Characterizing Uncertainties in Future Projections of Major Tropical Cyclone Events Due to Air-Sea Interactions

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Introduction

Projections of tropical cyclone (TC) activity under future warmer climates are characterized by many uncertainties. One substantial uncertainty comes from the lack of air-sea interactions in most numerical models used for simulating TCs in the current and future climates. TC winds can induce a cooling of the sea surface temperature (SST) by enhancing upwelling of colder water from below the ocean surface. This may impact air-sea enthalpy fluxes, which could in turn influence TC characteristics such as intensity and rainfall. The rate of TC-induced SST cooling may depend on ocean characteristics such as salinity and heat content, as well as TC properties, including TC speed and size, all of which will be better represented when the ocean and atmosphere interact in numerical models. Additionally, coupled global climate model simulations spanning several months or years are often characterized by large SST biases which can create uncertainties in future TC projections.

In this study, we investigated whether and how some of the most impactful TC events in recent years will change in future warmer climates when simulated with and without air-sea interactions. The event-based simulations are designed to minimize basin-scale SST biases typical of coupled simulations lasting more than a few weeks.

Regional Climate Model Simulations

- 2 major TC events:
  - Hurricane Michael (2018). Initialized on 7 October 2018 at 12:00:00
  - Hurricane Ida (2021). Initialized on 27 August 2021 at 12:00:00
- Two model configurations:
  - Atmosphere-only (atmos) → WRF model
  - Coupled atmosphere-ocean (coupled) → WRF & ROMS
- Climate states:
  - Historical conditions
  - Future pseudo-global warming conditions for 2081-2100. Anthropogenic climate change perturbations from CMIP6 SSP5-8.5 scenario projections of E3SM version 1.
- Initial and lateral boundary conditions prescribed from:
  - ERA5 for WRF
  - HYCOM for ROMS
- 12km resolution for both models, 10 ensemble members each.

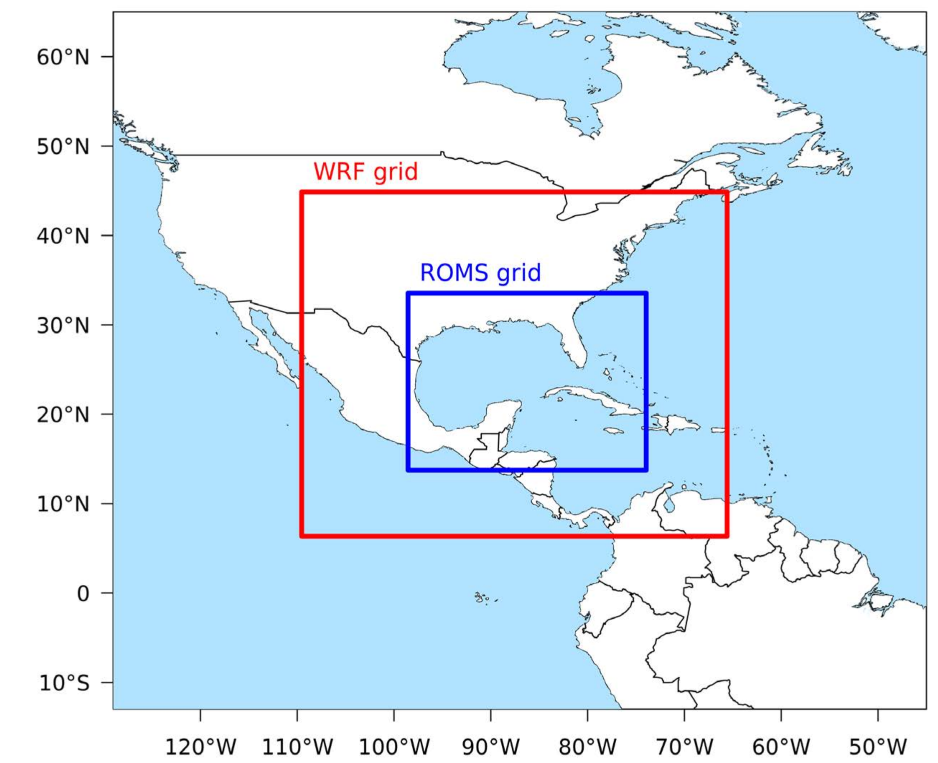

Figure 1: Simulation domains for the atmosphere (WRF) and ocean (ROMS) models.

Evaluation of simulated TC tracks

TC tracks from the historical TC simulations are compared with observations obtained from International Best Track Archive for Climate Stewardship (IBTrACS).

- Observed tracks for both TCs are captured well in the historical simulations.
- Minimal differences between atmos and coupled TC tracks.

Tropical cyclone track response to future climate change

- Substantial westward shifts of TC tracks in the future climate.
- Very little sensitivity of track shift to atmosphere-ocean coupling.

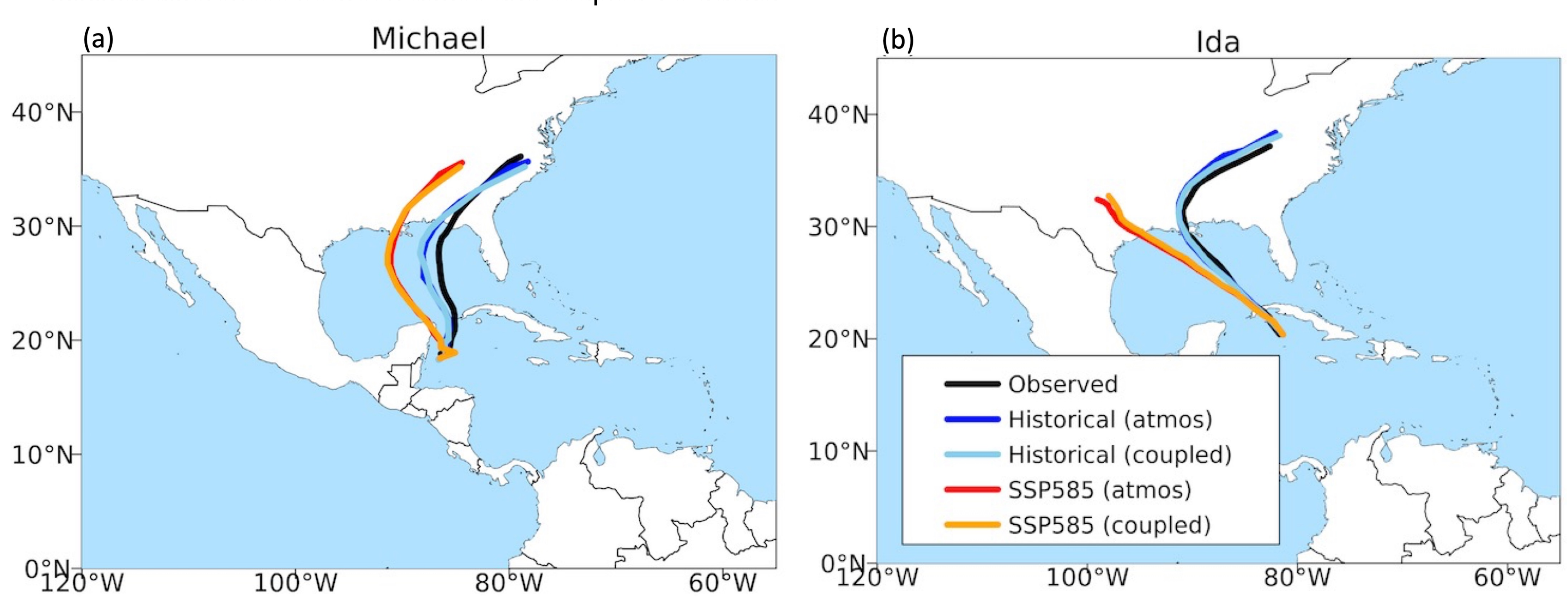

Figure 2: TC tracks for Hurricane (a) Michael and (b) Ida in IBTrACS observations and the ensemble mean of the historical and future climate simulations.

Tropical cyclone intensity response to future climate change

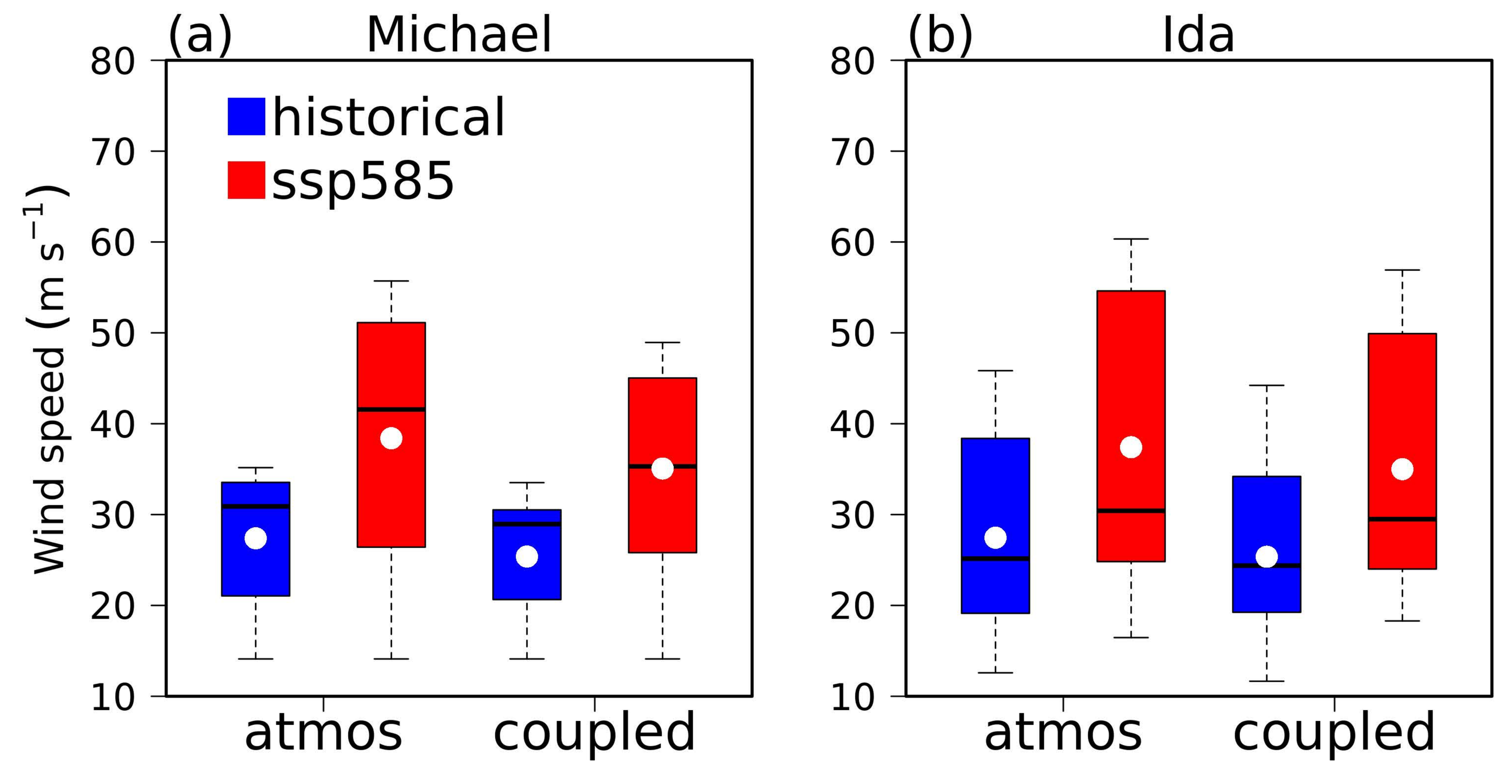

Figure 3: TC intensity (m/s) from the historical and future climate simulations.

- TC intensity increases in the future for both atmos and coupled simulations (Fig. 3).
- The future mean TC intensity increase in the atmos simulation is comparable to that in the coupled simulation (Table 1 & Fig. 3).
- The TC intensity response to warming is not very sensitive to atmosphere-ocean coupling (Table 1).

Table 1: Percentage change in TC intensity for future relative to historical in both the atmos and coupled simulations.

Intensity metric	TC	atmos: ssp585 minus historical	coupled: ssp585 minus historical
Max. wind speed	Ida	36%*	37.8%*
	Michael	40.1%*	38.2%*
Min. sea level pressure	Ida	-1.7%*	-1.4%*
	Michael	-2.7%*	-2.2%*

Tropical cyclone rainfall response to future climate change

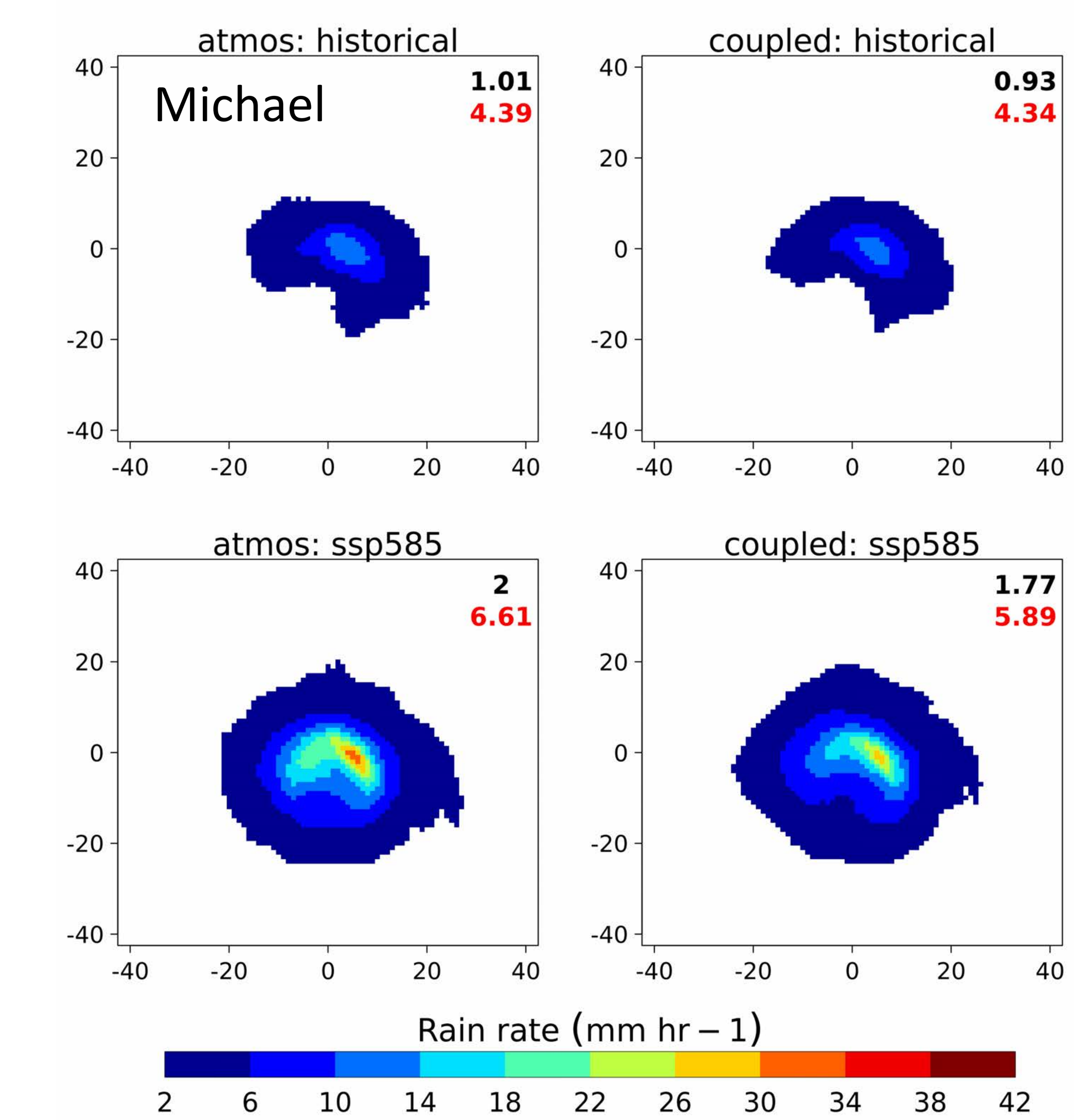

Figure 4: Rainfall rate (mm/hr) relative to TC center and throughout TC lifetime for Hurricane Michael. Values in black: Rainfall mean over 500 km radius around TC center. Values in red: same as in black but considering only rainfall of at least 2 mm/hr.

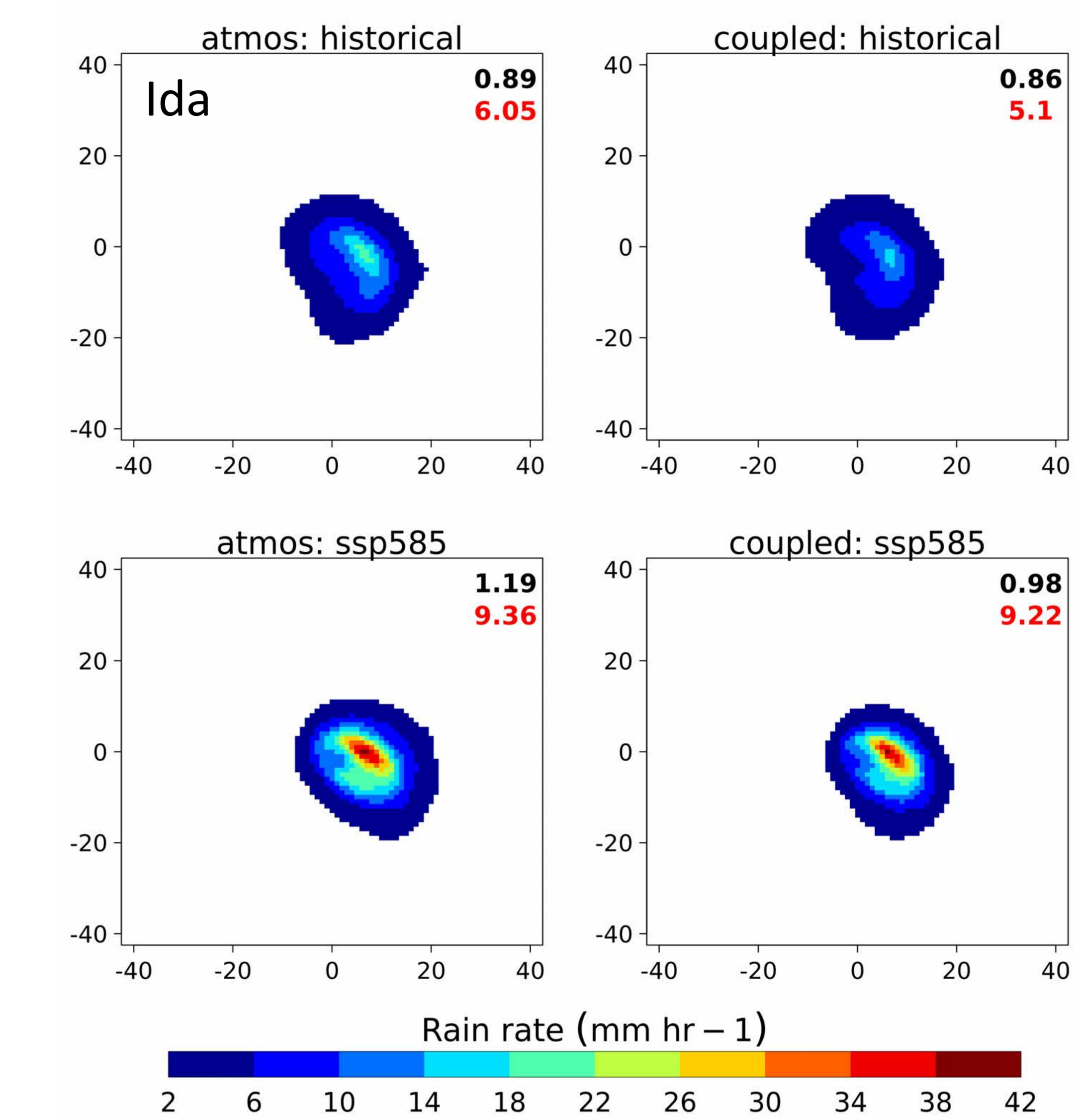

Figure 5: Same as Fig. 4 but for hurricane Ida.

- TC rainfall increases in the future climate for both events.
- The magnitude of the future TC rainfall increase can vary substantially depending on whether the simulations are coupled.
- The rainfall area is larger (especially for Michael) in the future climate.
- There is little sensitivity of rainfall area to atmosphere-ocean coupling in both historical and future climates.
- The rainfall difference between the atmos and coupled simulations is much larger in the future climate than in the historical (not shown).

Conclusions

- Warmer climates substantially modify TC tracks, with very little sensitivity to atmosphere-ocean coupling.
- Atmosphere-ocean coupling does not influence the sign of future TC rainfall and intensity projections.
- Both the coupled and uncoupled simulations project future increases in TC intensity, with similar magnitudes.
- Both the coupled and uncoupled simulations project future increases in TC rainfall, however, the magnitude can vary substantially depending on whether the simulations are coupled.