Mesoscale convective systems and extreme rainfall in the central United States

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Abstract Ten years of central United States warm season (May-August) observations of precipitation in mesoscale convective complexes (MCCs) are analyzed and compared with precipitation from all other sources for these months. Substantial differences are found in statistical properties of these subsets, including the diurnal cycle and the distribution of rainfall. In terms of the number of precipitation observations, MCCs make contributions well beyond those that would be expected based only on their relatively small number. This is especially true for large rainfall amounts, for which 20% of the observations occur in MCCs, even though less than 7% of all observations occur in MCCs. Analysis of individual Kansas and Missouri stations reveals that slightly more than 15% of 10-year station extremes of 1 h and 12 h (0000-1200 UTC) rainfall totals occur in MCCs.

INTRODUCTION

Evidence now exists to show that rainfall during the spring and summer convective season over much of the central United States is substantially modulated by mesoscale convective systems (MCSs). Fritsch et al. (1986), for instance, estimate that as much as one-third to one-half of all warm-season precipitation in any given year may fall from a few of the largest MCSs. Investigations of large MCSs on other continents (e.g., Velasco & Fritsch, 1987) suggest that the same may hold true over much of the globe. Given the large year-to-year changes in MCS location and frequency (Tollerud et al., 1989; Tollerud and Rodgers, 1991), it is likely that much of the variability in daily and perhaps in monthly and seasonal rainfall in these regions can also be explained by MCS activity.

A climate-related question naturally arises from these findings: To what extent do large MCSs determine historical extremes in hourly to daily rainfall totals in the central United States? Since the time scales of the largest MCSs approach one day, it is quite possible that a single event could produce record or near-record 12-24 h rainfall at a site that remains within an MCS for much of the MCS life cycle. To address this question, we examine 1 h and 12 h precipitation totals produced by a class of the largest MCSs, the mesoscale convective complexes, or MCCs, as defined by Maddox (1980; 1983). By comparing distributions and extrema of these data with those from other precipitation, we estimate the MCC contribution to heavy and extreme precipitation and describe the distinctive characteristics of precipitation in MCCs. In the conclusions, we
discuss how these results may be relevant to diagnostic climate studies and to climate models that include precipitation.

METHODOLOGY

MCCs are distinguished from other MCSs by their large size, long duration, and circular shape (Fig. 1). The specific criteria used over the years to define MCCs can be found in Maddox (1980) and Augustine & Howard (1991); each MCC can be determined by reference to infrared satellite imagery. Although not qualitatively different from other MCSs that approach but do not meet these criteria, MCCs have proven to be a useful and conveniently sized subset (about 40 per year) for research purposes over the last decade.

![Fig. 1 Infrared satellite imagery of two MCCs. Edges of the outer grey and inner black regions delineate clouds at the -32C and -52C levels, respectively.](image)

Ten years of thorough MCC summaries (1978-1987) are now available for the United States (Rodgers et al., 1983; Augustine and Howard, 1991). Included in these summaries is information about each system’s time, date, duration, size, and location during its life cycle. Tollerud & Rodgers (1991) present a climatological description of the more than 300 MCCs during this 10-year period.

To resolve precipitation with the length and time scales of MCCs, we employed hourly precipitation observations from the Hourly Precipitation Data set (HPD) obtained from the National Climatic Data Center. Figure 2 shows the location of observing sites of the HPD in the central United States. By collating these data with MCC tracks, and by making some simplifying assumptions about MCC shape and size evolution, it is possible to isolate a set of MCC precipitation observations from the larger set of all non-MCC observations. Fig. 3 illustrates the procedure by which MCC observations are assembled. We limited our analysis to the area of greatest MCC frequency (the area of Fig. 2), or where indicated, to the states of Kansas and Missouri, and to the months
of greatest MCC activity (May-August). For simplicity, we have not distinguished between stages of MCC development, although, as Fig. 3 indicates, it would be relatively easy to do so.

**DIURNAL CYCLE: MCC VS NON-MCC**

We begin with a description of the diurnal cycles of the sets of MCC and non-MCC precipitation (Fig. 4). Although both sets exhibit nocturnal maxima, MCCs reveal a markedly more dominant diurnal cycle. This modulation is a natural result of the development of MCCs, which have a strong tendency to reach their maximum extent and strength a few hours after local midnight. The nocturnal variability also varies seasonally; as Tollerud & Rodgers (1991) demonstrate, the midday minimum of MCC
precipitation reaches virtual zero in August.

In addition to a peak a few hours after midnight (possibly another MCS maximum), the non-MCC curve also exhibits a peak most likely related to afternoon convection. However, there is significant precipitation spread over the entire day, and the diurnal amplitude is only about one-fifth as large as the average hourly frequency. Apparently, synoptic and other variations not specifically tied to diurnally-varying processes make a major contribution to non-MCC precipitation.

Two preliminary conclusions are suggested by Fig. 4. First, the substantially different curves imply, though they do not prove, that different physical processes are acting to produce the two sets of precipitation observations. For the MCC set, in particular, adequate representation of the diurnal variation of atmospheric processes
would appear to be very important in climate models that hope to describe the bulk effect of mesoscale convection.

Second, the peak in MCC precipitation is largely contained in the 12 h period between 0000 and 1200 UTC. Since few other precipitation systems produce heavy convective rainfall that is as widespread or as long-lasting as 12 h, we might expect that MCCs, when they occur, could be responsible for more than their share of precipitation extremes on this time scale. These two facts suggest that it would be appropriate and useful to analyze 12 h precipitation totals between these hours. Several of our subsequent results describe distributions of these 12 h (0000-1200 UTC) amounts. We anticipate these results would not be substantially altered if UTC-based daily totals were used instead.

It is also worth pointing out the two quite different scales in Fig. 4. The non-MCC set samples about 16 times as many rainfall observations as the MCC set. The chance of an MCC occurring in a particular region are even smaller; during the 10 years of record, for instance, only about 35 MCCs concentrated their rainfall in Kansas. Roughly speaking, then, there is only a 1 in 300 chance that on any given summer day a particular station will experience an MCC, even in preferred regions of development like Kansas. Thus, despite their importance, MCCs are still relatively rare phenomena. As the next section shows, MCCs exhibit an effect on precipitation well out of proportion to their frequency.

ESTIMATING THE MCC CONTRIBUTION

In this section, we estimate the overall contribution that MCCs make to warm-season precipitation over the central United States. Fritsch et al. (1986) approach this question by producing maps of the percent of rain depth produced by MCCs during a single season. Since we are primarily interested in the contribution of MCCs to high and extreme rainfall, we choose to divide the 10-year set of observations (both 1 h and 12 h) into rainfall categories. The MCC effect is then represented as a percent of the total number of observations in each category.

Results for 12 h totals are displayed in Fig. 5. The distribution of 1200-0000 UTC totals is included for comparison with the 0000-1200 UTC totals, even though we

![Fig. 5 The within-category percent of observations made in MCCs.](image-url)
expect from Fig. 4 that the MCC effect will be much less during that period. Note that the percent values are computed within each rainfall category, so they are not expected to sum to 100.

The primary result in Fig. 5 is the increase in percent in progressively larger rainfall categories. In the large categories between 1.5 and 2.5 in (3.81 and 6.35 cm), 20% of all observations, on average, occurred during MCCs, a value that is considerably higher than the rate of occurrence of MCCs would suggest. In other words, randomly sampled rainfall observations in these large 12 h categories have about a 1 in 5 chance of being produced in MCCs. Rainfall larger than 2.5 in (6.35 cm) are encountered only a few times during the 10-year period, either in MCCs or elsewhere. Consequently, percents based on them are erratic and potentially unrepresentative. Nonetheless, it is clear that MCCs have a large effect on the distribution of heavy rainfall observations.

As expected, the 1200-0000 UTC contribution is significantly smaller. The same distribution of 1 h rainfall (not shown) exhibits a similar increase with increasing rainfall categories. However, the percent values are less, indicating that MCCs have less effect on heavy rainfall over these shorter periods. This latter result is not surprising, since it is reasonable to presume that MCCs would have their greatest effect over time scales close to their own.

**COMPARISON OF RAINFALL DISTRIBUTIONS AND STATION EXTREMES**

We address the MCC role in producing climatic extremes of precipitation in two ways. First, we present and discuss the overall distributions of MCC and non-MCC rainfall, at both 1 h and 12 h periods. Second, using observations from the set of HPD stations in Kansas and Missouri (abbreviated KS and MO; see Fig. 2 for locations), we establish a set of 10-year extreme values of 1 h and 12 h precipitation totals. These states were chosen because they fall in the center of the region of greatest historical MCC activity. Knowledge of whether each of these extremes (one per station) occurred in MCCs then helps to further determine the significance of MCCs.

Figures 6 and 7 show both the MCC and non-MCC rainfall distributions of 1 h and 12 h (0000-1200 UTC) rainfall, respectively. Although the 12 h distributions extend to larger amounts, as expected, the differences between the two sets of MCC and non-MCC curves are similar. Compared to non-MCC observations, MCC precipitation is more heavily dominated by larger rainfall, as the fatter MCC tail in each set shows. For the 12 h set, the percent of the MCC distribution made up of categories greater than 1 in (2.54 cm) is about twice as large as the corresponding values for the non-MCC set. A similar result holds for the 1 h data, except that the crossover point is roughly one-half of what it is for the 12 h data.

In part, the 12 h curves can be simply interpreted to indicate that MCC rainfall tends to be more concentrated within 12 h periods than rainfall in general, resulting in a shift of observations (relative to the non-MCC precipitation) from the small rainfall categories to the larger ones. The 1 h results, however, illustrate that it is not only a matter of packing more hourly observations into 12 h. Further statistical analysis should help determine whether differences in the MCC and non-MCC distributions are large enough to necessitate different treatment in statistical models or in statistically-based
parameterizations in numerical models.

The gist of our analysis of 10-year station extremes in Kansas and Missouri is set out in Table 1, which displays a monthly breakdown of the percent of stations having 1 h and 12 h extremes produced by MCCs. Overall, values for 12 h extremes exceed 17%, while 1 h values average almost 16%. In the month of August, these percents increase to 27 and 19, respectively. These values are substantially larger than MCC frequency alone would indicate.

![Fig. 6 The distribution of hourly rainfall for MCC and non-MCC subsets. The value for each category is computed as a percent of the total number of observations summed over all rainfall.](image)

![Fig. 7 As in Fig. 6 except for 12 h (0000-1200 UTC) rainfall totals.](image)

CONCLUSIONS

In this paper we have described several ways in which MCC precipitation (in particular, extreme values of precipitation) is distinct from other warm-season precipitation. Among our key findings are the following: 1) MCCs are significantly more diurnally modulated; 2) MCCs contribute to precipitation frequencies well beyond a rate suggested by their number; 3) the distribution of MCC rainfall is more heavily dominated by values larger than 0.5 in (1.27 cm) per hour than is non-MCC rainfall;
Table 1 Number and percent of stations in Kansas and Missouri that exhibit extremes of 1 and 12 h (0000-1200 UTC) rainfall produced in MCCs.

<table>
<thead>
<tr>
<th>Month</th>
<th>Total Number of Stations</th>
<th>Stations with 1 h extremes</th>
<th>Stations with 12 h extremes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>Number</td>
<td>Number</td>
</tr>
<tr>
<td>MAY</td>
<td>178</td>
<td>28</td>
<td>15.7</td>
</tr>
<tr>
<td>JUN</td>
<td>180</td>
<td>24</td>
<td>13.3</td>
</tr>
<tr>
<td>JUL</td>
<td>178</td>
<td>27</td>
<td>15.2</td>
</tr>
<tr>
<td>AUG</td>
<td>180</td>
<td>35</td>
<td>19.4</td>
</tr>
<tr>
<td>Average</td>
<td>177.2</td>
<td>29.6</td>
<td>15.9</td>
</tr>
</tbody>
</table>

4) the greatest influence of MCCs is felt for periods and for times of day that match the typical MCC life cycle (12 h totals between 0000 and 1200 UTC, for instance); and 5) a disproportionately large percent of 10-year station extremes of summertime precipitation in the central United States are produced in MCCs (for 1 h rainfall, 15.9% of extremes were found to be MCC-related while less than 7% of all precipitation observations occurred in MCCs).

Knowledge of the MCC component of precipitation extremes is relevant in several ways. First, the large component determined here suggests that if general circulation models are to correctly predict actual precipitation extremes or their tendency over time, then these models must somehow represent (in all likelihood, parameterize) the essential characteristics of MCCs, or at least their effects averaged over a grid area. In particular, the strongly diurnal character of MCC activity shown here argues for inclusion of a diurnal cycle in models applied to convective regimes like that of the central United States. Second, the concentration of extreme precipitation at specified time and space scales could influence how we choose to describe those extremes statistically. Careful analyses of the distributions of MCC and non-MCC extremes may help determine if the two are actually different.

Finally, if it is true that MCCs significantly alter the distribution of precipitation extremes, then the physical content of those extremes must be accordingly interpreted. For instance, the effect of changes in low-level moisture on the occurrence and efficiency of precipitation in MCCs might be qualitatively different from the effect of the same changes on a field of randomly distributed convective elements. In other words, the effect of climate changes on MCC precipitation extremes could be different from the effect of climate changes on other types of heavy precipitation. Changes in extreme precipitation predicted by climate-change scenarios might then have to be reconsidered.

REFERENCES


