Urban precipitation extremes: How reliable are regional climate models?

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[1] We evaluate the ability of regional climate models (RCMs) that participated in the North American Regional Climate Change Assessment Program (NARCCAP) to reproduce the historical season of occurrence, mean, and variability of 3 and 24-hour precipitation extremes for 100 urban areas across the United States. We show that RCMs with both reanalysis and global climate model (GCM) boundary conditions behave similarly and underestimate 3-hour precipitation maxima across almost the entire U.S. RCMs with both boundary conditions broadly capture the season of occurrence of precipitation maxima except in the interior of the western U.S. and the southeastern U.S. On the other hand, the RCMs do much better in identifying the season of 24-hour precipitation maxima. For mean annual precipitation maxima, regardless of the boundary condition, RCMs consistently show high (low) bias for locations in the western (eastern) U.S. Our results indicate that RCM-simulated 3-hour precipitation maxima at 100-year return period could be considered acceptable for stormwater infrastructure design at less than 12% of the 100 urban areas (regardless of boundary conditions). RCM performance for 24-hour precipitation maxima was slightly better, with performance acceptable for stormwater infrastructure design judged adequate at about 25% of the urban areas. **Citation:** Mishra, V., F. Dominguez, and D. P. Lettenmaier (2012), Urban precipitation extremes: How reliable are regional climate models?, *Geophys. Res. Lett.*, *39*, L03407, doi:10.1029/2011GL050658.

1. Introduction

[2] About half of the human population lives in urban areas [*Martine et al.*, 2007] in contrast with only about 10 percent a century ago [*Grimm et al.*, 2008]. Due to large increases in population and built infrastructure, urban areas are emerging as ‘first responders’ of climate change adaptation and mitigation [*Rosenzweig et al.*, 2010]. Changes in extreme precipitation as the climate warms may pose challenges for stormwater management in urban areas, because most stormwater infrastructure was designed under the assumption of stationary climate that is “dead” as argued by *Milly et al.* [2008].

[3] The design of urban drainage systems is mostly based on precipitation and stormwater discharge with return periods ranging from about 5 to 100 years, corresponding to events with a probability of 0.01–0.2 of occurring in any year. Because urban drainage areas are relatively small and have substantial impervious or semi-pervious fractions, their response times to extreme precipitation are usually short. Therefore, precipitation durations that control urban stormwater design usually range from less than an hour to a few hours at most. Hence, we focus here on sub-daily time scales.

[4] Consistent with observations [*Dirmeyer and Brubaker*, 2006; *Mishra and Lettenmaier*, 2011] most climate models project increases in precipitation extremes as the climate warms [*O'Gorman and Schneider*, 2009; *Wehner*, 2004]. Moreover, model-predicted changes in precipitation extremes are somewhat independent of changes in mean precipitation as they are largely controlled by variations in the atmosphere's moisture transport capacity [*Allen and Ingram*, 2002; *Trenberth et al.*, 2003; *Lenderink and van Meijgaard*, 2008]. Increased moistening of the atmosphere in a warmer climate could therefore lead to increases in extreme precipitation frequency and intensity, irrespective of changes in (seasonal and annual) means. Global Climate Model (GCM) simulations of future precipitation extremes generally show increases, which roughly follow the Clausius-Clapeyron rate of increase of atmospheric water holding capacity with temperature.

[5] Global climate models, which run over the entire globe and are self-consistent with respect to moisture and energy fluxes, are the primary source of information about possible changes in future precipitation. However, their spatial resolution (typically degrees latitude by longitude, equivalent to hundreds of km) is too coarse to resolve the processes that control precipitation extremes [*Salathé et al.*, 2010; *Wehner et al.*, 2009]. Furthermore, they are unable to resolve topographic variations that strongly affect precipitation and precipitation extremes in the Western U.S. Regional climate models (RCMs) provide higher-resolution climate projections that at least partially resolve finer scale variability associated with topography and land cover and hence are increasingly being used in studies aimed at helping society adapt to climate change [*Salathé et al.*, 2010]. Most previous evaluations of RCM-simulated precipitation extremes have examined seasonal or daily precipitation extremes at regional or larger scales [*Gutowski et al.*, 2010; *Leung et al.*, 2004; *Salathé et al.*, 2010; *Wehner et al.*, 2009]. The ability of RCMs to reproduce sub-daily precipitation extremes at local scales (which are most relevant to urban precipitation extremes) is still not well understood. In this study, we compare predictions of precipitation extremes archived as part of the North American Regional Climate Change Assessment Program (NARCCAP) with observations over a

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set of 100 U.S. urban areas, for precipitation accumulation intervals from sub-daily to daily.

2. Methods

[6] Our study region consists of 100 urban areas across the U.S., as defined by *Mishra and Lettenmaier* [2011]. Because observations of hourly precipitation do not exist for many urban areas, we selected nearby airports with long-term high quality observations of hourly precipitation as surrogates for the nearby urban areas. We obtained hourly precipitation data from the National Climatic Data Center (NCDC) for the period 1950–2009. Data quality was carefully checked and years with more than 10% missing data were removed. All of the 100 stations had observations for the period of record 1950–2009.

[7] We used RCM-simulated precipitation output from participating models in the North American Regional Climate Change Assessment Program (NARCCAP) [*Mearns et al.*, 2009]. For most of the NARCCAP RCMs, two distinct simulations were made: the first simulation forced the RCMs with output from the National Center for Environmental Prediction/Department of Energy (NCEP/DOE) reanalysis [*Kanamitsu et al.*, 2002] at the boundaries for the 1979–2000 period (RCM-reanalysis henceforth). For the second simulation, output from selected GCMs was used to provide the RCM boundary conditions both in the historical (1968–2000) and future (2038–2080) periods (RCM-GCM henceforth). In this study, we focus only on the RCM-reanalysis and RCM-GCM for the historical period, because our objective is to evaluate model skill when compared to observations. The spatial resolution for the NARCCAP RCMs was 50-km; the minimum archived precipitation aggregation time was 3-hours (Table S1 in Text S1 in the auxiliary material).[1] We used output from the six NARCCAP RCMs that used both reanalysis and GCM boundary conditions (Table S1).

[8] We extracted observed and RCM-simulated annual precipitation maxima at 3 and 24-hours precipitation durations from NCDC archives and NARCCAP model output for each of the 100 urban areas. RCM-simulated precipitation maxima were estimated for the RCM grid cell that was nearest to the selected precipitation station. We used areal reduction factors to convert point precipitation measurements to their areal equivalent for comparison with the precipitation maxima simulated by the RCMs following the method of *Leclerc and Schaake* [1972]. Details of the methods used for estimation of precipitation maxima are provided in section S1.1.

[9] We estimated annual precipitation maxima at 100-year return periods from the observations and RCM simulations. We estimated L-moments parameters and fit the Generalized Extreme Value distribution (GEV) to estimate X_T, the T-year return period precipitation at 3 and 24-hour durations for each of the selected precipitation stations. Details of the estimation approach are provided in section S1.2.

[10] To evaluate the seasonality of precipitation extremes in observations and RCMs, we identified the 10 most extreme precipitation events in summer (May through September) and winter (October through April) seasons. For each season, we estimated the mean intensity for these 10 events at 3- and 24-hour durations using the period of record 1979–2003 for the reanalysis boundary condition and 1968–1999 for the GCM boundary condition. The season (summer or winter) that received the higher mean intensity of the 10 most extreme precipitation events was taken to be the dominant season for precipitation extremes. To understand the seasonality of precipitation extremes in the RCMs, we evaluated seasonality in the individual RCMs as well as in their ensemble mean. The dominant season in which most of the RCMs simulated occurrence of precipitation extremes was considered in the ensemble mean seasonality.

3. Results

3.1. Seasonality of Precipitation Extremes

[11] Figure 1 shows the timing of annual precipitation maxima for the NARCCAP models (hereafter RCMs) with reanalysis (RCM-reanalysis) and GCM (RCM-GCM) boundary conditions. The observations show that the western coastal urban areas all receive their 3-hour and 24-hour annual maximum precipitation during winter (Figure 1) in both RCM-reanalysis and RCM-GCM simulations. On the other hand, observed precipitation maxima occur during summer at most of the locations in the rest of the United States except the Southeast, where 24-hour precipitation maxima occur during winter. For 3 and 24-hour precipitation maxima, both RCM-reanalysis and RCM-GCM showed disparities in the timing for many locations in the interior of the Western U.S. and the Southeast. (Figure 1). The RCMs successfully reproduced the observed timing of 3-hour precipitation maxima at most of the locations outside the interior West and Southeast for both RCM-reanalysis and RCM-GCM simulations (Figures 1c and 1d). The RCMs generally did better in simulating the timing of 24-hour precipitation maxima; the simulated season of the maxima was correct at most locations including the western U.S., coastal stations, and the Southeast (Figure 1).

[12] Performance of individual RCMs with respect to the season of 3-hour precipitation maxima is shown in Figure S1 in Text S1. The regions where most of the models show disagreement in the timing of 3-hour annual precipitation maxima from the observations are in the interior of the western U.S. and the Southeast. For both reanalysis and GCM boundary conditions, RCM3 better reproduced the timing of 3-hour annual precipitation maxima than other regional climate models (Figures S1k and S1l in Text S1). On the other hand, HRM3 with GCM boundary conditions and WRFG with reanalysis boundary conditions show winter dominance in 3-hour annual precipitation maxima (Figures S1h and S1m in Text S1) in many locations where the observations show summer. The individual RCM's ability to simulate seasonality of 24-hour precipitation maxima was better than that of 3-hour precipitation maxima (Figures S1 and S2 in Text S1).

3.2. 100-Year Return Period Precipitation

[13] We estimated 3 and 24-hour precipitation maxima at 100-year return periods for observed and RCM-simulated precipitation annual maxima using the GEV distribution (Figures 2 and 3). Our interest was to determine the ability of RCMs to reproduce extreme precipitation risk estimates that

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL050658.

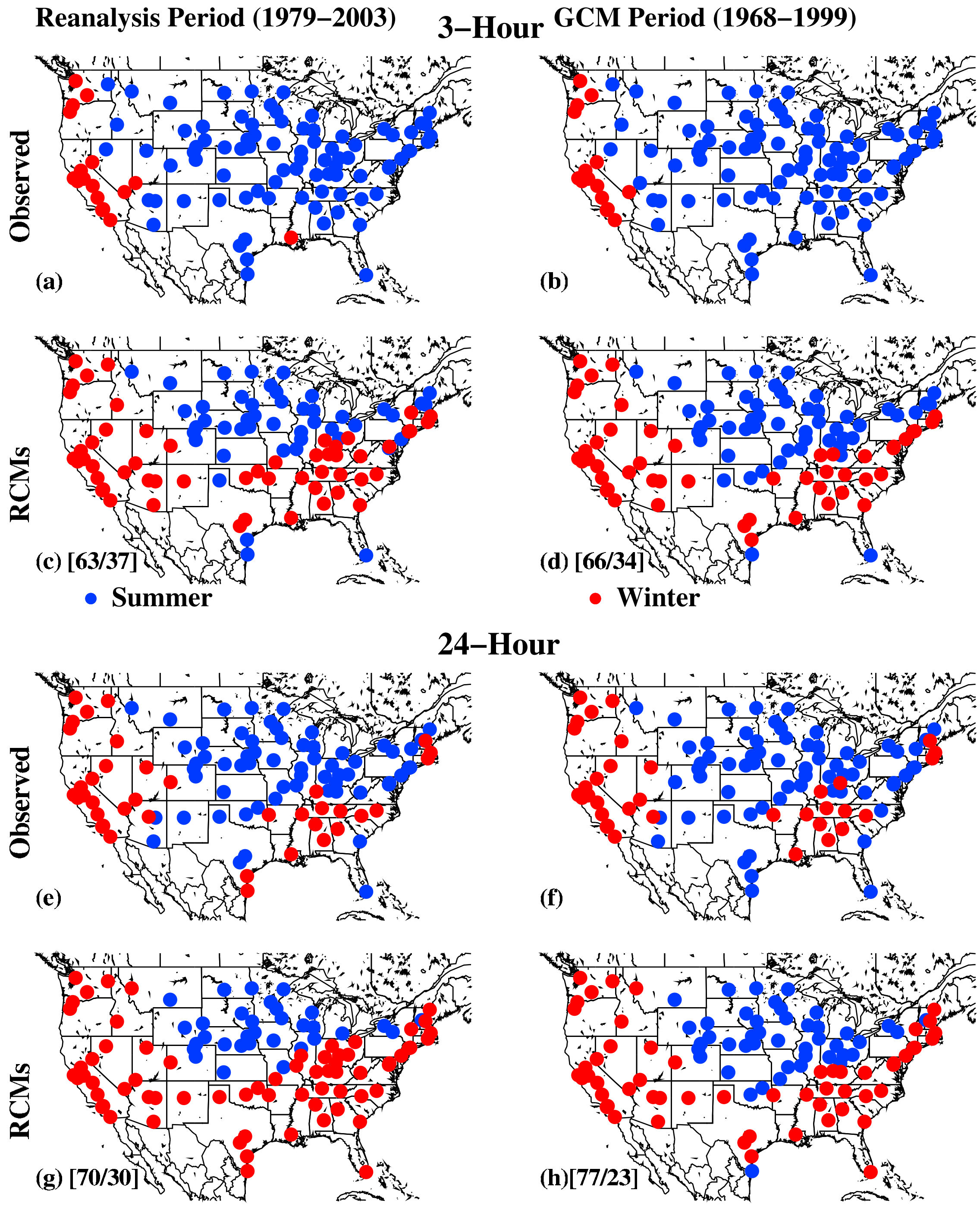

Figure 1. Performance of regional climate models (RCMs) in simulating seasonality (summer-blue; Winter-red) of 3 and 24-hour annual maximum precipitation (AMP) at selected urban areas in United States. Observed seasonality of AMP was compared with ensemble mean seasonality simulated by the RCMs for the period of record for RCM boundary conditions: reanalysis (1979–2003) and GCM (1968–1999). (a, b) observed seasonality of 3-hour AMP for the periods of reanalysis and GCM boundary conditions, (c, d) ensemble mean seasonality simulated by the RCMs for 3-hourly AMP for the reanalysis and GCM boundary conditions. (e, f) Same as Figures 1a and 1b but for 24-hour AMP and (g, h) same as Figures 1c and 1d but for 24-hour AMP. Numbers in parentheses give the number of urban areas where RCM-simulated timing was right/wrong compared with the observed timing of AMP.

are relevant to urban drainage system design. We compared estimates for ensemble mean percentage bias based on RCM-reanalysis and RCM-GCM simulations.

[14] Figure 2 shows estimated 3-hour 100-year return period precipitation (top panel) from observations and ensemble mean percentage bias for the 100-year return period estimates from RCM-reanalysis and RCM-GCM simulations. The 100-year return period 3-hour precipitation from observations is substantially higher in the eastern U.S. than in the Western U.S. (Figures 2a and 2b). The 3-hour

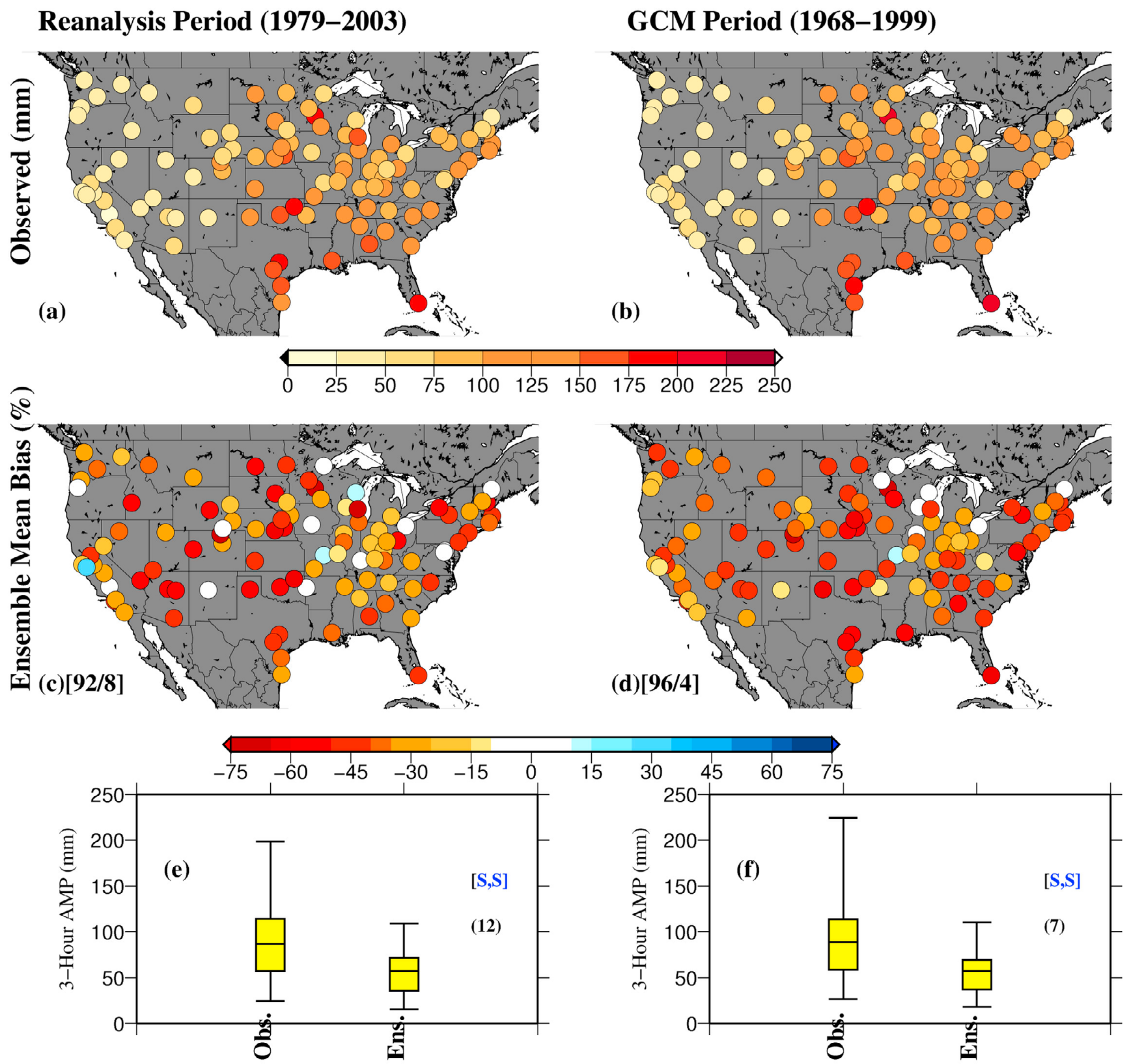

Figure 2. Performance of regional climate models (RCMs) in simulating 3- hour 100-year return period precipitation maxima. The analysis was conducted for two periods (reanalysis and GCM boundary condition) for observed as well as RCM-simulated precipitation maxima. (a, b) observed 3-hour precipitation maxima at 100-year return period for the periods of reanalysis and GCM boundary conditions and (c, d) ensemble mean percentage bias in 100-year return period 3-hour precipitation maxima simulated by the RCMs with the reanalysis and GCM boundary conditions. Numbers in parentheses indicate the urban areas where RCMs under/over estimated 100-year return period 3-hour precipitation maxima. (e, f) Box and whiskers plot compare 3-hour observed AMP and ensemble mean AMP simulated by RCMs with reanalysis and GCM boundary conditions, respectively. Numbers in black show the percentage of urban area where RCM-simulated 100-year return period 3-hour precipitation maxima were acceptable (ensemble mean bias within ±10%) for design purposes. Letters in brackets show if the mean and distributions of 100 year return period 3-hour ensemble mean precipitation maxima simulated by the RCMs were significantly (S)/non significantly (NS) different from the observed precipitation maxima.

100 year return period precipitation was underestimated at most locations. in RCM-reanalysis (Figure 2c) as well as RCM-GCM (Figure 2d) simulations. The inter-quartile range in RCM-reanalysis and RCM-GCM 100-year return period estimates for 3-hour precipitation was smaller than for observations (Figures 2e and 2f). RCM-reanalysis 100-year events were underestimated (overestimated) for 3-hour durations at 92(8) locations, while RCM-GCM also underestimated (overestimated) the same quantities at 96(4) locations (Figure 2f). The ensemble mean percentage bias in estimates of the 100-year event was within the range of ±10% at only 12 and 7 locations in RCM-reanalysis and RCM-GCM simulations, respectively. We considered bias within the 10% range acceptable for the stormwater infrastructure design. Ensemble mean 3-hour precipitation maxima at 100-year return period were statistically significantly different from observations for means as well as distributions in the RCM-reanalysis (Figure 2e) and RCM-GCM (Figure 2f) simulations.

[15] Similar to 3-hour precipitation maxima, 24-hour precipitation maxima is considerably higher at most locations in

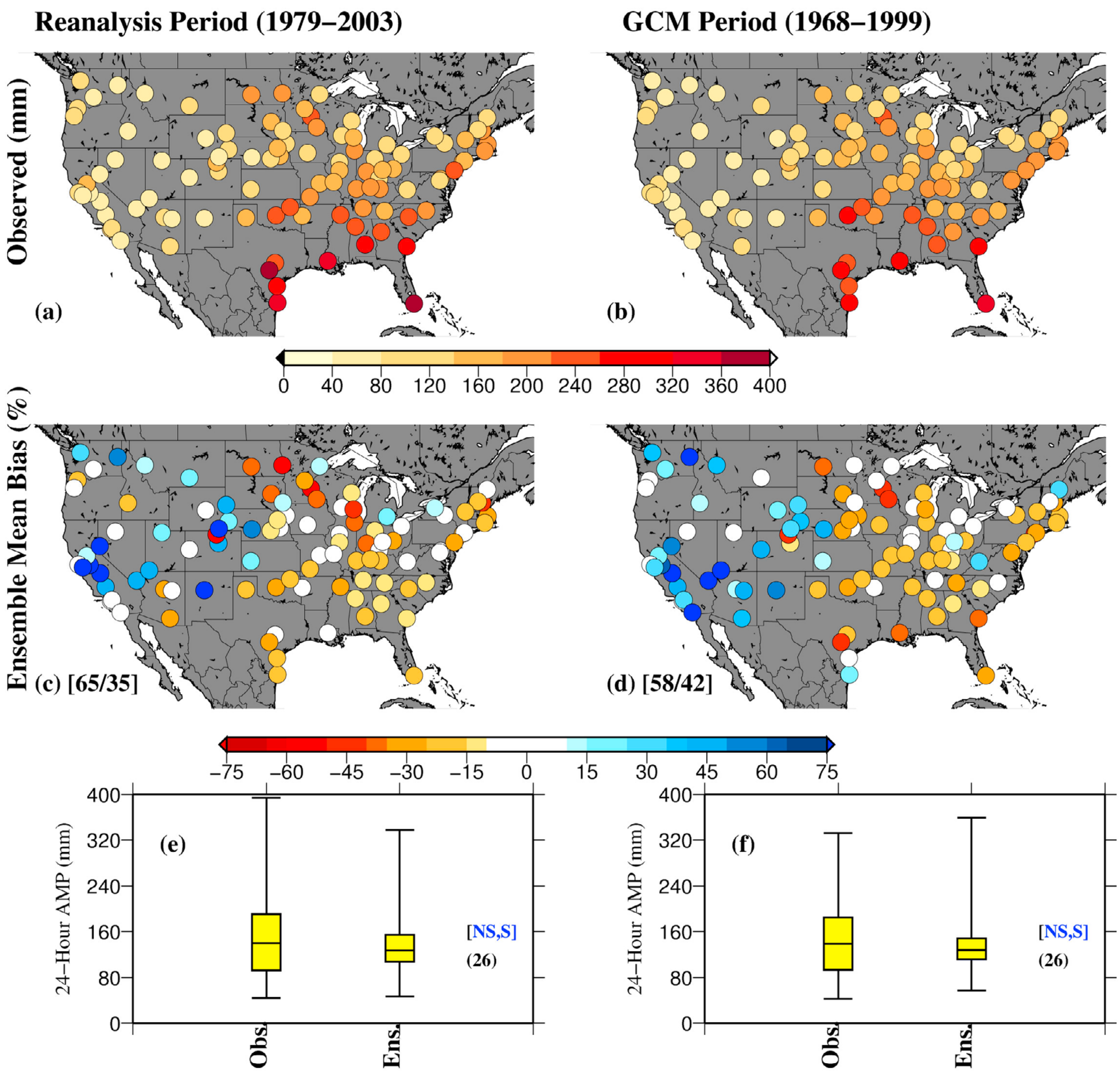

Figure 3. Same as Figure 2 but for 100 year return period 24 hour precipitation.

the eastern U.S. than in the Western U.S (Figures 3a and 3b) for the periods of record in both RCM-reanalysis and RCM-GCM. However, the spatial variability in ensemble mean percentage bias is somewhat different in 24-hour precipitation maxima (Figure 3) for 100-year return period events (Figure 2). For instance, for 24-hour 100-year return period events, the mean ensemble percentage bias was positive for most locations in the Western US., but negative in the majority of locations in the eastern U.S. in RCM-reanalysis (Figure 3b) and RCM-GCM (Figure 3c) simulations. At 65 (35) of the locations, 24-hour 100 year return period precipitation was under (over) estimated in the RCM-reanalysis simulations (Figure 3e). On the other hand, at 58(42) locations, it was under (over) estimated in RCM-GCM simulations (Figure 3f). In the both simulations (RCM-reanalysis and RCM-GCM) 26 locations fell within the range of ±10% ensemble mean percentage bias (Figures 3e and 3f). The ensemble mean 24-hour 100-year return period precipitation was not significantly different from the observation-based estimate indicating better performance than for the 3-hour duration. However, differences in distributions of the ensemble mean 24-hour 100-year return period precipitation and the observation-derived estimates were statistically significant at the 5% level.

[16] We also compared the regional (longitudinal) variability in 3 and 24-hour 100-year return period precipitation from observations as well as model simulations (RCM-reanalysis and RCM-GCM) (Figure 4). The variability of 3 and 24-hour 100 year return period precipitation reflects higher magnitudes of precipitation extremes in the eastern U.S. especially in the Great Plains region (−90 W to −100 W). Observed 3 and 24-hour 100 year return period precipitation estimates exhibit more regional variability than do estimates from the RCM-reanalysis (Figures 4a and 4c) and RCM-GCM (Figures 4b and 4d). 3-hour 100 year return period precipitation is mostly underestimated in RCM simulations as the simulated confidence bound falls below the observed range of variability (Figures 4a and 4b).

[17] Performance of RCMs for both reanalysis and GCM boundary conditions was better for 24-hour 100-year return period precipitation. For instance, the confidence bound of RCM-simulated 100-year return period precipitation falls

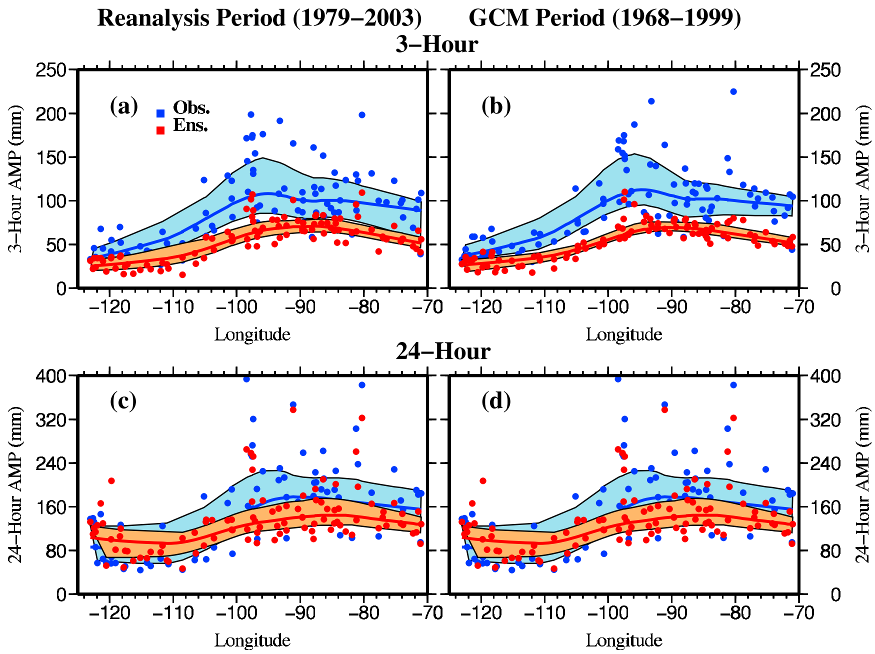

Figure 4. Variability in observed (blue) and RCM-simulated (red) 100-year return period 3 and 24-hour annual maximum precipitation (AMP): (a) observed and ensemble mean 100 year return period 3-hour AMP for reanalysis boundary conditions and (b) observed and ensemble mean 100 year return period 3-hour AMP for GCM boundary conditions. (c) Same as Figure 4a but for 24-hour AMP and (d) same as Figure 4b but for 100-year return period 24-hour precipitation. Filled circles represent observed (blue) and RCMs simulated (red) 100 year return period 3 and 24-hour AMP. Lines represents mean AMP for observed (blue) and ensemble mean simulated by the RCMs (red). Shaded regions (blue, red) represent 95% confidence bound derived using the Locally Weighted Scatter Plot Smoothing (LOWESS).

within the observed range of variability for both RCM-reanalysis and RCM-GCM simulations in the western U.S. We found a good agreement between the observed and simulated variability of 24-hour 100 year return period precipitation in the eastern U.S. despite the underestimation of the mean precipitation maxima (Figures 4c and 4d). In this respect, the results are consistent with other measures that indicate that RCMs are more successful in reproducing statistics of 24-hour precipitation maxima than 3-hour maxima. Additional information about 3 and 24-hour precipitation maxima at 100 year return period is included in section 1.3 of the auxiliary material.

3.3. Annual Maximum Precipitation Means

[18] We also estimated ensemble mean percentage bias in RCM simulations for annual maximum precipitation means for the 3 and 24-hour durations (Figures S3 and S4 in Text S1). In both the RCM-reanalysis and RCM-GCM simulations, ensemble mean percentage bias in 3-hr precipitation is negative for most locations (Figures S1c and S1d in Text S1). 3-hour precipitation maxima were underestimated in 98 of the locations in both the RCM-reanalysis and RCM-GCM simulations (Figures S3c and S3d in Text S1). In both simulations, only 5 locations fell within the ±10% bias that we considered acceptable for the stormwater infrastructure design purposes. Both the mean and distribution of the ensemble mean 3-hour annual precipitation maxima in model simulations were significantly different from observations.

[19] Both RCM-GCM and RCM-reanalysis perform better in reproducing 24-hour mean annual precipitation maxima (Figure S4 in Text S1) than they do for 3-hour mean annual precipitation maxima. For instance, despite the over (under) estimations in the western (eastern) parts of the U.S., the ensemble mean percentage bias was considerably lower for 24-hour annual precipitation maxima than for 3-hour precipitation maxima in both RCM-reanalysis (Figure S4c in Text S1) and RCM-GCM (Figure S4d in Text S1) simulations. In RCM-reanalysis simulations, 24-hour precipitation maxima were underestimated (overestimated) at 68 (32) locations (Figures S4e and S4f in Text S1). The locations in the RCM-reanalysis and RCM-GCM simulations where the ensemble mean percentage bias was within the acceptable 10% range were 26 and 29, respectively (Figures S4e and S4f in Text S1). Biases in 3- and 24-hour seasonal (summer and winter) precipitation maxima for the individual RCMs is included in section 1.4 of the auxiliary material.

3.4. Variability in Annual Maximum Precipitation

[20] We estimated the interannual variability (coefficient of variation, CV) in observed and RCM-simulated 3 and 24-hour annual precipitation maxima (Figures S5 and S6 in Text S1). RCM-reanalysis show both negative and positive mean ensemble percentage bias in CV of 3-hour annual precipitation maxima (Figure S5c in Text S1). On the other hand, there was a predominantly positive bias at the majority of locations in RCM-GCM simulations (Figure S5d in Text S1). RCM-reanalysis overestimated (underestimated) CV of 3-hour annual precipitation maxima at 42 (58) locations. The ensemble mean percentage bias was within ±10% of observed for 27 of the locations (Figure S5e in Text S1). Spatial variability in observed and ensemble mean percentage bias of CV of 24-hour annual

precipitation maxima was similar to that observed in the CV of 3-hour precipitation maxima (Figure S6 in Text S1). However, the number of locations where the ensemble mean percentage bias was within ±10% was higher than in the case of 3-hour precipitation maxima (Figures S6e and S6f in Text S1) for both RCM-reanalysis and RCM-GCM simulations. These results once again indicate the better performance of RCMs in simulating the variability in 24-hour precipitation maxima.

4. Discussion and Conclusions

[21] Our aim was to evaluate extreme precipitation as simulated by the NARCCAP RCMs to understand how well they capture the seasonality, magnitude, and variability of precipitation maxima for urban areas across the U.S. Our major findings are:

1. RCM performance is satisfactory in simulating the seasonality of 24-hour precipitation extremes across most of the U.S. However, for most urban areas in the western and southeastern U.S., the seasonality of 3-hour precipitation extremes was not successfully reproduced by the RCMs with either reanalysis or GCM boundary conditions. Specifically, the RCMs tended to predict 3-hour precipitation maxima in winter, whereas the observations indicated summer.

2. RCMs largely underestimated 3-hour precipitation maxima means and 100-year return period magnitudes at most locations across the United States for both reanalysis and GCM boundary conditions. However, performance was better for 24-hour precipitation maxima (means and 100-year events), although there were generally overestimates in the west, and underestimates in the east.

3. For both 3 and 24-hour annual precipitation maxima, RCMs with reanalysis boundary conditions underestimated interannual variability and overestimated interannual variability with GCM boundary conditions.

4. At only a very small number of locations was the bias in RCM-simulated 3 and 24-hour 100 year return period precipitation maxima within ±10% of the observed estimates, which might be deemed acceptable for stormwater infrastructure design purposes.

[22] The biases in RCM-simulated precipitation maxima appear to be the result of different physical mechanisms. One possible reason for the disparity in biases of 3 and 24-hour precipitation extremes is the spatial scale of the governing forcings. For instance, short duration (3-hour) precipitation extremes are largely governed by local convection while 24-hour precipitation extremes are more likely to be controlled by large-scale climate forcings [*Trenberth et al.*, 2003; *Trenberth*, 1999]. Because RCM performance is generally better for 24-hour precipitation maxima than for 3-hour, shortcomings in the convective parameterizations in the models may well be implicated. The spatial resolution (50 km) of the regional climate models might also be partially responsible for the biases in precipitation maxima, especially in the interior of the Western U.S., where the models are generally unable to reproduce the season of the 3-hour maximum precipitation (although orography is less likely to explain the inability of the RCMs to reproduce the season of 3-hour precipitation maxima in the Southeast). *Gutowski et al.* [2003] argued that 15 km spatial resolution was required to improve 6-hour precipitation intensity in the RCM. Therefore, simulations at much higher resolution (order of 2–5 km) might help in better capturing the statistics of precipitation extremes. Similar to earlier studies [*Gutowski et al.*, 2003, 2008; *Wehner et al.*, 2009; *Salathé et al.*, 2010], our results also highlight the importance of the higher temporal and spatial resolution of RCMs.

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