Synoptic Parameters as Discriminators between Hailfall and Less Significant Convective Activity in Northeast Colorado¹

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(Manuscript received 31 October 1977, in final form 13 January 1979)

ABSTRACT

Synoptic data are studied to determine which, if any, parameters representing large-scale physical processes can be used to discriminate effectively between days of insignificant convective activity and those with significant moist convection and high hail potential in northeast Colorado. Divergence, relative vorticity, vorticity advection, temperature advection, surface mixing ratio and a modified K index (George, 1969) were computed and associated with observed weather. Two methods were used to compare distributions of these parameters for their discriminative potential. The first involved ranking of the Student’s t statistics for both hail versus no-hail and significant versus insignificant convection stratifications. The second method was a graphical technique for plotting cumulative relative frequencies of the stratified distributions. The most effective parameter on a comparative basis for discriminating between significant and insignificant convection was a measure of low-level and middle-level tropospheric moisture content. Moisture content at the surface provided the best discrimination between hail and no-hail.

1. Introduction

As experience is gained in the design, conduct and analysis of weather modification experiments, it is becoming clear that classification and regressor variables are needed to reduce the unexplained variance of experimental units and thus the required number of such units. These are crucial to the design of experiments wherein treatment effects may be detected in economically feasible periods of time (Brier, 1974; Atlas, 1977). Classification of experimental units using discrete variables (or attributes) or regression of continuous covariates (whether measured prior to the weather event as predictors, or during or after as “nonpredictive” covariates) will contribute toward this end. The search for such variables in the National Hail Research Experiment (NHRE) analysis program is being conducted using all available types of data from microphysical to synoptic surface and upper air measurements. While the most definitive hail covariates are likely to be found in radar and microphysical data because of scale considerations, the synoptic data are being called on to provide, as a first step, a basis for discriminating between hailfall and less significant classes of convective activity.

¹ This research was performed as part of the National Hail Research Experiment, managed by the National Center for Atmospheric Research and sponsored by the Weather Modification Program, Research Applications Directorate, National Science Foundation.

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0021-8952/79/050671-11$06.75
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Much work has been done in relating kinematic parameters and other synoptic-scale variables to severe storms occurrence for the purpose of developing predictors or diagnostic tools. Examples of such studies include the following: Beebe and Bates (1955) related jet configuration and convergence–divergence patterns in the lower and middle troposphere to the production of maximum parcel instability. Landers (1955) found that integrated lower level divergence correlated quite well with the precipitation pattern. House (1958) extended the work of Beebe and Bates to consider wind structures at higher levels. Danard (1964) studied the role of latent heat release in amplifying observed convergence–divergence patterns. Endlich and Mancuso (1968) computed kinematic quantities and compared them with storm development. They found that certain quantities depending on the field of motion appeared to be more specific in identifying areas of severe storm formation than did thermodynamic parameters. Scoggin and Wood (1971) inferred the signs of large-scale vertical motion from synoptic parameters and related them to storm occurrence. McNulty (1977) presented further observational evidence relating severe weather and upper tropospheric kinematic features. In addition, the applicability of the divergence equation to severe storm forecasting has been discussed by Schaefer (1977).

Studies focusing on hail and thunderstorms occurring in hail-prone areas include those of Schlesinger and Auer (1964) in northeast Colorado and Longley and Thompson (1965) in Alberta. These studies provided insight and guidance, but quantitative discrimination
between hail and no-hail environments remained elusive.

This paper will report on studies aimed at determining which, if any, parameters derived from upper air synoptic-scale data and representing large-scale physical processes can be used to discriminate effectively between days of insignificant convective activity and those with significant moist convection (cumulonimbus) and high hail potential in northeast Colorado. These consisted of divergence, vorticity, vorticity advection and temperature advection. The physical rationale for anticipating effectiveness of these parameters in discrimination lies in their well-known relation to the behavior of the vertical velocity and its effect, in turn, on observed weather events (e.g., Panofsky, 1951; Petterssen, 1956; Palmén and Newton, 1969). Several additional parameters, the surface mixing ratio and a modified K stability index (George, 1960), were determined from surface synoptic and single rawinsonde data for comparison. The association of increased values of these parameters with storm occurrence is also well known.

It must be noted that a problem regarding scale is present in this study. The upper air data utilized describe the large-scale synoptic settings, and the hail and weather data available represent a smaller scale view. Mesoscale upper air features matching the scale of the hailstorm occurrences, for instance, may completely escape detection by the synoptic network. On the other hand, large-scale destabilization provides the setting for mesoscale development, so useful correlations between large-scale conditions and the convective activity observed in a more limited area may still be possible.

2. Data sources and methodology

a. Upper air data

Objectively analyzed National Meteorological Center (NMC) gridded wind and temperature data for 0000 GMT (1800 MDT) corresponding to NHRE operational days were used in this study. NHRE was conducted during the periods 15 May–31 July, 1972 and 1973, and 15 May–9 August, 1974. The gridded (initial conditions) data are those used for operational runs of the NMC primitive equation forecast model. The analysis grid covered the western two-thirds of the United States, and the vertical array consisted of data at mandatory reporting levels. Details of the NMC grid, including a discussion of the geometry of the projection, and transformation and scaling relationships, have been presented by Jenne (1970). Details of the magnetic tape formats and unpacking instructions for the NMC gridded data as archived at the National Center for Atmospheric Research (NCAR) were documented by Jenne and Mulder (1975). A detailed account of the NMC objective analysis procedure used during the period of this study is contained in McDonnell (1972). No significant procedural changes in the NMC objective analysis were made during the period of this study.

Rawinsonde observations made by NHRE at 2300 GMT at Sterling, Colorado (~103°15'W, 40°30'N), were also used. Details of the reduction and processing of the soundings are contained in Madden et al. (1971). Temperatures and dew points at appropriate levels were used in the determination of the modified K index.

b. Surface mixing ratio

This parameter was interpolated from objectively analyzed 2100 GMT surface mixing ratio fields at a location midway between Sterling and Grover, Colorado. Grover is located at ~104°15'W, 41°00'N. The analyses were made from airways synoptic reports. The analysis area (not shown) approximately covered a 10°x10° area centered on northeast Colorado. The mid-afternoon observation time was chosen to minimize perturbation of mixing-ratio fields by storm outflows. Analyses of mixing ratio and dew point were examined for evidence in the contour patterns of the presence of outflow air. No pools of outflow air were noted on any of the 2100 GMT maps, but later, on some strongly convective days, such effects were noted during the 0000–0200 GMT period.

A simplifying assumption was made in the derivation of surface mixing ratio from the observations at airways synoptic stations. Because of the difficulty in obtaining actual station pressure from these reports, standard atmosphere pressure-heights for each station were used in lieu of the actual station pressure. The error in mixing ratio from this source is negligible.

c. Stratification of weather events

Each operational day of the 1972, 1973 and 1974 NHRE hail seasons was classified in terms of the maximum convective activity observed within a 110 km radius (~38 000 km²) of Sterling during the 1700–0700 GMT period. The outcome of a given day's convective development cycle (thus the designated time span) within this area was assessed using the following sources:

1) Hourly records of observed weather and cloud forms (columns 3, 5 and 13 of the WBAN, or newer form MFI-10A) made at NHRE rawinsonde sites (these numbered variously from 2 to 5 during the experiment, but always included Grover and Sterling).

2) Hourly records from the several National Weather Service stations within or near this area (Cheyenne, Wyoming; Sidney, Nebraska; Akron, Colorado).

3) Precipitation occurrence reports from hail pads and Belford raingages located at NHRE rawinsonde and other sites throughout the region. The densest network of these instruments, however, occupied only ~1600 km² in association with the target area [see Dye et al. (1977) for a description of the target area].
4) Precipitation occurrence reports from mobile observers and precipitation survey crews.

Three categories of convective activity were defined: (i) clear days and days with cumulus congestus clouds as a maximum condition; (ii) days with rainshowers and thundershowers and, as far as known, no hail; and (iii) days with observed hail at the ground. In general terms, category (i) consists of “clear or fair weather clouds,” and mostly nonraining cumuliform clouds ranging in size from small to congested state. Categories (ii) and (iii) are composed of days which had cumulonimbus (Cb) occurrence. Table 1 shows the number of days in each convective category for which both NMC and NHRE (rawinsonde) data were consistently available for each of the parameters to be evaluated. (NHRE soundings were not taken on Sundays and holidays in the 1972 season. They were also cancelled during periods of steady “upslope” rain throughout the experiment. In addition to occasional mechanical outages of the sounding equipment, several gaps in the NMC data set due to computer outages were present.)

In addition to the preceding classification, other groupings of these days are useful: hail [(category (iii))] versus no-hail [(categories (i) and (ii))]; and Cb occurrence [(ii) and (iii)] versus no-Cb [(i)]. The latter stratification has also been termed significant moisture convection (SMC) versus insignificant moist convection (IMC). Reference to rainshowers or thundershowers in this paper will mean showers-without-hail [(ii)].

The problem of scale in this study has been only partially ameliorated by the choice of convective activity categories. Clear days can be identified quite well over an area approaching the scale of the NMC data. The tops of large cumulonimbus in semi-arid regions can be seen from long distances, perhaps 150 km, even 200 km, depending on the terrain. Detection of hail occurrence, however, is a special problem in sparsely populated rangeland areas. Usually, the largest and strongest storms in the general NHRE region were well probed at the surface by radar-directed mobile observers. Their reports, along with the information received from the mesonetwork of hail detection instruments, suggest that hail occurrence determinations are fairly reliable. Identification of cases becomes less reliable, however, with increasing distance from the central NHRE target area.

<table>
<thead>
<tr>
<th>Convective category</th>
<th>Number of days</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) Clear and Cu congestus</td>
<td>67 IMC</td>
</tr>
<tr>
<td>(ii) Rain and thundershowers without hail</td>
<td>56 SMC (cumulonimbus clouds)</td>
</tr>
<tr>
<td>(iii) Hail</td>
<td>48</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>171</strong></td>
</tr>
</tbody>
</table>

d. Computation and graphic display of parameters

The divergence, relative vorticity, absolute vorticity advection and temperature advection were computed from the gridded data at 200, 250 and 300 mb. The divergence was also computed at 850 mb. Figs. 1–5 are examples of the resulting maps showing 300 mb condi-
tions at 0000 GMT on 30 May 1974. Hail larger than 5 cm in diameter fell in the southwestern Nebraska panhandle (immediately north of the Colorado border) starting ~1 h after map time. The approximate location of the resulting hail swath is shown as a heavy line segment in Figs. 1–5.

From the standpoint of the hail outbreak in southwestern Nebraska in this example, the upper air situation is one of a trough to the immediate west encroaching on a rather flat ridge (Fig. 1). The polar jet axis is north of the outbreak area, with both anticyclonic horizontal wind shear and anticyclonic curvature providing an anticyclonic vorticity setting at this height (Fig. 3). The outbreak area is in the right-rear quadrant of an anticyclonically curved speed maximum in the jet, a location favorable for upward vertical motions (Beebe and Bates, 1955). Vorticity advection (Fig. 4) and divergence aloft (Fig. 2) are positive, and low-level winds (not shown) are convergent—circumstances which imply upward vertical motions. Temperature advection (Fig. 5) is negative, furthering air mass destabilization. Thus, the alignment of synoptic-scale parameters in this example is favorable for storm formation.

It will be noted from comparison of Figs. 2 and 4 that the divergence pattern in this case is centered at about the same location and has the same rough shape as the vorticity advection pattern. In many cases the agreement is not this good. Petterssen (1956) has noted that when air streams through a trough at high rates of speed, as in this case (see Fig. 1), and the vorticity pattern is not moving or changing rapidly, there will be positive divergence present in the area of positive vorticity advection.

For association with observed weather events, the above parameters for each operational day of the three hail seasons were interpolated at a point from analyses represented by the examples of Figs. 1–5. The interpolation point is marked by a dot in these figures. This location is at the west end of the NHRE study area in northeast Colorado, in the vicinity of Grover.

![Fig. 3. 300 mb vorticity (10^{-4} s^{-1}) at 0000 GMT on 30 May 1974. Dashed negative contours represent anticyclonic vorticity.](image)

![Fig. 4. 300 mb vorticity advection (10^{-4} s^{-1}) at 0000 GMT on 30 May 1974. Dashed negative contours represent negative vorticity advection. Positive and negative centers are denoted by P and N, respectively.](image)

![Fig. 5. 300 mb temperature advection (10^{-4} °C s^{-1}) at 0000 GMT on 30 May 1974. Dashed negative contours represent negative temperature advection. Positive and negative centers are denoted by P and N, respectively.](image)
Computation of the comparative synoptic-scale surface mixing ratio has already been described in Section 2b. In the computation of the comparative modified $K$ stability index, Sterling rawinsonde data were used. Because of the higher terrain and often deeper adiabatic layer over the NHRE study area compared to regions for which the index was initially developed, the formulation was modified as follows:

$$K = (T_{700} - T_{300}) + (T_{d95} - T_{d100}).$$

The 850 mb dew-point term remains the same as in the original formulation, but the temperature lapse rate and dew-point depression terms are taken at higher levels.

e. Discriminative potential

Two methods were used to determine which parameters were superior in terms of discriminative potential. The first involved computing Student's $t$ statistic for testing the null hypothesis that the sample distributions [hail and clear day sets initially—the clear days are a subset of category (i) in Table 1] were identical in mean value. If the null hypothesis had to be rejected at the 5% or better level of significance (two-tailed), suggesting that the samples were actually different, then the $t$ statistic magnitudes were considered indicators of "how different." This method assumes the normal distribution of the samples.

While the distinction between hail and clear is not particularly useful, at the beginning of the investigation these classes at the extremes of the convective activity spectrum were thought to provide the greatest opportunity for detecting a difference between the hail and no-hail synoptic settings. Also, exclusion of the sizeable number of intermediate cases (rainshowers, etc.) at this comparative stage minimized the analysis burden. Once having selected the most promising parameters, the intermediate cases were included in all further analyses.

The second method permitted a graphical interpretation of which parameters were the "best" discriminators. This method is based on a plotting technique presented by Grosh and Morgan (1975) in which the cumulative relative frequency of the hail distribution is plotted against the cumulative relative frequency of all of the days (without regard to the normality of the distributions). A point on the resulting curve represents both the percentage of hail days and the percentage of all days lying below a corresponding value of the parameter. Fig. 6 shows a similar diagram under two limiting conditions. The first (Fig. 6A) is the case where there is no overlap between distributions $X_1$ and $X_2$. As one proceeds along the abscissa $X_1$ from a to b, all of the cases in $X_1$ are accumulated. Thus the plotted curve marked by the heavy line remains along the top edge of the diagram ($X_1$ axis) from 0 to 1.0 ($X_2 = 0$). Similarly, the plotted curve remains on the left edge of the diagram as all of the cases in $X_2$ are accumulated (c to d). The second condition is shown in Fig. 6B. Here distributions $X_1$ and $X_2$ are identical, and their respective plotted cumulative relative frequencies for given values of the parameter fall along the diagonal.

![Graph](image-url)
Table 2. Summary of upper air meteorology statistics.

<table>
<thead>
<tr>
<th></th>
<th>Clear days (48) mean (standard deviations)</th>
<th>Hail days (48) mean (standard deviations)</th>
<th>Critical two-tailed ( t ) (0.05)</th>
<th>Computed ( t ) value</th>
<th>Are classes significantly different?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divergence (300 mb) ((10^{-4} \text{ s}^{-1}))</td>
<td>(-1.7 (5.2))</td>
<td>(1.9 (4.7))</td>
<td>(1.99)</td>
<td>(3.48)</td>
<td>yes ((p=7.5 \times 10^{-4}))</td>
</tr>
<tr>
<td>Vorticity advection (300 mb) ((10^{-4} \text{ s}^{-1}))</td>
<td>(-1.2 (5.5))</td>
<td>(1.9 (5.6))</td>
<td>(1.99)</td>
<td>(2.70)</td>
<td>yes ((p=8.2 \times 10^{-5}))</td>
</tr>
<tr>
<td>Vorticity (300 mb) ((10^{-3} \text{ s}^{-1}))</td>
<td>(-2.1 (3.0))</td>
<td>(-1.1 (2.4))</td>
<td>(1.99)</td>
<td>(1.70)</td>
<td>no ((p=9.3 \times 10^{-4}))</td>
</tr>
<tr>
<td>Temperature advection (300 mb) ((10^{-4} \text{ °C s}^{-1}))</td>
<td>(-1.1 (3.2))</td>
<td>(-1.3 (3.6))</td>
<td>(1.99)</td>
<td>(0.28)</td>
<td>no ((p=7.8 \times 10^{-4}))</td>
</tr>
<tr>
<td>Divergence (max) (maximum found in 300–200 mb layer)</td>
<td>(-3.5 (7.5))</td>
<td>(3.7 (7.8))</td>
<td>(1.99)</td>
<td>(4.62)</td>
<td>yes ((p=1.2 \times 10^{-4}))</td>
</tr>
<tr>
<td>Vorticity advection (max)</td>
<td>(-2.4 (7.3))</td>
<td>(3.1 (7.3))</td>
<td>(1.99)</td>
<td>(3.64)</td>
<td>yes ((p=4.4 \times 10^{-5}))</td>
</tr>
</tbody>
</table>

On this diagram, therefore, real distributions will have their cumulative relative frequency plots falling between the limiting curves. The “best” discriminator will be the one whose curve is closest to the curve in Fig. 6a, which describes “perfect” discrimination. From a practical standpoint, the distance from the upper left-hand corner of the diagram to the closest point on each curve will provide an indicial measure for all but highly unusual distributions.

In the present application of this graphical technique, the all cases distribution used in the Grosh and Morgan example has been stratified into hail and the complementary no-hail cases, and also into SMC and the complementary IMC cases. The hail or SMC cumulative relative frequency distribution is plotted along the ordinate of the diagram and that of the complementary distribution along the abscissa.

3. Results and discussion

a. Synoptic-scale parameters aloft

Table 2 summarizes the interpolations of the four synoptic-scale parameters at the 300 mb level for the initial set of cases. The means, standard deviations and the two-tailed critical (0.05 level of significance) tabular value of the Student's \( t \) statistic are shown, along with the computed value of \( t \) for tests of differences between the means for the hail and clear day samples (the equal sample sizes are coincidental). The parameters are ranked in order of decreasing value of computed \( t \) statistic. Considering first the mean vorticity and the mean temperature advection parameters, they both have the same sign for the hail and clear samples, and furthermore, the respective samples are not significantly different at the 5% level. Scoggins and Wood (1971) noted that temperature advection appeared to be of questionable values in determining the sign of vertical motion during the summer. The small difference between the hail and clear means (and small \( t \) value) questions its value in this study also. Based on the use of extremes of the convective activity spectrum, the vorticity parameter appears to be anticyclonic aloft as virtually a climatological fixture during the late spring and summer season represented in the data. It appears, however, to be less anticyclonic during hail occurrences. Note that the vorticity parameter aloft was anticyclonic in the hail case example presented in Section 2a (Fig. 3).

The divergence and vorticity advection parameters, in contrast to the above, have highly significant differences between their respective hail and clear sample means. The divergence parameter is divergent (positive) on hail days and convergent (negative) on clear days. The vorticity advection parameter is one of positive vorticity advection on hail days, and negative vorticity advection on the clear days. This is in accord with the previously discussed expectations regarding inferred vertical motions and the observed nature of the weather. The vorticity and temperature advection parameters were not further considered, based on their relatively poor performance in this comparison.

Table 2 also shows the improvement accruing to the hail versus clear discriminations by using the maximum value of divergence or vorticity advection \( (\text{labeled (max)}) \) found in the upper layer extending from 300 to 200 mb rather than using the value from the 300 mb level. Successive comparisons were made with values from the 250 and 200 mb levels with similar resulting increases (not shown). In this example, the difference between hail and clear means has been more than doubled, and the \( t \) statistic value increased by one unit. In all subsequent analyses, the layer-maximum value of these two parameters will be used and referred to as upper divergence or vorticity advection.

Considering that divergence is a significant factor both at upper levels and near the surface (Dines, 1919), it initially appeared advantageous to determine the net divergence through a deep layer of the atmosphere. This would utilize the low-level divergence which is often of sign opposite to that aloft. Sutcliffe (1939) employed this difference in divergence between the
lower and upper levels, and the inferred compensating vertical flow, to diagnose cyclonic and anticyclonic development. In the present case, however, further testing showed only marginal gains in discrimination from including the low-level divergence information (850 mb) on the scale available. Thus, except for the following discussion, the low-level divergence is not further considered.

When all the cases were considered, including the intermediate cases (rainshowers, etc.) previously omitted for brevity, the upper divergence tended from convergent (negative) to divergent (positive) as convective activity increased. Fig. 7 shows this, evidenced by the positive displacement of the peak frequency, as do the data in Table 2 for the limited sample. The cases in Fig. 7 have been stratified into the three categories of convective activity discussed in Section 2c, and a histogram presented for each. The labeling of the abscissa for the middle histogram is common to all three histograms. The upper histogram is comprised of the clear and cumulus congestus cases, the insignificant moist convection (IMC) category. The middle histogram shows rainshower and thundershower cases without hail, and the bottom panel shows the hail cases. The latter two distributions comprise the significant moist convection (SMC) category. Little difference is noted between these latter two histograms, but a clear difference between IMC and SMC is apparent.

![Figure 7](image-url)

Fig. 7. Distribution of upper divergence for three categories of convective activity.
parameter (not shown) is similar to that of the upper divergence in that it also provides little opportunity for separating the hail cases from the rain- and thundershower cases. As with the upper divergence parameter, greater difference is noted between the SMC and IMC distributions of this parameter than between the hail and no-hail distributions.

b. Comparative parameters—surface mixing ratio and modified K index distributions

For comparison with the upper dynamics, two other parameters are examined. First, Fig. 8 shows stratifications of synoptic-scale surface mixing ratio. The format is the same as in Fig. 7. The two no-hail (upper) histograms in Fig. 8 appear roughly similar to each other. The hail cases in the bottom panel, however, are distinctly biased toward the higher values of mixing ratio. Thus, this parameter appears to have potential for separating hail from no-hail cases that the upper air parameters previously presented do not have. The relatively small number of no-hail cases above 9–10 g kg⁻¹ mixing ratio indicates that the probability of cases in the peak frequency class interval of 10–10.9 g kg⁻¹ or beyond will have a high probability of being hail cases. Fig. 9 (solid curve) shows this probability (hail/all cases) to be very high. At the other end of the spectrum of mixing ratio values, the probability of cases being insignificant clear or cumulus congestus cases is high also. For mixing ratios as high as 6 g kg⁻¹, this probability is still greater than 50%.

In general, Figs. 8 and 9 show that hail cases are in relatively sharp contrast with the no-hail cases, and that the differences between the SMC and IMC stratifications are less well defined. This point will be discussed further.

While it is not the intent of this paper to select threshold or partitioning point values for stratifying days into event or no-event days based on the value of any parameter, it is obvious from inspection of Figs. 8 and 9 that a useful threshold value of mixing ratio lies between 9.0 and 10.0 g kg⁻¹. It should be noted that
threshold values may be sensitive to sampling fluctuations. Better selection may be made by considering the fitted distributions of these parameters which, as shown herein, tend toward the normal distribution.

Another comparative parameter is the modified $K$ index described in Section 2d. Distributions of this parameter equivalent to the stratifications shown in Figs. 7 and 8 are presented in Fig. 10. Again, displacement of the peak frequencies toward higher values of the parameter as convective activity increases is apparent. Whereas the surface mixing ratio (Fig. 8) showed relatively sharp contrast between hail and no-hail, the modified $K$ index appears to show a useful difference between the clear and cumulus congestus (ICM) distribution in the top panel, and that of the remaining cases (SMC). The concentration of shower-without-hail cases in the region of the $K$ index spectrum where the hail cases peak makes discrimination between these two classes of convection less distinct. This difficulty is similar to that existing for the upper divergence shown in Fig. 7 and also the vorticity advection (not shown).

As an illustrative example of the possibility of combining parameters to improve discrimination, an equally weighted linear combination of the upper divergence and the surface mixing ratio was made for each case. This parameter is called DIVSUM, for DİVergence plus SURface Moisture. The rationale for including the surface mixing ratio in this joint parameter was to improve the hail versus no-hail discrimination of the upper divergence, and also to improve the SMC versus ICM discrimination of the mixing ratio parameter by combining the complementary strengths of these two parameters. This combination will be compared with the other single parameters in the next section.

c. Ranking of parameters as discriminators

Comparisons of parameters for the SMC versus ICM and the hail versus no-hail stratifications were made using the cumulative relative frequency diagram described in Section 2e and in Fig. 6. The first comparison is presented in Fig. 11. On this plot of the SMC cumulative relative frequency distribution versus the ICM distribution are shown the following parameters ranked in order of “closeness” of each curve to the upper left-hand corner of the diagram: 1) modified $K$ index, 2) DIVSUM, 3) vorticity advection, 4) upper divergence and 5) surface mixing ratio. The combination of the last two parameters did indeed produce a better discriminator between SMC and ICM distributions, but the resulting DIVSUM parameter was still not as “close” to the corner as the “best” parameter—the modified $K$ index.

The modified $K$ index owes its comparative superi-
priority in discriminating between SMC and IMC distributions to two of its three component elements. Testing indicated that omitting the temperature lapse rate term from the index produced about the same result as did the complete index. Thus, the index could be simplified to include only the 850 mb dew-point temperature and the 500 mb dew-point depression.

A similar diagram comparing the same parameters for the hail and no-hail stratification is shown in Fig. 12. The "best" discriminator is the surface mixing ratio, followed by the modified K index, DIVSUM, upper divergence and vorticity advection. In this example the combination of the "best" discriminator (mixing ratio) with a less effective discriminator (upper divergence) served only to reduce its capability, with DIVSUM ranking only third. An additional point is that for this stratification the 850 mb dew-point component of the modified K index was itself as effective a discriminator as the complete K index. Thus, either of two measures of the low-level moisture provides relatively good discrimination for this stratification.

Table 3 summarizes the above examples and compares the ranking of the parameters by the two methods of this study. The methods failed to agree in only one instance. In the SMC/IMC ranking, the computed t value for the vorticity advection did not follow the ranking established by the "closeness" index. Where curves run close together, as in the SMC/IMC cumulative relative frequencies diagram (Fig. 11), the graphical interpretation is more difficult to make.

In the above examples, the upper air dynamic parameters seem to be generally less effective than thermodynamic parameters as discriminators. This may be due to the scale of the NMC data, as opposed to the scale of the local rawinsonde observations from which the modified K indices were computed, and the sub-synoptic scale of the surface humidity measurements. Availability of mesoscale upper air data might improve the relative utility of the dynamic parameters, especially that of the DIVSUM parameter. Also, in regions where the low-level moisture content is higher and less variable, the DIVSUM parameter may be of greater importance because of control by the divergence aloft component rather than by the surface moisture.

Further improvements in discrimination might also be obtained by redefining the classes of convective activity; for instance, basing them on quantitative measurements such as radar echo characteristics or precipitation size and character from penetrating aircraft. This would permit a better statistical distribution of the convective classes, i.e., one with greater normality. This goal could be furthered, for example, by subdividing the hail cases into minor, moderate and major events.

This paper has addressed only late afternoon environmental conditions. Comparative examination of

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Table 3. Summary of parameter ranking based on discriminative potential.

<table>
<thead>
<tr>
<th>Parameter ranking</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Student’s t</th>
<th>Graphical “closeness” index</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMC/IMC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modified K index (°C)</td>
<td>44.5/35.6</td>
<td>8.8/8.2</td>
<td>6.66</td>
<td>4.75</td>
</tr>
<tr>
<td>DIVSUM (10^+ s^{-1}+g kg^{-1})</td>
<td>17.6/6.5</td>
<td>11.6/10.9</td>
<td>6.51</td>
<td>5.40</td>
</tr>
<tr>
<td>Vorticity advection (10^+ s^{-2})</td>
<td>2.4/-3.3</td>
<td>9.1/8.0</td>
<td>4.11</td>
<td>5.41</td>
</tr>
<tr>
<td>Upper divergence (10^+ s^{-2})</td>
<td>3.0/-3.6</td>
<td>8.6/7.9</td>
<td>5.05</td>
<td>6.05</td>
</tr>
<tr>
<td>Surface mixing ratio (g kg^{-1})</td>
<td>8.2/6.5</td>
<td>2.4/2.0</td>
<td>4.92</td>
<td>6.35</td>
</tr>
<tr>
<td>Hail/No-Hail</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface mixing ratio</td>
<td>9.4/6.8</td>
<td>2.0/2.2</td>
<td>7.02</td>
<td>4.90</td>
</tr>
<tr>
<td>Modified K index</td>
<td>46.5/38.8</td>
<td>6.7/9.8</td>
<td>4.65</td>
<td>5.80</td>
</tr>
<tr>
<td>DIVSUM</td>
<td>19.3/10.8</td>
<td>10.0/12.6</td>
<td>4.19</td>
<td>6.05</td>
</tr>
<tr>
<td>Upper divergence</td>
<td>3.7/-0.8</td>
<td>7.8/9.0</td>
<td>3.08</td>
<td>6.90</td>
</tr>
<tr>
<td>Vorticity advection</td>
<td>3.1/-1.0</td>
<td>7.3/9.5</td>
<td>2.69</td>
<td>7.25</td>
</tr>
</tbody>
</table>
morning conditions (not shown) of the parameters treated herein indicate that discrimination of afternoon events based on morning data is largely ineffective. Diurnally development in the subsynoptic and mesoscale range is undoubtedly important to this problem, as shown by the mesoscale studies of Tsui and Kung (1977) and Sanders and Emanuel (1977). Also, Modahl (1979) has shown the marked diurnal development of low-level winds on haildays, but not on other days. It will be necessary to understand better these developments before highly effective discrimination between hailfall and less significant classes of convective activity will be possible.

4. Conclusions

Of the parameters compared in this study, the most effective synoptic-scale discriminator for attempting to separate significant moist convection from insignificant cases appears to be a combination of 850 mb dew point (near the surface in the NHRE study area) and 500 mb dew-point depression. Showing nearly as much capability is the DIVSUM parameter, a linear combination of upper divergence and surface mixing ratio. The most effective discriminator between hail and no-hail cases appears to be the low-level moisture content. Synoptic-scale, upper-level parameters based on dynamics appear to be less capable than moisture parameters in providing discrimination.

Data on the space and time scales capable of resolving diurnally developing subsynoptic and mesoscale features are required to further the description of classes of convective activity and to improve the discrimination between them. Redefinition of weather classifications using quantitative predicants should also help to improve discrimination.

Acknowledgments. The author acknowledges and appreciates the helpful discussions with Griffith Morgan, the review and comments by Alex Long and Edwin Crow, the programming assistance of Carl Mohr and Barbara Horner, and the data preparation by Dale Neiman and Bill Cobb. The contribution by Roy Jenne and Paul Mulder of the NCAR Computing Facility in providing the archived NMC gridded data is also especially acknowledged. The NCAR Graphics Department and Steve Connolly of NHRE prepared the figures, and Sharon Blackman and Carol Pearce typed the manuscript.

REFERENCES


* Available from National Center for Atmospheric Research, Box 3000, Boulder, CO 80307.