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Observations and Regional Climate Model Simulations of Heavy Precipitation Events and Seasonal Anomalies: A Comparison

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Abstract

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Disciplines

Atmospheric Sciences | Climate | Hydrology

Comments

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Observations and Regional Climate Model Simulations of Heavy Precipitation Events and Seasonal Anomalies: A Comparison

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ABSTRACT

A regional climate model simulation of the period of 1979–88 over the contiguous United States, driven by lateral boundary conditions from the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis, was analyzed to assess the ability of the model to simulate heavy precipitation events and seasonal precipitation anomalies. Heavy events were defined by precipitation totals that exceed the threshold value for a specified return period and duration. The model magnitudes of the thresholds for 1-day heavy precipitation events were in good agreement with observed thresholds for much of the central United States. Model thresholds were greater than observed for the eastern and intermountain western portions of the region and were smaller than observed for the lower Mississippi River basin. For 7-day events, model thresholds were in good agreement with observed thresholds for the eastern United States and Great Plains, were less than observed for the most of the Mississippi River valley, and were greater than observed for the intermountain western region. The interannual variability in frequency of heavy events in the model simulation exhibited similar behavior to that of the observed variability in the South, Southwest, West, and North-Central study regions. The agreement was poorer for the Midwest and Northeast, although the magnitude of variability was similar for both model and observations. There was good agreement between the model and observational data in the seasonal distribution of extreme events for the West and North-Central study regions; in the Southwest, Midwest, and Northeast, there were general similarities but some differences in the details of the distributions. The most notable differences occurred for the southern Gulf Coast region, for which the model produced a summer peak that is not present in the observational data. There was not a very high correlation in the timing of individual heavy events between the model and observations, reflecting differences between model and observations in the speed and path of many of the synoptic-scale events triggering the precipitation.

1. Introduction

Flooding from heavy precipitation is a frequent occurrence in the United States. Since 1970, annual losses have exceeded $1 billion many times. Notable recent events include the 1993 flood in the upper Mississippi River basin (Kunkel et al. 1994; Changnon 1996), the North Carolina flood in September of 1999 caused by Hurricane Floyd (Easterling et al. 2000), and floods along the upper Mississippi River in the spring of 2001. These events illustrate the vulnerability of our society to flooding. One possible outcome of global warming is an increase in the frequency and intensity of heavy precipitation events because of an accelerated hydrological cycle (Kattenberg et al. 1996). Recent studies have indicated that there has been an increase in the frequency of heavy precipitation events in the United States (Karl et al. 1995; Karl and Knight 1998; Kunkel et al. 1999a,b). An assessment of the potential societal impacts of climate change requires an accurate assessment of possible changes in flooding frequencies and intensities.

General circulation models (GCMs) have been extensively used to provide realizations of climate change scenarios. However, computational limitations have restricted the resolution of these simulations. In recent model simulations, grid spacings are approximately 150 km or greater. Although this may be adequate to capture the large-scale wave activity responsible for many precipitation episodes, individual heavy precipitation events are often highly localized in time and space. This behavior is in contrast to temperature extremes, which often cover large areas. Thus, the resolution of global climate models is often too coarse to resolve the specific meteorological features that result in heavy precipitation. This fact is an example of a meteorological process

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by which a regional climate model (RCM), with significantly higher spatial resolution, may provide a more accurate simulation of the climate system. Recent work using RCMs illustrates the potential benefits of the use of RCMs as a downscaling tool. Giorgi et al. (1996) performed a case study of the 1988 drought and 1993 flood events. Overall, the model successfully reproduced the precipitation distribution of these two extreme periods. However, the precipitation during July of 1993 was biased on the low side, illustrating the need for further improvements in RCMs. In another study, Bates et al. (1995) used an RCM to simulate the climate in the Great Lakes region for a 2-yr period. This model produced moderately good agreement with observations.

These were very short simulations from a climatological perspective. This paper describes an analysis of a 10-yr simulation from a regional climate model, comparing model estimates with observations of heavy precipitation and seasonal anomalies. This analysis provides an opportunity to examine the ability of an RCM to simulate climatological probabilities of heavy precipitation events and seasonal anomalies. It is important to assess the accuracy of the RCM so that intelligent use of simulation results can be made.

2. Data and methods

The second-generation Regional Climate Model (RegCM2) of the National Center for Atmospheric Research (NCAR) was used to produce a 10-yr simulation (1979–88) of climate conditions over the United States. The version of RegCM2 used for simulations reported herein is the same as that used by Giorgi et al. (1993a,b) except for elimination of rainwater as a predictive variable (for computational efficiency) and some entrainment and autoconversion coefficient modifications. The lateral boundary conditions used to drive the model were from the National Centers for Environmental Prediction (NCEP)–NCAR reanalysis (Kalnay et al. 1996). The grid spacing of the RegCM2 is 52 km in the horizontal direction, with 14 levels in the vertical direction.

Use of the reanalysis data, which represent a physically consistent assimilation of observations, as lateral boundary forcing on the RCM provides information on the fundamental ability of the RCM to represent processes that produce heavy precipitation. Although there may be errors in reanalysis data, particularly over data-poor ocean areas, that can affect RCM results (e.g., Liang et al. 2001), GCM simulations of the climate system are likely to contain larger biases (Pan et al. 2001b). When forcing the RCM boundary with GCM data, the RCM results will have an additional level of uncertainty that results from errors in the larger-scale forcing. Thus, the results reported herein represent the minimum level of uncertainty associated with RegCM2 simulations of heavy precipitation when forced at the lateral boundaries. It should also be possible to run the RCM in a data assimilation mode in which the domain interior is periodically nudged by observations. However, Pan et al. (1999) showed that the results are substantially affected because there is a continual spinup of the RCM water cycle. In the current study, the results would be distorted too much to be of value.

Daily gridded precipitation data for the same period (1979–88) were obtained from the Surface Water Modeling Group at the University of Washington from their Web site at http://www.hydro.washington.edu/Lettenmaier/gridded_data/, which was produced following the methodology described in Maurer et al. (2001a,b, manuscript submitted to *J. Climate*). The resolution of their grid is 0.125° latitude by 0.125° longitude. The gridded data were produced from daily observations of the National Weather Service Cooperative Observer Network using the Synagraphic Mapping (SYMAP) interpolation routine. After interpolation, the precipitation data were adjusted to match monthly values from the Parameter-Elevation Regression on Independent Slopes Model (PRISM; Daly et al. 1994, 1997). PRISM is a system that uses rules, decisions, and equations designed to incorporate the effects of topography on precipitation patterns in a manner similar to what a knowledgeable climatologist would do. This is critical because, in the western United States, cooperative stations are preferentially located at lower elevations. Because precipitation is a highly sensitive function of elevation, the spatial average of cooperative stations tends to produce values that are biased on the low side relative to a true spatial average. This consideration may also be a factor in the Appalachian Mountains, although the topographic variability is not as extreme, so biases should be less. The PRISM adjustment applied to these gridded data is intended to reduce these biases.

The grid spacing of these data is considerably smaller than that of the output of RegCM2. The frequency distribution of daily precipitation values is a sensitive function of spatial scale, with this distribution narrowing as the averaging area increases. For reasonable comparison between the two, the gridded observational data were spatially averaged. To be specific, the data for those grid boxes within a RegCM2 grid box were area averaged; this averaged time series was then compared with the RegCM2 gridbox time series. This point-by-point (or grid cell–by–grid cell) comparison is a stringent test of the model's accuracy.

Heavy precipitation events were defined by duration and return period. Because the observed data are at a daily resolution, 1 day is the shortest duration possible. Return-period thresholds were determined using standard hydrometeorological methods. For each grid point, the largest 100 events were identified and ranked. The empirical probability distribution was fit to the Gumbel distribution, a widely used function for extreme value analyses (Farago and Katz 1990), using the maximum likelihood method. Thresholds for selected return pe-

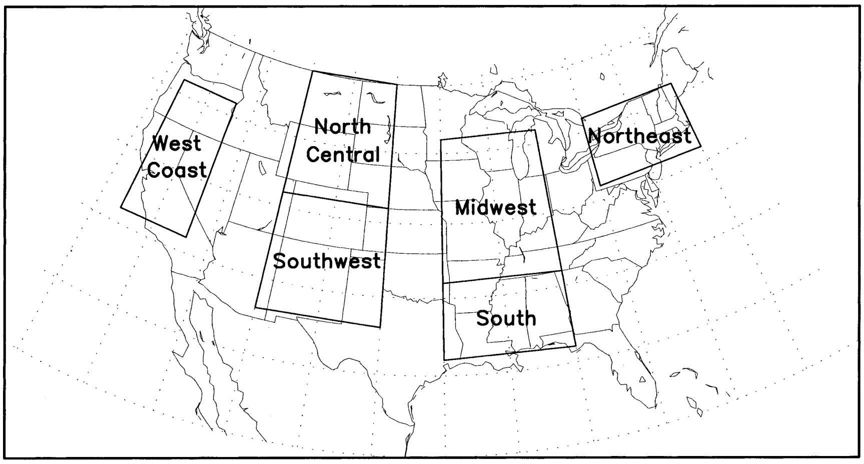

FIG. 1. Boundaries of six regions used in this study for regionalized analysis of heavy precipitation climatic behavior.

riods were estimated from the function. The statistical significance of the differences between model and observed thresholds was evaluated by first calculating the standard z score as

$$z = (T_m - T_o)/(s_m^2 + s_o^2)^{1/2}, \qquad (1)$$

where T_m and T_o are the threshold estimates for the model and observations, respectively, and s_m and s_o are standard errors of the estimates for the model and observations, respectively. Standard errors of the estimates were computed from formulas in Farago and Katz (1990). The null hypothesis that there is not a statistically significant difference between model and observations was rejected at the 95% level of confidence if $|z| > 1.96$. Precipitation events of two durations, 1 and 7 days, were analyzed. The cooperative observer network records precipitation on a daily basis, hence the selection of 1-day events. An extensive study of flood-producing rainfall events in the central United States found that floods on small to medium-sized drainage basins were related to multiday precipitation events (Changnon and Kunkel 1995). In particular, this study found a close correlation between flooding frequencies and precipitation events of 7-day duration and a return period of 1 yr. Because there has been a significant increase in the frequency of these 7-day events over much of the United States (Kunkel et al. 1999a) in the last 70 yr, 7-day events were also analyzed in this study. The direct correlation of these events with flooding events may be lower in regions outside the central United States.

Although 10 yr is a very long simulation period for an RCM, it is short for a climatological study of observed heavy events. Such studies have tended to consider events with return periods of 1 yr or longer. In this study, the longest return period studied is 5 yr. Heavy precipitation threshold results are presented for 3-month, 1-yr, and 5-yr return periods. A return period of 3 months is very short for typical heavyp recipitation analyses but was included here to increase the number of events and robustness of results for certain analyses, for example, the climatic anomaly results (section 3c). Remember that the 3-month return period simply means that events of this magnitude or greater are expected to occur four times per year, on average.

Section 3 describes several aspects of the comparison between model and observational data. First, the daily precipitation frequency distribution for one region is shown as an example. Heavy precipitation-event thresholds are then compared between the model and the observations, for several event lengths and return periods. Next, interannual variability in the frequency of extreme events is compared. Then, seasonal cycles and interannual variability in the frequency of extreme precipitation events are shown for six selected regions, shown in Fig. 1. Last, the correlation of the timing of individual events is discussed.

3. Results

a. Frequency distribution

Figure 2 shows the frequency distributions of model and observed daily precipitation values averaged for all grid boxes in the Midwest region (Fig. 1). There are fewer no-precipitation days and more light-precipitation (0–2 mm) days in the model when compared with observations. The distributions are otherwise very similar. Of particular importance to this study, the distributions at higher precipitation amounts (inset) are of similar shape and magnitude. The distributions for the other five regions (not shown) exhibit similar behavior. Thus, the use of a single function type (Gumbel) to fit both model and observed distributions is appropriate.

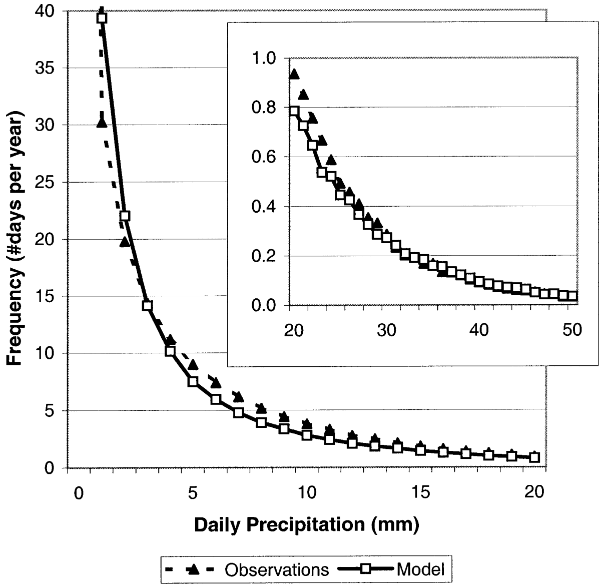

FIG. 2. Frequency of daily precipitation values averaged for the grid boxes located in the Midwest region (Fig. 1). The inset shows the tail of the distribution with an expanded vertical axis.

b. Heavy precipitation event thresholds

Figures 3a and 3b show the spatial distribution of the observations and model thresholds, respectively, for 1-day events with a 1-yr return period. In general, the thresholds are lowest over the Rocky Mountains and intermountain western region, moderate over the north-central plains, Midwest, and Northeast, and highest in the South near the Gulf Coast, and along the northwestern coast. This pattern of heavy precipitation not surprisingly closely matches the spatial pattern of mean annual precipitation for much of the contiguous United States. Figure 3c shows the ratio of model thresholds to those of observations. Shaded areas indicate that differences between model and observed thresholds are not statistically significant at the 95% level of confidence. In a region extending in two branches from the north-central plains south to Texas and to the southeast to Alabama, the differences between the thresholds are small (within 15%) and not statistically significant. The model thresholds tend to be higher than observed in the eastern United States and the intermountain western region and lower than observed in the southern plains, lower Mississippi River basin, and along the northwestern coast. In all of these areas, the differences between model and observed thresholds are statistically significant.

Figure 4 shows thresholds for 1-day events with a 5-yr return period. Although the magnitudes of the thresholds are higher, the general patterns in the spatial distribution of the observed thresholds (Fig. 4a), model thresholds (Fig. 4b), and ratio of model to observations (Fig. 4c) are all similar to those of 1-day events with a 1-yr return period. Figure 5 shows thresholds for 1-day events with a 3-month return period. The general pattern is similar to results for the 1- and 5-yr return periods. The most notable difference is that the area of statistically significant differences (Fig. 5c) in the lower Mississippi River valley and southern plains is more extensive than that found for the 1-yr (Fig. 3c) and 5-yr (Fig. 4c) return periods.

Figure 6 shows the thresholds and ratio for 7-day events with a 5-yr return period. Again, the magnitudes of the thresholds are different, but the general patterns are the same. When compared with Fig. 4c for the 1-day duration, the model thresholds for the 7-day duration (Fig. 6c) are somewhat lower relative to the observed thresholds across much of the United States east of the Rockies. This shifts the pattern of statistical significance, with differences for the 7-day duration statistically significant across much of the Mississippi River valley. Differences are not statistically significant for the eastern United States and High Plains, in contrast to the results for the 1-day duration.

c. Climatic anomalies

The ability of RegCM2 to simulate climatic anomalies was assessed by examining the differences between years with above-normal and below-normal frequencies of 1-day events with a 3-month return period. For each grid point, there are by definition 40 such events distributed throughout the 10 yr of the model simulation, that is, 120 months in the record divided by the 3-month return period. For each grid point, the total number of heavy precipitation events was calculated for the 3 yr with the greatest number of events and for the 3 yr with the least number of events. The difference between these two totals is a measure of the magnitude of the anomalies. The definition of above- and below-normal years was chosen to be consistent with the National Weather Service's classification of above- and below-normal periods, in their Climate Outlook (Van den Dool 1994) product, as the upper and lower thirds of the frequency distribution.

The difference was quantified by means of a ratio R, defined as

$$R = 100\%(T_{A,m} - T_{B,m})/(T_{A,o} - T_{B,o}), \qquad (2)$$

where T represents the total number of events, the subscripts "A" and "B" symbolize above normal and below normal, respectively, and the subscripts "m" and "o" symbolize the model data and observational data, respectively. Note that, for each grid point, years with the greatest or least number of events were identified separately for the model and observational data. A specific year could have a different classification in the model data than in the observational data. This analysis examines the ability of RegCM2 to simulate the climatological distribution of number of events, not its ability to simulate any specific event.

Figures 7a and 7b show the spatial distribution of the range in interannual variability for the observations and

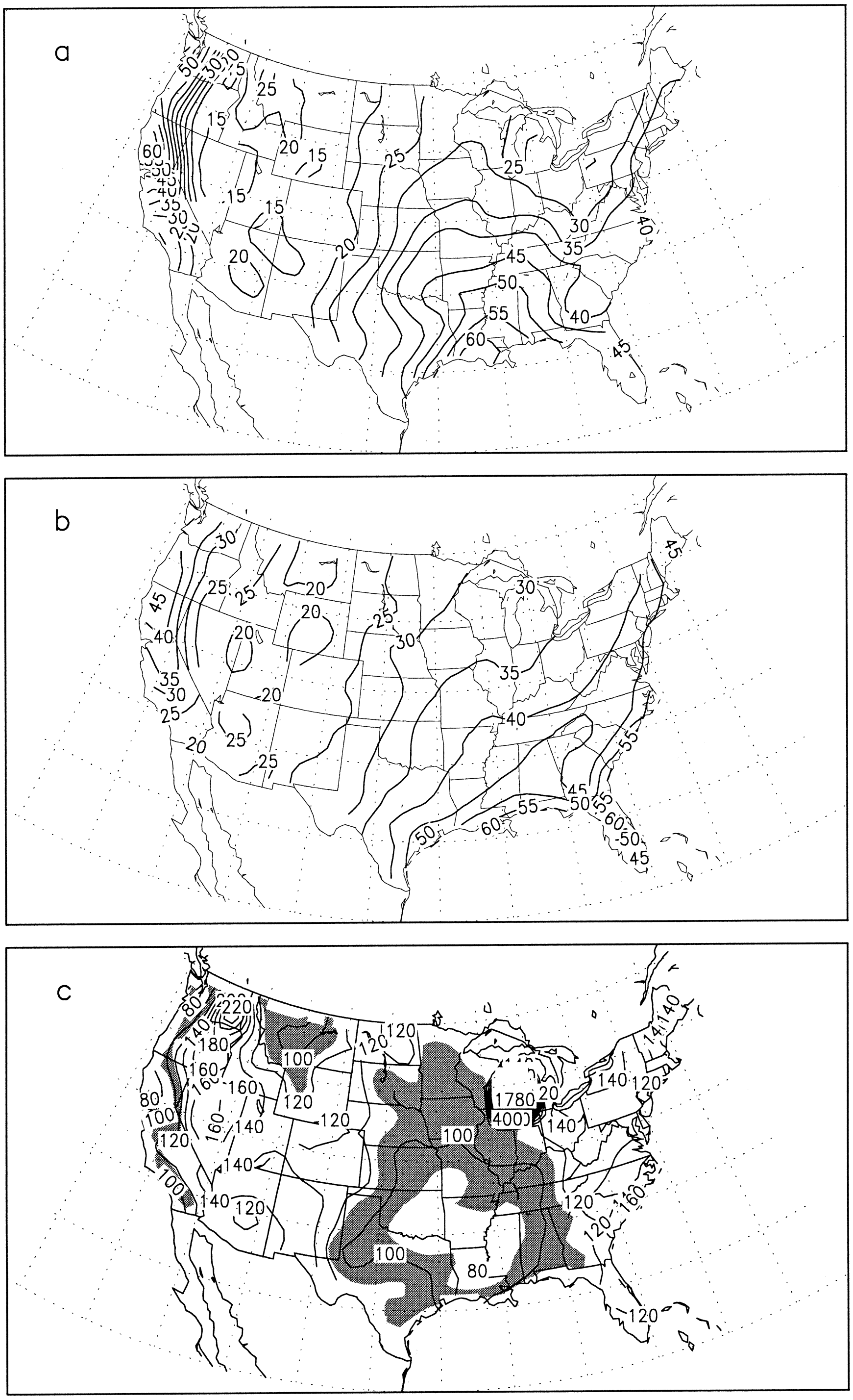

FIG. 3. Thresholds (mm) for 1-day 1-yr heavy precipitation events for (a) observations and (b) model. (c) The ratio of model to observations (×100); shaded area indicates where differences between model and observations are *not* statistically significant at the 95% level of confidence.

the model, respectively. Ranges for both observations and model show large variations over relatively small distances. The ratio *R* between the two, shown in Fig. 7c, also contains large variations over relatively small distances. This suggests that the range is sensitive to the small-scale nature of heavy precipitation events and to the relatively short length of record available for this climatological analysis. The model does tend to exhibit somewhat less interannual variability than is observed in the eastern third of the United States and somewhat

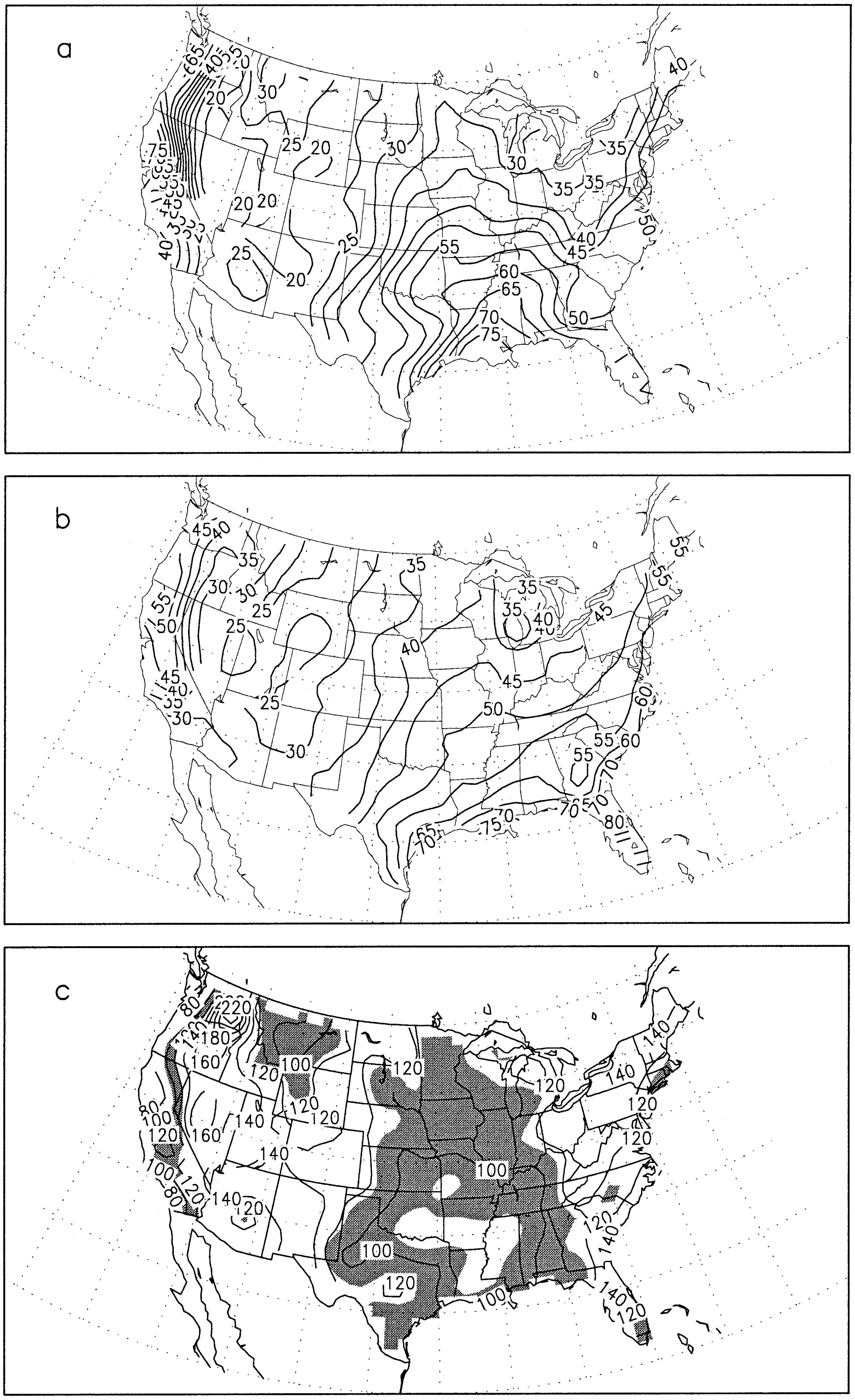

FIG. 4. Same as Fig. 3, but for 1-day 5-yr heavy precipitation events.

greater than observed (indicated by shading) in the western part; these differences, however, are not large in most areas. The differences were tested for statistical significance using a Student's *t*-test. Differences were not statistically significant anywhere.

Figure 8 compares time series of the annual number of events between model and observations for the six regions of Fig. 1. Annual values are averages of individual gridbox annual values for all grid boxes in the regions [the number of grid boxes is 199 (West), 282 (North-Central), 294 (Southwest), 329 (Midwest), 192 (South), and 160 (Northeast)]. There is general agreement between the model and observations in the basic features of the time series for the North-Central, South,

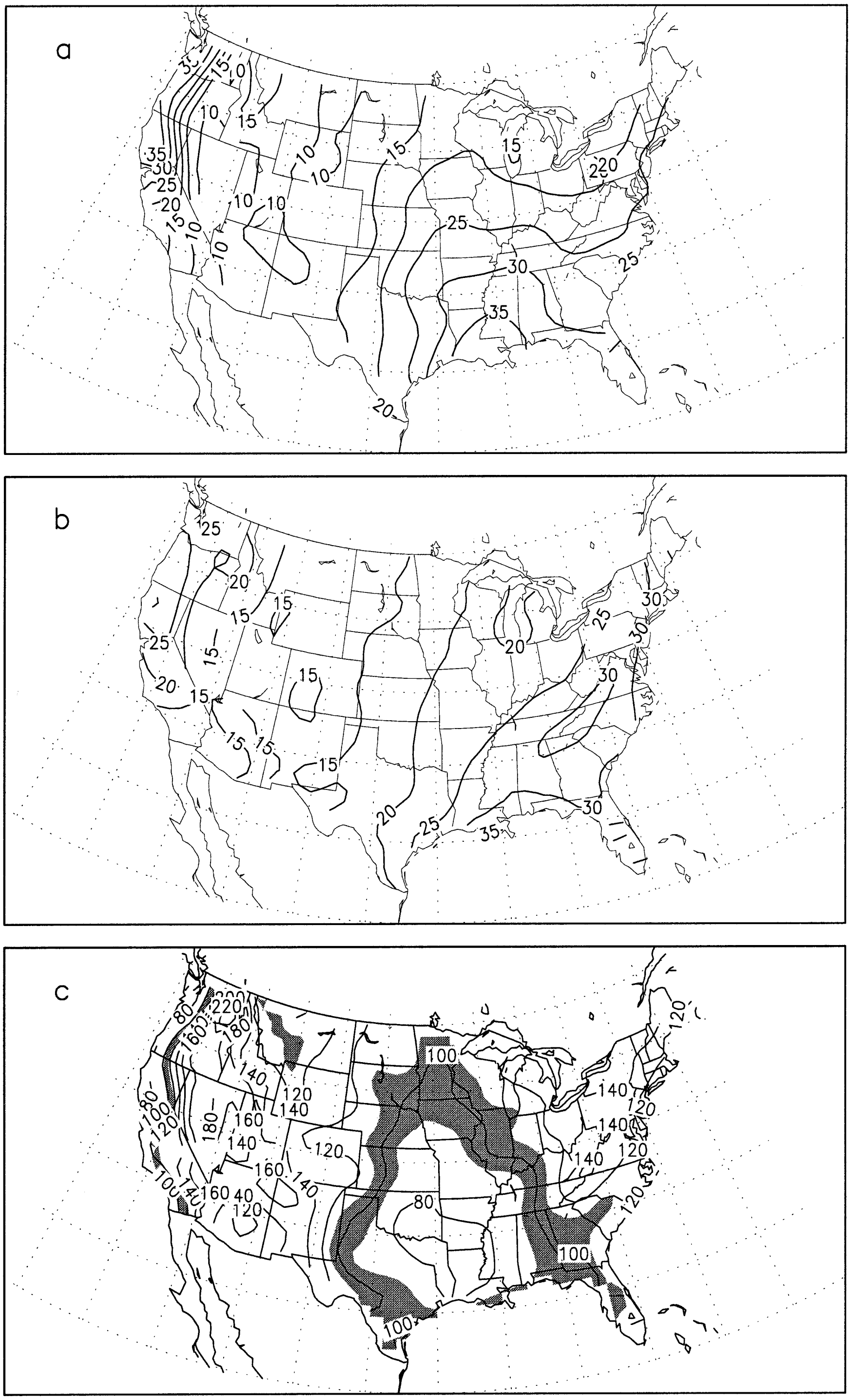

FIG. 5. Same as Fig. 3, but for 1-day 3-month heavy precipitation events.

and West Coast regions, with r^2 values in the range of 0.58–0.70. Correlations are lower in the Midwest and Southwest, but the model does simulate the generally lesser interannual variability found in those regions. The lowest correlation is found in the Northeast, a region in which interannual variability is also small. The Northeast is also near the model's outflow boundary, which is a part of the domain that tends to have large errors. Overall, the model generally reproduces the timing of anomalous years in those regions in which interannual variability is high but does not perform as well in regions of low interannual variability.

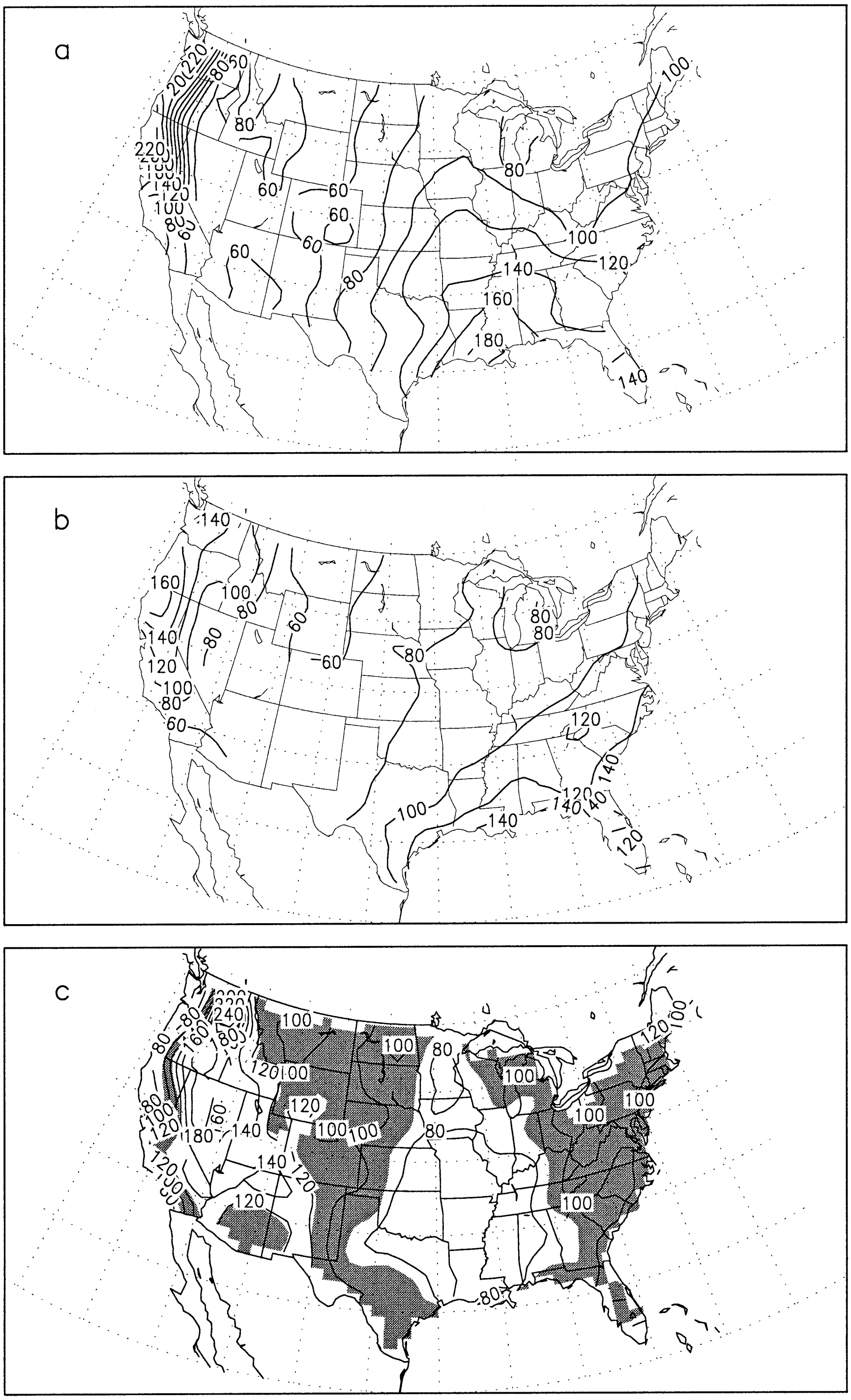

FIG. 6. Same as Fig. 3, but for 7-day 5-yr heavy precipitation events.

d. Annual cycle in heavy precipitation events

The annual cycles in 1-day 3-month precipitation events are shown in Fig. 9 for the six regions outlined in Fig. 1. Within each region, the annual cycle in frequency of heavy precipitation events is relatively consistent among stations. For each region, the number of 1-day events with a 3-month return period was averaged for each month for all grid boxes in the region for the model and for observations. The annual average (by definition) is 0.33 1-day 3-month events per month.

In the North-Central region, the model accurately reflects the observed peak in extreme precipitation events

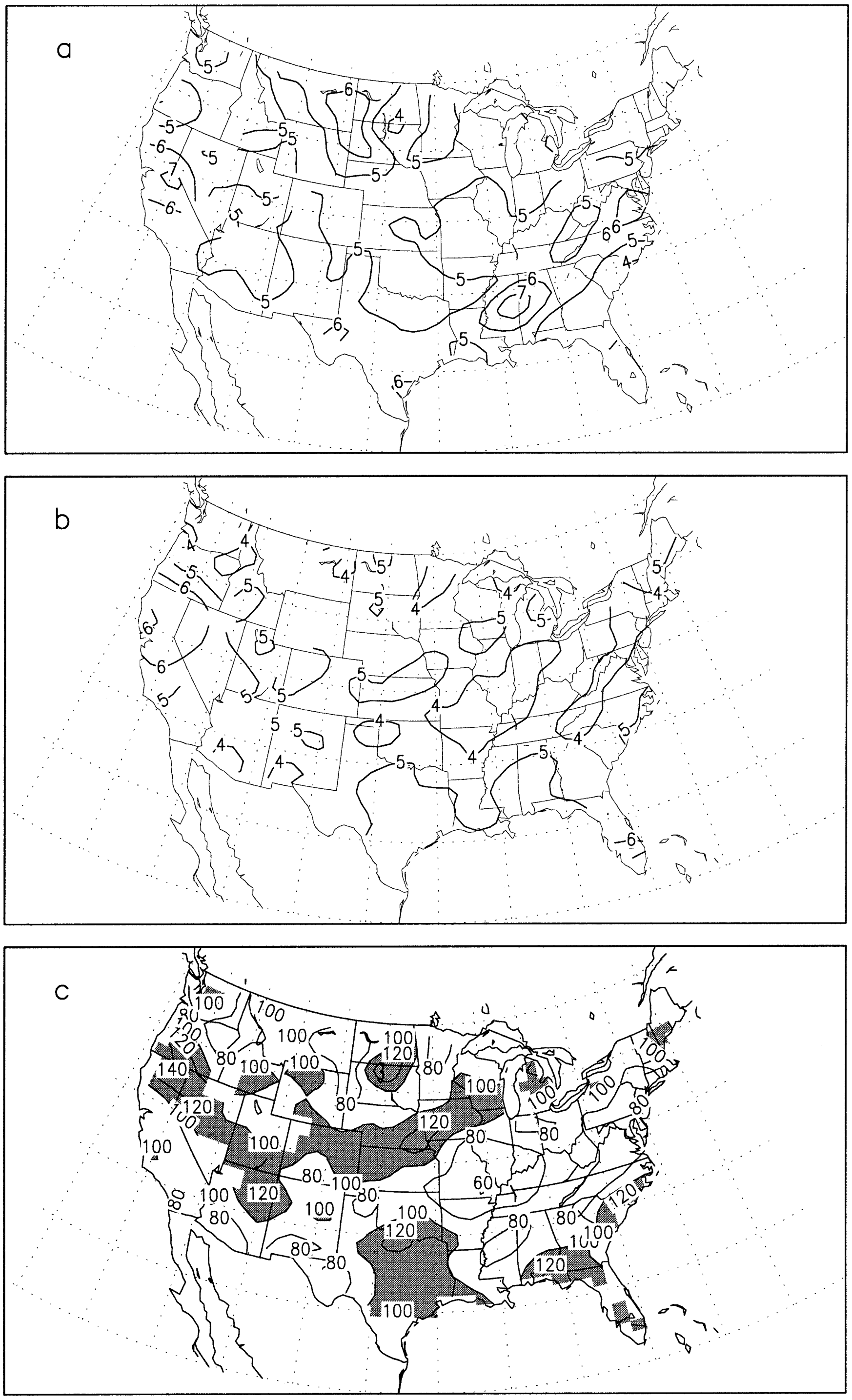

FIG. 7. Difference in the total number of 1-day 3-month events between above-normal and below-normal years for (a) observations and (b) model. (c) The ratio of the model to the observations (×100); shading indicates areas where the ratio is greater than 1.0 (100%).

in late spring and summer. In the Southwest, the observed annual cycle is of relatively small amplitude, with a peak in autumn. The model produces the general feature of the annual cycle with a warm-season peak and cool-season minimum. However, the peak in July may imply that the model overemphasizes the impact of the southwestern monsoon (Douglas et al. 1993). The observed late summer/early autumn peak, underestimated in the model, is due to eastern Pacific tropical storms and early-season extratropical storms, suggesting

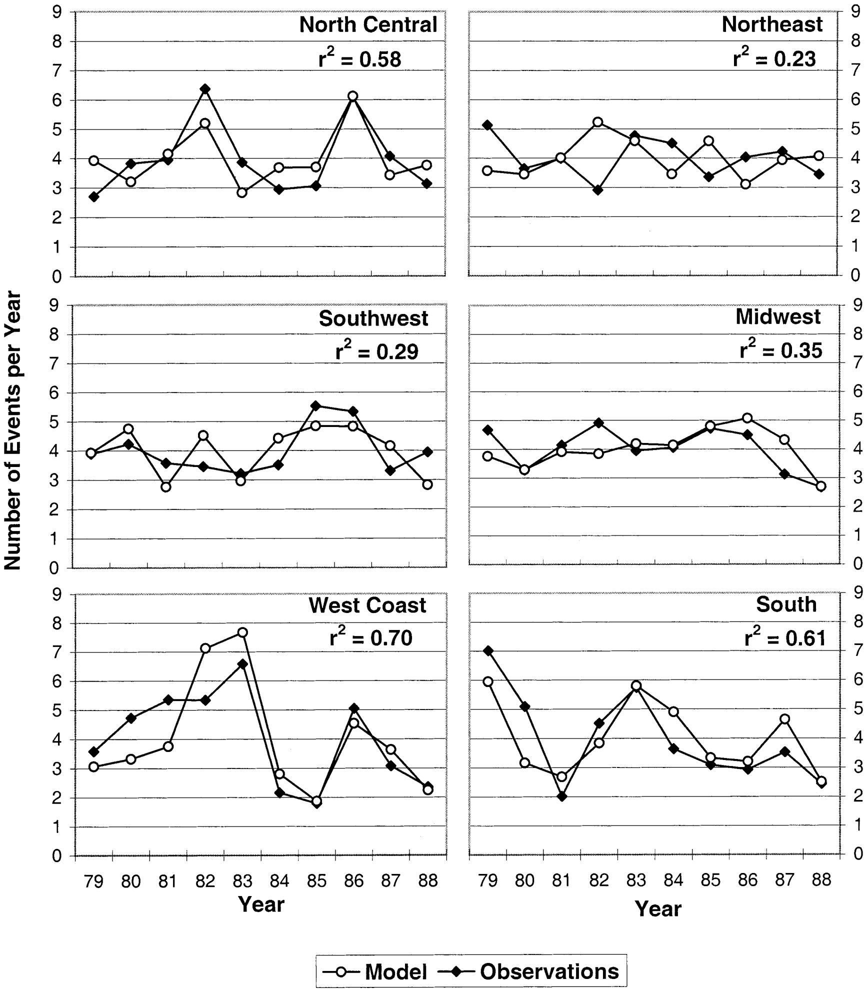

FIG. 8. Time series of the observed and modeled annual number of 1-day 3-month extreme precipitation events for the six regions outlined in Fig. 1. Also shown is the square of the correlation coefficient (r^2) between the two time series.

the possibility of model inaccuracies in the treatment of those features. The annual cycle along the West Coast is of large amplitude with a peak in the winter, typifying a Mediterranean climate; this pattern is reproduced well by the model. In the Northeast, the model peak in the annual cycle is earlier than observed, in summer rather than autumn. Likewise, the broader peak in the Midwest occurs earlier in the model (spring and summer) than observed (late summer and early autumn). In the South, the model annual cycle is reversed, with the greatest number of events occurring in the late spring and summer, rather than in the winter and spring. Previous studies have found that predictions of precipitation in this region are poorer than for other parts of the model domain (e.g., Pan et al. 2001a,b). Model deficiencies in these latter three regions are not easily explained and may reflect model errors/biases in the treatment of convective versus stratiform precipitation.

e. Timing of individual events

The results in sections 3c and 3d illustrate the general behavior of the model in simulating anomalies on climatic timescales. An additional, more detailed consideration is the degree to which individual observed heavy events are simulated by RegCM2 as events exceeding the return-period threshold. A simple measure of this, the percent of observed 1-day heavy events that were coincident in time with simulated events, was computed for each grid point. Events were considered to be coincident in time if they occurred within a window of ±2 days of each other. This window allowed for differences between the model and observations in the speed of propagation of large-scale systems across the United States and for differences in observation time.

Figure 10 shows results for 1-day events with a 3-month return period. Over most of the United States, values are in the range of 10%–40%. Thus, the majority

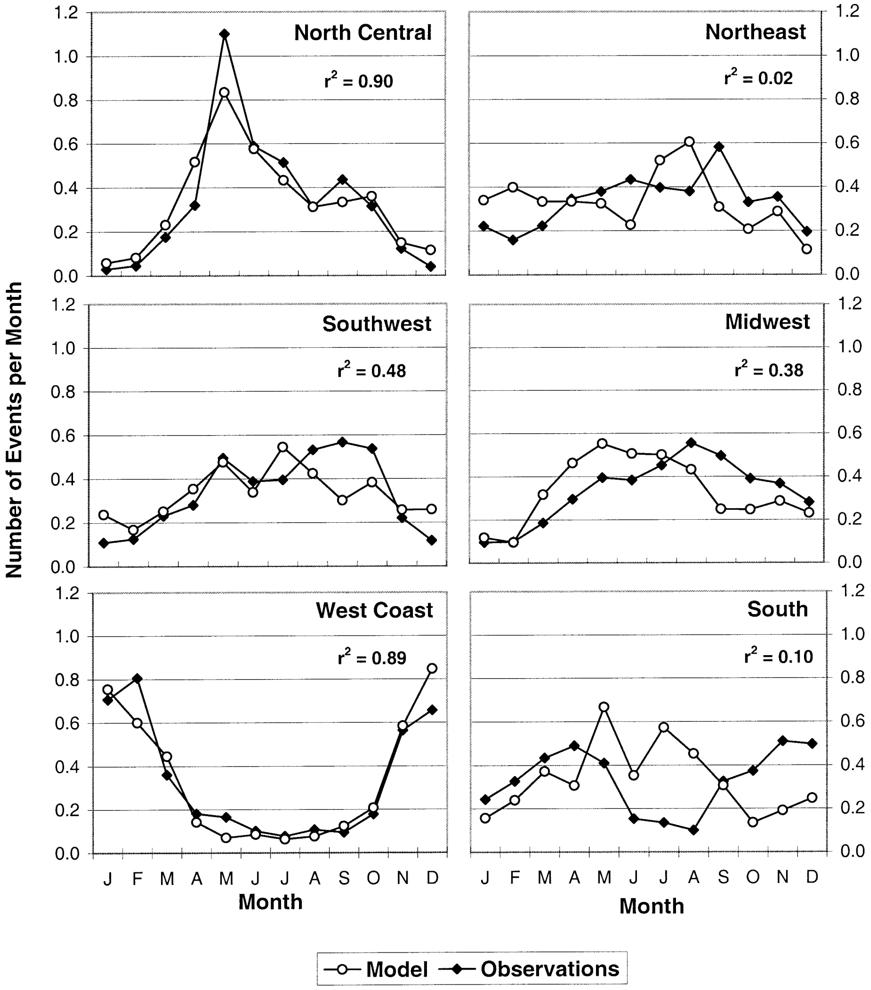

FIG. 9. The model and observed annual cycle in number of events per month for 1-day 3-month extreme precipitation events for the six regions outlined in Fig. 1. Also shown is the r^2 between the two time series.

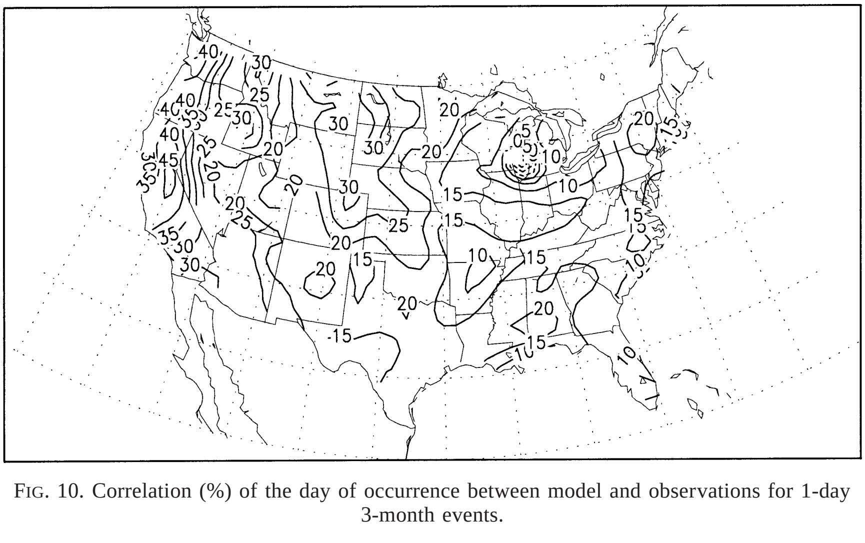

FIG. 10. Correlation (%) of the day of occurrence between model and observations for 1-day 3-month events.

of events are not coincident in time. There are regional variations in the correlations. Correlations are highest in the western coastal states and along the foothills of the Rocky Mountains, generally in the range of 25%–40%. For the eastern United States, correlations are less than 20%.

An inspection of daily maps indicates that the model consistently reproduces in a qualitative way the movement of systems and the occurrence of precipitation. An analysis of several individual heavy precipitation episodes (not shown) suggests a couple of possible reasons for the poor correlation in heavy events. One, the spatial pattern of heavy precipitation in the model is sometimes shifted relative to the observations. Thus, heavy precipitation is simulated in the model at different grid points from where it is observed. Because the correlations are computed on a point-by-point basis, even a small phase error can lead to very low correlations. Second, there are episodes for which the model produces only moderate amounts of precipitation while observed amounts are heavy; the reverse situation also occurs.

4. Summary and conclusions

This analysis of a 10-yr simulation using RegCM2, with lateral boundary conditions obtained from the NCEP–NCAR reanalysis, found the following key similarities and differences between the model heavy precipitation and observations:

1) Model thresholds for heavy precipitation events are generally somewhat greater than the observed thresholds in the mountainous regions of the western United States and less than observed along the West Coast. East of the Rockies, differences vary with event duration. For 1-day events, model thresholds are similar to observed over much of the central United States, except for the lower Mississippi River valley, and greater than observed for the eastern United States. For 7-day durations, model thresholds are similar to observed for the eastern United States and less than observed over the central United States.
2) The interannual variability of the frequency of model heavy events shows general similarity to the observed. However, although the correlation coefficients between modeled and observed frequencies of extreme events were positive for every region studied, they were statistically significant only for the West Coast.
3) The annual cycle in extreme precipitation events is best reproduced in the North-Central and West Coast regions. For the Midwest, Southwest, and Northeast regions, the results are mixed with some, but not all, features reproduced. The model simulation is poor for the South region.
4) The timing of specific events at individual grid points is generally not highly coincident between model and observations.

There are a number of possible causes for the differences between model results and observational data. First, because the western, eastern, and southern boundaries of the model domain are generally located over data-poor oceanic regions, there are uncertainties in the lateral boundary conditions used to drive the model. If the boundary conditions do not accurately reflect the climate of the boundary regions, the model may not produce an accurate climate in the interior regions. Second, precipitation is one of the more difficult variables to simulate accurately and is sensitive to many of the physical parameterizations of the model (Yang and Arritt 2002). Even with the higher resolution of the regional climate model simulation used here, the resolution remains too coarse to simulate convection directly, which is important in many heavy precipitation events. As computer capabilities increase, it will be possible to produce higher-resolution simulations, which may improve the simulation of convective precipitation.

The implications of this analysis for climate change studies are that studies of heavy precipitation using the RegCM2 can be conducted with the most confidence in the regions for which both the magnitude and the annual cycle in heavy precipitation events are reproduced well in the model. The thresholds for the heavy precipitation events examined here, 1-day 1-yr events, 1-day 5-yr events, and 7-day 5-yr events, were generally simulated with some accuracy in some regions, although this varied by return period; the dependence of accuracy on return period complicates the application of model simulations. The annual cycle in heavy events was reasonably reproduced for the West Coast and North-Central regions, but sizeable differences were observed elsewhere. The model performed poorly in the South along the Gulf Coast, where the model thresholds for the heavy events are low and the heavy events occur during the wrong part of the year. The interannual variability was simulated accurately along the West Coast, although thresholds were too low along the coast and too high in the interior, probably resulting from the fact that RegCM2 resolution is not sufficient to resolve the highly detailed orography along the coast.

Low correlations in the timing of events between model and observations may, on the surface, reduce confidence in the model results. This finding certainly suggests the need for further model improvements. Possible model deficiencies include the convective parameterization scheme and the inability to resolve well the circulation of mesoscale convective systems. However, systems producing heavy precipitation are likely to be affected both by forcing at the lateral boundaries and by processes completely internal to the RegCM2 domain, such as variable surface forcing from time-dependent soil moisture, snowpack, and vegetation conditions. The atmospheric response to these internal processes may be highly sensitive to initial conditions. Thus, individual events may not be simulated accurately, but the climatological frequency of heavy events may be accurate. To the extent that this is true, there is no expectation of an exact match between model and observations, and the usefulness of these results may be higher than is suggested by the low correlations.

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