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Floridian heatwaves and extreme precipitation: future climate projections

Ajay Raghavendra[1] · Aiguo Dai[1,2] · Shawn M. Milrad[3] · Shealynn R. Cloutier-Bisbee[3]

Abstract

Observational analysis and climate modeling efforts concur that the frequency, intensity, and duration of heatwaves will increase as the Earth's mean climate shifts towards warmer temperatures. While the impacts and mechanisms of heatwaves have been well explored, extreme temperatures over Florida are generally understudied. This paper sheds light on Floridian heatwaves by exploring 13 years of daily data from surface observations and high-resolution WRF climate simulations for the same timeframe. The characteristics of the current and future heatwaves under the RCP8.5 high emissions scenario for 2070–2099 were then investigated. Results show a tripling in the frequency, and greater than a sixfold increase in the mean duration of heatwaves over Florida when the current standard of heatwaves was used. The intensity of heatwaves also increased by 4–6 °C due to the combined effects of rising mean temperatures and a 1–2 °C increase attributed to the flattening of the temperature distribution. Since Florida's atmospheric boundary layer is rich in moisture and heatwaves could further increase the moisture content in the lower troposphere, the relationship between heatwaves and extreme precipitation was also explored in both the current and future climate. As expected, rainfall during a heatwave event was anomalously low, but it quickly recovered to normal within 3 days after the passage of a heatwave. Finally, the late 21st-century climate could witness a slight decrease in the mean precipitation over Florida, accompanied by heavier heatwave-associated extreme precipitation events over central and southern Florida.

Keywords Climate projection · Extreme precipitation · Florida · Heatwaves · WRF model

1 Introduction and motivation

When most people discuss the loss of human lives attributed to meteorological events, they often associate them with dynamically active or awe-inspiring events such as tornadoes, tropical cyclones, heavy precipitation and flooding, or lightning. On the contrary, it is relatively nondescript and slow-moving weather patterns that are usually associated with heatwaves that result in more deaths than

any other weather events (Borden and Cutter 2008). Heatwaves claim hundreds and thousands of lives each year. Recent heatwave events such as the 2015 Indian heatwave claimed upwards of 2500 lives (Wehner et al. 2016). In the United States alone, Luber et al. (2006) found that from 1999 to 2003, excessive heat exposure was a causal or contributing factor to an average of 700 deaths per year nationwide. The 1995 U.S. heatwave that occurred around mid-July stressed the effect of urban heat islands (since over 500 lives were lost in Chicago and the heatwave claimed over 800 lives nationwide; Changnon et al. 1996). In fact, they are dubbed "silent killer" for a variety of reasons, including the damaging health impacts after prolonged exposure to not only daytime heat, but also anomalously high and uncomfortable nighttime temperatures. A review paper by Perkins (2015) provided examples of past heatwave events, their mechanisms, and the alarming number of human fatalities and injuries associated with heatwaves. Also, the Intergovernmental Panel on Climate Change (IPCC 2013) has briefly discussed heatwaves

✉ Ajay Raghavendra
    araghavendra@albany.edu

1   Department of Atmospheric and Environmental Sciences, University at Albany, State University of New York, Albany, NY 12222, USA

2   National Center for Atmospheric Research (NCAR), Boulder, CO, USA

3   Meteorology Program, Applied Aviation Sciences Department, Embry-Riddle Aeronautical University, Daytona Beach, FL, USA

and associated risks in a warmer future climate. A robust and detailed report by the Florida Department of Health (2015) documented the significant health impacts including heat-related illness such as cardiovascular disease, mental health and behavioral disorders, and respiratory diseases resulting from extreme heat exposure. Factors that may amplify the impacts of Floridian heatwaves were also briefly described in Cloutier-Bisbee et al. (2018).

Since most of Florida is a peninsula, its weather and climate are strongly influenced by the surrounding bodies of water. The June, July, and August (JJA) Sea Surface Temperature (SST) around Florida varies between 25 °C–30 °C and plays a role in modulating the land surface and lower-tropospheric air temperatures. However, the ocean also moistens the lower troposphere and the resulting increase in humidity can limit the human body's ability to dissipate heat via evaporative cooling. It is also conjectured that the heatwaves in Florida can help to precondition the air mass such that is more conducive to anomalously high amounts of precipitation immediately following the heatwave; using observational datasets, Cloutier-Bisbee et al. (2018) investigated this theory. Since Floridian heatwaves result in an extremely warm and moist environment in the lower troposphere, the end of a heatwave will likely be associated with a shift in the synoptic environment from a convection-inhibiting high-pressure system and associated ridge to low pressure system and associated troughing, which is more conducive for producing ascent and thunderstorm development.

In a future warmer climate, the shift towards warmer mean temperatures and increase in variability will result in a more frequent occurrence of heatwaves and hotter temperature extremes (IPCC 2012). In fact, late twenty-first century regional climate simulations over Europe (e.g., Schär et al. 2004 and; Fischer and Schär 2009) have documented the effects of increasing greenhouse gases (GHGs) and stressed that the frequent occurrence of intense heatwaves can be attributed to an increase in temperature variability that increases the likelihood of hotter extreme temperatures.

This study seeks to understand the impact of future climate change on heatwave events in Florida and the heavy to extreme precipitation events that follow. The objectives of this paper are to:

- Compare the frequency, intensity, and duration of summer (i.e., JJA) heatwave events over Florida between the present (i.e., control run or CTL) and the future pseudo global warming (PGW) runs of a high-resolution modeling experiment (Liu et al. 2017) described in Sect. 2.
- Investigate whether heavy/extreme precipitation events occur shortly after the passage of a heatwave and document changes in the characteristics of the precipitation between the CTL and PGW runs over Florida.

The paper is organized as follows. Section 2 defines the heatwave metric, validates the model-simulated temperatures with surface observations (hereafter OBS), and describes the analysis. It also describes the data, which includes a brief description of the modeling experiment by Liu et al. (2017). Section 3 presents the results in two parts i.e., heatwaves and precipitation, and evaluates changes in the characteristics of heatwaves and precipitation between the CTL and PGW runs. Section 4 provides a brief summary and major conclusions of this paper.

2 Data and method

This study focuses on heatwaves and associated precipitation events in urban areas during the summer JJA months over Florida. Therefore, daily mean temperatures and daily total precipitation from the CTL and PGW runs were spatially averaged and collected for six cities in Florida. For illustrative purposes, Fig. 1a provides the grids over which the data was spatially averaged for each city. To justify the selection of the grids and to verify that the grids represent populated urban settlements, Fig. 1b shows a plot of the number of grids corresponding to a given city and the city's population. The linear trend line in Fig. 1b yielded a reasonably good *r-squared* value of 0.84. To assess whether the passing of a heatwave is associated with increased precipitation, the daily spatially averaged precipitation is analyzed for 3 days starting from the end date of each heatwave event separately for the CTL and PGW climates and compared with its respective JJA climatology. The precipitation amounts from the CTL and PGW runs associated with heatwaves are then compared to establish the impacts of global warming under the Representative Concentration Pathways 8.5 (RCP8.5) scenario (Riahi et al. 2011), which has high emissions of GHGs during the twenty-first century.

2.1 Definition of a heatwave

There is no universally agreed upon definition for a heatwave. Previous studies (e.g., Keellings and Waylen 2014, 2015) have investigated heatwaves by using various combinations of temperature and/or duration thresholds to define a heatwave metric (Perkins 2015). Following the definition used in Cloutier-Bisbee et al. 2018, this paper will use the following criterion to define a heatwave, its frequency, and duration:

- An event is considered a heatwave if the daily mean JJA 2-m air temperature exceeds the 95th percentile for 3 or more consecutive days (see Perkins and Alexander 2013). If the heat wave is interrupted by a brief temperature
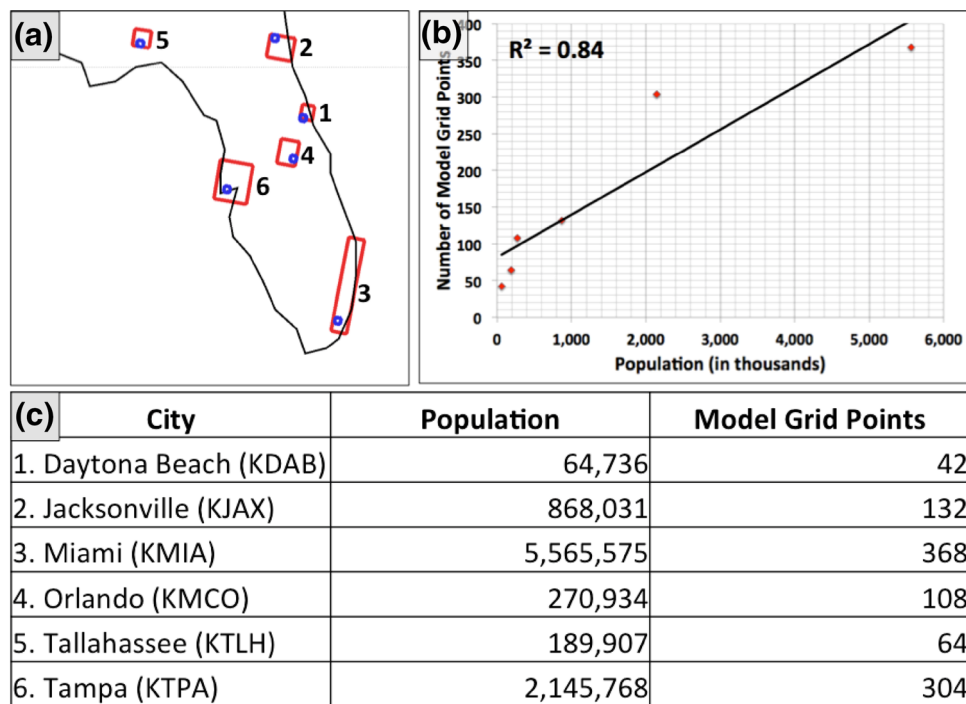
Fig. 1 Verification for the choice in WRF model grids used in defining the six cities analyzed in this paper. **a** The location of the six cities over Florida for illustrative purposes. The numbers next to the red boxes correspond to the name of the city described in (**c**). The blue boxes consisting of nine grid points each represent the location of the airport from which the model OBS was obtained in each city. **b** The population and number of grid points used in defining each city. **c** The city name and corresponding International Civil Aviation Organization (ICAO) airport code in parentheses, population, and number of model grid points for each city. Population data was obtained from Cubit (2015) for 1, 2, 4, and 5. Using data from the U.S. Census Bureau (2012), the population for 3 and 6 was estimated by adding the population of the representative counties

relapse for less than 4 days, it will be counted as part of the same heatwave event.

- To be considered a separate heatwave event and to ensure synoptic independence between events, the number of days that elapsed between the end date of a heatwave and the beginning date of the next heatwave is required to exceed 4 or more days.
- The duration of the heatwave is defined as the number of days between the start and end dates of a heatwave event, inclusive.

The above definition for a heatwave is used and applied to the daily mean surface air temperatures from observations (OBS) obtained from the Applied Climate Information System (ACIS, available at http://scacis.rcc-acis.org/) for major international airports in Florida, and the model simulations for the six cities shown in Fig. 1. For the model data, we first averaged the temperature data over all the grid cells within either the blue or red boxes outlined in Fig. 1a, and then applied the above criteria to define a heatwave. Alternations of the above heatwave criterion using the 92.5th and 97.5th percentile temperature thresholds were also analyzed and explored (see Sect. 3). ACIS is a data portal developed,

maintained, and operated by the National Oceanic and Atmospheric Administration (NOAA) Regional Climate Centers (RCCs). The website provides long-term and easily retrievable quality-controlled climate data suitable for this study (DeGaetano et al. 2015; Hubbard et al. 2004).

2.2 WRF modeling experiments

Daily model temperature and precipitation data were obtained from a pioneering convection-permitting simulation to study climate change by the National Center for Atmospheric Research (NCAR; Prein et al. 2015, 2017; Liu et al. 2017). Only a brief summary of Liu et al. (2017) is presented here. Using the Weather Research and Forecasting (WRF) model Version 3.4.1 (Skamarock et al. 2008), with 1360×1016 grid points and a 4-km horizontal grid spacing to encompass the entire contiguous United States (CONUS) and parts of Canada and Mexico, Liu et al. (2017) conducted two 13-year climate simulations from 1 October 2000 to 30 September 2013. The model was initialized and forced with 6-h ERA-Interim reanalysis data (Dee et al. 2011) for the CTL run. After obtaining the CTL run, the model was re-run again (PGW run) forced with the 6-h ERA-Interim

reanalysis data plus a climate perturbation (see Eq. 1 and Eq. 2) for the same time period and model configuration that was used to obtain the CTL run. Spectrum nudging was applied in both simulations. The mean climate perturbation for each month can be described as follows:

$$WRF_{input} = ERA\text{-}interim + \Delta CMIP5_{RCP8.5} \tag{1}$$

where $\Delta CMIP5_{RCP8.5}$ was obtained using 19 CMIP5 model monthly ensemble-mean change from 1976 to 2005 to 2070–2099 under the RCP8.5, which is a high emissions scenario (Riahi et al. 2011):

$$\Delta CMIP5_{RCP8.5} = \Delta CMIP5_{2070-2099} - \Delta CMIP5_{1976-2005} \tag{2}$$

The late twenty-first century climate perturbations were applied to the following fields: horizontal winds, geopotential, temperature, specific humidity, SST, soil temperature, mean sea level pressure, and sea ice. Further, the model setup incorporates a modified lake water temperature treatment where time-varying lake water temperature is calculated using the diurnal average of surface skin-temperatures. This approach is different from the default WRF setup for in-land lake temperature, which is obtained using the interpolated nearest SST. This modified treatment of lake temperature is critical for Florida given the number of lakes, including large lakes such as Lake Okeechobee. For more information and details on the method, model setup, and exact nature of the climate forcing applied to the PGW run, please refer to Liu et al. (2017) and Dai et al. (2017).

2.3 Evaluation of the CTL run

The evaluation of the CTL run was already performed by Liu et al. (2017). Other subsequent studies such as Dai et al. (2017) evaluated the precipitation fields from the CTL run against observations (e.g., Lin and Mitchell 2005). These studies found that the model can realistically simulate the seasonal and spatial variations in surface temperature and precipitation. Therefore, no effort was made in this work to compare the CTL run's precipitation fields with observations. Here, the observed (OBS) daily mean temperature data, were compared against the CTL run. The model daily mean temperature was spatially averaged over a square consisting of nine grid points located near the airports in this comparison (see blue contours in Fig. 1a).

Figure 2 shows the distribution of the daily maximum, mean, and minimum temperatures from OBS, and the CTL and PGW runs. The reason to study heatwaves using only the daily mean temperature criteria stems from the fact that the CTL run's daily maximum and minimum temperatures, while comparable to OBS, showed larger variability and inconsistency across the six cities when compared to the daily mean temperature. The CTL run slightly overestimates the daily minimum temperature and underestimates the daily maximum temperature (e.g., García-Díez et al. 2013). Therefore, we chose to use the daily mean temperature to define heatwaves in our analyses.

3 Results

Prior to converging on a definition for a heatwave as defined in Sect. 2.1, other heatwave criteria initially explored included standard deviation-based metrics, and the 92.5th and 97.5th percentile temperature thresholds. A temperature metric defined using a threshold of two standard deviations compared relatively well to the 95th percentile and did not alter the results significantly given the nature of the summer temperature distribution over Florida, which is characterized by a narrow temperature spread (Figs. 2, 3). On the other hand, altering the percentile threshold was found to change the number of heatwave events but appears not to strongly affect the mean duration of heatwaves, i.e., a smaller percentile threshold would increase the number of events and vice-versa (Fig. 4). When a lower percentile threshold criterion is applied (e.g., 92.5th), a larger number of days qualify towards being counted as heatwave days. This will naturally increase the probability of occurrence of heatwaves (frequency) and duration of heatwaves. As expected, we observed an increase in frequency and a relatively small increase in the duration of heatwaves (Figs. 4, 5) at lower temperature thresholds (i.e., in Fig. 4, we observed a three-fold increase in frequency from 97.5th to 92.5th, but only a small increase in duration from ~ 5.5 to ~ 7 days). In Figs. 4 and 5, the 97.5th percentile criterion resulted in fewer and relatively short duration heatwave events when compared to the 95th and 92.5th percentile temperatures thresholds.

Applying the 95th percentile threshold or other temperature metrics obtained from the CTL run to the PGW run (abbreviated as PGW w.r.t CTL) yielded a very large increase in both the number and mean duration of heatwave events (Figs. 4, 5). This result is a manifestation of a warmer future climate (by about 3.8 °C) and a broader distribution of PGW JJA daily temperatures over Florida than the OBS and CTL (Figs. 2, 3). This would imply that a moderate shift in the mean temperature in the future climate state will result in a very large increase in extreme hot weather defined using the current standard. In this paper, the 95th percentile temperature threshold from the future climate (PGW) was also used to evaluate future heatwaves. This allows for a comparison of the characteristics of heatwaves in the present (CTL) and future (PGW) climates for a case without the impact of the mean temperature shift (i.e., global warming signal).
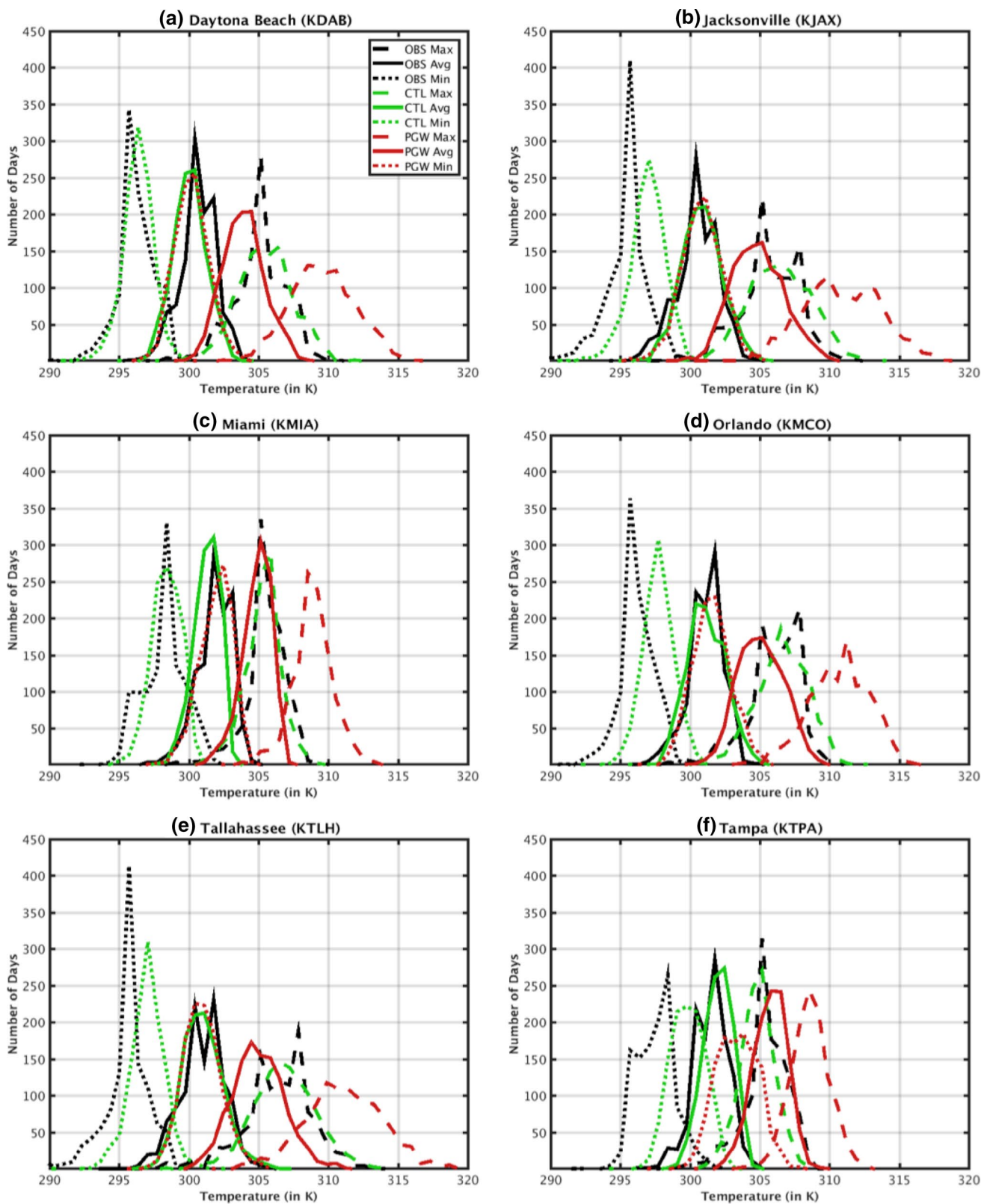
Fig. 2 Distribution of the daily maximum, mean, and minimum temperatures for all six cities (blue box in Fig. 1) for the days corresponding to the 2001–2013 JJA subset. The black curves represent the OBS, and the green curve represents the CTL run. The red curves that represent the PGW run illustrates key features such as a shift in the mean temperature towards a warmer future climate, and an increase in variance. The plot compares relatively well to the idealized schematic published in IPCC (2012)
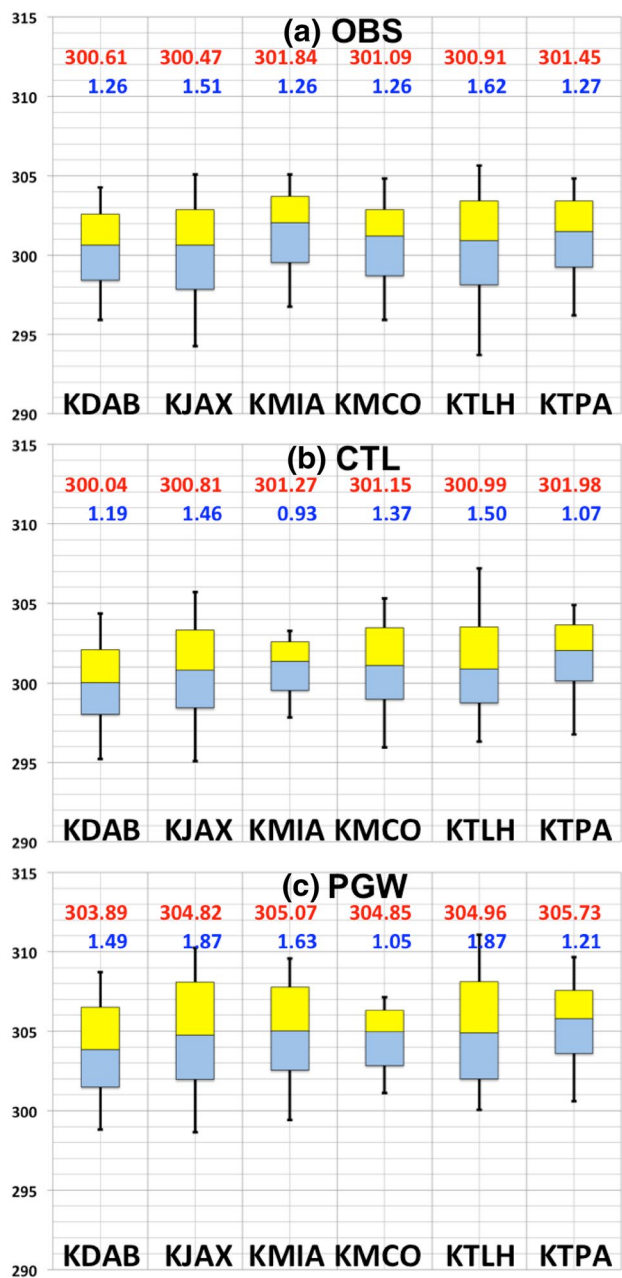
Fig. 3 Boxplot of various percentile temperature thresholds (K) obtained from the daily mean temperatures from **a** OBS, and the grid points representative of the OBS data in **b** CTL run, and **c** PGW run for the six cities (blue box in Fig. 1). The numbers above the individual boxplots represent the mean (red) and standard deviation (blue) of the distribution. The maximum (top whisker), 95th, 50th and 25th percentile (top, middle, and bottom parts of the box), and minimum temperatures (bottom whisker) are represented using the box and whisker

3.1 Changes in duration, frequency, and intensity of heatwaves

A comparison of the mean frequency and duration of JJA heatwaves is presented in Figs. 4 and 5 using three percentile-based thresholds. Using the definition for a heatwave
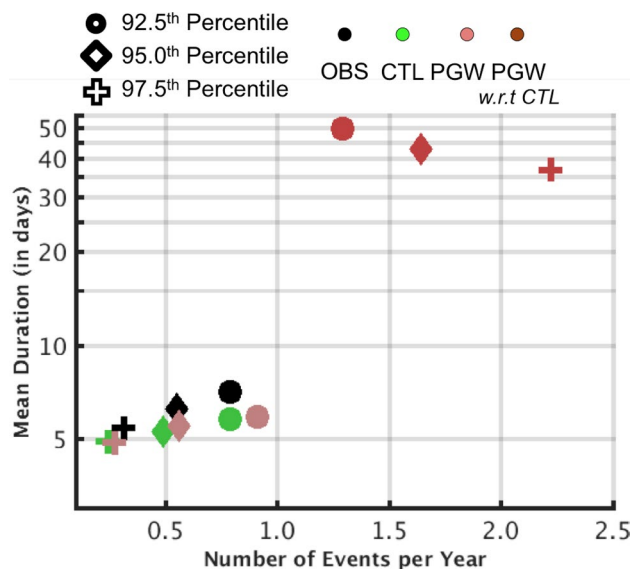

Fig. 4 Scatter plot showing the number of JJA heatwave events per year, and the mean duration of the events for three different percentile based (i.e., 92.5th, 95.0th, and 97.5th) temperature thresholds averaged for all six stations (or the blue areas of Fig. 1a for the model data) from 2001 to 2013

presented in Sect. 2.1, which uses the JJA 95th percentile daily mean temperature relative to the respective period, for the six cities as a whole, the OBS and CTL data produced similar number of heatwaves i.e., 0.55 and 0.49 per season with a mean duration of 6.4 and 5.2 days, respectively. The individual heatwave events did not occur on the same days consistently among the OBS, CTL, and PGW cases; however, this does not affect the statistics of heatwaves and associated precipitation analyzed here. The PGW run yielded 0.56 heatwaves per season that lasted on average 5.5 days (comparable with the CTL) when the 95th percentile of the future climate was used, but 1.64 heatwaves per season with a mean duration of 42.9 days when the present-day standard was used (i.e., PGW w.r.t. CTL). The PGW w.r.t. CTL case showed a relatively large spread among the different percentile thresholds (Fig. 4). The 97.5th percentile threshold produced a larger number of heatwaves (2.22 events per season with a mean duration of 37.9 days) than that for the 92.5th percentile threshold (1.29 heatwaves per season with a mean duration of 50.0 days) over the six cities in Florida for the PGW w.r.t. CTL case (Fig. 4).

This is in contrast to the OBS and CTL cases, in which the number of events decreases as the percentile threshold increases, as one would expect. This apparent inconsistency resulted from the fact that the future heatwaves exceeding the 92.5th threshold (of the CTL) would last much longer than those exceeding the 97.5th threshold, leading to fewer individual events. While changes in the frequency and duration of heatwaves depend on the metric used, there

Fig. 5 The frequency (**a**–**c**) and duration (**d**–**f**) of JJA heatwaves calculated using the 13-year OBS and model data (over the area enclosed by the blue contour in Fig. 1a) using the 92.5th, 95th, and 97.5th daily mean temperature for the six cities shown in Fig. 1
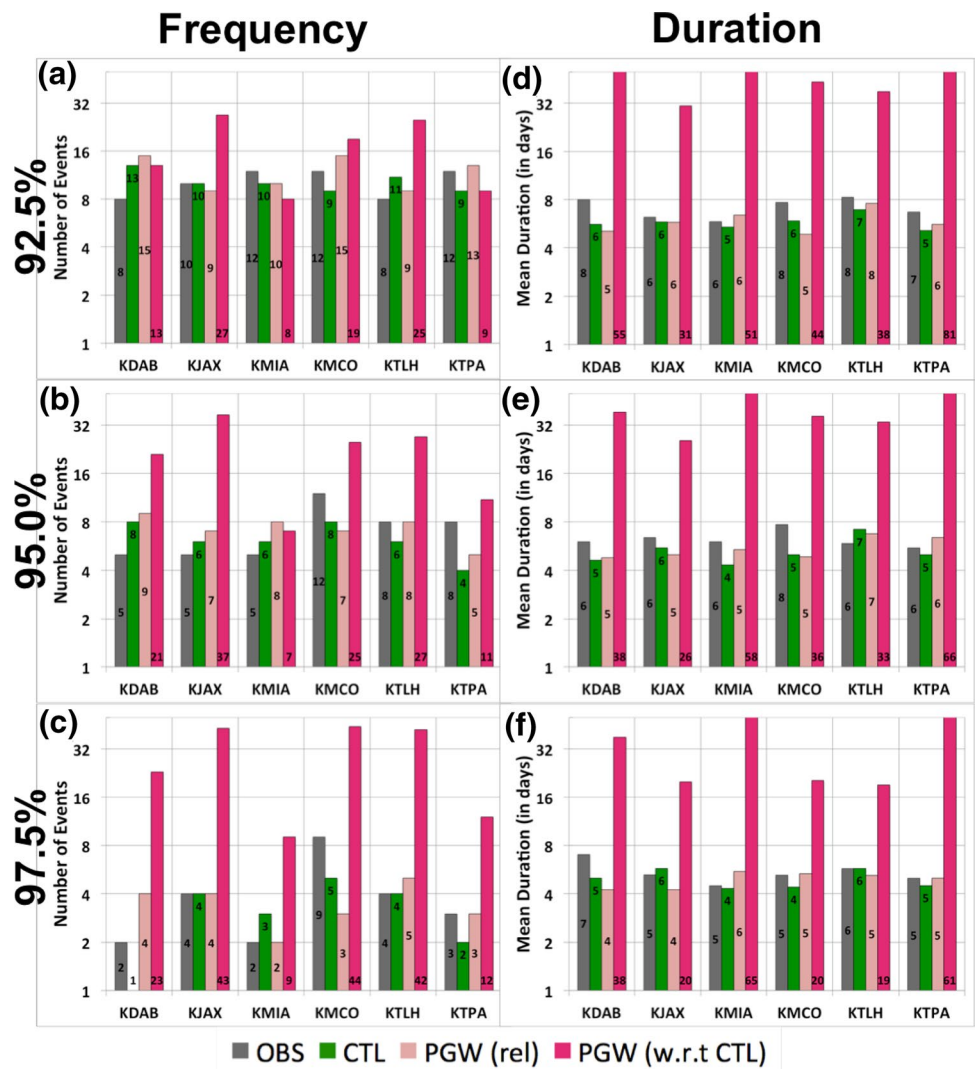

Table 1 Number of summer heatwaves per year, and mean duration (in days) of heatwaves obtained by using the 95th percentile temperature criterion from spatially averaged temperature over the six cities (areas enclosed by the red contour in Fig. 1a) from the CTL and PGW runs

	CTL		PGW		PGW w.r.t CTL	
	No. events	Mean duration	No. events	Mean duration	No. events	Mean duration
Daytona Beach	0.53	6.3	0.61	5.0	0.84	65.8
Jacksonville	0.53	5.6	0.53	5.4	2.00	37.1
Miami	0.46	5.2	0.61	5.6	0.38	83.6
Orlando	0.61	4.6	0.38	4.8	1.61	40.1
Tallahassee	0.46	6.0	0.53	6.1	2.07	33.9
Tampa	0.69	5.4	0.53	5.4	0.84	65.5
Mean	0.54	5.5	0.53	5.4	1.29	54.3

Table 2 The simultaneous occurrences of a temperature exceedance (at the 95th percentile temperature threshold), and a heatwave day over the six cities using the model temperature data from the CTL and PGW runs over the area enclosed by the blue contour in Fig. 1a that contains the weather station for the city

Number of cities	One	Two	Three	Four	Five	Six
95th percentile (CTL)	88	32	18	8	1	–
95th percentile (PGW)	80	29	13	10	8	2
Heatwave days (CTL)	60	17	15	3	–	–
Heatwave days (PGW)	57	26	7	8	7	–

is a clear upward trend in the number of heatwaves in the future climate even with respect to future thresholds (Figs. 4, 5a–c). The increases in the mean duration and frequency of heatwaves are alarmingly large when compared to the present climate (Figs. 4, 5). Some of the GHG-induced large increases may have already occurred, as Cloutier-Bisbee et al. 2018 found a statistically significant trend in the frequency of heatwave events over Florida through analyses of 66-years (1950–2015) of surface air temperature data.

Spatially averaging the temperature over the larger domains enclosed by the red boxes in Fig. 1a yielded similar numbers of heatwaves between the CTL and PGW runs. The mean frequency and duration of heatwaves averaged over the six cities relative to its own climate yielded 0.54 and 0.53 heatwaves per season with a mean duration of 5.5 and 5.4 days for the CTL and PGW runs, respectively, for the 13-year period from 2001 to 2013 (Table 1). The similarities between the CTL and PGW runs are likely an attribute of spatial averaging that tends to smooth the data, and the manner in which heatwaves were defined by using a percentile-based metric. On the other hand, the PGW w.r.t. CTL climate yielded 1.29 heatwaves per season with a mean duration of 54.3 days (Table 1). While warm conditions prevail over most of the Florida landmass during a heatwave event in one of the cities, generally there lies very little overlap between a > 95th percentile day or a heatwave occurring in one city and simultaneously in another city (Table 2). Heatwaves are obviously associated with hotter temperatures, but Fig. 6a shows that the mean temperature anomalies relative to the JJA climatology of heatwave days during PGW w.r.t. its own 95th percentile are 1–1.5 °C warmer than those of the CTL. This implies that even without the effect of the mean temperature shift, future heatwaves may become more intense due to the flattening of the temperature distribution (Fig. 2), which leads to more extreme temperatures. This shift in mean temperatures and an increase in temperature variability in a future warmer climate over Europe have been well documented by Schär et al. (2004) and Fischer and Schär (2009). Figure 6 shows the temperature anomaly change (PGW-CTL) patterns during the heatwave days, and it shows that the magnitude of the PGW-CTL difference is largest in the interior parts of central and panhandle Florida. The ubiquitous increases in temperature in Fig. 6c is mostly a function of the global warming signal (Fig. 6b), but is also supplemented by an increase in the mean temperature anomaly averaged over PGW heatwaves when compared to CTL heatwaves, which is consistent with the flattening of the temperature distribution in the PGW run (Fig. 2).

3.2 Trends in precipitation

The tendencies in precipitation before and after heatwave events were analyzed for the CTL and PGW runs, using the
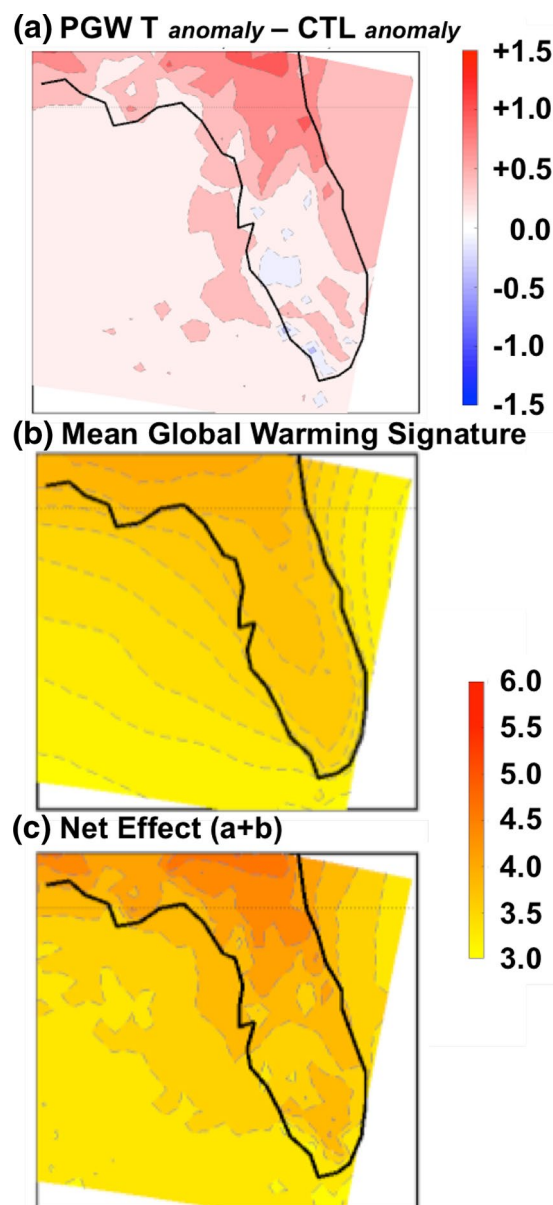

Fig. 6 **a** Differential temperature anomaly (K) between PGW and CTL heatwaves days calculated for each grid point. **b** The global warming signature obtained by calculating the difference between the PGW and CTL mean JJA temperature (K). **c** The combined effect of the differential temperature anomaly attributed to the increase in temperature variability (flatter distribution in the PGW run) and global warming (K)

categories of (Dai et al. 2017). It was found that the number of days with light to moderate precipitation (0–1 mm h^{-1}) decreases, while the number of days with heavy precipitation (> 1 mm h^{-1}) increases from the CTL to PGW runs all cities (Fig. 7). Probably due to the small sample size, none of the individual stations in the heavy precipitation category show statistically significant differences in the true median between the CTL and PGW runs. However, analyzing

differences in the true median for heavy precipitation between the CTL and PGW by aggregating all six individual stations (thus increasing the sample size) was statistically significant. Similar to Dai et al. (2017) a significant decrease in 4/6 stations for the light precipitation category was also documented. It is well known that the frequency of warm-season precipitation would decrease, while precipitation intensity would increase mainly due to increased water vapor (Dai et al. 2017). Over Florida, sea-breeze convergence is

a key ascent-forcing mechanism (e.g., Gentry and Moore 1954; Estoque 1962; Kingsmill 1995; Robinson et al. 2013; Milrad and Herbster 2017) and plays an important role in modulating warm-season precipitation over Florida. However, how the sea-breeze changes under the GHG-induced global warming and how that might affect precipitation over Florida require further investigation.

Given the nature of the experimental design where boundary conditions from the ERA-Interim reanalysis control the
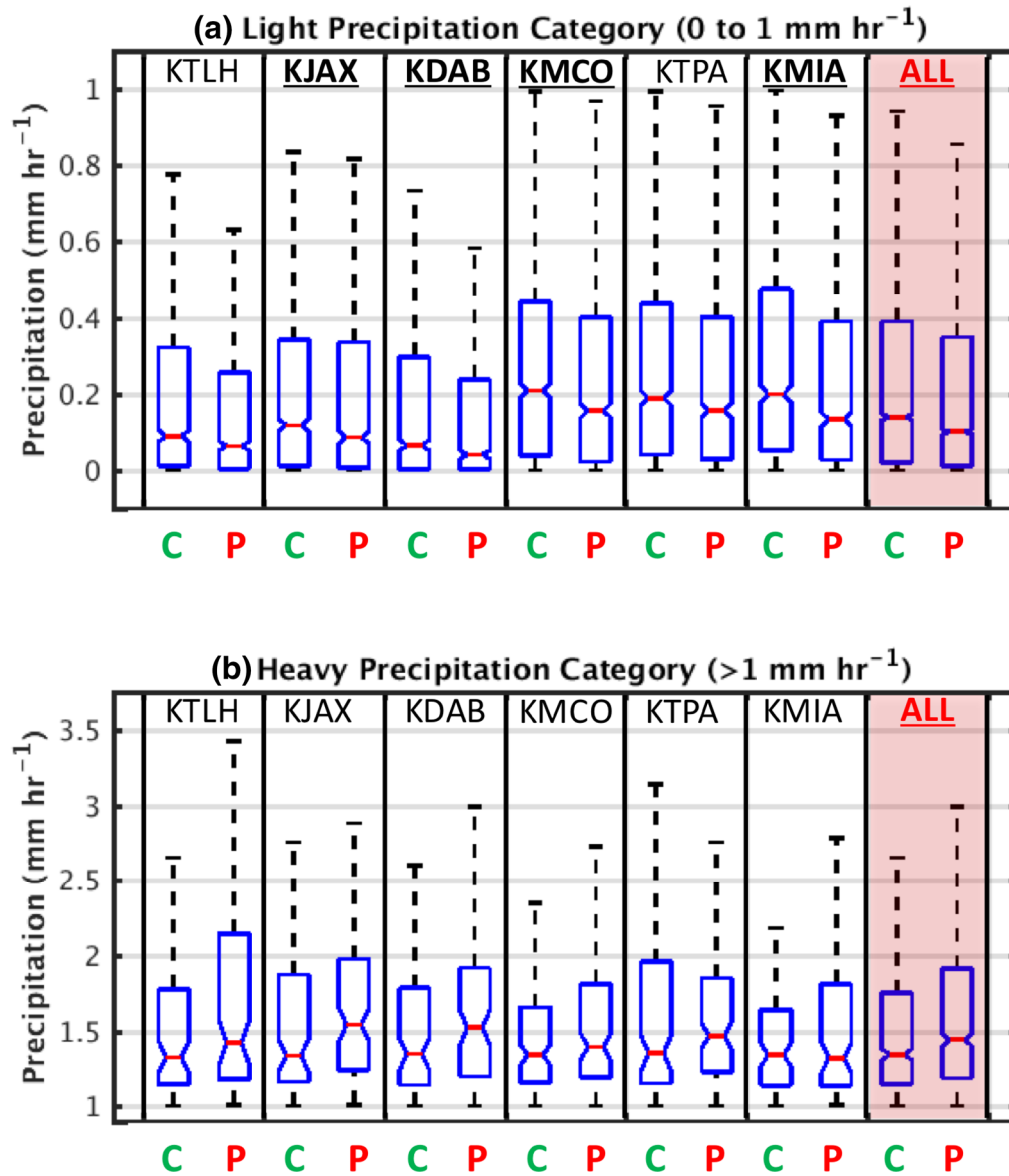

Fig. 7 Boxplot showing the distribution of summer (JJA) precipitation obtained for **a** light precipitation categories (i.e., precipitation rate between 0 and 1 mm h^{-1} range), and **b** heavy precipitation categories (i.e., precipitation rate > 1 mm h^{-1}). Notches in the box plot indicate that the true medians differ (statistically significant at the 95% confidence interval if notches are not overlapping). City names are abbreviated using their respective ICAO airport code (bold and underlined for statistically significant differences). The precipitation was calculated by spatially averaging daily precipitation over each city (the red areas in Fig. 1a) for the CTL and PGW runs. The precipitation distribution from the CTL ('C' in green text) and PGW ('P' in red text) runs are shown next to each other for all six cities, and the aggregate

free evolution of large-scale circulation changes within the model domain, i.e., large-scale circulation change little over Florida in the PGW run (not shown), the higher air temperature and associated water vapor increases would lead to large increases in heavy precipitation events when a climatological assent mechanism (e.g., sea-breeze convergence) is present, as explained by Dai et al. (2017). This is indeed what we see in the PGW over Florida (Fig. 7). The mean precipitation rate over the 3-day period after the passing of a heatwave was slightly larger than the JJA climatology at most stations, while the last three days of a heatwave were generally characterized by reduced precipitation (Fig. 8). We also found that precipitation at KDAB (Daytona Beach) steadily increased beyond the climatological mean over a 4–7 day period after the passing of the heatwave in the CTL run (not shown). In general, this confirms the notion that normal to above-normal precipitation generally succeeds Floridian heatwaves as seen in observations (e.g., Cloutier-Bisbee et al. 2018). Figure 8 also shows that there will be less respite brought by precipitation after a heatwave, possibly due to an increase in the vertical stability of the atmosphere (e.g., Trenberth 1998).

Figures 9 and 10 show precipitation anomalies (relative to the respectively 13-yr mean) averaged over the three days after the passage of a heatwave occurred at each of the six cities from the CTL and PGW run, respectively. Summer Florida precipitation comes mostly from scattered thunderstorms, thus its spatial distribution is relatively random and sporadic (Doswell 1987; Hodanish et al. 1997; Williams et al. 1999; Curran et al. 2000), and the relatively small sample size used in Figs. 9 and 10 further contributes the spatially sporadic nature. Nevertheless, Fig. 8 shows that in the CTL run above-normal precipitation after a heatwave at Jacksonville is widespread over Florida. To a smaller degree, this is also for heatwaves at Daytona Beach and Tallahassee. For the PGW run, widespread large above-normal precipitation is seen not only after Jacksonville heatwaves but also after Miami heatwaves (Fig. 9).

4 Summary and discussion

We have examined the changes in heatwaves and associated extreme precipitation events over Florida using two 13-year simulations of the present (CTL) and future (PGW) climates by the WRF model with 4-km grid spacing. The model-simulated heatwaves for the current climate was compared with station observations from six cities across Florida. The nature of the temperature distribution over Florida (Fig. 2) results in a non-linear effect, where a small shift in the distribution will result in a large increase in the number of days satisfying the 95th percentile heatwave threshold defined for the present climate. Since water bodies are able to regulate

the daytime maximum and nighttime minimum diurnal temperature difference, temperature increase attributed to a mean shift in a future climate, and corresponding increase in the probability of occurrence of extreme high temperatures when compared to the present-day climate is enhanced for coastal locations (e.g., Miami) given the closer proximity to water bodies (i.e., the Atlantic Ocean and Gulf of Mexico). Schär et al. (2004) found similar results over the European continent.

An increased number of hotter days in the future climate could lead to more occurrence of heatwaves, increased duration of individual heatwave events, and higher intensity of heatwaves. By the late twenty-first century under the RCP8.5 high emissions scenario, the frequency of heatwaves may quadruple to approximately two events per season together with over a six-fold increase in their duration when the heatwaves are defined using current thresholds. These changes are qualitatively consistent with the observational aspect of this research, which explored Floridian heatwave events using 66-years of observations (Cloutier-Bisbee et al. 2018) and found a significant increase in the frequency and duration of heatwaves, although no significant changes were found in the intensity of heatwaves. The shift in the mean temperature may increase the intensity of future heatwaves by 3–4 °C, while a flattening of the temperature distribution may enhance the intensity by additional 1–2 °C (Fig. 6). This flattening also leads to increased future heatwaves even when the heatwaves are defined using the 95th percentile of the future temperature distribution (i.e., without the effect of a shifted mean).
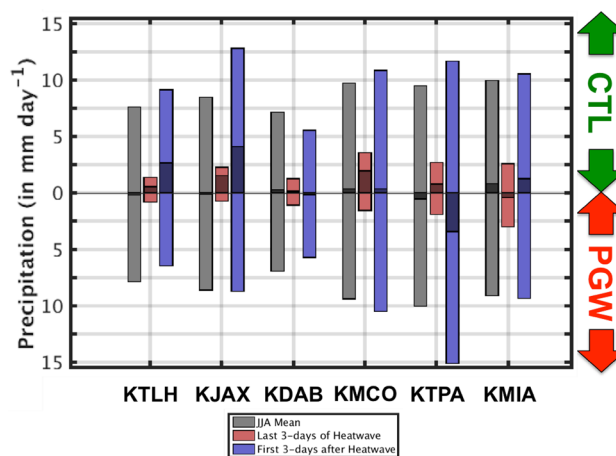

Fig. 8 Mean precipitation rate (in mm day^{-1}; y–axis) averaged over the last 3 days of a heatwave (red), and the first three days after a heatwave (blue) from the CTL (above) and PGW (below) runs for the six cities abbreviated using their respective ICAO airport code (cf. Fig. 1). The difference between the CTL and PGW are highlighted with darker shading on the larger bar (e.g., a darker shading on the CTL bar indicates a decrease from CTL to PGW and vice versa)
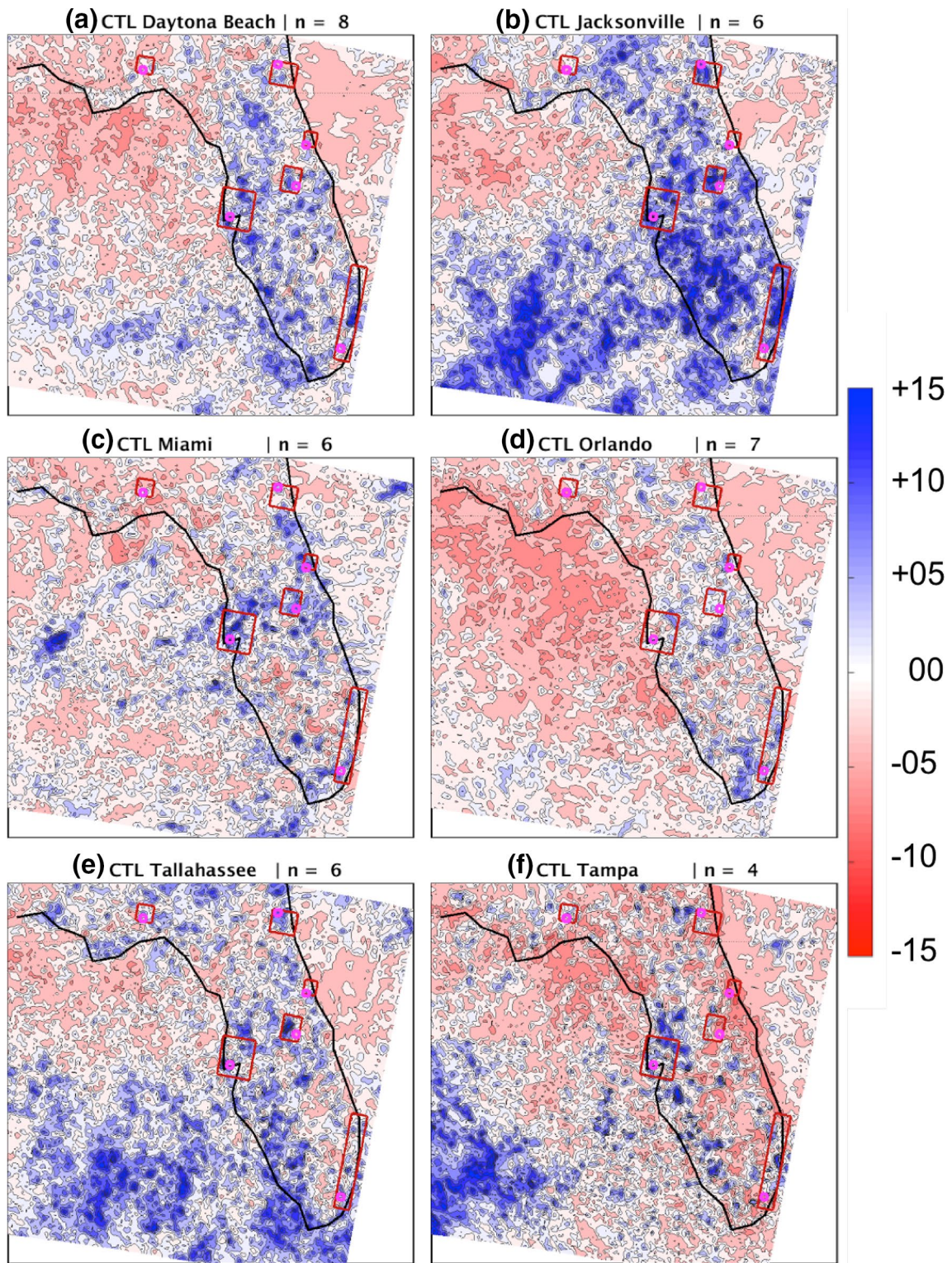
Fig. 9 Spatial distributions of the mean precipitation anomalies (in mm day^{-1}, relative to the JJA climatology) averaged over the first 3 days after the passage of a heatwave at each of the six cities for JJA from the 13-year CTL run. The total number of JJA heatwave events (*n*) during the 13-year period is shown next to the name of each city
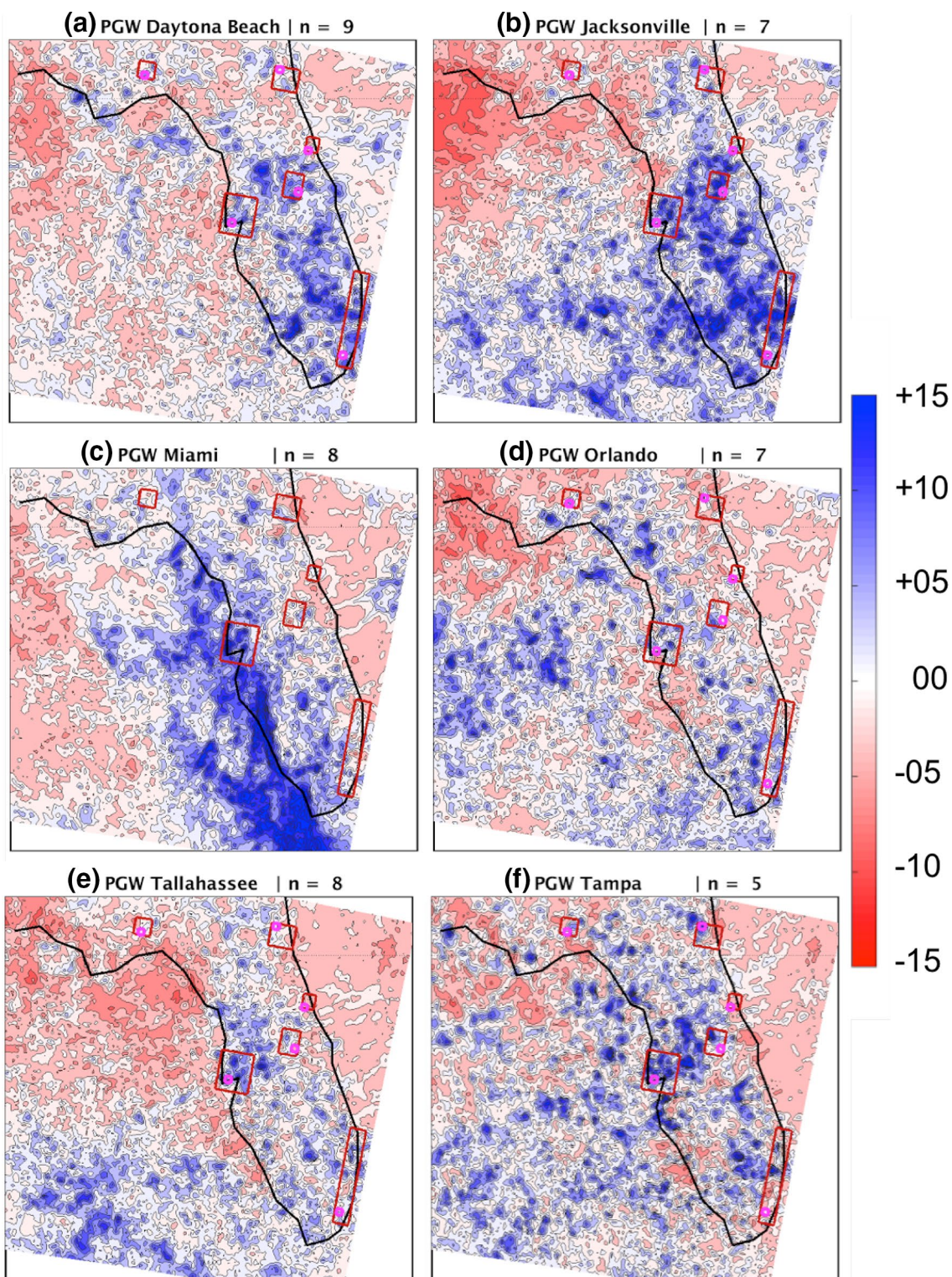
Fig. 10 As in Fig. 9 but for the PGW run

We also explored the link between heavy precipitation events and the termination of a heatwave. During a heat-wave, precipitation is significantly reduced compared to the climatological mean, while it increases to normal or above during the 1–3 days after the passage of a heatwave over central and southern Florida (i.e., peninsula; Fig. 8).

The late 21st-century climate could witness a slight decrease in the mean precipitation over Florida, accompanied by heavier heatwave-associated extreme precipitation events over central and southern Florida. The WRF model simulations also suggest less light rain but more heavy rain in the Florida peninsula in the future (Fig. 7). These results were similar when compared to Prein et al. (2017) who found an increase in hourly extreme precipitation coupled with a decrease in mean and moderate intense precipitation across the CONUS.

This study, along with other studies that use different analysis techniques, study regions, and data (e.g., Schär et al. 2004; Anderson and Bell 2009; Fischer and Schär 2009; Greene et al. 2011; Wu et al. 2014), serves yet as another example to illustrate the potential impacts of anthropogenic climate change and the dire future projections for heatwaves attributed to increasing GHGs. It further supports the urgent need for world's governments to take action to curb GHG emissions.

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