Anthropogenic Influences on Major Tropical Cyclone Events

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There is no consensus on whether climate change has yet impacted tropical cyclone (TC) statistics, owing to large natural variability and a limited period of consistent observations. In addition, projections of future TC activity are uncertain, as they often rely on coarse-resolution climate models that parameterize convection and have difficulty directly representing TCs. Here we investigated how historically destructive TCs could change if similar events occurred in pre-industrial and future climates, using convection-permitting regional climate model simulations. We found that climate change to date enhanced average and extreme rainfall of Hurricanes Katrina, Irma, and Maria, but did not change TC intensity. In addition, future anthropogenic warming robustly increases wind speed and rainfall of intense TCs among 15 events sampled globally. Additional simulations suggest convective parameterization introduces minimal uncertainty into the sign of projected TC intensity and rainfall changes, supporting confidence in projections from models with parameterized convection and TC-permitting resolution.

Tropical cyclones (TCs) are among the deadliest and most destructive natural disasters. Hurricane Katrina holds the record for costliest U.S. natural disaster and caused at least 1,833 deaths and $160 Billion in damages (adjusted to 2017) along the Gulf Coast in August 2005[1]. In close second is Hurricane Harvey, which stalled over the Houston metropolitan area in August 2017, causing record flooding. Harvey was followed in September by Hurricane Irma, which heavily impacted the Virgin Islands and Florida Keys, and Hurricane Maria, which caused lasting devastation in Puerto Rico. In total, the hyperactive 2017 Atlantic hurricane season caused at least $265 Billion in damages and 251 fatalities, likely a staggering underestimate owing to crippled communications and infrastructure in Puerto Rico that led to numerous unconfirmed hurricane-related deaths. In order to advance the resiliency of coastal and island communities, it is critical to understand the drivers of TC variability and change. However, the response of TC activity to climate change, so far and into the future, remains uncertain[2-4].

There is no consensus regarding whether climate change through present has influenced TC activity, as natural variability is large and TC observation methodologies have changed over time. As of yet, there has been no detectable trend in TC frequency. Although a positive trend in Atlantic TC number has been observed since 1900, it is due primarily to increases in short-lived TCs, which were likely undersampled during the pre-satellite era when observations over ocean were taken by ship[5]. Subjective measurements and variable observation procedures pose serious challenges to detecting trends in TCs[6]. This is apparent even when observations are adjusted in attempt to normalize for changing sampling procedures over time, owing to large natural variability[7]. In addition, it remains inconclusive whether there have yet been trends in global TC intensity, with significant increases in some basins[8-11]. The strong influences on TCs of multi-decadal variability including the Atlantic Multidecadal Oscillation[12,13] and interannual variability including the El Niño-Southern Oscillation and Atlantic Meridional Mode[14-17] make disentangling the influences of climate variability and change on trends in TC activity all the more challenging.

Looking into the future, there is no consensus regarding how anthropogenic emissions are expected to change global TC frequency, with the majority of climate models projecting fewer TCs[18-22] but others more TCs[23] (see also references within [2-4]). However, maximum potential intensity (MPI) theory and recent climate modeling studies suggest increases in the future number of intense TCs[24-29,21-22]. In addition, climate model simulations suggest rainfall associated with TCs will increase in future warmer climates, but with large uncertainty in magnitude[18,20,28,30-33]. The Clausius-Clapeyron (C-C) relation dictates that the saturation specific humidity of the atmosphere increases by 7% per 1°C of warming, providing a constraint on changes in moisture available for precipitation. If TC precipitation efficiency does not change, then changes in precipitation follow C-C scaling as the oceans warm[34]. However, recent studies of Hurricane Harvey found 15-38% increases in storm total precipitation attributable to global warming, well above the C-C limit of 7% given anthropogenic warming of 1°C in the Gulf of Mexico[35-37]. Such rainfall over Houston – a 2,000-year event in the late 20th century – is expected to become a more common 100-year event by the end of the 21st century[38].

There is no theory of TC formation to predict how TCs are expected to change in the future, and the problem is complicated by potentially compensating influences of greenhouse gases. Although the factors that influence TCs are well understood, with favorable conditions including warm upper-ocean temperature, an unstable atmosphere with a moist mid-troposphere, and weak vertical wind shear[39], the way in which these factors will change, and which will dominate, is unknown. Sea-surface temperature (SST) warming has been observed and is expected to continue, which would intensify TCs[8]. However, sub-surface ocean structure changes are also important for TC intensity, and may be a dampening effect in the future[40]. Considering atmospheric factors, anthropogenic warming is expected to be greater in the upper compared to lower troposphere in response to increased greenhouse gases, which could weaken TCs. However, the tropical tropopause is expected to cool as its height increases, which would strengthen the MPI of TCs, as observed in the Atlantic[41,42]. Since MPI theory applies to mature TCs, this means the strength of intense TCs may increase. In addition to thermodynamic influences on TCs, changes in atmospheric circulation are also important. Projected increases in vertical wind shear could work to suppress TCs regionally[43]. Finally, it is uncertain as to how the seedling disturbances that serve as TC precursors may change.

Observational consistency issues and compensating physical mechanisms for TC changes are only some of the challenges in understanding anthropogenic influences on TCs. In addition, it can be difficult for climate models to represent the observed climatology of intense TCs, even at the 0.25° horizontal resolution considered fine for global models[21]. Furthermore, the decades-long simulations used to project future TC activity typically parameterize convection. However, the associated uncertainty introduced into TC projections has not been systematically understood.

The purpose of this study is to advance our understanding of anthropogenic influences on TCs by quantifying the impact of climate change so far, and into the future, on the intensity and rainfall of destructive TC events using convection-permitting regional climate model simulations. We first addressed the question, how could TC intensity and rainfall change if hurricanes like Katrina, Irma, and Maria occurred in pre-industrial or future warmer climates? We then investigated the robustness of our results by extending the analysis to 15 TC events sampled globally under three future climates. Finally, we quantified the uncertainty in these estimates associated with convective parameterization for Hurricane Katrina.

Convection-permitting TC simulations

We performed simulations with the Weather Research and Forecasting (WRF) regional climate model, which is developed by the National Center for Atmospheric Research (NCAR). Control simulations for each TC event consist of 10-member ensemble hindcasts representing the historical conditions in which the TC actually occurred, with boundary conditions from reanalysis or observations (Methods). We also performed experiments representing Hurricanes Katrina, Irma, and Maria if they were to occur in a pre-industrial climate, as well as 15 TC events sampled globally at the end of the 21st century under RCP4.5, RCP6.0 and RCP8.5 emissions scenarios (listed in Table 1). Although previous studies considered individual TCs, the modeling frameworks differ among them (Methods). Our use of one model for many events allows us to more directly assess the robustness of the climate change responses among cases. We selected TCs that were particularly impactful (in terms of fatalities and/or economic losses) and represent various TC basins. Many of the TCs were intense in terms of wind speed, but two were weak TCs with moderate-heavy rainfall (typhoon Morakot and Hurricane Bob). Boundary conditions for the pre-industrial and "RCP" (Representative Concentration Pathways) experiments were based on those from the historical, adjusted to remove and add, respectively, the thermodynamic component of climate change (Methods). Simulations of all TCs were performed at a convection-permitting horizontal resolution of 4.5 km. To investigate uncertainty in the response of TCs to anthropogenic forcings due to convective parameterization, we performed additional simulations of Hurricane Katrina at horizontal resolutions of 3 km, 9 km (both without and with parameterization), and 27 km.

Anthropogenic influences on TC intensity

In order to evaluate anthropogenic influences on Hurricanes Katrina, Irma, and Maria, we first verified that the hindcasted TC tracks reasonably represent the observed. Indeed, this is the case for each ensemble member of the historical simulations, as well as the ensemble-means (Fig. 1 and Extended Data Fig. 1). (We note a bias in Irma's landfall that is noticeable owing to Florida's longitudinally-narrow geography, as well as simulated Maria's slight miss of direct landfall over Puerto Rico.) In addition, the simulated TC tracks are robust to anthropogenic perturbations (Fig. 1b-d), indicating that comparisons among experiments are fair (Methods). Next, we estimated the model's ability to simulate the observed intensity of the TCs, recognizing the challenges of such observation-model comparison (Methods). The timeseries of maximum 10-m wind speed (Fig. 2a-c) and minimum sea-level pressure (SLP) (Extended Data Fig. 2a-c) show that the hindcasted intensity is close to observed for Hurricane Katrina, but underestimated for Hurricanes Maria and Irma. In addition, a period of rapid intensification was observed for all three hurricanes, which was most pronounced for Maria. However, the hindcasts failed to represent rapid intensification, a challenge that remains in operational forecasting[44].

Given that the simulated hurricane tracks and intensities compare reasonably well with the observed, albeit with a failure to reproduce rapid intensification, we evaluated the response in hurricane intensity to past and future anthropogenic forcings. For each of the hurricanes, the ensemble-mean wind speed and SLP based intensity timeseries are indistinguishable between the pre-industrial and historical simulations, whereas there is a distinct increase in intensity from the historical to RCP8.5 climates for a substantial portion of each hurricane's lifetime (Fig. 2a-c and Extended Data Fig. 2a-c). To assess the significance (5% level) of the intensity changes, we calculated the peak intensity over each hurricane's lifetime based on maximum wind speed (Fig. 2d-f) and minimum SLP (Extended Data Fig. 2d-f) for each ensemble member of the pre-industrial, historical, and RCP8.5 simulations. We found that climate change at the time of the event weakly and insignificantly influenced the intensity of Hurricanes Katrina, Irma, and Maria (Table 1 and Extended Data Fig. 3), corresponding with similar ensemble spreads between the pre-industrial and historical simulations (Fig. 2d-f). On the other hand, hurricanes like Katrina, Irma, and Maria are expected to significantly intensify with continued warming (Table 1 and Extended Data Fig. 3), corresponding to a shift towards greater intensities for the RCP8.5 simulations compared to the historical (Fig. 2d-f).

We extended the investigation to 15 TC events sampled globally under 3 future climate scenarios, to address the robustness of the results. We performed the same analysis for all 15 TCs that was presented above for Katrina, Irma, and Maria including an evaluation of the historical hindcast's ability to reproduce the observed TC track. Of the 45 experiments, 4 were discarded for TC tracks that deviated substantially from the historical case (Methods). Of the 15 TCs, 13 of which were intense, 11 show significant (5% level) intensity increases, regardless of emissions scenario, with peak wind speed increases of 6–29 knots and minimum SLP reduced by 5–25 hPa (Table 1 and Extended Data Fig. 3). Changes are insignificant for Hurricanes Andrew and Iniki, and Hurricane Bob significantly weakens. Therefore, the experiments provide substantial support for strengthening of intense TC events globally for the three future climate scenarios considered.

Finally, we quantified the uncertainty in the response of TCs to anthropogenic forcings owing to convective parameterization using simulations of Hurricane Katrina at resolutions of 3 km, 9 km, and 27 km. Regardless of resolution, these simulations produced insignificant changes in Katrina's intensity from the pre-industrial to historical climates, and a significant increase in intensity from the historical to RCP8.5 climates (Fig. 2d), indicating that the qualitative simulated TC response to anthropogenic forcing may be insensitive to use of convective parameterization and model resolution between 3 km and 27 km in this model, with additional work needed to make a generalized conclusion. Furthermore, the range of the future response is relatively small between resolutions, covering a 11 – 15 knot increase in maximum wind speed and a 11 – 14 hPa decrease in minimum SLP. However, model resolution substantially impacts absolute intensity, as expected, with an ensemble mean Category 5, Category 4, and Category 3 hurricane produced by the historical simulations at 3 km, 9 km, and 27 km resolutions, respectively.

Anthropogenic influences on TC rainfall

Although TC winds can cause substantial damages, heavy rainfall can pose an equal, if not greater, hazard. We analyzed anthropogenic changes in rainfall within a reference frame centered on the TC, called a "composite" (Fig. 3), since even small changes in TC track and translation speed confound a geographically-fixed analysis. The composites include the simulated TC lifetime, excluding a generous 12-hour spin-up, and cover ocean and land. Two levels of statistical significance (5% and 10%) are presented, as changes in rainfall tend to be noisy compared with wind speed and SLP. We found that climate change at the time of Katrina significantly (at least 10% level) enhanced rainfall rates by 4-9% over a ~5°x5° box centered on the TC, a result qualitatively insensitive to model resolution and use of convective parameterization (Table 2). Likewise, climate change at the time of Hurricanes Irma and Maria significantly (at least 10% level) increased rainfall by 6% and 9%, respectively, but over a ~1.5°x1.5° box centered on the TC (Table 2), due to a concentration of the rainfall enhancements near the TC center (Fig. 3). Therefore, we find evidence that climate change to date has begun to enhance rainfall for these three TCs, with investigation of additional cases needed before making a general conclusion.

In addition, we found robust increases in TC rainfall with continued climate change along RCP4.5, 6.0, and 8.5 scenarios, which are significant for at least one RCP scenario for all 15 TCs except two (10% level) or three (5% level) (Table 2). The largest increases in rainfall tend to occur over the regions of heaviest historical rainfall (Fig. 3 and Extended Data Fig. 4). For some TCs, including Irma and Maria (Fig. 3), there is a coherent spatial pattern in the future rainfall response characterized by drying in the outer TC radii, resulting in rainfall responses that are stronger over a ~1.5°x1.5° compared with a ~5°x5° box (Table 2). Such outer-TC drying is not apparent or is weak for most TCs considered, including Katrina, Floyd, Gafilo, and Yasi (Fig 3 and Extended Data Fig. 4). The future rainfall changes reach 25-30% for some TCs under an RCP8.5 scenario (Table 2), exceeding what would be expected by C-C scaling alone given regional SST warming of about 2.5°C in these cases.

We next evaluated changes in extreme rainfall, which can be important for localized flooding, by considering probability density functions of rainfall rates sampled 3-hourly and including each model grid point within ~5°x5° centered on the TC for the lifetime of the simulated storm (Fig. 4). The individual ensemble members of the 3 km Hurricane Katrina simulations exhibit probabilities of extremely intense rainfall rates that consistently increase from the pre-industrial, to historical, to RCP8.5 experiments (Fig. 4a). This behavior is also apparent in the ensemble means for simulations at 3 km and 27 km resolution, however, the coarser resolution simulation consistently produces weaker extremes (Fig. 4b). The increasing probability of extremely intense rainfall rates with anthropogenic warming is robust among Hurricanes Katrina, Irma, and Maria (Fig. 4).

Discussion

There is no consensus on whether climate change has yet impacted TC statistics, and how continued warming may influence many aspects of future TC activity. Here we advanced our understanding of anthropogenic influences on TCs by quantifying how the intensity and rainfall of historically impactful TC events could change if similar events occurred in cooler and warmer climates, using 10-member ensembles of convection-permitting hindcast simulations with boundary conditions adjusted to reflect the different climate states. We found that climate change so far weakly and insignificantly influenced the wind speed and SLP based intensities for Hurricanes Katrina, Irma, and Maria, suggesting the possibility that climate variability – rather than anthropogenic warming – may have driven the active 2005 and 2017 Atlantic Hurricane seasons, which were indeed characterized by especially warm tropical Atlantic SSTs. However, climate change at the time of these hurricanes significantly enhanced rainfall by 4-9% and increased the probability of extreme rainfall rates, suggesting that climate change to date has already begun to increase TC rainfall. Investigation of additional TCs is needed before making a general conclusion.

We then considered how 15 TC events sampled globally could change if similar events were to occur at the end of the 21st century in RCP4.5, 6.0. and 8.5 scenarios. We found a substantial and significant future intensification in the majority (11 of 13) of intense TC events based on wind speed and SLP, consistent with MPI theory. Analysis of SST and tropical tropopause temperature changes is planned to understand the physical mechanisms behind these responses. In addition, we found robust increases in future TC rainfall, with some events exceeding what would be expected by C-C alone and some events demonstrating a spatial pattern with concentrated rainfall increases near the TC center and drying in the outer TC radii. These future changes in TC intensity and rainfall can exacerbate societal impacts associated with ocean wind-waves[45], storm surge, flooding, and forests and ecosystems[46]. Simulations with and without convective parameterization suggest that convective parameterization introduces minimal uncertainty into the sign of projected TC intensity and rainfall changes, supporting confidence in projections of TC activity from models with parameterized convection and TC-permitting resolution (< 0.25°).

Detection and attribution of anthropogenic changes in TC events is a rapidly emerging science and methodology[47], especially as supercomputing advancements enable ensembles of convection-permitting simulations. Our use of a dynamical climate model allows us to perform controlled experiments that focus on specific events and include various complexities of relevant physical processes. One important physical process for TCs that is missing from our model design is atmosphere-ocean coupling. In reality, TC winds typically induce a "cold wake" of upper-ocean temperatures which can provide a negative feedback on TC intensity, depending on TC intensity and translation speed and ocean heat content and salinity structure[40,48,49]. Therefore, lack of coupling in the model can lead to TCs that are more intense and frequent compared to slab-ocean and fully-coupled atmosphere-ocean simulations[50,51]. The atmosphere-only simulations presented in this study may overestimate TC intensity, and additional research would be beneficial to quantify this uncertainty. In addition, since we used a single climate model, we have not examined model structural uncertainty, as results from other convection-permitting models could vary from those presented here.

Tables

Table 1 | Tropical cyclone peak 10-m wind speed. The ensemble mean difference in TC peak 10-m wind speed (kt) between the historical minus pre-industrial simulation and the RCP4.5, RCP6.0, and RCP8.5 simulations minus the historical simulation, with TC peak 10-m wind speed (kt) from observations and the ensemble mean historical simulation. Cases of substantial differences between simulated and observed TC track denoted by X and simulations that were not performed are blank. Changes denoted by * are significant at the 10% level and by ** are significant at the 5% level. Simulations that used convective parameterization are denoted by (P).

Basin	**TC**	**resolution**	**hist.-preind.**	**RCP4.5-hist.**	**RCP6.0-hist.**	**RCP8.5-hist.**	**historical**	**observ**
Atlantic	Katrina	27 km (P)	-1.0			11.0 **	101	150
		9 km (P)	2.0			15.2 **	123	150
		9 km	-0.5			13.5 **	127	150
		3 km	-2.4			13.7 **	149	150
		4.5 km		6.0 **	8.5 **	13.8 **	142	150
	Irma		-1.9	7.3 **	10.4 **	12.4 **	143	160
	Maria		-1.5	7.5 **	10.9 **	12.9 **	132	150
	Andrew			-3.3	-2.4	-1.7	118	150
	Bob			-6.1 **	-2.4 *	2.1	78	100
	Floyd			11.2 **	13.5 **	X	118	135
	Gilbert			18.0 **	18.6 **	28.8 **	109	160
	Ike			12.8 **	14.1 **	18.0 **	127	125
	Matthew			10.6 **	11.1 **	15.8 **	123	145
Eastern Pacific	Iniki			-0.4	-3.9	4.6 *	114	125
North West Pacific	Haiyan			6.7 **	3.8	12.3 **	124	170
	Morakot			0.5	X	X	71	80
	Songda			10.4 **	5.5 **	X	109	125
South Pacific	Yasi			11.2 **	13.7 **	18.9 **	95	135
South West Indian	Gafilo			8.6 **	8.8 **	16.8 **	110	140

Table 2 | Changes in tropical cyclone rainfall. The ensemble-mean change in rainfall (%) between the historical and pre-industrial, and the RCP4.5, RCP6.0, and RCP8.5 and historical simulations averaged over ~5°x5° and ~1.5°x1.5° (denoted by ^) boxes centered on the TC. Cases of substantial differences between simulated and observed TC track denoted by X and simulations that were not performed are blank. Changes denoted by * are significant at the 10% level and by ** are significant at the 5% level. Simulations that used convective parameterization are denoted by (P).

Basin	**TC**	**resolution**	**hist.-preind. / preind.**	**RCP4.5-hist. / hist.**	**RCP6.0-hist. / hist.**	**RCP8.5-hist. / hist.**
Atlantic	Katrina	27 km (P)	4.7 **			13.0 **
		9 km (P)	4.5 *			12.7 **
		9 km	5.0 *			13.5 **
		3 km	8.7 **			14.4 **
		4.5 km		7.1 **	14.6 **	16.5 **
	Irma		4.2	4.5	8.8 **	2.1
	Irma ^		6.3 *	17.5 **	26.1 **	27.8 **
	Maria		4.4	7.0 *	7.2 *	7.7 *
	Maria ^		8.9 **	21.8 **	23.4 **	36.9 **
	Andrew			0.3	5.1	4.8
	Bob			6.5 **	11.9 **	13.5 **
	Floyd			12.3 **	13.5 **	X
	Gilbert			13.5 **	16.5 **	25.3 **
	Ike			15.0 **	20.2 **	26.5 **
	Matthew			2.0	1.1	4.0
Eastern Pacific	Iniki			5.8 *	4.9	15.2 **
North West Pacific	Haiyan			9.5 **	12.8 **	31.3 **
	Morakot			6.8 *	X	X
	Songda			19.5 **	10.6 **	X
South Pacific	Yasi			15.6 **	23.1 **	35.2 **
South West Indian	Gafilo			19.7 **	16.8 **	41.6 **

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Author contributions

CMP and MFW conceived the project and developed the methodology. CMP performed the simulations, with climate perturbations from MFW, and analyzed the data. CMP wrote the manuscript with contributions from MFW.

Competing Interests

The authors declare no competing financial interests.

Materials & Correspondence

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Data availability

Simulation data are available at the National Energy Research Scientific Computing Center (NERSC) at http://portal.nersc.gov/cascade/TC/

Code availability

Code for the WRF model, version 3.8.1, is available at http://www2.mmm.ucar.edu/wrf/users/downloads.html. Analytical scripts are available from the corresponding author on request.

Figure Legends

Fig. 1 | Tropical cyclone tracks. Hurricane Katrina's observed track (black) with simulated TC tracks from (a) 10 ensemble members (grey dash) and the ensemble mean (grey solid) of the historical simulation and (b) the ensemble mean of historical (grey), pre-industrial (blue), and RCP8.5 (red) simulations at 3 km resolution. As in (b), for Hurricanes (c) Irma and (d) Maria at 4.5 km resolution.

Fig. 2 | Time series and boxplots of tropical cyclone maximum 10-m wind speed. The time series of maximum 10-m wind speed (kt) from observations (black) and the ensemble mean of the pre-industrial (blue), historical (grey), and RCP8.5 (red) simulations of Hurricanes (a) Katrina at 3 km resolution, and (b) Irma, and (c) Maria at 4.5 km resolution. Boxplots of peak 10-m wind speed (kt) from the 10-member ensemble of pre-industrial (blue), historical (black), and RCP8.5 (red) simulations of (d) Hurricane Katrina at 3 km, 9 km, and 27 km resolution, and Hurricanes (e) Irma and (f) Maria at 4.5 km resolution. Center line denotes the median, box limits denote lower and upper quartiles, and whiskers denote the minimum and maximum. The observed peak intensity is marked with a horizontal black line. Simulations that used convective parameterization denoted by *

Fig. 3 | Tropical cyclone rainfall composites. Rainfall rate (mm / hr; shaded) relative to TC center and throughout the simulated TC lifetime from the ensemble mean of the (a) historical, (b) historical minus pre-industrial, and (c) RCP8.5 minus historical simulations of Hurricane Katrina at 27 km resolution. As in (a-c) but for simulations of Hurricanes (d-f) Katrina at 3 km resolution and (g-i) Irma and (j-l) Maria at 4.5 km resolution. Contours denote the rainfall rate (mm / hr) from the corresponding historical simulation. The units on the x-axis and y-axis are number of model grid points from TC center.

Fig. 4 | Probability density functions of tropical cyclone rainfall rates. Probability density functions of rainfall rates (mm / hr) from (a) each of 10 ensemble members of the pre-industrial (blue), historical (black), and RCP8.5 (red) simulations of Hurricane Katrina at 3 km resolution, and from the ensemble means of simulations of (b) Hurricane Katrina at 3 km (solid) and 27 km (dot) resolution and Hurricanes (c) Irma and (d) Maria at 4.5 km resolution.

Methods

We performed hindcast simulations with the Weather Research and Forecasting (WRF) regional climate model[52] version 3.8.1, which is developed by the National Center for Atmospheric Research (NCAR). The regional model is well-suited for this study for several reasons. First, the use of lateral boundary conditions (LBCs) allows us to prescribe a tighter constraint on the large-scale circulation (i.e., steering flow) of the TC hindcast than if a global model were used. This is beneficial because it is necessary for the hindcasts to reproduce observed TC tracks well, as TC characteristics such as intensity and rainfall are sensitive to underlying SST and surrounding environmental conditions. In addition, such well-behaved tracks among different climate scenarios enables a "fair" comparison of the TC responses. That is, a simulated TC that deviates substantially from the observed track does not truly represent that TC. (We typically used a criterion of ~3° of latitude or longitude, with some subjective judgment.) Second, whereas global climate models typically use the hydrostatic approximation to simplify the vertical momentum equation, WRF is non-hydrostatic and therefore more appropriate for simulating small-scale convective processes. Finally, the regional domain allows us to perform ensembles of simulations at convection-permitting resolution, which would be computationally less feasible with a global model.

The control simulations consist of hindcasts representing 15 TC events (Fig. 1 and Extended Data Table 1) in the historical conditions in which they actually occurred. We selected TCs that were particularly impactful and represent various TC basins. The North Indian Ocean was omitted owing to model instability likely associated with the Tibetan Plateau, and Hurricane Harvey was omitted owing to poor hindcast skill. Initial conditions (ICs) and LBCs for the historical hindcast simulations were taken from the 6-hourly National Centers for Environmental

Prediction (NCEP) Climate Forecast System (CFS) Reanalysis[53] for all TCs occurring before March 2011, and CFSv2[54] for TCs occurring in March 2011 or later. No adjustments or data assimilation were performed on the ICs or LBCs. Model initialization time (Extended Data Table 1) was chosen to represent the TC for as much of its lifetime as possible, while still being able to realistically simulate the observed track, since an earlier initialization time generally reduced the simulated TC track skill. The TC intensity within the model adjusts from its IC within hours. We did not test whether the simulated anthropogenic influence on TCs is sensitive to initialization time. SST was prescribed from the daily 0.25° National Oceanic and Atmospheric Administration Optimum Interpolation (NOAA-OI) dataset[55] for all TCs, except Hurricanes Irma and Maria, which used the CFSv2. Greenhouse gas concentrations, including CO_2, CH_4, N_2O, CFC-11, CFC-12, and CCl_4, were prescribed according to [56,57]. A 10-member ensemble of each simulation was generated using the Stochastic Kinetic Energy Backscatter Scheme (SKEBS)[58], which represents uncertainty from interactions with unresolved scales by introducing temporally and spatially correlated perturbations to the rotational wind components and potential temperature. The SST, IC, and LBCs are identical for each ensemble member within a simulation set.

We also performed experiments representing Hurricanes Katrina, Irma, and Maria if they were to occur in a pre-industrial climate and all 15 TC events at the end of the 21st century under RCP4.5, RCP6.0, RCP8.5 emissions scenarios, as permitted by supercomputing resources. SSTs, ICs, and LBCs for the pre-industrial and "RCP" experiments were based on those from the historical simulations, with adjustments to remove and add, respectively, the thermodynamic component of anthropogenic climate change, using the "pseudo-global warming" approach detailed in [59,47]. In pseudo-global warming experiments, the model's boundary conditions use the same input data as in the control simulations for the historical period, but with a climate change signal added. This methodology has been used to study anthropogenic influences on individual TC events at similar horizontal resolutions used in this study[60-65]. The novelty here is in investigating over a dozen TC cases under multiple emissions scenarios at such a resolution. The variables adjusted in the LBCs include temperature, relative humidity, and geopotential height. We did not adjust horizontal winds in the LBCs to minimize possible perturbations to the simulated hurricane track, although tests on a subset of simulations showed that the response in TC intensity to anthropogenic forcing is insensitive to whether circulation changes were applied to the LBCs. The experimental design, therefore, prescribes no changes in large-scale vertical wind shear. We note that any potential changes in vertical wind shear[43] may be expected to change the summary statistics of TC activity (e.g., average annual number of TCs). However, even given average changes in wind shear, it is conceivable that individual TC events may occur under similar shear conditions as during the present climate, especially since some climate models project relatively weak shear changes in the Atlantic and Pacific basins[66]. Therefore, by prescribing zero change in horizontal winds in the climate change simulations, the large-scale vertical shear state is included in the conditionally of the "worst-case-scenario" TC event occurrence. This allows us to evaluate changes in TC magnitudes given similar shear conditions, which may become more or less likely in changing climates.

The variables adjusted in the ICs include surface temperature, 2-m air temperature, 2-m specific humidity, sea-level pressure, and surface pressure. Greenhouse gas concentrations were modified in WRF according to [56,57,67]. The experimental design is similar to the hindcast methodology used to understand anthropogenic contributions to the extreme flood event that impacted the Boulder, Colorado region in September 2013[68].

Anthropogenic climate change from the pre-industrial to historical period was estimated using Community Atmosphere Model (CAM) simulations from the Climate of the 20th Century Plus Detection and Attribution (C20C+ D&A) Project[69,70]. The "factual" C20C+ simulation consists of a 50-member ensemble of 1° resolution CAM5.1 integrations forced with historical radiative and land-surface boundary conditions and SST, and the "counterfactual" simulation uses radiative forcing from the year 1855, with SST and sea-ice modified using perturbations from coupled atmosphere-ocean simulations of the Coupled Model Intercomparison Project Phase 5 (CMIP5)[71]. The climate change perturbation for the pre-industrial Hurricane Katrina experiment was calculated as the difference between the factual minus counterfactual C20C+ simulations for August 2005; this perturbation was then subtracted from the historical boundary conditions. For Hurricanes Irma and Maria, the perturbation was estimated as the difference between the September 1996-2016 climatology of the factual minus counterfactual C20C+ simulations, as the C20C+ simulations did not extend to 2017 at the time of this study.

Anthropogenic climate change for the end of the 21st century was based on simulations from the Community Climate System Model (CCSM4) of the CMIP5. The climate change perturbation for the RCP8.5 Hurricane Katrina experiment was calculated as the 2081-2100 August climatology from the CCSM4 RCP8.5 simulation minus the 1980-2000 August climatology from the CCSM4 historical simulation. This perturbation was then added to the historical boundary conditions. The perturbations for all other TCs were calculated in the same way, but for the month in which the TC occurred (e.g., September for Hurricanes Irma and Maria).

By using one global model to provide climate change perturbations, the results here apply for the climate sensitivity characteristic of that model. The uncertainty owing to the range of climate sensitivities among different models was not accounted for, in favor of using supercomputing resources towards 15 TC events, convection-permitting resolution, 10-member ensembles, and multiple RCP scenarios. We note that the climate sensitivity of the CCSM4 model is among the lower of the coupled atmosphere-ocean global climate models of CMIP5[72,73], suggesting that the estimates of future change provided by this study may be conservative. The SST forcings for the CAM simulations from the C20C+ D&A Project were based on the multi-model mean of the CMIP5, suggesting that the estimates of climate change influences from pre-industrial to present are near the center of the range of models.

Simulations of all TC events were performed at a convection-permitting horizontal resolution of 4.5 km, with 44 levels in the vertical and a model top at 20 hPa. In order to investigate uncertainty in the response of TCs to anthropogenic forcings due to convective parameterization, we performed additional simulations of Hurricane Katrina at horizontal resolutions of 3 km without parameterization, 9 km both without and with parameterization (Kain–Fritsch), and 27 km with parameterization, with 35 levels in the vertical and a model top at 50 hPa. The results are insensitive to vertical resolution and model top choices.

Simulated TC coordinates are defined using the location of minimum SLP. Simulated 3-hourly instantaneous maximum 10-m TC wind speeds are compared with the observed 6-hourly maximum 1-minute average sustained 10-m wind speed from the Revised Hurricane Database (HURDAT2[74,76]) and the Joint Typhoon Warning Center (JTWC) dataset as archived in the International Best Track Archive for Climate Stewardship (IBTrACS[76]) v03r10 database. Such differences in maximum wind speed definitions generate uncertainty in comparisons between observations and model simulations, and it is unclear whether there is a tendency for one definition to be systematically biased in a particular direction. The historical simulations appear to produce TCs with slightly weaker intensities than observed (Fig. 1), which may be related to these differences in intensity definitions between the model and observations, or to model limitations in horizontal resolution and/or physical approximations. Despite this uncertainty, the convection-permitting resolution simulations perform substantially better in reproducing the approximate TC intensities than simulations with convective parameterization (Fig. 3d). In addition, we acknowledge that while climate models can have imperfections, the robust climate change response for Hurricane Katrina at horizontal resolutions between 3 – 27 km provides support that 4.5 km resolution is sufficient to capture the influence of climate change on TCs in the full set of experiments.

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Extended Data Table and Figure Legends

Extended Data Table 1 | List of TC events. List of TC events considered in this study, with simulation period. All times are 00z.

Extended Data Fig. 1 | Tropical cyclone tracks. The observed hurricane track (black) with simulated TC tracks from 10 ensemble members (grey dash) and the ensemble mean (grey solid) of the historical simulation for Hurricanes (a) Irma and (b) Maria at 4.5 km resolution.

Extended Data Fig. 2 | Time series and boxplots of tropical cyclone minimum sea-level pressure. The time series of minimum sea-level pressure (hPa) from observations (black) and the ensemble mean of the pre-industrial (blue), historical (grey), and RCP8.5 (red) simulations of Hurricanes (a) Katrina at 3 km resolution, and (b) Irma, and (c) Maria at 4.5 km resolution. Boxplots of minimum sea-level pressure (hPa) from the 10-member ensemble of pre-industrial (blue), historical (black), and RCP8.5 (red) simulations of (d) Hurricane Katrina at 3 km, 9 km, and 27 km resolution, and Hurricanes (e) Irma and (f) Maria at 4.5 km resolution. Center line denotes the median, box limits denote lower and upper quartiles, and whiskers denote the minimum and maximum. The observed minimum sea-level pressure is marked with a horizontal black line. Simulations that used convective parameterization denoted by *

Extended Data Fig. 3 | Tropical cyclone minimum sea-level pressure. Heatmaps of the ensemble mean difference in minimum SLP (hPa) between the historical minus pre-industrial simulation and the RCP4.5, RCP6.0, and RCP8.5 simulations minus the historical simulation (blue/red), with minimum SLP (hPa) from observations and the ensemble mean historical simulation (yellow/magenta). Light grey denotes substantial differences between simulated and observed TC track and dark grey denotes simulations that were not performed. Changes denoted by * are significant at the 10% level and by ** are significant at the 5% level. Simulations that used convective parameterization are denoted by (P).

Extended Data Fig. 4 | Tropical cyclone rainfall composites. Rainfall rate (mm / hr; shaded) relative to TC center and throughout the simulated TC lifetime from the ensemble mean of the (a) RCP6.0 minus historical simulation of Hurricane Floyd and the RCP8.5 minus historical simulation of (b) Cyclone Gafilo, (c) Typhoon Haiyan, and (d) Cyclone Yasi at 4.5 km resolution. Contours denote the rainfall rate (mm / hr) from the corresponding historical simulation. The units on the x-axis and y-axis are number of model grid points from TC center.