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Dynamical downscaling projections of late twenty-first-century U.S. landfalling hurricane activity

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Abstract

In this paper, U.S. landfalling tropical cyclone (TC) activity is projected for the late twenty-first century using a two-step dynamical downscaling framework. A regional atmospheric model, is run for 27 seasons, to generate tropical storm cases. Each storm case is -resimulated (up to 15 days) using the higher-resolution Geophysical Fluid Dynamics Laboratory hurricane model. Thirteen CMIP3 or CMIP5 climate change scenarios are explored. Robustness of projections is assessed using statistical significance tests and comparing changes across models. The proportion of TCs making U.S. landfall increases for the warming scenarios, due, in part, to an increases in the percentage of TC genesis near the U.S. coast and a change in climatological steering flows favoring more U.S. landfall events. The increases in U.S. landfall proportion leads to an increase in U.S. landfalling category 4–5 hurricane frequency, averaging about + 400% across the models; 10 of 13 models/ensembles project an increase (which is statistically significant in three of 13 models). We have only tentative confidence in this latter increase, which occurs despite a robust decrease in Atlantic basin category 1–5 hurricane frequency, no robust change in Atlantic basin category 4–5 and U.S. landfalling category 1–5 hurricane frequency, and no robust change in U.S. landfalling hurricane intensities. Rainfall rates, averaged within a 100-km radius of the storms, are projected to increase by about 18% for U.S. landfalling TCs. Important caveats to the study include low correlation (skill) for interannual variability of modeled vs. observed U.S. TC landfall frequency and model bias of excessive TC genesis near and east of the U.S. east coast in present-day simulations.

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Keywords Climate change · Hurricane activity · Tropical cyclone

1 Introduction

U.S. landfalling tropical cyclones (TCs, which include hurricanes and tropical storms) can cause major damage to coastal and inland infrastructure, and it is of great interest to better understand how landfalling TC activity may change under future anthropogenic climate change, with a particular focus on landfalling hurricanes. Relatively long records (since at least about 1900) are available for tropical storm, hurricane, and major U.S. hurricane landfalls (e.g., Vecchi and Knutson 2008, 2011; Klotzbach et al. 2020; Vecchi et al. 2021); these time series do not show any significant increases since 1900. This lack of a significant change contrasts with the case for global mean temperature, where a clear anthropogenic warming signal has been identified (IPCC AR5). This indicates that U.S. landfalling TC frequency in the above regions is not a strongly detectable anthropogenically forced metric over the past century.

A previous dynamical downscaling study of Atlantic TCs (Knutson et al. 2013, hereafter K13) explored the impact of global warming on several aspects of TCs, but focused mainly on the lifetime maximum intensity stage of TCs, by performing 5-day high-resolution downscaling simulations of storms near their times of maximum intensity. Thus, K13 did not focus on the U.S. landfalling stages, which often were outside of the 5-day window simulated with their downscaling model. In the present study, we revisit K13, but focusing on U.S. landfalling storm activity. To accomplish this, we integrate the higher-resolution hurricane model forward for 15 days for each storm case study. Through this study, we aim to provide more societally relevant information about the potential damage impacts of the storms (in terms of intensity, frequency, and rainfall at landfall) under various climate change scenarios.

Previous studies on possible future changes in U.S. landfalling TCs have reported model projections including changes in vertical shear and potential intensity near the U.S. coastline (Ting et al. 2019); reduced probability of TC landfall over the southeastern U.S. and increased probability over the northeastern U.S. (Murakami and Wang 2010); decreased TC occurrence over the southeastern U.S. (Liu et al. 2018); increased TC occurrence over most of the eastern U.S. for a downscaled CMIP5 model ensemble, but slight decreases for CMIP3 (Wright et al. 2015); reduced TC occurrence over the southern Gulf of Mexico and Caribbean (Colbert et al. 2013); increased average post-landfall TC rain rates over the eastern U.S. (Wright et al. 2015; Liu et al. 2018; Stansfield et al. 2020); and increased likelihood of faster-moving landfalling TCs in the Texas region (Hassanzadeh et al. 2020). The last study result is qualitatively in contrast to an observed finding for historical TC behavior: a significant reduction in propagation speed over the U.S. land regions since 1900 (Kossin 2019). This reduced propagation speed in observations over the twentieth century was not reproduced in a historical forcing model simulation (Zhang et al. 2020) which covered most of the twentieth century. However, Gori et al. (2022) project that over the eastern U.S., decreased TC propagation speeds and increased TC intensity will intensify TC rainfall events and, along with sea level rise, exacerbate U.S. coastal flood risk by 2100. Levin and Murakami (2019) found that historical increases in anthropogenic climate forcing led (qualitatively) to increased frequency of U.S. major hurricane landfall in their model, although a significant increase in U.S. major hurricane frequency is not seen in observations since 1900 (Klotzbach et al. 2020) nor since the late nineteenth century (Vecchi et al. 2021).

Our study uses a two-step dynamical downscaling framework, together with tropical climate change projections from multiple CMIP3 and CMIP5 climate models—the same models as used in K13. For the present-day simulations, the Zetac regional atmospheric model was run over 27 seasons in order to generate tropical storm genesis case studies. Each storm case was then resimulated using the higher-resolution Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model. In addition to the present-day runs, 13 CMIP3 or CMIP5 climate change scenarios were explored. As discussed in K13, the Zetac model does simulate hurricanes but only with intensities of up to about 50 m s^{-1} surface wind speed. For this reason, the second downscaling step using the higher-resolution GFDL hurricane model (with about 9-km spacing for the inner grid) was necessary.

2 Methodology and present-day simulation evaluation

The methodology for our study is described in more detail in the Supplemental Material. Our methodology mostly follows that in K13, Knutson et al. (2007), and Bender et al. (2010) and is described in detail in those studies.

2.1 Experimental design for present-day hurricane simulations

We performed control (present-day) simulations for 27 August–October seasons (1980–2006) and 27 *warm-climate* seasons based on modified versions of the 1980–2006 season boundary conditions. We first assess how well our two-step modeling system is able to simulate present-day Atlantic hurricane activity and its interannual variability using the time-evolving National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis I (Kalnay et al. 1996) to specify the boundary conditions and nudge the interior large-scale conditions. To assess the interannual variability vs. observations, for the present-day runs, we simulated an expanded set of 37 years (i.e., 1980–2016). For reasons of computational expense, we did not expand the climate change runs to cover these additional years.

Tropical storm cases are identified in these 3-month simulations using the automated TC search procedure described in Knutson et al. (2007), including a requirement for warm-core structure, surface wind speeds for the storm of at least 17.5 m s^{-1}, and total duration of tropical storm conditions of at least 48 h (not necessarily consecutive).

Each individual tropical storm case from the Zetac regional model was then rerun as an individual 15-day case study using the GFDL hurricane model, which is a triply nested moveable mesh system with grid spacing as fine as about 9 km. Ocean coupling in the model allows the storm to generate a "cold wake" in the interactive sea surface temperature (SST) field as it passes over the model ocean. Each tropical storm case was initialized in the hurricane model beginning from the time it first reached tropical storm intensity in the Zetac model.

2.2 Evaluation of present-day hurricane simulations

Figure 1 compares the observed August–October (IBTrACS, version 4, revision 0, Knapp et al. 2009) and model-simulated tropical storm genesis density and tropical cyclone

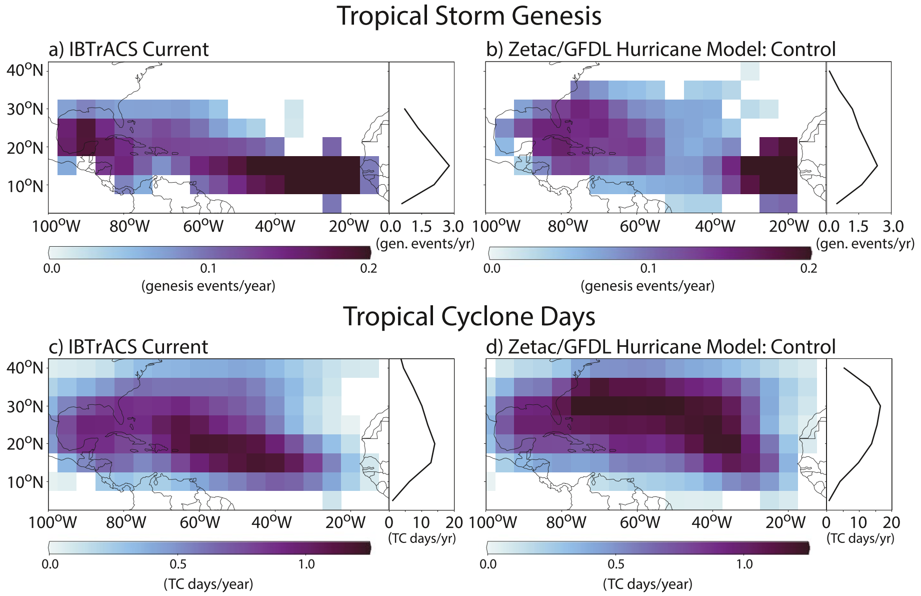


Fig. 1 Distribution of tropical storm genesis locations (**a**, **b**) in events per year and tropical cyclone (TC) track density (**c**, **d**) in TC days per year based on IBTrACS observations (**a**, **c**) and downscaled simulations. The downscaled simulations use the NCEP Reanalysis to provide the initial conditions, boundary conditions, and the target for the large-scale interior spectral nudging for the initial Zetac model control (present-day) simulations. The storms from the Zetac model were further downscaled (individually by storm) using the GFDL hurricane model. Observations and models cover the months of August–October for the years 1980–2016. The insets along the right edge of each panel show the zonally accumulated value for each row of grid points (or latitude row) on the map

(tropical storms and hurricanes) track density from the GFDL hurricane model runs. The observed tropical storm genesis points and tropical storm tracks from IBTrACS are based on the official best track data from the National Hurricane Center. Model tropical storm genesis occurrences are determined from the Zetac regional model runs (except for storms which failed to run in the hurricane model) and are based on the tropical storm identification scheme described in the Supplemental Material.

The comparison in Fig. 1 shows that the model framework generates more subtropical (higher latitude) genesis cases than observed, including along and near the U.S. East Coast. Similarly, the TC day (track density) comparison (Fig. 1c vs. d) shows more subtropical occurrence (25–35° N) in the hurricane model than in observations, including near the U.S. East Coast. These model biases would be expected to affect U.S. landfalling TC statistics. While the tropical storm genesis events in the Zetac regional model were confirmed to have warm-core (tropical) characteristics, the evolving downscaled storms in the GFDL hurricane model were not monitored for such characteristics. Therefore, it is possible that a small fraction of the simulated excess storm occurrence in the subtropical latitudes may be due to storms with extratropical or mixed tropical/extratropical characteristics. However, the GFDL hurricane model storms typically do not propagate poleward of about 38° N due to model boundary influences (Supplemental Material), which limits the likelihood of extratropical storm segments in our simulations.

A further test of the performance of our two-step downscaling model framework is a comparison of the year-to-year variability of August–October-modeled storm counts with that from observations for tropical storms and different categories of hurricanes (Fig. 2). The model was provided only time-varying Atlantic basin SSTs, lateral boundary conditions, and large-scale atmospheric circulation, applied via large-scale interior spectral nudging. If the model is still able to generate useful information about tropical storm, hurricane, and intense hurricane numbers and their year-to-year variation, this increases our confidence that the framework can translate information about atmospheric and SST variability and change (if reliable) into useful information about resulting hurricane activity.

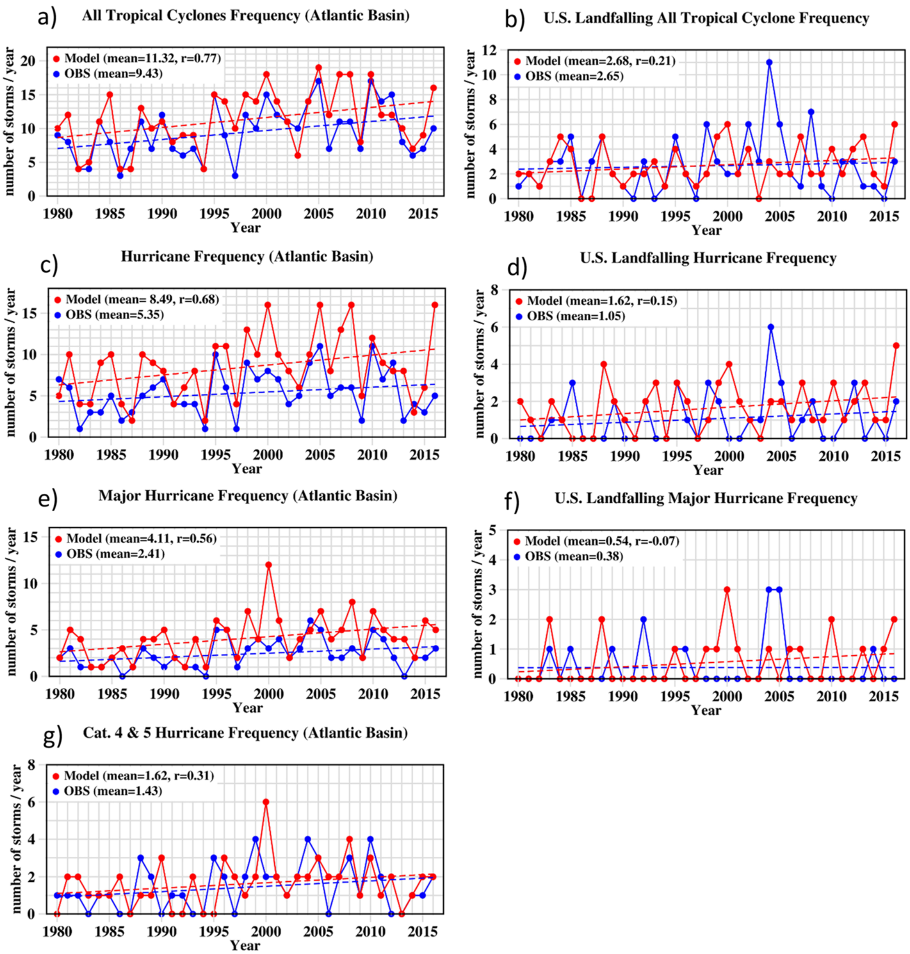


Fig. 2 Annual (August–October) counts of Atlantic basin-wide (**a**, **c**, **e**, **g**) and contiguous U.S. landfalling (**b**, **d**, **f**) tropical cyclones in observations (blue) or as simulated in the downscaling framework using NCEP Reanalysis large-scale forcing. Intensity categories are as follows: **a**, **b** tropical storm and higher; **c**, **d** category 1–5 hurricanes; **e**, **f** major (category 3–5) hurricanes; or **g** very intense (category 4–5) hurricanes. The series means and correlations (*r*) between the observed and modeled series are shown in each panel. Dashed lines are linear trends. Differing *y*-axis scaling is used

The time series in the left column of Fig. 2 show that our downscaling framework is useful for simulating Atlantic basin-wide hurricane activity given specified large-scale atmospheric, oceanic, and SST conditions. Specifically, the system simulates the following correlations versus observations for the 37-year series of Atlantic basin August–October storm counts: (1) all TCs (tropical storms and hurricanes), $r = 0.77$ (explained variance: 59%); (2) category 1–5 hurricanes, $r = 0.68$ (explained variance: 46%); (3) major (category 3–5) hurricanes, $r = 0.56$ (explained variance: 31%); and (4) very intense (category 4–5) hurricanes, $r = 0.31$ (explained variance: 10%). Assuming independence among years, correlations above 0.33 are significant at the 0.05 level, so for all cases except category 4–5 hurricanes, the results indicate significant correlation. For the category 4–5 hurricanes, which comprise a small number of cases compared to the other TC frequency metrics, the results are nearly statistically significant. Our regional modeling framework is not the first model to show such skill at hindcasting Atlantic basin-wide TC activity and its interannual variability (e.g., Zhao et al. 2009; Chen and Lin 2013; Murakami et al. 2016, and others). Ours is the highest-resolution framework among these studies, which provides our study with some advantages in terms of simulating more realistic hurricane structure compared to coarser-grid models.

Rising trends are evident in many of the basin-wide time series in Fig. 2a, c, e, and g. The modeled trends are similar to the observed trends, with the notable exception of basin-wide hurricane frequency (Fig. 2c) where the modeled trend is stronger than the observed trend. The cause of the observed rising trends remains an unanswered research question. The time period (1980–2016) is relatively short for detection of a greenhouse gas warming influence, and both internal variability and changes in aerosol forcing are possible contributors to such TC-related trends (e.g., Dunstone et al. 2013; Yan et al. 2017; Murakami et al. 2020). Our simulations indicate only that changes in the large-scale environment (including SSTs) help to explain the observed rising trends but do not explain the causes of the environmental changes. Nonetheless, we expect that the observed Atlantic hurricane trends and tropical Atlantic SST changes since 1980 have multiple causes; several studies suggest the TC frequency increases are likely not primarily a response to increasing greenhouse gases alone (e.g., Murakami et al. 2020). Thus, the over-prediction of the observed trend in hurricane frequency (1980–2016) in our model does not invalidate the model's potential use for greenhouse gas–driven warming scenarios. Figure 2 also shows that our model framework has a slight positive bias in basin-wide TC frequency, hurricane frequency, and major hurricane frequency.

The model framework's performance is much less skillful for U.S. landfalling storm counts (right column in Fig. 2). None of the simulated time series of U.S. landfalling TC counts is significantly correlated with observed variations: (1) all TCs, $r = 0.21$ (explained variance: 4%); (2) category 1–5 hurricanes, $r = 0.15$ (explained variance: 2%); and (3) major (category 3–5) hurricanes, $r = -0.07$ (no explained variance).

The above results provide an important caveat to our study. While the two-step model framework is relatively skillful at reproducing the year-to-year variation of basin-wide tropical storm and hurricane counts, this skill does not carry through to U.S. landfalling counts. Thus, while the basin-wide results provide model-based evidence that the year-to-year variability in the basin-wide numbers is not random "weather noise" but rather is controlled to a large extent by large-scale environmental conditions, the U.S. landfalling count variations seem much more difficult to capture using our modeling framework. While we are not aware of many other modeling systems that can successfully simulate U.S. landfalling TC frequency, one exception is the HiFLOR model (Murakami et al. 2016), which has shown some skill in predicting seasonal U.S. landfalling TC frequency over the period 1980–2015, suggesting that there are large-scale controls on this metric that are not being well captured in our two-step model framework. We hypothesize two mechanisms that may be important for our model's shortcoming with simulating U.S. landfalling TCs and their variation. First, the model has a bias toward too much TC genesis and TC occurrence near the U.S. East Coast, compared to the Gulf Coast region. This will degrade the model's ability to simulate interannual variations reliably. It is less likely that we have large issues with unrealistic steering flows, since we are nudging the large-scale winds and other variables toward a realistic (NCEP Reanalysis) target in our modeling procedure. Our second proposed explanation for the model's shortcoming is that U.S. landfalling activity is, in general, likely to be more difficult to hindcast skillfully using models compared to basin-wide TC activity. This is because basin-wide activity is strongly correlated with—and therefore appears to be largely controlled by—relative SSTs and vertical wind shear in the main development region (MDR) of the tropical Atlantic. The MDR clearly has a relatively pronounced and correlated multidecadal variability in SST, vertical wind shear, and basin-wide major hurricane frequency (e.g., Yan et al. 2017). On the other hand, Kossin (2017) has shown that vertical shear near the U.S. coast varies in opposition to that in the MDR such that when conditions are favorable in the MDR for TC development, they tend to be less favorable for TCs near the U.S. coast (i.e., high vertical wind shear). This characteristic of the Atlantic basin climate suggests that the task of simulating the interannual variability of U.S. landfalling TCs will be inherently more complex than for basin-wide variability, owing to the competing influence of conditions in the MDR vs. near the U.S. coast, which corrupts an otherwise simpler multidecadal signal.

Despite the limitations of our framework at simulating interannual variability of U.S. landfalling TCs, we have still chosen to use our model to explore future U.S. landfalling behavior under global warming in this study. We justify this decision by recognizing the importance of the issue for stakeholders and the need to take advantage of our model's high-resolution capability for simulating intense hurricanes and storm structure.

2.3 Specification of climate change downscaling simulations

Following on the above present-day simulations, here we analyze similar sets of experiments under climate change conditions. We focus here on 27 seasons (1980–2006) for computational efficiency.

We first created a series of climate change "delta" fields for SST, surface pressure, air temperature, relative humidity, and winds, which we added to the NCEP/NCAR Reanalysis, to create a series of warm-climate perturbation experiments that use realistic conditions (i.e., the reanalysis) as the baseline case. The warm-climate conditions were for the CMIP3 models (18-model ensemble mean or 10 individual models) based on years 2081–2100 minus 2001–2020 of the Special Report on Emission Scenarios A1B (SRES A1B) scenario. We constructed two 18-model ensemble mean CMIP5 model warm-climate scenarios using the 2016–2035 (early twenty-first-century) or 2081–2100 (late twenty-first-century) period of the CMIP5 RCP4.5 scenario versus a baseline period of 1986–2005. The global temperature difference between present-day and late twenty-first-century warm-climate condition was 1.69 °C for the CMIP3 and 1.70 °C for the CMIP5 ensemble means.

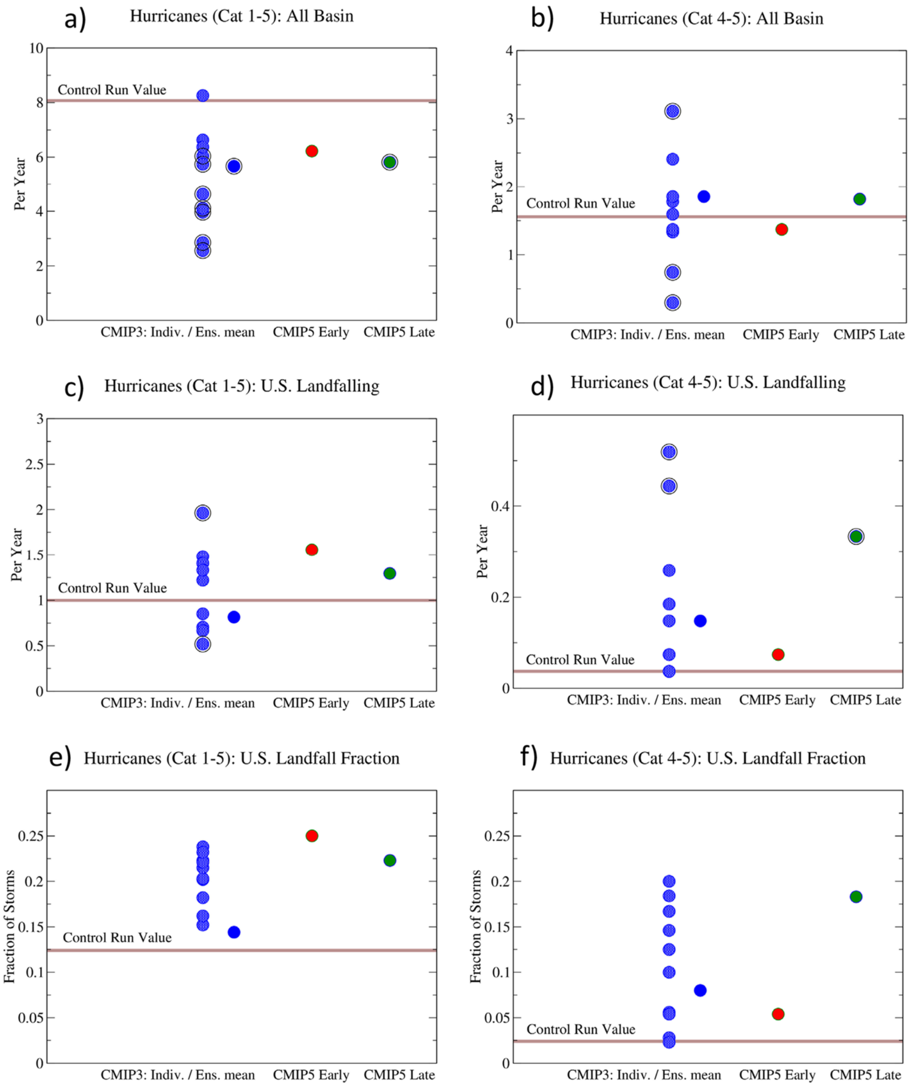
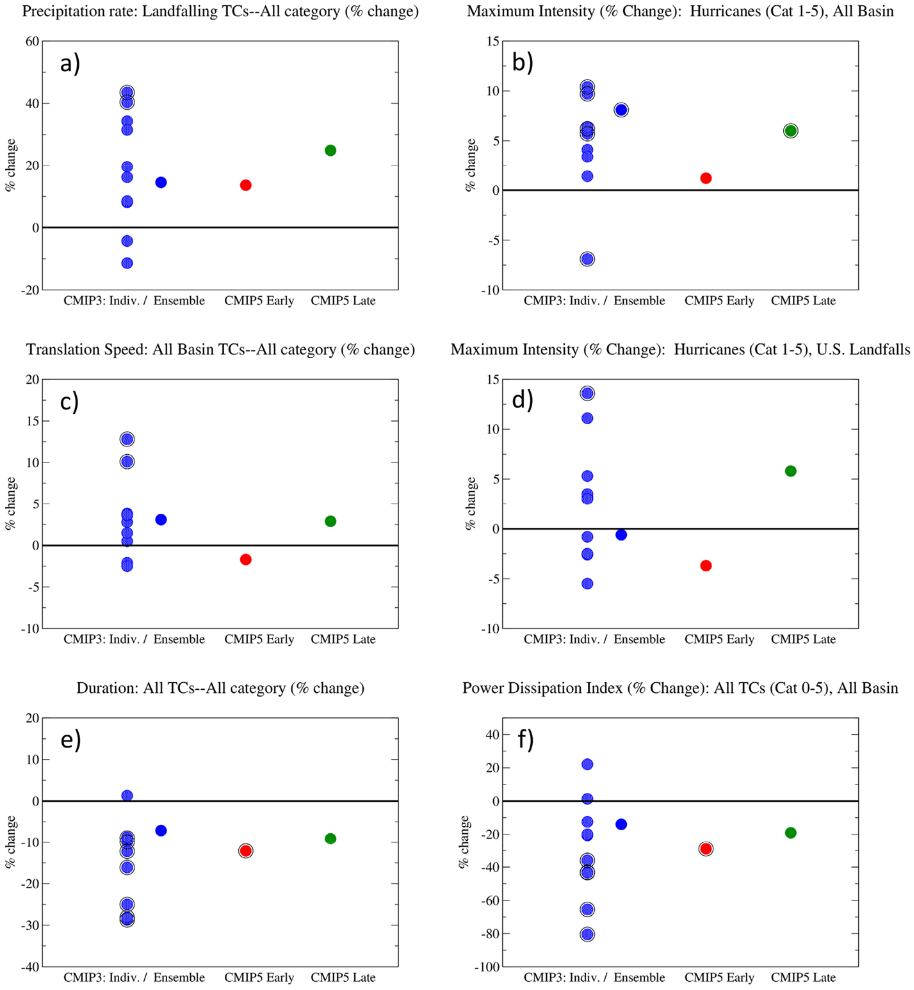


Fig. 3 Summary comparison of hurricane activity measures for the control (present-day, thick line) and CMIP3 or CMIP5 warming climate scenarios (see *x*-axis labels). In panels **a**–**d**, the average number of storms per year of a given storm type is shown for Atlantic basin-wide **a** category 1–5 or **b** category 4–5 hurricanes and for U.S. landfalling **c** category 1–5 or **d** category 4–5 hurricanes. Panels **e** and **f** show the fraction of storms making U.S. landfall for **e** category 1–5 or **f** category 4–5 hurricanes. The slightly larger “ringed” dots denote statistically significant changes according to the Mann–Whitney test

3 Results of climate change downscaling experiments

In this section, we examine the results of our climate change downscaling experiments. In the discussion below, we refer to the 13 sets of experiments as 13 different *models*, even though these can be based on an individual model or on ensemble mean climate change from a set of CMIP3 or CMIP5 models.

A number of TC metrics were examined for our 13 different sets of experiments (see Table 1 of the Supplemental Material for a complete set). To focus on results from our experiments where most models agree on the sign of the projected changes, we present the results for selected TC metrics in a summary form (Figs. 3 and 4) showing both the levels of agreement across the models for projected changes for a given metrics, along with statistical significance test indicators for the individual model results. Using this approach,


Precipitation rate: Landfalling TCs--All category (% change)

Maximum Intensity (% Change): Hurricanes (Cat 1-5), All Basin

Translation Speed: All Basin TCs--All category (% change)

Maximum Intensity (% Change): Hurricanes (Cat 1-5), U.S. Landfalls

Duration: All TCs--All category (% change)

Power Dissipation Index (% Change): All TCs (Cat 0-5), All Basin

Fig. 4 Summary comparison of hurricane activity measures for the control (present-day) and CMIP3 or CMIP5 warming climate scenarios (see *x*-axis labels). For each panel, the percentage change (from present-day to warm climate scenario) in the given TC metric is shown. The slightly larger “ringed” dots denote statistically significant changes according to the Mann–Whitney test (see Table 1 in the Appendix). Metrics include percent changes in **a** precipitation rate for U.S. landfalling TCs (within 100 km of the TC center), **b** lifetime maximum 10 m wind speed intensity of Atlantic basin hurricanes, **c** basin-wide average TC translation speed, **d** maximum intensity (10 m wind speeds) at or just prior to U.S. landfall, **e** basin-wide average TC duration, and **f** TC basin-wide Power Dissipation Index. See the main text and Supplemental Material (Table 1) for further details

Fig. 5 Tracks of all tropical cyclones that made U.S. landfall while at category 4 or 5 intensity based on **a** ▶ observations or **b** NCEP Reanalysis–driven present-day simulations (control) for August–October of the years 1980–2006. The remaining simulation panels used the reanalysis variability from 1980 to 2006 while their mean climate conditions were altered from the reanalysis according to warming scenarios derived from **c** CMIP3 18-model ensemble (late twenty-first-century A1B scenario); **d**, **e** CMIP5 multimodel ensemble early (**d**) and late (**e**) twenty-first-century RCP4.5 scenarios; or **f**–**o** individual CMIP3 models. See the main text for details

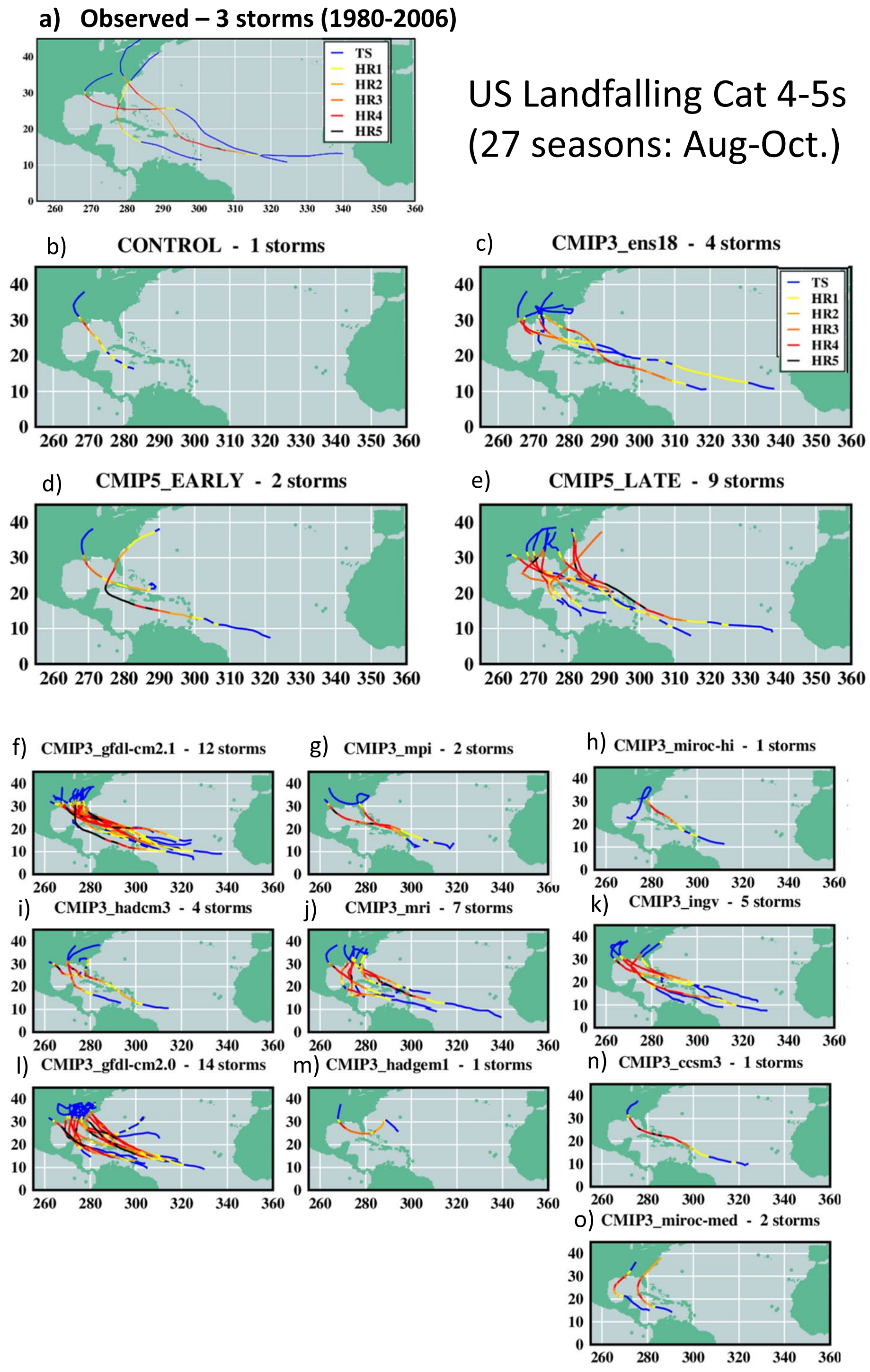
Figs. 3 and 4 examine two distinct but important sources of uncertainty in projections: modeling uncertainty, as indicated by the agreement in sign of the projected change for the 13 different models, and internal variability uncertainty, as assessed by the statistical significance tests. Both U.S. landfalling TC frequencies (or surface wind intensities and precipitation rates at the time of landfall) and the basin-wide results are summarized in Figs. 3 and 4. Basin-wide results are based either on conditions at the time of maximum storm wind speed intensity for the storm or on the entire life cycle of each TC in each year for the case of accumulated activity metrics like duration, propagation speed, or the Power Dissipation Index (PDI). The mechanisms behind the changes summarized in Figs. 3 and 4 will be explored further in Section 4 (Discussion).

3.1 TC frequency projections

Figure 3a indicates that a robust projection is a decrease in basin-wide hurricane frequency (categories 1–5). A decrease is simulated in 12 of 13 models (statistically significant in 9 of 13 models), with an average decrease across all models of − 34%. Detailed data (in the Supplemental Material) indicates this decrease is particularly robust for basin-wide frequency for category 1 hurricanes (− 42%), category 2 hurricanes (− 45%), category 3 hurricanes (− 43%), all tropical storms and hurricanes combined (− 28%), all hurricanes combined (categories 1–5; − 34%), and major hurricanes (categories 3–5; − 25%). In contrast, the most intense (category 4–5) hurricanes show little consistent change in basin-wide frequency with warming (Fig. 3b), with seven (six) of 13 models projecting a positive (negative) change.

This contrasting behavior of Atlantic basin hurricanes vs. intense hurricane frequency has been discussed previously (K13) and is related to the increase in the average intensity of the TCs in the model, as will be discussed further below. Comparisons with other studies, for example Knutson et al. (2020), show that the majority of published projections of Atlantic overall TC frequency (tropical storms plus hurricanes) indicate a decrease in frequency with climate warming, but an increase in the frequency of category 4–5 TCs. However, there is a wide variation in these projections across models for both all TC frequency and category 4–5 TC frequency, with some disagreeing on even the sign of the change. However, a relative increase of category 4–5 TC frequency compared to all TC frequency is a consistent feature of the multimodel TC assessment in Knutson et al. (2020). A recent attempt at better understanding the controls on TC frequency change in models has focused on the role of seed disturbances (Hsieh et al. 2020).

U.S. landfalling TCs (Fig. 3c, d) show a contrasting behavior to the highly significant and robust decreases seen for basin-wide TC frequency. In particular, there is no robust increase or decrease for U.S. landfalling category 1–5 hurricane frequency (Fig. 3c). On the other hand, for U.S. landfalling category 4–5 storms (Fig. 3d), the average change across models is + 390%, with at least nominal increases for 10 of 13 models, and statistically significant increases for three of the 13 models. No change was found for three models.


a) Observed – 3 storms (1980-2006)
US Landfalling Cat 4-5s
(27 seasons: Aug-Oct.)
TS
HR1
HR2
HR3
HR4
HR5
b) CONTROL - 1 storms
c) CMIP3_ens18 - 4 storms
d) CMIP5_EARLY - 2 storms
e) CMIP5_LATE - 9 storms
f) CMIP3_gfdl-cm2.1 - 12 storms
g) CMIP3_mpi - 2 storms
h) CMIP3_miroc-hi - 1 storms
i) CMIP3_hadcm3 - 4 storms
j) CMIP3_mri - 7 storms
k) CMIP3_ingv - 5 storms
l) CMIP3_gfdl-cm2.0 - 14 storms
m) CMIP3_hadgem1 - 1 storms
n) CMIP3_ccsm3 - 1 storms
o) CMIP3_miroc-med - 2 storms
0
10
20
30
40
260
270
280
290
300
310
320
330
340
350
360

The projected increase in U.S. landfalling category 4–5 hurricane frequency is noteworthy from a climate impact perspective because these storms have historically caused almost 50% of normalized TC damage in the USA, despite representing only 6% of historical TC occurrences (Pielke et al. 2008). As a sensitivity test, we have assessed U.S. landfalling category 4–5 frequency based on surface pressure, rather the surface wind speed criteria (not shown), and found similar though slightly less statistically robust results.

To visually illustrate this relatively important finding in Fig. 3, Fig. 5 shows the tracks and intensities of the observed and simulated U.S. landfalling hurricanes that are category 4 or 5 at landfall. A clear tendency for an increase in these very intense landfalling cases is seen across downscaled storms from most of the models, including the CMIP3 and CMIP5 late twenty-first-century ensembles.

The differing response of basin-wide vs. U.S. landfalling TC frequency to climate warming indicates that the proportion of TCs making U.S. landfall increases in the projections according to most models. Figure 3e shows, for example, that for all hurricanes (category 1–5), the proportion making U.S. landfall is projected to increase by all 13 models, with an average increase of 64% above the control proportion value of 0.12. Similarly, for category 4–5 hurricanes, the proportion of such storms making U.S. at category 4–5 intensity increases by + 350% over the control run fraction of 0.024, with an increase projected for 12 of 13 models. Increases in U.S. landfalling proportion for other classes of TCs are shown in the Supplemental Material.

3.2 TC rain rate projections

Climate change projections for several other TC metrics are summarized in Fig. 4. Increasing TC precipitation rate with climate warming has been identified as among the most robust projections for TCs across different modeling studies (K13; Knutson et al. 2015, 2020; Liu et al. 2018, 2019; Stansfield et al. 2020; Gori et al. 2022). Figure 4a shows a robust increase for TC rainfall rates at (or just prior to) U.S. landfall (+ 18% on average across the models), based on rain rates averaged within 100 km of the storm center. Eleven of 13 models show increases in this metric, while three of 13 show statistically significant increases. For basin-wide TCs, a statistically more robust increase in TC rain rates is projected (Table 1 in the Supplemental Material) with an average change of + 19%, positive in 12 of 13 models, and statistically significant increases in seven of 13 models. The more significant projected climate change signal in basin-wide TC rain rates (for roughly the same sized climate change signal) is probably due in part to the larger sample size available vs. the U.S. landfalling subset of storms.

3.3 TC intensity projections

Maximum lifetime hurricane intensity (based on modeled near-surface (10 m) wind speeds) is a metric which relatively higher-resolution models have consistently projected to increase with climate warming (Knutson et al. 2020). Figure 4b shows that the hurricane (category 1–5) intensity increases in our experiments are robust for the Atlantic basin as a whole, with all but one of 13 models showing an increase, significant for six of 13 models. For U.S. landfalling hurricanes (Fig. 4d), the projected intensity changes are more mixed, with seven of 13 models showing an increase and only one being statistically significant. The U.S. landfalling hurricane intensities are based on intensities in the model at or just prior to the time of landfall.

The one outlier model for basin-wide hurricane intensity change is the CMIP3 HadGEM1 model, for which we simulate a significant decrease. As discussed in K13, this particular model exhibits a much more enhanced warming of the upper tropical troposphere (compared to the surface warming) than other CMIP3 models. Such amplified upper tropospheric warming has been shown to a detrimental factor for modeled TC intensification (Tuleya et al. 2016).

The average TC intensity change across the 13 models is about + 5%. This result is relatively consistent with other high-resolution modeling studies (Knutson et al. 2020). Interestingly, the increase is absent if one includes weaker (tropical storm-strength) TCs in the sample, but we consider the hurricane intensity result as the more relevant one for potential climate impacts. In summary, despite the increase in basin-wide hurricane intensity, the average intensity of landfalling hurricanes shows little significant change, nominally averaging about + 2%.

3.4 TC translation speed, duration, and Power Dissipation Index projections

Figure 4c indicates that the basin-wide TC translation speed tends to increase in the models, with 10 models projecting an increase (only two are significant) and three models projecting a decrease. As will be illustrated later in this report, the two models with significant translation speed increases both have substantial increases in easterly steering flow in the central tropical Atlantic, which leads to faster westward propagation across that region. Average TC duration (Fig. 4e) shows a clear tendency to decrease by about 13% on average (decreasing in 12 of 13 models, with 8 of 13 models projecting a significant decrease). The slight increase of translation speed may be one factor contributing to a decrease in duration, as the life cycle of the storm over a given track would be shortened by the faster propagation speed. Furthermore, the greater fraction of TCs making U.S. landfall in the warm climate runs means that more storms have truncated lifetimes as they dissipate after U.S. landfall as opposed to recurving out to sea without encountering land. Also, storms forming closer to the coast will tend to have shorter lifetimes before they dissipate over land compared to storms forming further away from the coast. However, we have not quantitatively diagnosed the reasons for the decreased duration under climate change in detail. Duration of storms in the model (both control and warm climate cases) can also be artificially limited by the 15-day limit of the simulations and by the effective northern boundary near 38°N (Supplemental Material). Finally, Fig. 4f shows that the PDI (see the Supplemental Material) has a robust projected decrease, with a decrease simulated in 11 of 13 models (averaging − 28%) and with five models projecting a statistically significant decrease.

4 Discussion

In this section, we discuss mechanisms behind several key model projections and provide some assessments of our confidence in the projections.

4.1 Increase in proportion of TCs making U.S. landfall

A potentially important finding in our study is the tendency for a greater fraction of TCs to make landfall over the USA in the warmer climate. This is a key factor associated with

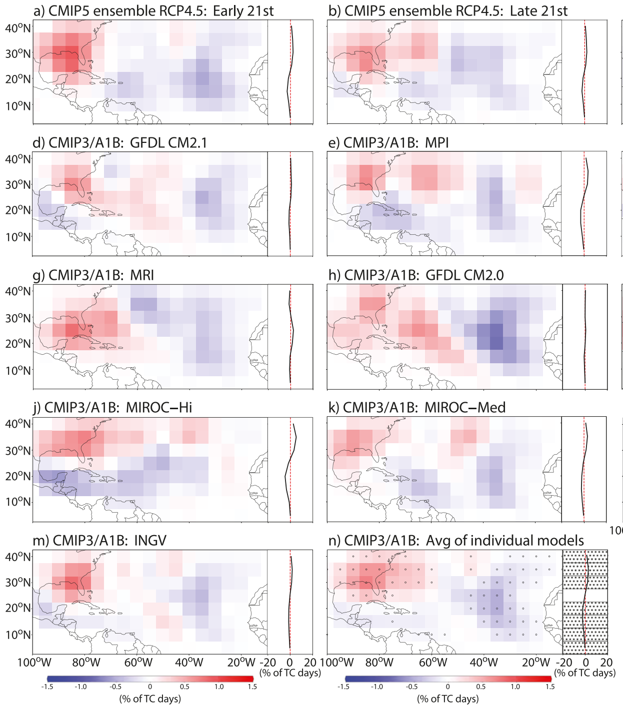


Fig. 6 Each panel shows the difference in percentage of total TC days occurring at each grid point between the warm climate and control climate (warm minus control). In panel **n**, the average of the 10 individual CMIP3 model results is shown, with dots where results from 8 or more of the 10 individual CMIP3 models agree on the sign of change. The insets along the right edge of each plot (**a**–**n**) show the difference between the zonal accumulated values for the warm climate runs minus those of the control run

the lack of significant change in the frequency of landfalling hurricanes despite the reduction in their basin-wide frequency; it also is associated with an increase in landfalling category 4–5 hurricanes despite no significant increase in their basin-wide frequency. Thus, the increase in fraction of landfalling TCs enhances damage risk for the USA according to our simulations. Another recent study (Garner et al. 2021) projected a relative shift in TC activity toward the USA in a warming climate.

To explore potential mechanisms for this projected change in TC behavior, Fig. 6 depicts the difference (warm climate minus control) in percent of total TC occurrence days at each grid point. Before computing this difference, the percent occurrence for either warm climate or control is found for each grid point, which sums to 100% separately over both the warm climate and control run maps. The U.S. and near-U.S. coastal regions in all the maps tend to be red-shaded, indicating a robust tendency for a greater fraction of TCs to occur in those areas, and consistent with the increase in the fraction of hurricanes or intense hurricane making U.S. landfall (Fig. 3e, f).

The above changes in Fig. 6 could be associated with a similar shift in TC genesis. To investigate this, we show in Fig. 7 the difference (warm climate minus control) in the percentage of total TC genesis events occurring at each grid point. This metric tends to show reddish colors near the USA, meaning a tendency for TC genesis to occur closer to the USA in the warmer climate, but this is not seen in all models (e.g., CCSM3, CM2.0,

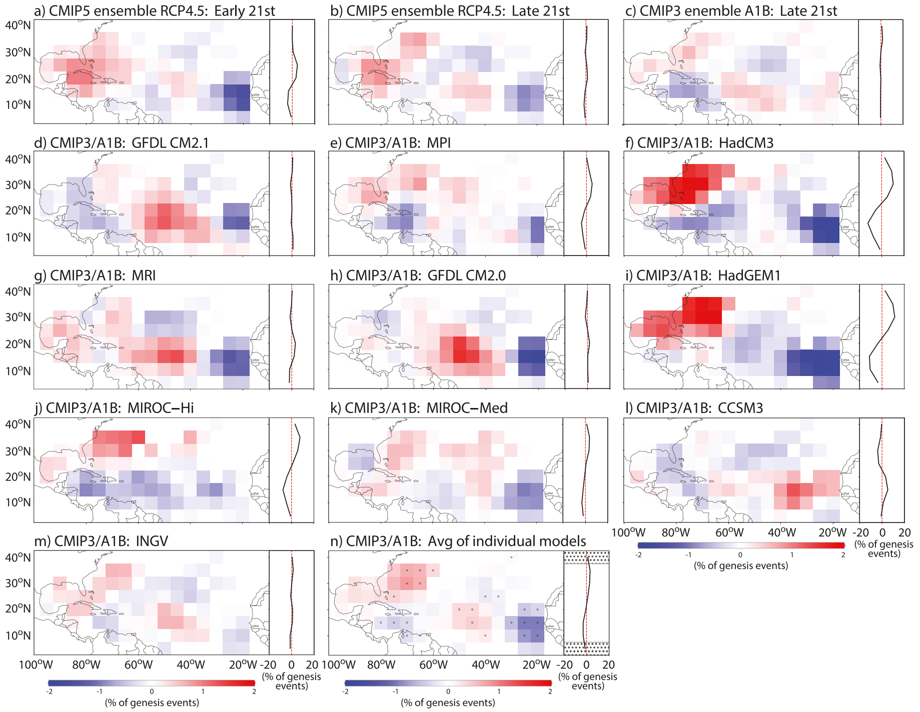


Fig. 7 Each panel shows the difference in the percentage of total TC genesis events occurring at grid point, with the difference taken between the warm climate and control climate maps (warm minus control). In panel **n**, the average of the 10 individual CMIP3 model results is shown, with dots where results from 8 or more of the 10 individual CMIP3 models agree on the sign of change. The insets along the right edge of each plot (**a**–**n**) show the difference between the zonal accumulated values for the warm climate runs minus those of the control run

CM2.1, and MRI show a mix of increases and decreases near the U.S. coast). This particular projected change may be influenced by the TC genesis and track density bias in our modeling framework discussed earlier (Fig. 1). That analysis showed that TC genesis and track density were both excessive off the U.S. East Coast in our control simulations compared to observations. Such a bias is a caveat on further projected increases in such genesis and track density because the projected change has some of the same spatial structure as the bias.

Another possible contributor to the relative increase in TC track density near the U.S. coast is a shift in TC tracks, as would occur with a change in steering flows, for example. To explore this, Fig. 8 shows the change (warm climate minus control) in the vector winds averaged over the 300–850-mb layer. We use this as an approximation for the climatological steering flow that intense TCs, in general, will experience on average (e.g., Velden and Leslie 1991). The salient features on these maps are wind anomalies directed from the open Atlantic back toward the U.S. East Coast. This indicates a weakening of the westerly winds that act to recurve hurricanes and tropical storms out to sea and away from the USA before they make landfall. Thus, such a change will tend to make U.S. landfalls more likely by weakening the recurvature effect of the westerlies. These easterly anomalies off the U.S. East Coast are a relatively robust feature of the

Fig. 8 Change (warm climate minus control) in the climatological average of the vector winds in the 300–850-mb layer. This is an approximate indicator of the change in steering flow that TCs, on average, would experience. Panel titles identify the model or model ensemble shown. Solid white shading: magnitudes exceeding 2 m s^{-1} ▶

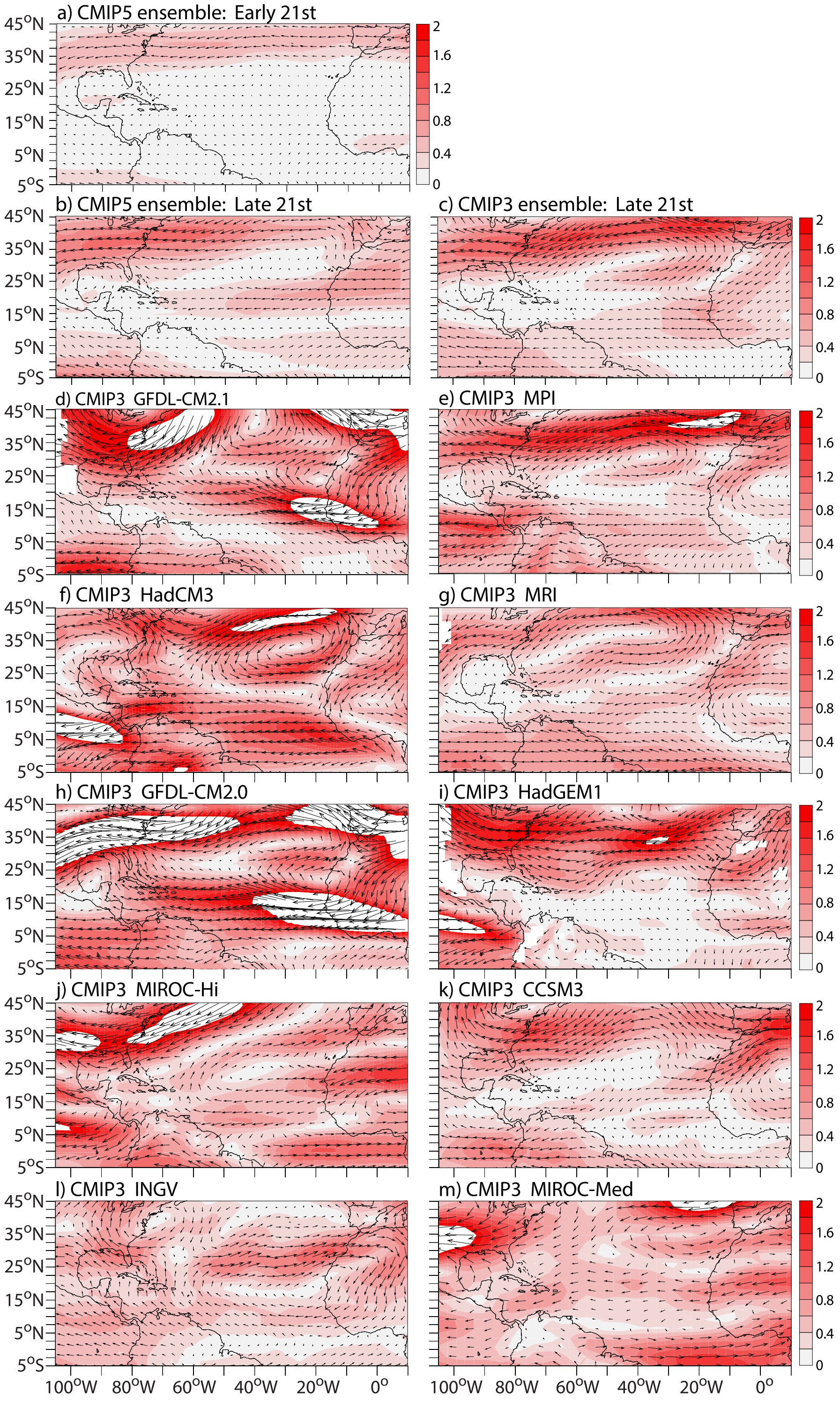
individual CMIP3 models and the CMIP3 and CMIP5 ensembles we examined for the August–October season. We have relatively more confidence in this steering influence than in the increased relative TC genesis near the U.S. East Coast with climate warming because of the robustness of the steering flow change in the CMIP models. Related to these flow changes, projected reductions in vertical wind shear off the U.S. East Coast (K13, their Fig. 9; Ting et al. 2019) may also contribute to the increased TC frequency there.

Returning to the issue of only two models (CMIP3 GFDL CM2.0 and CM2.1) showing statistically significant changes in TC propagation speed, Fig. 8 shows that those two models are distinguished by particularly pronounced easterly anomalies in 300–850-mb averaged vector winds across the tropical Atlantic (10–20° N). These anomalies imply an increase in the easterly steering flow for TCs moving westward across the tropical Atlantic, which would contribute to increased average propagation speed, although the weakened westerlies at higher latitudes in these and other models would tend to decrease propagation speeds after recurvature.

In short, we have only tentative confidence at this stage in the increase in proportion of TCs making U.S. landfall in our simulations, particularly since the changing TC genesis location factor is one where we have concerns about model biases, while for the steering flow influence, we have more confidence based on relatively high model agreement on the wind changes in the climate models we examined.

4.2 Insignificant change in U.S. landfalling hurricane intensity

While the average maximum lifetime intensity of hurricanes increases for the Atlantic basin as a whole, the increase is not robust for U.S. landfalling hurricanes (Fig. 4b, d) though the latter is a smaller sample in both space and time. The increase in basin-wide hurricane intensity is consistent with other modeling studies (Knutson et al. 2020). The key mechanism behind this change can be understood as the increase in environmental potential intensity due to greenhouse warming (e.g., Emanuel 1987). In the GFDL hurricane model, Tuleya et al. (2016) have shown that the hurricane intensity increase with climate warming depends on a competition between intensification due to higher SSTs, and an offsetting reduction of intensity due to amplified warming of the upper troposphere compared to the surface. They also documented the importance of environmental vertical wind shear for modeled hurricane intensity. Here, we review these potential environmental influences on our simulated hurricane intensities. Maps of ensemble mean changes in potential intensity and vertical wind shear for the CMIP3 A1B, CMIP5 early twenty-first-century, and CMIP5 late twenty-first-century scenarios have been previously shown in Fig. 9 of K13. Those maps show generally increased potential intensity near the U.S. TC landfalling regions but also increased vertical shear, especially in the Caribbean region, with decreased shear in some regions off the U.S. East Coast. The increased vertical shear would, in a climatological sense, have negative impact on intensities for hurricanes traversing westward toward the USA across the western Caribbean and Gulf of Mexico. Ting et al. (2019) have also examined the changes in projected vertical shear and potential intensity near the USA,


a) CMIP5 ensemble: Early 21st
b) CMIP5 ensemble: Late 21st
c) CMIP3 ensemble: Late 21st
d) CMIP3 GFDL-CM2.1
e) CMIP3 MPI
f) CMIP3 HadCM3
g) CMIP3 MRI
h) CMIP3 GFDL-CM2.0
i) CMIP3 HadGEM1
j) CMIP3 MIROC-Hi
k) CMIP3 CCSM3
l) CMIP3 INGV
m) CMIP3 MIROC-Med
45°N
35°N
25°N
15°N
5°N
5°S
100°W
80°W
60°W
40°W
20°W
0°
2
1.6
1.2
0.8
0.4
0

noting the reduced vertical shear along the East Coast and enhanced shear in the Caribbean region, the latter being a weakening influence on future Gulf Coast landfalling TCs. We interpret the lack of robust projected change in the intensity of U.S. landfalling TCs overall in our study as resulting from several competing effects, including increased potential intensity and regional-scale changes in vertical shear (which appear particularly important for limiting intensification in the Gulf Coast region). Another factor which can influence TC intensity is the change in ocean thermal structure (Huang et al. 2015), although this is currently thought to be of only secondary importance as discussed by Emanuel (2015) and Tuleya et al. (2016).

In summary, we have only tentative confidence that there will be little change in the average intensity of U.S. landfalling TCs, owing to the complexity of the problem and the competing influences of several important regionally dependent factors.

4.3 Increase in frequency of U.S. landfalling category 4–5 hurricanes

The projected increase in U.S. landfalling category 4–5 hurricane frequency (Fig. 3d) is potentially important for societal impacts, yet the statistical evidence in our experiments is not decisive (with three of 13 models indicating a statistically significant increase and ten of 13 models indicating at least a nominal increase). In addition, only one landfalling category 4–5 hurricane occurred in our control run (27 seasons) compared with three in observations (Fig. 5)—a bias which makes the projected increase in the model more difficult to interpret statistically. Yet clearly, there is a projected increase in our warm climate runs relative to the control. This results from a number of competing factors. For example, there is a decrease in the basin-wide number of hurricanes, but no significant change in the basin-wide number of category 4–5 hurricanes. This contrast at the basin-wide scale is presumably due to increased average TC intensity over the basin (K13), and it also implies that the probability of a given hurricane reaching categories 4–5 is projected to increase. However, there is not a robust increase in the average intensity of U.S. landfalling hurricanes (Fig. 4d), nor is there an increase in the total number of U.S. landfalling hurricanes. Apparently, the combined influence of the increase in proportion of hurricanes making U.S. landfall (and the proportion of category 4–5 hurricanes making U.S. landfall) leads to an increase in total number of U.S. landfalling category 4–5 storms despite there being no change in the basin-wide number of category 4–5 hurricanes. Clearly, the multiple factors contributing to the frequency of U.S. landfalling category 4–5 hurricanes imply that it is a difficult metric to project. Therefore, the projected increase in U.S. landfalling category 4–5 hurricanes is a change for which we have only tentative confidence at present.

4.4 Increase in TC precipitation rates

Although we do not focus on TC rain rates as much as other TC metrics in the present study, here we discuss in some detail the TC rain rate behavior with climate warming over the Atlantic, including revisiting some previous studies that included more detailed analyses of our model framework (e.g., K13) as well other models. The general mechanism producing an increase in TC precipitation rates with climate warming is the increase in tropospheric water vapor content in a warmer atmosphere, together with the moisture convergence mechanism which supplies moisture to a hurricane from its surrounding environment (Wang et al. 2015). K13 (see their Fig. 11) showed that the precipitation rate in the GFDL hurricane model increased the most (in percent) near the composite storm's core rainfall region and was especially large within about 100 km of the storm center. This result influenced our choice of using TC rain rates averaged within 100 km of the storm center as our primary metric for this study. K13 found that the TC rain rate increases were generally at or above the rate at which tropical tropospheric water vapor increases with warming (i.e., about 7% per 1 °C rise in SST (Held and Soden 2006)). In our current study, the 18% increase in 100-km radius averaged rainfall rate also exceeds this Clausius-Clapeyron scaling, as the average tropical Atlantic SST increase is about 1.7 °C, giving an expected increase in TC rain rate of 12% from water vapor increase alone, assuming constant relative humidity. Liu et al. (2019) found that increased TC intensity with climate warming can lead to "super-Clausius-Clapeyron" increases in projected TC rain rates. As discussed above, there is some indication in our experiments for increased TC intensities with warming (especially considering basin-wide intensities).

Overall, model-based evidence for a substantial TC rain rate increase with climate warming continues to grow. For example, Reed et al. (2021) modeled substantial increases in rain rates for U.S. landfalling TCs. Considering TC rain rates over the Atlantic Ocean basin (as opposed to U.S. landfalling), Patricola and Wehner (2018), Hill and Lackmann (2011), and several other studies reviewed in Knutson et al. (2020) reported broadly similar sensitivities of TC rain rates to climate warming to those simulated here.

The reasons for the higher percentage increase in TC rain rate for higher-intensity U.S. landfalling hurricanes (discussed in Section 3) remain uncertain, but this finding could be influenced by the relatively small sample size of intense U.S. landfalling TCs in our experiments. Additionally, there is a strong relationship observed between the TC rainfall rate itself and TC intensity at landfall (Tuleya et al. 2007) which could play some role in this behavior.

In short, for TC precipitation at the time of U.S. landfall, our study supports previous findings of an increase in Atlantic basin-wide TC rain rates, with the caveat that the statistical significance and robustness across models are not as high for U.S. landfalling TCs as for basin-wide TCs. Nonetheless, we have—at this stage—relatively high confidence that precipitation rates will increase for U.S. landfalling TCs with twenty-first-century climate warming, based on results presented here as well as other assessments of TC precipitation changes (Knutson et al. 2020).

5 Summary and conclusions

In this analysis, we explored future projections of U.S. landfalling TCs, examining a large number of cases generated using different climate model projections of large-scale environmental conditions, generally for the late twenty-first century under the CMIP3 A1B scenario or the CMIP5 RCP4.5 scenario. We examined 13 different sets of projected warmed climate conditions based on 10 individual CMIP3 models or on the multimodel ensemble mean projection from the CMIP3 or CMIP5 models.

A robust projection we simulated was an increase in the proportion of TCs making U.S. landfall. Our analysis suggests that this increase is due primarily to changes in the climatological winds which impacted the large-scale steering by favoring TC movement more toward the U.S. East Coast. These changes in the 300–850 hPa wind were evident in most of the CMIP model or ensemble model environments examined. A second related influence was an increase in the percent of TC genesis occurring near the U.S. East Coast in our warm climate downscaling simulations. However, we have less confidence in the robustness of this influence, due to the existence of a positive bias in the frequency of TC genesis in this region in our control simulations.

The increase in proportion of landfalling TCs led to an increase in the number of category 4–5 hurricanes making U.S. landfall. This increase in category 4–5 landfalling frequency averaged + 390% across the models, with at least nominal increases projected for 10 of 13 models (with no change for the other three models); increases in three of 13 models were statistically significant. This projection, while not definitive, contrasts with the robust decrease in category 1–5 hurricane frequency projected for the Atlantic basin, the projected decrease in basin-wide PDI, and the lack of significant change in the frequency of U.S. landfalling category 1–5 hurricanes. While basin-wide hurricane intensity increased, there was little significant change projected for intensity of U.S. landfalling hurricanes. Duration of TCs showed a significant decrease (averaging − 13%) while basin-wide average propagation speed showed a slight increasing tendency.

Another robust projection was an increase in the precipitation rate for U.S. landfalling TCs—a signal that averaged 18% considering rain averaged within 100 km of the storm center for all categories of hurricanes. At least near the storm, the change appeared to exceed the Clausius-Clapeyron rate of about 7% per °C of warming, but the changes overall were not as statistically significant for U.S. landfalling storms as for basin-wide storms. Furthermore, the magnitude of the projected increase was larger in percentage terms for more intense categories of landfalling hurricanes for reasons that were not clear. The limited statistical significance for changes in rain rates of U.S. landfalling TCs at landfall and the increased percentage change of rain rate for higher-category TCs may be both related to the relatively limited number of cases available.

There are several important caveats for our study. First, the model framework shows limited skill in simulating the historical year-to-year variability of U.S. landfalling TC activity using SSTs and the NCEP/NCAR Reanalysis as large-scale climate forcings. Excessive TC genesis near to and east of the U.S. East Coast in the control run raises some concerns about confidence in projected increases in TC genesis in those regions in the climate change scenarios. There is also uncertainty in the climate change signal in large-scale environmental parameters, which is partly reflected in the spread of results across the different model-derived scenarios. The spread shown in our various results cannot be assumed to represent the true confidence intervals for results in this study. Despite these limitations, it is important to test our models with such future climate change scenarios and continue to compare modeled scenarios with the growing observational database to work toward a better understanding of the changes in landfalling hurricane risk facing society in the coming decades.

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Author contribution T. Knutson designed the study, directed Joe Sirtutis on the analysis and model runs, and wrote the manuscript. J. Sirutis, who is now deceased, performed all the model runs and most of the analysis contained in the study. R. Tuleya and M. Bender assisted in the model setup and technical issues for the GFDL hurricane model and assisted in writing the manuscript. B. Schenkel contributed several analysis plots to the paper, and assisted in writing the manuscript.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request. There are no special materials involved in the study.

Declarations

Ethics approval and consent to participate Not applicable because the study does not report the results of studies involving humans and/or animals. Consent to participate is not applicable because the study does not report the results of studies involving humans and/or animals.

Consent for publication Not applicable because the study does not report the results of studies involving humans and/or animals.

Competing interests The authors declare no competing interests.

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