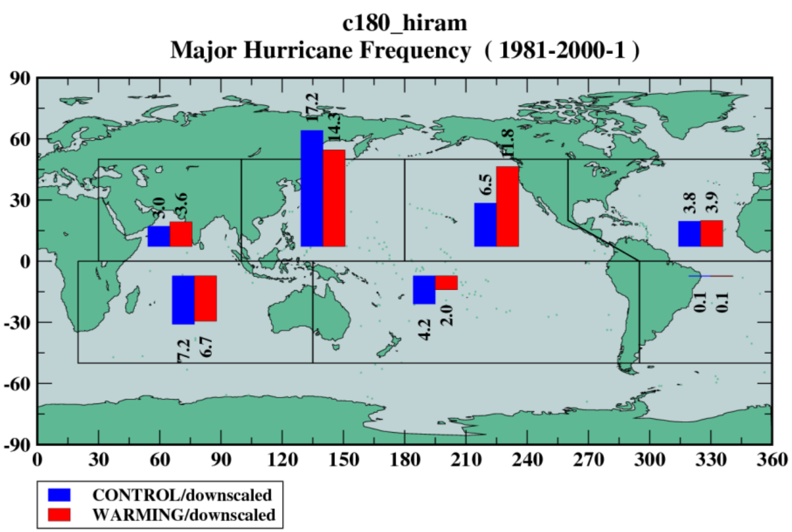
Future work: Simulations of US landfalling tropical storms



CMIP5/RCP4.5 Late 21st Century Projection

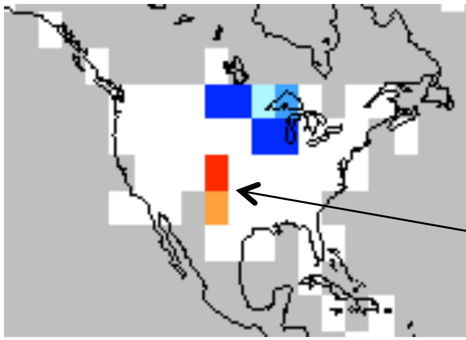




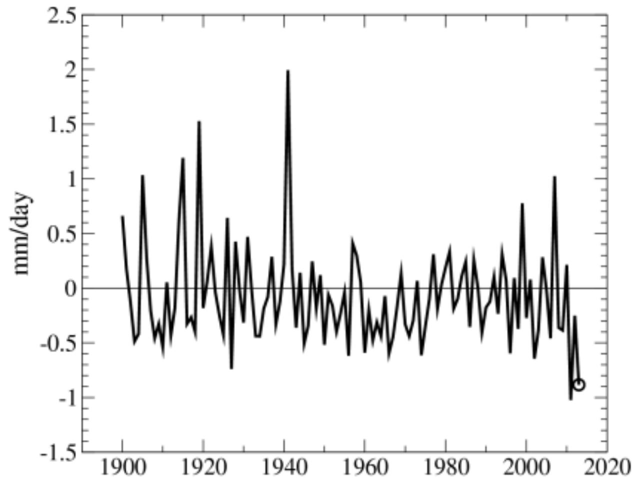


2013 Seasonal-Mean Precipitation Extremes: Climate Perspective

Mar.-May 2013 Extremes - Precipitation

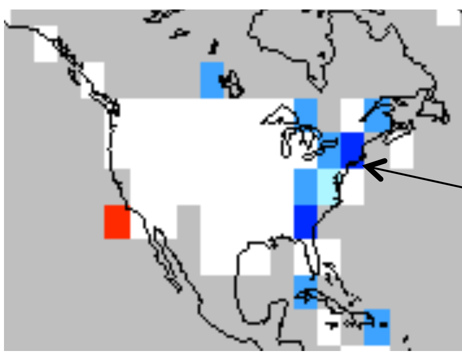


U.S. Southern Plains—Mar.-May

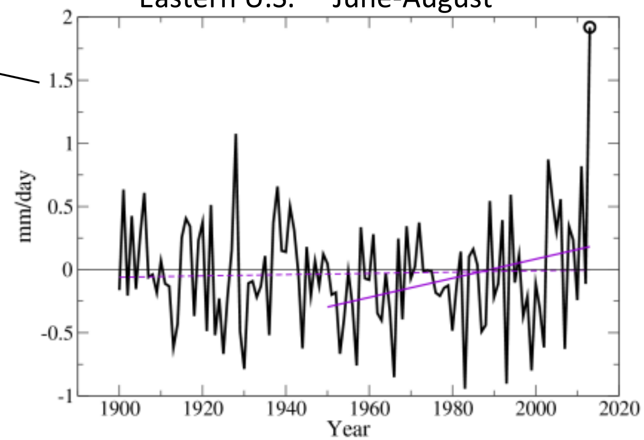


<u>U.S. Southern Plains region—Mar.-May:</u>
Non-significant trend;
Data inhomogeneities?

June-Aug. 2013 Extremes - Precipitation



Eastern U.S. – June-August

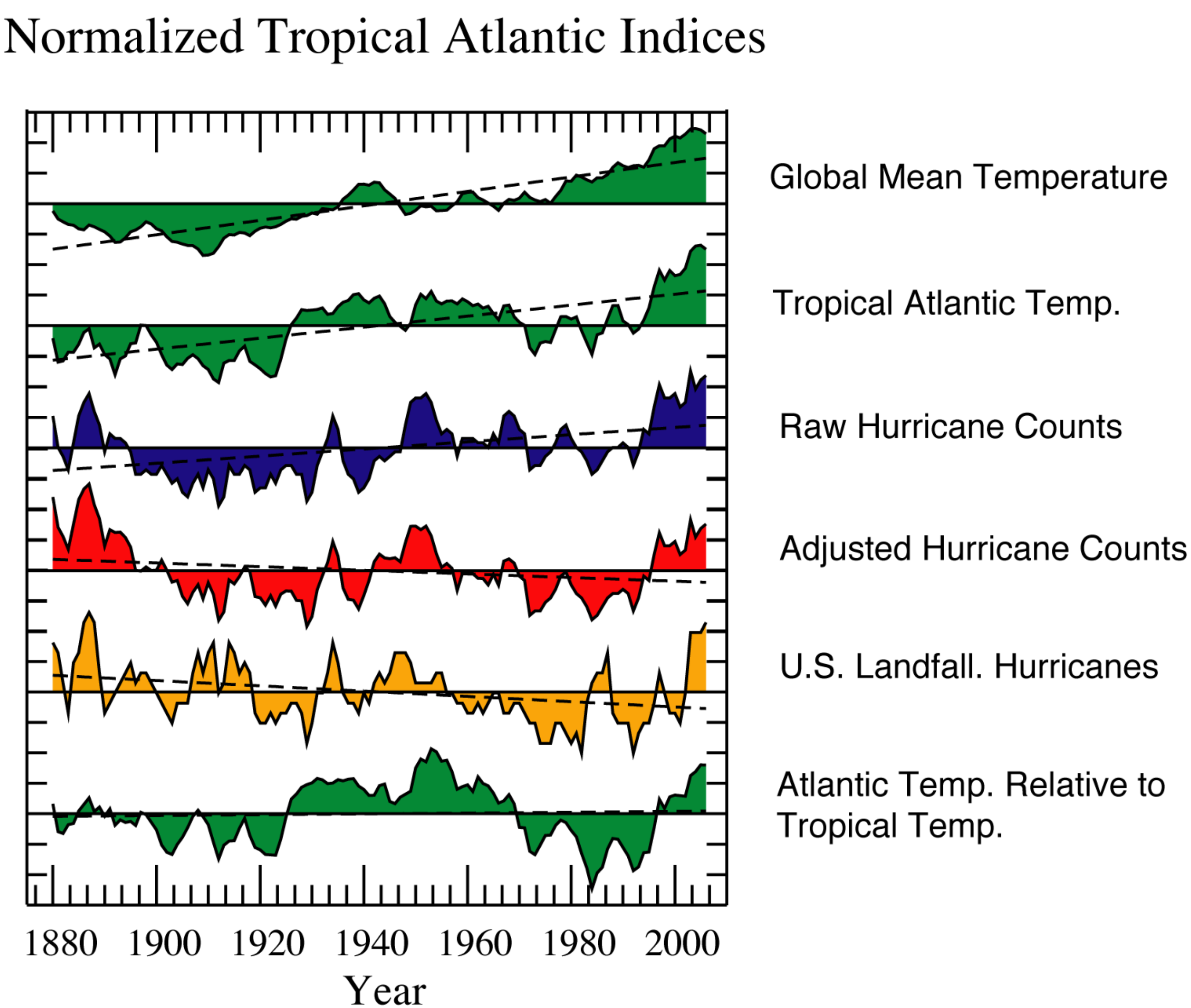


<u>Eastern U.S. region -- JJA:</u>
Non-significant trend from 1900;
Detectable trend from 1950 or later;
Detection not robust to excluding 2013
Trend attributable to Anthro. + Natural
Occurrence Ratio = 1.7 or undefined

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)

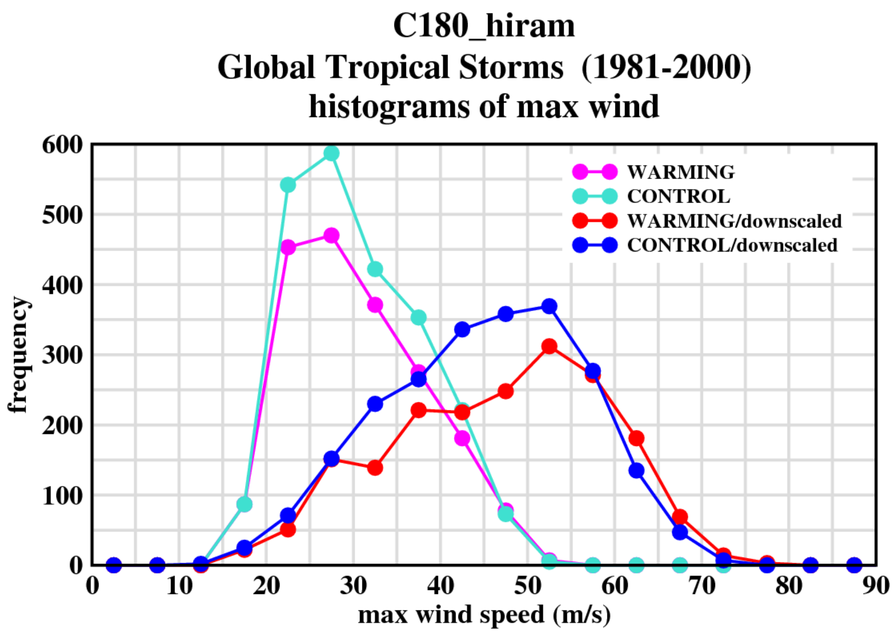
Future TC Projections: Atlantic Basin Methodology

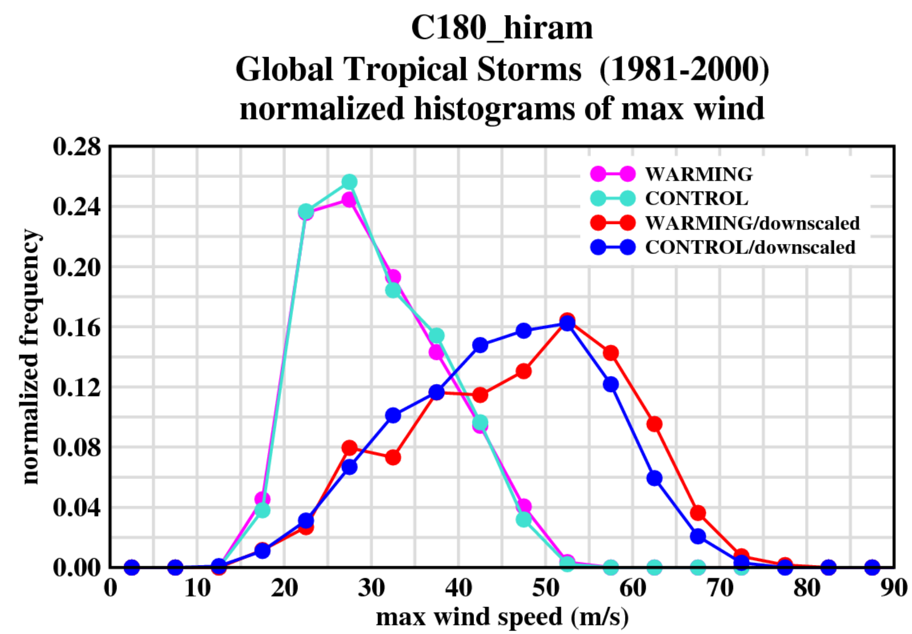
- Simulate Atlantic tropical cyclone activity with 18 km grid regional atmospheric model (Zetac)
  - Observed SSTs and NCEP Reanalyses (1980-2008)
  - Control boundary conditions + CMIP3 or CMIP5/ RCP4.5 Early and Late 21st century climate changes
- Downscale all individual storm cases into GFDL hurricane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

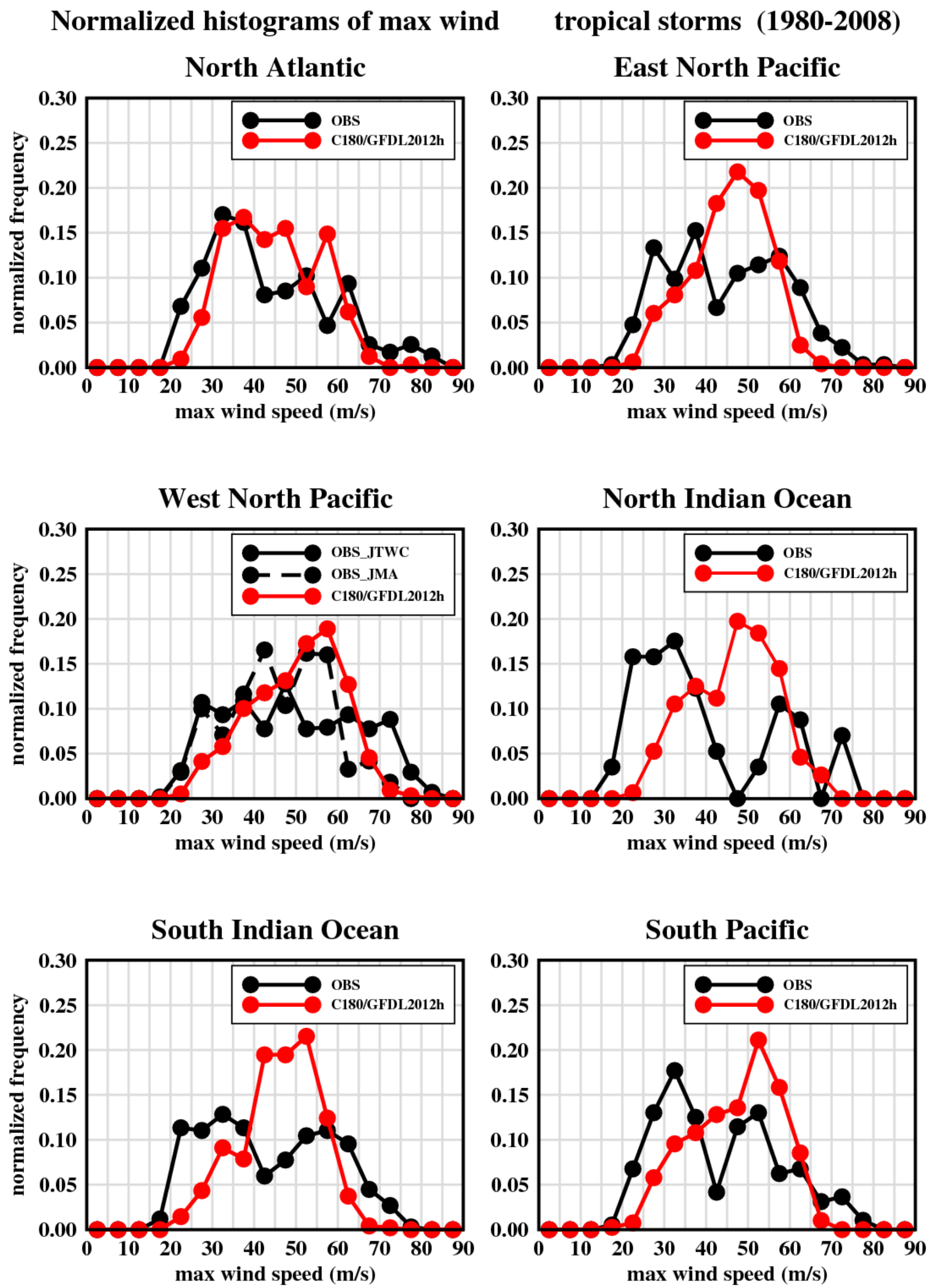
Power Dissipation Index: Global: **-9.7%**

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.

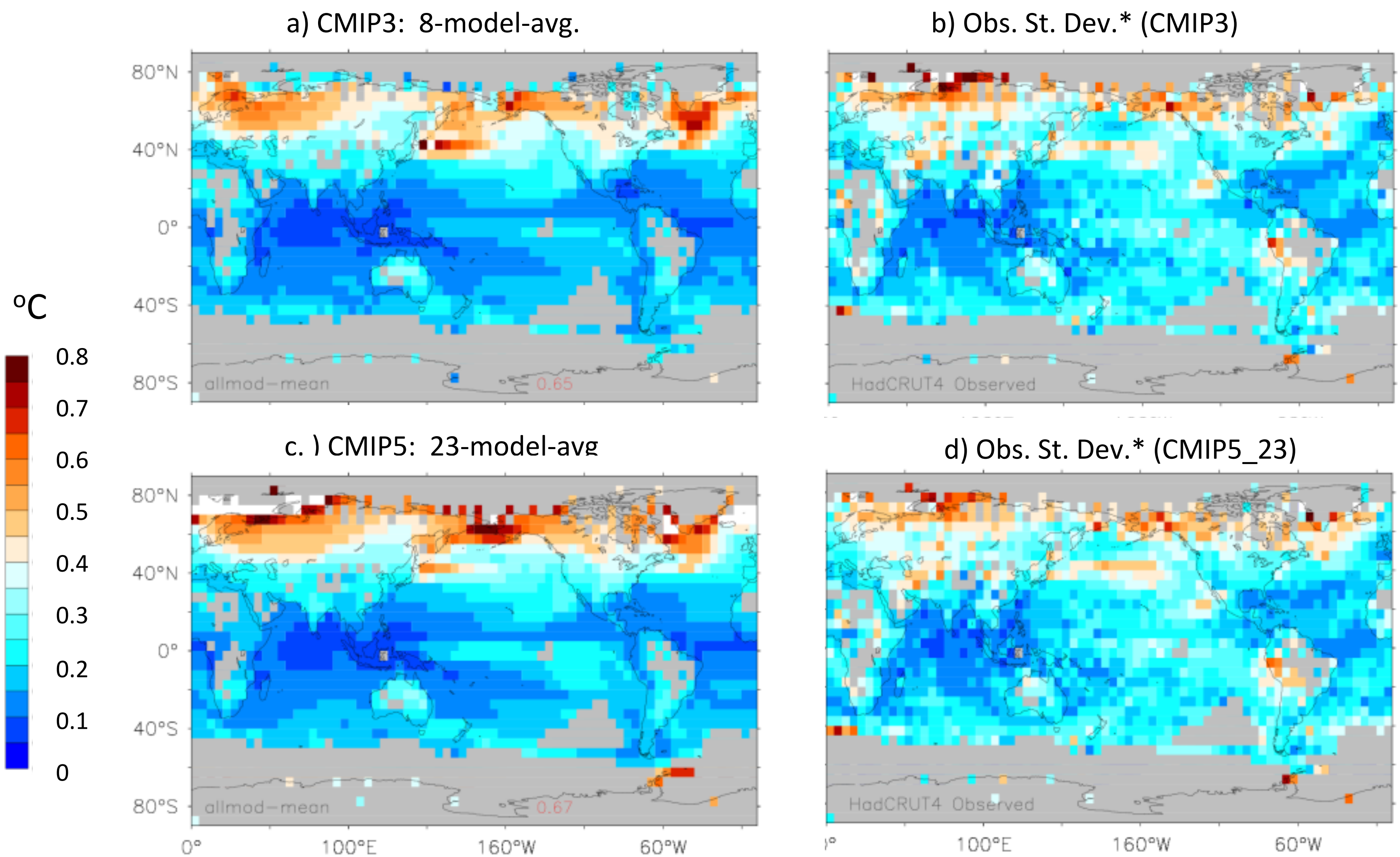
Preliminary Conclusions: Global TC Projections

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%

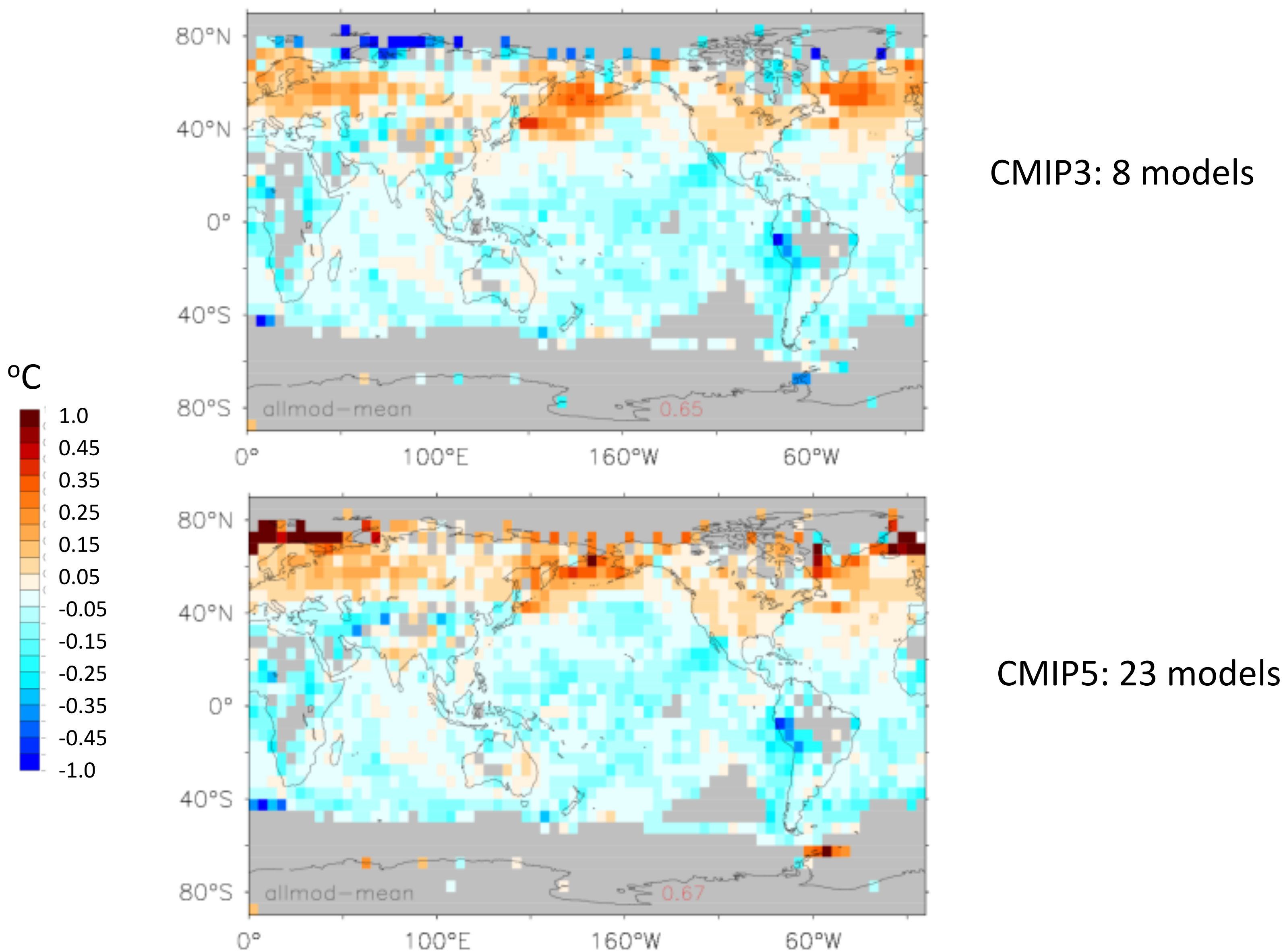
2. These projections vary considerably by basin:
   Cat 4-5 frequency increases +24% globally; +42 in North Atlantic; +340% in NE Pacific; +200% in N. Indian Ocean; but decreases by -6% in NW Pacific and -59% in SW Pacific.

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



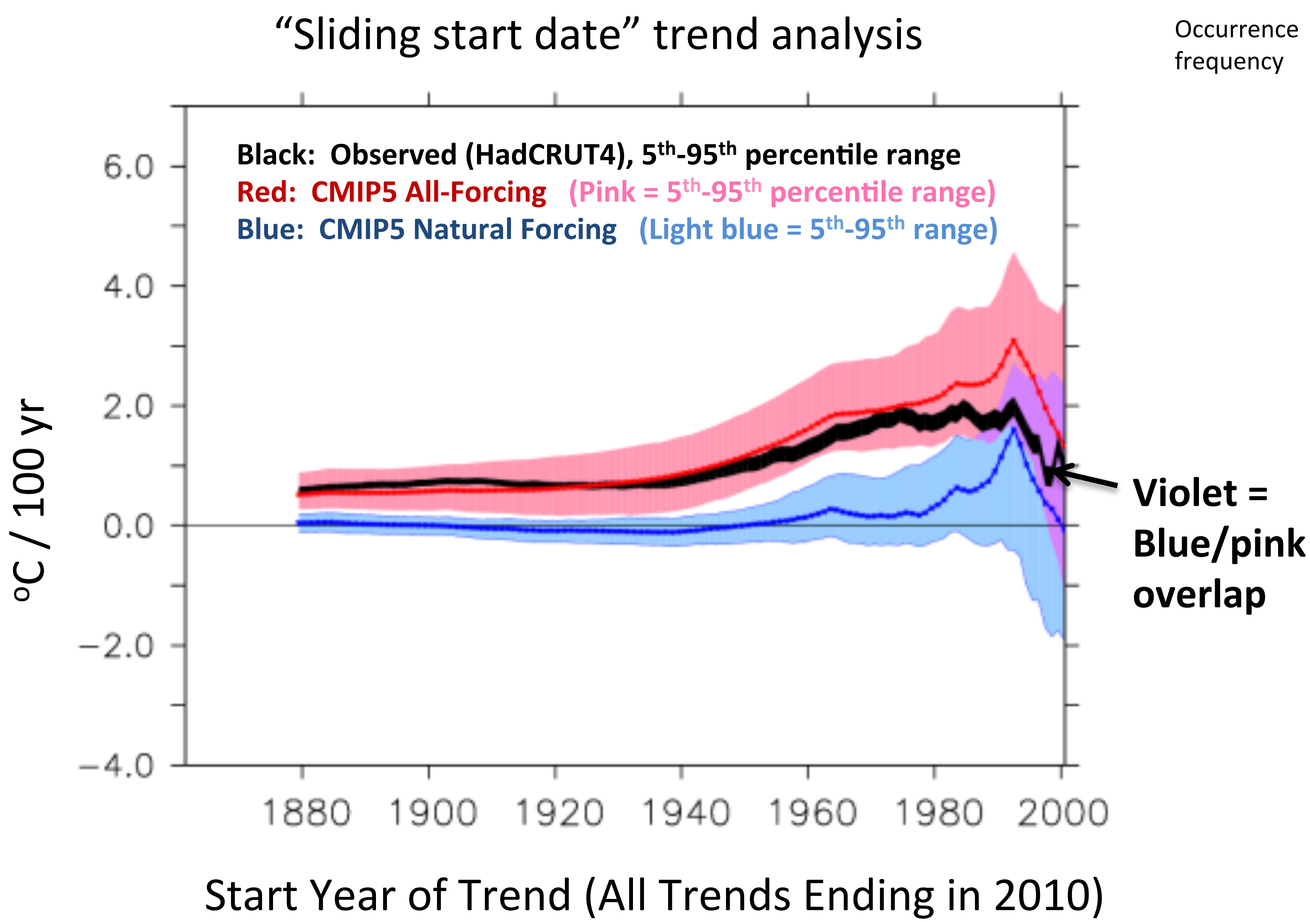
Notes: Model estimate is from control runs; observed estimate is based on the residual with All-Forcing ensemble mean subtracted. An additional adjustment was made to reduce the systematic error due to the computation method for creating the residual. We let each ensemble member substitute for observations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

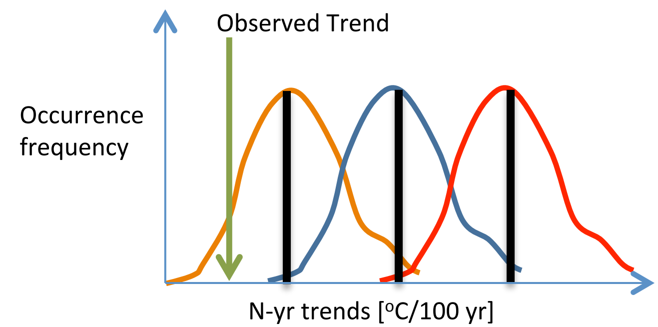
St. Deviation of low-freq. (>10 yr) variability: Model – Observed*



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

Global temperature attribution analysis: CMIP5 7-model ensemble

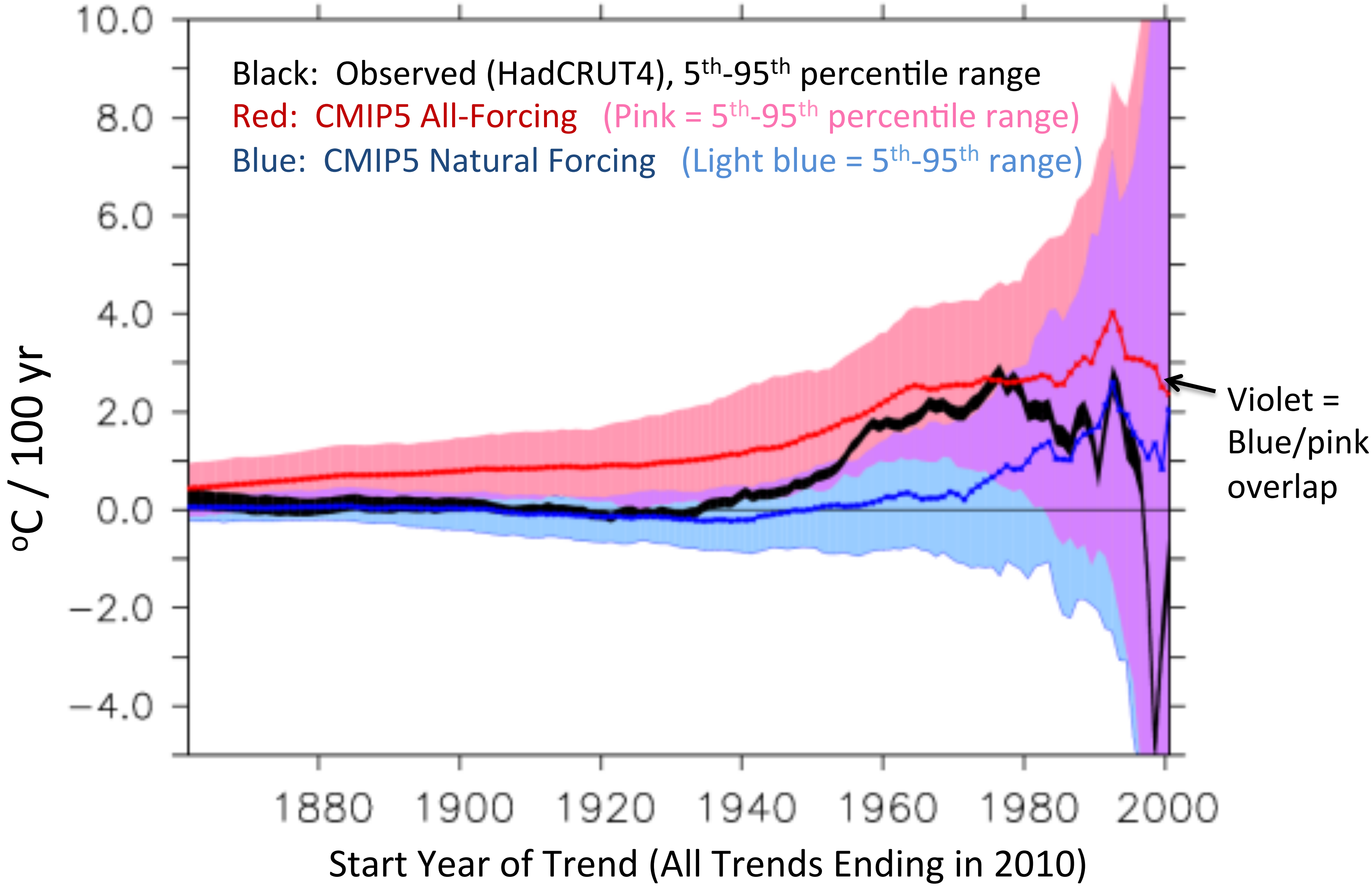




Note: Shaded regions are multi-model combined trend distributions and not formal 90% confidence intervals.

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

Southeast United States: Sliding Trend Analysis

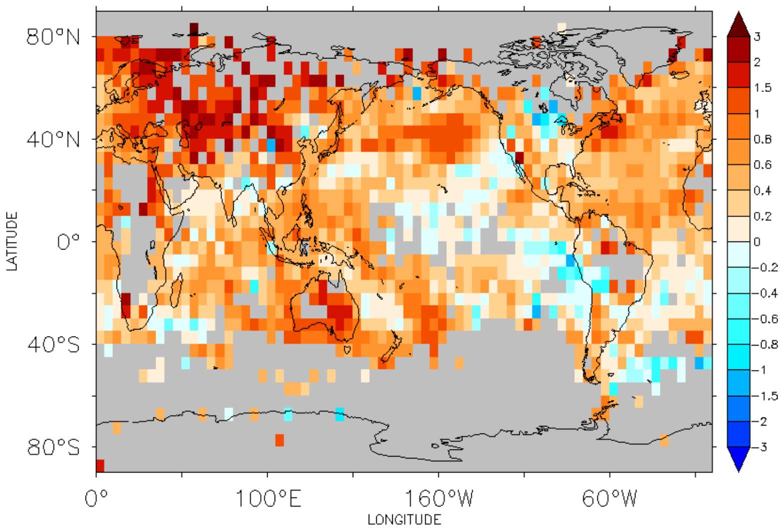


Source: Knutson, Zeng, and Wittenberg, *J. Climate* (2013)

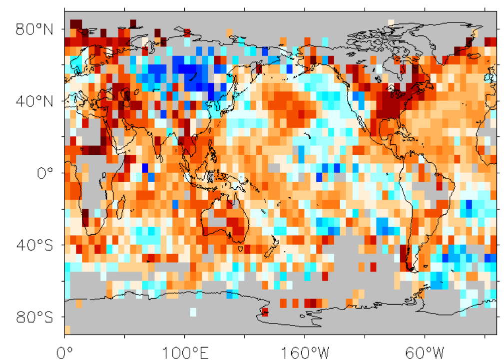
Explaining Extreme Events from a Climate Perspective…

Regional Surface Temperature anomalies for 2013

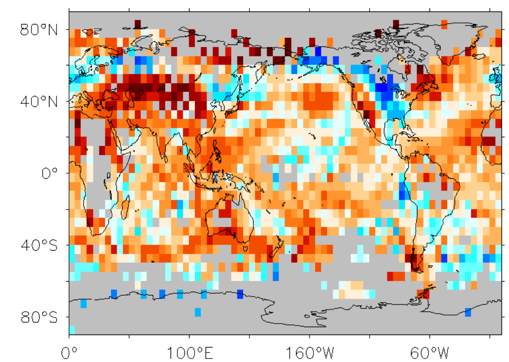
Annual 2013 anomalies



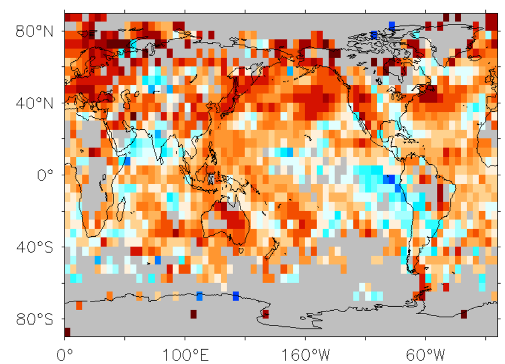
Dec.-Feb. 2013 anomalies



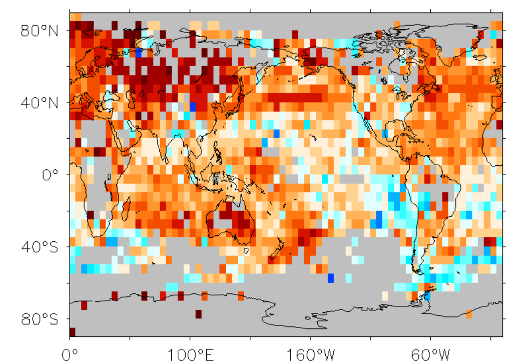
Mar.-May 2013 anomalies



June-Aug. 2013 anomalies



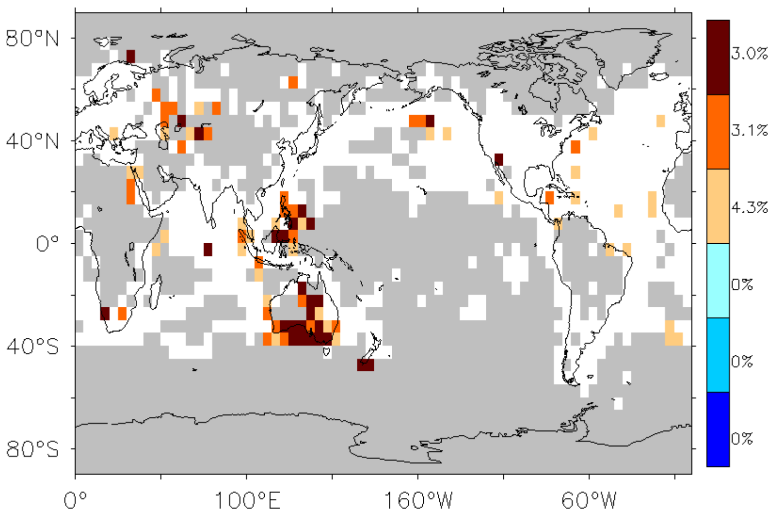
Sept.-Nov. 2013 anomalies



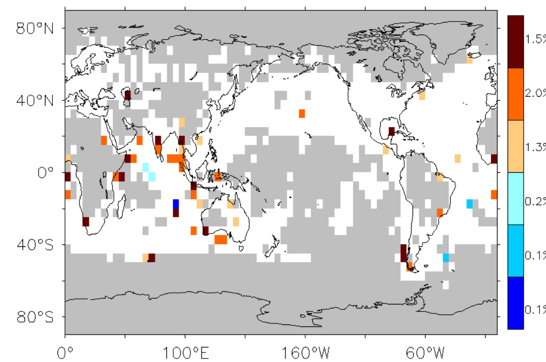
Source: Knutson, Zeng, and Wittenberg, *BAMS,* accepted (2014)

Surface temperature seasonal- or annual-mean extremes for 2013

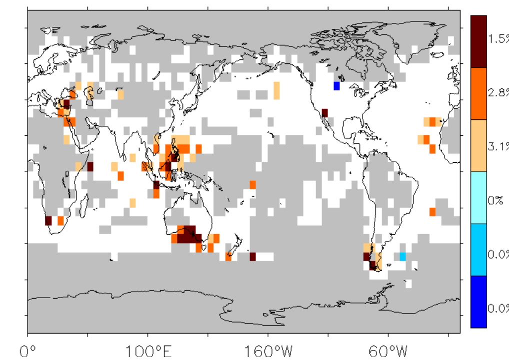
Annual means: 2013 extremes



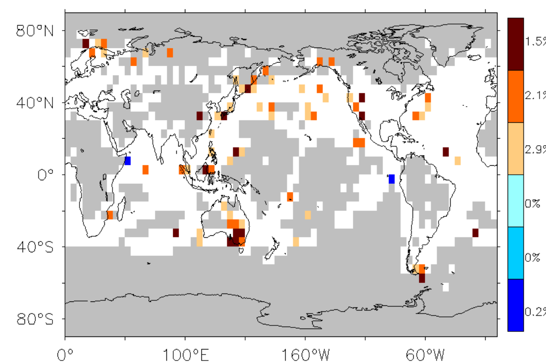
Dec.-Feb. 2013 seasonal extremes



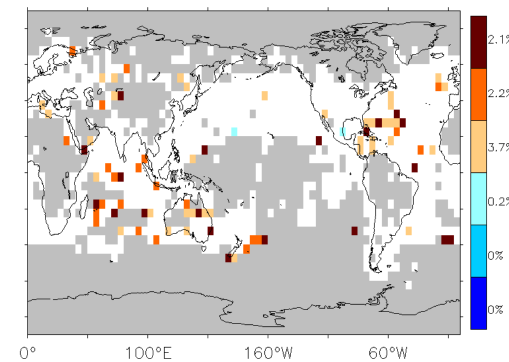
Mar.-May 2013 seasonal extremes



June-Aug. 2013 seasonal extremes



Sept.-Nov. 2013 seasonal extremes



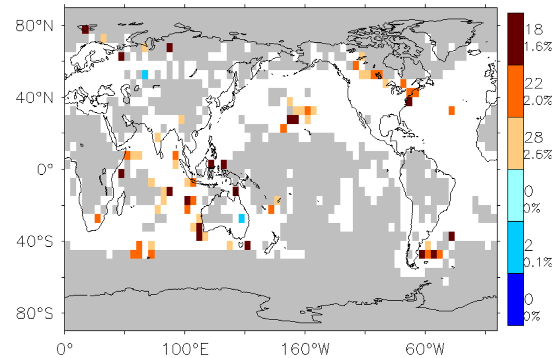
Map Legend

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

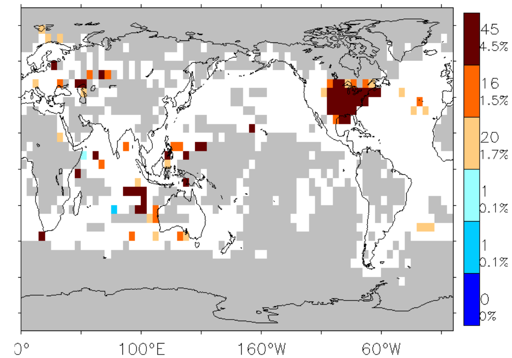
Source: Knutson, Zeng, and Wittenberg, *BAMS,* accepted (2014)

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

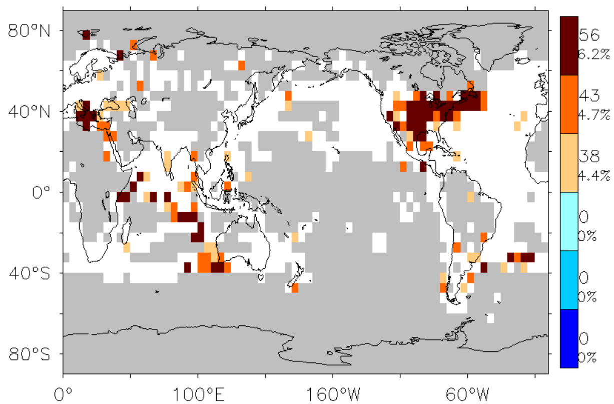
DJF 2012 extremes



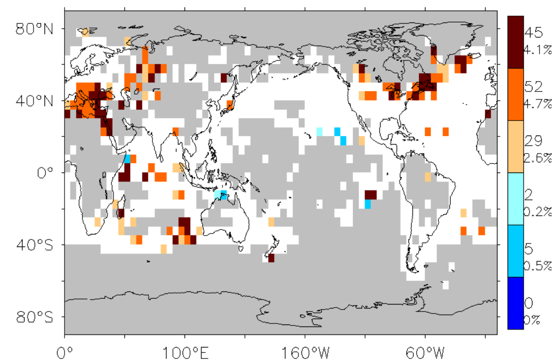
MAM 2012 extremes



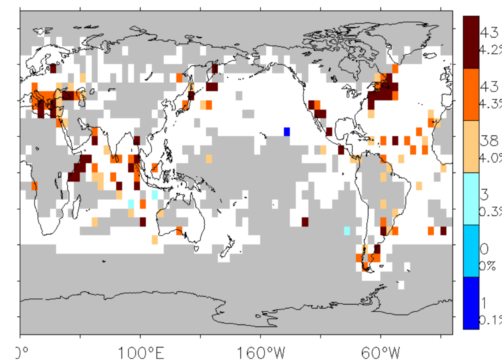
Annual 2012 extremes



JJA 2012 extremes



SON 2012 extremes

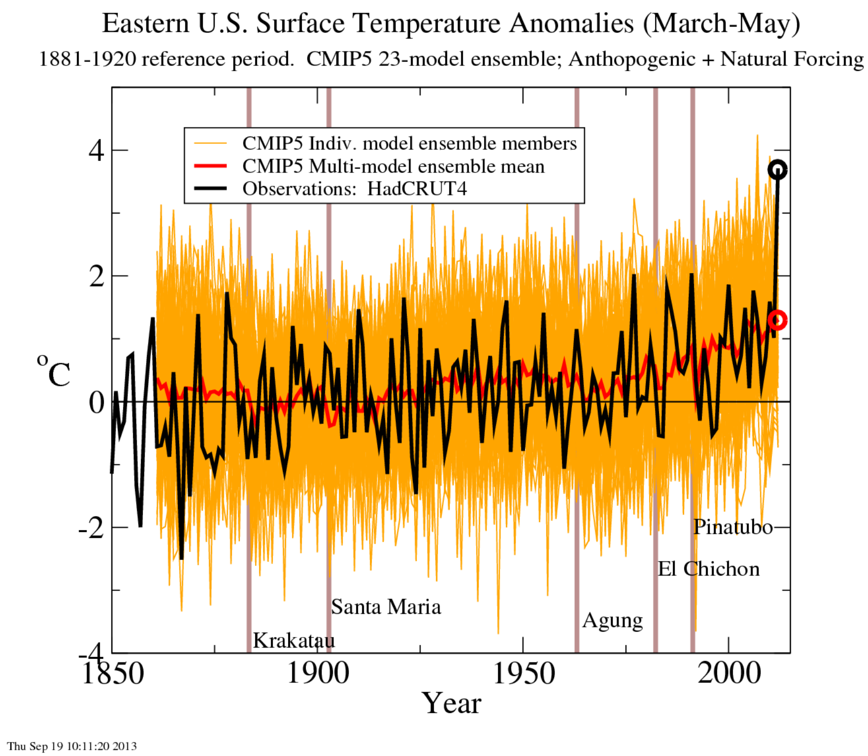


Map Legend

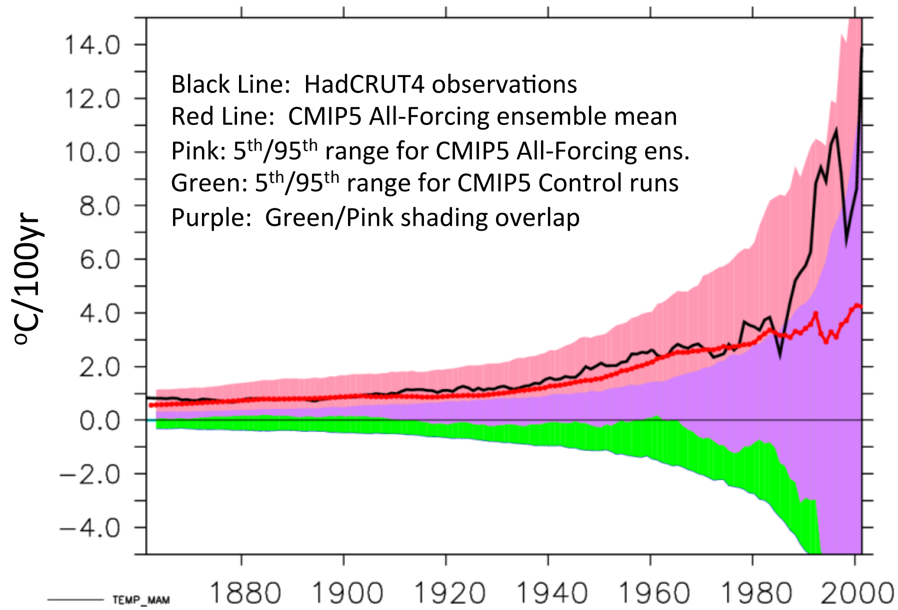
- Highest
- 2nd highest
- 3rd highest
- 3rd lowest
- 2nd lowest
- Lowest

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

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



b) Trend assessment



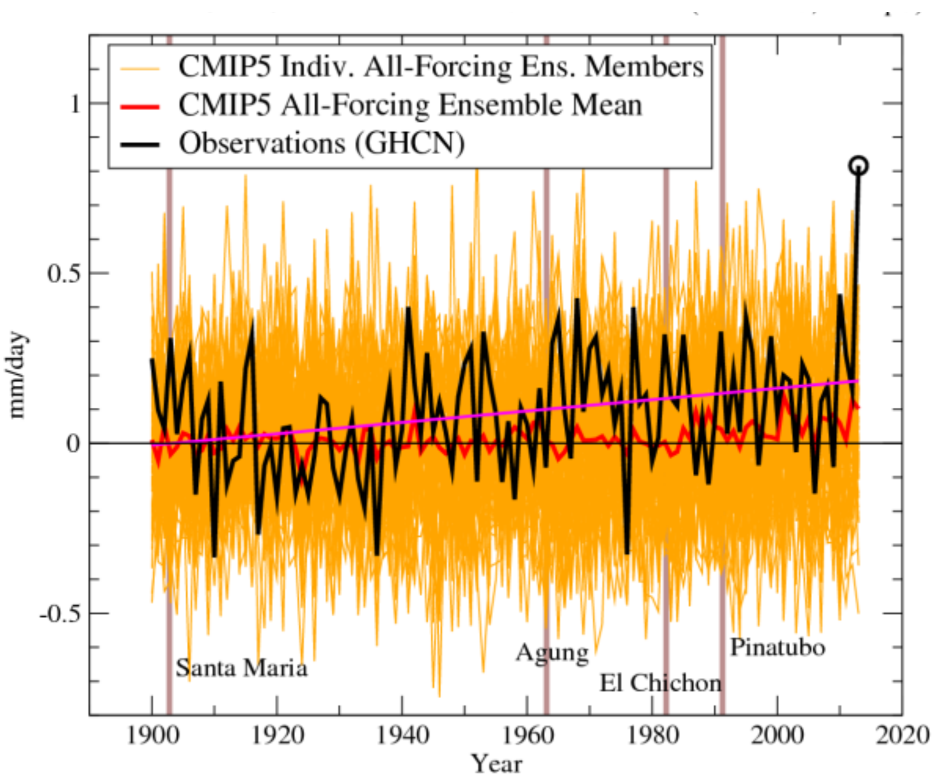
Trend start year (all trends ending in 2012)

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

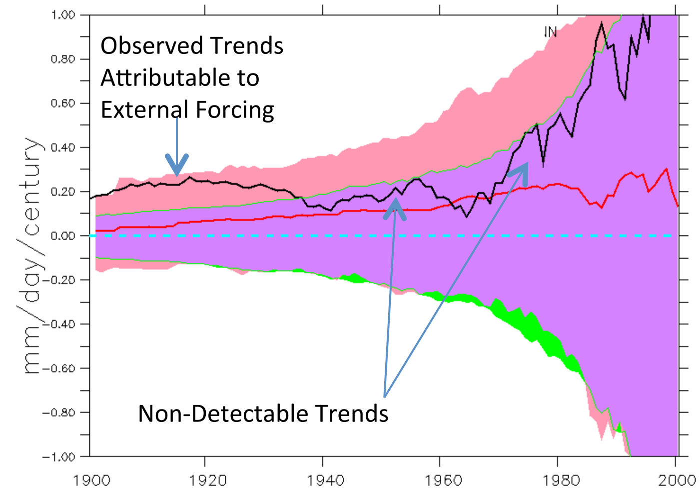
p_{ALL} and p_{CON} : probabilities of exceeding the 2012 or 1991 thresholds in the All Forcing and Control distributions.
Source: Knutson, Zeng, and Wittenberg, *BAMS* (2013)

2013 Annual Mean Precipitation Extremes: Climate Perspective

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

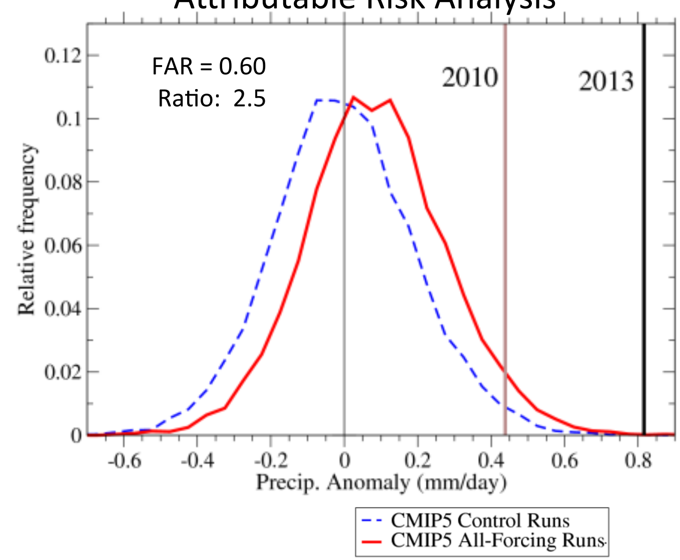


Sliding Trend Analysis



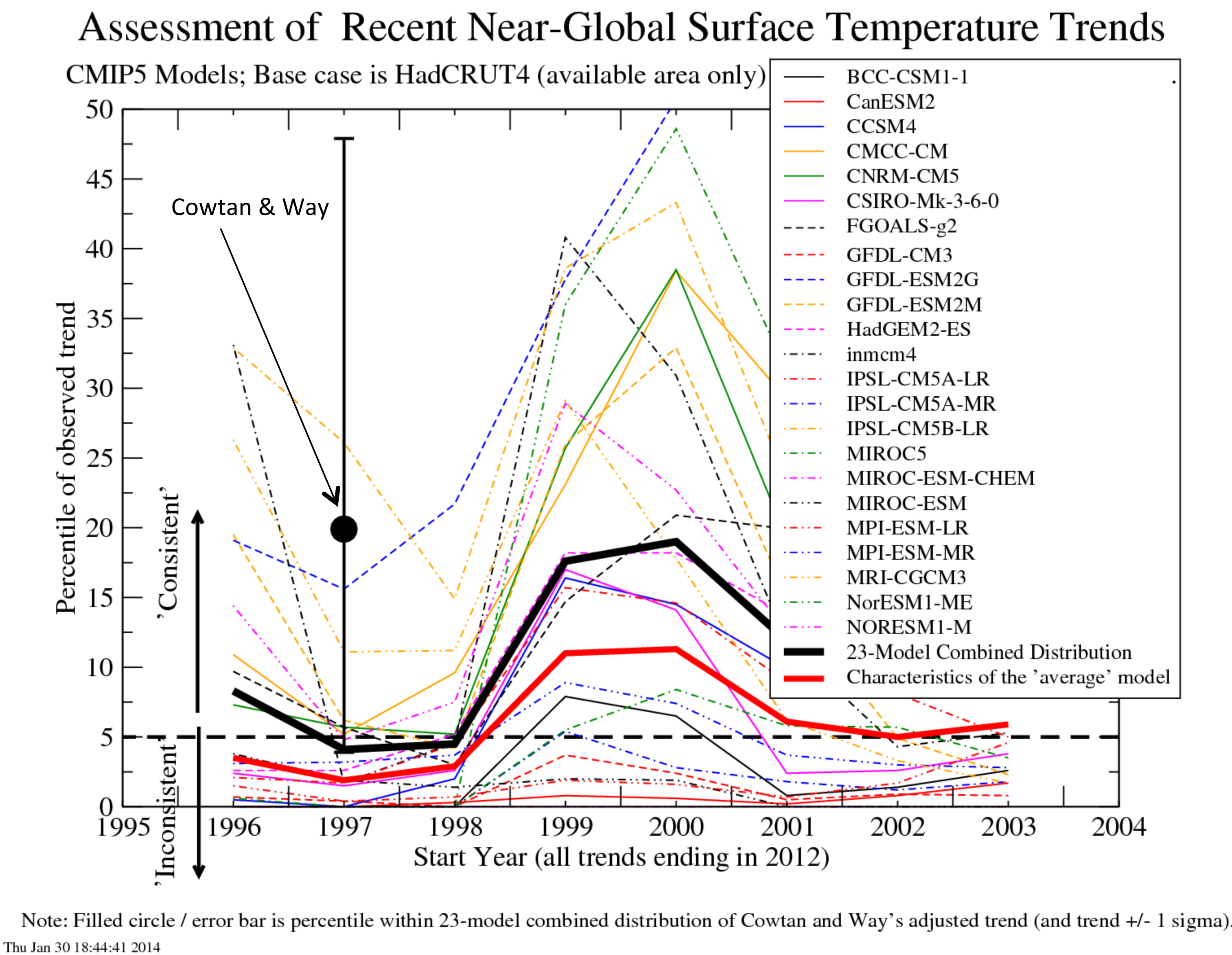
Beginning Year of Trend (All Trends Ending in 2013)

Attributable Risk Analysis



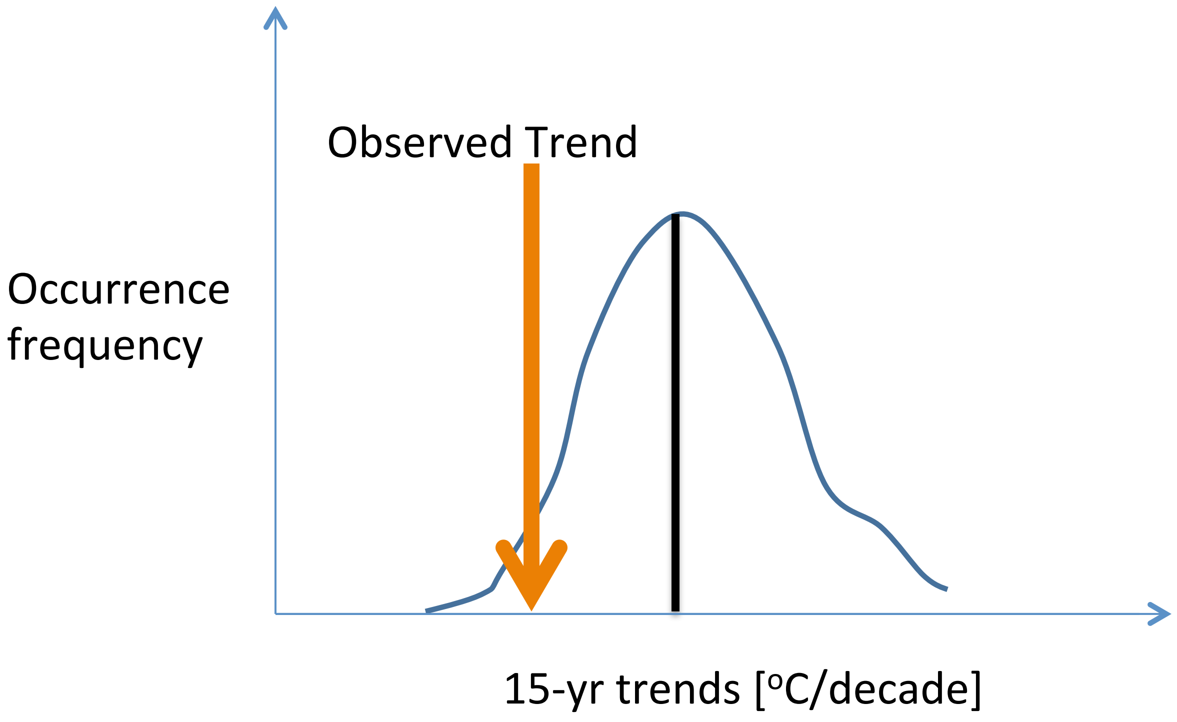
$$\text{Ratio} = \frac{p_{ALL}}{p_{CON}}$$

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)


Assessment of Recent Near-Global Surface Temperature Trends
CMIP5 Models; Base case is HadCRUT4 (available area only)
Percentile of observed trend
Start Year (all trends ending in 2012)
Cowtan & Way
'Consistent'
'Inconsistent'
BCC-CSM1-1
CanESM2
CCSM4
CMCC-CM
CNRM-CM5
CSIRO-Mk-3-6-0
FGOALS-g2
GFDL-CM3
GFDL-ESM2G
GFDL-ESM2M
HadGEM2-ES
inmcm4
IPSL-CM5A-LR
IPSL-CM5A-MR
IPSL-CM5B-LR
MIROC5
MIROC-ESM-CHEM
MIROC-ESM
MPI-ESM-LR
MPI-ESM-MR
MRI-CGCM3
NorESM1-ME
NORESM1-M
23-Model Combined Distribution
Characteristics of the 'average' model
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

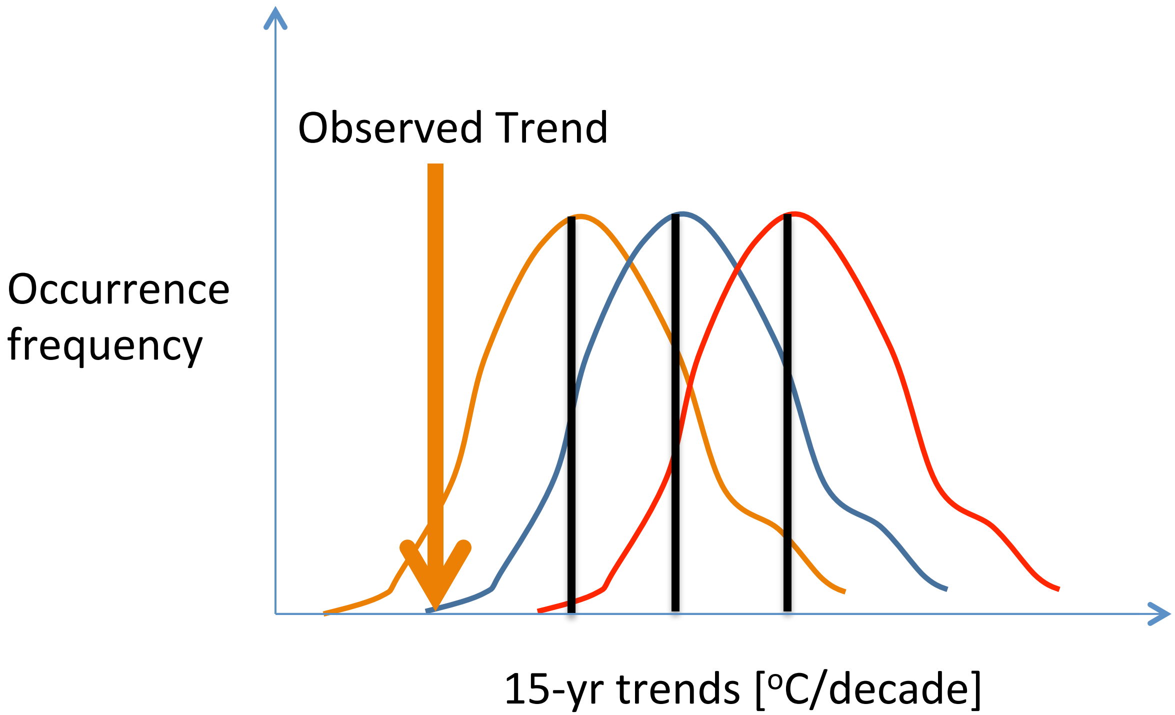
Consider the distributions of 15-yr trends from a climate model for the period 1997-2012.

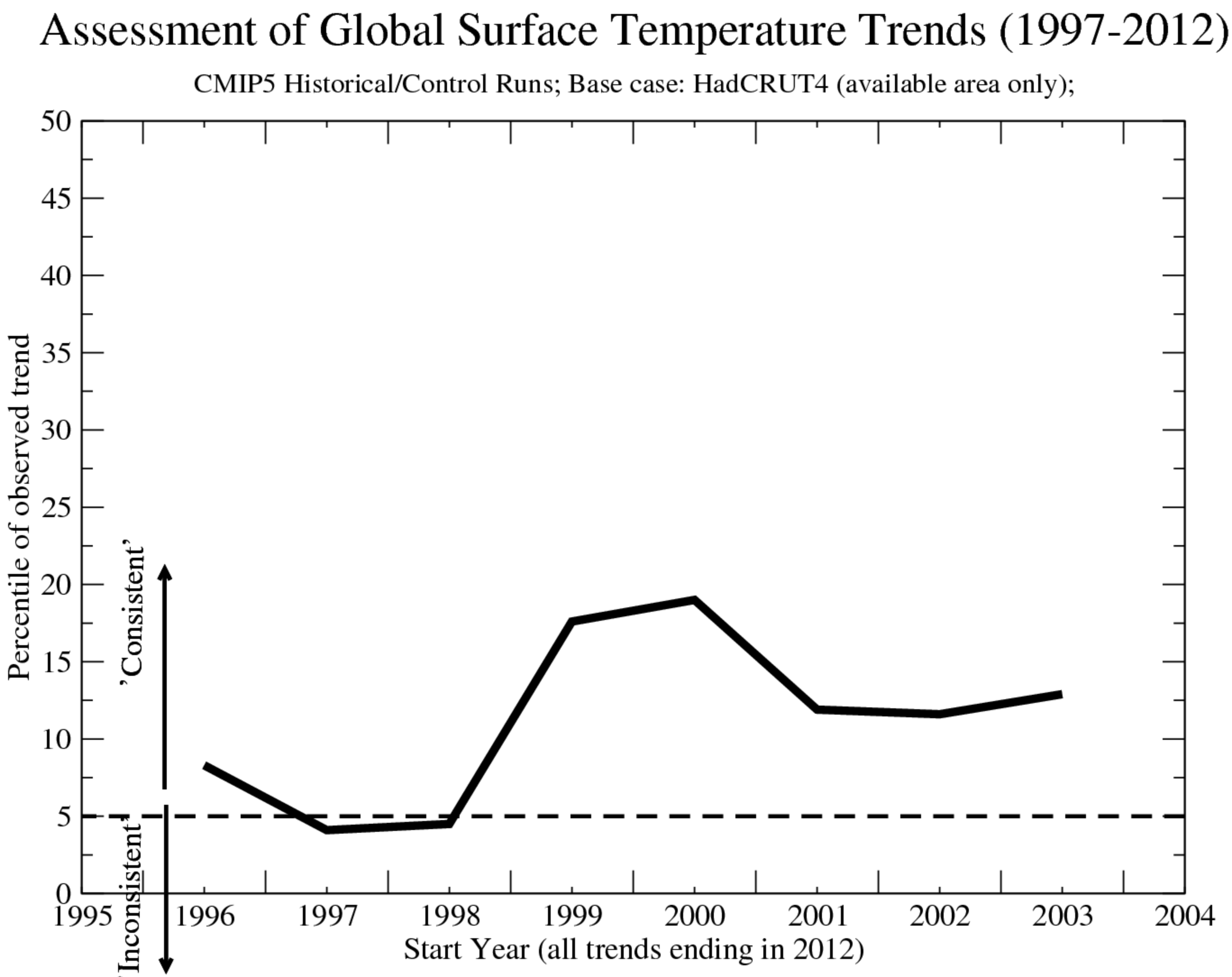
- The mean of the model's distribution is the ensemble mean of the model's historical run ensemble over the period in question.
- The spread about the mean for the model is the distribution of 15-year trends from the model's control run.



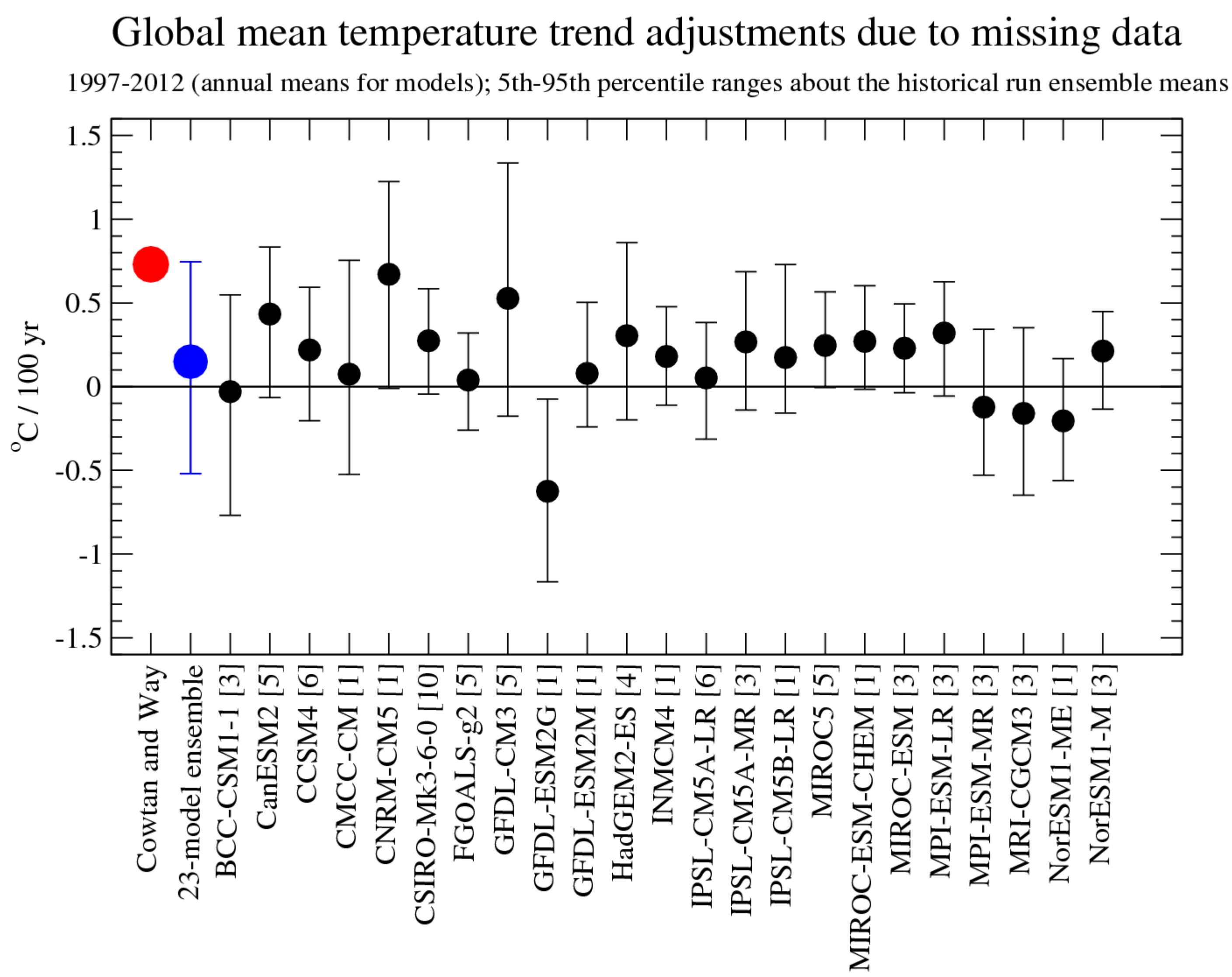
Consider three distributions of 15-yr trends from three different models for the period 1997-2012.

- 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.



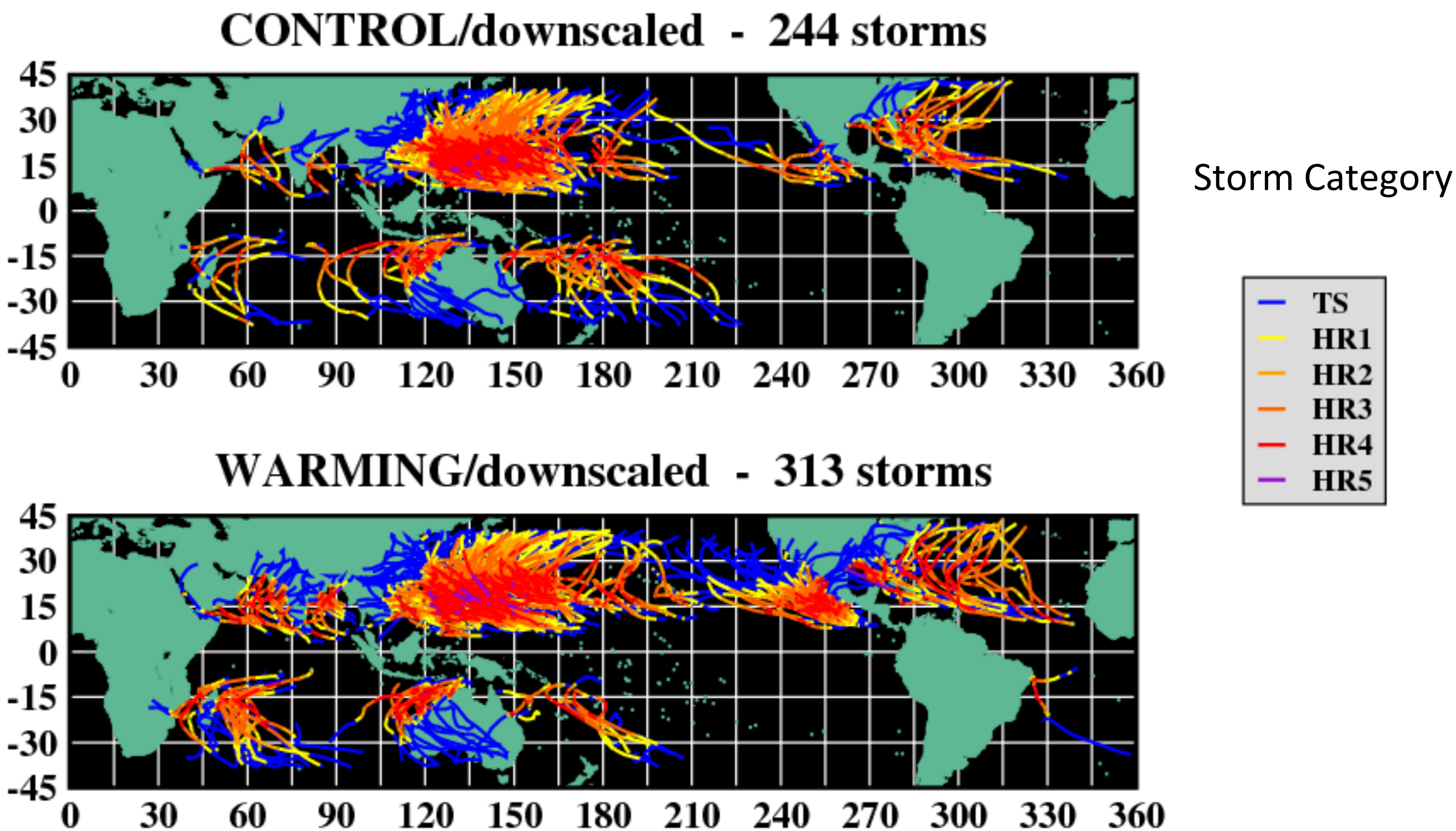


Thu Apr 10 13:38:34 2014



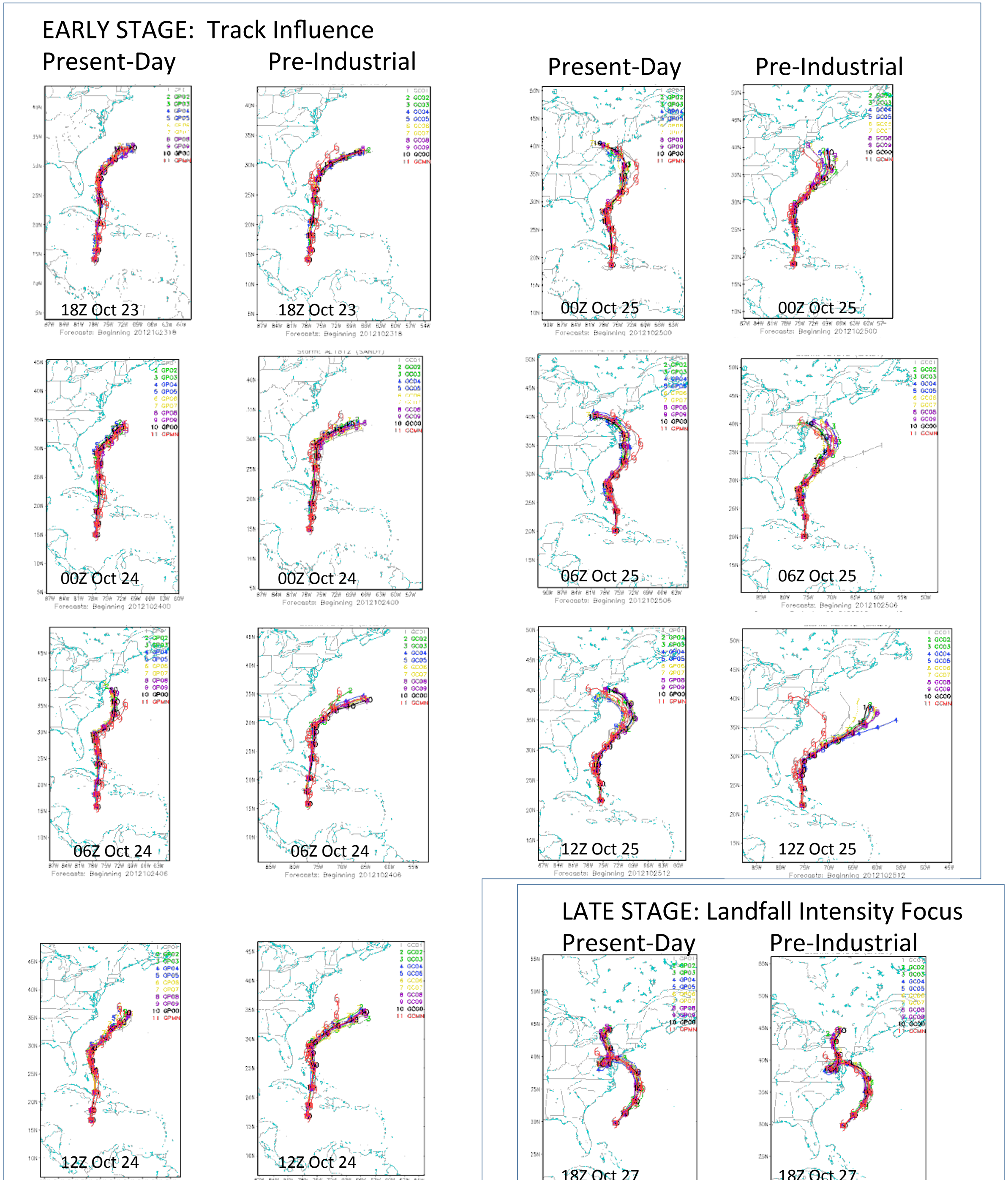
Global mean temperature trend adjustments due to missing data
1997-2012 (annual means for models); 5th-95th percentile ranges about the historical run ensemble means
°C / 100 yr
1.5
1
0.5
0
-0.5
-1
-1.5
Cowtan and Way
23-model ensemble
BCC-CSM1-1 [3]
CanESM2 [5]
CCSM4 [6]
CMCC-CM [1]
CNRM-CM5 [1]
CSIRO-Mk3-6-0 [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]

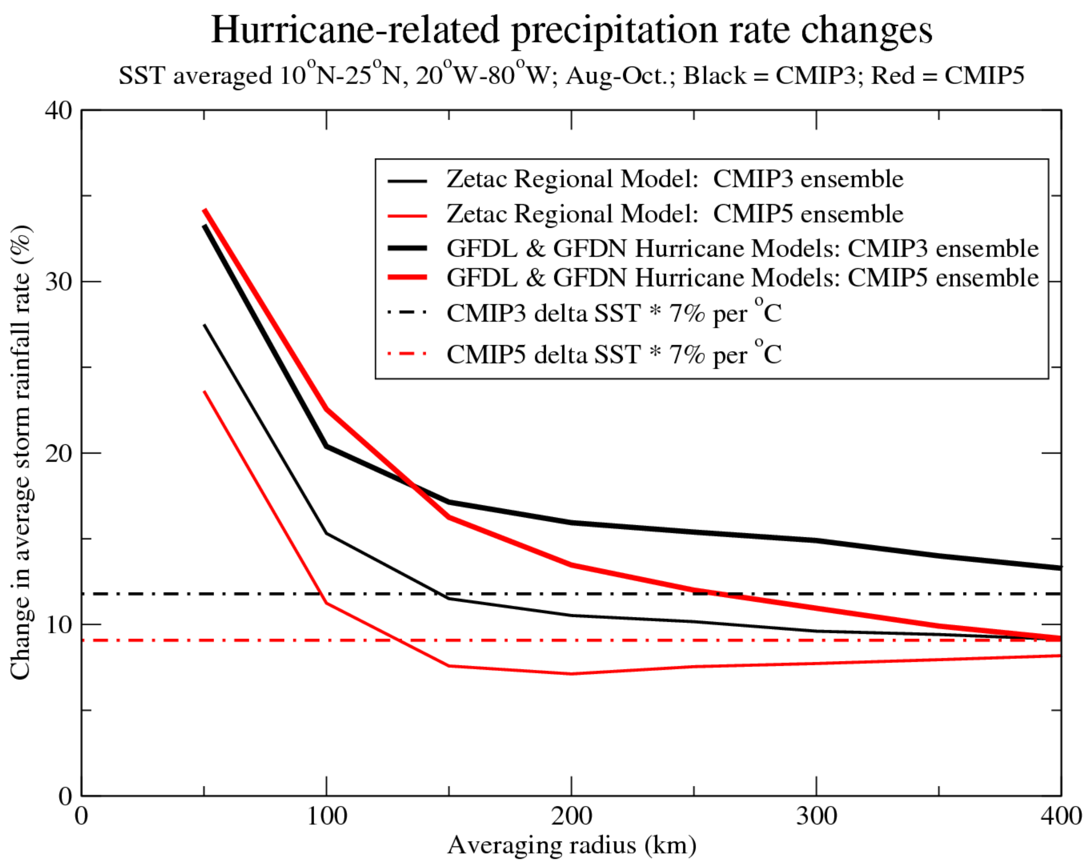
Category 4-5 Tropical Cyclones: 20 yr simulations CMIP5/RCP4.5 Late 21st Century vs. Present Day



24% increase in Cat 4-5 frequency globally

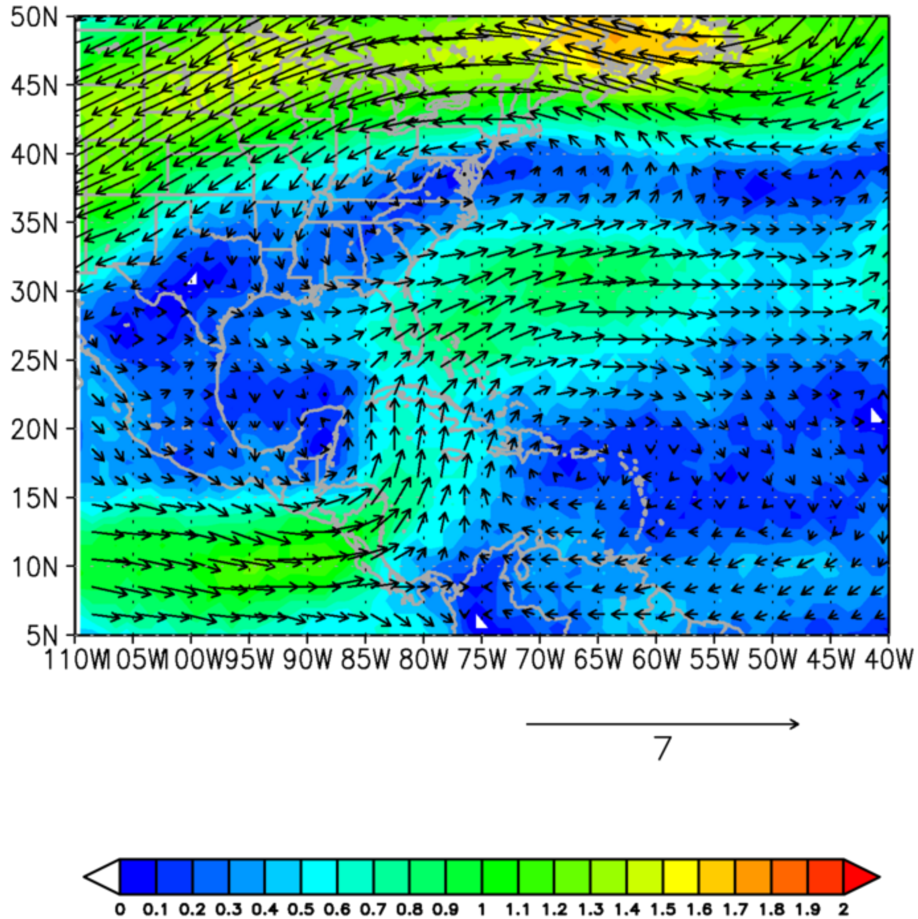
GFDL dynamical downscaling to 6 km grid model; preliminary results, 2014.


EARLY STAGE: Track Influence
Present-Day
Pre-Industrial
Present-Day
Pre-Industrial
18Z Oct 23
18Z Oct 23
00Z Oct 25
00Z Oct 25
00Z Oct 24
00Z Oct 24
06Z Oct 25
06Z Oct 25
06Z Oct 24
06Z Oct 24
12Z Oct 25
12Z Oct 25
12Z Oct 24
12Z Oct 24
LATE STAGE: Landfall Intensity Focus
Present-Day
Pre-Industrial
18Z Oct 27
18Z Oct 27



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

500 mb winds: Pre-industrial – Control



Experimental Design:

Perturbing 2012 SSTs with climate change signal.