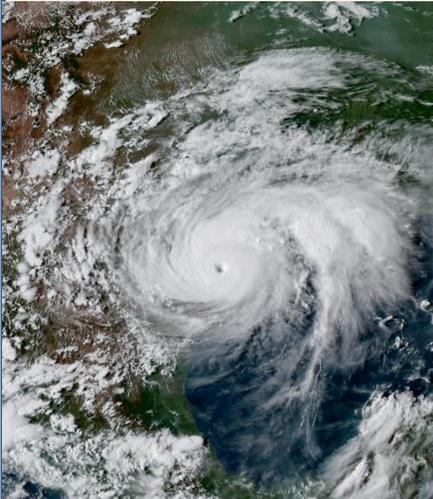


Tropical Cyclones and Climate Change: Historical Trends and Future Projections

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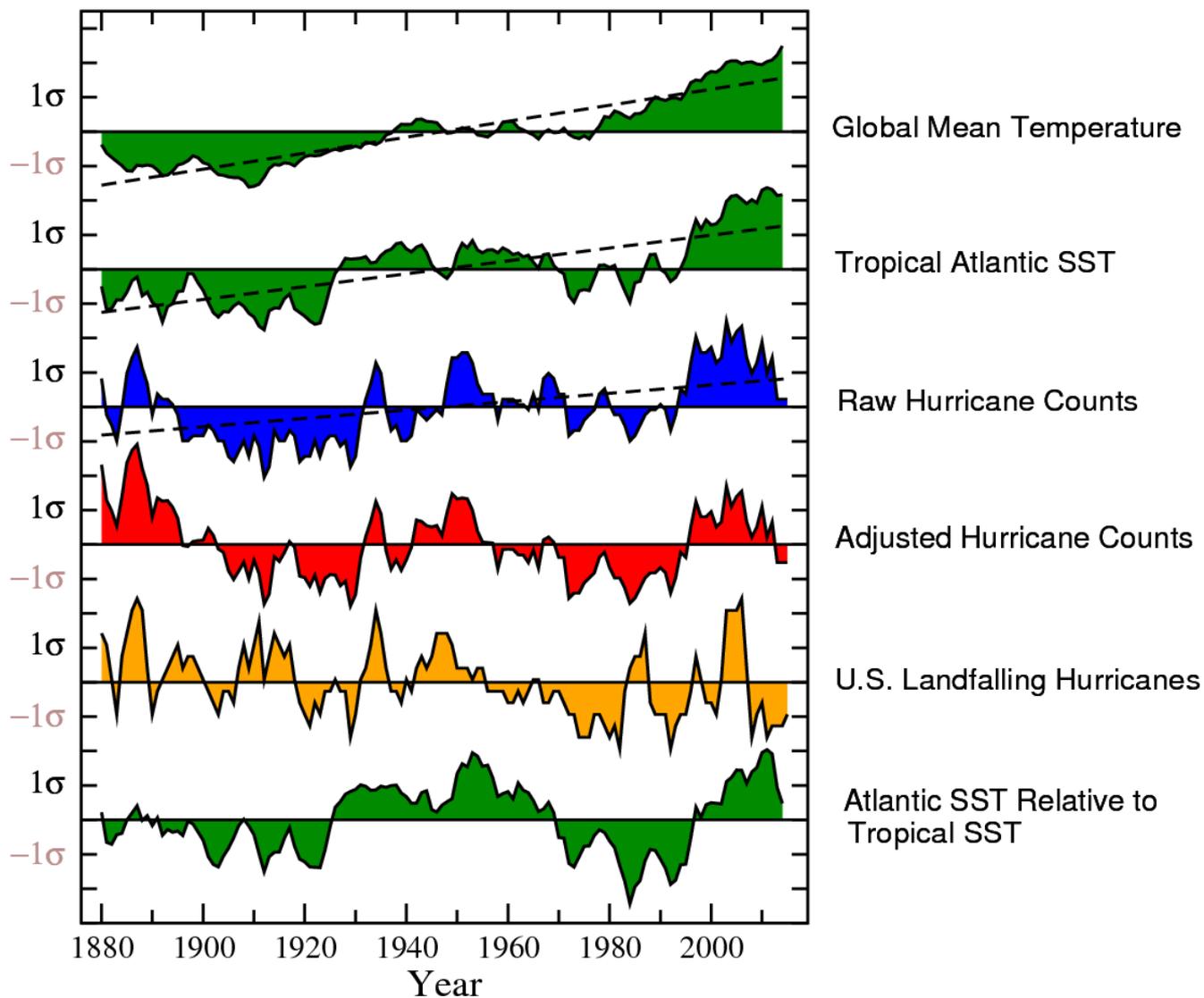
Targeted Questions to Address:

- How has our understanding of changes and model projections evolved since 2008? ***Greater confidence in projections. Some emerging potential influences of anthropogenic forcing on tropical cyclone activity (confidence is still relatively low in most cases).***
- What is current best practise, including the most appropriate models, downscaling approaches and analysis techniques? ***New higher resolution global models; dynamical downscaling using regional models; trend analysis for climate change detection (accounting for data quality issues).***
- Is current practice at a state where it can be relied upon for long-term business decisions? ***Yes. Projected changes in surge (sea level rise), hurricane precipitation rates, and intensity could be considered at some level, in my opinion.***
- What are the recognised gaps and uncertainties in current practise – and what needs to be done to close these gaps and address the uncertainties? ***Limited evidence for clearly detectable anthropogenic trends in hurricane activity limits our confidence in future projections compared to that for temperature-related variables and sea level rise.***

- Observed Historical Trends in Key Storm Parameters
- How well to model historical runs simulate these?

No clear evidence for detectable century-scale trend in Atlantic hurricane frequency

Normalized Tropical Atlantic Indices



Source: Vecchi and Knutson (2011). Five-year running means, updated through 2017.

Some Long Tropical Cyclone Datasets

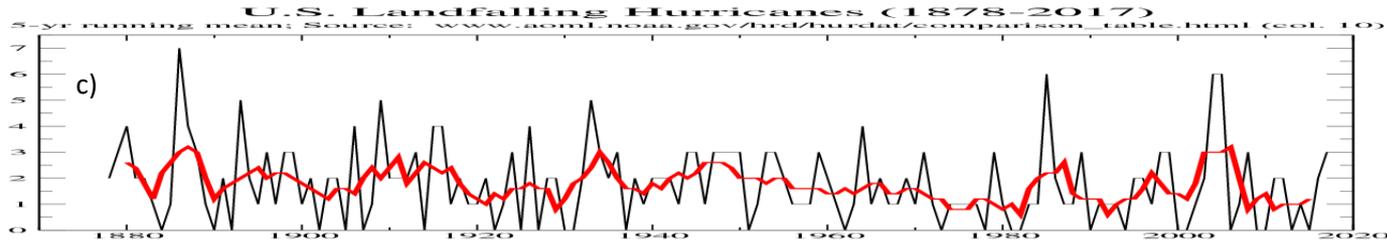
a)

(Figures not available for public distribution)

Severe landfalling TCs
in eastern Australia
(Callaghan and Power)

b)

Landfalling TCs in Japan
(Kumazawa et al. 2016)

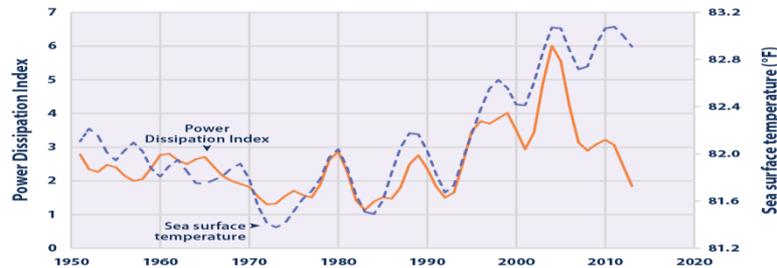


U.S. Landfalling
hurricanes (HURDAT)

d)

U.S. Surge index for
moderately large events
(Grinsted et al)

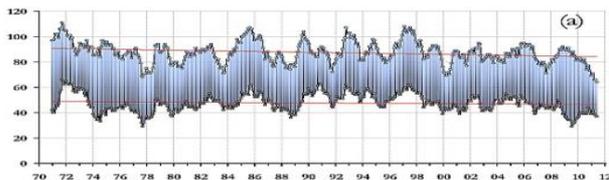
1930 1940 1950 1960 1970 1980 1990 2000



Atlantic TC Power
Dissipation Index
and SST (Emanuel)

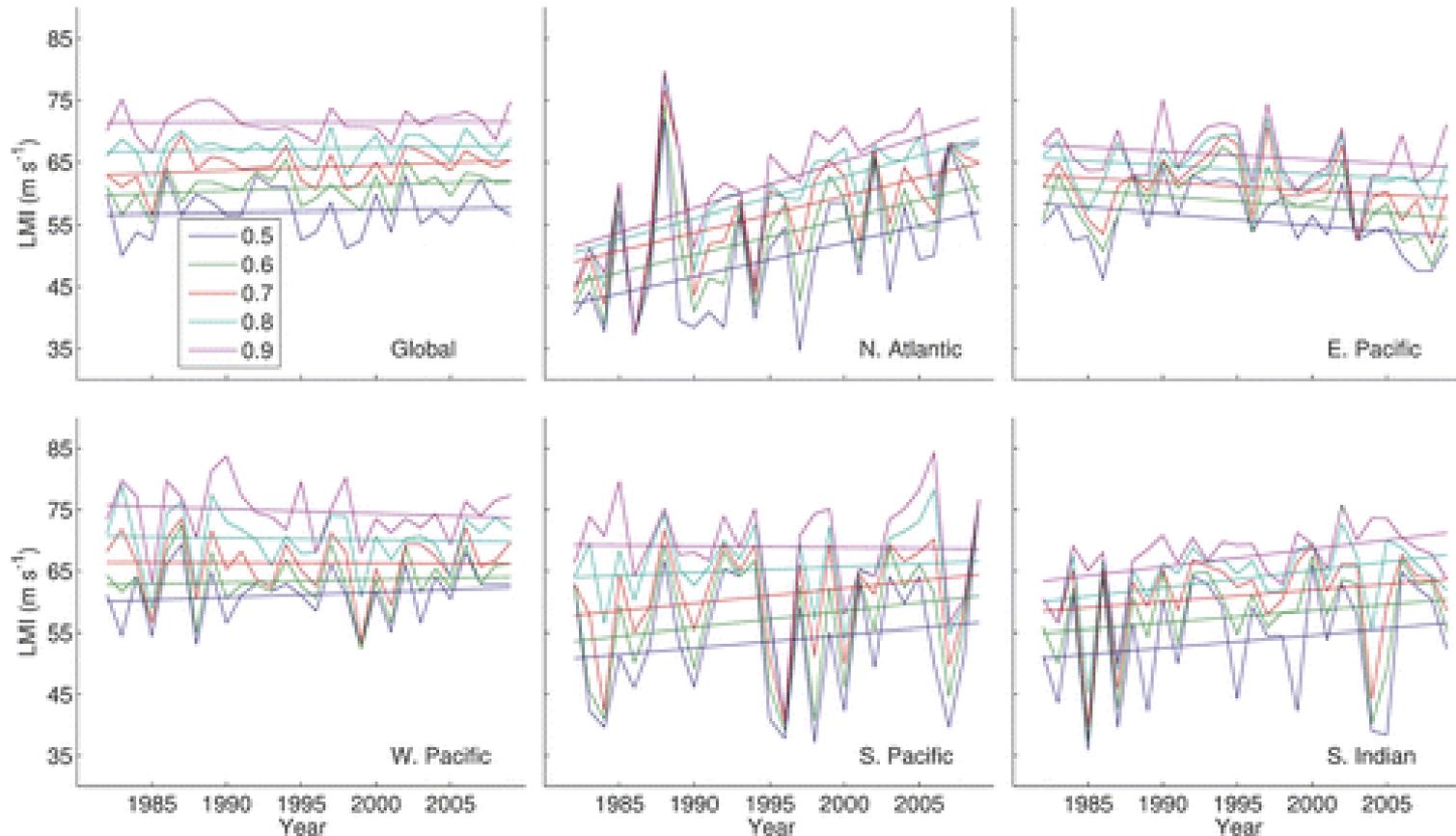
e)

f)



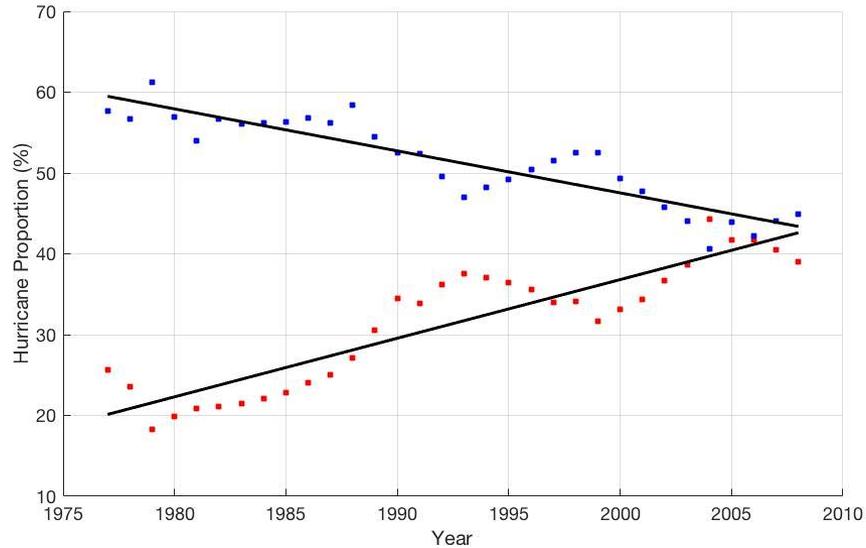
Global TC and Hurricane Frequency (Maue, GRL, 2011)

TC maximum intensity trends by quantile from ADT-HURSAT

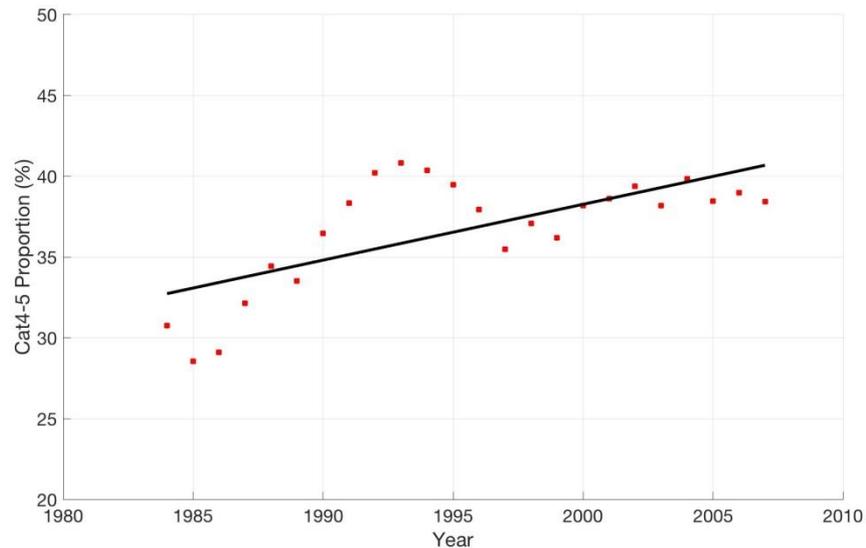


- Global: Slight upward trend ($p = 0.1$)
- N. Atlantic: Strong upward trend, but record is short compared to multidecadal variability there
- Consistent in sign with expected response to greenhouse warming

The global proportion of tropical cyclones that reach Cat 4-5 levels has increased significantly, consistent in sign with expected responses to greenhouse warming...



Cat 4-5 proportion
NHC + JWTC data

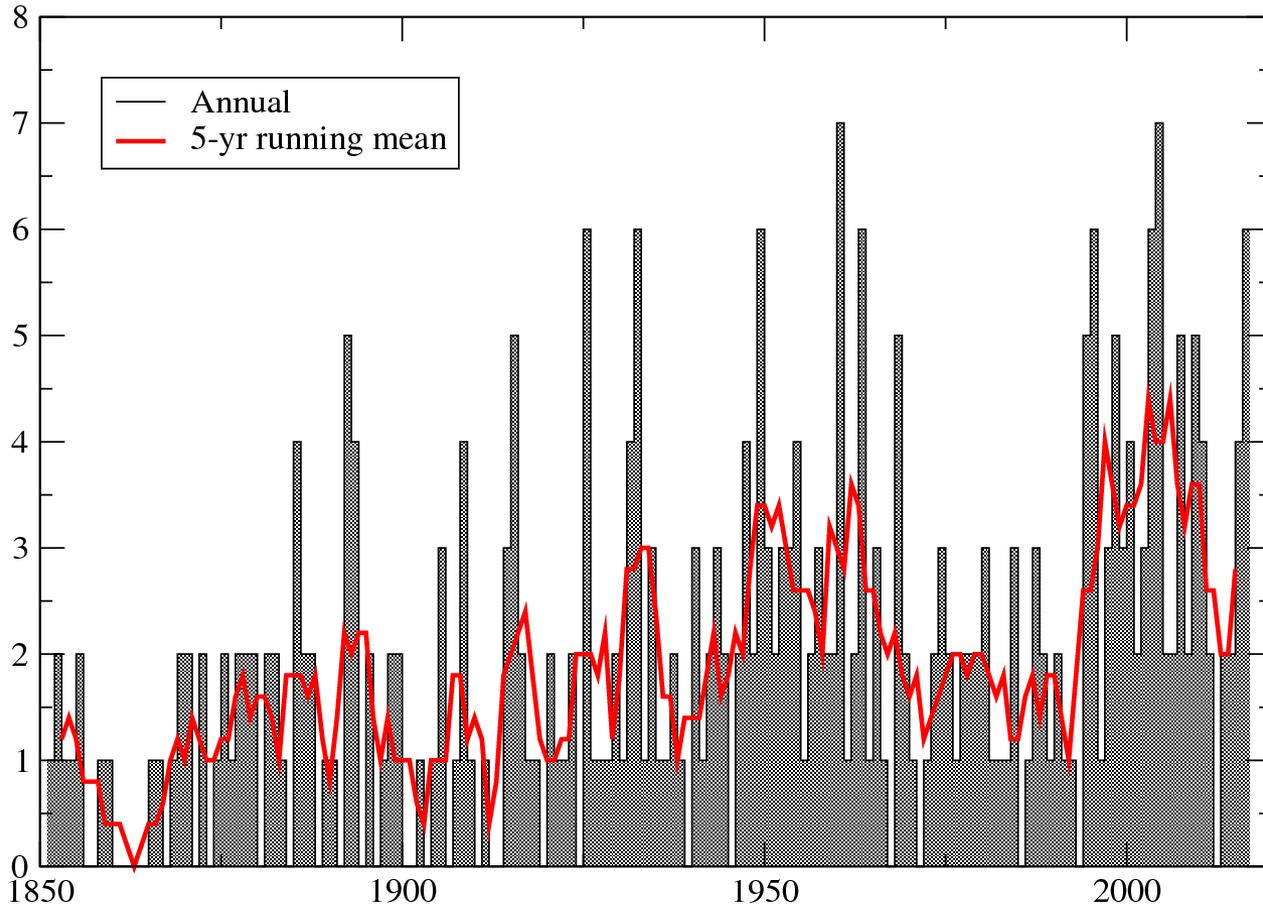


Cat 4-5 proportion
from ADT-HURSAT data

Source: Jim Kossin; see also: Holland and Bruyere (2014) Climate Dynamics.

Atlantic Major Hurricanes (1851-2017)

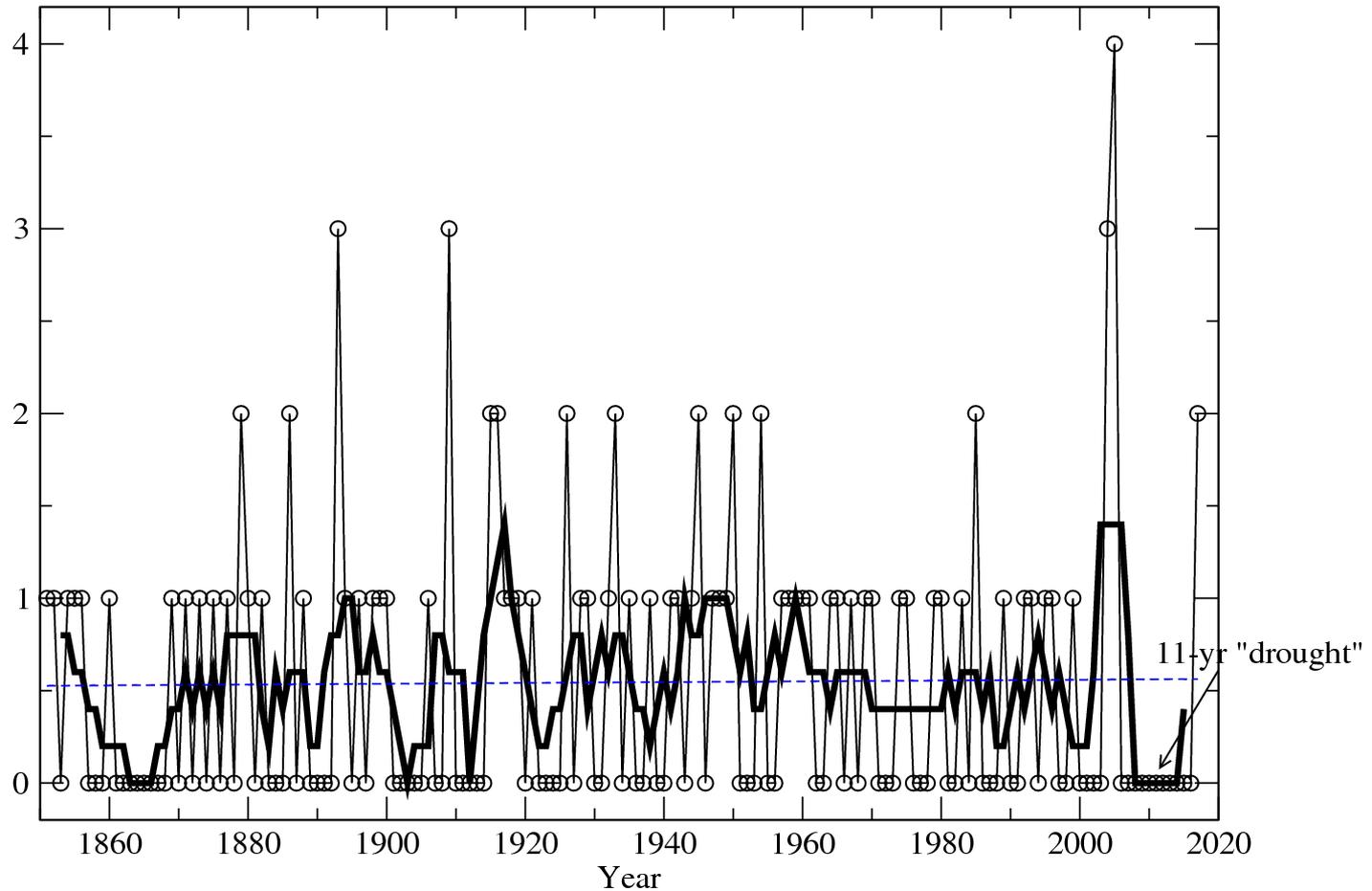
Source: www.aoml.noaa.gov/hrd/hurdat/comparison_table.html



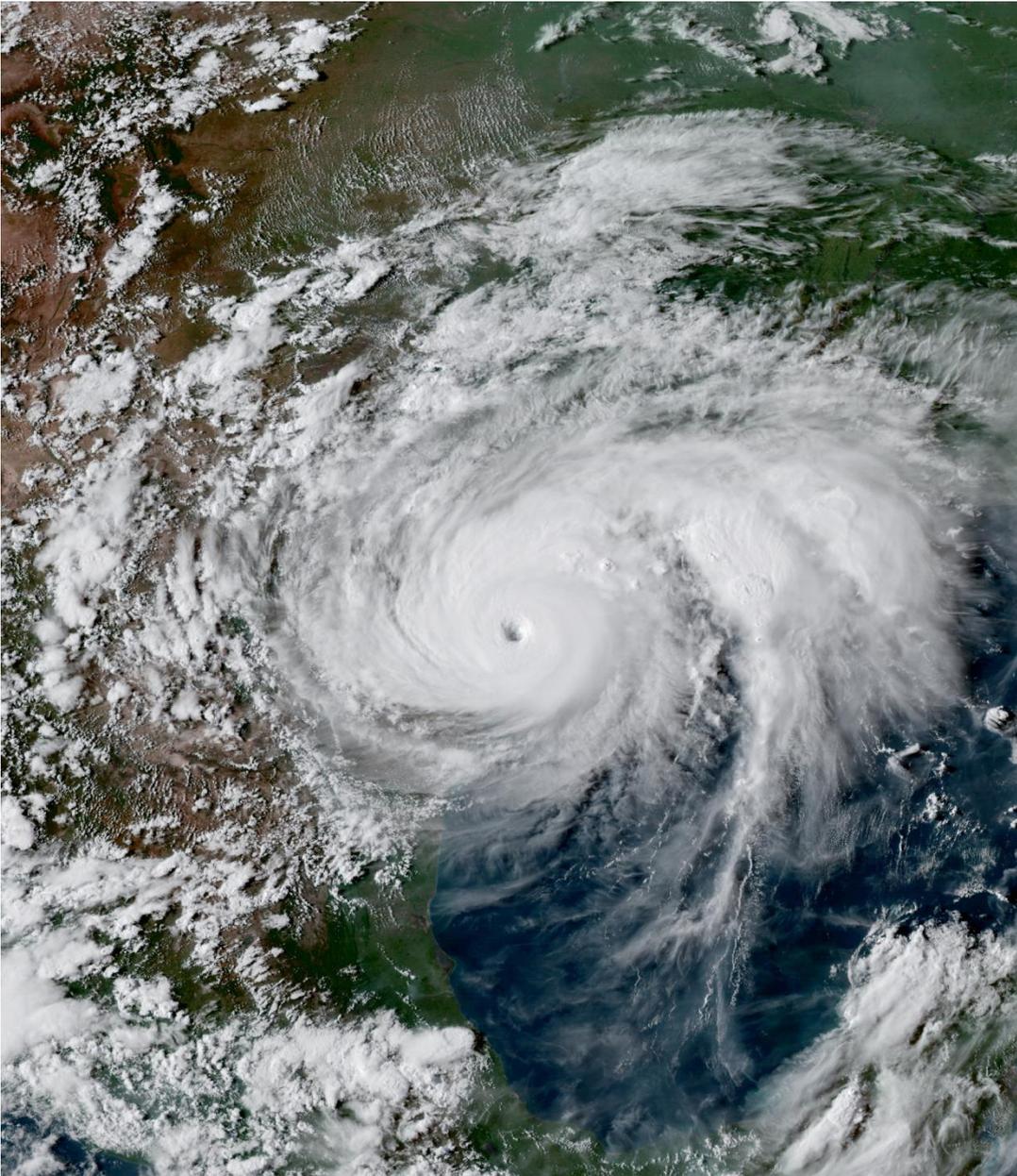
Caution: This dataset not presumed to be appropriate for trend analysis.

US Major Landfalling Hurricanes (1851-2017)

5-yr running mean and annual count; Continental US only; Dashed = linear trend (non-significant)



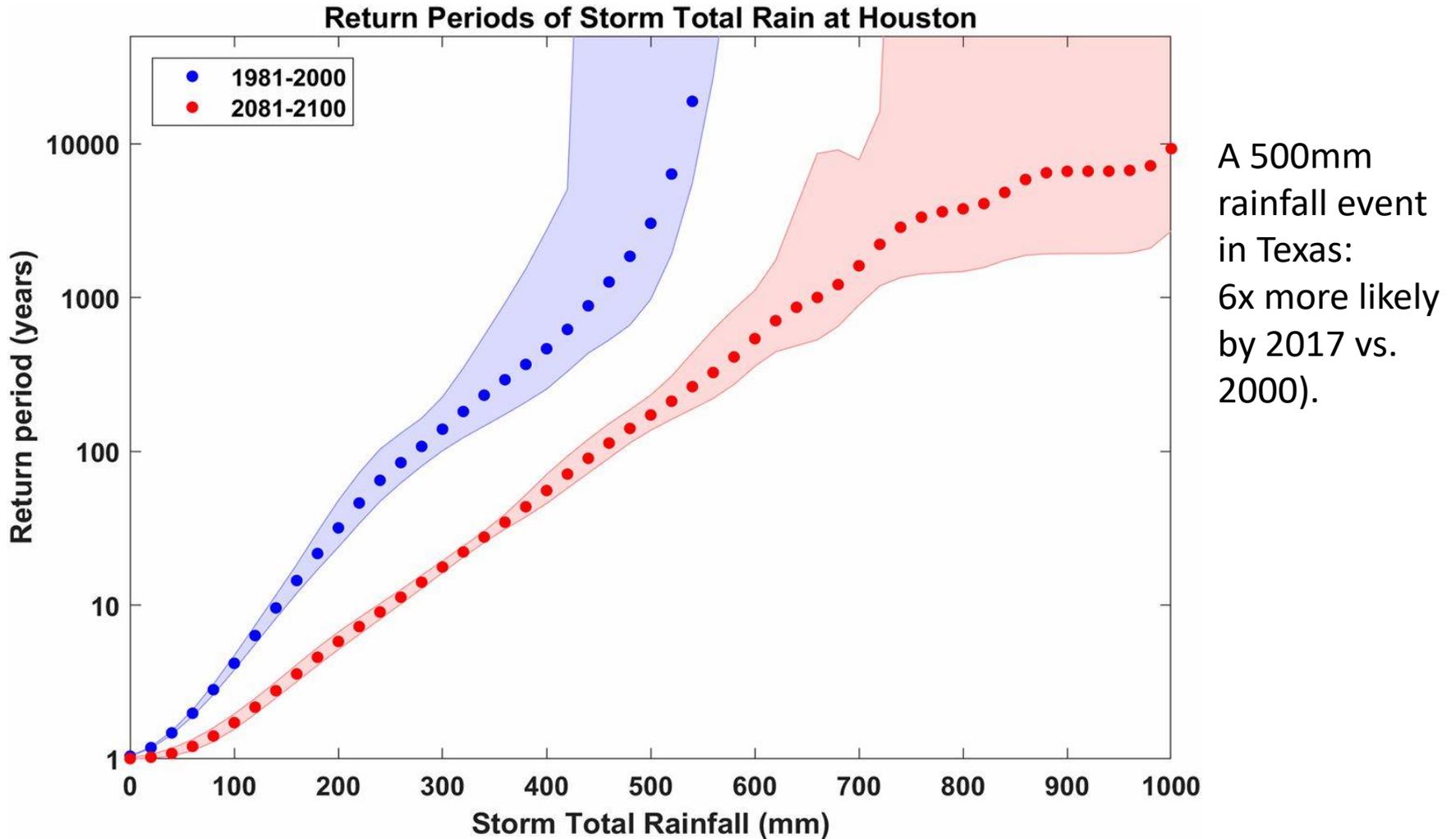
Data Source: http://www.aoml.noaa.gov/hrd/hurdat/All_U.S._Hurricanes.html; updated by TK



Harvey Aug. 17-Sept.1, 2017

- 1-min. sustained winds: 130 mph (at landfall)
- 938 mb (Cat 4)
- Damage est: \$198 B
- 91 fatalities (90 in U.S.)
- Rainfall total: 60.58 inches (record for US Tropical cyclone)
- Stalling characteristic
- Rapid intensification (Aug. 24-25) to Cat 4 near Texas

**3,700 simulated events each from six global climate models (Historical and RCP8.5);
Shading: 1 st. dev. in storm frequency distribution**



Source: Kerry Emanuel PNAS doi:10.1073/pnas.1716222114



- 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...

Observations

Model

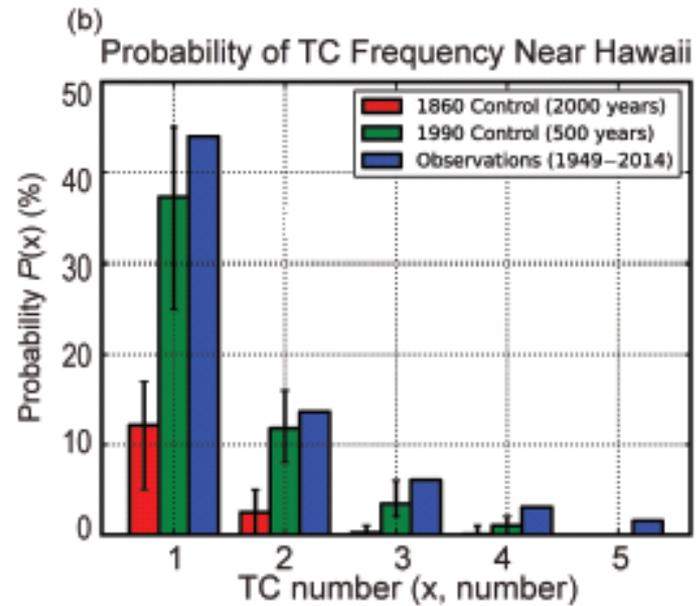
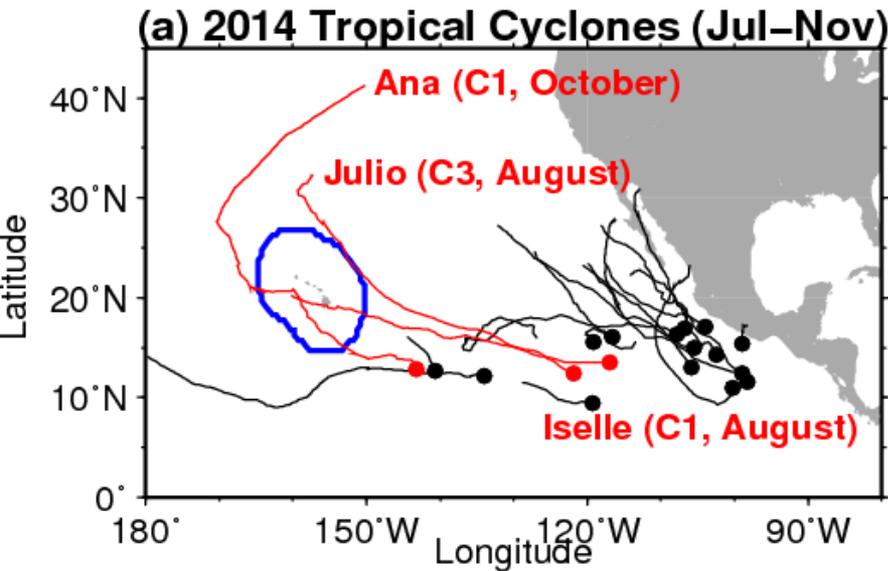
Projection

Tropical
Storm
Frequency

(Figures not available for public distribution)

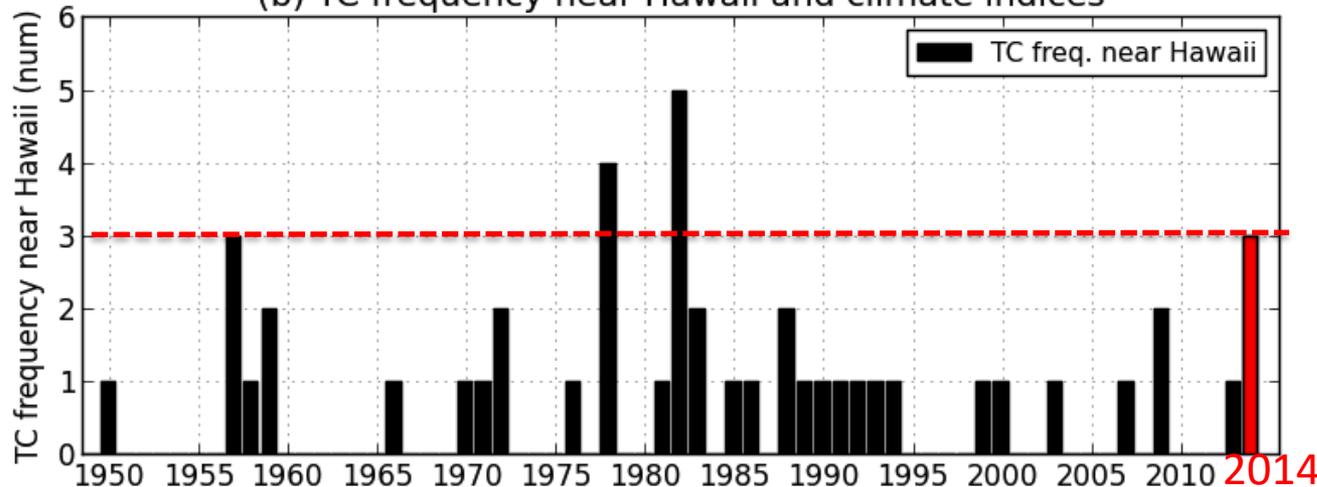
Sea Surface
Temperature
Anomaly

2014 Hurricane Season in the Eastern Pacific



Three hurricanes approached near Hawaii in 2014.

(b) TC frequency near Hawaii and climate indices



No significant trend;
(Attribution without
Detection).

Source: Murakami et al. BAMS (2015)

Extremely Severe Cyclonic Storm ($\geq 46\text{ms}^{-1}$; ESCS \approx Major Hurricane)

- Frequency of occurrence of ESCS has been abruptly **increasing only during post-monsoon season** since 2014.
- **What caused the increase?**
anthropogenic forcing?
intrinsic natural variability?

(Figures not available for public distribution)

Probability of Exceedance for ESCS Occurrence

$$P(1) \equiv \frac{\text{Number of years with ESCS number more than or equal to 1}}{\text{Total number of simulated years}}$$

Ex) If there are 50 years in which ESCS number ≥ 1 among the total 600 years,
 $P(1) = 50/600 = 8\%$

Post-Monsoon Season (October – December)

$P(1)$ is more than **3** times larger in
2015 Cntl than 1860 Cntl.

(Figures not available for public distribution)

Anthropogenic forcing has
substantially changed the odds
of active ESCS seasons
relative to natural variability
alone.

Changes in Large-scale Parameter during Post-Monsoon Season

Post-Monsoon Season

SST

Vertical Wind Shear

HiFLOR

(2015Cntl – 1860Cntl)

CMIP5 (RCP8.5₂₀₀₅₋₂₀₂₅ – PiCntl) (Figures not available for public distribution)

CMIP5 (RCP8.5₂₀₈₀₋₂₀₉₉ – RCP8.5₂₀₀₅₋₂₀₂₅)

HiFLOR projects larger increase in SST as well as weaker vertical wind shear over the Arabian Sea. Similar changes are also projected by the CMIP5 models. Source: Murakami et al., 2017, *Nature Climate Change*

Summary: Detection and Attribution of TC Changes

1) **Type I error avoidance** (i.e., avoid overstating anthropogenic influence or detection):

- Observed poleward migration of the latitude of maximum intensity in the western North Pacific is detectable, or highly unusual compared to expected natural variability (*low-to-medium confidence*).

2) **Type II error avoidance** (i.e., avoid understating anthropogenic influence or detection):

- A balance of evidence suggests an anthropogenic influence on the following detectable changes:
 - poleward migration of the latitude of maximum intensity in the western North Pacific;
 - increased occurrence of extremely severe (post-monsoon season) Arabian Sea TCs;
 - increase of global average intensity of the strongest TCs since early 1980s;
 - increase in global proportion of TCs reaching Category 4 or 5 intensity in recent decades;
 - increased frequency of Hurricane Harvey-like extreme precipitation events in the Texas region.
- A balance of evidence suggested an anthropogenic influence (without detection) on:
 - unusually high TC frequency near Hawaii in 2014
 - unusually active TC season in the western North Pacific in 2015.
 - increase in N. Atlantic TC activity since the 1970s partly due to reduced aerosol forcing
- A balance of evidence suggests detectable (but not attributable) changes:
 - decreases in frequency of severe landfalling TCs in eastern Australia since the late 1800s;
 - decreased global TC translation speeds since 1949.

Projected Changes in TCs?

- Track, intensity, structure, frequency, season length, precipitation, surge?
- Regional variation in these?

TC Frequency (Model Projections): tendency for decrease

Global:

Individual Basins:

(Figures not available for public distribution)

Cat 4-5 TC Frequency (Model Projections): Proportion of Cat 4-5's increases

Global (% Change):

Individual Basins (% Change):

(Figures not available for public distribution)

% Change in Global Proportion of Cat 4-5s

TC Intensity (Model Projections): tendency for increases

Global:

Individual Basins:

(Figures not available for public distribution)

TC Rain Rates (Model Projections): tendency for increases

Global:

Individual Basins:

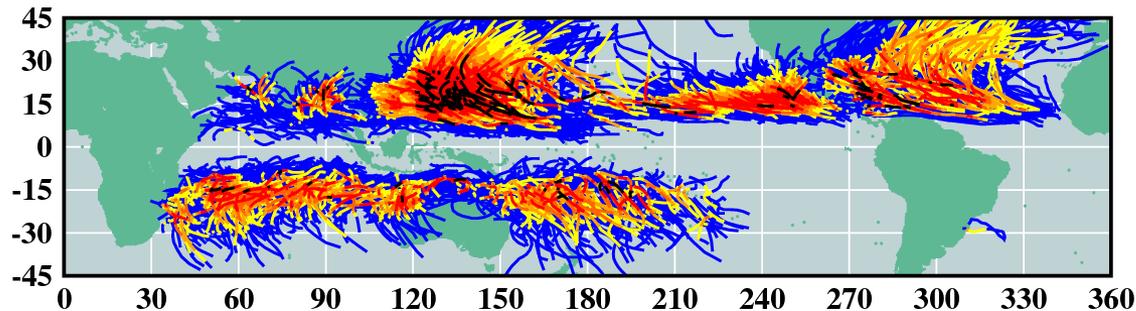
(Figures not available for public distribution)

Tropical Storms (1980-2008)

Present-Day Climate

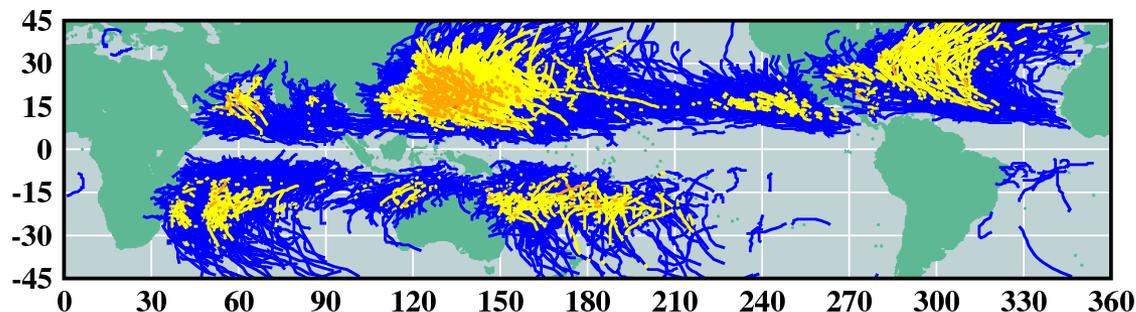
OBS (2518)

Observed



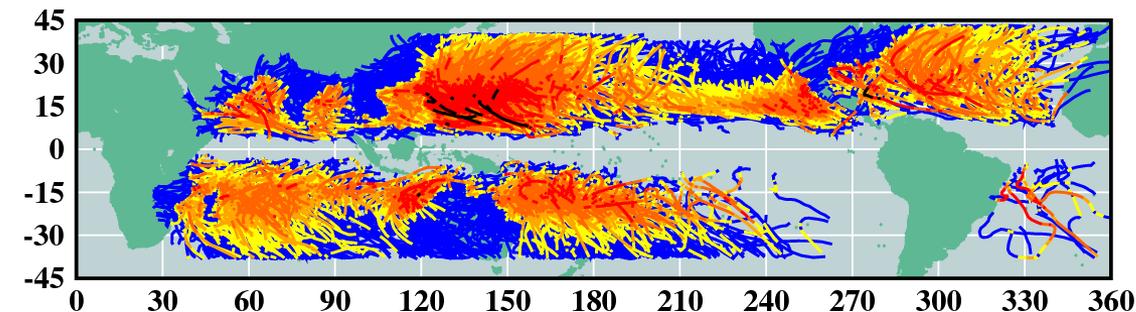
C180 (3081)

50-km grid
global
model

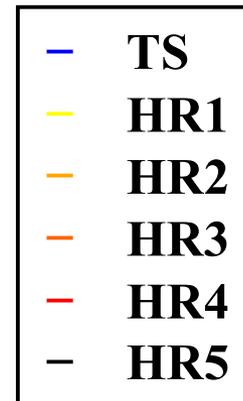


C180_HR/GFDL2012h (3031)

6-km grid
dynamical
downscale



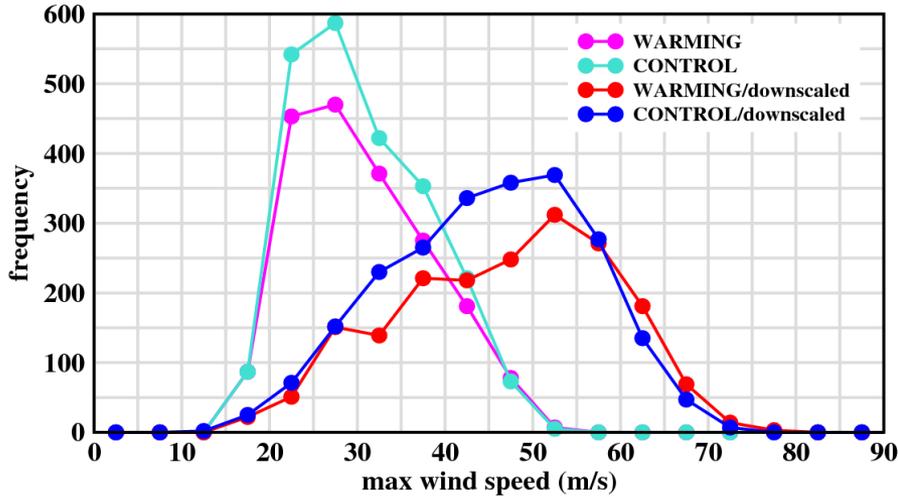
Storm
Category:



CMIP5/RCP4.5 Late 21st Century Projection

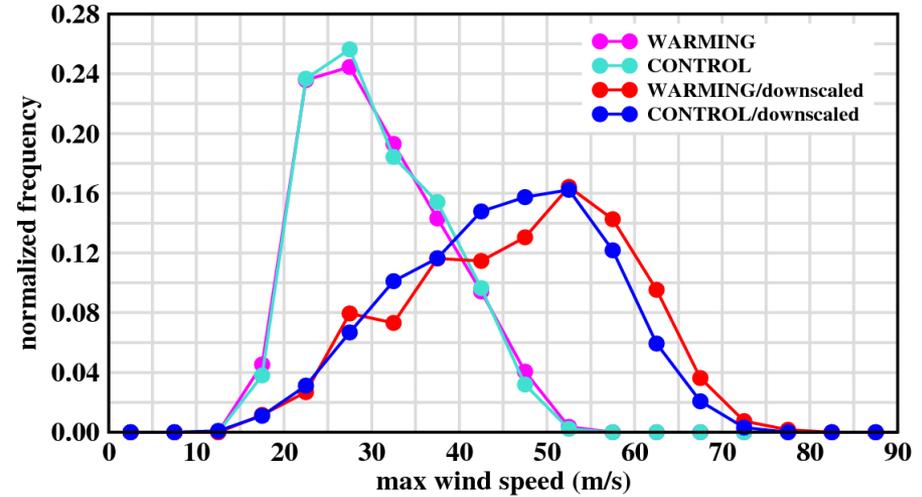
C180_hiram

Global Tropical Storms (1981-2000) histograms of max wind



C180_hiram

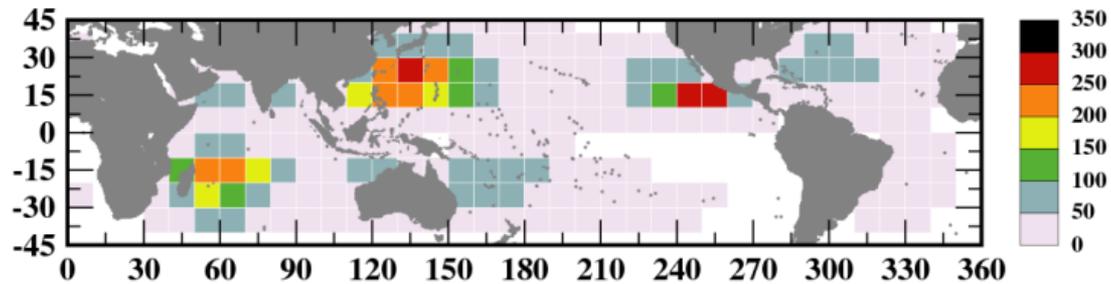
Global Tropical Storms (1981-2000) normalized histograms of max wind



Despite fewer storms overall, there remains a tendency for more stronger tropical cyclones in the warmer climate.

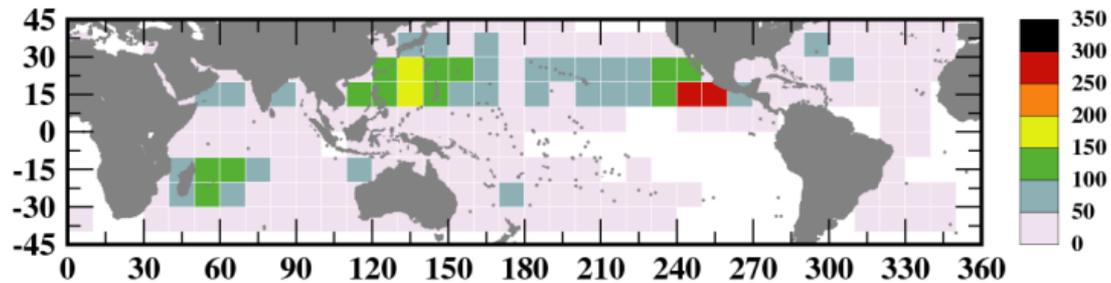
Tropical Storm Occurrence Simulations (Category 0-5)

Present-day simulation

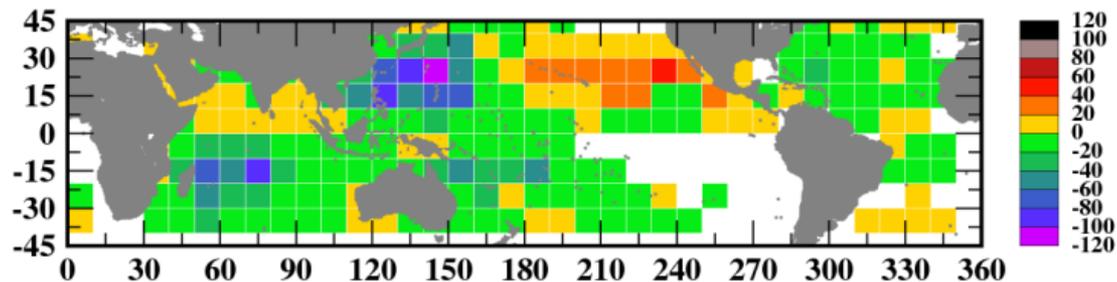


Unit: Number of storm days per 20 years

RCP4.5 Ensemble: Late 21st Century Projection



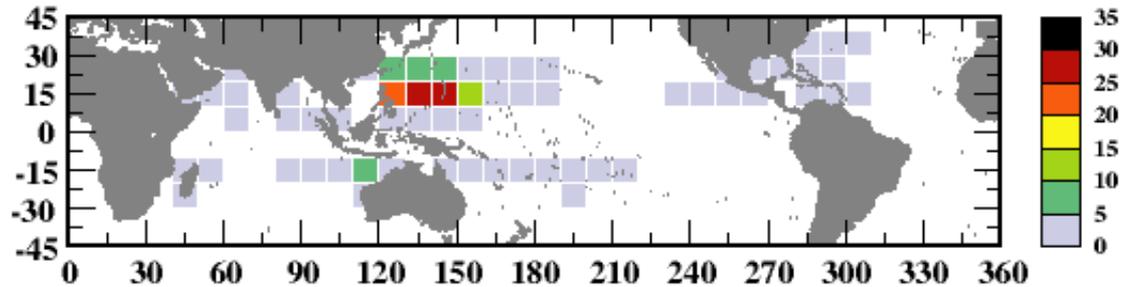
Late 21st century minus present-day



16% reduction by late 21st century

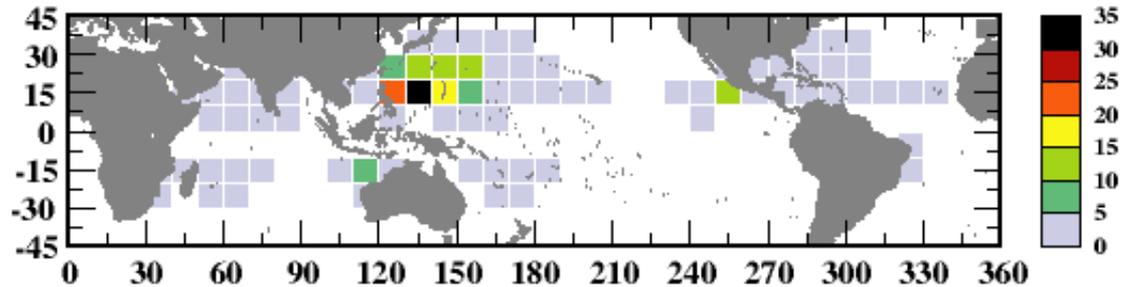
Category 4-5 Tropical Cyclone Occurrence

Present-day simulation

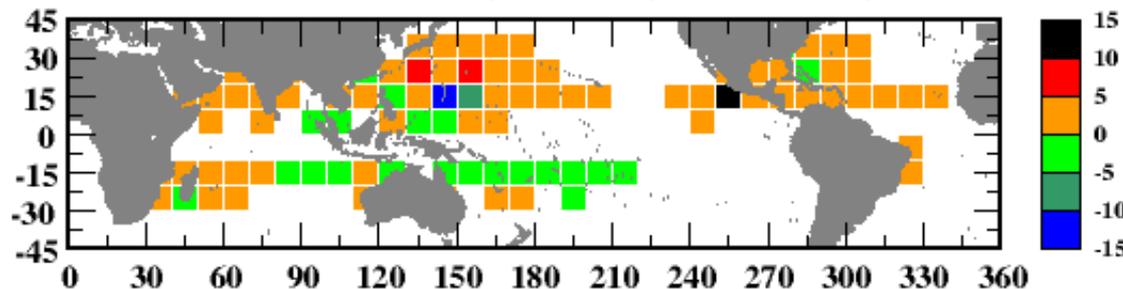


Unit: Number of storm days per 20 years

RCP4.5 Ensemble: Late 21st Century Projection

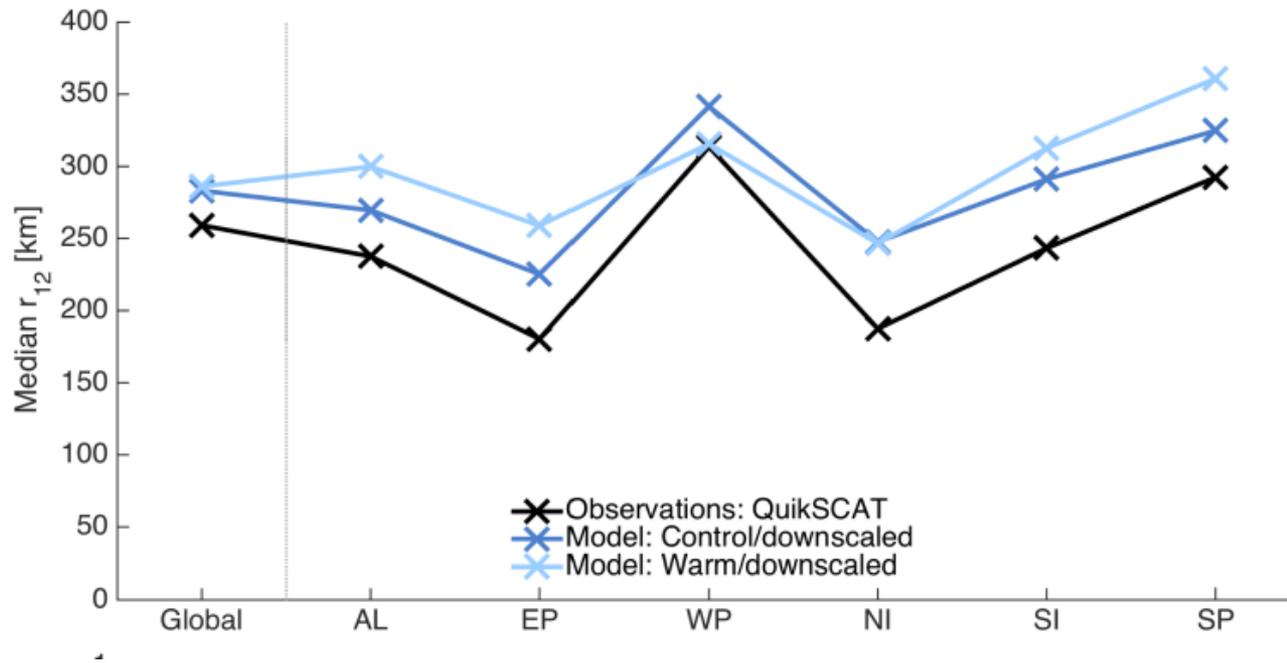


Late 21st century minus present-day



34% increase projected globally in Cat 4-5 days

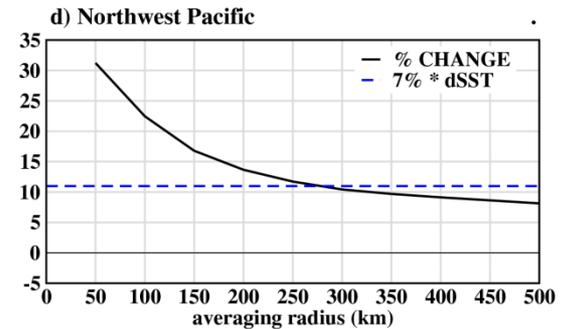
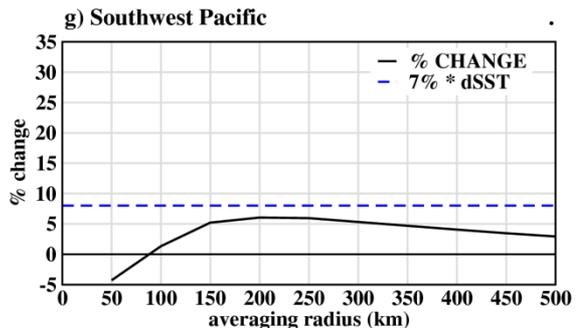
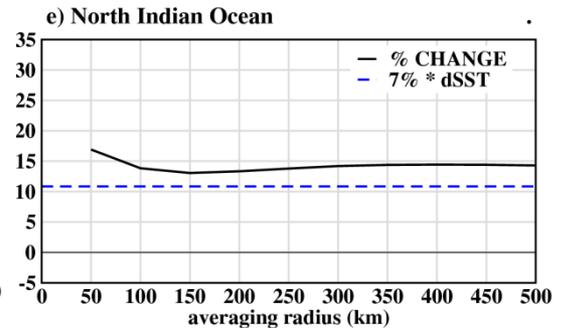
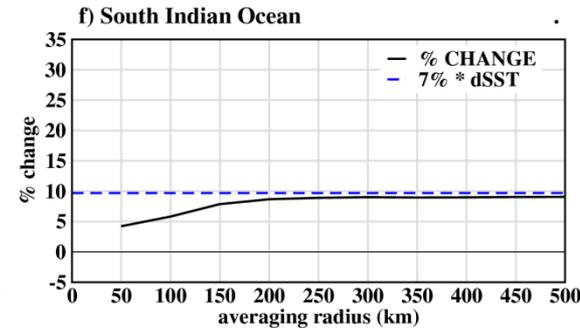
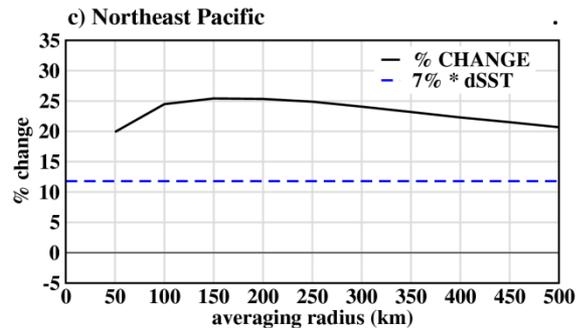
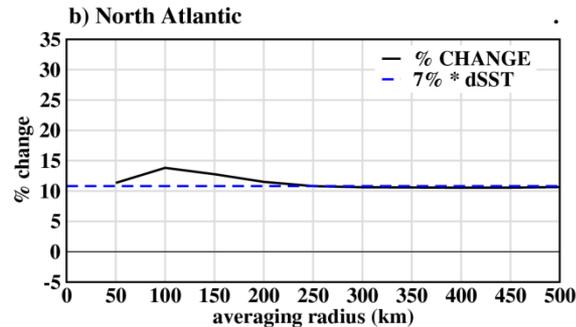
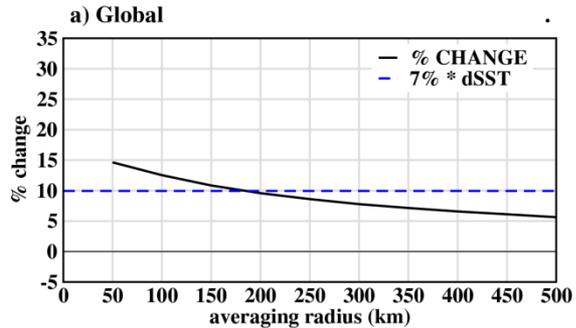
Tropical Cyclone Size: Simulated vs. Observed – Inter-Basin Variability



Source: Adapted from Knutson et al., *J. of Climate* (2015).

Simulated Increased Tropical Cyclone Rainfall in a Warmer Climate

Model Projections (CMIP5/RCP4.5 downscaled):
Percent change in tropical cyclone rainfall compared to
Clausius-Clapeyron (7% per degree C SST change) in
each basin (dashed line).



Model limitations: How are they being addressed?

- Model Resolution: ability of climate models to resolve hurricanes
- Overall uncertainty in global climate sensitivity (TCR) and sea level rise
- Uncertainty in details of projections (GHG + aerosols):
 - SST patterns (relative SST? Tropical Pacific/Walker Circ. change?)
 - Tropical lapse rate change
 - Circulation (tracks) and wind shear change
 - Changes in ENSO or other modes of variability (and their linkage to TCRs)

Summary and Conclusions –

TC Projections for a 2°C global warming

- 1) **Storm Surge:** sea level rise will lead to higher storm surge levels on average for the TCs that do occur, assuming all other factors are unchanged.
- 2) **TC precipitation rates:** increase *likely* at the global scale (*medium-to-high confidence*). About +12% for a 2°C global warming, or close to the rate of tropical water vapor increase expected for warming at constant relative humidity).
- 3) **TC intensity:** global increase *likely* (*medium-to-high confidence*). About 1 to 10% for a 2°C global warming
- 4) **Proportion of TCs that reach very intense (Category 4-5) levels** *likely* to increase (*medium-to-high confidence*)
- 5) **Poleward expansion of the latitude of maximum intensity in the western North Pacific** (*low-to-medium confidence*)
- 6) **TC frequency:** global decrease (*medium confidence*). Most modeling studies project a decrease, though mechanism not well known. About -10% for a 2°C global warming.
- 7) **Very intense TC frequency (Category 4-5):** global increase (*low-to-medium confidence*)