Climate Change and its Impact on Extreme Precipitation Events:
Examining Tropical Cyclones

AOS 112
A Presentation by Jillian Dessing

OUTLINE

BACKGROUND

Clausius - Clapeyron (CC) Relation: describes how the water vapor holding capacity of air increases with temperature. For a typical low-level tropospheric temperature, the saturated specific humidity content increases by approximately 7% per degree Celsius increase in temperature

Ocean Heat Content (OHC): refers to the total amount of heat energy stored in the ocean.

Sea Surface Temperature (SST) : refers to the temperature at the top few millimeters of ocean's surface.

Saffir–Simpson Hurricane Wind Scale: 1 to 5 rating based only on a hurricane's maximum sustained wind speed.

1	64-82 kts	Very dangerous winds will produce some damage
2	83 - 95 kts	Extremely dangerous winds will cause extensive damage
3	96 - 112 kts	Devastating damage will occur
4	113 - 136 kts	Catastrophic damage will occur
5	137 + kts	Catastrophic damage will occur

OBSERVED CHANGES IN PRECIPITATION EXTREMES

Global Assessment of extreme daily precipitation to identify and compare changes in the frequency and magnitude of daily extremes: analyzing 8,730 high– quality daily precipitation records from 1964 –2013

Figure 1. Spatial distribution of suitable stations in 5° × 5° grid cells. We consider 8,730 extreme precipitation records over the 1964–2013 period.
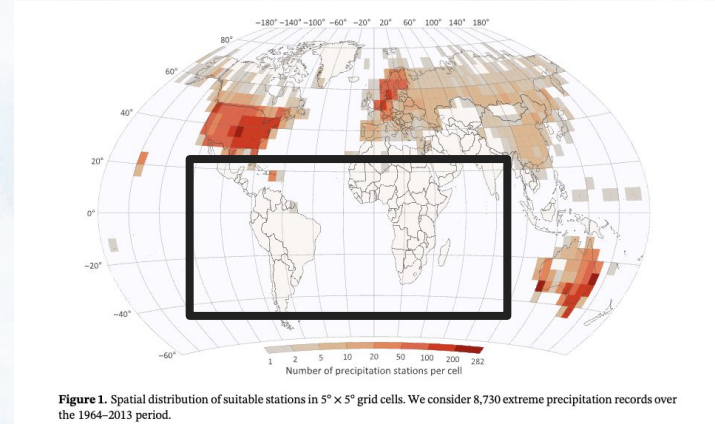
Specific Criteria of Records:
1. 50+ years of data
2. Less than 20% missing values
3. 5+ complete years in each of the 5 decades included in the study period

Classification of Extremes: For each daily precipitation record of N years, the study identifies the N largest values as extremes

Two Types of Time Series:
1. Frequency of Extremes: Counting the number of extremes per year
2. Magnitude of Extremes: Averaging the extreme events that occurred within each year

Papalexiou, S. M., & Montanari, A. (2019). Global and regional increase of precipitation extremes under global warming. *Water Resources Research*, 55, 4901–4914.
https://doi.org/10.1029/2018WR024067

OBSERVED CHANGES IN PRECIPITATION EXTREMES

Trends in Frequency

Global Trends: 66.4% of grid cells showed positive changes in frequency. Ratio of stations with positive trends to negative trends: 1.5

Regional Patterns: Frequency changes exhibited strong regional consistency
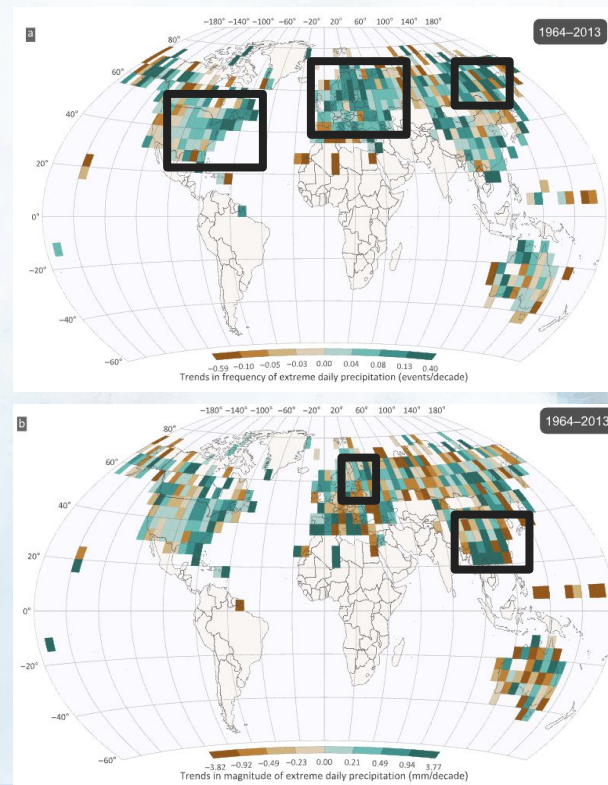1. Eurasia: 74% positive trends. Ratio: 2.8
2. Eastern Russia and China: mild to strong positive trends
3. US (excluding west coast): positive trends, intense changes in NE

Trends in Magnitude

Global Trends: 56.7% of grid cells showed positive changes in magnitude. Ratio of stations with positive trends to negative trends: 1.1

Regional Patterns: High-value magnitude trends in parts of Eurasia
1. Vietnam, Cambodia, Thailand
2. Central Russia

Changes in magnitude of extreme precipitation were less pronounced than frequency changes.

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OBSERVED CHANGES IN PRECIPITATION EXTREMES

Conclusions: No significant correlation between magnitude and frequency trends. However, among the 4 possible combinations of trends, the most common was positive changes in both frequency and magnitude, ranging from 33.0% to 39.1% in all zones except SE asia.

There are clear increasing trends in the frequency of daily precipitation.

While magnitude trends show increases, they are not as evident as the frequency trends.

Trends in Frequency

Trends in Magnitude

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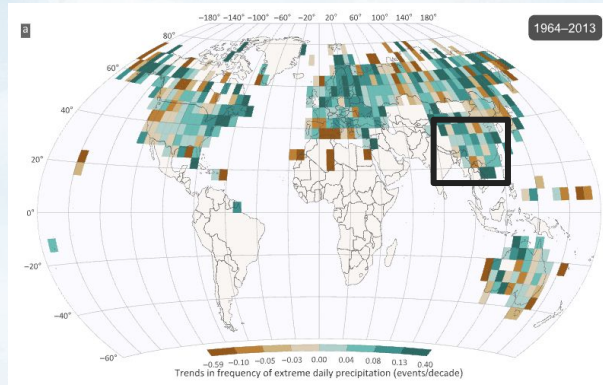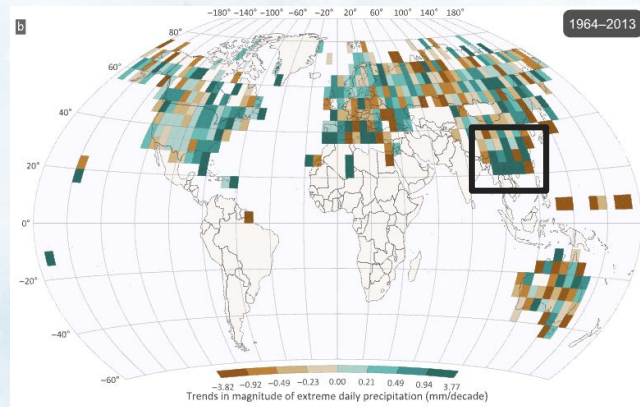
OBSERVED EXTREME PRECIPITATION IN TROPICAL CYCLONES: HURRICANE HARVEY CASE STUDY

"Hurricane Harvey made landfall on the coast of Texas on 26 August 2017 as a category 4 storm. Rather than proceeding to track inland and dissipate, Harvey stalled with a portion of the storm system remaining over the warm waters of the Gulf of Mexico for another 4 days. While damages from high winds were significant, it was the unprecedented amount of rain that fell on the greater Houston area from 25 to 31 August and the resultant inland flooding that caused this tropical storm to be one of the most damaging since Hurricane Katrina in 2005."

https://www.nesdis.noaa.gov/news/hurricane-harvey-look-back-seven-years-later

Risser, M. D., & Wehner, M. F. (2017). Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey. *Geophysical Research Letters*, 44, 12,457–12,464. https://doi.org/10.1002/2017GL075888

CONDITIONS ENABLING HURRICANE HARVEY'S DEVELOPMENT: HURRICANE HARVEY CASE STUDY

Ocean Heat Content (OHC): Gulf of Mexico experienced the highest OHC on record both globally and regionally before the Northern summer of 2017, providing fuel for the storm.

Sea Surface Temperature (SST): SST's exceeded 30°C in the weeks leading up to the storm, sustained by the high OHC.

Water Vapor Content: As SST rises, more heat energy is available to drive evaporation from the ocean's surface. Warmer SST's lead to increased moisture in the atmosphere as warmer air holds more water vapor. Thus more latent heat is released in storms, resulting in record-breaking rainfalls.

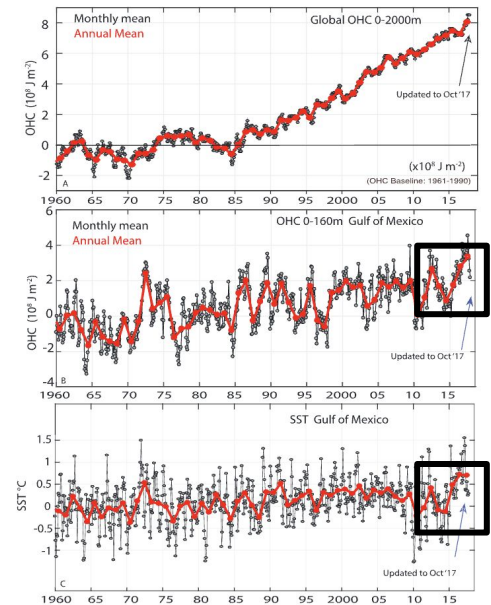As the ocean absorbs and stores heat, the sea surface temperature warms.

Figure 1. Ocean heat content anomalies for the monthly (black) and annual (red) for (a) the top 2,000 m for the global ocean and (b) for the top 160 m in the Gulf of Mexico (dashed box in Figure 2), in 10^{8} J m^{-2}. (c) The sea surface temperature anomalies in the Gulf of Mexico. For all time series, the last month is October 2017 and the last red dot is for January to October 2017. The baseline is 1961–1990.
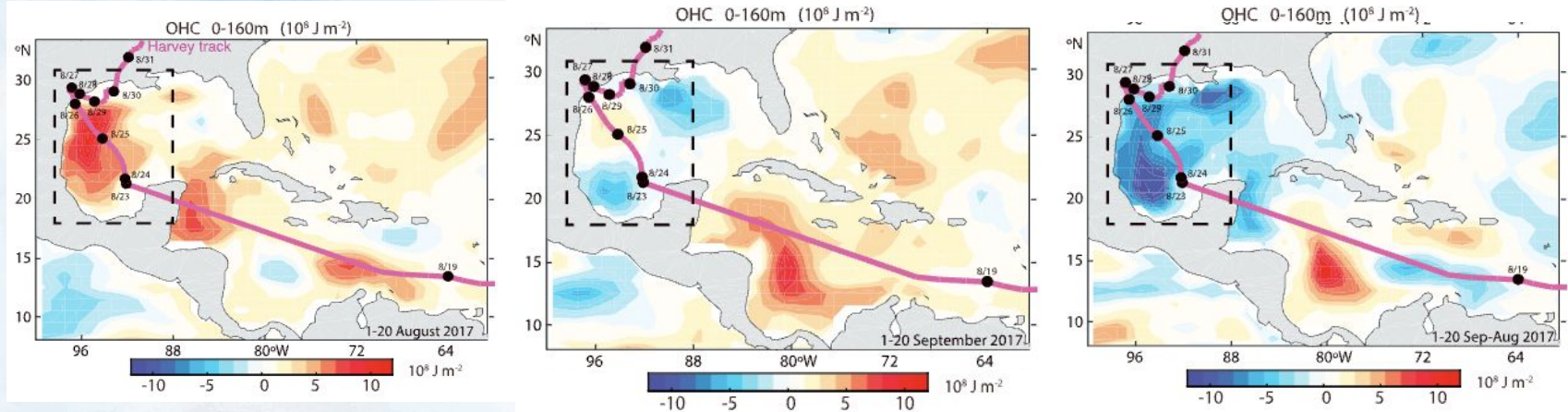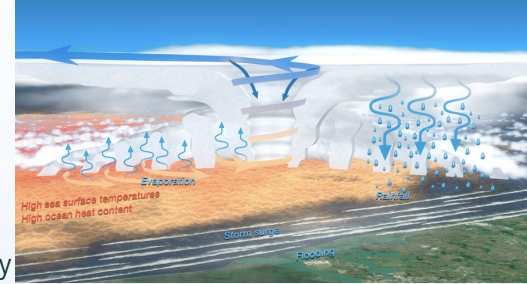
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https://doi.org/10.1029/2018EF000825

CONDITIONS ENABLING HURRICANE HARVEY'S DEVELOPMENT:

HURRICANE HARVEY CASE STUDY

Before Hurricane Harvey (August): The Gulf of Mexico had record-high OHC levels

After Hurricane Harvey (September): significantly reduced OHC

Difference in OHC (Bottom Panel): Shows a net reduction in OHC after Harvey. The Gulf of Mexico's
   OHC decreased by ~5.93 × 10²⁰ Joules after Harvey. This heat loss corresponds to a monthly energy
   flux of **201 W/m²** over 31 days, a significant transfer of heat from the ocean to the atmosphere.

Trenberth, K. E., Cheng, L., Jacobs, P.,Zhang, Y., & Fasullo, J. (2018). Hurricane Harvey links to ocean heat content and climate change adaptation. Earth's Future, 6, 730–744.
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ATTRIBUTION OF HARVEY'S EXTREME PRECIPITATION TO ANTHROPOGENIC WARMING

Methodology:

- Analyzed daily precipitation data for Houston, Texas from 1950 to 2017, focusing on two regions: ~33,000km^2 centered on highest Harvey rainfalls and 105,000km^2

- Extracted the largest 7-day rainfall total for each station for hurricane season (July - Nov, 1950 - 2016)

- To identify the role of human-induced climate change in altering patterns, researchers analyzed total atmospheric anthropogenic influences and the Niño3.4 index, to separate human and natural variability from El Niño

Findings:

Precipitation Totals: The lowest estimates for Hurricane Harvey (700.2 mm for the small region and 481.6 mm for the large region) far exceeded the previous records (315.8 mm and 300.3 mm, respectively)

Changes in Return Periods: The return period for the previously largest observed 7 day total decreased from a several hundred year storm in 1950 to a 25-50 year storm in 2017

Attributable Increase in Precipitation:Small region: The best estimate of the attributable increase was over 30%, with a likely lower bound of 18-19%. **Large region**: The best estimate was around 23%, with a likely lower bound of 5-7%

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WHY TROPICAL CYCLONE PRECIPITATION IS PROJECTED TO INCREASE WITH GLOBAL WARMING
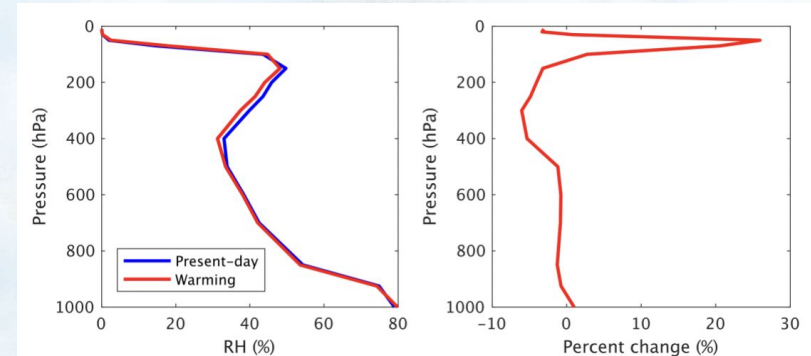
Methodology:

HiFLOR Model: A high-resolution climate model (~25 km grid spacing) accurately simulates tropical cyclone (TC) intensity and rainfall. A 70-year control simulation aligns sea surface temperatures (SSTs) with observed climatological data (1986–2005) to establish a baseline.

Projected SST and Atmospheric Moisture: SST changes in Tropical Cyclone development regions are used to estimate increased atmospheric moisture under global warming, assuming low-level relative humidity remains nearly constant (<1% change from the surface to 500 hPa).

Rainfall Rate Analysis: TC rainfall rates within 100 km of the storm center are computed using 6-hourly data, focusing on storms of at least tropical storm intensity (≥34 kt).

Storm Intensity Categorization: TCs are grouped by Saffir-Simpson intensity scale to examine how stronger storms amplify rainfall rates beyond increases due to atmospheric moistening.
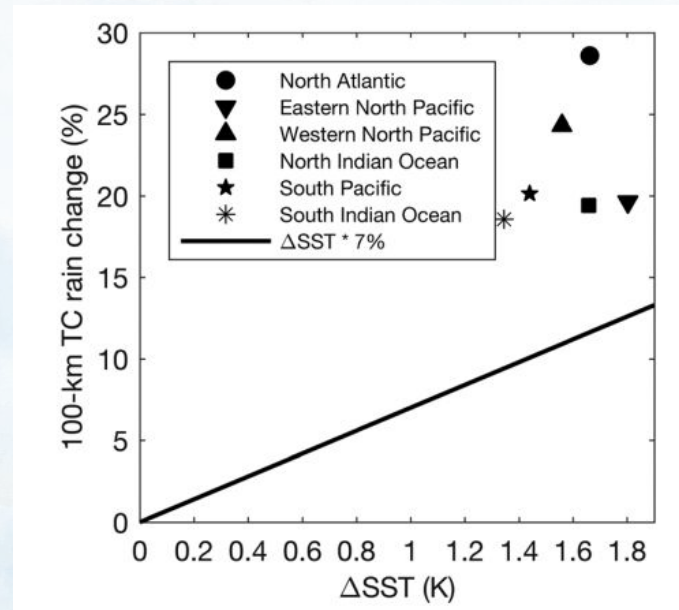
WHY TROPICAL CYCLONE PRECIPITATION IS PROJECTED TO INCREASE WITH GLOBAL WARMING

Findings:

Increase in TC Rainfall Rates: The projected increase of 100-km Tropical Cyclone rainfall rate under the late 21st-century warming scenario ranges from 19% (13% per °C) to 29% (17% per °C) for each ocean basin

- The largest increase occurs in the North Atlantic and North Western Pacific. The increase in the other four oceans reaches approximately 20% (approximately 13% per °C)

Super Clausius - Clapeyron (CC) Scaling: In the warming scenario, SSTs over the MDRs in various basins show an increase ranging from 1.3°C to 1.8°C, implying an increase of low-level atmospheric moisture content from 9.1 to 13%
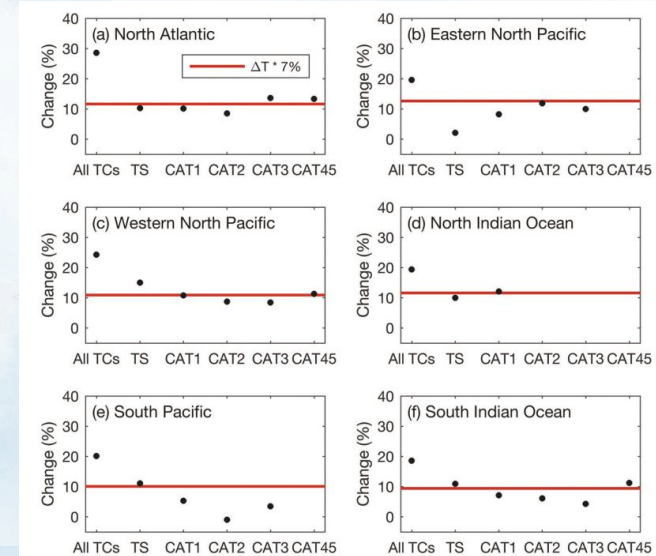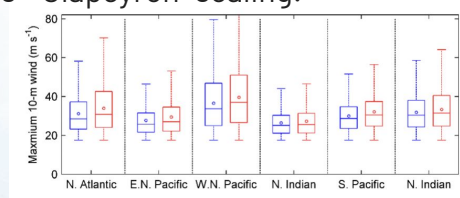
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https://doi.org/10.1038/s41612-019-0095-3

WHY TROPICAL CYCLONE PRECIPITATION IS PROJECTED TO INCREASE WITH GLOBAL WARMING

Findings:
Increased Storm Intensity: HiFLOR projects a significant increase of mean Tropical Cyclone intensity in terms of maximum surface winds for each ocean basin as climate warms. The magnitude of intensity increase ranges from 3.2 to 9.0% across oceans.

Role of Storm Intensification:
When TC samples are divided into categories based on the Saffir–Simpson intensity scale, the projected increase of Tropical Cyclone rainfall rate within each storm category shows a much better match with the Clausius-Clapeyron scaling than that for all storm samples combined. This highlights the role of storm intensification in the "Super Clausius - Clapeyron" scaling.

Liu, M., Vecchi, G.A., Smith, J.A. *et al.* Causes of large projected increases in hurricane precipitation rates with global warming. *npj Clim Atmos Sci* 2, 38 (2019).
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PROJECTED CHANGES IN TROPICAL CYCLONE PRECIPITATION: Findings of Knutson 2020

Projected Changes:
- Median projected 14% in near-storm precipitation rates for a 2°C global warming scenario
- 16 global projections from 8 studies global mean increase. Range of projected increases: 6% – 22%
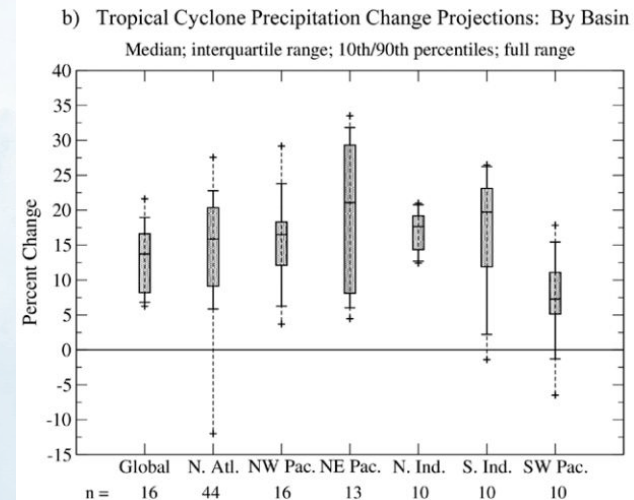
Confidence Levels:
- Medium to high confidence in global increase
- 5 authors had medium to high confidence, 6 had high confidence

Underlying Mechanisms:
- Increased Water Vapor
- Moisture Convergence over local evaporation as primary moisture source

Comparison to Clausius–Clapeyron Scaling:
- Projected Increase at least as large as CC scaling

b) Tropical Cyclone Precipitation Change Projections: By Basin
Median; interquartile range; 10th/90th percentiles; full range

Knutson, T., Camargo, S. J., Chan, J. C. L., Emanuel, K., Ho, C., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., & Wu, L. (2020). Tropical Cyclones and Climate Change Assessment: Part II: Projected Response to Anthropogenic Warming. *Bulletin of the American Meteorological Society*, *101*(3), E303-E322. https://doi.org/10.1175/BAMS-D-18-0194.1

CONCLUSIONS

Observed Changes in Precipitation Events: Observations highlight a general trend towards more frequent and, to a lesser extent, more intense precipitation extremes globally, with significant regional variations.

Attribution of Harvey to Anthropogenic Warming: attributable increase in precipitation was over 30%, with a likely lower bound of 18-19%. Extreme precipitation events have become more common over time with smaller return rates.

Super Clausius – Clapeyron relation: Under late 21st-century warming scenarios, Tropical Cyclone rainfall rates are projected to increase by 19% to 29% globally, equivalent to 13%-17% per degree Celsius of warming. However, The percentage increase for Tropical Cyclone rainfall rates markedly exceeds the (CC) rate, indicating a "super Clausius-Clapeyron" scaling. The greater TC rainfall rate increase compared to the moisture content increase suggests that atmospheric moistening is only part of the mechanism responsible for the projected increase of TC rainfall rate

Future Projections: 6 global projections from 8 studies global mean increase. Range of projected increases: 6% - 22% . Medium to high confidence in global increase in precipitation rates affiliated with Tropical Cyclones.

QUESTIONS?

WORKS CITED

Allen, M., Ingram, W. Constraints on future changes in climate and the hydrologic cycle. *Nature* 419, 224–232 (2002). https://doi.org/10.1038/nature01092

Knutson, T., Camargo, S. J., Chan, J. C. L., Emanuel, K., Ho, C., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., & Wu, L. (2019). Tropical Cyclones and Climate Change Assessment: Part I: Detection and Attribution. *Bulletin of the American Meteorological Society*, *100*(10), 1987-2007. https://doi.org/10.1175/BAMS-D-18-0189.1

Knutson, T., Camargo, S. J., Chan, J. C. L., Emanuel, K., Ho, C., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., & Wu, L. (2020). Tropical Cyclones and Climate Change Assessment: Part II: Projected Response to Anthropogenic Warming. *Bulletin of the American Meteorological Society*, *101*(3), E303-E322. https://doi.org/10.1175/BAMS-D-18-0194.1

Knutson, T.R., Sirutis, J.J., Bender, M.A. *et al.* Dynamical downscaling projections of late twenty-first-century U.S. landfalling hurricane activity. *Climatic Change* 171, 28 (2022). https://doi.org/10.1007/s10584-022-03346-7

Knutson, T. R., Sirutis, J. J., Zhao, M., Tuleya, R. E., Bender, M., Vecchi, G. A., Villarini, G., & Chavas, D. (2015). Global Projections of Intense Tropical Cyclone Activity for the Late Twenty-First Century from Dynamical Downscaling of CMIP5/RCP4.5 Scenarios. *Journal of Climate*, *28*(18), 7203-7224. https://doi.org/10.1175/JCLI-D-15-0129.1

Liu, M., Vecchi, G.A., Smith, J.A. *et al.* Causes of large projected increases in hurricane precipitation rates with global warming. *npj Clim Atmos Sci* 2, 38 (2019). https://doi.org/10.1038/s41612-019-0095-3

O'Gorman, P.A. Precipitation Extremes Under Climate Change. *Curr Clim Change Rep* 1, 49–59 (2015). https://doi.org/10.1007/s40641-015-0009-3

Papalexiou, S. M., & Montanari, A. (2019). Global and regional increase of precipitation extremes under global warming. *Water Resources Research*, 55, 4901–4914. https://doi.org/10.1029/2018WR024067

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Trenberth, K. E., Cheng, L., Jacobs, P.,Zhang, Y., & Fasullo, J. (2018). Hurricane Harvey links to ocean heat content and climate change adaptation. Earth's Future, 6, 730–744. https://doi.org/10.1029/2018EF000825

van Oldenborgh, G. J., and Coauthors, 2017: Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environ. Res. Lett.*, 12, 124009, https://doi.org/10.1088/1748-9326/aa9ef2.