ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

A storyline analysis of Hurricane Irma’s precipitation under various levels of climate warming

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
18 August 2023

REVISED
31 October 2023

ACCEPTED FOR PUBLICATION
14 November 2023

PUBLISHED
29 November 2023

LETTER

A storyline analysis of Hurricane Irma's precipitation under various levels of climate warming

Annika S Huprikar[1,2], Alyssa M Stansfield[1,3] and Kevin A Reed[1,*]

1 School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY, United States of America
2 Department of Computer Science, Harvard University, Cambridge, MA, United States of America
3 Department of Atmospheric Science, Colorado State University, Fort Collins, CO, United States of America
* Author to whom any correspondence should be addressed.

E-mail: kevin.reed@stonybrook.edu

Keywords: tropical cyclones, precipitation, extremes, storylines, climate change

Supplementary material for this article is available online

Abstract

Understanding how extreme weather, such as tropical cyclones, will change with future climate warming is an interesting computational challenge. Here, the hindcast approach is used to create different storylines of a particular tropical cyclone, Hurricane Irma (2017). Using the community atmosphere model, we explore how Irma's precipitation would change under various levels of climate warming. Analysis is focused on a 48 h period where the simulated hurricane tracks reasonably represent Irma's observed track. Under future scenarios of 2 K, 3 K, and 4 K global average surface temperature increase above pre-industrial levels, the mean 3-hourly rainfall rates in the simulated storms increase by 3–7% K^{-1} compared to present. This change increases in magnitude for the 95th and 99th percentile 3-hourly rates, which intensify by 10–13% K^{-1} and 17–21% K^{-1}, respectively. Over Florida, the simulated mean rainfall accumulations increase by 16–26% K^{-1}, with local maxima increasing by 18–43% K^{-1}. All percent changes increase monotonically with warming level.

1. Introduction

Tropical cyclones (TCs) are impactful extreme weather events in many ways, not just monetarily in the form of economic damages. The damage from their extreme precipitation, intense winds, severe flooding, and storm surges is costly to the strength and livelihoods of communities. Given that Earth's surface has warmed by over 1 °C since 1880 due to human actions (Eyring *et al* 2021), analyzing changes in TC genesis, intensity, and extreme precipitation is important for gauging how TCs and their societal impacts are influenced by anthropogenic climate change (Knutson *et al* 2019). It is also useful to study TCs under potential warming conditions to see how their characteristics and impacts may continue to change into the future (Knutson *et al* 2020).

Two main drivers of TCs are warm ocean water and abundant atmospheric moisture—properties that are increasing globally due to climate warming (Eyring *et al* 2021); therefore, it is becoming clear that climate change is affecting certain characteristics of TCs, including their intensity and precipitation rates (Kossin *et al* 2020, Seneviratne *et al* 2021, Utsumi and Kim 2022). The research community has high confidence that TC maximum wind speeds will increase with a warming climate, implying a larger proportion of Category 4 and 5 storms on the Saffir–Simpson scale (Sobel *et al* 2016). Higher atmospheric temperatures result in a higher saturation vapor pressure for water and therefore an increased capacity for holding water vapor. According to the Clausius–Clapeyron relationship, the saturation vapor pressure increases about 7% per K increase in air temperature, and thus this rate is a rough estimate for expected increases in extreme precipitation with climate warming since extreme precipitation tends to happen in saturated atmospheric environments (Allen and Ingram 2002). For TCs, their intensities, precipitation rates, and environmental ocean temperatures are all related (Stansfield and Reed 2021, 2023, Xi *et al* 2023), which suggests that as climate warming continues

TC precipitation rates will increase due to a combination of increasing available atmospheric moisture and increasing TC intensities (Liu *et al* 2019).

Over time, new approaches have developed to quantify the impacts of climate change on extreme weather events. Storylines are a physically self-consistent unfolding of past events and their plausible unfolding in the future (Shepherd *et al* 2018). Such approaches have been used to quantify the impact of past climate change on recent devastating North Atlantic hurricanes (Patricola and Wehner 2018, Reed *et al* 2020, 2021, 2022). To yield actionable climate science in a decision-making setting for relevant stakeholders and policymakers, event-based storylines allow for consideration of climate vulnerability and exposure risks on a more localized level (Shepherd *et al* 2018). Rather than relying solely on a probabilistic approach using large model ensembles, the focus has shifted to incorporating plausibility with the storyline approach; this allows for the analysis of low-likelihood, high-impact events that are conditional on plausible assumptions about potential future hazards to ecological systems and the environment (Sillmann *et al* 2021). The analysis is especially informative when there is uncertainty around the likelihood of the cause of a weather event, but more certainty about the effects such an event would have, which is the case for TCs. With event-based storylines, individual events can be focused on with high-resolution simulations to enable in-depth mapping of their effects (Sillmann *et al* 2021). These event-focused simulations are typically run at finer resolutions than traditional climate model simulations and can consider a variety of future climate scenarios, which is challenging for ensemble climate models due to the computational costs of decadal to century long simulations (Brogli *et al* 2023). Two downsides of the storyline approach are that it does not provide insight on potential future changes in the frequency of weather events and it does not take into account potential future changes in large-scale wind fields that are not forced by thermodynamic changes in the atmosphere. The storyline approach, in conjunction with a probabilistic framework on the quantification of impact, represents uncertainty in climate change's physical aspects and frames risk around concrete events (Shepherd *et al* 2018).

Building off recent work using storyline frameworks for hurricanes, we will focus our study on Hurricane Irma. Hurricane Irma began as a tropical wave moving westward from the West African coast on 27 August 2017 (Cangialosi *et al* 2018). The storm system intensified over waters that were marginally warmer than average and was officially categorized as a hurricane on 31 August, after which it made landfall seven times and its intensity oscillated between Categories 3, 4, and 5. Irma struck the Florida Keys, specifically Cudjoe Key around 1300 UTC on 10 September and later hit the continental United States on southwestern Florida's Marco Island around 1930 UTC that same evening (Cangialosi *et al* 2018). Between millions of people losing power, property loss due to major flooding, and other damages, costs added up to around $50 billion (NOAA 2023). At the time, Hurricane Irma was the first category 5 hurricane to hit the Leeward Islands and was the most intense hurricane on record to exist in the open Atlantic Ocean. Because of Irma's record-setting strength and devastating damage throughout the Caribbean and Florida, the World Meteorological Society retired the name Irma from the rotation for future Atlantic hurricane names.

Previous studies have attributed aspects of individual TCs to anthropogenic climate change using a variety of methodologies ranging from statistical techniques using observations to model simulations of the storms under various historical and future climate scenarios (e.g. Risser and Wehner 2017, Van Oldenborgh *et al* 2017, Patricola and Wehner 2018, Wang *et al* 2018). For this study, we apply the hindcast technique with the Community Atmosphere Model version 5 (CAM5) to simulate Hurricane Irma under multiple potential future climate warming levels. This methodology was previously developed and tested on other TCs, such as Hurricane Dorian (Reed *et al* 2021), Hurricane Florence (Reed *et al* 2020), and Typhoon Haiyan (Wehner *et al* 2019). These previous studies focused on the impacts of climate change up to the present, but not of future warming scenarios, and demonstrated CAM5's capability to simulate hurricane tracks, intensities, and precipitation that match well with observations. While Patricola and Wehner (2018) performed hindcast simulations of TCs under future scenarios, they examined changes in the individual TCs at the end of the century under three representative concentration pathway (RCP) scenarios. In contrast, our methodology simulates Hurricane Irma under specific levels of atmospheric warming above pre-industrial temperatures, which allows for the quantification of how Irma would be different at any time in the future when (or if) the level of climate warming reaches these levels. The goal of this study is to demonstrate the usefulness of the storyline approach to quantify plausible changes in TC precipitation under potential future climate warming. This paper is structured as follows: section 2 details the CAM5 ensemble simulations, the TC tracking and precipitation extraction methodology, and the observational datasets; section 3 compares Hurricane Irma's track and precipitation in CAM5 to observations and then examines the changes in storm precipitation in the future warming scenarios compared to the present warming scenario; and section 4 concludes with a discussion of the implications of the results and the usefulness of the storyline approach for studying TCs under future warming.

2. Methodology

2.1. Model simulation design

The simulation component of our storyline analysis makes use of CAM5 within the Community Earth System Model (CESM) framework (Neale and Coauthors 2012, Hurrell *et al* 2013). CAM5 is configured with a variable resolution grid (Zarzycki and Jablonowski 2014), with grid spacing of 28 km over much of the North Atlantic, following the approach of Zarzycki and Jablonowski (2015) to initialize hindcasts at various lead times in advance of Hurricane Irma's landfall in Florida. In particular, CAM5 is initialized using the Global Data Assimilation System (GDAS) and Optimum Interpolation Sea Surface Temperature (OISST), the NOAA atmospheric and ocean analyses (National Centers for Environmental Prediction, National Weather Service, NOAA, U.S. Department of Commerce 2015, Huang *et al* 2021), and a digital filter is used to remove any hydrostatic imbalance associated with the initial state (Zarzycki and Jablonowski 2015). This scenario, which was initialized with the climate experienced by the real Hurricane Irma in 2017, is referred to as the 'present warming' scenario. To quantify the impact of potential future climate change on Hurricane Irma, future storyline simulations are conducted with the GDAS and OISST initial conditions adjusted using estimates of a future warming fingerprint on the SST and 3D temperature and specific humidity fields. Following the guidance from similar studies of TCs (e.g. Lackmann 2015, Patricola and Wehner 2018, Liu *et al* 2020), we chose to only modify the thermodynamic initial conditions and not geopotential or wind. This is to ensure Hurricane Irma's tracks among all the model simulations are as close as possible so we can compare the precipitation fields directly, since large-scale winds tend to steer hurricanes and precipitation fields are greatly impacted by the exact track of the storm. These fingerprints are estimated using the 40-member CESM Large Ensemble under a future high-emissions (RCP8.5) scenario (Kay *et al* 2015), calculated from the first year that global average surface temperature is 2 K, 3 K and 4 K warmer than the 1500-year 1850 control simulation (preindustrial). Note that in 2017, when Hurricane Irma occurred, the global average temperature was about 1 K warmer than preindustrial. Since CAM5 is the atmospheric component of CESM, there is consistency between the modeling system used to run the Irma storyline simulations and to calculate the climate change fingerprints.

Four initialization times of 8 September 00Z, 8 September 12Z, 9 September 00Z and 9 September 12Z are used for each of the four scenarios (present warming and the three future warming levels). For each combination of initialization time and climate scenario, 20-member ensembles of 7-day long simulations are completed, resulting in four scenarios for each initialization time and 320 total simulations. The ensembles are created by slightly varying parameters in CAM5's deep convection parameterization package (Zhang and McFarlane 1995), as in Reed *et al* (2020) and Reed *et al* (2022). The three parameters in the deep convection scheme that were modified to create the ensembles are precipitation coefficient (c0_ocn), convective time scale (tau), and parcel fractional mass entrainment rate (dmpdz). Following suggestions from He and Posselt (2015) on reasonable ranges for these parameters, random values were sampled between 0.001 and 0.045 for c0_ocn, 1800 and 28 800 for tau, and −0.002 and 0 for dmpdz. Other parameterization packages used are the University of Washington (UW) shallow convection scheme (Park and Bretherton 2009), the UW moist boundary layer turbulence scheme (Bretherton and Park 2009), the Morrison and Gettelman cloud microphysics scheme (Morrison and Gettelman 2008), cloud macrophysics (Park *et al* 2014), and the rapid radiative transfer method for GCMs radiation scheme (Iacono *et al* 2008). All settings are exactly the same as described in Reed *et al* (2022). The CAM5 hindcast approach has been applied to explore the impact of historical climate change on the precipitation during recent devastating hurricanes, including Hurricane Florence (Reed *et al* 2020), Hurricane Dorian (Reed *et al* 2021) and the entire 2020 Atlantic hurricane season (Reed *et al* 2022). Further, in traditional decadal-scale climate simulations, CAM5 has shown the ability to simulate realistic North Atlantic hurricane frequency (Wehner *et al* 2014, Reed *et al* 2019) and precipitation (Stansfield *et al* 2020).

2.2. TC track and precipitation analysis

This work utilizes TempestExtremes (Ullrich *et al* 2021) to detect and track the simulated Hurricane Irma in each ensemble hindcast, as in Reed *et al* (2022). Furthermore, storm-specific precipitation is extracted following the approach of Stansfield *et al* (2020), in which TempestExtremes calculates the outer radius of the storm, taken to be the azimuthally-averaged azimuthal wind speed of 8 m s^{-1}, and all precipitation within this radius is identified as Hurricane Irma's. The storms' simulated tracks were compared to observations to assess the error in track, landfall location, and landfall timing and characterize the simulations' goodness-of-fit for a storyline analysis. Large variations in track can greatly alter the storms' precipitation amounts, so the tracks in the different simulations must be comparable to quantify differences in precipitation under different climate scenarios. Hurricane Irma's observed track was obtained from the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp *et al* 2010) database. Precipitation observations are from the U.S. National Weather Service Stage IV precipitation analysis, which combines observations from ground-based radars and rain gauges (Seo and Breidenbach 2002). Before any analysis, the Stage IV data is conservatively regridded from its native 4 km resolution onto the native CAM5 grid. To compare the Stage IV data to data from weather stations, we have plotted Irma's precipitation accumulation using data from the Global Historical Climatology Network daily dataset (Menne *et al* 2012), which is shown in figure S1.

3. Results

3.1. Storm track

Since TC track and translation speed impact precipitation (Tu *et al* 2022), we first compare the simulated storm tracks and landfall metrics to observations to determine if the storm is represented well in the CAM5 simulations. Figure 1 shows the ensemble-mean simulated TC tracks across the four model scenarios (Present warming, 2 K warming, 3 K warming, and 4 K warming), grouped by initialization time of the simulations (09-08 0Z, 09-08 12Z, 09-09 0Z, and 09-09 12Z). For comparison, each panel contains Hurricane Irma's observed track (black line). Calculating a time series of track error (i.e. the distance between the simulated track and observed track) demonstrates that the 09-09 0Z initialization time has the lowest track error for a continuous 48 h period (09-10 0Z to 09-12 0Z) starting 24 h after the initialization time to allow for model spin-up (see figure S2 and table 1). All the ensembles, initialization times, and model scenarios simulate landfall in Florida, but the timing and location vary. Again, the 09-09 0Z initialization time has the smallest mean error in landfall location and timing (table 1). Considering the well-simulated track with the smallest errors in landfall location and timing, the 09-09 0Z initialization time is used for the remainder of this study.

3.2. Storm precipitation

Figure 2 presents the (panels (b)–(e)) model 09-09 0Z initialization time ensemble-mean accumulated precipitation in Florida from Hurricane Irma over the selected 48 h period of interest (09-10 0Z to 09-12 0Z) compared to (panel (a)) observations. For observations and all model scenarios, there are precipitation accumulations above 0.1 m over most of the Florida peninsula. The maximum accumulated precipitation amount (see bottom left of each panel) is about 30% higher in the present warming scenario compared to observations, which is likely related to the regridding onto the coarser CAM5 grid and underestimation of the extreme precipitation rates that occur for hurricanes in modern observations (Medlin *et al* 2007, Omranian *et al* 2018). The underestimation is further evidenced by comparing to the official National Hurricane Center report on Irma (Cangialosi *et al* 2018), which mentions that the maximum accumulated precipitation amount was about 22 inches (0.56 m), although that amount is for the full lifetime of the hurricane and not the 48 h period used in this study. The locations of the maxima in the models are within 180 km to 270 km from the location of the maximum from observations (27.6° N, 80.4° W). Variations in the exact maximum precipitation amounts and locations between the model ensembles are to be expected due to internal variability and slight variations in Irma's track since the models were initialized a few days before the storm's landfall. The mean accumulated precipitation amount (see bottom left of each panel) increases with warming and is more comparable between the observations and present warming scenario than the maximum. Overall, there is an increase in precipitation accumulations over many areas of Florida under all the warming scenarios compared to the present warming scenario.

Figure 3(a) shows the frequency distributions of Hurricane Irma precipitation rates for each of the model simulations and observations. With greater warming, the frequency of precipitation rates between 3 mm d^{-1} and 300 mm d^{-1} decreases, while the more extreme rates greater than 400 mm d^{-1} become more frequent. Additionally, the right tails of the distributions extend further to the right as warming increases, indicating that the most extreme precipitation rates are larger. Figure 3(b) shows the distributions of precipitation amounts attributed to each precipitation rate (i.e. the amount of precipitation that came from different precipitation rates). More details about how the distributions in figure 3 are calculated can be found in Pendergrass and Hartmann (2014). For all the simulations scenarios, the most precipitation comes from rates greater than 200 mm d^{-1}. The 2 K, 3 K, and 4 K warming scenarios have their largest precipitation amounts coming from rates of at least 400 mm d^{-1}. As the warming level for the scenario increases, less precipitation comes from the lower rates between 30 mm d^{-1} and 300 mm d^{-1} and more comes from the higher precipitation rates greater than 400 mm d^{-1}. Based on the distribution peaks, the precipitation rate that contributes the largest precipitation amount also increases with warming.

Observations show a peak precipitation rate frequency of about 100 mm d^{-1}, with the greatest precipitation amounts coming from rates around 300 mm d^{-1}. The simulated amount distributions, particularly for the present warming scenario, show peak amounts of precipitation coming from rates

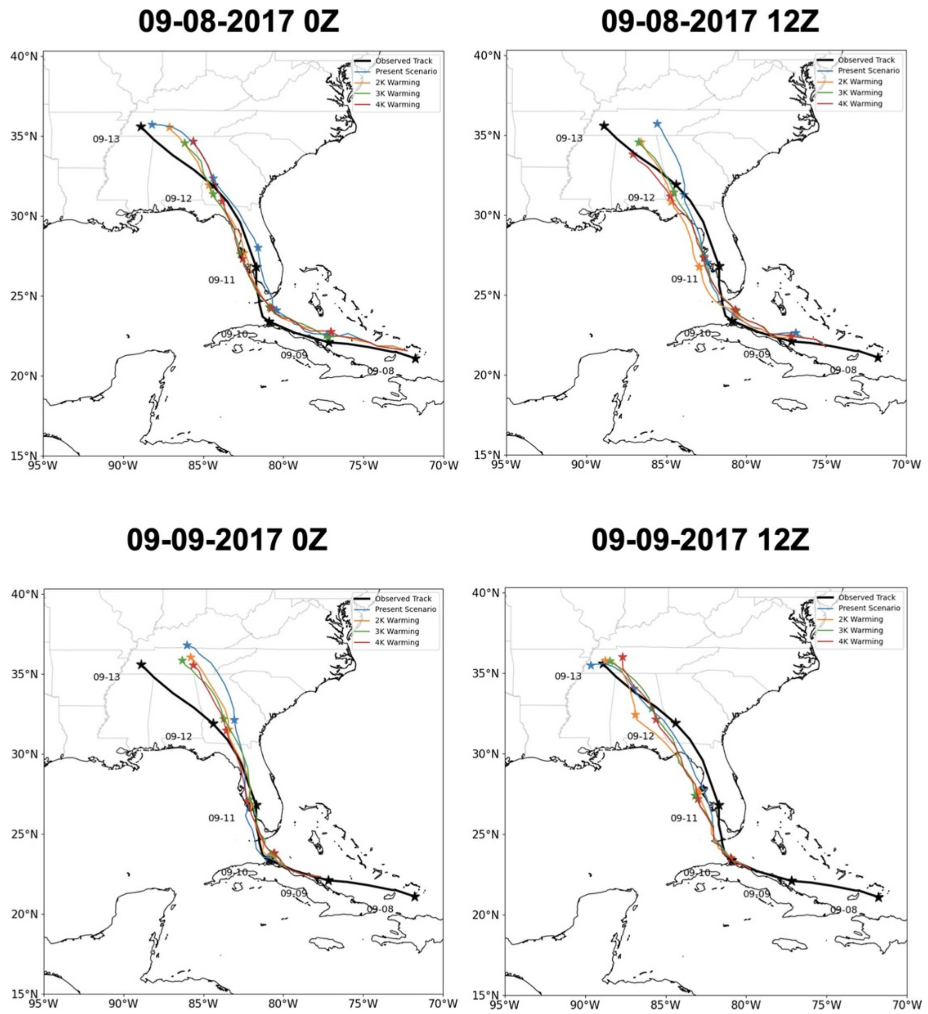

Figure 1. Ensemble-mean simulated tracks of Hurricane Irma for the four scenarios (colored lines), along with the observed track (black lines). The panels show different initialization times, ranging from 09-08 0Z to 09-09 12Z. The star markers pinpoint the storm's location at the 0Z timestamps for each labeled date.

Table 1. Metrics used to compare CAM5 hindcasts at different initialization times to observations. These metrics represent a mean statistic across the four warming scenarios (present, 2 K, 3 K, and 4 K) for each initialization time. The first metric is the mean track error over a 48 h period, starting 24 h after the corresponding initialization time to account for model spin-up. The second and third metrics are the mean landfall location and timing errors.

Initialization time	09-08 0Z	09-08 12Z	09-09 0Z	09-09 12Z
Track	96 km	78 km	51 km	161 km
Landfall location	129 km	365 km	79 km	467 km
Landfall timing	4.5 h	25.0 h	3.0 h	13.5 h

around 300 mm d^{-1}, suggesting some consistency between the observed and simulated storm rainfall. More generally, the observed precipitation distributions shown in figure 3 differ from the simulated distributions for a few reasons. For one, observations are just one realization while the model distributions are 20-member ensemble means. Additionally, the observed precipitation field is measured from land-based data sources with limited availability off the coast. This may cause the distributions to exclude some of Irma's precipitation when it was over the ocean at the beginning of the 48 h period of interest, as well as the outer bands of precipitation while the storm is overland. Modern observational technology tends to underestimate precipitation rates within TCs (Medlin *et al* 2007, Omranian *et al* 2018), which could partially explain the lower maximum precipitation rates in observations compared

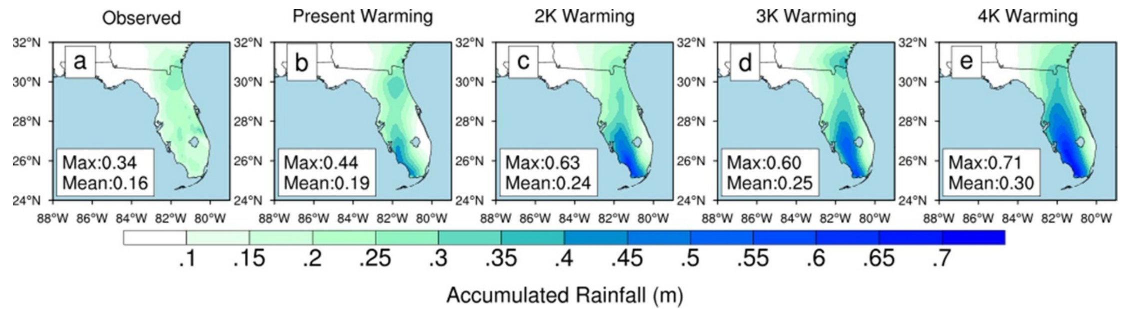

Figure 2. Ensemble-mean accumulated precipitation (meters) in Florida from Hurricane Irma, from 09-10 0Z to 09-12 0Z for (a) observations and (b)–(e) the model warming scenarios using the 09-09 0Z initialization. The ensemble-mean maximum and mean accumulated precipitation amount (m) in Florida are noted in the bottom left of each panel.

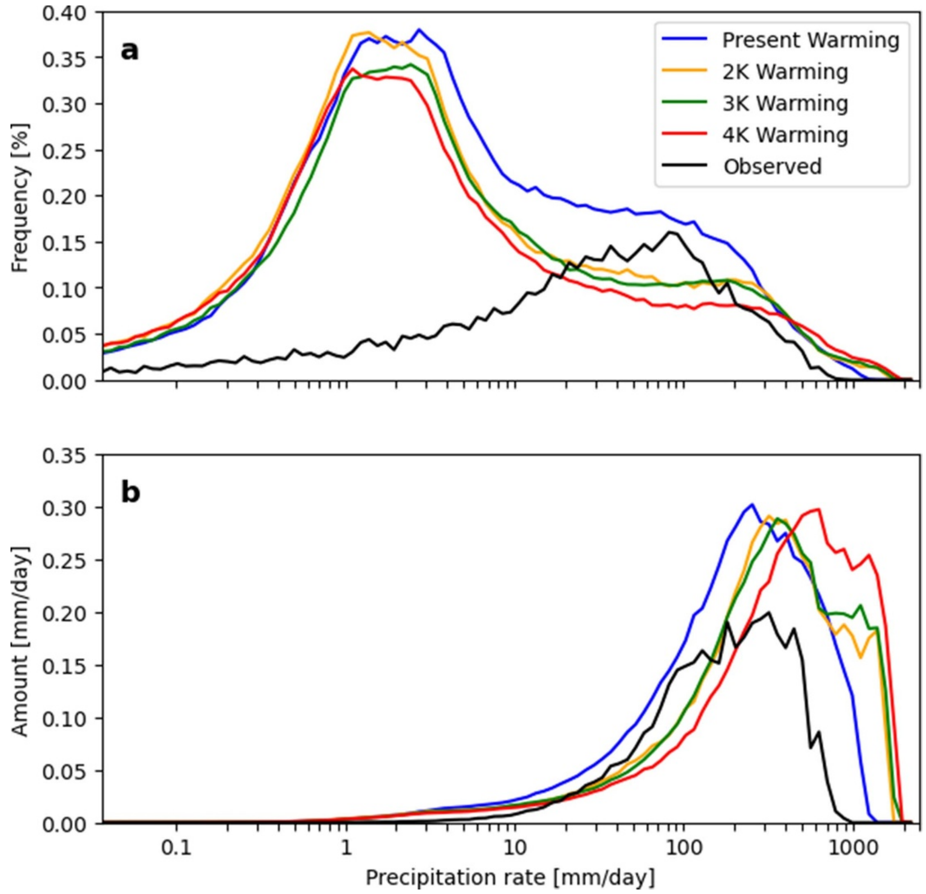

Figure 3. Distributions of Hurricane Irma precipitation rate (a) frequencies (%) and (b) amounts (mm d^{-1}) for observations and each model scenario using the 09-09 0Z initialization. The *x*-axis shows precipitation rates (mm d^{-1}), binned on a logarithmic scale. Panel a represents a distribution of proportions of each precipitation rate's occurrence. Panel b represents a distribution of the precipitation amount that is attributed to each precipitation rate on the *x*-axis.

to the models. Climate models are also known to produce too much drizzle compared to observations (Chen *et al* 2021, Ahn *et al* 2023), which may explain the first peak in the model frequency distributions in figure 3(a) around 1–3 mm d^{-1}. The high bias in the frequency of these low precipitation rates in the models does not impact the precipitation amount distributions (figure 3(b)) since most of the precipitation accumulation comes from rates above 100 mm d^{-1}.

To more directly quantify the potential impact of climate change on extreme precipitation, figure 4 shows the percent increase in Irma's 3-hourly precipitation rates in the model warming scenarios

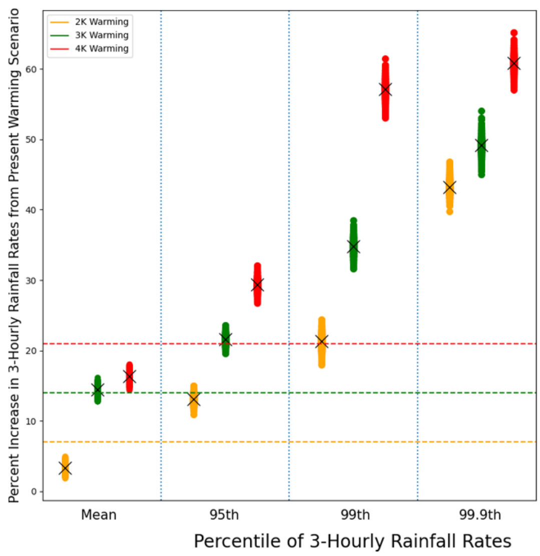

Figure 4. Percent increases in Hurricane Irma's 3-hourly precipitation rates in the 2 K (yellow), 3 K (green), and 4 K (red) warming scenarios compared to the present warming scenario. The *x*-axis shows different precipitation metrics: the mean 3-hourly rate and certain percentiles to quantify extreme precipitation metrics (95th, 99th, 99.9th). Using bootstrapping techniques, 1000 samples were taken from the ensemble member data for each warming scenario, recording the mean and relevant percentiles from each sample. The percent increases between the 1000 sample values from each warming scenario as compared with the present warming scenario were then calculated for each of these rainfall rate metrics. The X markers denote the average percent increase of these samples, and the colored dots behind the X markers show the spread of the percent increases from the individual samples. The colored dashed horizontal lines show the expected precipitation increases based solely on the Clausius-Clapeyron relationship (e.g. 7% increase for the 2 K warming scenario, which is 1 K warmer than the present warming scenario).

compared with the present warming scenario. Bootstrapping techniques were used to calculate the precipitation percent changes; for each warming scenario, 1000 samples were taken from the ensemble member precipitation data and percent increases for each of the rainfall rate metrics were calculated. The figure shows the average percent increase across 1000 samples and the resulting spread from the individual samples. A percent increase is calculated for the mean 3-hourly precipitation rate, as well as select extreme precipitation rate percentiles: the 95th, 99th, and 99.9th. The horizontal dotted lines demonstrate the Clausius–Clapeyron scaling (i.e. 7% for every degree of warming) for each warming scenario and show that for the 95th percentile of precipitation and above, the precipitation increases exceed the Clausius–Clapeyron scaling for all warming scenarios. For all the precipitation rate metrics, the percent increase pattern is consistent and monotonic with the 4 K warming scenario demonstrating the largest percent increase and the 2 K scenario with the smallest percent increase. Additionally, the percent increase becomes more extreme as the percentile becomes more extreme (e.g. the 95th percentile has percent increase metrics in the 13%–29% range or 10–13% K^{-1}, while the 99.9th percentile has percent increase metrics in the 43%–61% range or 20–43% K^{-1}). Figure 4 suggests that the change in Hurricane Irma's extreme precipitation with warming increases with more extreme percentiles of the precipitation rate distribution. Previous studies also see this effect for changes in distributions of global precipitation from a variety of climate model simulations, which they attribute to differences in upward velocities (O'Gorman and Schneider 2009, Pendergrass 2018, Norris *et al* 2019).

In these simulations, Hurricane Irma's maximum intensity during the 48 h period of interest does strengthen with warming (see figure S3) at an estimated 9.8% K^{-1} for maximum low-level wind speed and 1.0% K^{-1} for minimum sea level pressure. TC intensity has been identified as a mechanism that can increase precipitation rates beyond the Clausius-Clapeyron scaling (Liu *et al* 2019, Stansfield and Reed 2021); therefore, this increase in Irma's intensity at least partially explains the large precipitation rate increases demonstrated in figure 4. When focusing on precipitation rates over Florida only, instead of over land and ocean, the percent changes in precipitation rates are larger. The mean 3-hourly precipitation rates over Florida increase by 17–26% K^{-1}, compared to 3–7% K^{-1} for Irma overall (see figure S4 for a version of figure 4 for precipitation over Florida only). This is consistent with a recent study that looked at many North Atlantic hurricane seasons and also found a larger increase in TC precipitation per K over the eastern United States than over the ocean (Hallam *et al* 2023).

4. Conclusion

This paper demonstrates the utility of the storyline framework in assessing potential future changes in precipitation for recent TCs under different warming scenarios. When using this framework, it is important to first evaluate the model's ability to simulate the TC track, landfall, and precipitation accumulations realistically compared to observations. This ability may not be sufficient for all models and all TCs, such as TCs where the steering flow was not simulated well in the models (Brennan and Majumdar 2011, Galarneau and Davis 2013). For Hurricane Irma, CAM5 demonstrated reasonable track, landfall location and timing, and precipitation accumulation in all warming scenarios when the model was initialized on 9 September at 00Z. Given this realistic simulation, the present warming scenario Irma was compared with Irma under three warming scenarios (a 2 K, 3 K, and 4 K warmer climate). Under these warming scenarios, the mean accumulated precipitation from Hurricane

Irma over Florida increased by 24%–55%, the maximum precipitation within the storm increased by 43%–61%, and larger precipitation amounts are the result of more extreme precipitation rates.

For the 3-hourly precipitation rates within the storm, the percent change compared to the present warming scenario increased more for higher precipitation percentiles when comparing the 95th, 99th, and 99.9th percentiles. The 4 K warming scenario consistently showed the greatest percent increases in 3-hourly precipitation rates. It can be helpful to discuss changes in these different precipitation metrics as a percentage change per degree of global average warming. Compared with present warming, the mean and maximum accumulated precipitation over Florida increased by 16–26% K^{-1} and 18–43% K^{-1}, respectively. Likewise, the mean and 99.9th percentile for 3-hourly precipitation rates over Florida increased by 17–26% K^{-1} and 21–43% K^{-1}, respectively. For the 95th, 99th, and 99.9th percentiles, the precipitation increases exceeded the Clausius–Clapeyron scaling for all warming scenarios, likely due to the increase in intensity of Irma. Overall the %/K changes found here are comparable to results for similar precipitation metrics for other individual hurricanes (Risser and Wehner 2017, Reed *et al* 2021) and the 2020 Atlantic hurricane season (Reed *et al* 2022). For simulations of Hurricane Irma under various RCP scenarios using the Weather and Research Forecasting (WRF) model at 4.5 km grid spacing, Patricola and Wehner (2018) found increases of 2.1–8.8% K^{-1} for precipitation averaged within a 5° box around the TC center and 17.5–27.8% K^{-1} within a 1.5° box around the center. Despite using different precipitation metrics, different models, and different methodologies, the %/K increases in precipitation for Hurricane Irma are quite similar between this study and Patricola and Wehner (2018).

The results here are consistent with more traditional approaches to exploring the projected impact of climate change on TC precipitation (e.g. Knutson *et al* 2020, Stansfield *et al* 2020) and with event attribution studies (e.g. Patricola and Wehner 2018, Reed *et al* 2022). One caveat of this analysis is that only the thermodynamic fingerprints of climate change (i.e. changes in temperature, moisture, and SST) are incorporated into the storyline simulations so there may be large-scale atmospheric dynamic changes that are not accounted for. By focusing on recent impactful storms, the storyline approach allows for decision-makers and practitioners to view such an event with a future lens as they are assessing damages and resiliency planning. In this sense, the framework can be used to inform adaptation planning at local, region and national levels. Furthermore, such storyline frameworks could be coupled to economic loss models or infrastructure operations models (e.g. water, energy, transportation sectors) to aid in the assessment of the potential impacts of future similar storms on society. Such storyline approaches provide a pathway for operational weather modeling centers to quantify the past impacts of climate change (Wehner and Reed 2022) and provide relevant climate information of possible futures at operational-scales. Finally, this warming level-based storyline approach may enable easier communication about the impacts of limiting climate change to specific warming amounts in the context of regional, national and international policy.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5061/dryad.m905qfv6b. The International Best Track Archive for Climate Stewardship (IBTrACS; Knapp *et al* 2010) database is available online at https://www.ncei.noaa.gov/products/international-best-track-archive. The NWS Stage IV precipitation analysis data is available for download at https://water.weather.gov/precip/download.php.

Acknowledgments

This work was supported, in part, by the Department of Energy (DOE) Office of Science Award Number DE-SC0016605 'A Framework for Improving Analysis and Modeling of Earth System and Intersectoral Dynamics at Regional Scales,' the National Science Foundation Award #1950052 'REU Site: Data + Computing = Discovery' and the Stony Brook Foundation's Minghua Zhang Early Career Faculty Innovation Fund. A. M. Stansfield acknowledges support from NSF Award Number 2204138. We would like to acknowledge high-performance computing support from Cheyenne (doi:10.5065/D6RX99HX) provided by NCAR's Computational and Information Systems Laboratory, sponsored by the National Science Foundation.

ORCID iDs

Annika S Huprikar https://orcid.org/0000-0002-9697-412X
Alyssa M Stansfield https://orcid.org/0000-0003-0380-607X
Kevin A Reed https://orcid.org/0000-0003-3741-7080

References

Ahn M-S, Ullrich P A, Gleckler P J, Lee J, Ordonez A C and Pendergrass A G 2023 Evaluating precipitation distributions at regional scales: a benchmarking framework and application to CMIP5 and 6 models *Geosci. Model Dev.* **16** 3927–51

Allen M R and Ingram W J 2002 Constraints on future changes in climate and the hydrologic cycle *Nature* **419** 228–32

Brennan M J and Majumdar S J 2011 An examination of model track forecast errors for hurricane Ike(2008) in the Gulf of Mexico *Weather Forecast.* **26** 848–67
Bretherton C S and Park S 2009 A new moist turbulence parameterization in the community atmosphere model *J. Clim.* **22** 3422–48
Brogli R, Heim C, Mensch J, Sørland S L and Schär C 2023 The pseudo-global-warming (PGW) approach: methodology, software package PGW4ERA5 v1.1, validation and sensitivity analyses *Geosci. Model Dev.* **16** 907–26
Cangialosi J P, Latto A S and Berg R 2018 Hurricane Irma tropical cyclone report *National Hurricane Center* AL112017
Chen D, Dai A and Hall A 2021 The convective-to-total precipitation ratio and the "drizzling" bias in climate models *J. Geophys. Res. Atmos.* **126** e2020JD034198
Eyring V *et al* 2021 *Human Influence on the Climate System* (Cambridge University Press) pp 423–552
Galarneau T J and Davis C A 2013 Diagnosing forecast errors in tropical cyclone motion *Mon. Weather Rev.* **141** 405–30
Hallam S, McCarthy G D, Feng X, Josey S A, Harris E, Düsterhus A, Ogungbenro S and Hirschi J J-M 2023 The relationship between sea surface temperature anomalies, wind and translation speed and north Atlantic tropical cyclone rainfall over ocean and land *Environ. Res. Commun.* **5** 93–111
He F and Posselt D J 2015 Impact of parameterized physical processes on simulated tropical cyclone characteristics in the community atmosphere model *J. Clim.* **28** 9857–72
Huang B, Liu C, Banzon V, Freeman E, Graham G, Hankins B, Smith T and Zhang H-M 2021 Improvements of the daily optimum interpolation sea surface temperature (DOISST) version 2.1 *J. Clim.* **34** 2923–39
Hurrell J W *et al* 2013 The community earth system model: a framework for collaborative research *Bull. Am. Meteorol. Soc.* **94** 1339–60
Iacono M J, Delamere J S, Mlawer E J, Shephard M W, Clough S A and Collins W D 2008 Radiative forcing by long-lived greenhouse gases: calculations with the AER radiative transfer models *J. Geophys. Res. Atmos.* **113** D13103
Kay J E *et al* 2015 The community earth system model (CESM) large ensemble project: a community resource for studying climate change in the presence of internal climate variability *Bull. Am. Meteorol. Soc.* **96** 1333–49
Knapp K R, Kruk M C, Levinson D H, Diamond H J and Neumann C J 2010 The international best track archive for climate stewardship (IBTrACS) unifying tropical cyclone data *Bull. Am. Meteorol. Soc.* **91** 363–76
Knutson T *et al* 2020 Tropical cyclones and climate change assessment, part II: projected response to anthropogenic warming *Bull. Am. Meteorol. Soc.* **101** 303–22
Knutson T, Camargo S J, Chan J C L, Emanuel K, Ho C-H and Kossin J 2019 Tropical cyclones and climate change assessment, part I: detection and attribution *Bull. Am. Meteorol. Soc.* **100** 1987–2007
Kossin J P, Knapp K R, Olander T L and Velden C S 2020 Global increase in major tropical cyclone exceedance probability over the past four decades *Proc. Natl Acad. Sci.* **117** 11975–80
Lackmann G M 2015 Hurricane sandy before 1900 and after 2100 *Bull. Am. Meteorol. Soc.* **96** 547–60
Liu M, Vecchi G A, Smith J A and Knutson T R 2019 Causes of large projected increases in hurricane precipitation rates with global warming *npj Clim. Atmos. Sci.* **2** 38
Liu M, Yang L, Smith J A and Vecchi G A 2020 Response of extreme rainfall for landfalling tropical cyclones undergoing extratropical transition to projected climate change: hurricane Irene (2011) *Earth's Future* **8** e2019EF001360
Medlin J M, Kimball S K and Blackwell K G 2007 Radar and rain gauge analysis of the extreme rainfall during hurricane Danny's (1997) landfall *Mon. Weather Rev.* **135** 1869–88
Menne M J, Durre I, Vose R S, Gleason B E and Houston T G 2012 An overview of the global historical climatology network-daily database *J. Atmos. Ocean. Technol.* **29** 897–910
Morrison H and Gettelman A 2008 A new two-moment bulk stratiform cloud microphysics scheme in the community atmosphere model, version 3 (CAM3). Part I: description and numerical tests *J. Clim.* **21** 3642–59
National Centers for Environmental Prediction, National Weather Service, NOAA, U.S. Department of Commerce 2015 NCEP GDAS/FNL 0.25 degree global tropospheric analyses and forecast grids (available at: https://doi.org/10.5065/D65Q4T4Z)
Neale R *et al* 2012 Description of the NCAR Community Atmosphere Model (CAM5.0) *NCAR Tech. Note NCAR/TN-486+STR* (National Center for Atmospheric Research)
NOAA 2023 Costliest u.s. tropical cyclones (available at: www.ncei.noaa.gov/access/billions/dcmi.pdf)
Norris J, Chen G and Neelin J D 2019 Thermodynamic versus dynamic controls on extreme precipitation in a warming climate from the community earth system model large ensemble *J. Clim.* **32** 1025–45
O'Gorman P A and Schneider T 2009 The physical basis for increases in precipitation extremes in simulations of 21st-century climate change *Proc. Natl Acad. Sci.* **106** 14773–7
Omranian E, Sharif H O and Tavakoly A A 2018 How well can global precipitation measurement (GPM) capture hurricanes? Case study: hurricane Harvey *Remote Sens.* **10** 1150
Park S and Bretherton C S 2009 The university of Washington shallow convection and moist turbulence schemes and their impact on climate simulations with the community atmosphere model *J. Clim.* **22** 3449–69
Park S, Bretherton C S and Rasch P J 2014 Integrating cloud processes in the community atmosphere model, version 5 *J. Clim.* **27** 6821–56
Patricola C M and Wehner M F 2018 Anthropogenic influences on major tropical cyclone events *Nature* **563** 339–46
Pendergrass A G 2018 What precipitation is extreme? *Science* **360** 1072–3
Pendergrass A G and Hartmann D L 2014 Two modes of change of the distribution of rain *J. Clim.* **27** 8357–71
Reed K A, Bacmeister J T, Huff J J A, Wu X, Bates S C and Rosenbloom N A 2019 Exploring the impact of dust on north Atlantic hurricanes in a high-resolution climate model *Geophys. Res. Lett.* **46** 1105–12
Reed K A, Stansfield A M, Wehner M F and Zarzycki C M 2020 Forecasted attribution of the human influence on hurricane florence *Sci. Adv.* **6** eaaw9253
Reed K A, Wehner M F, Stansfield A M and Zarzycki C M 2021 Anthropogenic influence on hurricane Dorian's extreme rainfall *Bull. Am. Meteorol. Soc.* **102** S9–S15
Reed K A, Wehner M F and Zarzycki C M 2022 Attribution of 2020 Hurricane season extreme rainfall to human-induced climate change *Nat. Commun.* **13** 1–6
Risser M D and Wehner M F 2017 Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during hurricane Harvey *Geophys. Res. Lett.* **44** 457–64
Seneviratne S *et al* 2021 *Weather and Climate Extreme Events in a Changing Climate* (Cambridge University Press) pp 1513–766
Seo D-J and Breidenbach J P 2002 Real-time correction of spatially nonuniform bias in radar rainfall data using rain gauge measurements *J. Hydrometeorol.* **3** 93–111
Shepherd T G *et al* 2018 Storylines: an alternative approach to representing uncertainty in physical aspects of climate change *Clim. Change* **151** 555–71
Sillmann J, Shepherd T G, van den Hurk B, Hazeleger W, Martius O, Slingo J and Zscheischler J 2021 Event-based storylines to address climate risk *Earth's Future* **9** e2020EF001783
Sobel A H, Camargo S J, Hall T M, Lee C-Y, Tippett M K and Wing A A 2016 Human influence on tropical cyclone intensity *Science* **353** 242–6

Stansfield A M and Reed K A 2021 Tropical cyclone precipitation response to surface warming in aquaplanet simulations with uniform thermal forcing *J. Geophys. Res. Atmos.* **126** e2021JD035197

Stansfield A M and Reed K A 2023 Global tropical cyclone precipitation scaling with sea surface temperature *npj Clim. Atmos. Sci.* **6** 60

Stansfield A M, Reed K A and Zarzycki C M 2020 Changes in precipitation from north Atlantic tropical cyclones under RCP scenarios in the variable-resolution community atmosphere model *Geophys. Res. Lett.* **47** e2019GL086930

Stansfield A M, Reed K A, Zarzycki C M, Ullrich P A and Chavas D R 2020 Assessing tropical cyclones' contribution to precipitation over the eastern united states and sensitivity to the variable-resolution domain extent *J. Hydrometeorol.* **21** 1425–45

Tu S, Chan J C, Xu J, Zhong Q, Zhou W and Zhang Y 2022 Increase in tropical cyclone rain rate with translation speed *Nat. Commun.* **13** 7325

Ullrich P A, Zarzycki C M, McClenny E E, Pinheiro M C, Stansfield A M and Reed K A 2021 Tempestextremes v2. 1: a community framework for feature detection, tracking and analysis in large datasets *Geosci. Model Dev.* **14** 5023–48

Utsumi N and Kim H 2022 Observed influence of anthropogenic climate change on tropical cyclone heavy rainfall *Nat. Clim. Change* **12** 436–40

Van Oldenborgh G J, Van Der Wiel K, Sebastian A, Singh R, Arrighi J, Otto F, Haustein K, Li S, Vecchi G and Cullen H 2017 Attribution of extreme rainfall from hurricane Harvey, august 2017 *Environ. Res. Lett.* **12** 124009

Wang S, Zhao L, Yoon J-H, Klotzbach P and Gillies R R 2018 Quantitative attribution of climate effects on hurricane Harvey's extreme rainfall in Texas *Environ. Res. Lett.* **13** 054014

Wehner M F *et al* 2014 The effect of horizontal resolution on simulation quality in the community atmospheric model, CAM5.1 *J. Adv. Model. Earth Syst.* **6** 980–97

Wehner M F and Reed K A 2022 Operational extreme weather event attribution can quantify climate change loss and damages *PLoS Clim.* **1** e0000013

Wehner M F, Zarzycki C and Patricola C 2019 *Estimating the Human Influence on Tropical Cyclone Intensity as the Climate Changes* (Springer International Publishing) pp 235–60

Xi D, Wang S and Lin N 2023 Analyzing relationships between tropical cyclone intensity and rain rate over the ocean using numerical simulations *J. Clim.* **36** 81–91

Zarzycki C M and Jablonowski C 2014 A multidecadal simulation of Atlantic tropical cyclones using a variable-resolution global atmospheric general circulation model *J. Adv. Model. Earth Syst.* **6** 805–28

Zarzycki C M and Jablonowski C 2015 Experimental tropical cyclone forecasts using a variable-resolution global model *Mon. Weather Rev.* **143** 4012–37

Zhang G and McFarlane N 1995 Sensitivity of climate simulations to the parameterization of cumulus convection in the Canadian Climate Centre general circulation model *Atmos.-Ocean* **33** 407–46