Projected Increase in Tropical Cyclone Induced Extreme Rainfall Over Coastal Areas Under Climate Change

Dan Fu

Department of Atmospheric Sciences, Texas A&M University

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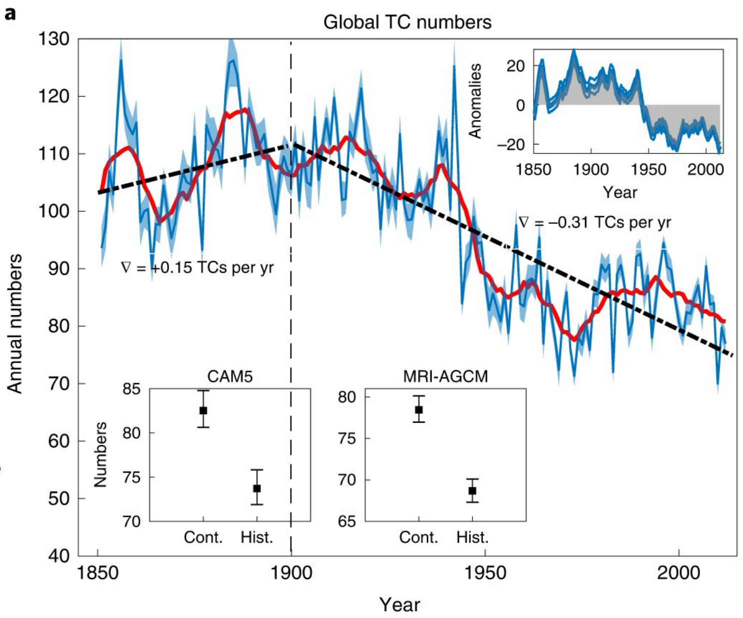
Co-authors: Ping Chang, Xue Liu, Frederic S. Castruccio, Gokhan Danabasoglu

NSF CLD Grant: AGS-2231237 MESACLIP Project;

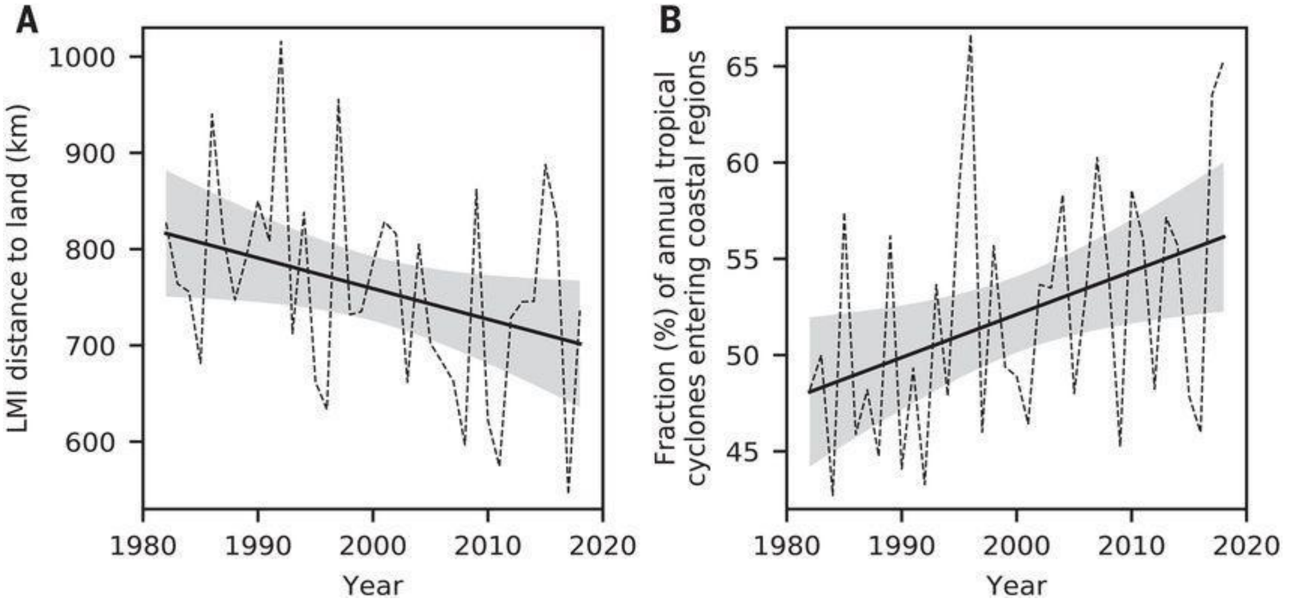
Historical Tropical Cyclone Activity

"TC circulations" in the 1-degree resolution NOAA 20th century reanalysis suggests <u>decreasing trend since 1900s</u>

Chand et al. 2022 Nature Climate Change

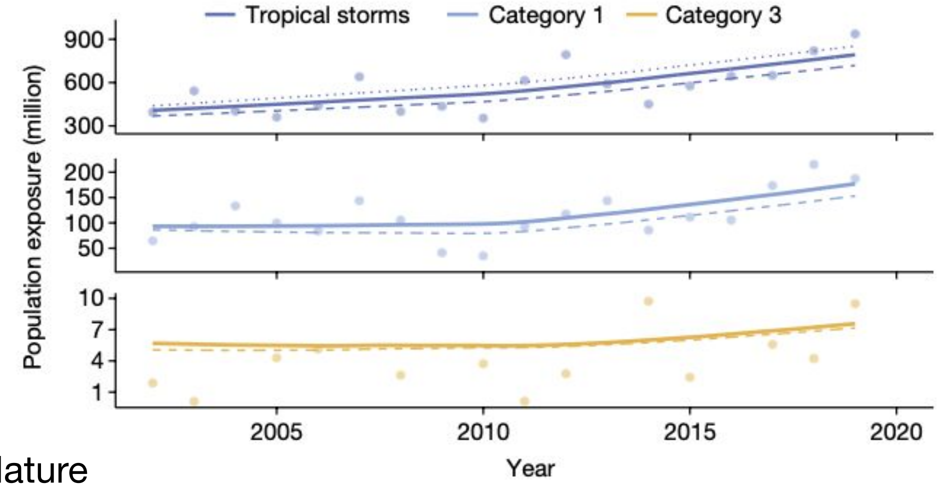


Recent 4 decades observation suggests TCs' location that reach of maximum intensity also have been coming closer to land since 1982;



Wang and Toumi 2021; Science

Global population exposure to TC is increasing during 2002–2019.



Jing et al. 2024; Nature

- ***<u>But so far, no comprehensive assessment of TC induced precipitation and strong wind trend/extreme analysis has been conducted on the global scale, particularly in the context of climate change.</u>***

GCM Projected Tropical Cyclone Activity

Knutson et al. 2020; BAMS

Precipitation rates of TCs are projected to increase globally. Confidence: high (6); medium-to-high (5)
Intensity of TCs is projected to increase globally. Confidence: high (3); medium-to-high (7); low-to-medium (1)
Proportion of category 4–5 TCs is projected to increase globally. Confidence: high (3); medium-to-high (8)
Frequency of category 4–5 TCs is projected to increase globally. Confidence: high (1); medium-to-high (4); medium (1); low-to-medium (2); low (3)
Frequency of all TCs (category 0–5) is projected to *decrease* globally. Confidence: medium-to-high (3); medium (1); low-to-medium (7)
Latitude of maximum TC intensity in western North Pacific will migrate poleward. Confidence: medium-to-high: (2); medium (4); low-to-medium (4); low (1)

Based on CMIP3 and CMIP5, TC assessment study by Knutson et al. (2020) suggest that under global warming:

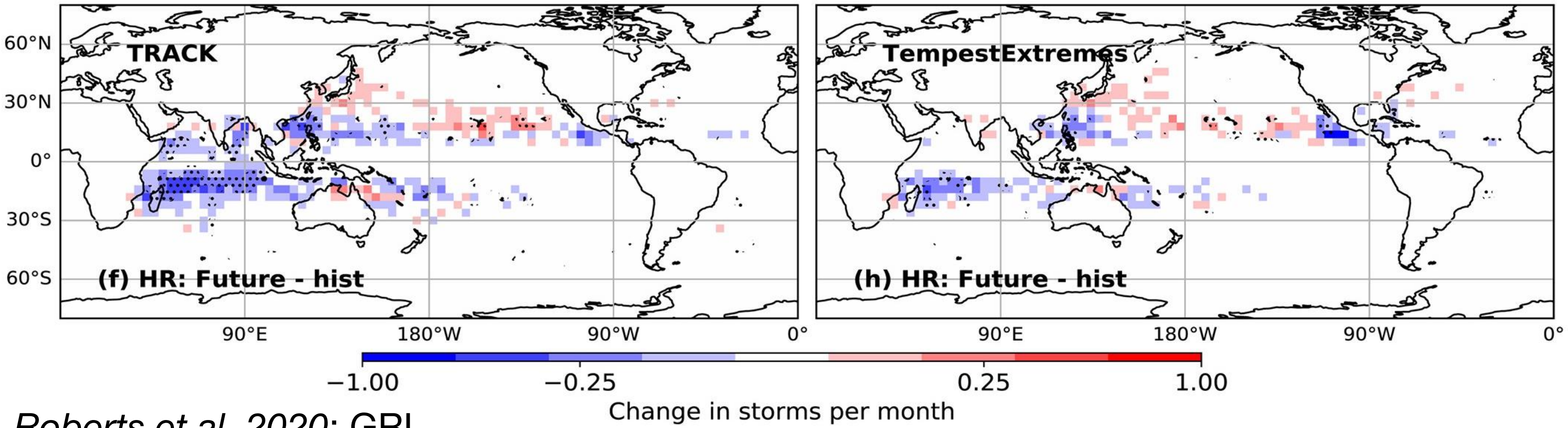
- High confidence in increase of TC precipitation rates,
- Medium-to-high confidence in more frequent intense TCs,
- Low-to-medium confidence in decrease of TC number

-> Uncertainty in TC induced total precipitation

In CMIP6 HighResMIP, TCs in fully coupled GCM simulation during 1950-2050 are analyzed (CNRM-CM6-1, EC-Earth3P, HadGEM3-GC31, CMCC-CM2-VHR4, MPI-ESM1-2, and CESM1.3):

Projected TC activity by 2050 generally declines in the South Indian Ocean, while changes in other ocean basins are more uncertain

TC track density between historic (1950–1980) and future (2020–2050) time periods



Roberts et al. 2020; GRL

TCs and TC-induced precipitation changes up to 2100 are uncertain

10-member ensemble high-resolution Community Earth System Model (CESM-HR)

Recap of CESM-HR

CESM1.3:

- Community Atmosphere Model (CAM) ***v5.3***: **Spectral Element dynamical core** (SE-DYCORE); ne120 (~25km) horizontal resolution and 30 vertical levels with a model top of 3 hPa;
- Community Land Model (CLM) v4: ne120 (~25km) horizontal resolution with the River Transport Model Version (MOSART) v1;
- Parallel Ocean Program (POP) v2: ~10km horizontal resolution and 62 vertical levels with a maximum depth of 6,000 m, and with no mesoscale, submesoscale and overflow parameterizations;
- Community Ice Code (CICE) v4: ~10km horizontal resolution;
- CESM-HR code is ported and optimized on Frontera at Texas Advanced Computing Center (TACC). **At 806 CPU Frontera nodes, 6 YPD with IO.**

1. *CMIP6 HighResMIP Ensemble*
   - Tier 1 - 1950-2014 AMIP (65 years)
   - Tier 2 - 1950 control and 1950-2100 transient (230 years)
   - Tier 3 - 2015-2050 AMIP (35 years)

ESGF

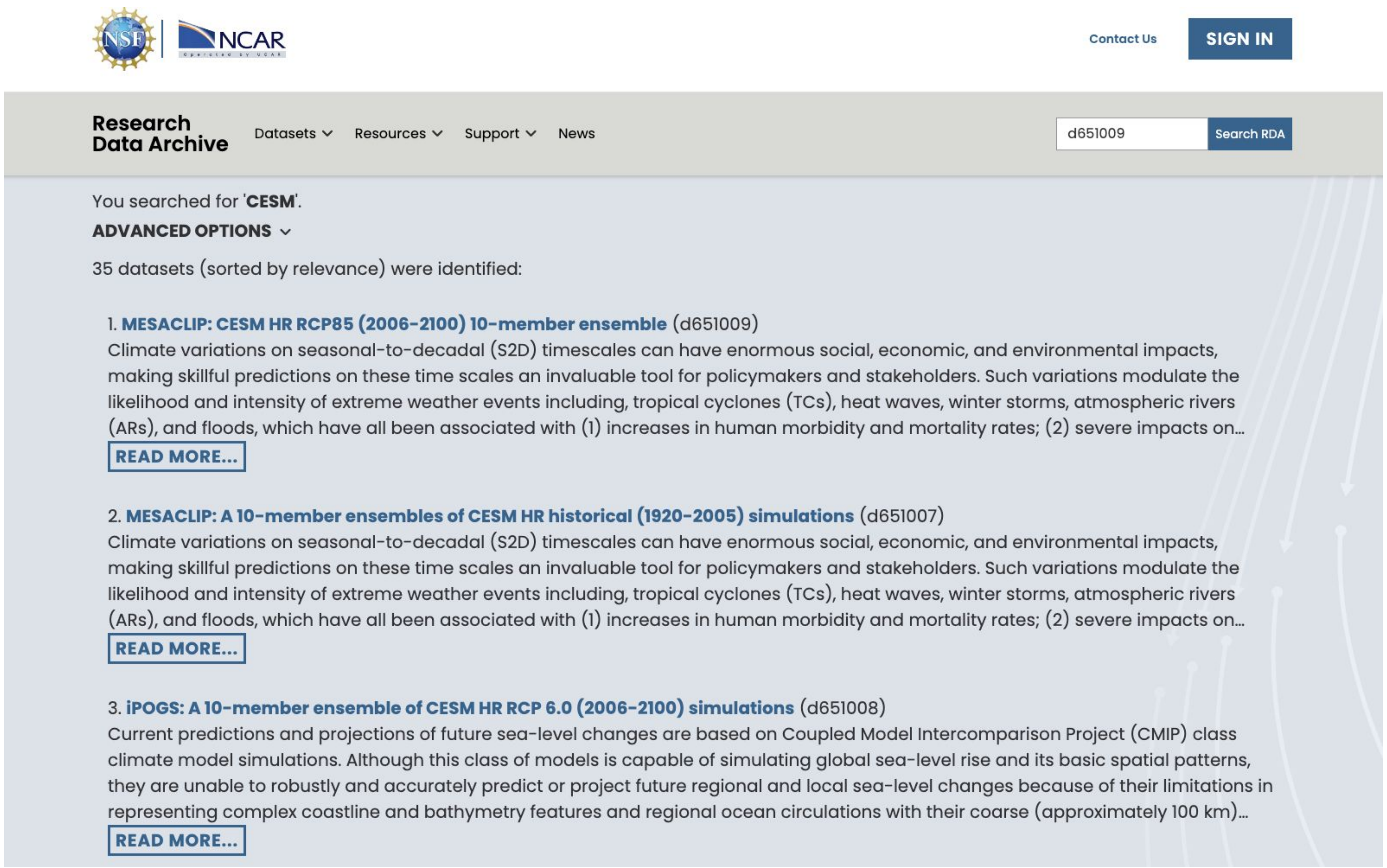
2. *CMIP DECK Set*
   - 1850 Pre-industrial control (650 years)
   - 1850 – 2100 historical and future climate simulation under RCP 8.5 (251 years)
   - 9 ensemble members of 1920 – 2100 climate simulation under RCP 8.5
   - 10 ensemble members of 2006 – 2100 RCP6.0
   - 1% CO_2 simulation (150 years)
   - 4xCO_2 simulation (150 years)
   - 5-member ensemble of 1950-2014 AMIP (5x65 years)

NCAR RDA: d651007, d651008, and d651009

4. *Decadal Prediction Ensemble*
   - 5 cycles of forced ocean-sea ice (FOSI) simulations from 1958 to 2018 (5x61 years)
   - Ensembles of 5-year, 10-member decadal prediction runs initialized in May/November 1st, 1970…2024

Data Availability

10-member ensemble CESM-HR 1920-2100 RCP8.5 and 6.0 simulations are NOW publicly available from the Research Data Archive (RDA) at NCAR:



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d651009

Search RDA

You searched for '**CESM**'.

ADVANCED OPTIONS

35 datasets (sorted by relevance) were identified:

1. **MESACLIP: CESM HR RCP85 (2006-2100) 10-member ensemble** (d651009)
Climate variations on seasonal-to-decadal (S2D) timescales can have enormous social, economic, and environmental impacts, making skillful predictions on these time scales an invaluable tool for policymakers and stakeholders. Such variations modulate the likelihood and intensity of extreme weather events including, tropical cyclones (TCs), heat waves, winter storms, atmospheric rivers (ARs), and floods, which have all been associated with (1) increases in human morbidity and mortality rates; (2) severe impacts on...
READ MORE...

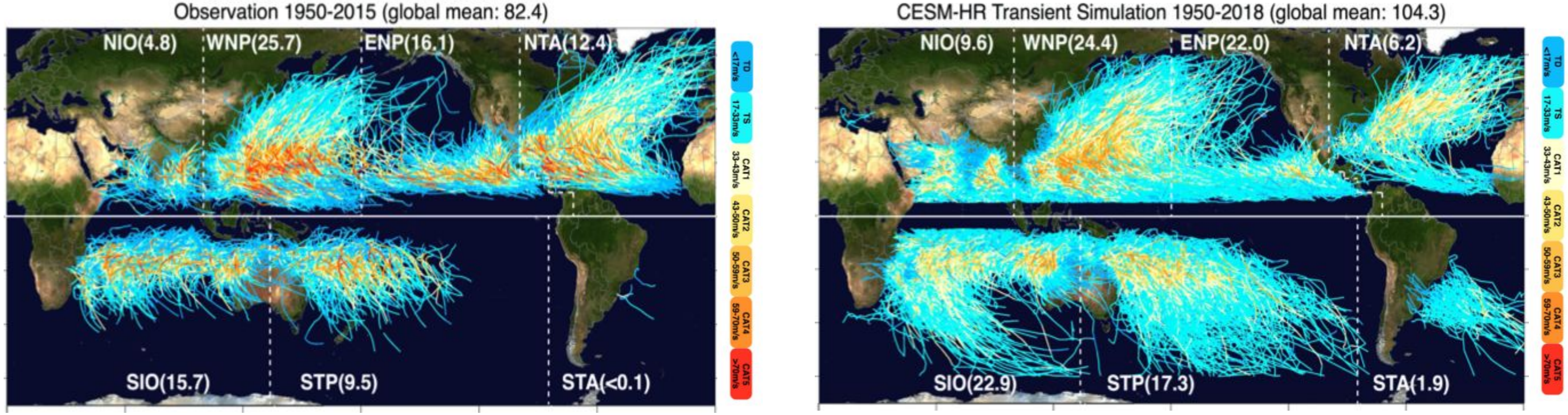
2. **MESACLIP: A 10-member ensembles of CESM HR historical (1920-2005) simulations** (d651007)
Climate variations on seasonal-to-decadal (S2D) timescales can have enormous social, economic, and environmental impacts, making skillful predictions on these time scales an invaluable tool for policymakers and stakeholders. Such variations modulate the likelihood and intensity of extreme weather events including, tropical cyclones (TCs), heat waves, winter storms, atmospheric rivers (ARs), and floods, which have all been associated with (1) increases in human morbidity and mortality rates; (2) severe impacts on...
READ MORE...

3. **iPOGS: A 10-member ensemble of CESM HR RCP 6.0 (2006-2100) simulations** (d651008)
Current predictions and projections of future sea-level changes are based on Coupled Model Intercomparison Project (CMIP) class climate model simulations. Although this class of models is capable of simulating global sea-level rise and its basic spatial patterns, they are unable to robustly and accurately predict or project future regional and local sea-level changes because of their limitations in representing complex coastline and bathymetry features and regional ocean circulations with their coarse (approximately 100 km)...
READ MORE...

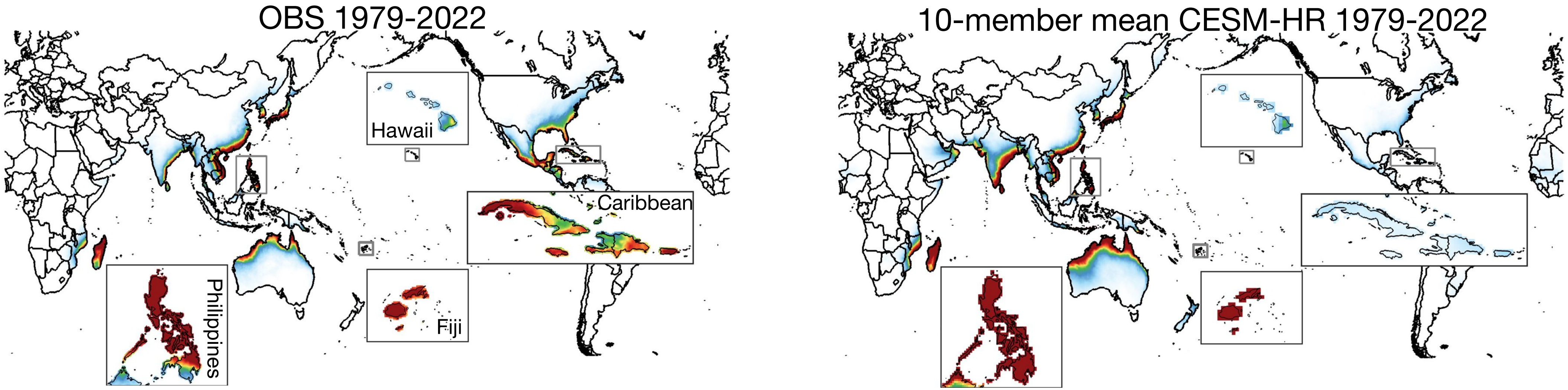
In addition to the RDA dataset citation, please also cite:

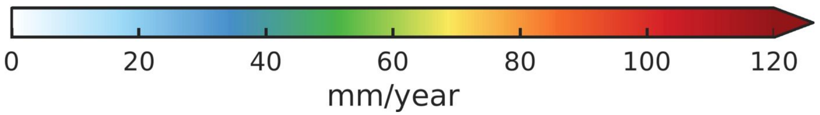
1. Ping Chang, Dan Fu, Xue Liu, Frederic S. Castruccio, Andreas F. Prein, Gokhan Danabasoglu, Xiaoqi Wang, Julio Bacmeister, Nan Rosenbloom, Teagan King, and Susan C. Bates (2024): ***Atmospheric Dynamical Amplification Intensifies Future Extreme Precipitation Risks***. *Under review, Nature Geoscience*
2. Ping Chang, Shaoqing Zhang, Gokhan Danabasoglu et al. (2020). Journal of Advances in Modeling Earth Systems, 12, e2020MS002298. *DOI: 10.1029/2020MS002298*.

Historical TCs and TCs-induced Precipitation



Annual-accumulated TC rainfall (mm/day)

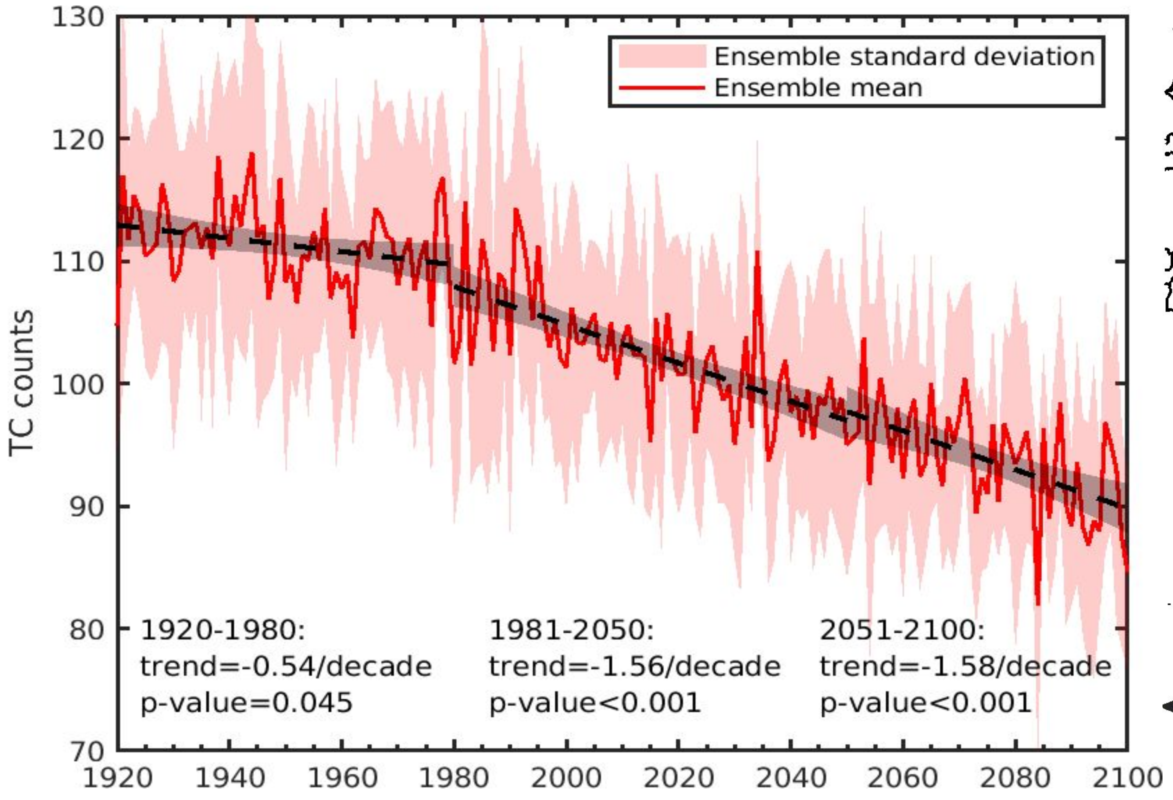




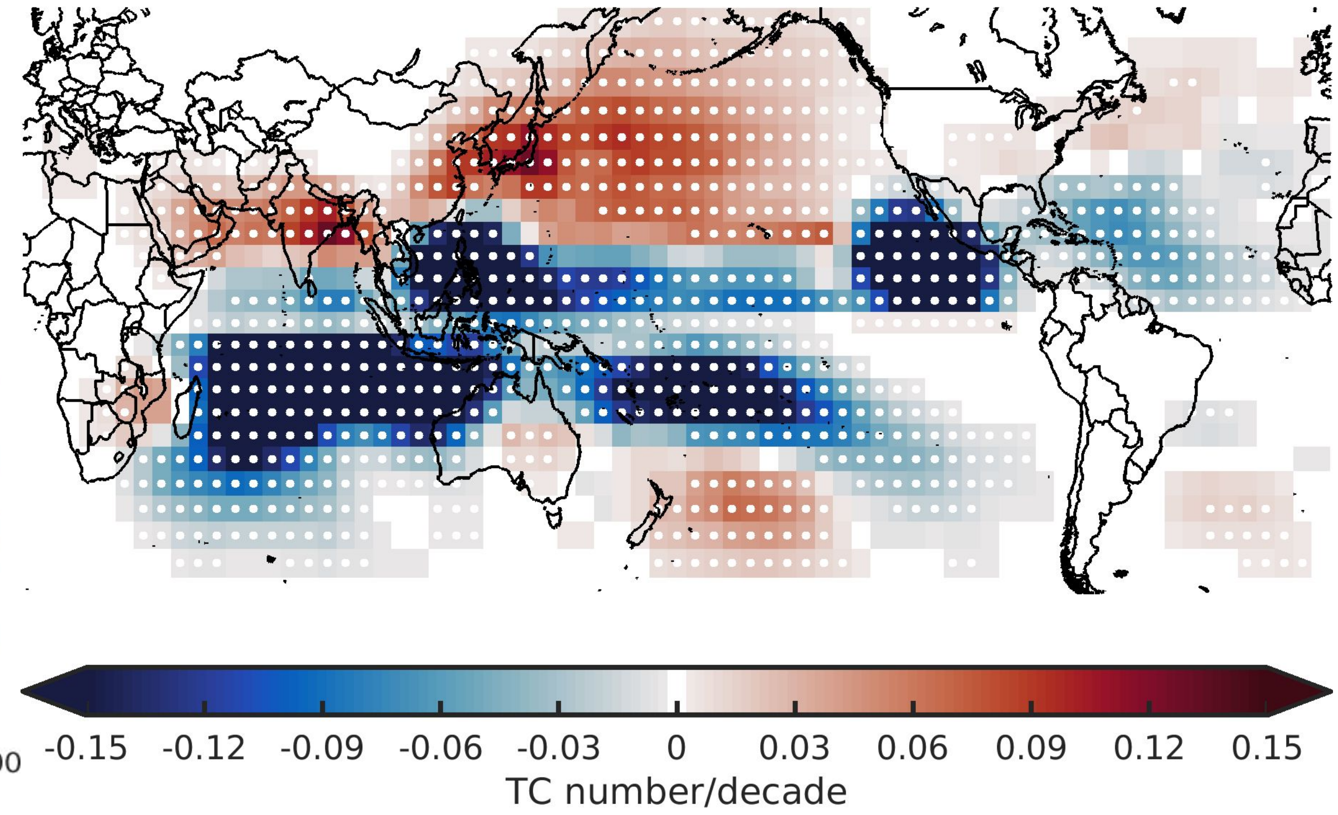
<u>Observation</u>: average of MSWEPv2.8, CHIRPSv2, PERSIANN-CCS-CDR, and IMERGv07; all regridded to 0.1°x 0.1° resolution

Projected Future Changes in TC counts and distributions

Annual mean global TC number



1980-2100 TC track density trend



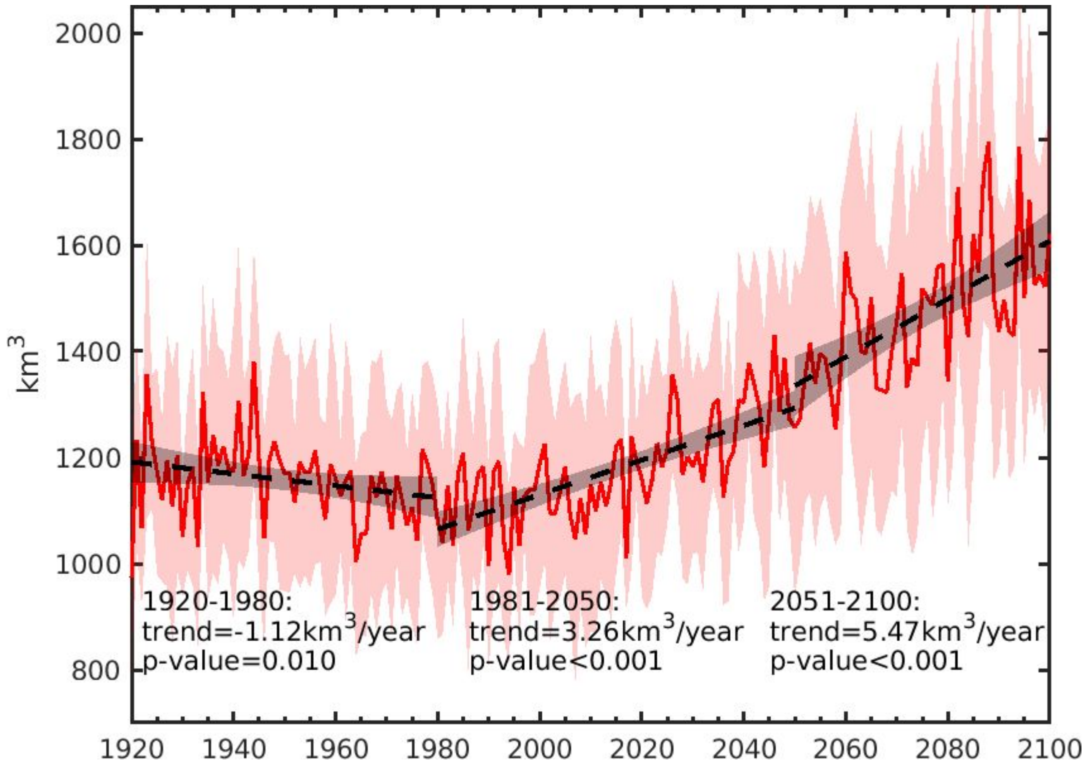
- Consistent with Chand et al. 2022, CESM-HR suggests decrease trend during early 20th century, and continues to decrease in the rest of 21st century.

- However, TC activities are projected to migrate poleward, increasing landfall possibilities

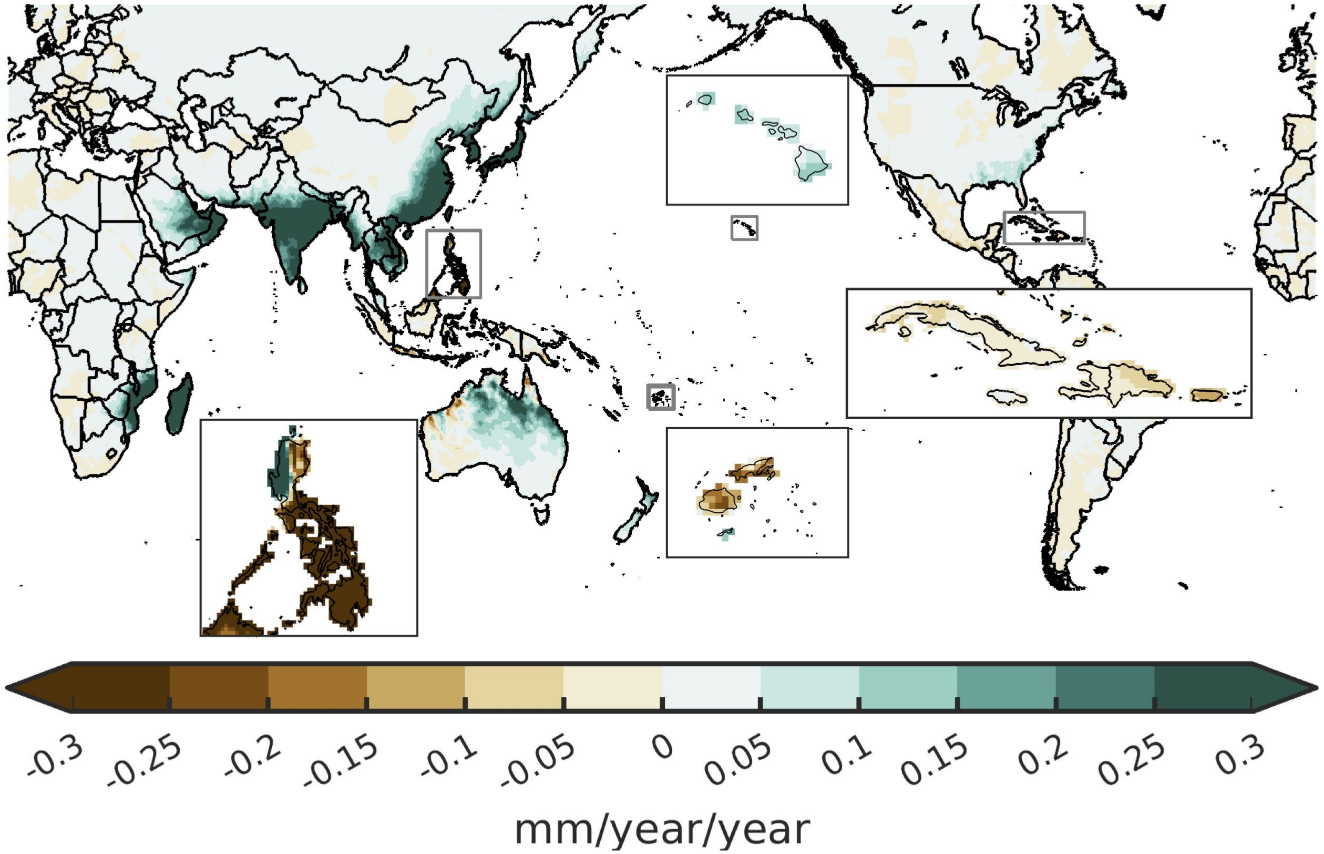
Projected Future Changes of TCs-induced Precipitation

- As the consequence, TC-induced precipitation:

Annual accumulated TC rainfall over land area



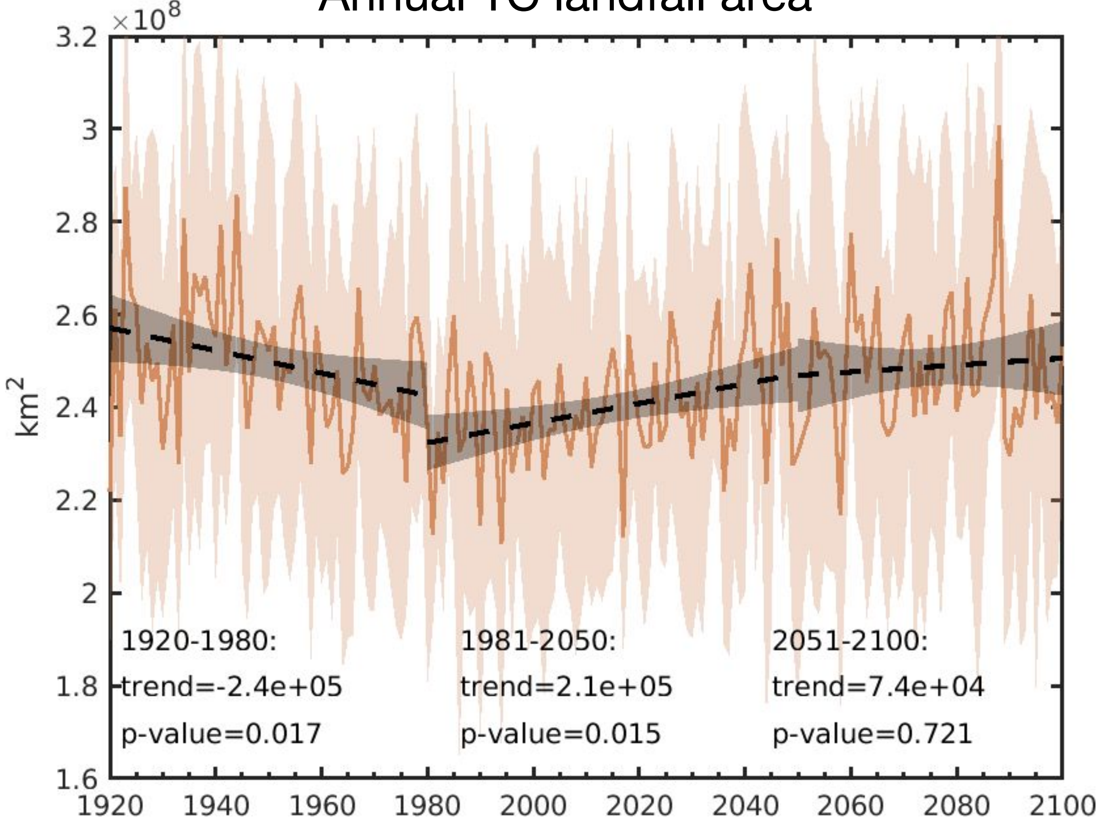
CESM-HR 1980-2100 trend



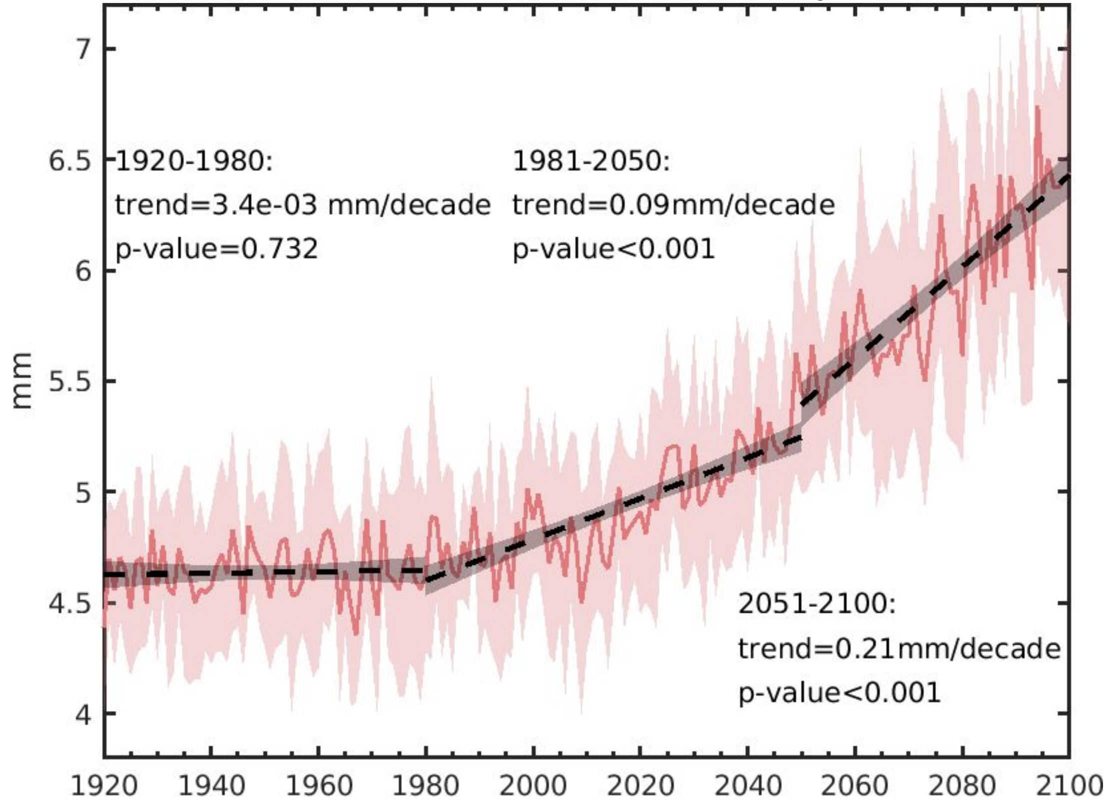
Projected Future Changes of TCs and TCs-induced Precipitation

TC rainfall over land (unit: km^3) = TC landfall area(unit: km^2) × TC mean rainfall intensity over land(unit: mm)

Annual TC landfall area



Annual mean TC rainfall intensity over land



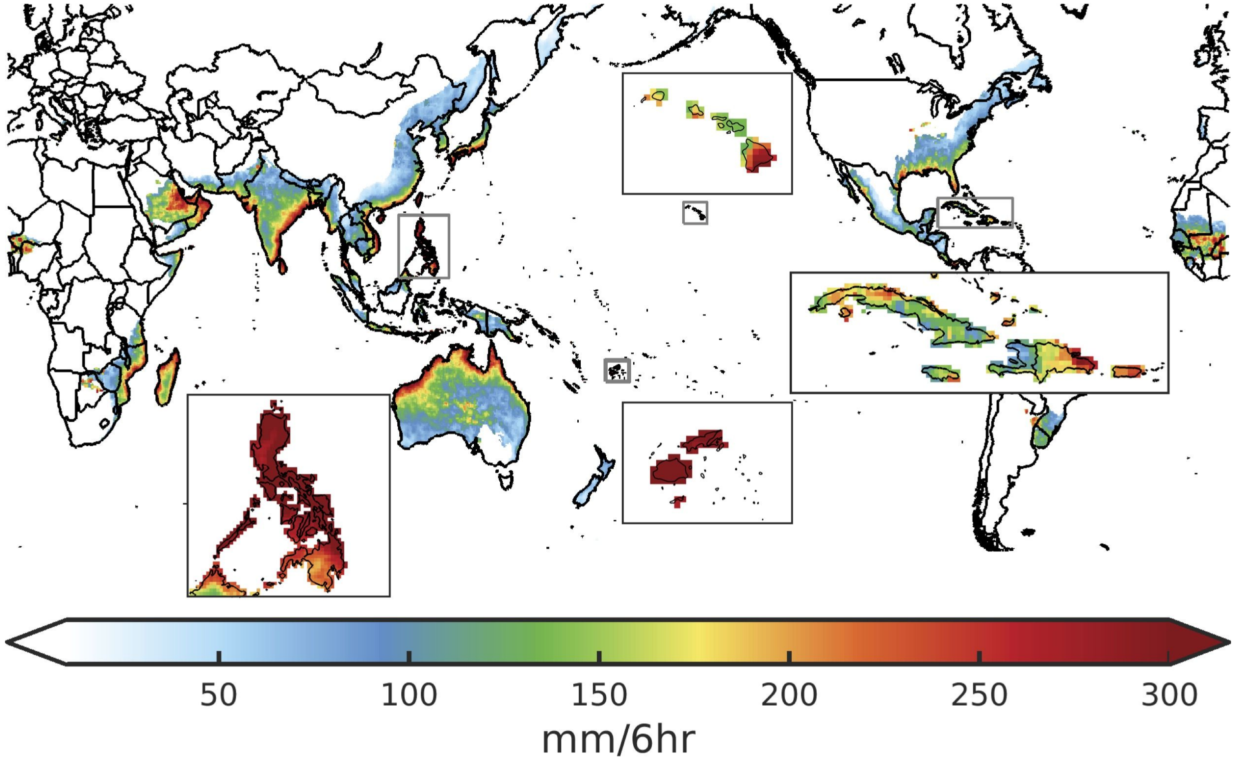
- During 1981-2050, increasing trend of TC landfall area dominates landfalling TC rainfall upward trend, while TC mean rainfall intensity also play important role;
- During 2051-2100, more significant increasing trend of TC mean rainfall intensity dominates landfalling TC rainfall upward trend;

Projected Future Changes of TC-Precipitation Return Period

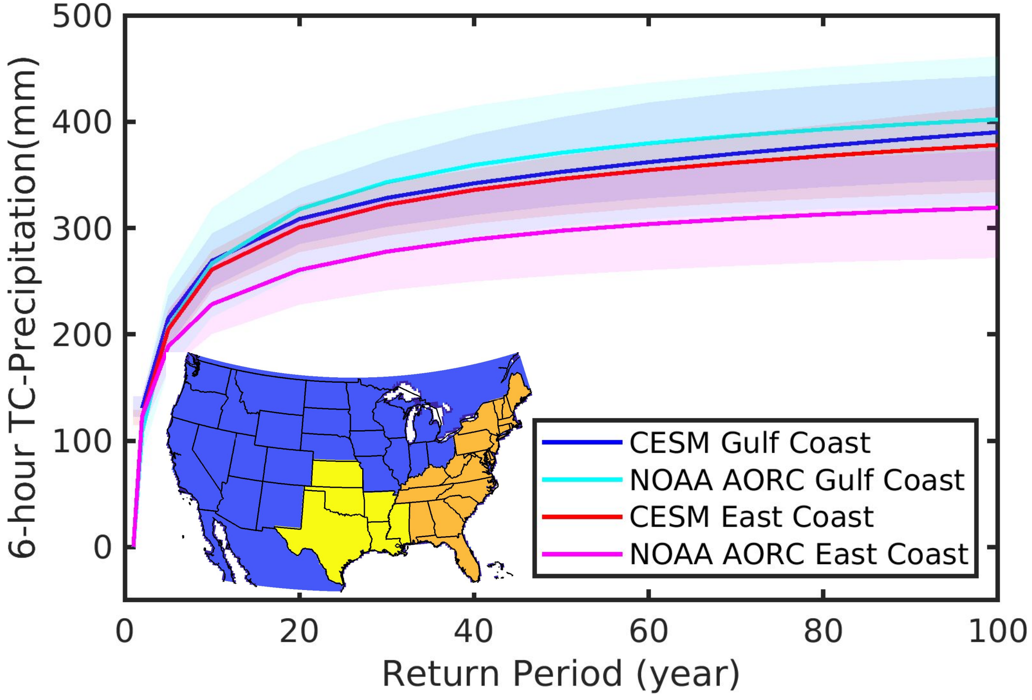
Following Zhu et al. (2022), we applied non-parameteric kernel density estimation (KDE) function to compute cumulative distribution function (CDF) of 6-hourly averaged TC-precipitation over each grid point. Thus, Return Period (RP) value can be computed as:

$$RP = \frac{1}{1 - CDF}$$

10-member CESM-HR
100-year Return Period value during 1981-2020



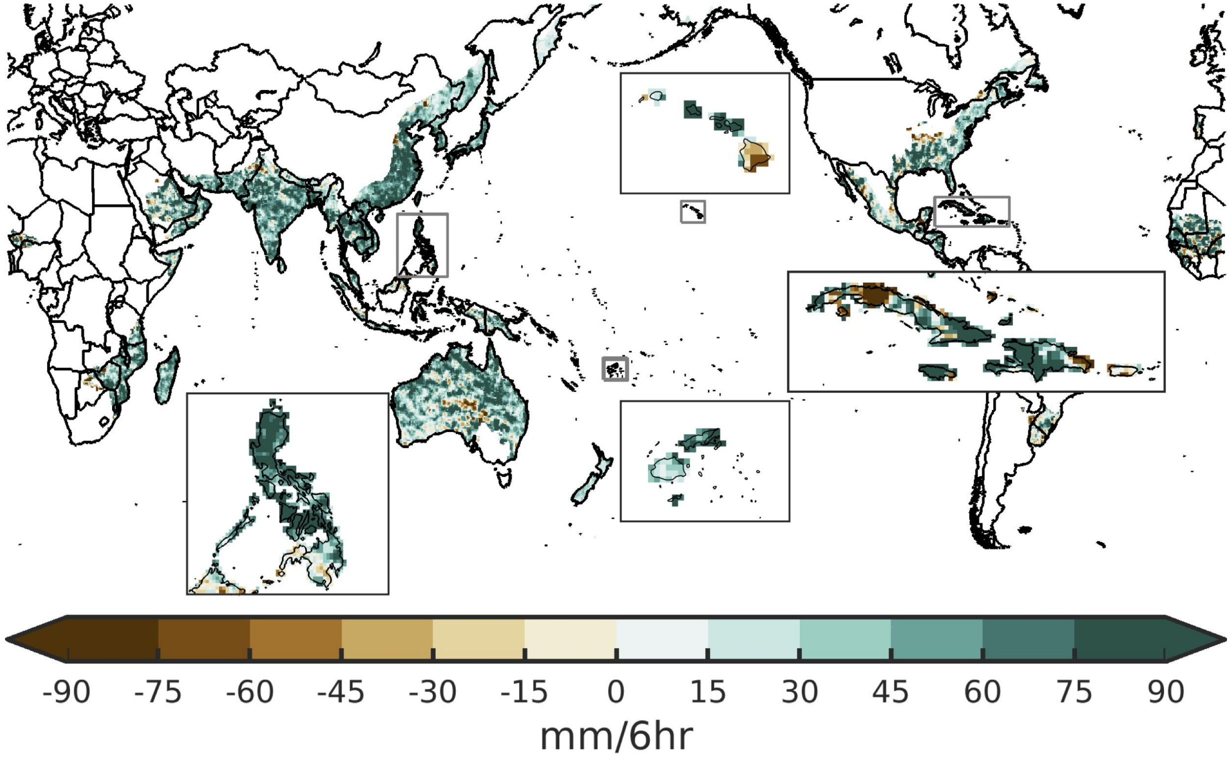
Comparison with NOAA Analysis of Record for Calibration (AORC) 1-km hourly data



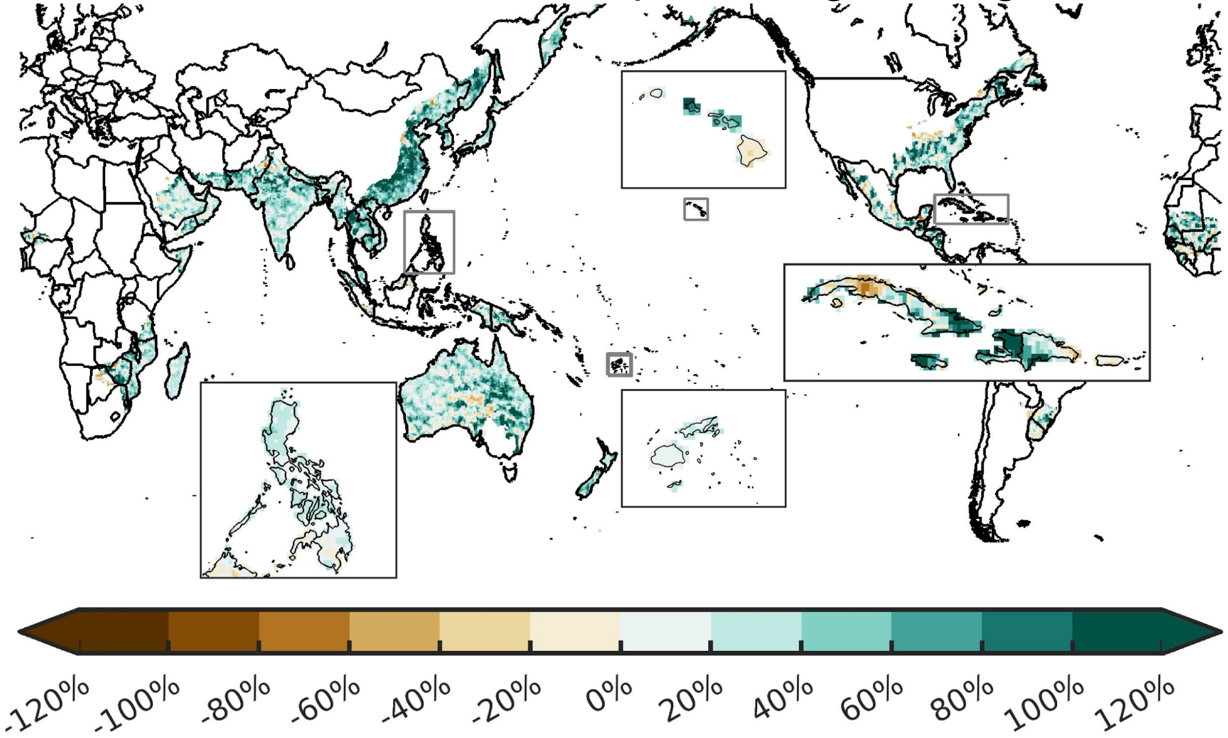
Projected Future Changes in TC-Precipitation Return Period

10-member CESM-HR
100-year Return Period TC-precipitation rate difference (20612100 - 19812020)

Difference in terms of absolute changes



Difference in terms of percentage changes



- Unlike accumulated TC-precipitation, TC-precipitation rate is projected to increase ubiquitously;
- Percentage increase in inland area is more significant, indicating extended TC influences

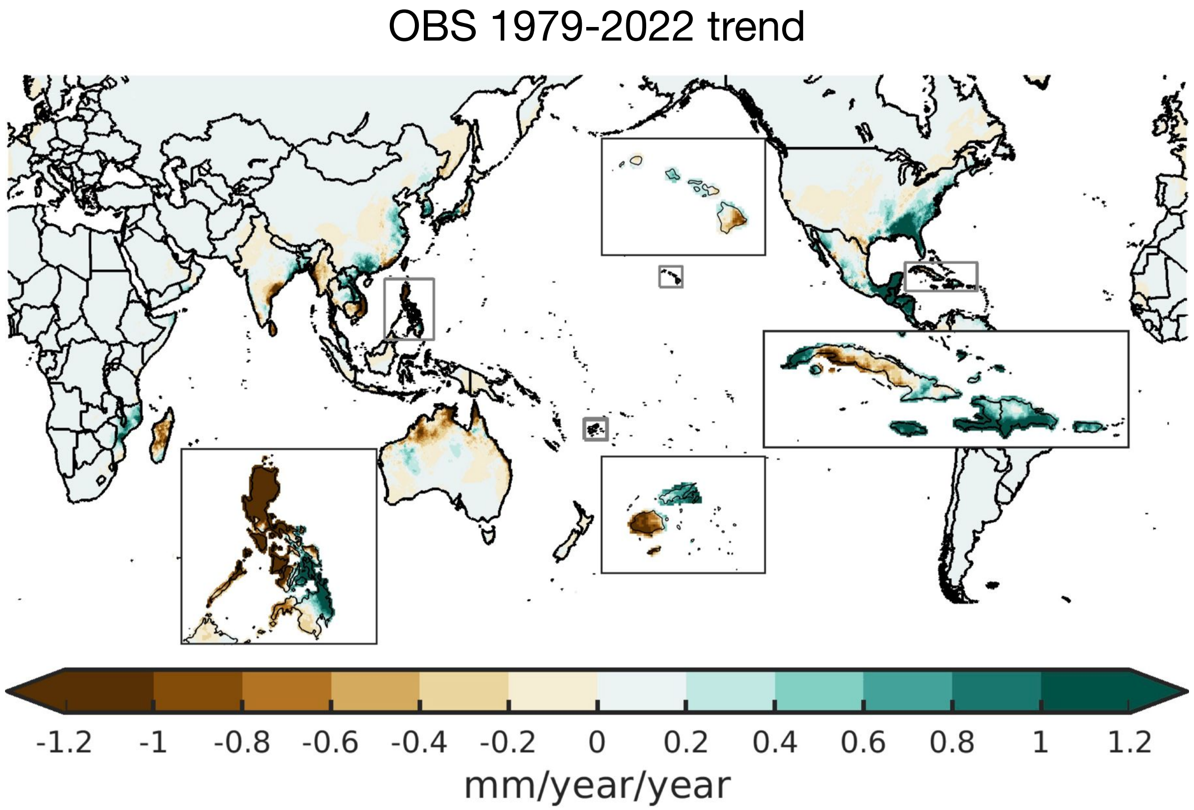
Summary

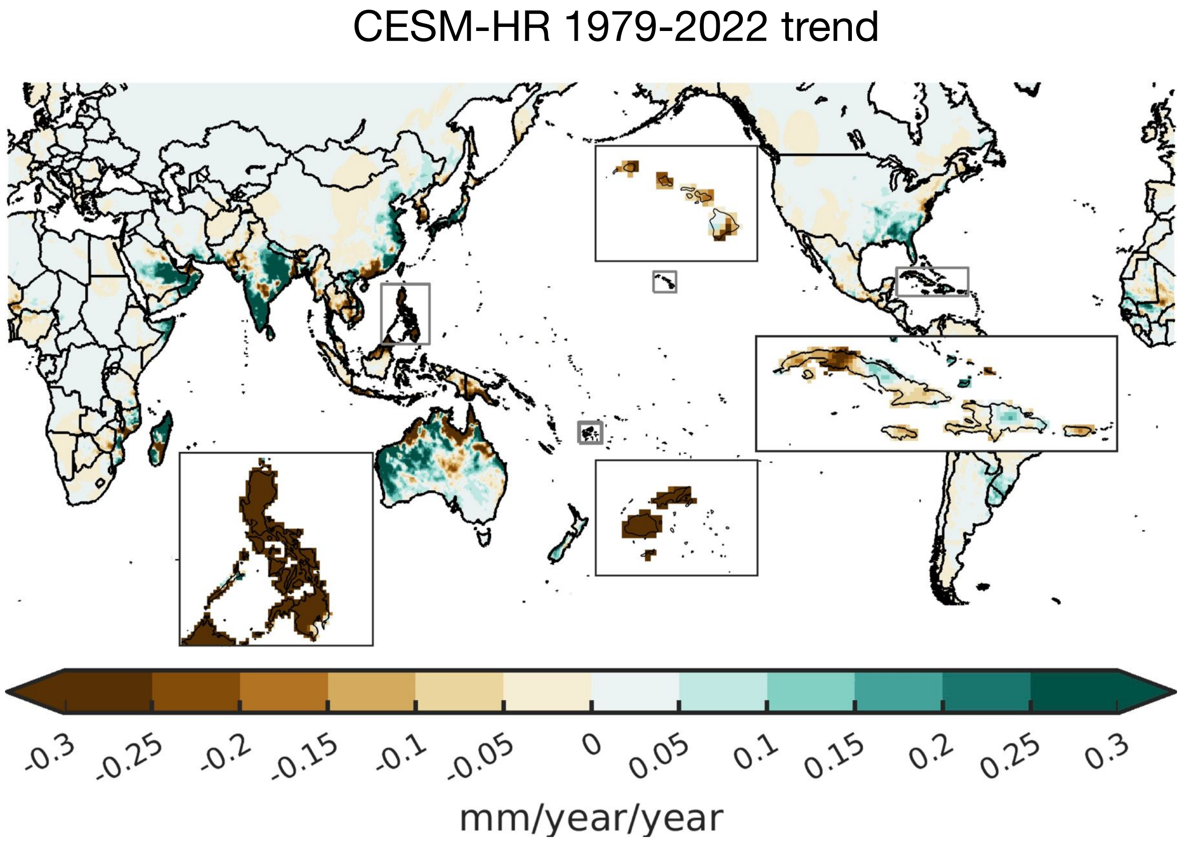
- TAMU-NCAR collaboration (PI: Chang, Danabasoglu, coPI: Fu, Castruccio) led to large suites of eddy-rich ocean (~10km) and tropical-cyclone-permitting atmosphere resolution (~25km) simulations:
  - CMIP6 HighResMIP Ensemble – Data are publicly available at ESGF.
  - CMIP Deck suite (e.g., AMIP, PI-CTRL, 10-member ensemble 1920-2100 transient climate simulations under RCP8.5 and 6.0) - Data are publicly available at NCAR RDA.
  - Initialized decadal prediction set: HRDP (10-member ensemble; Initialized on May and November 1st, 1970-2024; 5-year predictions) – entire sets will be finished in 2026

- Global TC number is projected to decrease in the future warmer conditions;
- However, TC induced accumulated precipitation over land area is projected to increase;
- By decomposing TC induced precipitation into dynamical impact (TC occurrence density) and thermodynamical impact (TC precipitation rate), we found dynamical impact dominates this upward trend up to 2050, but thermodynamical impact will take the leading role in the upward trend in the second half of 21st century.
- In addition, TC induced extreme precipitation risk will be amplified ubiquitously over the globe.

Question? Email to fudan1991@tamu.edu

Appendix: Historical TCs and TCs-induced Precipitation



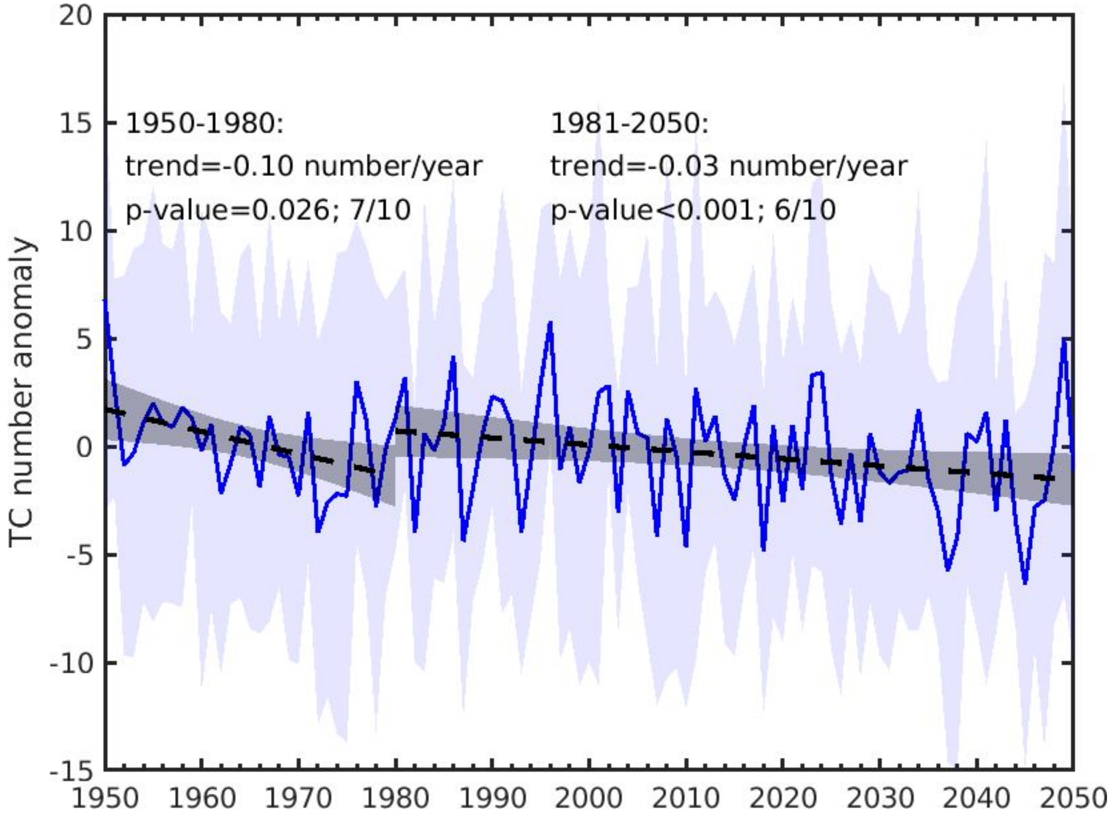


- Both observation and CESM-HR suggest increase trend of accumulated TC induced precipitation in East Asia and Eastern U.S.;

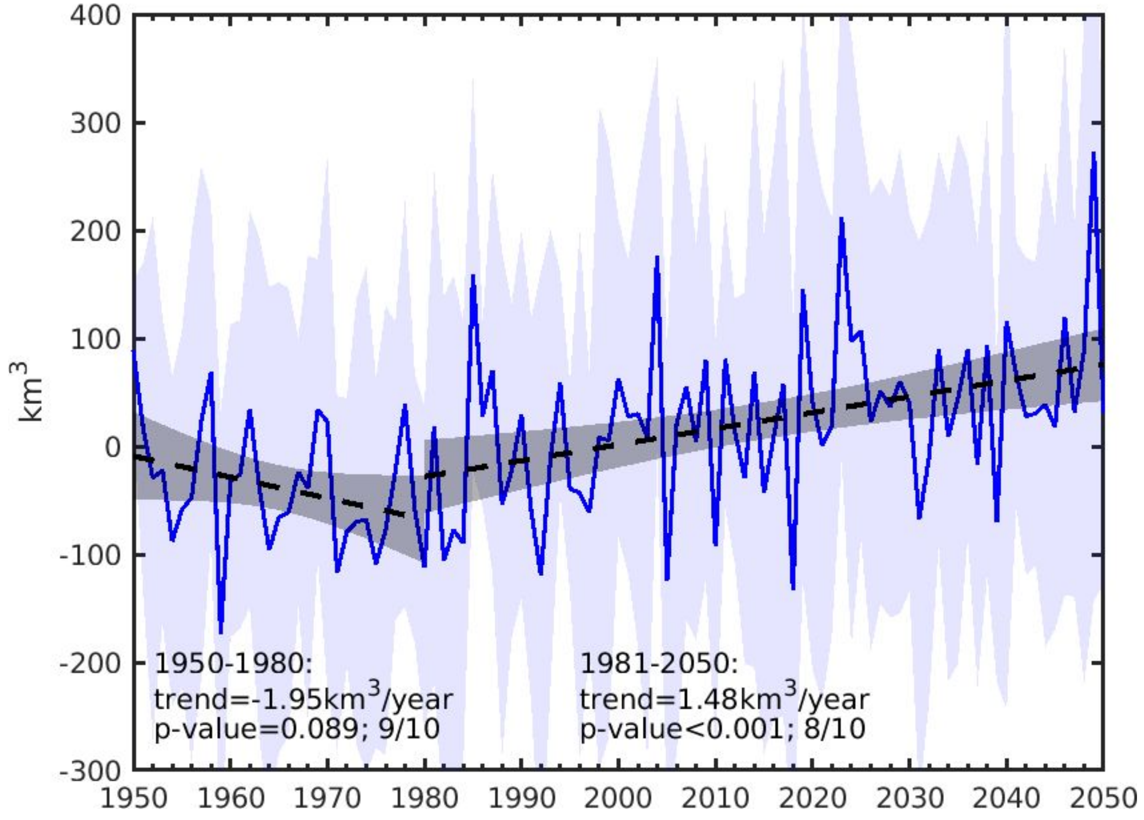
Appendix: Projected Future Changes of TCs and TCs-induced Precipitation

7 CMIP6 HighResMIP fully coupled models, 10-member ensemble in total: CESM-HR (1), CMCC-CM2-VHR4 (1), CNRM-CM6-1-HR (1), EC-Earth-3P-HR (2), HadGEM3-GC31-HM (3), HadGEM3-GC31-HH (1), MPI-ESM1_2_XR (1)

Annual mean global TC number



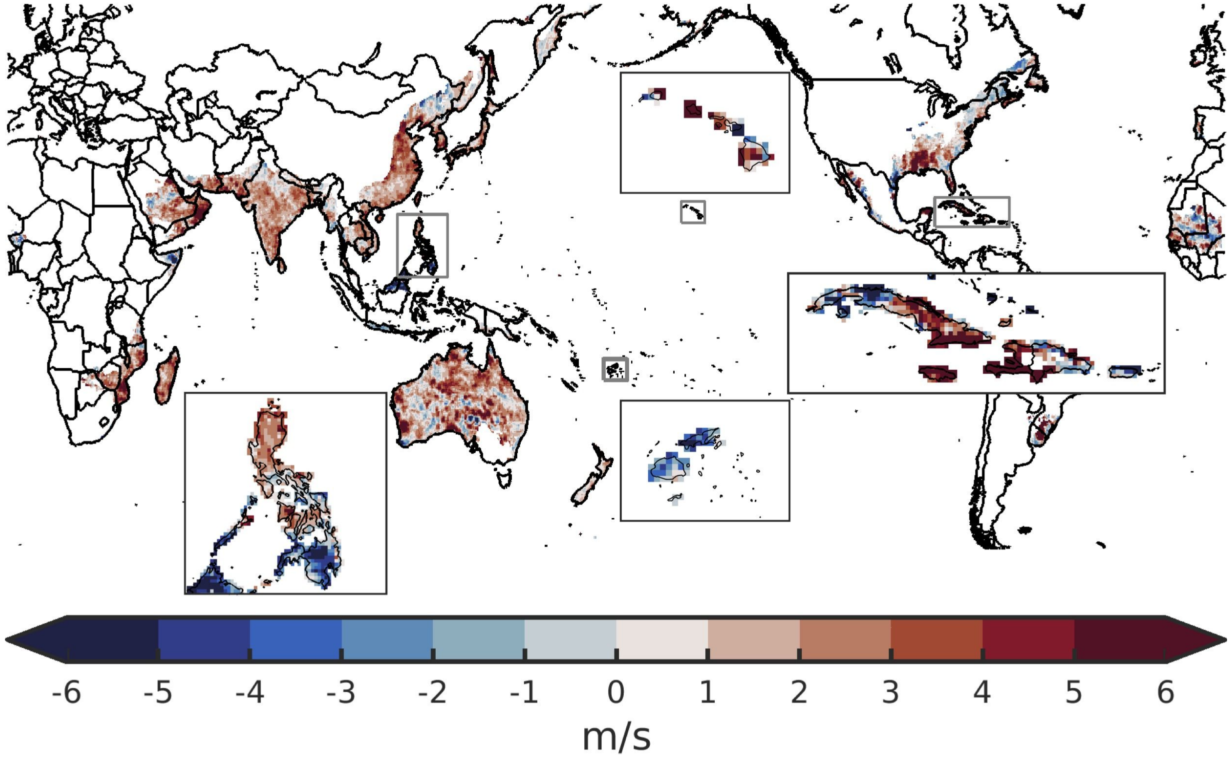
Annual accumulated TC precipitation over land area



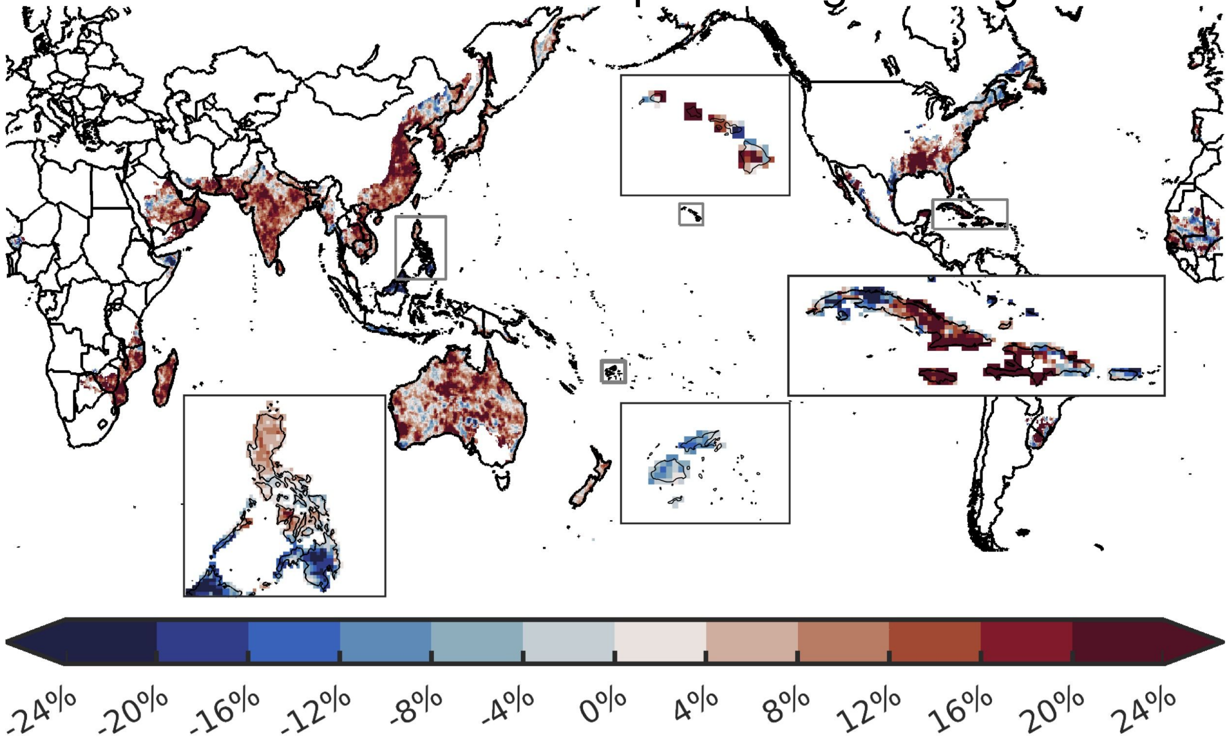
Appendix: Projected Future Changes of TC 10m Wind Speed Return Period

10-member CESM-HR

100-year Return Period TC 10m wind speed difference (20612100 - 19812020)



Difference in terms of percentage changes



- In many region over the world, TC-induced strong wind events will also be enhanced