

# Regional climate model projections of rainfall from U.S. landfalling tropical cyclones

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**Abstract** The eastern United States is vulnerable to flooding from tropical cyclone rainfall. Understanding how both the frequency and intensity of this rainfall will change in the future climate is a major challenge. One promising approach is the dynamical downscaling of relatively coarse general circulation model results using higher-resolution regional climate models (RCMs). In this paper, we examine the frequency of landfalling tropical cyclones and associated rainfall properties over the eastern United States using Zetac, an 18-km resolution RCM designed for modeling Atlantic tropical cyclone activity. Simulations of 1980–2006 tropical cyclone frequency and rainfall intensity for the months of August–October are compared against results from previous studies and observation-based datasets. The 1980–2006 control simulations are then compared against results from three future climate scenarios: CMIP3/A1B (late twenty-first century) and CMIP5/RCP4.5 (early and late twenty-first century). In CMIP5 early and late twenty-first century projections, the frequency of occurrence of post-landfall tropical cyclones shows little net change over much of the eastern U.S. despite a decrease

in frequency over the ocean. This reflects a greater land-falling fraction in CMIP5 projections, which is not seen in CMIP3-based projections. Average tropical cyclone rain rates over land within 500 km of the storm center increase by 8–17 % in the future climate projections relative to control. This is at least as much as expected from the Clausius–Clapeyron relation, which links a warmer atmosphere to greater atmospheric water vapor content. Over land, the percent enhancement of area-averaged rain rates from a given tropical cyclone in the warmer climate is greater for larger averaging radius (300–500 km) than near the storm, particularly for the CMIP3 projections. Although this study does not focus on attribution, the findings are broadly consistent with historical tropical cyclone rainfall changes documented in a recent observational study. The results may have important implications for future flood risks from tropical cyclones.

**Keywords** Tropical cyclones · Extreme rainfall · Floods · Climate impacts · Climate modeling · Dynamical downscaling

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## 1 Introduction

The eastern United States is highly vulnerable to rainfall from landfalling tropical cyclones, as illustrated by extreme flooding in Pennsylvania during Hurricane Agnes in 1972 and more recently in the mid-Atlantic states during Hurricane Irene in 2011. Flooding due to rainfall has been a leading cause of tropical cyclone-related fatalities in the United States in recent decades (Rappaport 2000). Due to the large size of such storms, associated rainfall can affect large areas, including at locations far from the coast (see, for example, Rowe and Villarini 2013 and Villarini et al.

2014a). How rainfall from these storms will change in the future is a key question for flood risk managers, insurers, and others. Karl et al. (1996), Groisman et al. (2005), Min et al. (2011), Villarini et al. (2012) and others have reported increases in the frequency of heavy precipitation in recent decades and there is broad agreement among GCMs that the frequency of heavy rainfall will increase over the twenty-first century (IPCC 2012). Nonetheless, efforts have not focused on identifying which types of storms are responsible for these increases at the regional scale. Wright et al. (2013), Wright et al. (2014a, b) and Smith et al. (2011), for example, demonstrate that in the eastern United States, flood risk in medium to large watersheds is driven primarily by tropical and extratropical cyclones while flood risk in small watersheds is primarily driven by organized thunderstorm systems.

While general circulation models (GCMs) have been invaluable tools for studying past and future climate, there are numerous challenges in the use of GCMs for studying extreme weather phenomena (see, for example, Chen and Knutson 2008; Min et al. 2011). Dynamical downscaling of GCM output using higher-resolution regional climate models (RCM) simulations is one promising direction to better understand the relationship between climate change and extreme weather including tropical cyclones (see, for example, Gao et al. 2012). In this study, we use the Zetac RCM, developed primarily to simulate Atlantic-basin hurricane activity, to explore the frequency and rainfall intensity of landfalling tropical cyclones in the eastern United States. Knutson et al. (2007, 2008, 2013) have used this RCM to examine various properties of Atlantic-basin tropical cyclones, including rainfall, but did not focus on landfalling systems. This study focuses on exploring changes in future rainfall and not on attributing these changes to a particular physical mechanism. It is reasonable to suspect, however, that physical characteristics of the land such as elevated surface roughness, thermal properties, and the existence of large-scale topographic features would lead to differences in tropical cyclone rainfall over land relative to over the ocean. It is possible that the influence that these properties exert on tropical cyclone rainfall is not fixed in a changing climate.

Substantial resources have been focused on understanding both the historical and future storm climatology in the Atlantic tropical cyclone basin and globally (see Knutson et al. 2010). Recent work suggests that there is little evidence in the historical record for systematic century-scale changes in the frequency of Atlantic-basin tropical cyclone activity (see, for example, Vecchi and Knutson 2008), although observational studies do show an increase in the destructive potential of Atlantic hurricanes since the mid-1970s Emanuel (2005, 2007). A growing number of model studies point to possible increases in tropical cyclone

intensity over the Atlantic basin in the twenty-first century (Villarini and Vecchi 2012a; Knutson et al. 2013), while projected changes in frequency are less robust (Villarini and Vecchi 2012b; Knutson et al. 2010, 2013).

While numerous studies have focused on characterizing tropical cyclone rainfall using observations (Lonfat et al. 2004; Shepherd et al. 2007; Matyas and Cartaya 2009; Matyas 2010; Villarini et al. 2011; Jiang et al. 2012; Prat and Nelson 2012) or models (Tuleya et al. 2007; Kimball 2008; Langousis and Veneziano 2009a, b), fewer have focused on examining past or future time trends in tropical cyclone rainfall based on observations or modeling. Lau et al. (2008) found increasing trends in extreme rainfall from tropical cyclones in the North Atlantic over the 1979–2005 period using satellite-based precipitation observations. Kunkel et al. (2010) show that extreme rainfall from U.S. landfalling tropical cyclones has been higher during the 1994–2008 period than the historical average, even when fluctuations in changing cyclone frequency are considered. In terms of models, Knutson et al. (2008, 2013) project increases in twenty-first century tropical cyclone rainfall rates in the Atlantic basin using the same Zetac RCM used in this study. Villarini et al. (2014b) found increases in twenty-first century tropical cyclone rainfall in all tropical cyclone basins under a range of idealized modeling scenarios. These studies have focused on basin-wide rain rates, however, rather than rainfall over land.

With this paper, we hope to advance the understanding of rainfall properties from landfalling tropical cyclones at the regional scale from a modeling perspective, and examine how these rainfall properties may change in a changing climate. In Sect. 2, we introduce the RCM, modeling approach, and model scenarios. In Sect. 3 we present analyses of observed and simulated frequency of landfalling tropical cyclones over the eastern United States. In Sect. 4 we present analyses of observed and simulated tropical cyclone rainfall, focusing on the eastern United States and contrasting these findings with results over the ocean. We close with discussion and conclusions in Sect. 5.

## 2 Description of climate model and output

In this paper, we use model output from climate scenarios introduced in Knutson et al. (2008) and expanded in Knutson et al. (2013). Each scenario is comprised of 27 seasons of August–October simulated Atlantic-basin hurricane activity using the Zetac atmospheric RCM, which is principally designed for simulating Atlantic basin hurricane activity (Knutson et al. 2007). Due to the high computational demands of the Zetac model, we focus on the core months of the North Atlantic hurricane season (August–October). While we are able to simulate the 3-month “core”

of more individual years this way, it does mean that we cannot examine the climate change simulations for changes in the length of the hurricane season under climate change.

The experimental design used here assumes that the interannual and shorter-timescale variability from the NCEP reanalysis (see Kalnay et al. 1996) is also applicable to the climate change scenarios. Therefore, the seeding of disturbances at the eastern boundary of the model also remains unchanged in the climate change runs. Though this an idealized assumption, the climate change-induced modifications to such variability are highly uncertain, providing some rationale for using such an experimental design at this stage. Similar idealized approaches have been used to define the climate change environment for simulations in a number of previous studies (e.g. Knutson et al. 2008; Hara et al. 2008; Mallard et al. 2013; Rasmussen et al. 2011; Lackmann 2013), although the procedures vary in their degree of idealization. For example, Hara et al. (2008) and Rasmussen et al. (2011) add averaged three-dimensional perturbation fields that vary by month of the year to the control fields, including initial and boundary conditions, for regional snow depth simulation, similar to the seasonal mean perturbation method used here and in Knutson et al. (2008) but assuming no changes in relative humidity. Mallard et al. (2013) conduct hurricane-climate change simulations with a regional atmospheric model that used atmospheric temperature change perturbations that are a function of pressure alone, and a uniform SST change, and thus they do not include changes in the vertical wind shear, relative humidity, nor the incipient disturbances in model initial or boundary conditions. Lackmann (2013) simulates climate change effects on a single storm/flooding event using time-averaged atmospheric temperature change perturbations which vary spatially and thus lead via geostrophic influence to changes in the environmental wind fields, while assuming no change in relative humidity or initial/boundary disturbances.

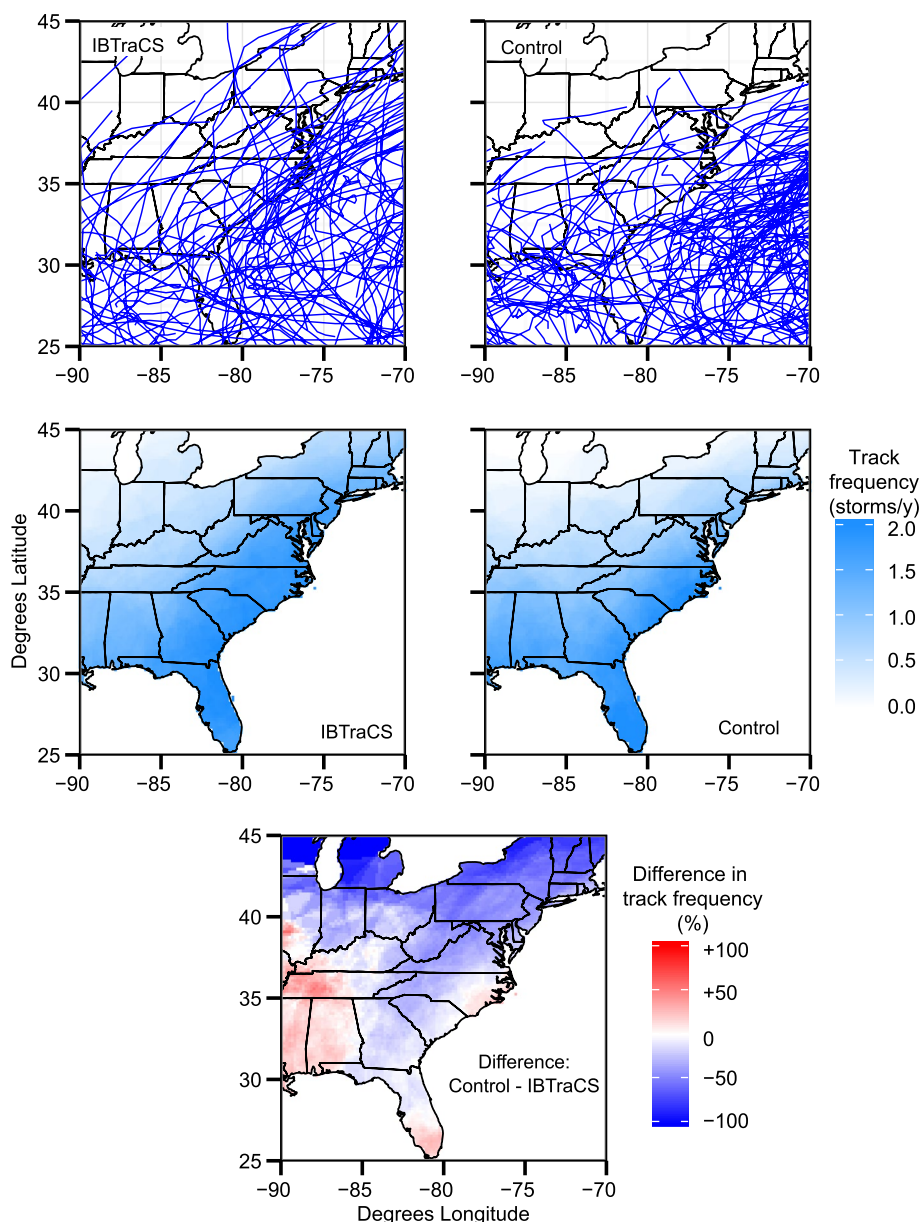
The model domain covers the tropical and subtropical Atlantic, parts of west Africa, the Gulf of Mexico, and eastern North America, with a  $1^\circ/6^\circ$  (approximately 18 km) grid size. 45 unevenly-spaced vertical levels are used, with the lowest model level at a height of 22 m. Spectral nudging is applied in both the control and climate change simulations using NCEP reanalysis fields of sea surface temperature (SST), atmospheric temperature, moisture, and winds (with modifications described below in the climate change runs). This technique maintains a realistic large-scale simulation (wavenumbers 0–2 of the model domain in both zonal and meridional direction) in the control (1980–2006) simulations, while smaller-scale disturbances such as hurricanes are relatively unconstrained within the model. Radiative atmospheric constituents (e.g.,  $\text{CO}_2$ , aerosols) are not explicitly modified in the climate change runs, although

their effects are implicitly included as the atmospheric profiles are nudged toward modified profiles based on difference fields derived from the climate models. The nudging time scale (3 h) is short enough that it prevents significant atmospheric temperature drift during the simulations and eliminates the need to explicitly include changes in trace gas concentrations. No convective parameterization is used due to the negative impacts that such parameterizations can have on cyclone genesis (see Han and Pan 2006; Gentry and Lackmann 2006; Zhao et al. 2012).

Knutson et al. (2007) describe a procedure for identifying hurricane and tropical storm tracks in Zetac based on simulated storm properties. Six-hourly tropical storm tracks are generated, as well as concurrent instantaneous rainfall rates, maximum windspeeds, and minimum pressures. It should also be noted that the tracking procedure will not necessarily follow a storm through extratropical transition, despite the fact that the transitioning storm may still produce heavy rainfall. Knutson et al. (2007) demonstrate that the Zetac model can reproduce observed multi-decadal trends as well as interannual variations in Atlantic-basin tropical cyclone activity for the 1980–2006 period. When run with NCEP Reanalyses as large-scale nudging conditions updated for 1980–2013, the Pearson correlation coefficient ( $r$ ) between the model simulated August–October and observed storm counts over the entire Atlantic tropical cyclone basin are 0.75 for tropical storms and 0.70 for hurricanes. For U.S. landfalling cyclone counts, the model's correlation with the observed is  $r = 0.54$  for tropical storms, though negligible ( $r = 0.17$ ) for hurricanes. Knutson et al. (2008) use the model to compare simulated 1980–2006 storm activity (henceforth referred to as “control”) to 27 years of late twenty-first century climate conditions forced by the 18-member ensemble mean climate perturbation from the Climate Model Intercomparison Project 3 SRES A1B scenario (Meehl et al. 2007; henceforth referred to as “CMIP3”), projecting a decrease in Atlantic-basin tropical cyclone frequency and a significant increase in tropical cyclone intensity including rainfall. Knutson et al. (2013) compare control simulations to simulations from ten individual CMIP3 models and to early and late twenty-first century simulations forced using the 18-member ensemble mean of the CMIP5 RCP4.5 scenario [Taylor et al. 2011, henceforth referred to as “early (or) late CMIP5”]. It should be noted that while previous work using Zetac includes the same landfalling storms that are analyzed in this study, the previous studies did not focus on the properties of rainfall during or after landfall.

For simulations of future climate, the NCEP reanalysis fields are modified using a time-invariant three-dimensional climatological change field based on the GCM ensemble results. For the CMIP3 scenario, this change field is computed as the difference between the August–October time

**Fig. 1** Comparison of tropical cyclone tracks from IBTraCS and from the Zetac control simulations for the 1980–2006 period. *Top panels:* raw tracks. *Middle panels:* number of tracks per year that pass within 500 km of a given point. *Bottom panel:* percentage difference between the number of tracks per year that pass within 500 km of a given point between Zetac control and IBTraCS



averages of the 2081–2100 and 2001–2020 periods. For the early and late twenty-first century CMIP5 scenarios, the change field is computed as the difference between August–October time averages for 2016–2035 and 2081–2100 periods of the RCP4.5 scenario, respectively, and the baseline 1986–2005 period from the historical climate simulations. This implies an earlier baseline, and hence a longer timespan between averaging periods for the late twenty-first century runs than that used for CMIP3. Additional details on the procedure can be found in Knutson et al. (2013).

Knutson et al. (2013) also examine 5-day simulations of individual storms from the Zetac simulations using a higher-resolution hurricane model. They find a significant increase in maximum windspeed and rain rates in both CMIP3 and CMIP5 ensemble means relative to control.

Maximum wind speeds and rainfall rates from the downscaled hurricane model simulations are generally higher than those from the Zetac model. The 5-day downscaled hurricane simulations were focused on the time of maximum storm intensity rather than the landfalling or overland stages, however, and thus are not generally suitable for the purposes of this study.

### 3 Tropical cyclone frequency

We examine both observed and simulated August–October tropical cyclone tracks over the 1980–2006 period. Observed tracks are drawn from the International Best Track Archive for Climate Stewardship (IBTraCS; see



Knapp et al. 2010), which provides estimates of historical track locations and intensities (maximum sustained wind speed, and minimum central pressure) at 6-h intervals. We show the observed and simulated control tracks, the frequency of tracks passing within 500 km of a given point, and the percentage difference between the simulated and observed storm track frequency (Fig. 1). The 500 km distance criteria has been used to define tropical storm activity such as extratropical transition Hart and Evans (2001), rainfall (Lonfat et al. 2004; Kunkel et al. 2010; Wright et al. 2013, 2014a, c), and flooding (Villarini and Smith 2010; Wright et al. 2014b). In this study, we define landfall as when the track passes within 500 km of the coast. While more strict definitions of landfall could be used, the one chosen is reasonable in the context of flood-inducing rainfall because even if the storm center does not pass directly over land, significant inland rainfall and flooding may still occur.

Raw tracks and track frequency in the control simulations show geographic biases compared with IBTraCS (see Fig. 1; Table 1). There is a slight underestimation of storm tracks over land in the control simulations relative to IBTraCS. Knutson et al. (2007) show that Zetac simulated storm frequency is more closely correlated with historical track counts over the entire Atlantic tropical cyclone basin than with U.S. landfalling tropical cyclone counts. Encouragingly, the control simulations capture the reduction in frequency west of the Appalachians. The simulations, however, overestimate frequency in the southern tip of Florida and show too sharp a reduction in frequency moving northward along the coast. The frequency of tracks passing within 500 km of major cities along the east coast reveals systematic geographic biases between IBTraCS and the Zetac control runs ranging from 20 % overestimation near Miami to 48 % underestimation near New York (Table 1). It should be noted, however, that despite these persistent geographic biases, none of the differences between simulated and observed annual track frequencies shown in Table 1 are significant at the 5 % level. The negative bias in storm occurrence in the northern part of the domain can be explained to some degree by the artificial dissipation of storms as they approach the Zetac model's northern boundary at 45°N (see e.g. Knutson et al. 2007). Another source of bias may be the transition of some storms from tropical to extratropical within the simulation domain, in which case they may no longer be identified by the tropical storm tracking algorithm and are thus not included in the analyses. Finally, the criteria used for identifying Zetac storm tracks differ somewhat from those used in IBTraCS, so some variations may be attributable to differences in track identification algorithms.

We examine storm frequency and the relative change in frequency relative to control for the three future climate scenarios (Table 2 and the left and right panels of Fig. 2). Consistent with results over the entire Atlantic tropical cyclone basin in Knutson et al. (2008) and Knutson et al. (2013), all future climate scenarios show statistically significant reductions in tropical cyclone frequency over the ocean. Over land, there is less consistency across the future climate scenarios. The reductions in CMIP3 tropical cyclone frequency relative to control over the eastern United States is similar to the reduction over the ocean. In the CMIP5 scenarios, however, the reduction over land is much less pronounced. Storm frequency is generally lower in late CMIP5 than in the early CMIP5 runs in the southeastern United States, consistent with Knutson et al. (2013). The differences between the early and late CMIP5 simulations are minimal in the mid-Atlantic states and New England.

We also examine the fraction of storms that make landfall, which is defined here as any tropical cyclone track that passes within 500 km of land (Table 3). The fraction of storms that make landfall is not statistically different at the 5 % level between the control simulations (43 %), IBTraCS (40 %), and the CMIP3 simulations (44 %). In both

**Table 1** Comparison of tracks per year over land, over the ocean, and passing within 500 km of six east coast cities over the 1980–2006 period in IBTraCS and the Zetac control simulations

	(Tracks/year)		Difference (control–IBTraCS) (%)
	IBTraCS	Zetac control	
Over land	4.4	4.1	–7
Over ocean	6.7	7.0	+4
Miami	1.7	2.0	+20
Orlando	1.9	1.9	–2
Atlanta	1.3	1.2	–3
Charlotte	1.7	1.3	–24
Washington, DC	1.6	1.1	–31
New York City	1.0	0.5	–48

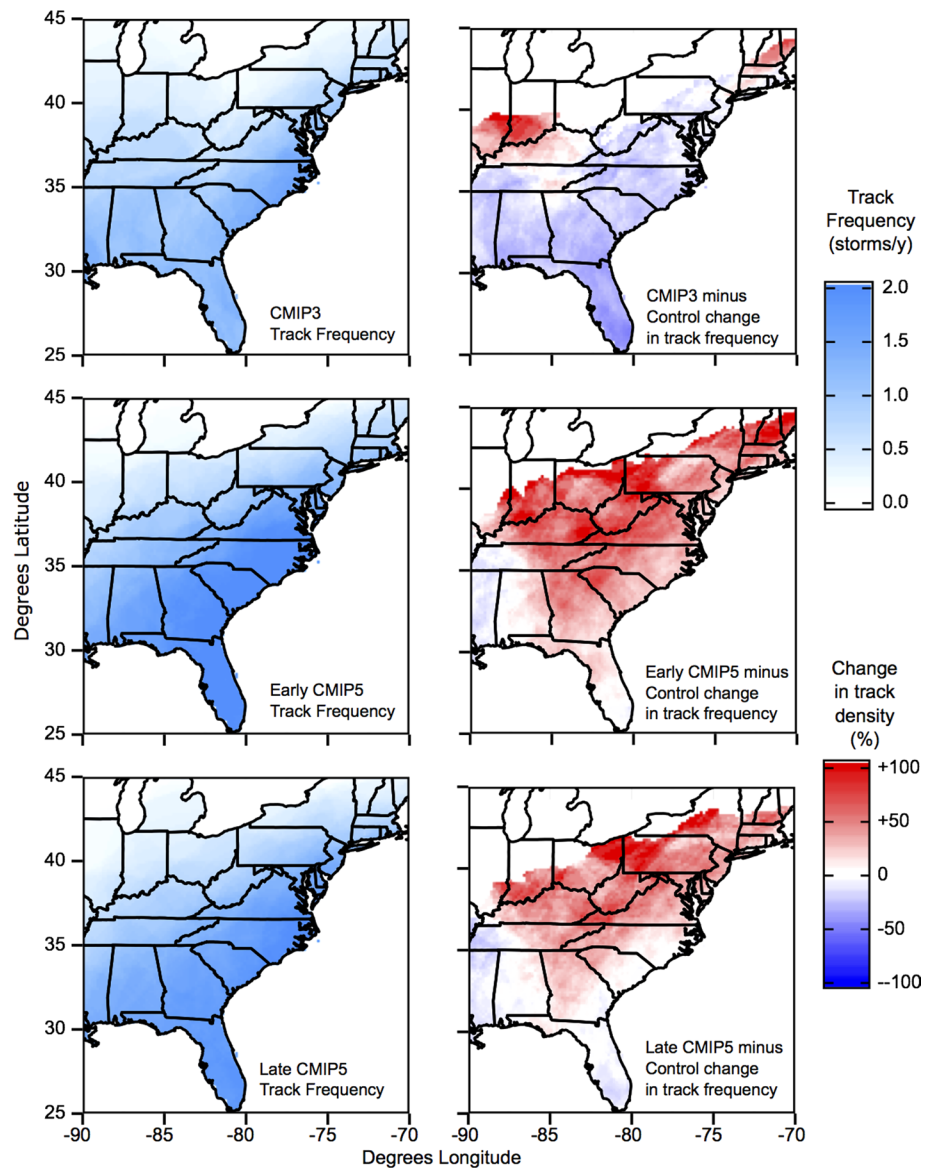
Differences between control simulations and IBTraCS are not significant at the 5 % level

**Table 2** Comparison of storm tracks per year over land and over the ocean in the Zetac future climate and control simulations

	CMIP3	Early CMIP5	Late CMIP5
Tracks/y (% change over control)			
Over land	3.0 (–27 %)	4.1 (no change)	3.9 (–5 %)
Over ocean	5.1 (–27 %)	4.9 (–30 %)	4.8 (–31 %)

Numbers in parentheses indicate the percent change in the number of tracks in the future climate runs compared with the control run. Differences in bold are significant at the 5 % level

**Fig. 2** Comparison of tropical cyclone tracks from Zetac future climate scenarios. *Left panels* number of tracks per year that pass within 500 km of a given point. *Right panels* percentage difference between the number of tracks per year that pass within 500 km of a given point in the future climate scenarios and the control simulations. The percentage difference is masked out for clarity in regions where the number of tracks per year is less than 0.5



**Table 3** percentage of total tracks that make landfall

Scenario	Landfalling percentage
Control	43
IBTraCS	40
CMIP3	44
Early CMIP5	<b>52</b>
Late CMIP5	<b>52</b>

A landfalling storm is defined as any tropical cyclone track that passes within 500 km of land. Values in bold are significantly different than the control simulation landfalling percentage at the 5 % level

the early and late CMIP5 simulations, however, the fraction of storms that make landfall is 52 %, statistically different at the 5 % level from the control simulations.

#### 4 Tropical cyclone rainfall

Before presenting differences between the control and future climate simulated tropical cyclone rainfall, we compare Zetac control rainfall against several observation-based studies. Building on the intercomparisons of observations in Lonfat et al. (2004), we compare the probability density function (PDF) of gridded instantaneous rain rate from the control simulations against results from several previous studies of tropical cyclone rainfall structure (Table 4). Miller (1958) groups hourly rain gage observations from ten landfalling hurricanes in Florida into a grid of 1° boxes. Frank (1977) studies the rainfall structure of western Pacific typhoons within 2° bands centered on the storm center using hourly rain gage data from observing stations on number of small islands. Marks

**Table 4** Comparison of Zetac per grid cell rain rates compared with previous studies

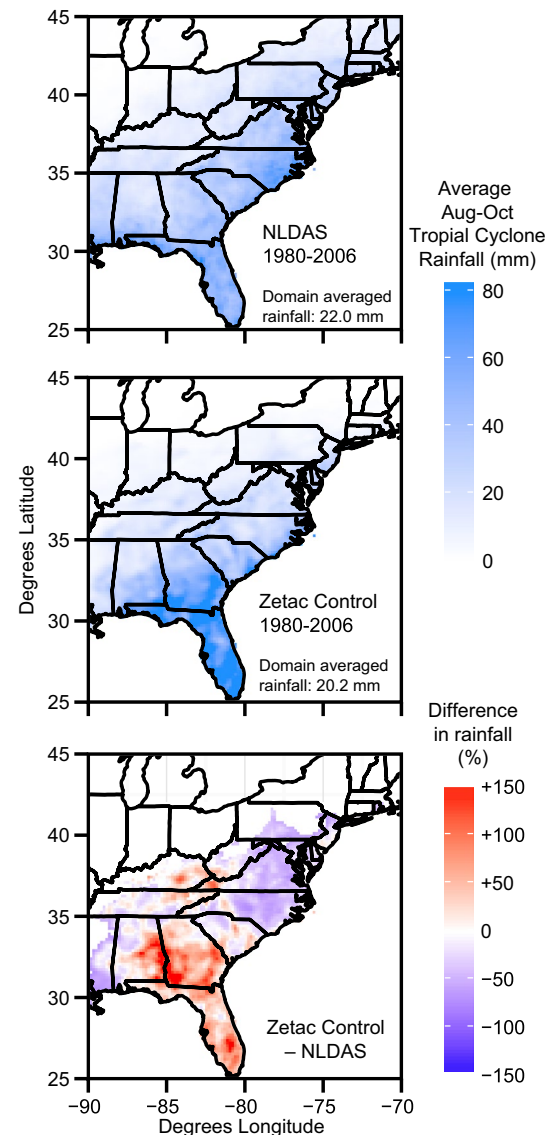
Study	Rain rate threshold (mm/day)			
	<6	6–150	150–450	>450
Gages, 1° grid (Miller 1958)	32	47	17	4
Gages, 2° band (Frank 1977)	30	54	13	3
radar, 111-km radius (Marks 1985)	23	69	6	2
TRMM, 111-km radius (Lonfat et al. 2004)	0.5	74	21	4.5
TRMM, 222-km radius (Lonfat et al. 2004)	1	81	16	2
TRMM, 500-km (Lonfat et al. 2004)	1	84	13	2
Zetac, 111-km radius over ocean	24	41	19	15
Zetac, 222-km radius over ocean	39	40	13	8
Zetac, 500-km radius over ocean	57	32	8	3
Zetac, 111-km radius over land	21	44	20	15
Zetac, 222-km radius over land	35	43	15	7
Zetac, 500-km radius over land	55	34	8	3

Zetac rainfall is partitioned into rain rate intervals used in previous studies. In the results from Marks (1985), Lonfat et al. (2004), and the Zetac model, rain rate statistics are expressed as the percentage of the total number of grid cells with a rain rate at the indicated distance from the storm center

(1985) uses airborne radar to characterize the precipitation from Hurricane Allen in 1980. Lonfat et al. (2004) derive PDFs from three years (1998–2000) of instantaneous rain rates from tropical cyclones from the Tropical Rainfall Monitoring Mission (TRMM) microwave imager (see Kummerow et al. 1998) in the Atlantic, Pacific, and Indian Oceans. The results in Table 4 from Marks (1985), Lonfat et al. (2004), and the Zetac model are presented for several concentric range “bands” centered on the storm center.

As Lonfat et al. (2004) emphasize, these different methodologies, datasets, time periods, and geographic settings make direct quantitative comparison of the results difficult. They note, for example, pronounced biases in the measurement of low rain rates using TRMM, which can be seen in Table 4. Likewise, Habib et al. (2009) find underestimation of both low and extreme tropical cyclone rain rates using a TRMM-based rainfall product, while Berg et al. (2006) note regional biases in TRMM estimates.

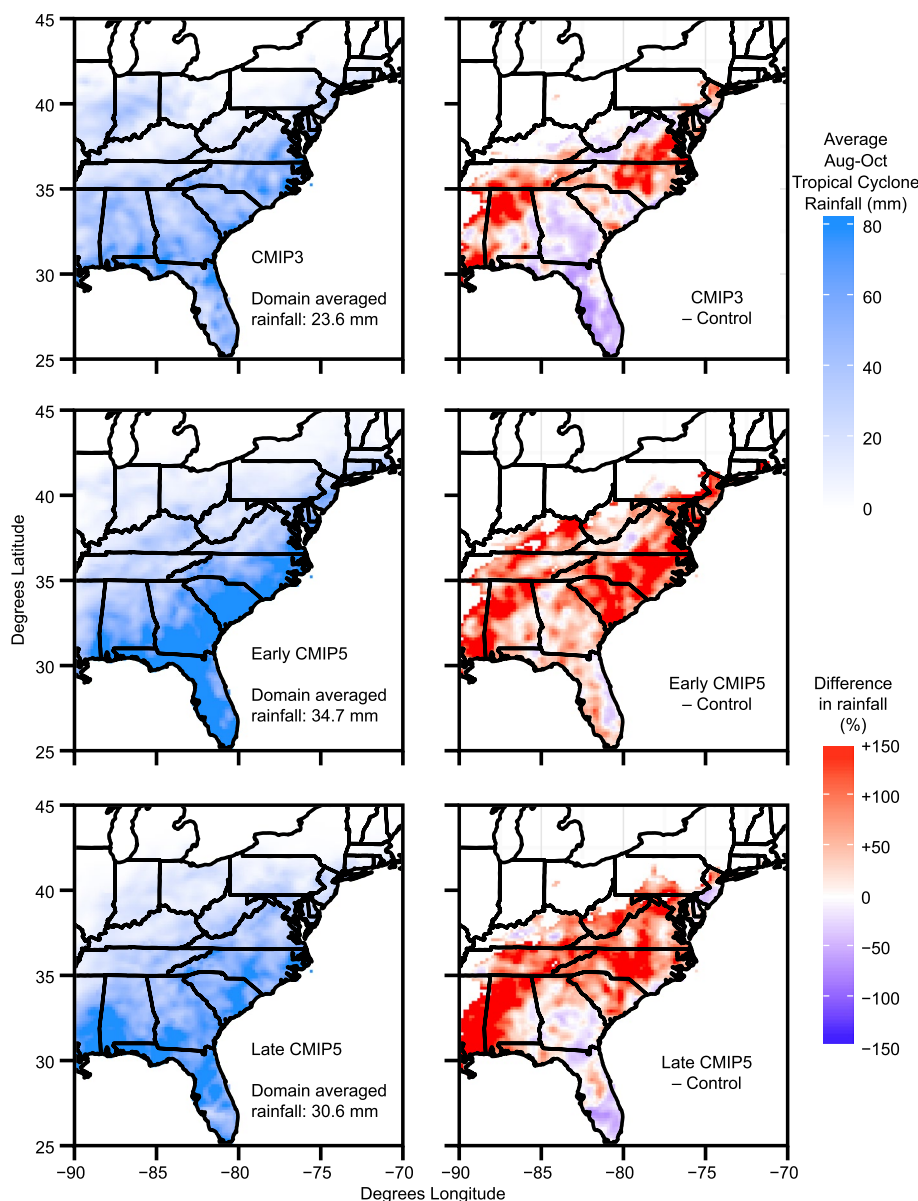
To facilitate comparisons, we aggregate the Zetac rainfall to match the spatial resolution of TRMM (1/4°, approximately 25 km). The low rain rates shown in Table 4 (<6 mm/day) are similar between Zetac and the remaining results (i.e. those not based on TRMM). While the highest rain rates (>450 mm/day) in Zetac are higher than from other studies, it is not clear whether these simulated rain rates are indeed unrealistic. The aforementioned underestimation of extreme rainfall using TRMM-based products



**Fig. 3** Comparison of average August–October tropical cyclone rainfall between NLDAS and Zetac control simulations for the 1980–2006 period. In the *bottom panel*, areas in which rainfall is less than 2.5 mm are excluded for clarity

by Habib et al. (2009) suggests that the estimates of high rain rates from Lonfat et al. (2004) may also be biased low. Meanwhile, the coarse resolutions used in Miller (1958) and Frank (1977) suggest that extreme rainfall estimates from these studies should be lower than higher-resolution results due to spatial averaging. Finally, the estimates in Marks (1985) are based on a single storm. In summary, while it is difficult to validate rain rates and rainfall structure, the simulated results from Zetac are not obviously contradicted by previous observation-based studies. Another important observation from Table 4 is that Zetac rain rate PDFs do not vary significantly between tracks over land and over the ocean.

**Fig. 4** Average August–October tropical cyclone rainfall for the three future climate scenarios (*left panels*) and change in tropical cyclone rainfall between future climate and control (*right panels*). In the *right panels*, areas in which rainfall is less than 2.5 mm are excluded for clarity



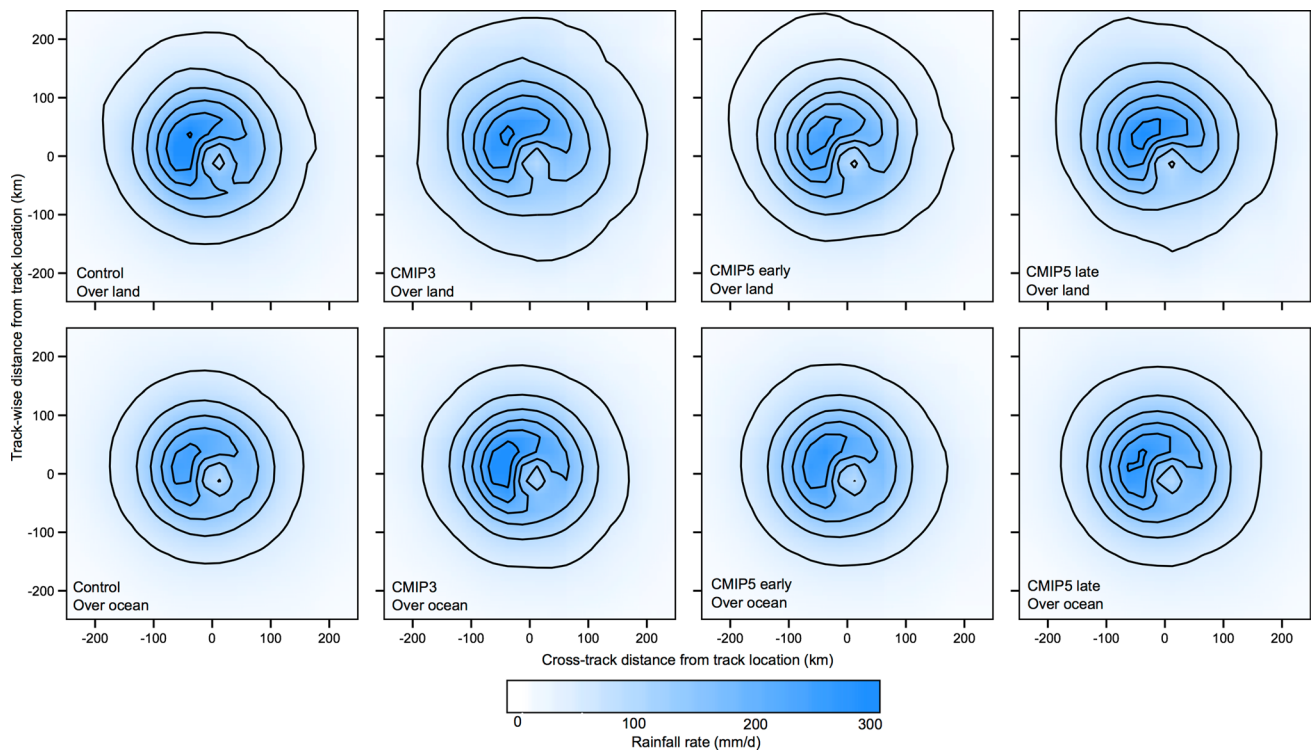
**Table 5** Counts of storms and individual 6-h track periods that are used in the computation of track-centered rainfall composites shown in Figs. 5, 6, 7, 8 and Table 6

	Over land		Over ocean	
	Storms	6-h track periods	Storms	6-h track periods
Control	111	1238	300	8542
CMIP3	82	968	221	6036
Early CMIP5	111	1392	242	5915
Late CMIP5	106	1215	235	7098

We also compare average August–October 1980–2006 tropical cyclone rainfall from Zetac control simulations to radar and rain gage-based precipitation observations

from the North American Land Data Assimilation System (NLDAS; see Mitchell et al. 2004). The NLDAS precipitation has been regridded from its native 1/8° resolution to the same spatial resolution as Zetac (Fig. 3). Only rainfall that is concurrent to and within 500 km of a storm track is included in the calculations. Both the modeled and observed August–October tropical cyclone precipitation is similar in magnitude to results presented in Prat and Nelson (2012). The Zetac model shows high tropical cyclone rainfall in the Southeast, particularly in Florida and Georgia, and lower rainfall in North Carolina and the mid-Atlantic states. The differences in modeled rainfall relative to observations do not coincide fully with differences between modeled and observed storm tracks. Despite spatial differences, the domain-averaged rainfall is similar between





**Fig. 5** Average track-centered rain rates for storms in control and future climate simulations. Rainfall fields have been oriented so the positive y-axis is oriented in the direction of track motion. The num-

bers of storms/6-h time periods included in each average composite are shown in Table 5

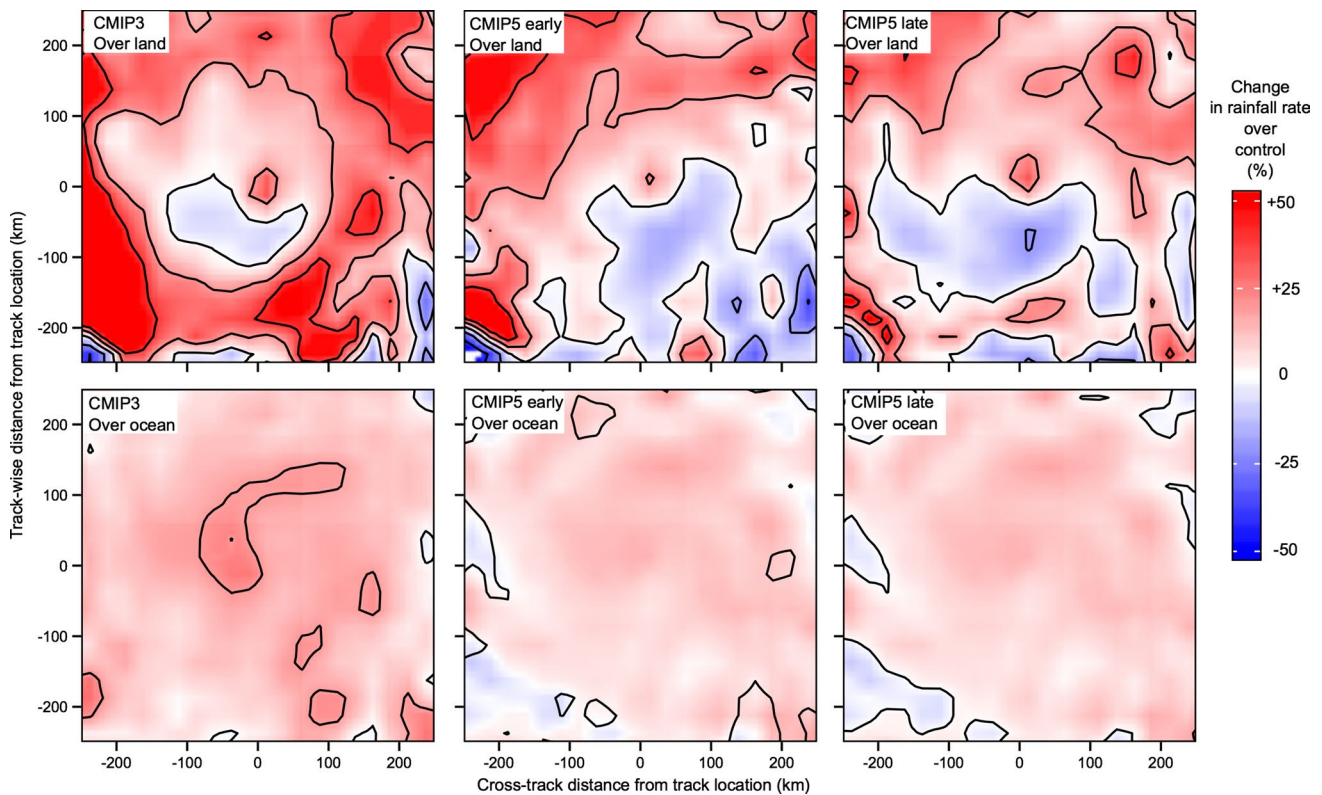
NLDAS observations and Zetac control simulations (22.0 and 20.2 mm, respectively).

We calculate the average August–October tropical cyclone rainfall from the three future climate scenarios (Fig. 4). These show heavier rainfall over North Carolina, Tennessee, and Virginia in the future climate. In the CMIP3 and CMIP5 late scenarios, rainfall over Florida and Georgia is generally less than in the control simulations. In some locations, such as southern Florida, the rainfall differences coincide with differences in storm frequency. Along with the variability amongst the future climate scenarios and differences between these scenarios and the control rainfall, this suggests that at least some geographic differences in simulated rainfall may be due to small-sample variation in storm frequency rather than significant geographic shifts in tropical cyclone rainfall. Domain-averaged seasonal rainfall is greater in the climate change scenarios than in the control simulations. It is also greater in the CMIP5 than in CMIP3. This is due to the greater storm frequency in CMIP5 relative to CMIP3, rather than increased rainfall per storm, as demonstrated below.

We examine average composite track-centered simulated rain rates for tropical cyclones over land and over the ocean (Fig. 5). The rainfall field at time  $t$  in Fig. 5 is translated so that the track location is located at the origin and rotated

such that the direction of track motion is oriented along the positive y-axis. Rain rates are not axisymmetric, with the heaviest rainfall in the composites ahead and somewhat to the left of the track location. It should be noted that these composites mask considerable variations in asymmetry between storms. The number of storms and individual 6-hourly track periods that go into each of the average composites shown in Fig. 5 are provided in Table 5. These counts also pertain to Figs. 6, 7 and 8 and Table 5. Note that the percentage of storms over land relative to over the ocean in Table 5 does not match exactly with those shown in Table 3 because only rainfall fields in which the 500 km radius from the track location falls completely within the modeling domain are included in the average composites.

The results are consistent with previous examinations of tropical cyclone rainfall structure including Lonfat et al. (2004) and Chen et al. (2006). In both the control and future climate scenarios, the rainfall contours farthest from the storm center in Fig. 5 more closely resemble regular circles over the ocean than over land, suggesting that the model captures the breakdown in storm cyclonic structure during and after landfall. Some increase in the spatial extent of average composite track-centered simulated rain rates can be seen in the future climate scenarios relative to control over land. In contrast, over the ocean, there is an



**Fig. 6** Change in average track-centered rain rate for storms for future climate simulations compared with control simulations. Rainfall fields have been oriented so the positive y-axis is oriented in the

direction of track motion. The numbers of storms/6-h time periods included in each average composite are shown in Table 5

increase in rainfall intensity in the future scenarios relative to control, but little impact in terms of spatial extent, at least in the outermost rainfall contours. Other changes in spatial structure, such as asymmetry, appear to be minimal.

We also calculate the percent change between average composite track-centered simulated rain rates over land and over the ocean in the future climate scenarios and the control (Fig. 6). Over land, the greatest increases in track-centered rain rates occur distant from the storm center, with some reduction in rainfall near the storm center to the rear of the track location. This contrasts with results over the ocean, where there is generally more uniform increase in rainfall across the domain with larger increases near the storm center. It also contrasts with the differences in track-centered rain rates for all Atlantic-basin storms between CMIP3 and control simulations in Knutson et al. (2008) (Supplemental Material) and CMIP3 and CMIP5 versus control simulations in Knutson et al. (2013). This discrepancy is examined and discussed in more detail below.

Using the composite rain rates shown in Fig. 5, we calculate the azimuthally-averaged rain rate for averaging radii up to 500 km for tracks over the United States and

again for tracks over the ocean (Fig. 7, top panels). From these azimuthally-averaged rain rates, we calculate the percent change between the future climate and control simulations (Fig. 7, bottom panels). The results show that over land, the greatest increases in future tropical cyclone rain rates are far from the storm center, (i.e. outside of the eyewall region). This contrasts with the results over the ocean, and with the results shown in Knutson et al. (2008) (Supplemental Material) and Knutson et al. (2013) for all Atlantic-basin storms, in which the greatest increases in rainfall rates are shown to be near the eyewall. The result is generally consistent when one calculates the means and medians of the composite rain rates at 150 and 500 km averaging radii (Table 6), though the increase in the median late CMIP5 rain rates over control at the 500 km averaging radius is lower over land (4 %) than over the ocean (7 %). It should also be noted that the increases in azimuthally-averaged rainfall rates projected using Zetac, both in this study and from Knutson et al. (2008) (Supplemental Material) and Knutson et al. (2013), are less than the increases projected by higher-resolution modeling efforts using a dedicated numerical hurricane model (Knutson et al. 2013) and the Weather Research and Forecasting model with idealized tropical cyclone conditions from the CMIP3/A1B scenario

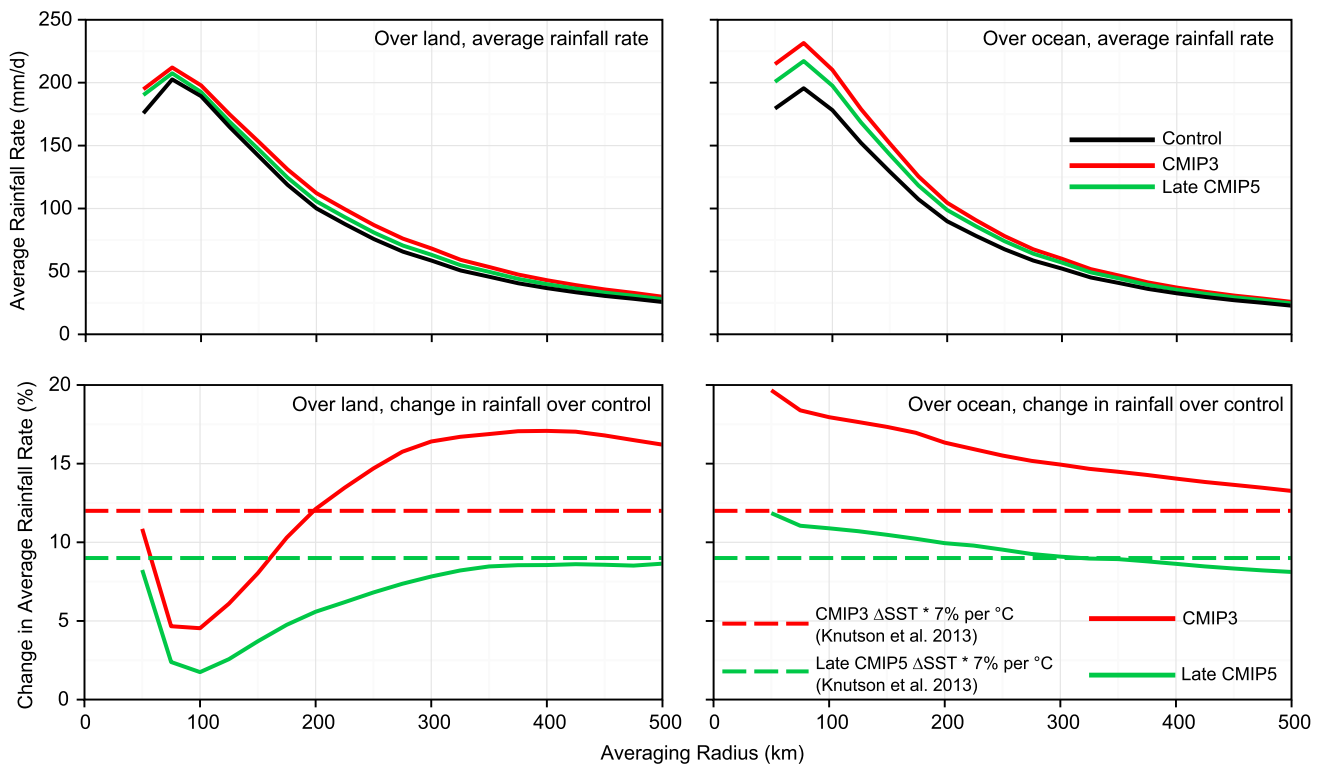
**Table 6** Mean and median simulated track-centered tropical cyclone rain rates from control and three future climate scenarios

	150 km radius		500 km radius	
	Mean rain rate	Median rain rate	Mean rain rate	Median rain rate
	mm/day (% change over control)			
<b>Over land</b>				
Control	140.5 (-)	121.2 (-)	25.7 (-)	23.4 (-)
CMIP3	151.7 (+8)	134.1 (+10)	29.9 (+16)	28.4 (+21)
Early CMIP5	148.9 (+6)	134.5 (+11)	28.6 (+11)	26.7 (+14)
Late CMIP5	145.5 (+4)	126.7 (+5)	27.9 (+9)	24.4 (+4)
<b>Over ocean</b>				
Control	128.2 (-)	113.7 (-)	22.8 (-)	20.5 (-)
CMIP3	150.2 (+17)	134.8 (+19)	25.8 (+13)	23.6 (+15)
Early CMIP5	139.1 (+9)	124.6 (+10)	24.8 (+9)	22.6 (+10)
Late CMIP5	141.3 (+10)	128.6 (+13)	24.6 (+8)	22.0 (+7)

The number of storms/6-h time periods included in each scenario is shown in Table 5

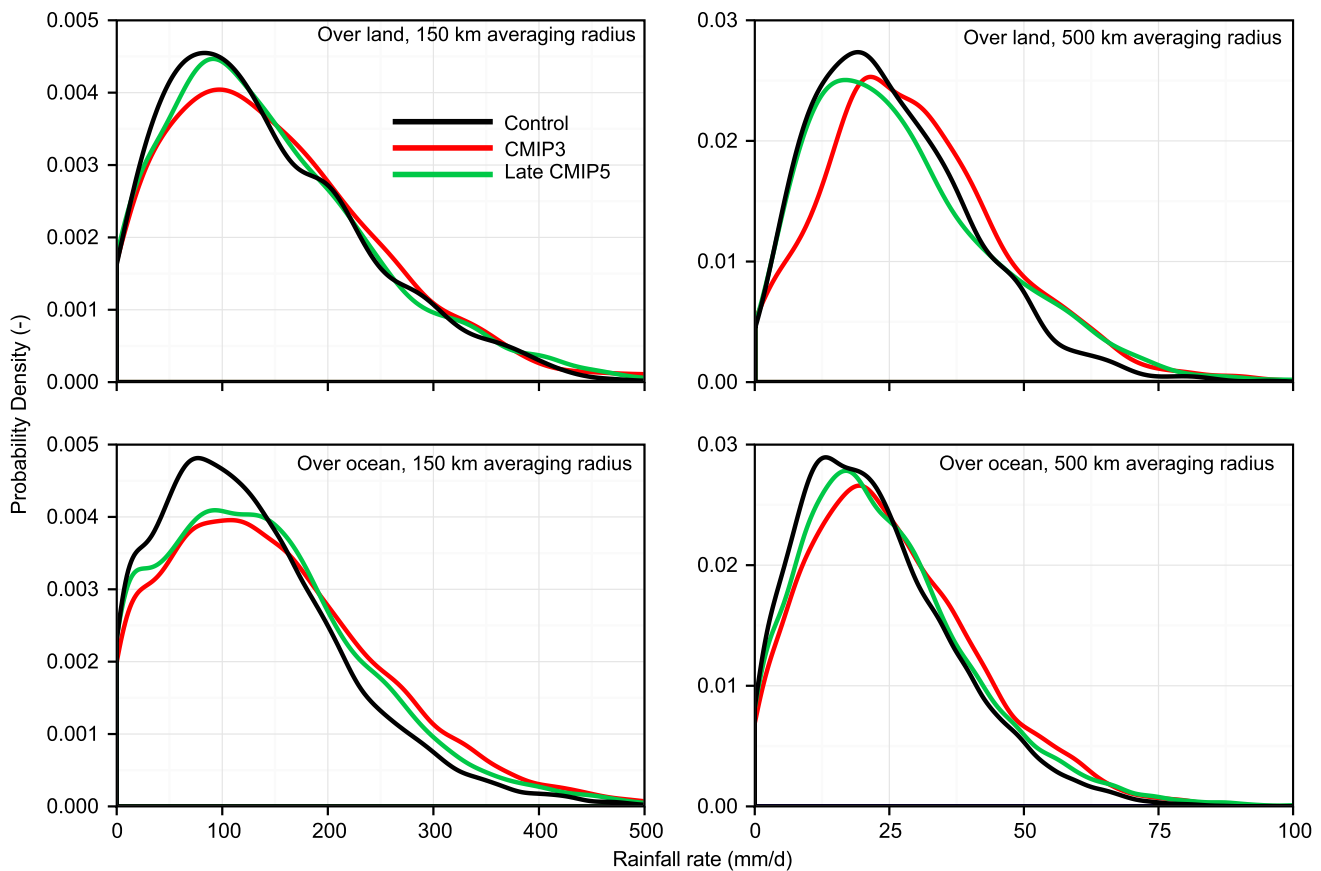
(Hill and Lackmann 2011). Neither of these higher-resolution modeling studies focused on landfalling cyclones, however.

We compare the simulated changes in late twenty-first century tropical cyclone rain rates to the idealized Clausius-Clapeyron scaling relationship of an increase in atmospheric moisture content of approximately 7 % per degree Celsius increase in projected average change in SST in the region 10–25°N, 20–80°W (bottom panels of Fig. 7). Projected increases in azimuthally-averaged rainfall rates over the ocean are greater than those predicted by the Clausius-Clapeyron scaling at distances relatively close to the storm center, but converge toward this scaling as the averaging radius increases. This is broadly similar to analysis of idealized scenarios presented in Villarini et al. (2014b) using three CMIP5 GCMs. Over land, the rain rate increases in the eyewall region are quite small but increase with increasing averaging radii. While the late CMIP5 rain rates over land converge to the Clausius-Clapeyron scaling relationship, the



**Fig. 7** Top panels average track-centered rain rates as a function of azimuthal averaging radius for control and late twenty-first century climate scenarios. Bottom panels change in average track-centered rain rates as a function of azimuthal averaging radius for late twenty-first century climate scenarios relative to control. Results are shown

for landfalling tracks over the eastern United States (left panels) and for tracks over the ocean (right panels). Dashed lines in the bottom panels are explained in the text. The numbers of storms/6-h time periods included in each scenario are shown in Table 5



**Fig. 8** Comparison of PDFs of azimuthally-averaged track-centered rain rates in the control and late twenty-first century climate scenarios for two averaging radii: 150 km (*left panels*) and 500 km (*right panels*)

for landfalling tracks over the eastern United States (*top panels*) and for tracks over the ocean (*bottom panels*). The numbers of storms/6-h periods included in each scenario are shown in Table 5

CMIP3 rain rates surpass this relation for averaging radii greater than 200 km. Rainfall rates for landfalling storms at large averaging radii over the eastern United States are projected to increase roughly 8–17 %, depending on the scenario. This is of particular importance for future inland flood risk because of the large areas potentially affected. An analysis of the time distribution of rainfall intensities in landfalling tropical cyclones does not reveal any significant differences in rainfall duration (results not shown).

We compute PDFs of the azimuthally-averaged track-centered rain rates for landfalling tracks over the eastern United States and tracks over the ocean (Fig. 8, top and bottom panels, respectively) for 150 and 500 km averaging radii. Consistent with previous results, and of importance with respect to future flood risks, the biggest increases in rain rates over land in the late twenty-first century climate scenarios can be seen in the 500 km averaging radius PDFs, which show a shift toward higher rain rates compared to control simulations. These shifts are less evident at the 150 km averaging radius. The relationship is reversed over the ocean, where the biggest changes are at the 150 km averaging radius.

## 5 Discussion and conclusions

In this study, we examine the frequency of landfalling tropical cyclones and their associated rainfall intensity using a dynamical downscaling approach with the Zetac RCM. The Zetac results for the 1980–2006 August–October seasons are compared against observations of cyclone tracks and rainfall. Three future climate scenarios, based on early twenty-first century CMIP5 and late twenty-first century CMIP3 and CMIP5 GCM ensemble mean changes, are compared against 1980–2006 RCM control simulations.

All future climate scenarios show statistically significant reductions in tropical cyclone frequency over the Atlantic ocean. CMIP3 simulations show a decrease in landfalling tropical cyclone frequency of 27 % in the eastern United States in the late twenty-first century, contrasting with the CMIP5 simulations, which show little to no significant change from the control simulations. Thus, the fraction of tropical cyclones that make landfall increases in the CMIP5 climate scenarios compared to the control. Geographic biases in simulated landfalling tropical cyclone frequency



highlight the need to better understand the sources of model error and variability, but may be attributable to the small number of samples. Future work should also assess other track characteristics such as recurvature in the control and future climate simulations.

The distributions of simulated tropical cyclone rainfall rates over the eastern United States and over the Atlantic Ocean compare favorably with the results of observational studies. Tropical cyclone rainfall simulated using the Zetac RCM shows spatial biases relative to observations, with heavier rainfall in the southeast and lighter rainfall over the mid-Atlantic states.

Projected track-centered instantaneous tropical cyclone rainfall intensities show the largest percentage increases over the eastern United States over the twenty-first century occurring outside of the eyewall region. The largest increases, of approximately 15 %, are projected in the CMIP3 simulations. Increases of approximately 10 % over the eastern United States are projected in the late twenty-first century CMIP5 simulations. Over the ocean, projected increases are similar in magnitude but occur closer to the storm center. There is also a shift toward more positively skewed tropical cyclone rain rate distributions in the future climate scenarios. The fact that there is a projected increase in rainfall intensity at relatively large radii over land has important implications for flood risk, since it implies that future landfalling storms may produce heavy rain over larger land areas. This result also provides a possible mechanism to explain observational findings by Kunkel et al. (2010), who report a recent increase in the number of heavy tropical cyclone rainfall events measured by a network of 935 long-term climate stations across the eastern United States, beyond what would be expected based solely on trends in landfall frequency. If, due to climate warming, recent storms are on average producing more intense rainfall at distances far from the storm center relative to the historical average, then one would expect a corresponding increase in the number of heavy rainfall events detected by the climate station network, even in the absence of secular increases in landfalling storm frequency.

While this study focuses exclusively on trend detection, the reported differences between projected changes in rain rates over land and over the ocean suggest that physical properties of the land such as elevated surface roughness, distinct thermal characteristics, and the existence of large-scale topographic features may be important for understanding the response of tropical cyclone rainfall in a warming climate. On the other hand, preliminary downscaling results for all tropical cyclone basins indicate that the fractional rate of precipitation increase shows varying behavior in different basins, suggesting that the apparent tendency for rain rates to increase more near the storm

center than at larger radii may not be a robust modeling result (study forthcoming).

The results, along with differences in tropical cyclone rainfall projected by the Zetac regional model and higher-resolution 5-day simulations (generally over the ocean) using a numerical hurricane model shown in Knutson et al. (2013), suggest that more attention should be placed on high-resolution simulations over land. In that study, the authors show larger increases in near-track rainfall in future climate simulations relative to control using the higher-resolution hurricane model than in Zetac. The 5-day hurricane model simulations in Knutson et al. (2013), however, generally do not extend through landfall and so are not suitable for the purposes of this study.

One key challenge highlighted in this study is the need for relatively long model simulation periods for robust inference about tropical cyclone rainfall properties. Although the results are not presented in this paper, there is considerable noise when analyses are restricted to landfalling storms passing within 500 km of a specific location, due to the significant reduction in the number of storms available for examination. The 27-year simulation length using Zetac is imposed primarily by computational resource limits and concerns about homogeneity of the NCEP reanalysis, especially prior to 1980. One path for future work could be to expand the sample size from the Zetac model by running multiple ensemble members over the available years for the control and future climate scenarios. A further analysis of the tropical cyclone rainfall from Zetac runs based on the output of individual CMIP3 models (e.g. Knutson et al. 2013), rather than with ensemble means, would demonstrate the sensitivity of the downscaled climate change projections to forcing from different GCMs. Our experiments are not designed to examine the issue of possible attribution of past tropical cyclone rainfall changes to radiative forcings. This question requires investigation of CMIP3 or CMIP5 historical runs as well as possibly downscaling long CMIP3/CMIP5 control runs (internal variability only) to assess the influences of such factors as Atlantic multidecadal internal variability.

Landfalling tropical cyclones can produce significant rainfall independently of other commonly-used intensity measures such as maximum wind speed and central pressure (see, for example, Jiang et al. 2008). This means that conventional methods of defining and tracking storms, such as those used in IBTraCS or in this and previous studies using the Zetac model, may be limited for diagnosing flood-producing storms and storm structures. It would be useful to develop metrics for measuring storm intensity that are better suited for characterizing rainfall and flood magnitudes. This is nontrivial; despite the criteria used here and elsewhere in which rainfall within 500 km of the track location is considered, Rowe and Villarini (2013)

show that tropical cyclone “precursor” rainfall can produce significant flooding at distances as far as 1000 km from the storm center and very far inland (see also Galarneau et al. 2010). Tropical cyclones can include complex interactions with other weather systems, such as those seen in “super-storm” Sandy in 2012. Also important to flooding are the rainfall properties of cyclones that undergo extratropical transition. Extratropical transition and its role in flooding is poorly understood (see Jones et al. 2003). Some efforts have been made to examine the climatology of transitioning cyclones (see Hart and Evans 2001; Evans and Hart 2003), but additional modeling, theoretical, and observational studies are needed, particularly for future climate conditions. Zetac is not ideal for such studies due to the artificial dissipation of storms near the northern boundary of its modeling domain.

We believe that more emphasis should be placed on understanding the dynamics of rainfall-producing storm systems. Wright et al. (2013, 2014a, b) and Smith et al. (2011) demonstrate that in the eastern United States, flood risk in medium to large watersheds is driven primarily by tropical and extratropical cyclones, while flood risk in small watersheds is primarily driven by organized thunderstorms. Analyses of a long-term rainfall time series, whether from observations or from climate model output, that does not consider the rainfall time and length scales of these storm systems will likely yield results that are of limited use for flood risk assessment. Unfortunately, most analyses of extreme rainfall, including trend analyses and frequency analyses, do not consider storm types or other storm properties. Climate change will likely impact different types of storm systems in different ways, and so understanding future rainfall and flood risks will require careful examination of how well these impacts are represented in different modeling frameworks.

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