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NOTES AND CORRESPONDENCE

On the Forecasting of Orogenic Mesoscale Convective Complexes

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ABSTRACT

Evidence is presented to support the hypothesis that mesoscale convective complexes (MCCs) near the Rocky Mountains are more likely to form when the middle-tropospheric relative humidity is greater than average and the lower-tropospheric relative humidity is less than average. Radiosonde data for MCC events are chosen at the nearest place to first storm development and at the nearest time before first storms occurred. A sounding representing an average seasonally adjusted climatological location of orogenic MCC first storms was used to represent non-MCC days. The 500-hPa relative humidities were significantly higher for MCC events than for non-MCC days. The 700-hPa relative humidity was significantly lower for MCC events than for non-MCC days. MCC days also have somewhat less stability than non-MCC days but this factor appears to be related to higher temperatures at 500 hPa on days when the 500-hPa relative humidity is low. The values of various quantities used to assess the utility of this information for weather forecasting indicate that this method needs to be combined with other MCC forecasting methods to be useful.

1. Introduction

Investigators have noticed that the region just to the lee of the Rocky Mountains is a preferred region for mesoscale convective complexes (MCCs) to form. Maddox (1980) defined the MCC based on size and shape of the phenomenon on infrared satellite imagery and found that about half of the MCCs he studied had their initial storms near the eastern slopes of the Rocky Mountains. Mesoscale convective systems (MCSs) are a more general phenomenon that would include MCCs as well as large, long-lived (>6 h) clusters of thunderstorms that do not meet the size and/or shape criteria for the MCC. This preferred area for first storms is also apparent in the nocturnal MCSs examined by Augustine and Caracena (1994). In their study the initial storms of the larger MCSs were especially favored in this region. Anderson and Arritt (1998) found that the MCCs were more likely to develop in the area just to the east of the Rocky Mountains than were storms with areas of equally low cloud-top temperatures that did not meet the shape criteria for MCCs.

Motivation for this work is that forecasting of the formation of MCCs remains difficult. Maddox et al. (1986) summarized the synoptic-scale (>500 km) conditions that give rise to MCCs. They occur in a region of upward vertical motion (5–10 μb s^{-1}), typically caused by warm air advection, ahead of a middle-level short-wave trough with an environment that is conditionally unstable and becoming more moist with time. These conditions are those that typically give rise to convective weather and do not differentiate the days when large clusters of thunderstorms such as MCCs form and those for which there are scattered thunderstorms. Augustine and Caracena (1994) found that frontogenetical forcing also encouraged MCC development and that MCC development was favored near the nose of the low-level jet. Multicellular storms are more likely under conditions with straight-line hodographs (Chisholm and Renick 1972) but they are not necessarily large enough to be MCCs nor are they always maintained for several hours. Forecasting of MCCs is extremely important, however, because these storms provide 30%–70% of the summertime precipitation in the central United States (Fritsch et al. 1981) and are also more likely to generate flash floods than other types of storms (Tollerud and Collander 1993).

Tripoli and Cotton (1989) used a two-dimensional nonhydrostatic model to test their proposed mechanism by which an MCS could develop from mountain convection. They theorized that an MCS could begin when convective activity moved into a region with favorable upward motion brought about by orographically produced gravity waves and thermally produced upslope flow. The conditions described by Tripoli and Cotton

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(1989) would be present on most days during the warm season. Yet MCSs occur on less than 50% of these days. Thus, additional factors must exist that control the development of MCSs but have greater variability from day to day.

Recently, Tucker and Crook (1999) presented numerical simulation evidence that an MCS could develop from the outflow from mountain convection. One of the major factors producing this outflow was the cooling of air in the thunderstorm caused by evaporation of falling rain. For the case they investigated model sensitivity studies revealed that the MCS was more likely to form under conditions that favored stronger thunderstorm outflow. In addition, model results indicated that the strength of the outflow and its ability to generate the MCSs was sensitive to the ice sedimentation. This finding is consistent with that of Srivastava (1987), who concluded that precipitation in the form of ice generated stronger downdrafts than precipitation in the form of rain. It would follow that conditions that encourage the formation of ice in the cloud would be more favorable for the formation of MCSs. Ice formation would be enhanced when the cloud is in an environment with high relative humidity. At higher relative humidities, environmental air entrained into the cloud will not reduce the cloud's relative humidity as much as less humid environmental air. Ice forms at lower temperatures high in the cloud and thus its formation would be enhanced by high relative humidities at these levels. Indeed, middle- to upper-tropospheric moisture can be essential for the generation of MCCs near the Rocky Mountains (Culverwell 1982). Cotton et al. (1983) observed that a middle-level moisture maximum passed though the region at the time when the MCC they studied was developing. Tucker and Crook (1999) did not discuss the sensitivity of the downdraft strength to the relative humidity at lower levels but environments with low relative humidities in lower levels of the troposphere would have increased potential for evaporation of precipitation due to the entrainment of dry air. On the other hand, high relative humidity environments do enhance the melting of ice though latent heat released when water condenses on the ice. There is reason to believe that better conditions for the formation of MCSs near the Rocky Mountains would occur when the relative humidities in the middle to upper troposphere are higher than average and relative humidities in the lower troposphere are lower than average. We will test this hypothesis for the larger MCC events whose initial storms are near the Rocky Mountains. The dataset for this study will be described in section 2. Section 3 will present the results and their implications and section 4 will summarize and provide an outlook for future research.

2. Data and methodology

MCC cases for the western United States were chosen from the years 1978–87. Since most MCCs form during the months May–August, only these months were used in this study. The western United States is dominated by fairly dry conditions during the warm season and surface heating is strong. Thunderstorms occur almost every day in the central Rocky Mountains in the warm season, especially over the highest terrain, but are somewhat less common on the adjacent plains (Klitch et al. 1985). MCC generation, on the other hand, is more likely to take place on the plains than in the mountains. MCC locations in the dataset were defined according to the criteria given by Maddox (1980). The available dataset had longitude and latitude locations for the first storms of the MCC (i.e., when the initial storms that would go on to form the MCC could be detected on the satellite imagery), for the initiation of the MCC (when the storm first met the criteria for being an MCC), for the point of maximum extent of the MCC, and for the point of dissipation of the MCC (when the storm no longer met the criteria to be an MCC). A number of these systems have been studied by other investigators (Maddox 1980; Maddox et al. 1982; Rodgers et al. 1983, 1985; Augustine and Howard 1988; Augustine and Howard 1991) who show plots of the storm paths. Only first-storm locations were used in this study. Those cases that had first-storm locations west of 100°W longitude were deemed to be orogenic MCCs and were included in the study. Days when no MCCs formed with first-storm locations west of 100°W longitude were considered to be non-MCC days. Sounding data reflecting MCC environments are analyzed with one sounding per event and non-MCC occurrence is analyzed with one sounding per day. There were a total of 150 days on which MCC events occurred and 168 actual MCC events. There were 1080 non-MCC days. For these days at 500 and 700 hPa there were 56 days on which data were missing.

For the days when MCCs occurred, relative humidities were calculated from rawinsonde data at 500 and 700 hPa. The rawinsonde release chosen for the calculation was the one preceding the development of the first storms of the MCC at the nearest geographical location. For non-MCC days, the sounding used is based on the climatological locations of MCCs during the warm season. For May, the Albuquerque sounding is used, for 1 June–15 July the Denver sounding was chosen, and for 16 July–31 August the Lander sounding is used. The first storms for MCCs typically occur in the late afternoon (Maddox 1980). Thus, the rawinsonde releases could precede the first storm development by as much as 9–12 h.

One difficulty with this method is that the way the soundings are chosen is not identical for both sets of data. For the MCCs it is selected synoptically, near where the MCC actually began. For the non-MCC cases it is chosen climatologically. An alternative might be to do a synoptic analysis of each non-MCC case to determine where an MCC would be most likely to develop. Such a method would be fairly subjective since expe-

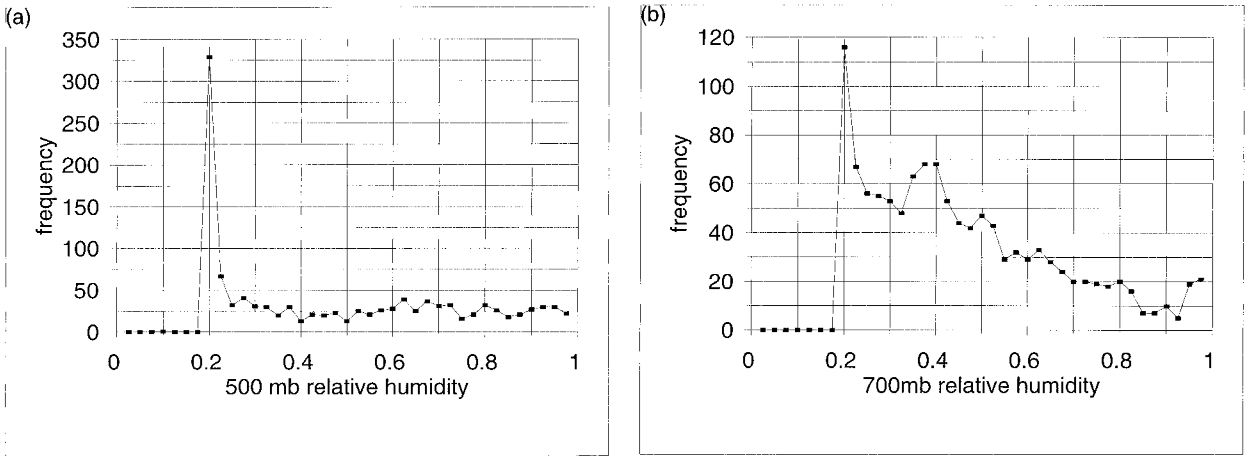

FIG. 1. Frequency distributions of relative humidity values for all cases for (a) 500 and (b) 700 hPa. Frequencies are plotted every 2.5%.

rienced forecasters may differ as to where an MCC is most likely to develop on a given day. This problem would be especially difficult if MCC development did not appear likely anywhere in the western United States as would probably be so for some cases. In addition, the time-consuming nature of this procedure would necessitate reducing the number of non-MCC events included in the study. Such a situation would be unfortunate, since a major strength of the dataset is its size. Nonetheless, it must be conceded that MCC–non-MCC differences could be deduced in this study that are due to the variation in sounding selection method.

The frequency distributions of the relative humidities at 700 and 500 hPa for the entire dataset are presented in Fig. 1. The large frequency counts near 20% are due to the limitations of the measuring instrument on the radiosonde. This limitation is more of a problem at 500 hPa than at 700 hPa where atmospheric conditions are more likely to be moister. Still, it is clear that the distributions are skewed toward lower relative humidities.

To determine whether the difference in MCC and non-MCC relative humidities is significant we used Student's *t*-test and multivariate randomized permutation procedures (MRPP) (Mielke 1984, 1986). These statistical tests both yield the probability that the differences in the datasets could have been produced by chance. For Student's *t*-test this value is typically referred to by the symbol alpha and for MRPP it is called the p value. When this quantity is less than 0.05 the differences in the data may be considered statistically significant and unlikely to be have been produced by chance. Student's *t*-test is familiar to most investigators but it assumes the data are normally distributed and because it uses squared differences it can give undue weight to a few data points that deviate greatly from the mean. MRPP assumes the data are distributed according to the Pearson type-III distribution and accounts for possible skewness of the data distribution. In addition, MRPP is not based on squared differences. To assess the utility of the results for operational forecasting we have also included values for probability of detection (POD), threat score (TS), and false-alarm rate (FAR) for combinations of these parameters.

3. Results and discussion

The mean dewpoint and relative humidity values for the MCC and non-MCC cases are presented in Table 1. Note that at both 500 and 700 hPa the dewpoints of the MCC cases are higher than those of the non-MCC cases. Although not shown in Table 1, the 700-hPa temperatures are over 1°C warmer for the MCC than those of the non-MCC cases. Therefore, the 700-hPa relative humidities for the MCC cases are noticeably smaller than those of the non-MCC cases. Mean temperatures of the MCC and non-MCC cases differ by <1°C at 500 hPa so that the major cause of differences in the relative humidity fields is due to atmospheric moisture content at this level. Miller type-IV (Miller 1972) soundings, often referred to as *inverted V*, are characterized by low

TABLE 1. Average values of sounding parameters for MCC and non-MCC days.

	700-hPa dewpoint (°C)	700–hPa relative humidity (%)	500-hPa dewpoint (°C)	500-hPa relative humidity (%)	700–500-hPa temp difference (K)
MCC cases	−3.4	42.1	−18.6	57.4	20.8
Non-MCC cases	−3.8	45.4	−22.4	44.9	19.9

TABLE 2. Results of MRPP and Student's t statistical tests for relative humidities at all levels studied.

	700-hPa relative humidity	500-hPa relative humidity	700–500-hPa temp difference
MRPP p value	2.8×10^{-2}	2.9×10^{-8}	1.5×10^{-5}
Student's t alpha value	3.0×10^{-2}	2.5×10^{-8}	3.6×10^{-6}

relative humidity with steep lapse rate in the lower troposphere and high relative humidity in the middle troposphere. This type of sounding is common in this region so that higher relative humidities at 500 than at 700 hPa are not unusual. These results indicate, however, that the higher relative humidities at 500 hPa are more common on MCC days. The mean temperature differences between 700 and 500 hPa for the MCC and non-MCC cases are also given in Table 1. The MCC cases have about a 1° larger difference than the non-MCC cases, indicating that the MCC cases have weaker stability.

The MRPP p values and the Student's t-test alpha values are given in Table 2. The two values are comparable; that is, they both represent the probability that the distributions of MCC and non-MCC relative humidities or temperature differences have the same mean. As can be seen in Table 2 both statistical methods agree that the difference between the means of the two groups is highly statistically significant (probability of <1% of occurring by chance) for relative humidities at 500 hPa and for the 700–500-hPa temperature difference. At 700 hPa the methods agree that the difference between the two groups is still statistically significant. Since high humidities can cool the downdraft by encouraging condensational warming on the ice crystal and enhancing melting, the relationship between the 700-hPa relative humidity and MCC formation could be less strong. The small difference in the results from the two statistical tests indicates that the skewness of the distribution and the effect of outlying points had virtually no effect on the results of the test. Thus, MCC development for the situations represented by the data sample would be favored for greater than average relative humidity in the middle to upper troposphere and smaller-than-average relative humidity in the lower troposphere, and lower static stability.

The results here show that higher-than-average (as presented in Table 1) middle- to upper-tropospheric relative humidities would favor their development. We argue that the environments with higher humidities at these levels provide a better situation for the formation of an abundance of ice crystals due to reduced dry air entrainment. The entrainment would occur on time- (less than 1 h) and space (less than 15 km) scales of an individual thunderstorm cell. The storms forming in this environment would have stronger downdrafts and therefore would be more likely to become large multicellular storms. This situation would explain why the flash-flood-producing storms have been associated with high brightness values in the water vapor (6.7 μm) imagery (Thiao et al. 1995). Bright values in such imagery are associated with high moisture values in the middle to upper troposphere. The reason for their association with flash floods is not clear from a precipitable water point of view. Most of the precipitable water in the atmosphere is below the levels sensed by the water vapor imagery. But if MCC generation is especially favored by high relative humidities in the middle and upper troposphere, this result is more reasonable because the MCCs are the storms more likely to cause flash floods. Generally high relative humidities in the lower troposphere have been emphasized with MCC generation with middle- to upper-tropospheric relative humidity receiving less attention (e.g., Maddox 1983)

To assess how this information is best used in forecasting MCCs, contingency tables were set up to represent forecast, nonforecast, observed, and nonobserved MCCs for various forecast criteria. Details on how these contingency tables are used to find the various forecasting parameters are given in Wilks (1995). The following forecast parameters are computed: hit rate, POD; FAR; and TS. Table 3 presents the values of the forecasting parameters for three different forecast criteria.

It can be seen that for 63% of MCC environments in the study, the relative humidity at 500 hPa was greater than 50% and for 59% the relative humidity at 700 hPa was less than 40% but only a third of the MCC environments met both criteria. The majority of forecasts are correct (hit rate) for both of the individual forecast criteria but the percentage correct rises if both criteria are used. The 500-hPa relative humidity and 700–500-hPa temperature difference had the strongest statistical

TABLE 3. Values of various forecast parameters based on different forecast criteria.

	500-hPa relative humidity >50%	700-hPa relative humidity <40%	500-hPa relative humidity >50% and 700-hPa relative humidity <40%	700–500-hPa temp difference >20 K	500-hPa relative humidity >50% and 700–500-hPa temp difference >20 K
Hit rate	0.60	0.53	0.76	0.53	0.73
Probability of detection	0.63	0.59	0.33	0.63	0.40
Threat score	0.18	0.15	0.16	0.16	0.17
False alarm rate	0.80	0.83	0.76	0.82	0.77

relationship but their combination had only marginally better forecast parameters than the humidity combination. Operationally, higher TS and lower FAR would be more useful. In this dataset the number of times the MCC event did not occur far outnumber the ones when it did. Thus the low TS and high FAR occur even though over half of the non-MCC events are correctly forecast with this technique. The problem is with the number of events that would be forecast with this technique and did not occur. It should be kept in mind that the dataset included only the storms that met the criteria to be MCCs. Storms that did not meet the size and shape criteria for MCCs were not included. It is possible that storms of this type occurred on some of the days that are indicated as false alarm days in this study. For example, according to the results of Anderson and Arritt (1998) the system studied by Tucker and Crook (1999), which provided some motivation for this paper, did not meet the size and intensity criteria to be considered an MCC. It should also be noted that the sounding data used in the study were often taken more than 9 h prior to the occurrence of the first storms. Environmental conditions can change a great deal in this time. In a number of the cases studied here environmental relative humidity as measured by the soundings was less than 20% at all levels studied. Considerable moisture advection could have occurred between the time the sounding was taken and the time when the first storms developed. Alternatively, the sounding could have been unrepresentative of the conditions in the region where the storm developed. In the operational environment, forecasters can estimate likely changes to the sounding since time of the observation. Finally, this method attempts to forecast the occurrence of MCCs solely from two variables: relative humidity and stability in one layer. It does not address whether the the vertical wind shear of the environment is appropriate for multicellular thunderstorms. Thus, this method points out conditions that are favorable for MCC development but those conditions are not sufficient for MCC development. Thus, we would recommend that knowledge of these conditions be combined with other atmospheric parameters known to favor MCC development in order to determine whether or not MCCs will occur on a particular day.

Although high middle-tropospheric relative humidities and small low-level relative humidities have not been stressed in the past as especially useful for forecasting MCCs, they are most useful as forecast parameters when included with conditions known to be associated with MCCs. For example, on a particular day, the forecaster could first assess whether conditions in this region would be appropriate for thunderstorms in general by examining the atmospheric stability. The hodograph for places where thunderstorms are possible could then be used to judge the likelihood of multicellular thunderstorms. At times and places where conditions would be appropriate for multicellular thunderstorms, the 500- and 700-hPa relative humidities can be combined with other relevant information such as the frontogenesis function to determine if an MCC is likely to occur and where it is most likely to begin.

4. Conclusions

This paper has presented evidence to show that MCCs are more likely to develop in the region just east of the Rocky Mountains when the low-level environmental relative humidity is less than average and the middle-to upper-level relative humidity is greater than average. It should be noted that this relationship cannot be assumed to hold for MCC development in regions farther east of the study area. The area just to the east of the Rocky Mountains has consistently strong solar heating during the late spring and summer. Thus, the environmental lapse rate below about 500 hPa is frequently close to dry adiabatic, a condition that generally favors strong downdrafts in thunderstorms. We have shown that steeper lapse rates themselves favor MCC formation. The frequency of marginally stable lapse rates is offered as a partial explanation as to why so many MCCs form in this region. In other regions, where the warm season lapse rate is more variable it may be a stronger controlling factor. Further research is needed to determine whether the factors discussed in this paper or other ones are strong influences on the development of MCCs in other regions.

A Miller type-IV (inverted V) sounding is frequently observed on the high plains during the warm season. This sounding has lower relative humidities nearer the earth's surface but high relative humidites in the middle layers of the troposphere. The frequent occurrence of this type of sounding could be another factor that contributes to making the high plains a preferred region for MCC initiation.

Forecasters generally look for low tropospheric moisture to bring favorable conditions for MCC formation. This study shows that in this region MCC formation is preferred when there is a dry layer in the lower troposphere and a moist one in the middle troposphere. It should be emphasized that the vertical relative humidity distribution discussed in this paper is only one of several factors controlling whether an MCC will develop on the high plains on a given day. Forecasters need to examine environmental stability and wind shear patterns as well.

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