Climate Change over North America Simulated by A Regional Climate Model For Doubled CO_2

Ming Chen
Climate Change Research Center
University of New Hampshire, Durham, New Hampshire 03824

Total precipitation, including its intensity and frequency, has increased in the U.S. since about 1910. Observations show that 53% of the precipitation increase is reflected in the upper 10th percentile of precipitation events [*Karl and Knight*, 1998]. Model results largely attribute the increased precipitation to elevated atmospheric temperatures that are related to amplified greenhouse gas concentrations [*Leung et al.*, 1999; *Mearns et al.*, 1995; *Giorgi et al.*, 1994]. Land areas in the U.S. characterized with severe moisture deficiency or surplus have been expanding since the 1970s, in concert with record high mean temperatures [*Dai et al.*, 1998]. While the occurrence of these events and patterns coincide with increased atmospheric greenhouse gases, natural variability is also interwoven into these trends [*Kunel et al.*, 2003].

Studies employing GCMs have investigated severe flooding and drought using daily precipitation frequency and intensity distributions as quantitative indices [*Gordon et al.*, 1992; *Hennessy et al.*, 1997; *Meehl et al.*, 2000]. However, the coarse resolution of GCMs limits the capture of subgrid processes (e.g., convection, turbulence, and various land surface physics) and may underestimate precipitation intensity due to large spatial averaging. In particular, model biases might be enhanced in regions where topography and localized convection are important drivers of precipitation.

Regional climate models, with high spatial resolution, can provide increased accuracy in estimates of daily precipitation, especially in the regions with complex terrains [*Giorgi et al.*, 1993]. For example, trends of drying in Western/Central Europe and increased wetness in Western Russia obtained with the RegCM3 regional model are remarkably consistent with observations in recent decades [*Pal et al.*, 2004]. Despite these encouraging results, insufficient attention has been placed on understanding and predicting future changes in precipitation characteristics.

We applied an MM5-based regional climate modeling system to quantify changes in precipitation characteristics across the U.S. for a future condition of doubled CO_2 (i.e., 2090-2099). To describe precipitation characteristics we used the daily amount, precipitation intensity (monthly total precipitation/rainy days), frequency (number of rainy days in the month), and regime (convective versus large-scale precipitation). Our study addressed three questions: (1) What are the future changes in precipitation characteristics over North America?, (2) Are the predicted changes consistent with observed recent trends?, and (3) What are the key physical and dynamical mechanisms driving the identified spatial and seasonal variations in these changes?

The regional climate modeling system (RCMS) used in this study was developed by *Chen et al.* [2004]. Its atmospheric component is the Penn State/NCAR MM5 coupled with the LSX land-surface-transfer model [*Pollard et al*., 1995] to provide a physics-oriented description of the hydrologic cycle in soils and vegetation. In the RCMS, the intensity of precipitation affects its interception by canopy vegetation, soil moisture and runoff. This transfer of moisture feeds back through the hydrologic cycle to ultimately impact precipitation. Unique model features include the cascade of precipitation through the canopy and a surface-ponding reservoir to buffer interactions between precipitation, infiltration and runoff.

The RCMS domain spans the U.S. with a grid size of 108 km (Figure 1). There are 29 vertical levels with the top of the model at 100 mb. Two 10-year simulations were performed for present-day (1990-1999) and future climate (doubled CO_2, 2090-2099). These runs were driven by output from a transient 145-year experiment of the NCAR CSM [*Boville and Gent*, 1998]. CSM outputs for years 15-24 (i.e., present decade of 1990-1999) and years 95-104 (future decade of 2090-2099) were used to provide large-scale forcing.

The RCMS simulated precipitation was compared with the Climate Research Unit (CRU) monthly climatology for 1981-1990 [*New et al.*, 1999] and the Climate Prediction Center daily precipitation observations for the U.S. [*Higgins et al.*, 2000]. Note that model results are only comparable to these observational data as climatological averages, since the CSM forcing does not correspond to actual weather sequences.

We compared simulated with observed precipitation trends in four subregions of the U.S. that belong to different climatic regimes (Figure 1) [*Trewartha*, 1961]: (1) Pacific Northwest (PNW), (2) Central U.S. (CEN), (3) Southeastern U.S. (SE), and (4) Northeastern U.S. (NE). The overall patterns of modeled present-day precipitation were in good agreement with observations for both winter and summer seasons (not shown). In winter, the rainbelts along the PNW and Atlantic seaboard were captured well by the model, as was the rainshadow area over the CEN. Both model results and observations show that summertime precipitation was concentrated over the eastern and CEN, where the latter had more precipitation in summer than in winter. Pattern correlations (r) between simulations and CRU observations were 0.77 and 0.63 with root mean square errors of 0.92 mm day^{-1} and 1.21 mm day^{-1} in winter and summer respectively. For future climate, precipitation was predicted to increase over most of the U.S. The largest increases were located in the SE during winter and downwind areas of the Great Lakes during summer (not shown).

The cumulative frequency distributions (CFDs) calculated from observations of daily precipitation for the time periods of 1963-1972 and 1989-1998 averaged over the PNW and SE in January (winter) and the CEN and NE in July (summer) are shown in Figure 2a. The choice of the subregions and seasons was based on the consideration that the PNW and SE have abundant precipitation in winter, the NE has precipitation distributed evenly year-round, and the CEN has copious precipitation in summer contrasted by a dry winter. The contrast between the cool period of 1963-1972 and the abnormally warm period of 1989-1998 [*IPCC*, 2001] provides an analogy for our RCMS results of present-day and a future warmer climate. Despite some differences between simulations and observations, the predicted trends in precipitation statistics for future climate remarkably resembled those for the two 20th century decades in all sub-regions and gives confidence in our RCMS predictions.

The CFDs of daily precipitation for the present-day and future climate scenarios are shown in Figure 2b. Changes in the cumulative probability of simulated daily precipitation differed between the four subregions and exhibited distinct spatial variability in precipitation characteristics. The most significant changes were as follows. Over the NE in summer, a large difference was predicted at the high end, indicating increases in both intensity and frequency of heavy precipitation events. In winter over the SE, daily precipitation was increased uniformly at all probability levels, with median values increased from a present-day 2.3 mm day^{-1} to a predicted 3.2 mm day^{-1}. The number of days in January with heavy precipitation (defined as >12.8 mm day^{-1}, following *Hennessy et al.* [1997]) increased from the present 5 days to 19 days in 2090-2099. In the CEN, daily precipitation changed little at both low and high ends of the probability distribution, but was enhanced between the 45th and 85th percentiles. No distinct changes over the 21st century were found for the PNW.

To further quantify changes in precipitation characteristics for future climate, daily precipitation was split into three categories classified as weak (<8 mm day^{-1}), moderate (8 - 32 mm day^{-1}), and heavy (>32 mm day^{-1}) events. The percentage change in precipitation frequency was calculated for each category and month averaged over the land area in the appropriate domain (Figure 3a). Compared to present-day climate, the frequency of heavy precipitation events in 2090-2099 increased significantly in all seasons except fall. Moderate events should occur most frequently in the warm months, with a maximum increase of 30% in summer. Weak precipitation events should increase by 5 - 15% in summer with less frequency over the rest of the year compared to present climate. Since the number of weak precipitation events comprised ~82% of the total events for both present-day and future climate simulations, a small percentage increase or decrease in the number of weak events dominates the total number of rainy days. Hence, despite the general increase in frequency of heavy precipitation events, the total annual rainy days actually decreased by ~3% for future climate due to fewer weak precipitation events.

Monthly mean precipitation and intensity for present-day and future climate scenarios are compared in Figures 3b and 3c. Both variables increased in nearly every season with their maximum increases in summer. For future climate, increases in precipitation intensity are larger than those in mean precipitation, especially in winter. This indicates more heavy precipitation events and fewer rainy days in winter, as shown in Figure 3a. These results suggest that precipitation in the future will become more episodic than at present and be distributed over fewer days, but with relatively larger daily amounts.

To examine changes in precipitation regimes, we compared monthly average convective precipitation and its percentage of the total (only over land) for present-day and future climate. The model results show that for future climate, convective precipitation and the ratio of convective/total precipitation increase year-round with large enhancements in summer (Figure 4). This result agrees with the findings from the GCM study by *Hennessy et al.* [1997], and suggests that precipitation will be more convective under doubled CO_2. This is physically consistent with an increased frequency of heavier precipitation events, which are associated mostly with convective precipitation. This result may be caused by positive feedback between increased convective precipitation and a warmer climate. Latent heat released from convective precipitation could feed back into the atmosphere leading to stronger convection and more precipitation. In a warmer climate, with more water loading in the atmosphere, this feedback could be intensified and promote increased convective precipitation.

Trenberth et al. [2003] speculated that for a warmer climate, there would be a decrease in the number of weak and moderate precipitation events and an increase in precipitation intensity, which are supported by our RCMS results. Our observational analysis showed that there are significant increases in both frequency and intensity of heavy precipitation events during a warm period compared to a cool one. This observed trend provides compelling support for our prediction of increasing trends in intensity and frequency of heavy precipitation events for future climate. Furthermore, our study illustrates that total precipitation amount will not necessarily change in the same direction as precipitation frequency.

The mechanisms behind these changes might arise from large scale changes in storm tracks or, modification of convective activities. Detailed analyses of changes in atmospheric circulation and related anomalies in storminess are beyond the scope of this study. Here we briefly investigate the physical processes associated with changes in precipitation characteristics in a warmer climate in the NE, SE, and CEN subregions.

Over the CEN in summer, humid air advected from the Pacific Ocean and Gulf of Mexico can become unstable due to surface warming and produce favorable conditions for development of summertime convective precipitation. Under doubled CO_2, surface heating should be intensified and evapo-transpiration enhanced by ~10% compared to the present - a condition conducive to increased precipitation. However, the anticyclonic ridge that resides over the southern Great Plains may become stronger under this scenario, and its associated dry subsiding air dampens convection in the unstable surface layer. In this case our model results indicate that surface processes are strong enough to counteract atmospheric dynamics. In addition, convection could quickly dry out the boundary layer such that insufficient moisture is available to sustain convective precipitation. The combination of these factors likely contributed to the predicted small changes in the CEN at the high end of the CFD (Figure 2). Nonetheless, precipitation increased between the 45^{th} and 80^{th} percentiles, reflecting the important effects of enhanced humidity and surface heating.

Heavy precipitation over the SE was associated with depressions developed along the jet stream, which should be positioned over this region in winter. For future climate, passages of synoptic-scale systems increased and cyclonic control became stronger regionally. Both types of processes appeared to contribute to the increased frequency and intensity of precipitation, and resultant increases across the CFD spectrum. In the NE, however, passages of synoptic systems decreased slightly, but cyclonic disturbances were intensified. Together with more water capacity and convective activities during summer, heavy precipitation events above the 90^{th} percentile increased by 15% over this region.

Our study indicates that for a future climate with doubled CO_2, the precipitation regime tends to be more convective with a higher intensity across the U.S. Heavy precipitation events should become more frequent. Although precipitation amounts are expected to increase in the future,, precipitation will become more episodic and be distributed over fewer days with larger daily amounts. This implies that drying periods between events will become longer and more frequent. Consequently, the probability of flooding and droughts should increase in the future. Particular attention should be paid to the NE in summer and the SE in winter for a higher risk of flooding.

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