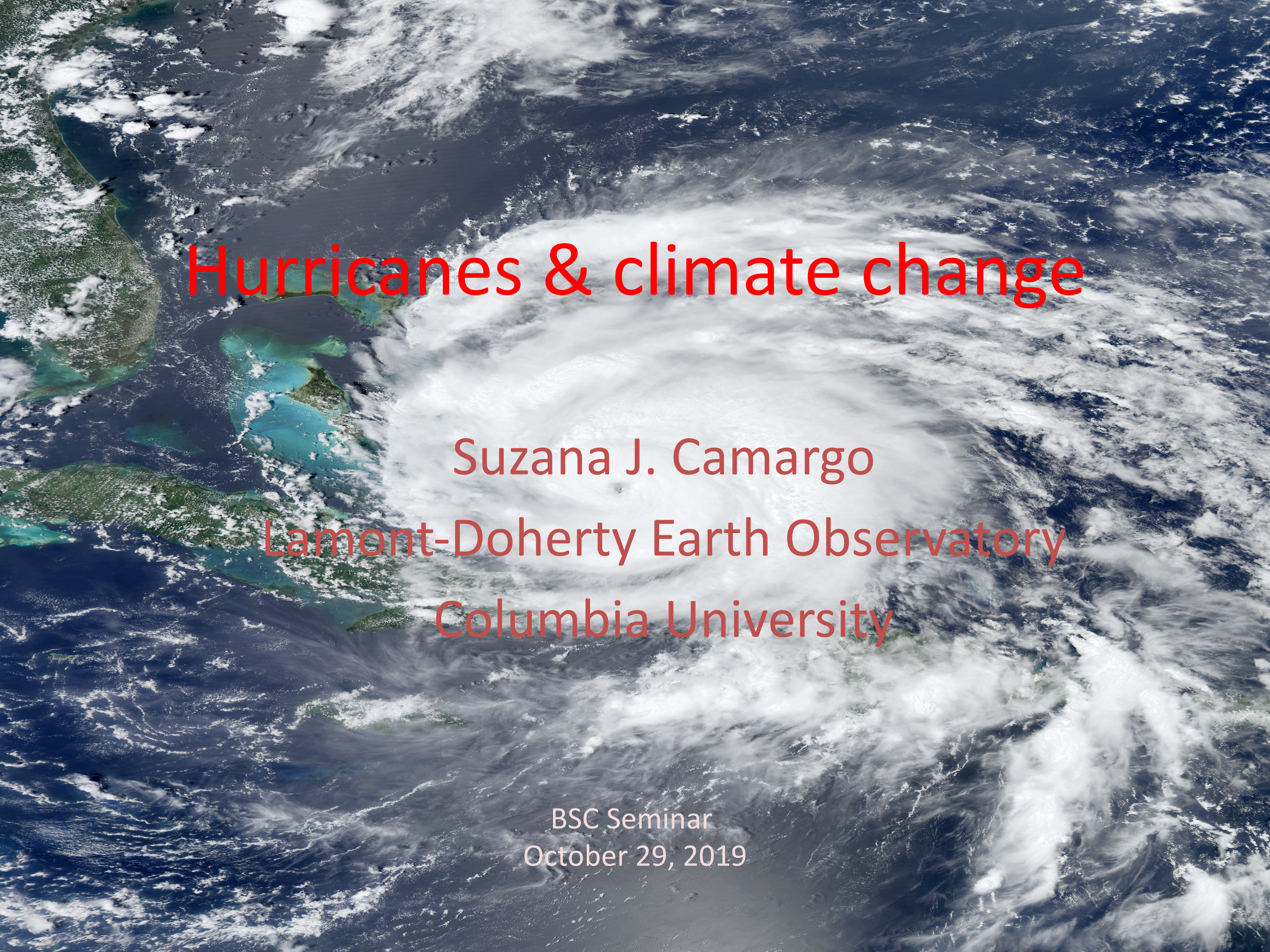


Hurricanes & climate change

Suzana J. Camargo
Lamont-Doherty Earth Observatory
Columbia University

BSC Seminar
October 29, 2019

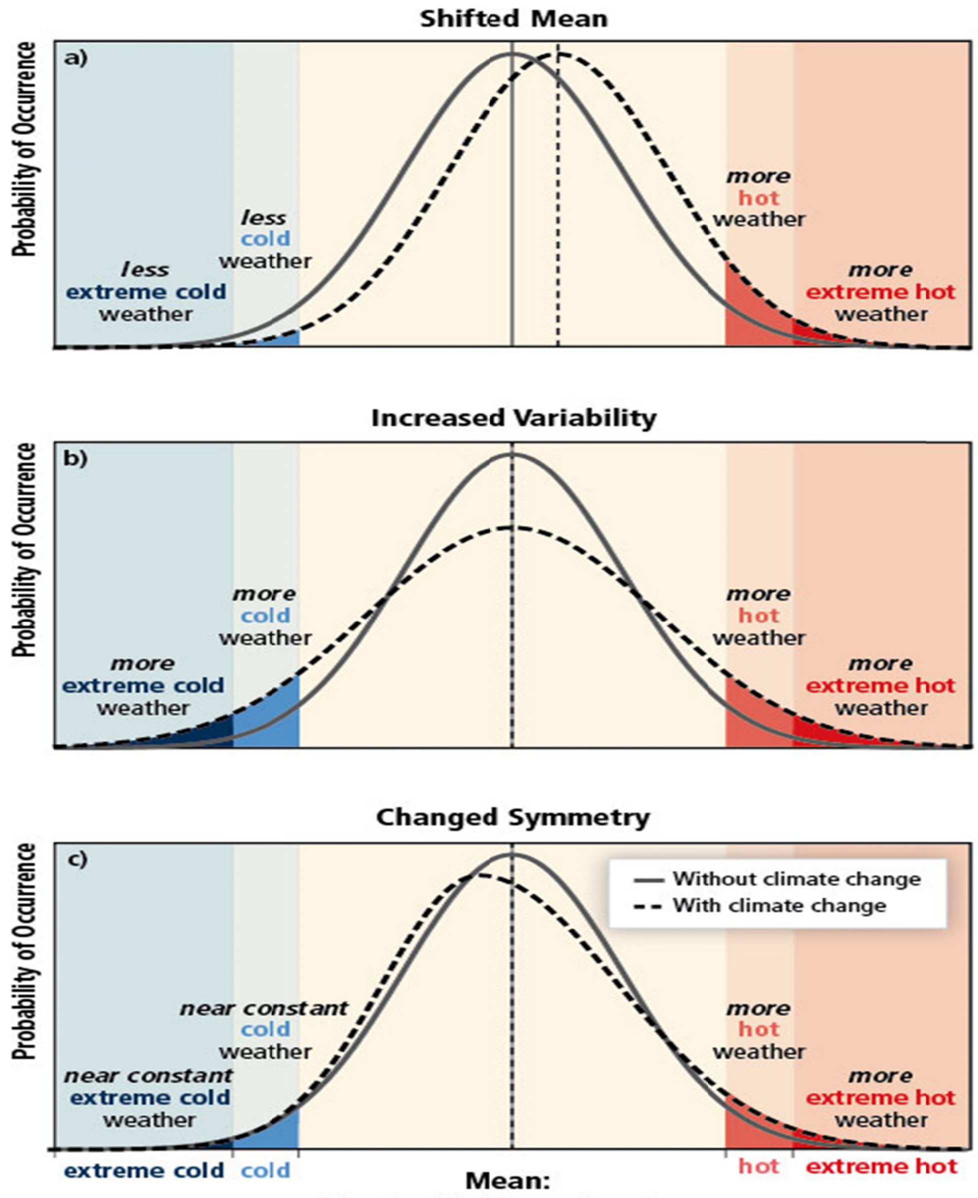
Outline

1. Introduction – extreme events & climate change
2. Hurricanes and Climate Change overview:
   – Detection and Attribution
   – Projections
3. CHAZ (Columbia Hazard model)
   – Model description
   – Example
   – Climate change results

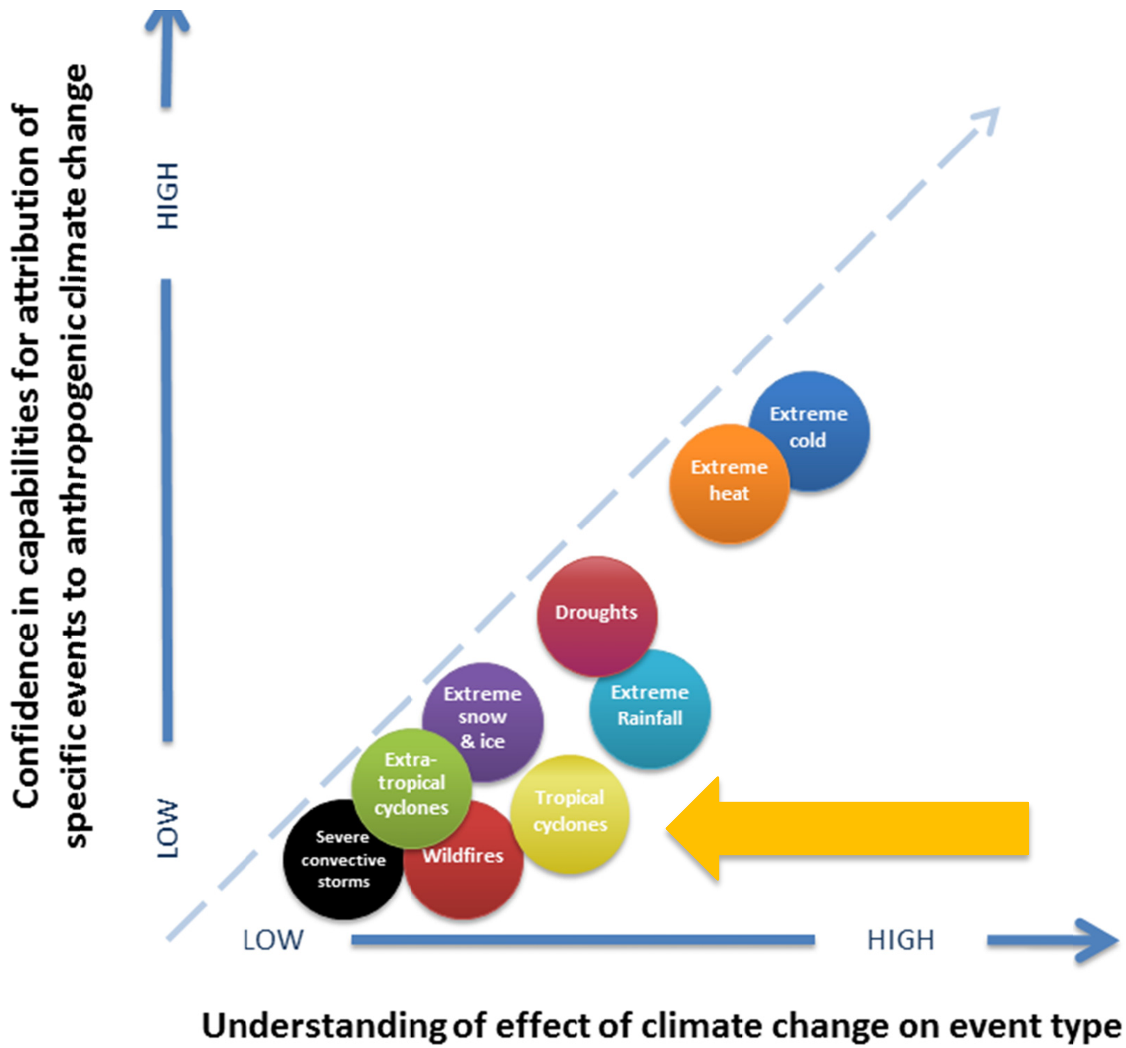
Extreme Events Issues

- Society has become more vulnerable to extreme events.
- Lack of long-term climate data suitable for analysis of extremes
- Did climate change contribute to a specific extreme event?
- Are there significant trends in the characteristics of (frequency, intensity, …) an extreme event?
- How will climate change modify extreme events?

Typical IPCC view of extreme events



Extreme events and climate change

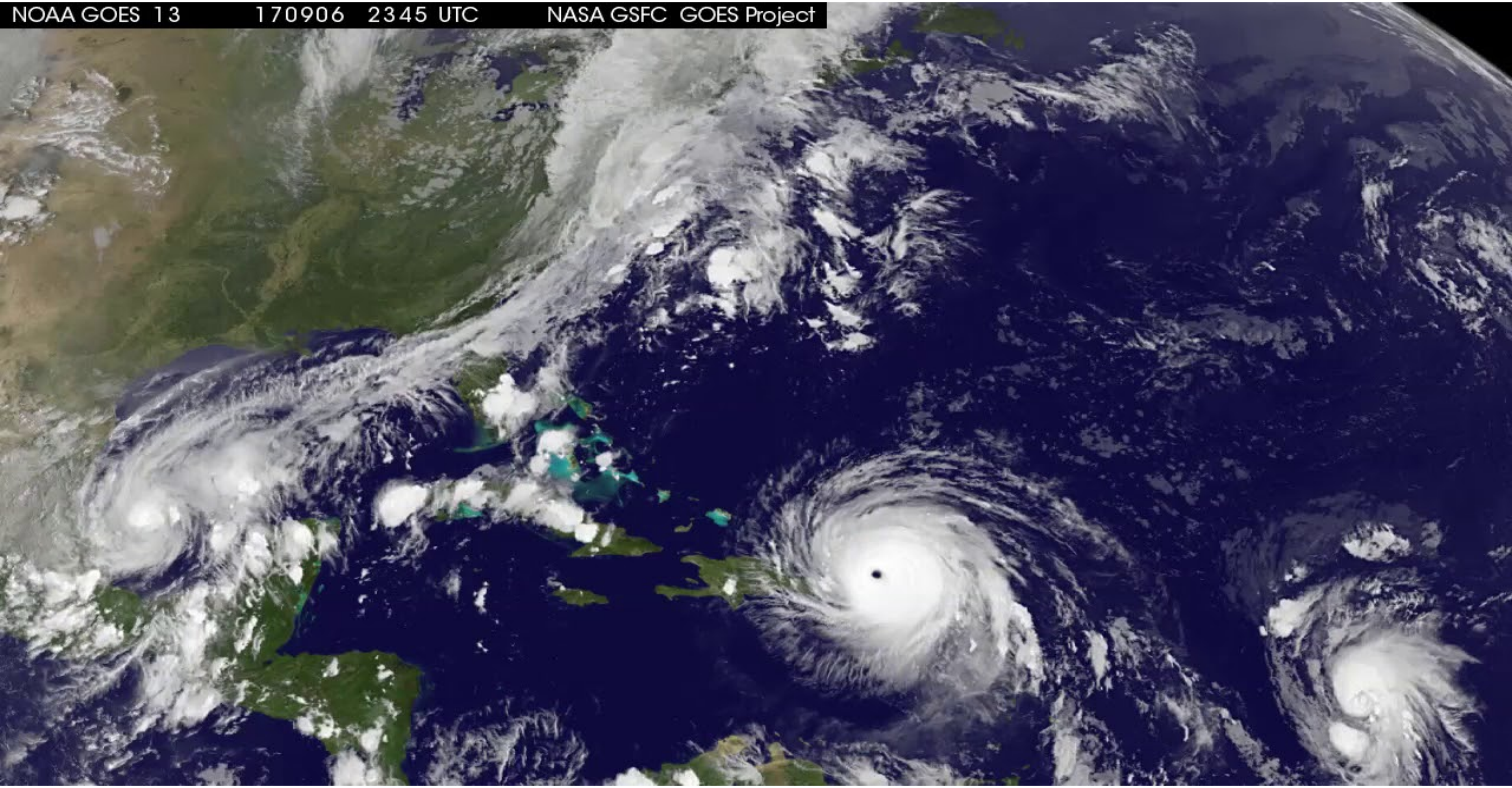


PNAS, 2015

Extremes and climate climate change II

● = high ◉ = medium ○ = low	Capabilities of Climate Models to Simulate Event Class	Quality/Length of the Observational Record	Understanding of Physical Mechanisms that Lead to Changes in Extremes as a Result of Climate Change
Extreme cold events	●	●	●
Extreme heat events	●	●	●
Droughts	◉	◉	◉
Extreme rainfall	◉	◉	◉
Extreme snow and ice storms	◉	○	◉
Tropical cyclones	○	○	◉
Extratropical cyclones	◉	○	○
Wildfires	○	◉	○
Severe convective storms	○	○	○

PNAS, 2015



Katia Irma Jose

Issues – TCs Detection and Attribution

- Large amplitude fluctuations of climate variability for TCs (frequency and intensity) – trend attribution is difficult.
- Global historical records of TCs – availability and quality limited – large error bars
- Uncertainty: past changes in TC variability have exceeded what is expected from nature climate variability.

Knutson et al. 2010

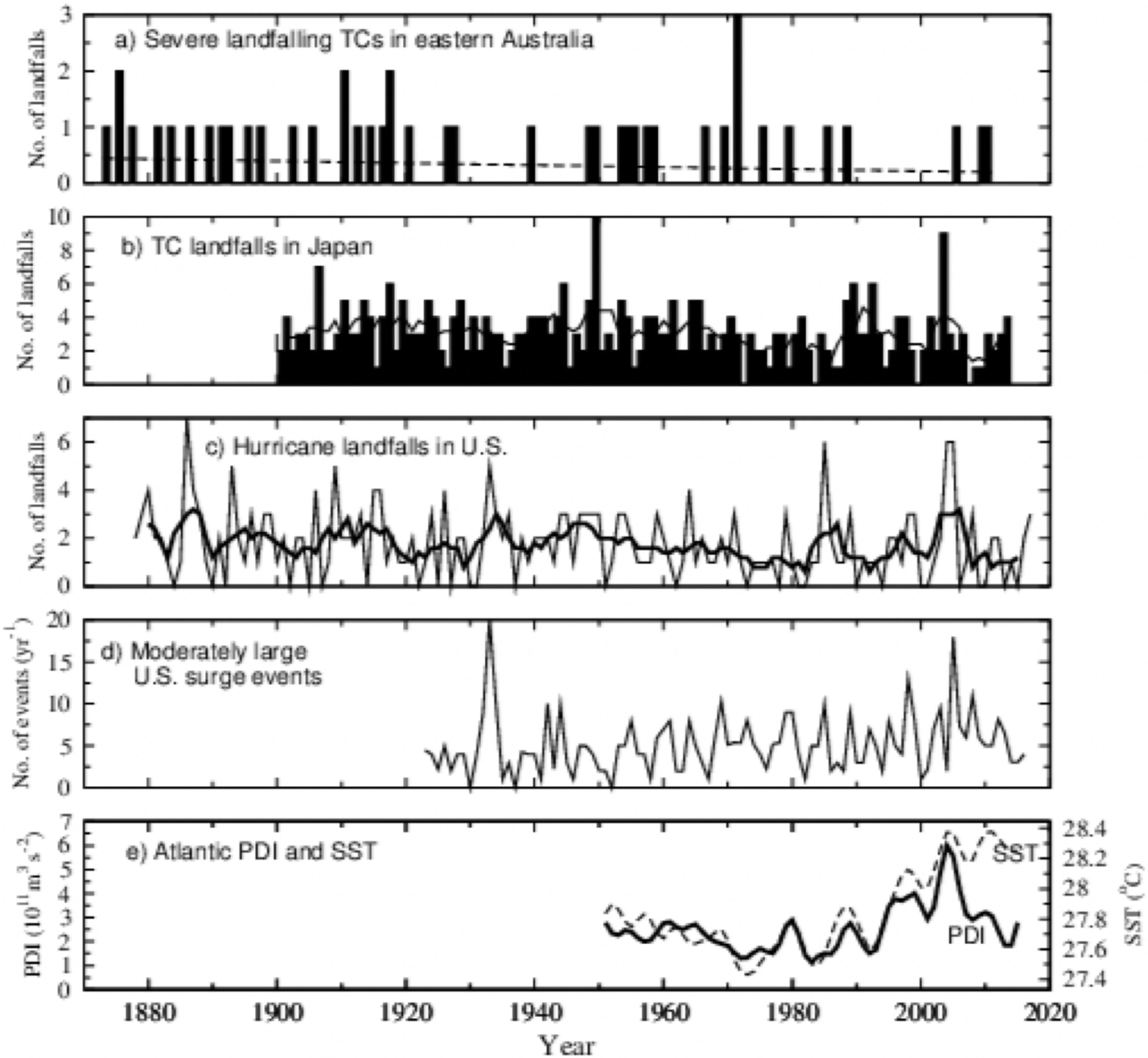
TROPICAL CYCLONES AND CLIMATE CHANGE ASSESSMENT

Part I: Detection and Attribution

Thomas Knutson, Suzana J. Camargo, Johnny C. L. Chan, Kerry Emanuel, Chang-Hoi Ho, James Kossin, Mrutyunjay Mohapatra, Masaki Satoh, Masato Sugi, Kevin Walsh, and Liguang Wu

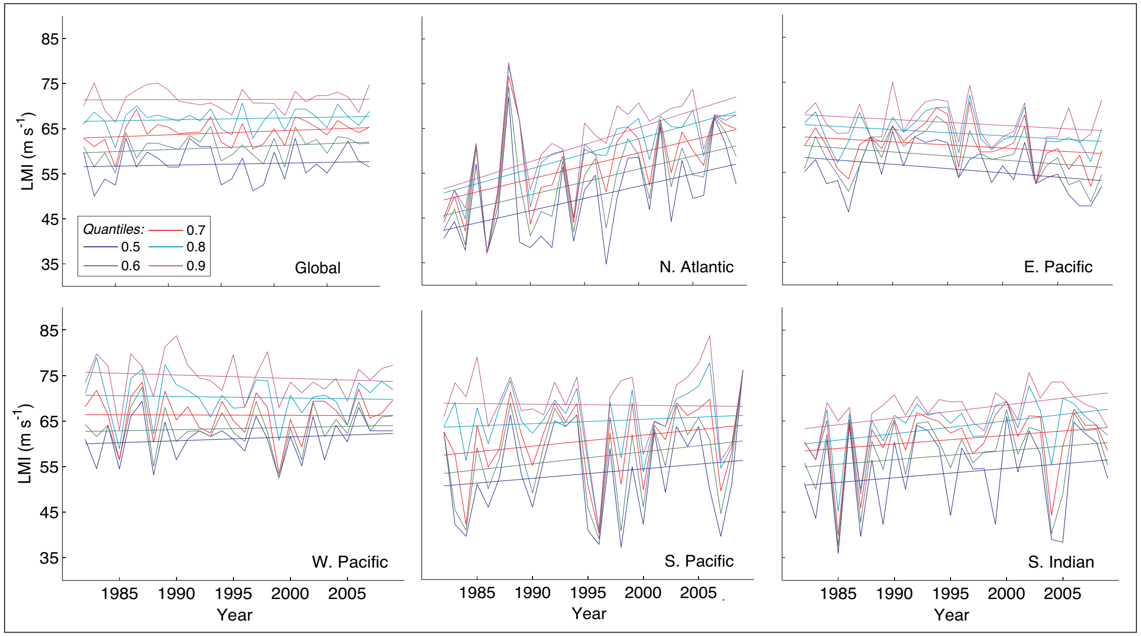
We assess whether detectable changes in tropical cyclone activity have been identified in observations and whether any changes can be attributed to anthropogenic climate change.

TCs trends

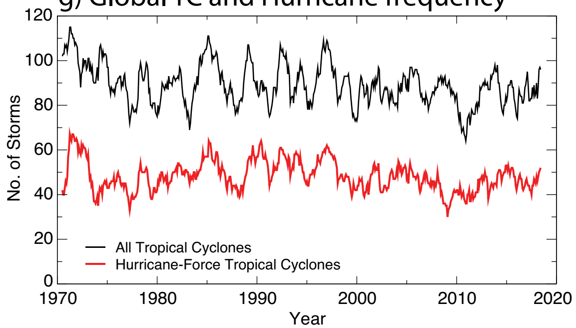


Knutson et al. BAMS 2019a

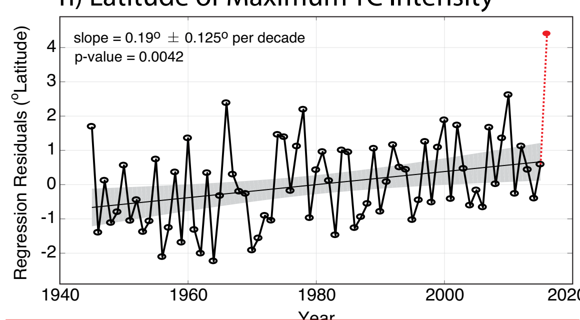
f) TC maximum intensities by quantile (Global and individual basin)



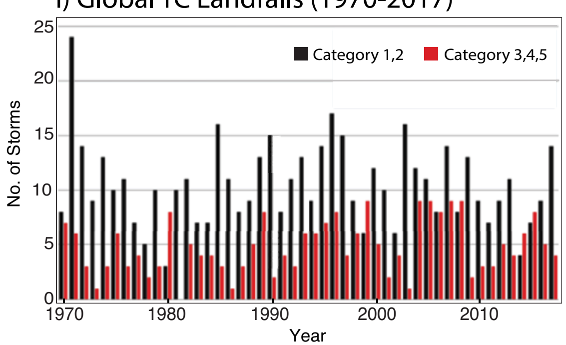
g) Global TC and Hurricane frequency



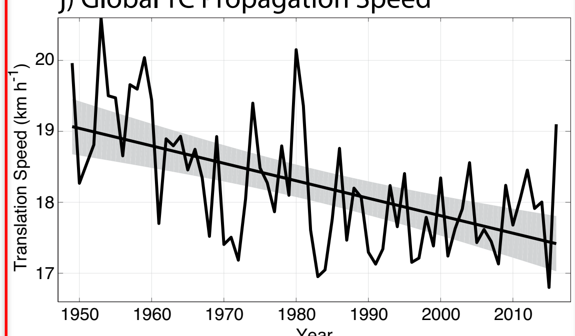
h) Latitude of Maximum TC Intensity



i) Global TC Landfalls (1970-2017)



j) Global TC Propagation Speed



Controversial:
Kossin 2018
& responses

Knutson et al. BAMS2019a

Error Types for Detection & Attribution

- **Type I error:** conclusion that anthropogenic forcing has contributed to an observed change/event when it has not done so.
- **Type II error:** NOT concluding that anthropogenic forcing has contributed to an observed change/event when it has done so.
- If only type I error is considered: miss anthropogenic influences that have not yet emerged or identified with high confidence

See Lloyd and Oreskes (2018)

TABLE 1. Distribution of author opinion on potential tropical cyclone detection and attribution statements elicitation. For the type II error avoidance, both detection and attribution substatements are prefaced by "The balance of evidence suggests…" and "Detectable" refers to "unusual compared to natural variability, e.g., $p < 0.1$." Numbers in parentheses indicate the number of authors reporting this confidence level.
Perspective: Type I error avoidance
1) The estimated contribution of decreased anthropogenic aerosol forcing to the increased Atlantic TC frequency since the 1970s is large and positive and is highly unusual (e.g., $p < 0.05$) compared to natural variability. **Confidence: low (7); low to medium (2); medium (1); medium to high (1).**
2) Observed poleward migration of latitude of maximum intensity in northwest Pacific basin is highly unusual (e.g., $p < 0.05$; statistically distinguishable) compared with expected natural variability. **Confidence: low to medium (8); medium (1); medium to high (2).**
3) Anthropogenic forcing has contributed to the observed poleward migration of the latitude of maximum intensity in the northwest Pacific basin. **Confidence: low (6); low to medium (2); medium (3).**
4) There has been a detectable decrease (highly unusual compared to natural variability; e.g., $p < 0.05$) in the global-scale propagation speed of TCs since 1949. **Confidence: low (6); low to medium (4); medium (1).**
5) Anthropogenic forcing has contributed to the observed decrease in the global-scale propagation speed of TCs since 1949. **Confidence: low (8); low to medium (3).**
6) List any other observed multidecadal- to century-scale change in TC activity that is highly unusual (e.g., $p < 0.05$; statistically distinguishable) compared with expected natural variability (from a type I error avoidance perspective), and provide confidence level. **None identified.**

Knutson et al. BAMS 2019a

Summary – Type I error

- Strongest cases:
  - Observed poleward migration of latitude of lifetime maximum intensity (LMI) in the Western North Pacific – Low to Medium confidence (8/11)
  - Anthropogenic forcing contributed to the LMI poleward shift - Low confidence (6/11)
- All other changes (detectable or attributable to CC): low confidence

Knutson et al. BAMS, 2019a

Knutson et al. 2019a

Table 1. Continued.
Perspective: Type II error avoidance
7) Detectable increase in North Atlantic TC activity since the 1970s **(9% agree)**; and anthropogenic forcing (reduced aerosol forcing) has contributed to this increase **(45% agree)**.
8) Observed poleward migration of latitude of maximum intensity in northwest Pacific basin is detectable **(all agree)**; and anthropogenic forcing has contributed to the observed poleward migration of the latitude of maximum intensity in the northwest Pacific basin **(82% agree)**.
9) Detectable increase in TC intensity over the Arabian Sea (premonsoon) over 1979–2010 **(none agree)**; and anthropogenic forcing has contributed to this increase **(none agree)**.
10) Detectable increase in the frequency of extremely severe cyclonic storms over the Arabian Sea (postmonsoon) over 1998–2015 **(all agree)**; and anthropogenic forcing has contributed to this increase **(73% agree)**.
11) Detectable increase in the global proportion of TCs reaching category 4 or 5 intensity in recent decades **(all agree)**; and anthropogenic forcing has contributed to this increase **(73% agree)**.
12) Detectable increase in the global average intensity of strongest (hurricane intensity) TCs since the early 1980s **(91% agree)**; and anthropogenic forcing has contributed to this increase of global average intensity of strongest (hurricane intensity) TCs **(73% agree)**.
13) Detectable multidecadal increase in TC occurrence near Hawaii **(none agree)**; and anthropogenic forcing contributed to the recent unusually active TC season near Hawaii in 2014 **(55% agree)**.
14) Detectable increase in TC occurrence activity in the western North Pacific in recent decades **(none agree)**; and anthropogenic forcing contributed to the recent unusually active TC season, including the record-setting (1984–2015) TC intensity, in the western North Pacific in 2015 **(73% agree)**.
15) Detectable increase in the intensity of Hurricane Sandy–like storms in the Atlantic in recent decades **(none agree)**; and anthropogenic forcing contributed to the intensity of Hurricane (Superstorm) Sandy in 2012 **(none agree)**.
16) Detectable increase in the intensity of Haiyan-like supertyphoons in the western North Pacific in recent decades **(18% agree)**; and anthropogenic forcing contributed to the intensity of Supertyphoon Haiyan in 2013 **(45% agree)**.
17) Detectable long-term increase in the occurrence of Hurricane Harvey–like extreme precipitation events in the Texas region **(all agree)**; and anthropogenic forcing has contributed to increased frequency of Hurricane Harvey–like precipitation events in the Texas region **(all agree)**.
18) Detectable increase in the frequency of moderately large U.S. surge events since 1923 as documented by the index of Grinsted et al. (which strongly filters out sea level rise influences) **(18% agree)**; and anthropogenic forcing has contributed to this increase **(18% agree)**.
19) Detectable decrease in the global-scale propagation speed of TCs since 1949 **(73% agree)**; and anthropogenic forcing has contributed to this decrease **(9% agree)**.
20) Detectable decrease in severe landfalling TCs in eastern Australia since the late 1800s **(82% agree)**; and balance of evidence suggests anthropogenic forcing has contributed to this decrease **(none agree)**.
21) Detectable decrease in U.S. landfalling-hurricane frequency since the late 1800s **(none agree)**; and anthropogenic forcing has contributed to this decrease **(none agree)**.
22) Detectable increase in global major hurricane landfall frequency in recent decades **(none agree)**; and anthropogenic forcing has contributed to this increase **(none agree)**.
23) Detectable decrease in TC frequency in the southeastern part of the western North Pacific (1992–2011) **(none agree)**; and anthropogenic forcing (changes in aerosol emissions) has contributed to this decrease **(50% agree)**.

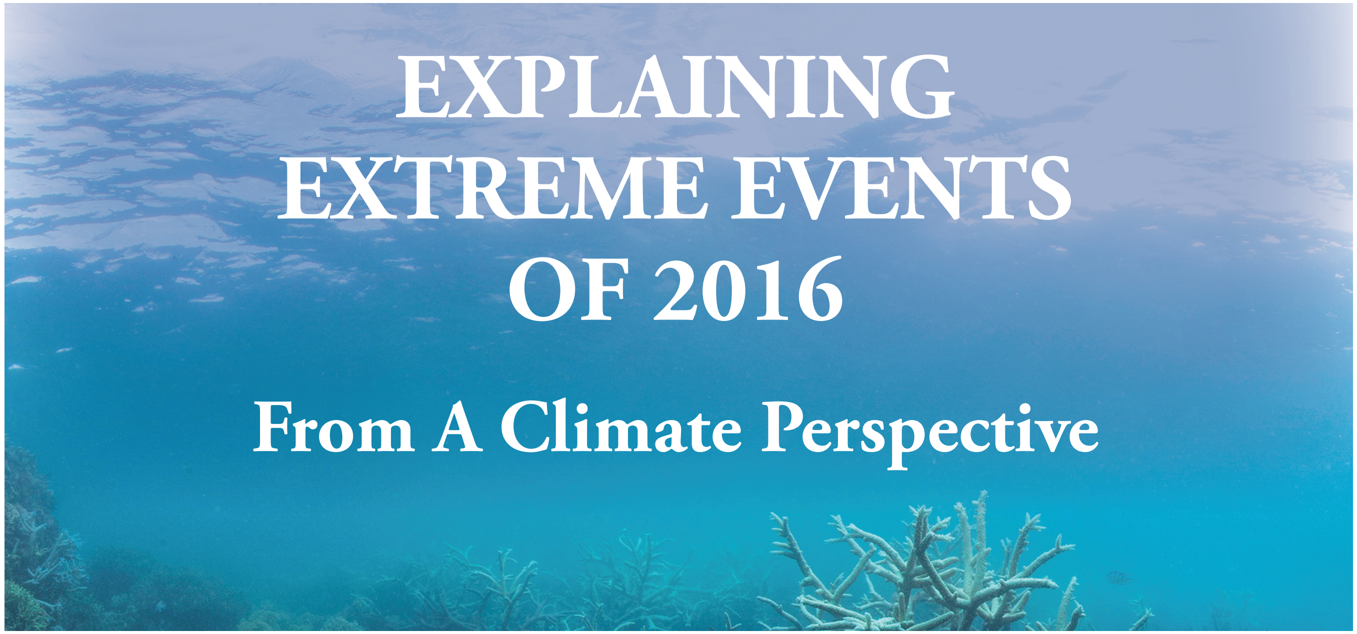
Summary – Type II Errors
(Chance for false alarm)

- Main detectable Anthropogenic contributions:
  - LMI poleward migration in the Western North Pacific
  - Increased global average intensity of strongest TCs
  - Increase in proportion of cat 4 and cat 5 TCs
  - Increase frequency of hurricane Harvey-like precipitation events in Texas
  - Increased occurrence of intense Arabian Sea TCs

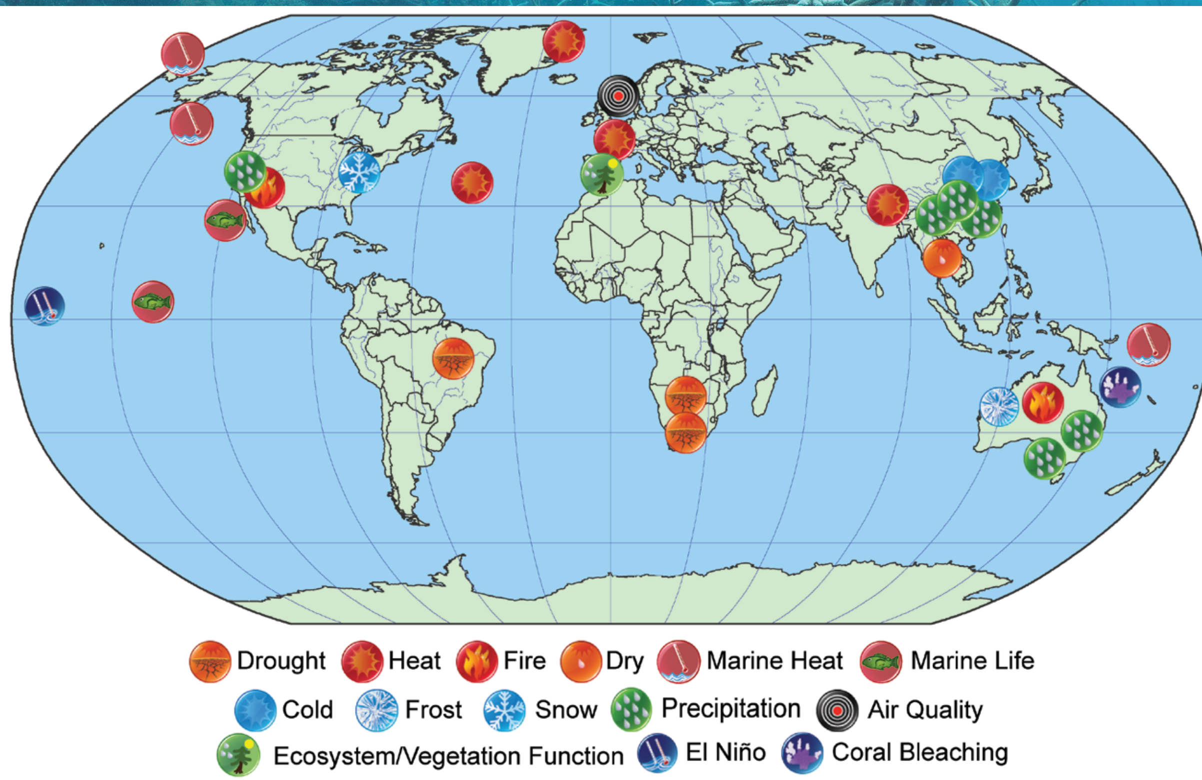
Knutson et al. BAMS, 2019a

Attribution of individual TC events

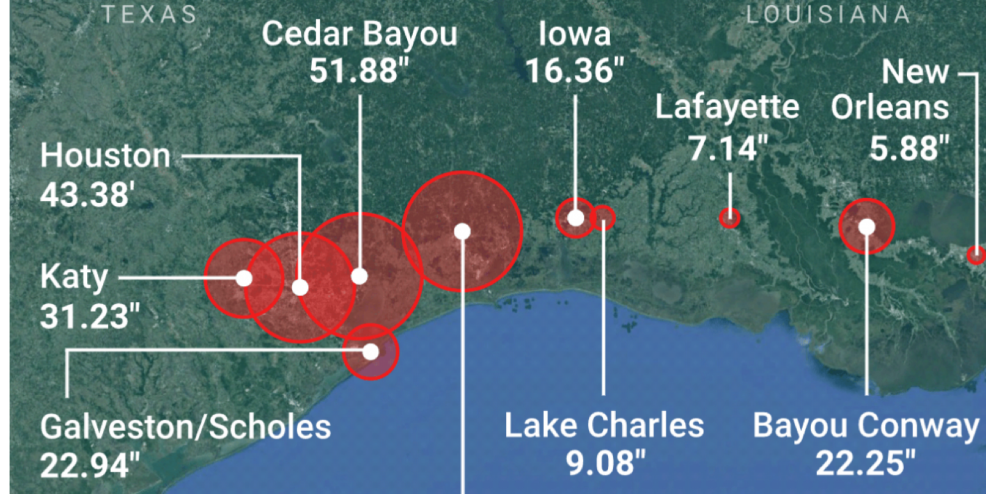
BAMS



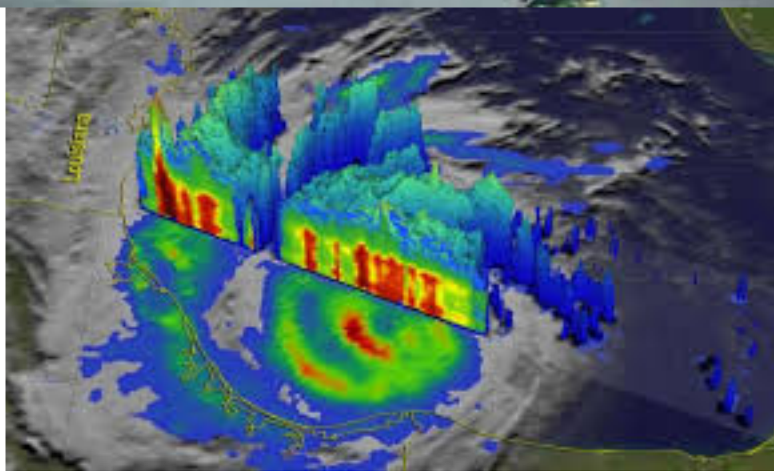
EXPLAINING
EXTREME EVENTS
OF 2016
From A Climate Perspective



Drought
Heat
Fire
Dry
Marine Heat
Marine Life
Cold
Frost
Snow
Precipitation
Air Quality
Ecosystem/Vegetation Function
El Niño
Coral Bleaching



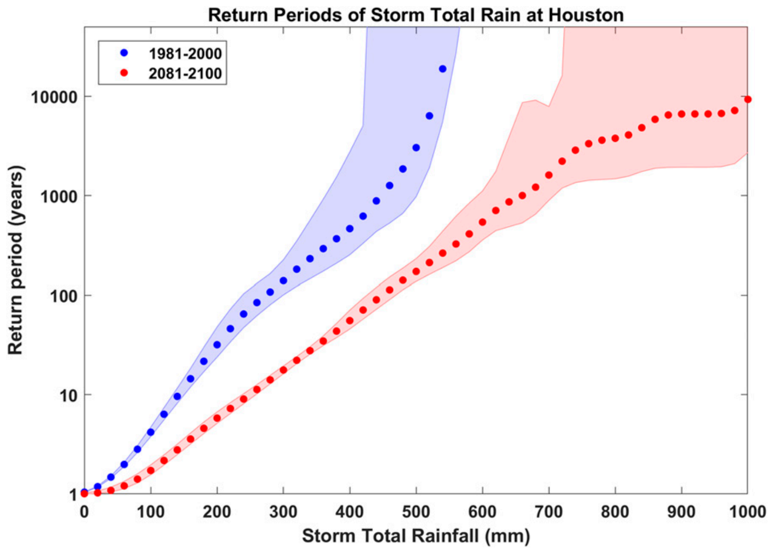
TEXAS
LOUISIANA
Cedar Bayou
51.88"
Iowa
16.36"
Lafayette
7.14"
New
Orleans
5.88"
Houston
43.38'
Katy
31.23"
Galveston/Scholes
22.94"
Lake Charles
9.08"
Bayou Conway
22.25"



Observed Precipitation
Houston

Expected Storm Total Rainfall
Hurricane Harvey
Austin / San Antonio
WEATHER FORECAST OFFICE
10-20 inches along and east of I-35 Friday through Tuesday.
Local amounts in excess of 25 inches possible near and south of I-10
Rainfall forecast amounts still subject to large changes depending on path of Harvey after landfall.
Expecting steep drop off in rainfall values on western extent of rain area.
Note: There will likely be locally higher amounts

Hurricane Harvey attribution studies



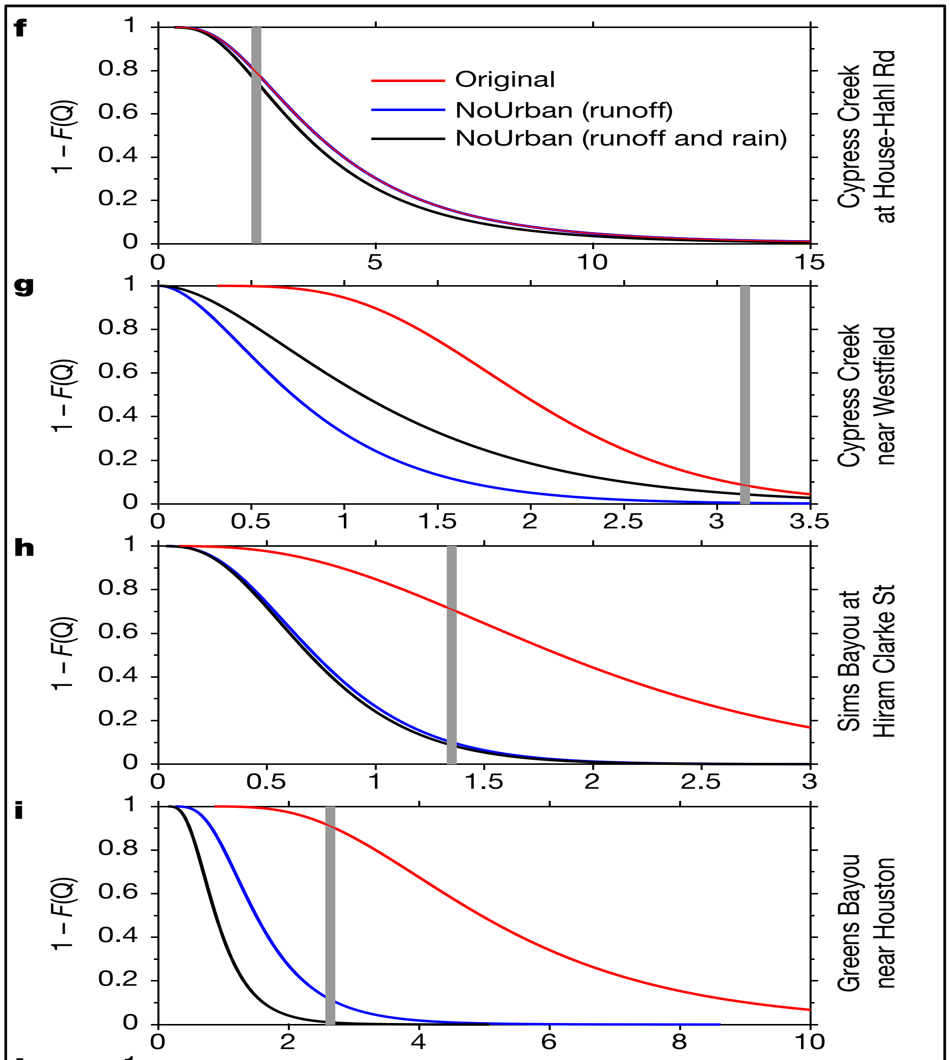
Emanuel PNAS, 2017

Likely increase of 6% in 2017

- Risser & Wehner GRL, 2017: Likely increase of ~ 19%
- van Oldenborgh et al. ERL, 2017: Likely increase of ~ 15%
- S.-Y. Wang et al. ERL, 2018: Likely increase of ~ 20%

Urbanization exacerbated the rainfall and flooding caused by hurricane Harvey in Houston

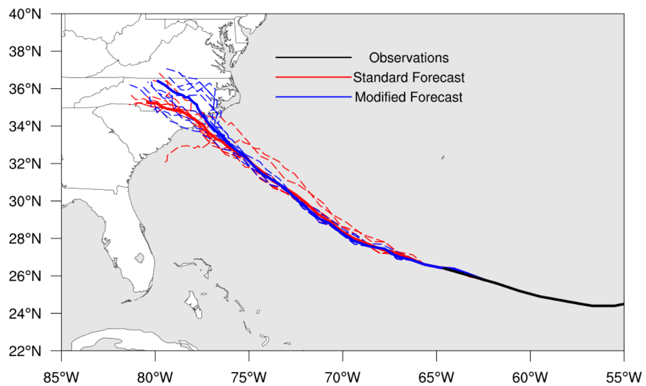
Wei Zhang[1], Gabriele Villarini[1]*, Gabriel A. Vecchi[2,3] & James A. Smith[4] Nature, 2019

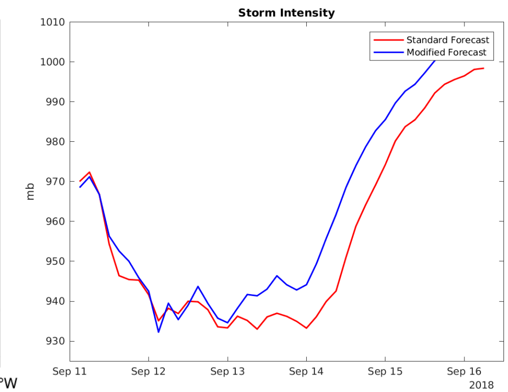


The human influence on Hurricane Florence

Kevin A. Reed, Stony Brook University
Alyssa M. Stansfield, Stony Brook University
Michael F. Wehner, Lawrence Berkeley National Laboratory
Colin M. Zarzycki, National Center for Atmospheric Research

Intensity: *Hurricane Florence is slightly more intense for a longer portion of the forecast period due to climate change according to the forecasted minimum surface pressure.*

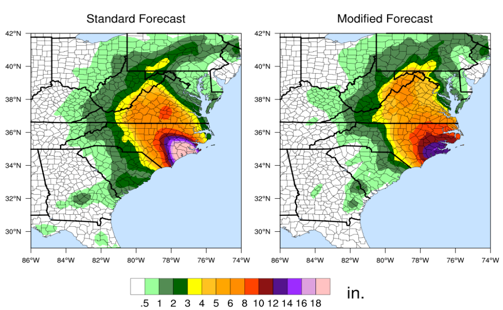


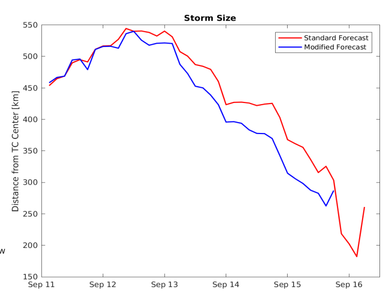


Left: Individual ensemble forecasts (dashed) and ensemble mean (solid) of Hurricane Florence.
Right: Time evolution of the ensemble average central minimum surface pressure.
Red: Florence in the world that is. ***Blue:*** Florence in the world that might have been without climate change.

Rainfall: *The forecasted Hurricane Florence rainfall amounts over the Carolinas are increased by over 50% due to climate change and are linked to warmer sea surface temperatures and available moisture in the atmosphere.*

Storm Size: *The forecasted size of Hurricane Florence is about 80 km larger due the effect of climate change on the large-scale environment around the storm.*





Left: Ensemble average accumulated rainfall Hurricane Florence forecasts.
Right: Evolution of the ensemble average outer storm size (radius at peak wind speed of approximately 18 mph).
Red: Florence in the world that is. ***Blue:*** Florence in the world that might have been without climate change.

Future Projections – TCs

- Based on theory and models
- Increase in storm surge due to sea level rise (SRL)
- Globally averaged intensity of TCs shift towards stronger storms – 2-11% by 2100
- Globally averaged frequency of TCs: decrease 6-34%
- Increases of ~ 20% of the precipitation rate within 100km of the storm center (mean and peak)
- Projected changes for individual basins – uncertain.
- Regions with hurricane occurrence is NOT expected to change.

Knutson et al. 2010

Tropical Cyclones and Climate Change Assessment: Part II. Projected Response to Anthropogenic Warming

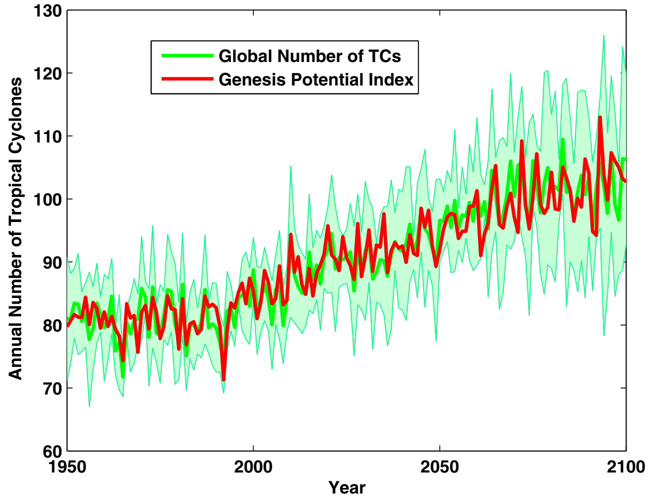
Thomas Knutson[1], Suzana J. Camargo[2], Johnny C. L. Chan[3], Kerry Emanuel[4], Chang-Hoi Ho[5], James Kossin[6], Mrutyunjay Mohapatra[7], Masaki Satoh[8], Masato Sugi[9], Kevin Walsh[10], *and* Liguang Wu[11]

BAMS, in press

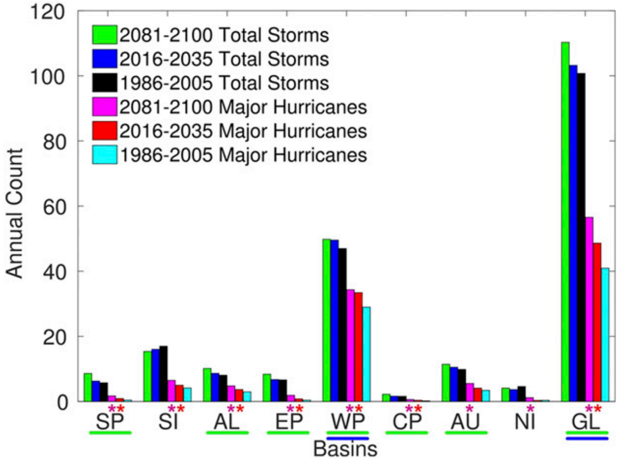
- **Highest confidence:** SLR + warming: lead to higher storm inundation levels.
- **Medium to high confidence**:
  - Increase of TC precipitation rates (~ 14%)
  - Global average intensity increase (~ 5%)
  - Increase of proportion of cat 4-5 TCs (13%)
- **Mixed confidence**:
  - Poleward shift
  - Frequency of intense TCs
  - Slowdown in TC translation speed
  - Decrease in global TC frequency

Knutson et al. BAMS, 2019b

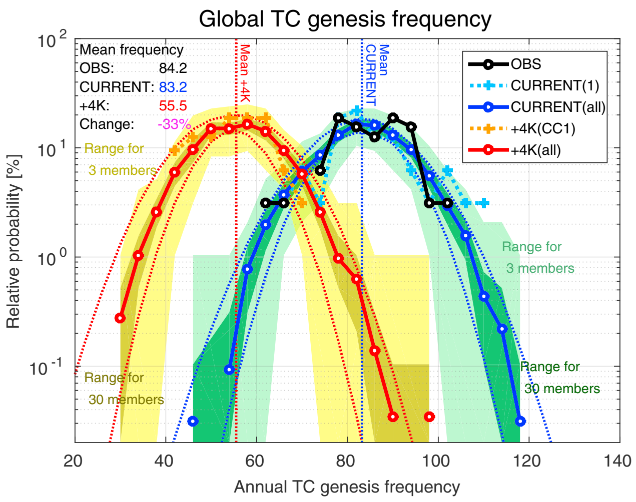
TC frequency projections – increase in uncertainty



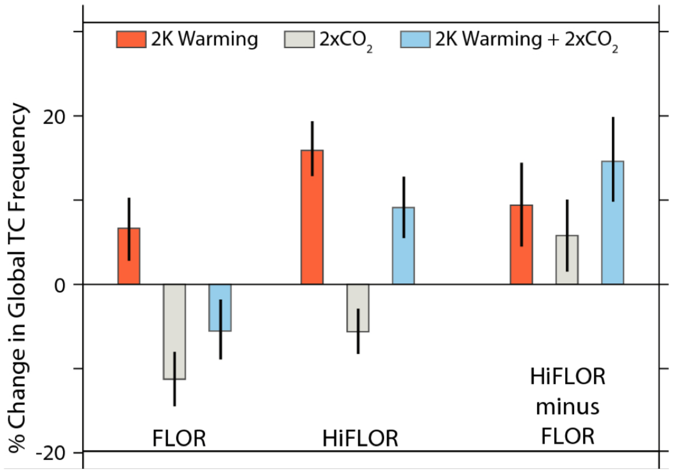
Emanuel PNAS, 2013



Bhatia et al. J. Climate, 2018



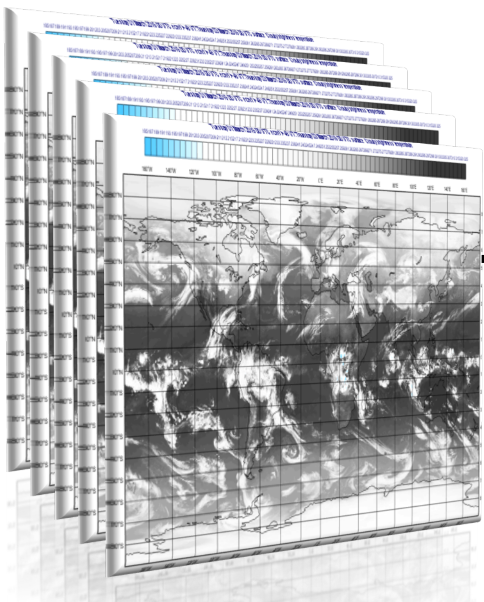
Yoshida et al., GRL 2017

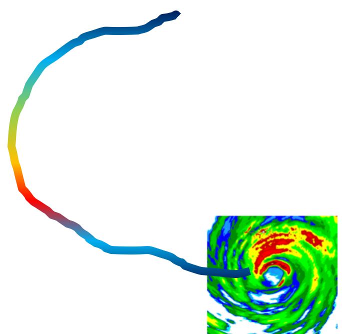


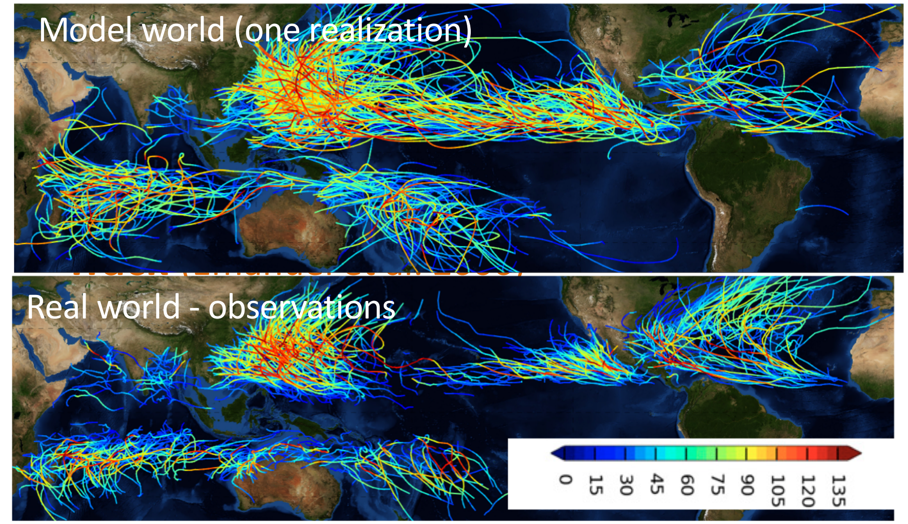
Vecchi et al. Clim. Dyn., 2019

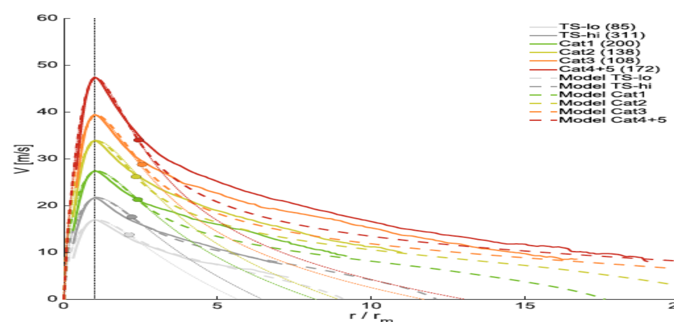
Columbia HAZard model (CHAZ):

A generator of synthetic TCs genesis, track, intensity, and winds are functions of the environment







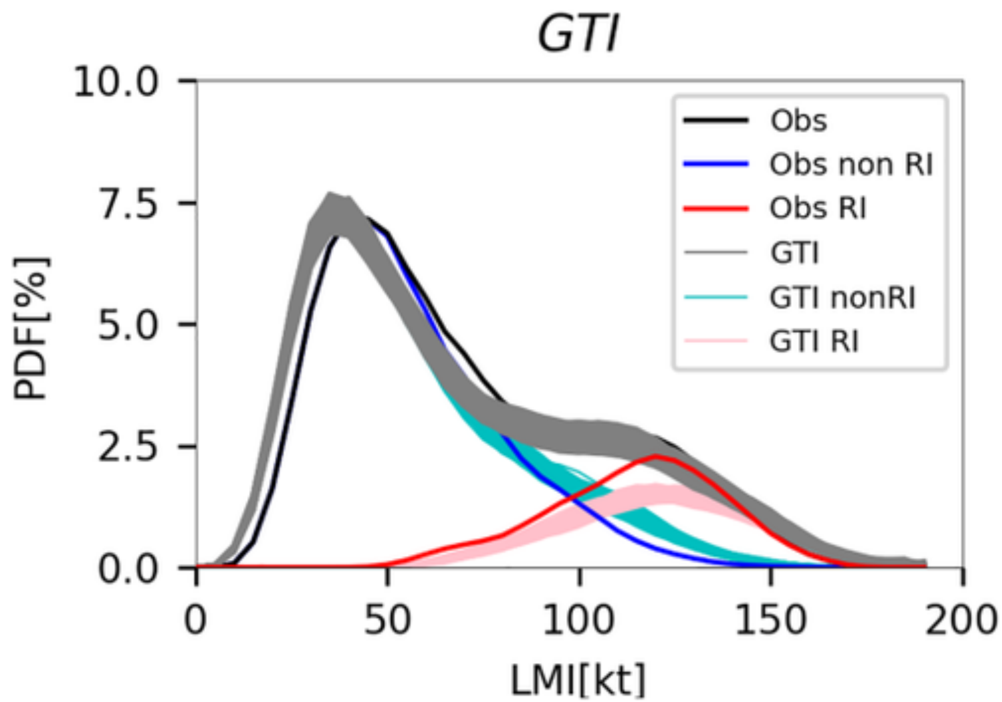


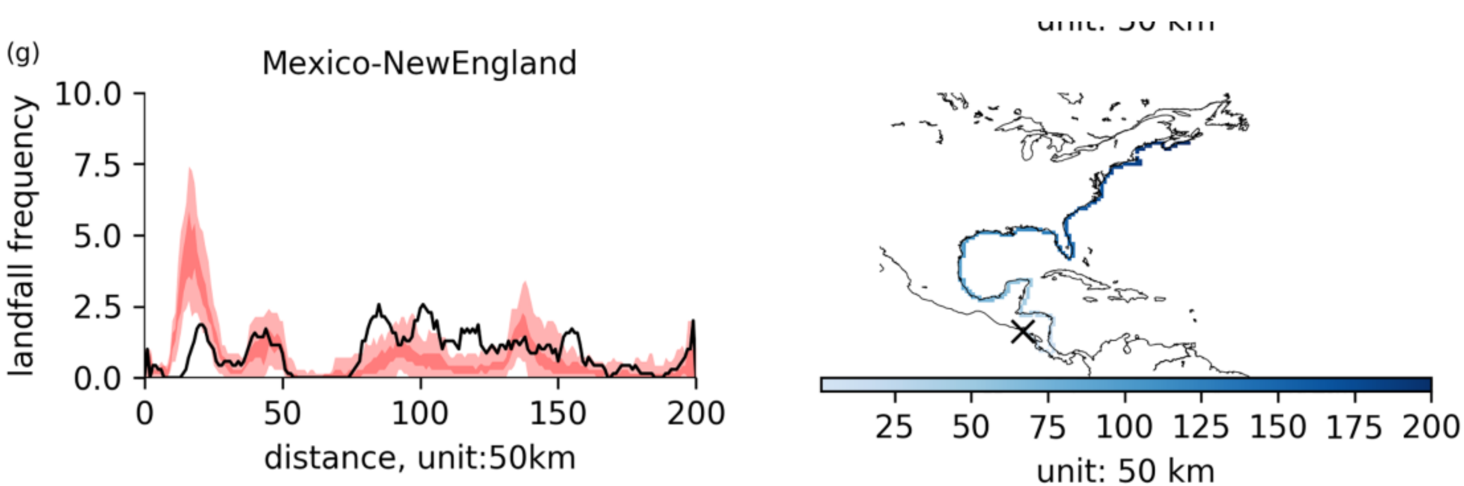
MONTHLY PI, vorticity, humidity, shear, large-scale circulation
DAILY winds

Chavas et al. 2015, JAS

Lee, Tippett, Sobel & Camargo, JAMES 2018

Figures by Chia-Ying Lee

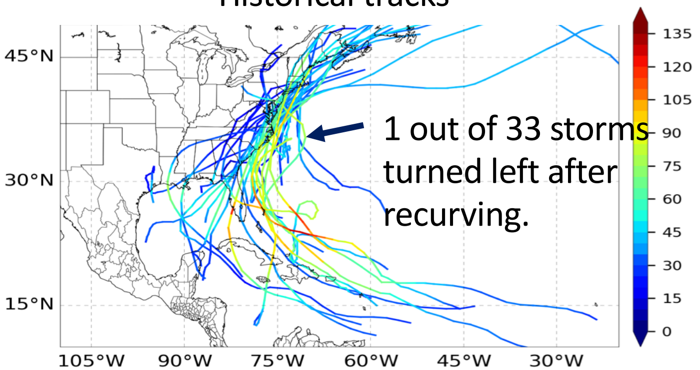




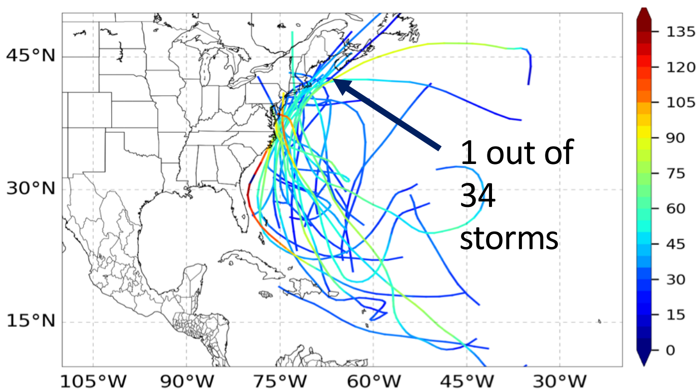
Lee et al. JAMES 2018

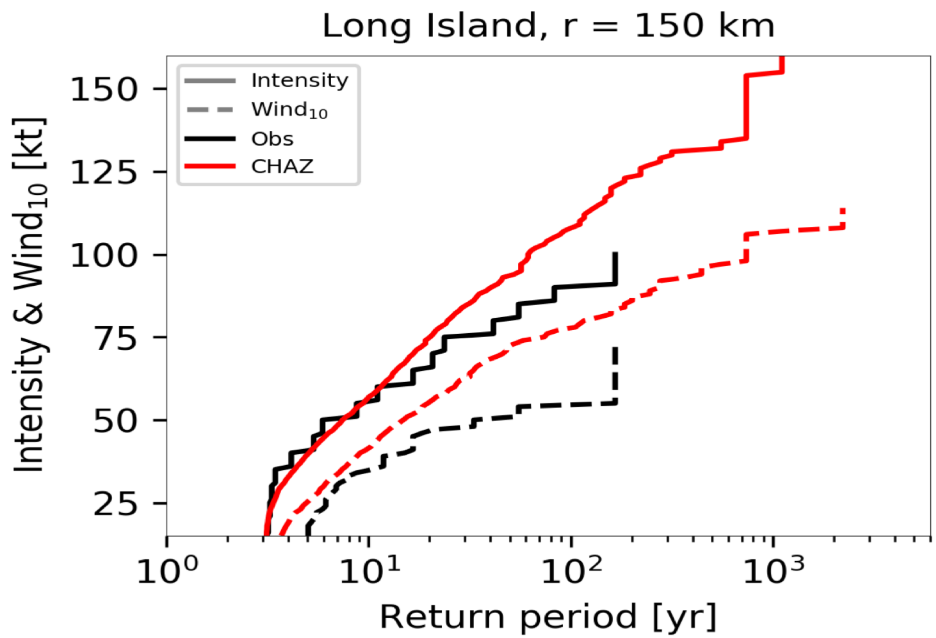
Sandy-like tracks

Historical tracks



CHAZ simulations for 1981 to 2012 env.

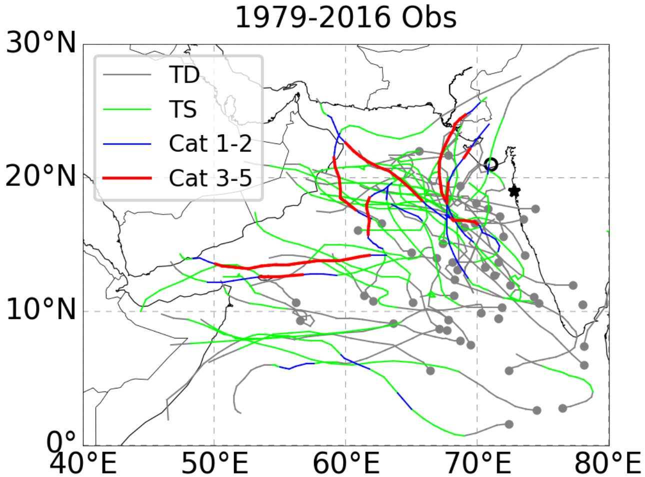


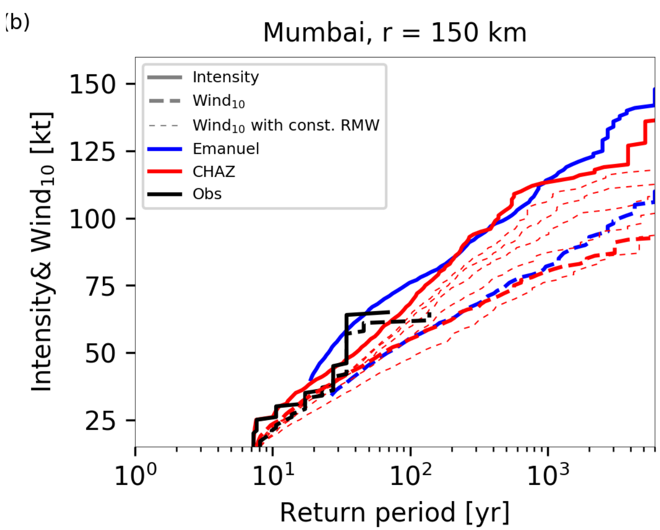


Figures by Chia-Ying Lee

TC Risk for Mumbai

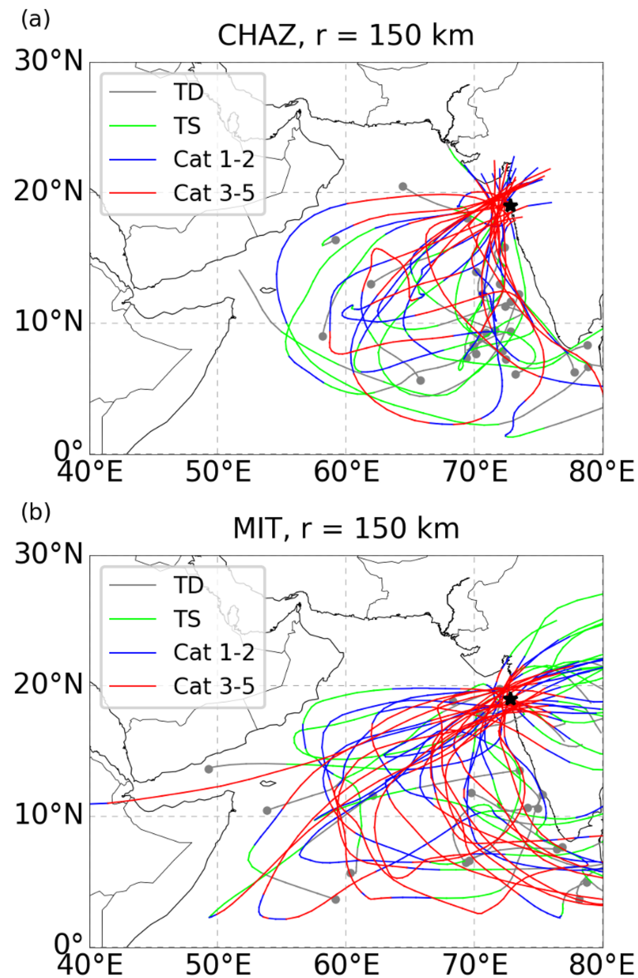
Observations





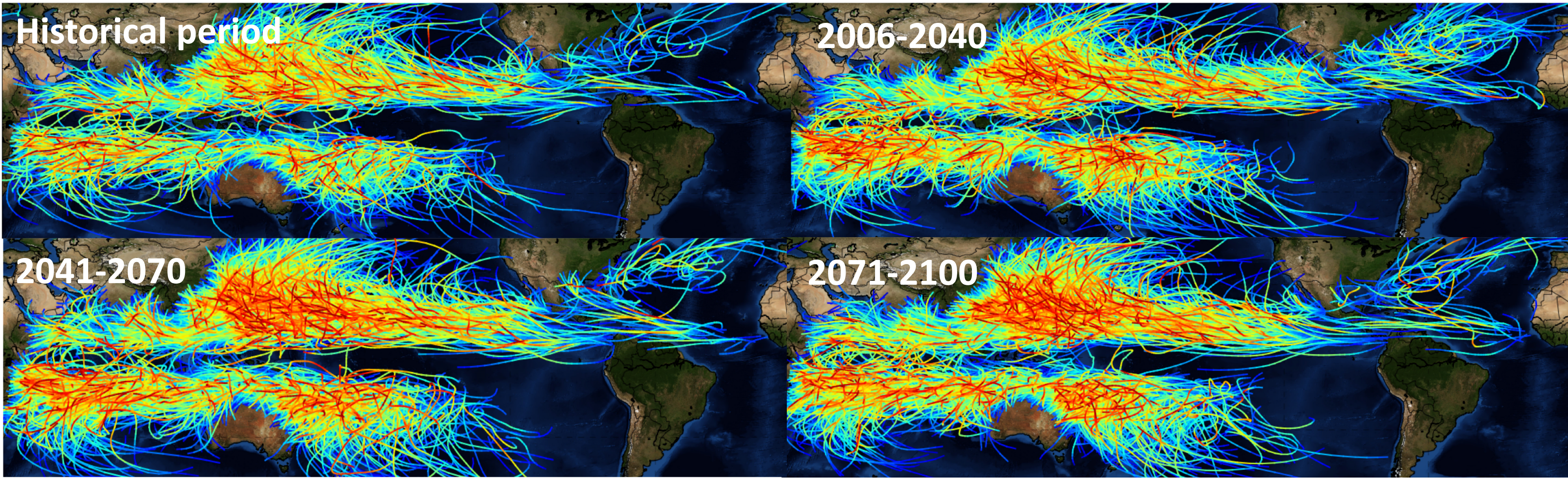
Models

Synthetic storms



Sobel, Lee, Camargo et al. MWR, 2019

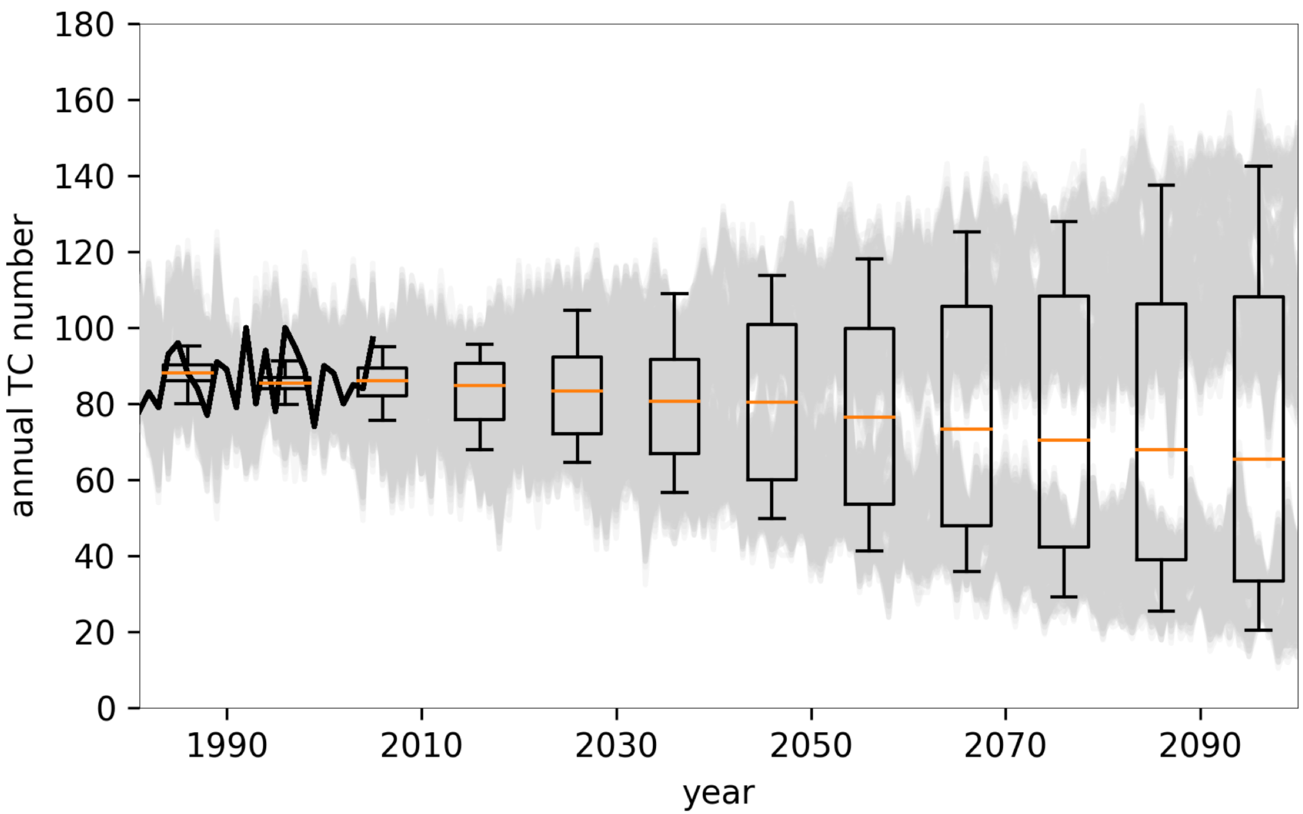
CHAZ climate change simulations



Example: one ensemble member
Forced by CMIP5 models

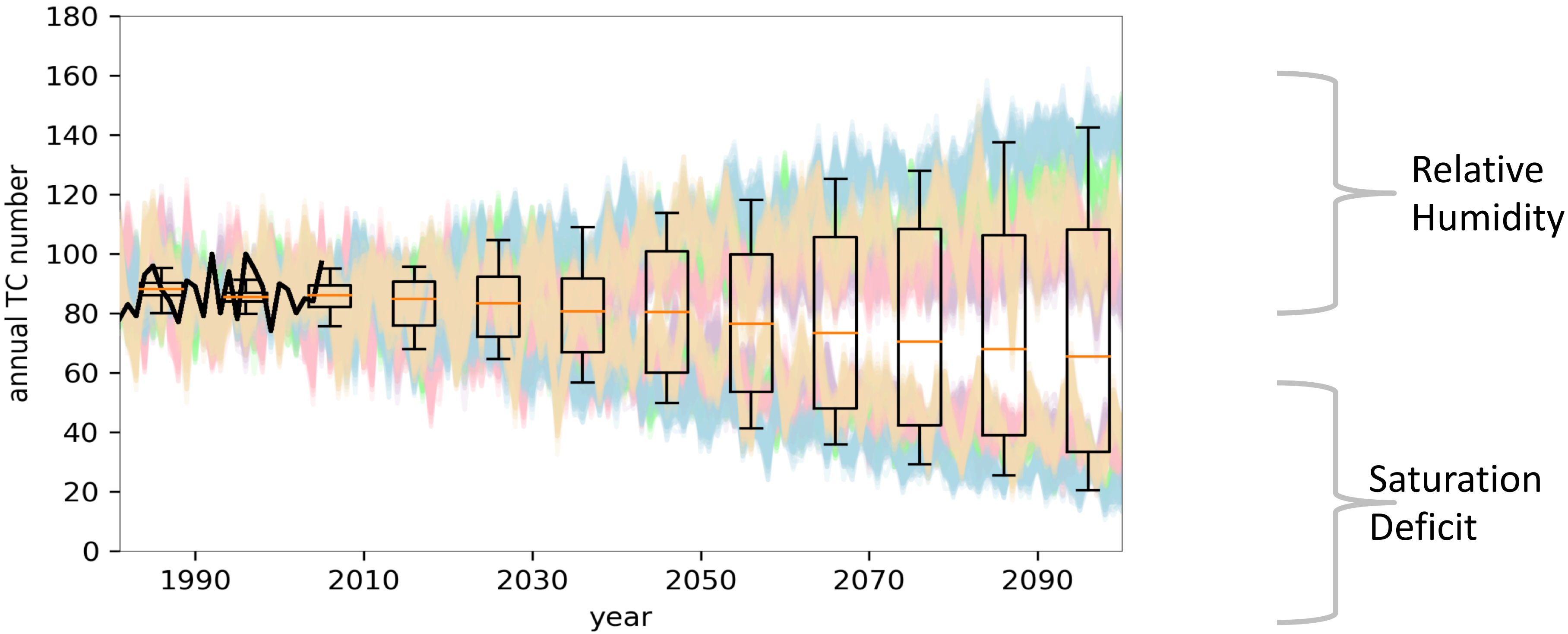
Figures by Chia-Ying Lee

CHAZ Climate change simulations



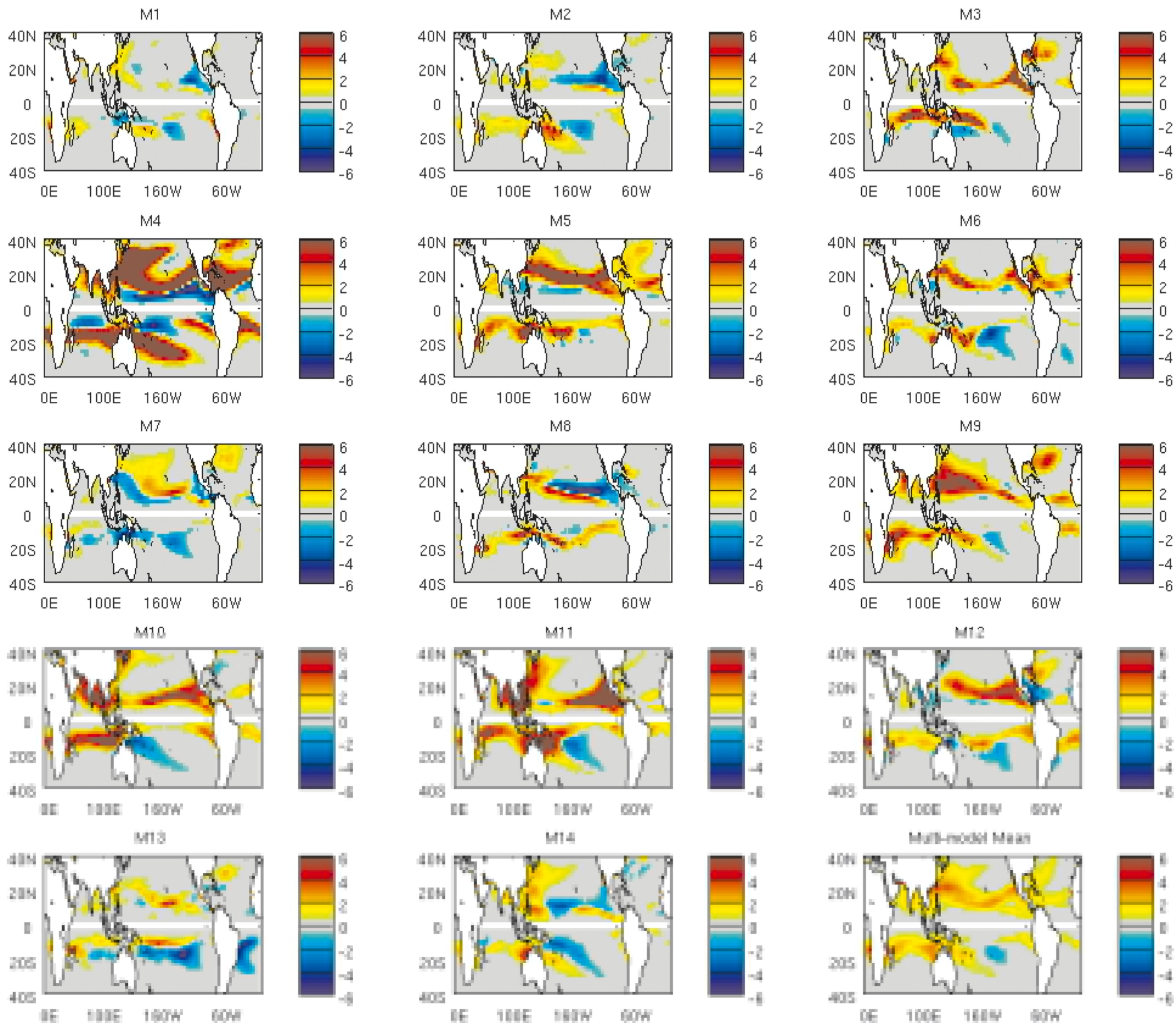
Lee, Camargo, Sobel & Tippett, J. Climate, 2019, in review

CHAZ Climate change simulations



Lee et al. J. Climate, 2019, in review

Genesis Indices and climate change



Camargo,
J. Climate 2013

Tropical Cyclone Genesis Index - TCGI

Poisson regression:

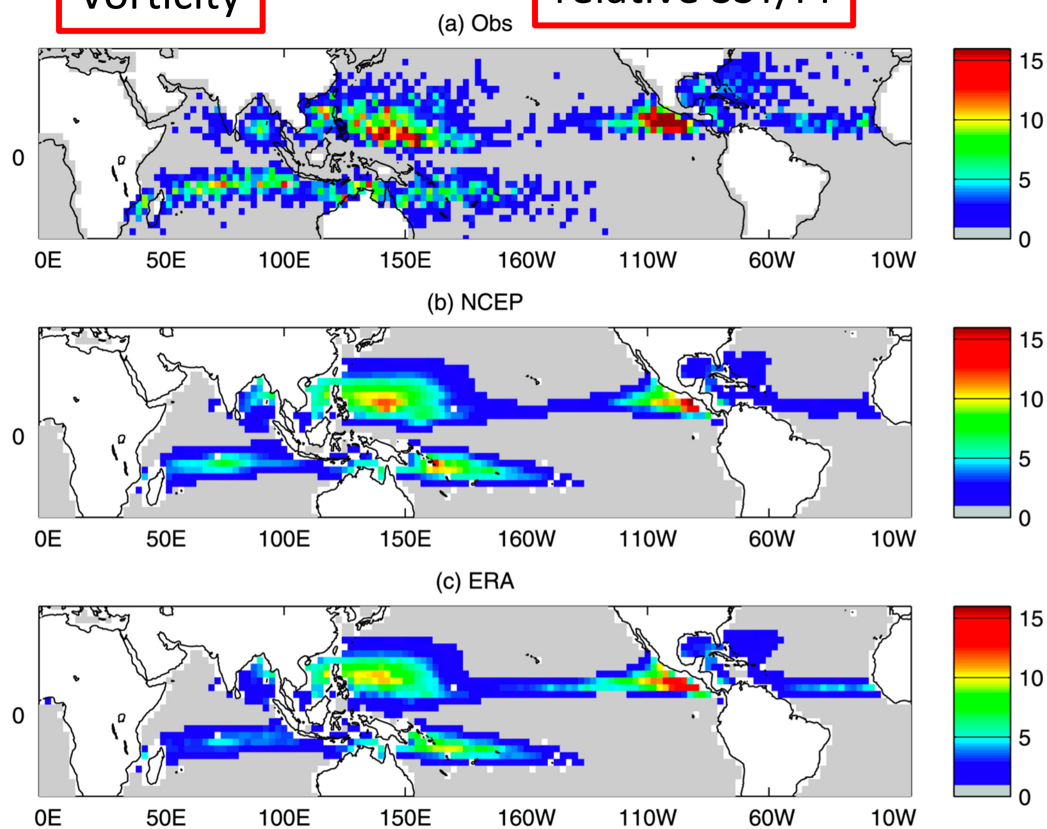
Humidity: RH/SD

Vertical Shear

$$\mu = \exp(b + b_\eta \eta + b_{\mathcal{H}} \mathcal{H} + b_T T + b_V V + \log \cos\phi),$$

Vorticity

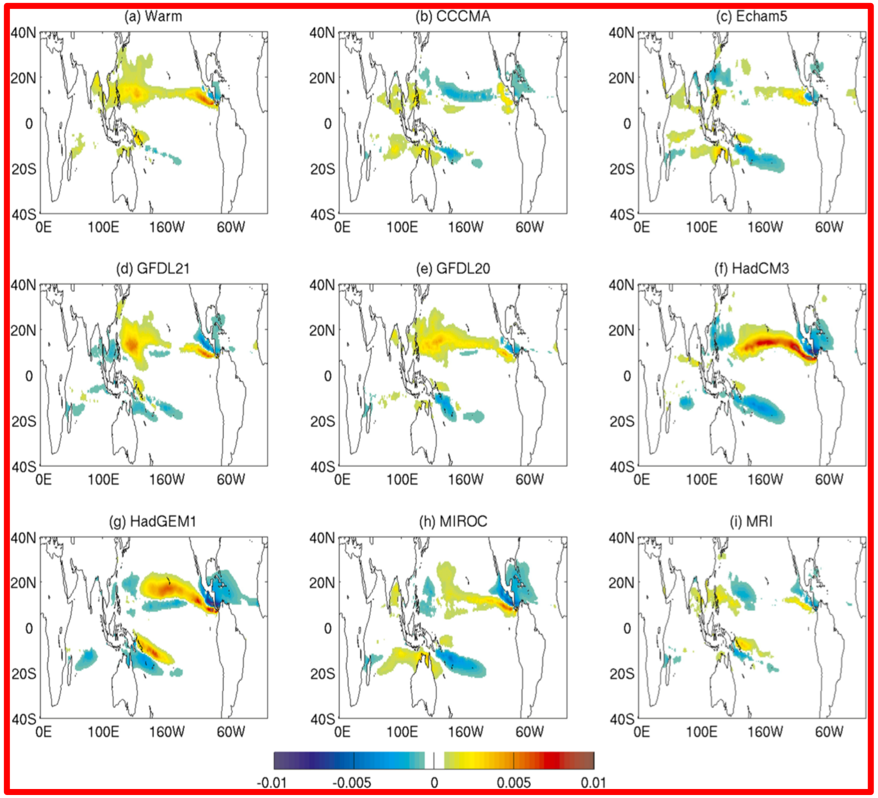
relative SST/PI



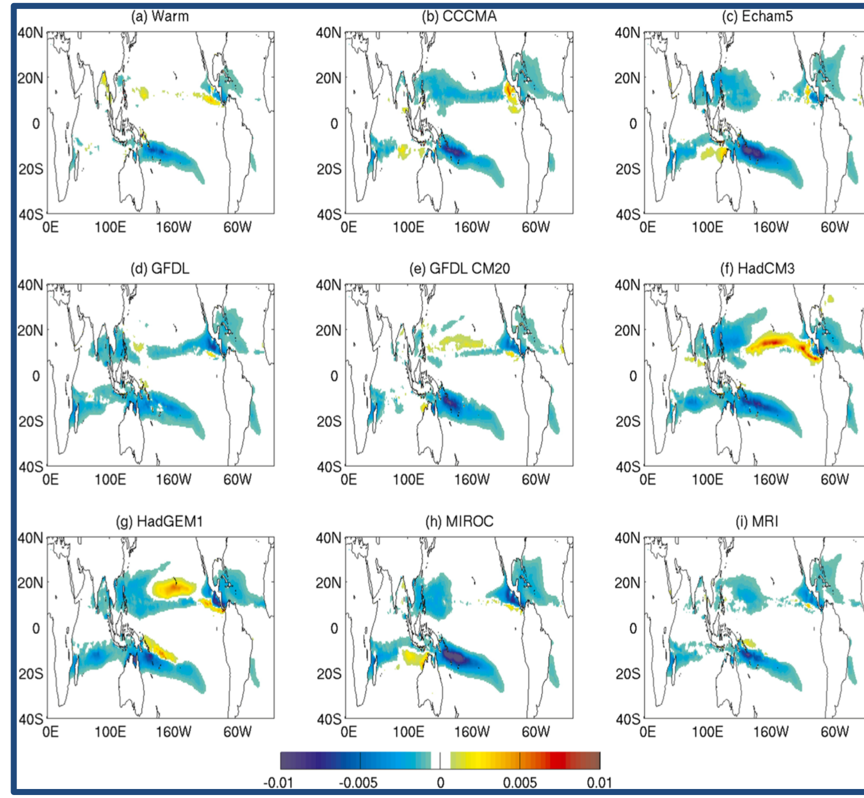
Tippett et al. J. Climate, 2011

HiRAM – perfect model experiment

Column Integrated Relative Humidity



Saturation Deficit



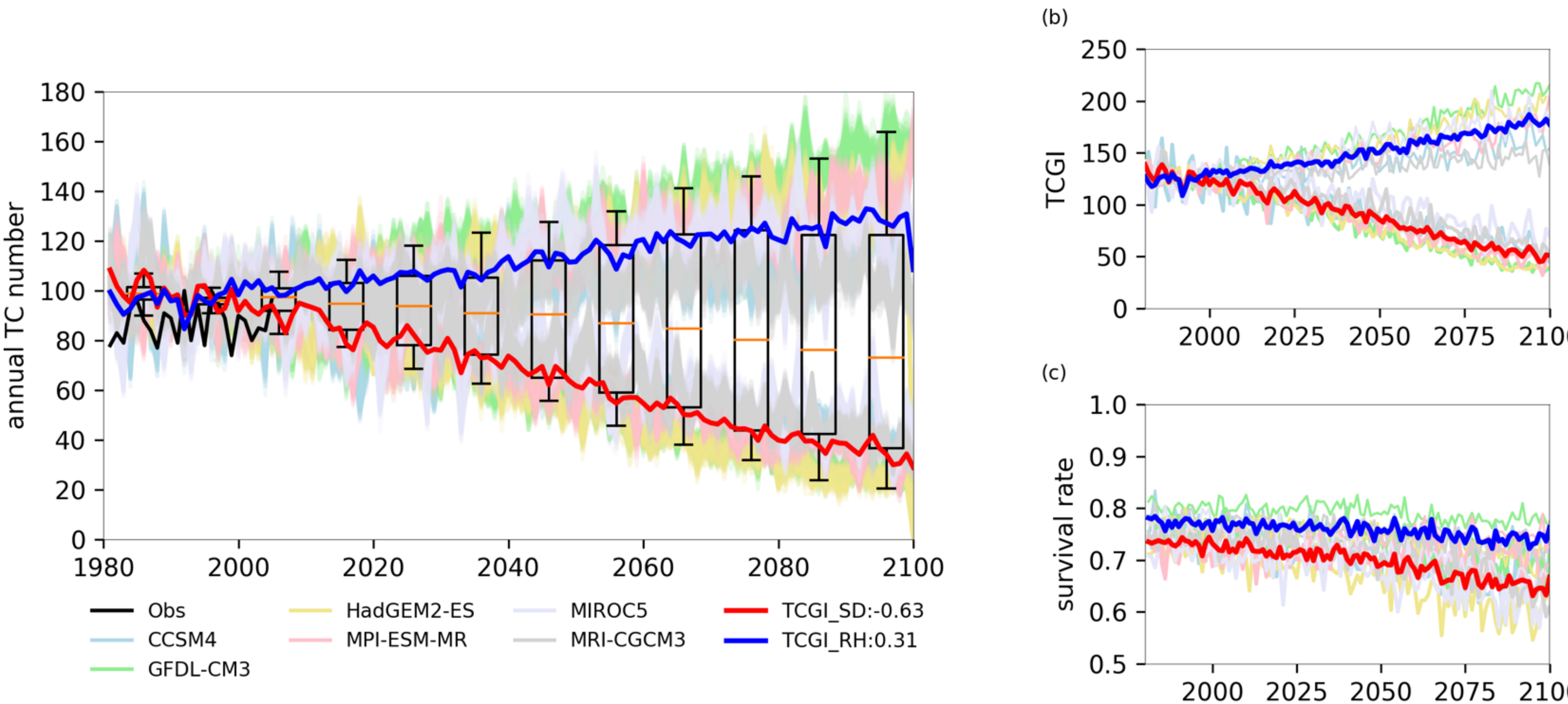
CRH = CIWV/CIWVs

SD = CIWV - CIWVs

CIWV = column integrated water vapor
CIWVs = saturated column integrated water vapor

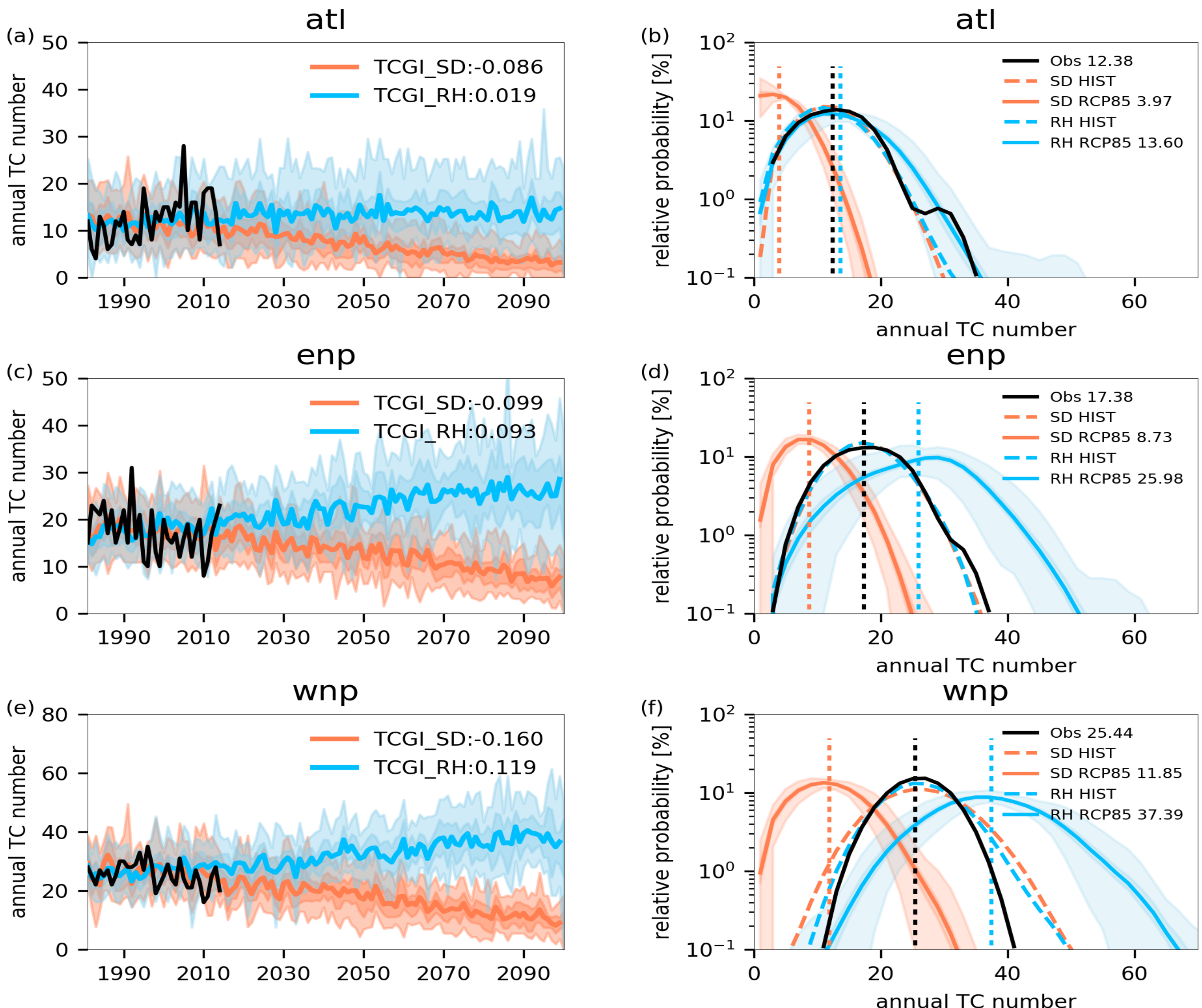
Camargo et al. J. Climate, 2014

CHAZ climate change simulations - Frequency changes



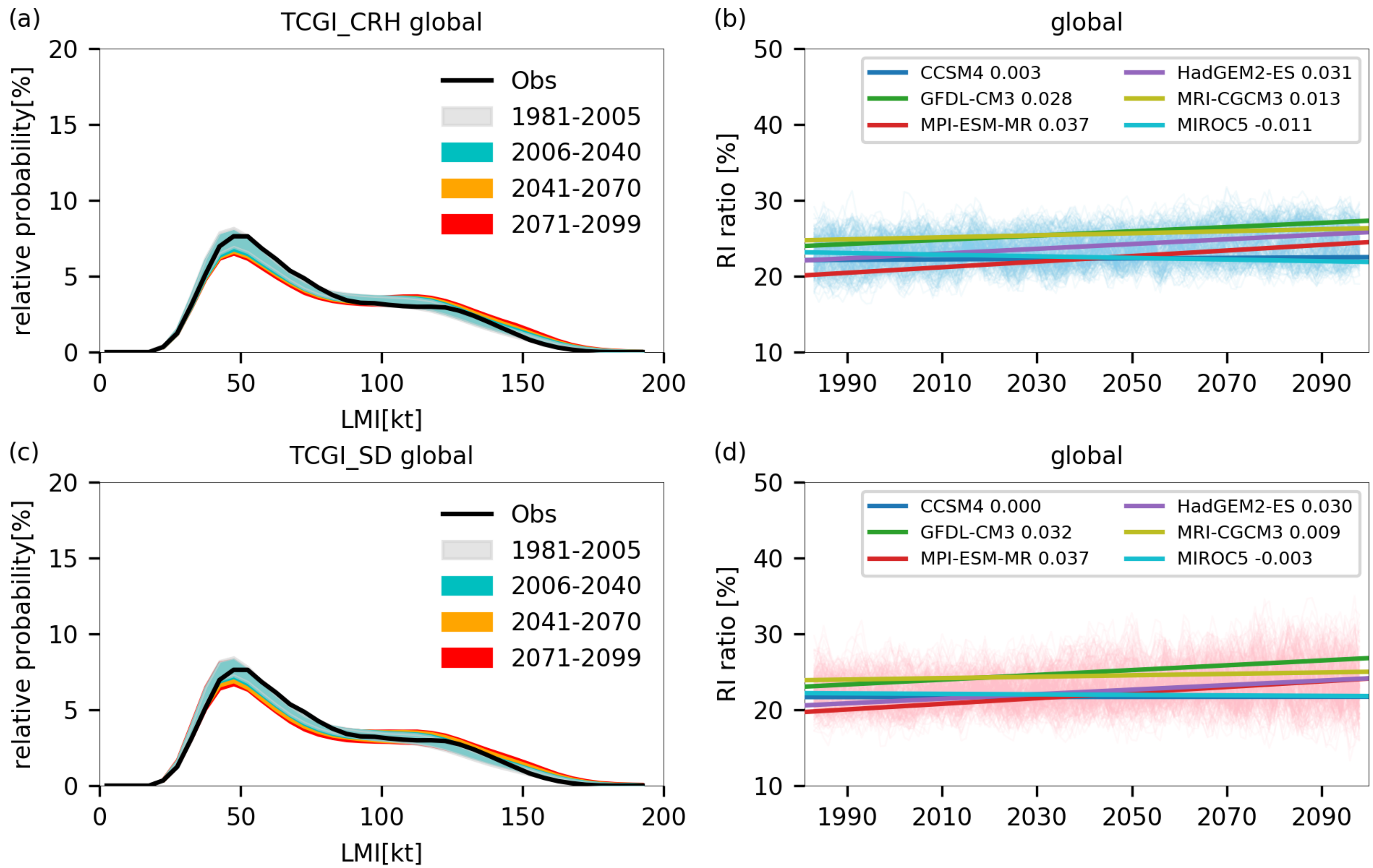
Lee et al. J. Climate, 2019, in review

CHAZ climate change simulations - Frequency changes



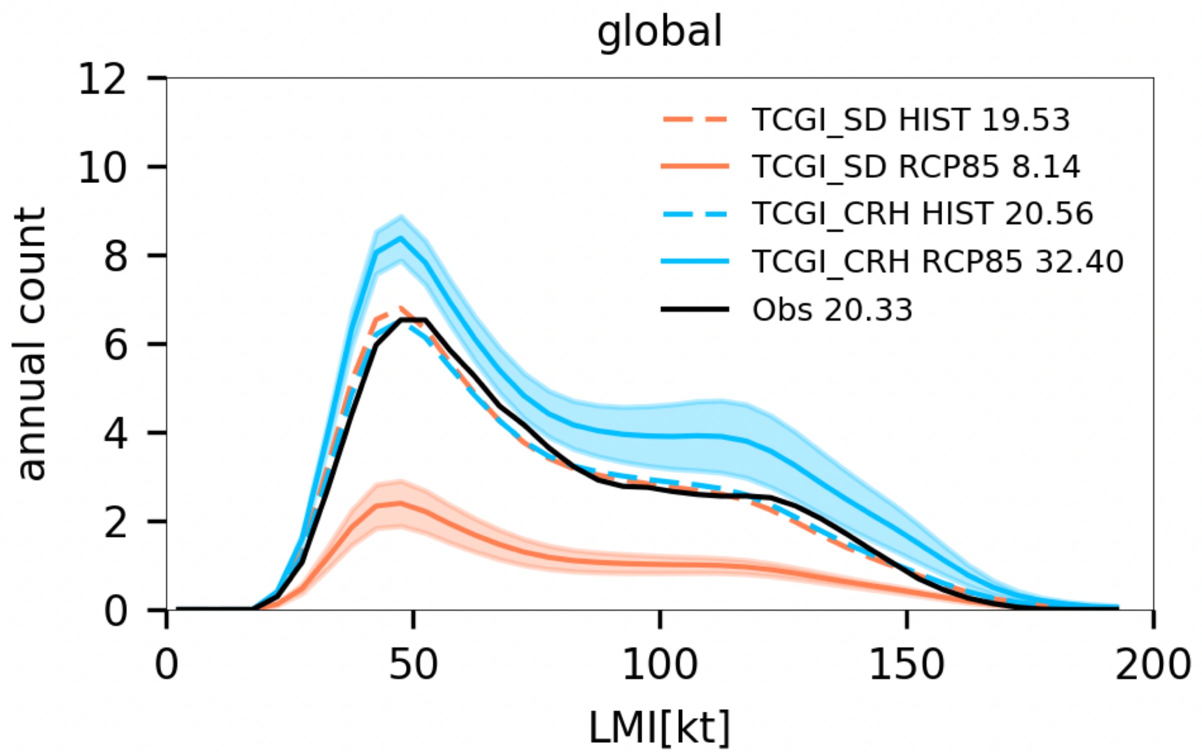
Lee et al. J. Climate, 2019, in review

CHAZ climate change simulations
Intensity changes



Lee et al. J. Climate, 2019, in review

CHAZ climate change simulations Intensity + frequency changes



Lee et al. J. Climate, 2019, in review

CHAZ climate change simulations poleward shift

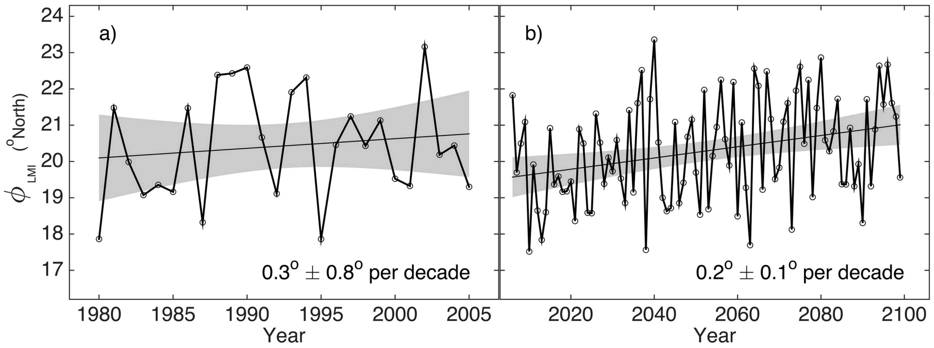
	global	atl	enp	wnp	ni	sin	aus	spc
TCGI_CRH	0.31±0.06	0.63±0.23	0.87±0.10	0.73±0.11	-0.02±0.24	0.57±0.14	-0.07±0.12	-0.14±0.18
TCGI_SD	0.10±0.08	0.79±0.32	0.72±0.13	0.49±0.15	-0.35±0.47	0.08±0.19	0.08±0.15	-0.14±0.19

Annual mean LMI latitude changes (degrees per 100 years)

Lee et al. J. Climate, 2019, in review

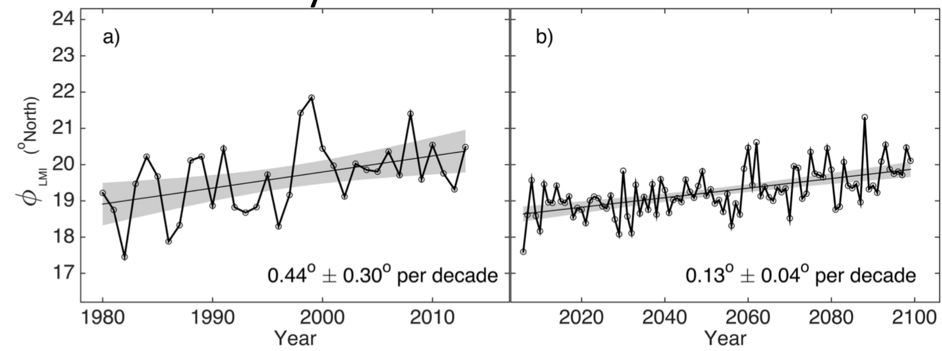
Western North Pacific poleward shift

Observations CMIP5 models



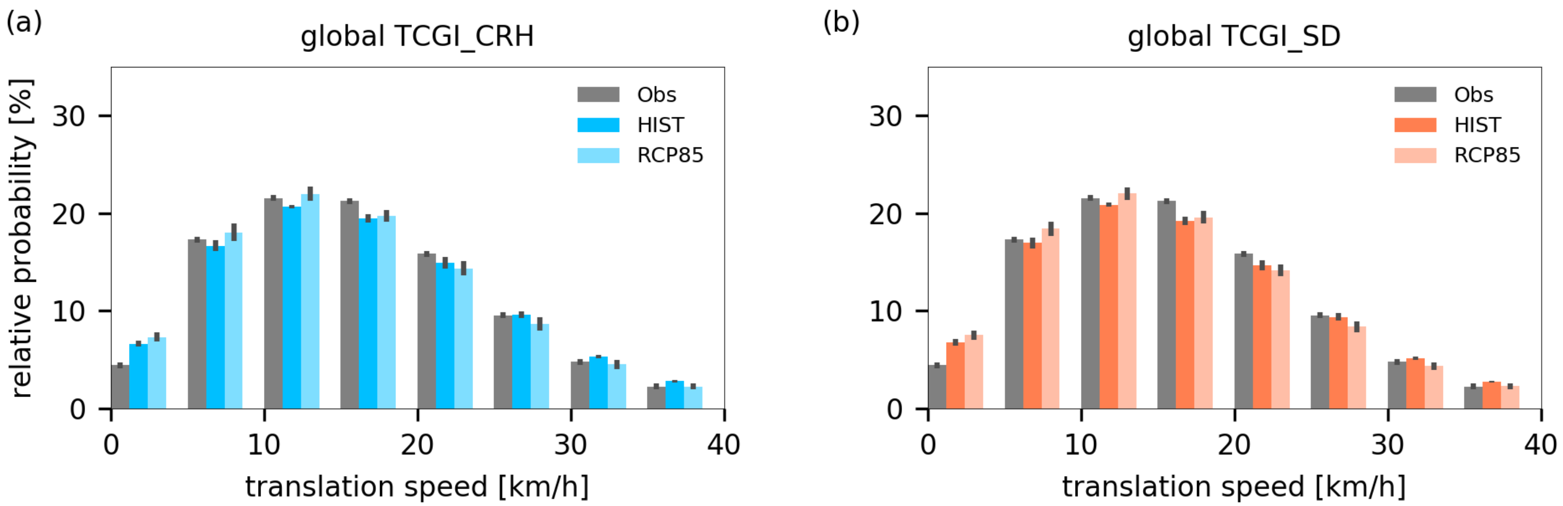
MIT downscaling

Reanalysis CMIP5



Kossin, Emanuel & Camargo, J. Climate, 2016

CHAZ climate change simulations Translation speed



Lee et al. J. Climate, 2019, in review

Summary

- Lack of a clear emergence of the signal of anthropogenic changes of TC characteristics due to: large variability, data quality, length of data record.
- Projections of TC frequency have become more uncertainty in the last few years.
- CHAZ results show that TC frequency is sensitivity to type of humidity variable used when downscaling projections.