NOTES AND CORRESPONDENCE

A Statistical Study of Dependence of Hailstorm Severity on Environmental Conditions

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ABSTRACT

Rawinsonde observations taken during the National Hail Research Experiment are analyzed by multiple-linear regression techniques to study the influence of environmental factors on hailstorm severity. The latter is inferred from integrated radar returns. The roles of mixed-layer flow and thermodynamic properties as well as upper tropospheric kinematic properties are emphasized. The low-level properties are found to be more important discriminators of storm severity over the High Plains.

1. Introduction

The small space and time scales of severe convective storms preclude their being routinely examined through the use of the conventional meteorological observing system. Remote sensing by satellite and radar provides considerable information on the structure and evolution of these systems after condensation begins; however, diagnosis of the mesoscale forcing and precondensation response is not yet routinely possible. Consequently, statistical techniques must continue to play a major role in the search for clues to the controls which the larger scale environment exerts over convective storm development. The present study seeks to relate dynamically significant properties of the severe storm environment to the intensity of convection over the National Hail Research Experiment (NHRE) area of northeastern Colorado in the years 1972–74. Our purpose is to improve understanding of the control exerted by the environment over the storm scale.

2. Procedure

Our analysis is confined to "declared hail days," defined by Foote and Knight (1979) to be those days on which a storm exhibiting an S-band radar reflectivity factor of 45 dBZ or greater in portions of the cloud having temperatures between −5 and −30°C either existed over the NHRE target area or was estimated to be within 20 min of entering the target area. Using the data of Crow *et al.* (1979) we find that hail was detected at the surface within the NHRE target area on 58% of the days in our sample. Thus, in contrast to many similar statistical studies of convection (Mahrt and Pierce, 1980; Modahl, 1979; and Mahrt, 1977), the present study deals with a much narrower range of convective intensities.

The selection of a set of independent variables for statistical analysis is based on previous studies of hailstorms and the environmental conditions leading to their development. Four parameters commonly related to severe convective storm development are selected from among those presented by Summers *et al.* (1979). All parameters are defined in Table 1. The thermodynamic state of storm environment is represented by the low-level moisture, the net parcel energy (NETE) and the negative parcel energy (NEGE; positive for downward buoyancy force) for parcels representative of the storm updraft. Preliminary analyses using a down-draft parcel energy failed to show significant results and were abandoned. The energy resident in a sheared environment is represented by the wind shear through the storm layer. Again, the reader is referred to Summers *et al.* (1979) for details on the computation of these variables.

Mahrt (1977), additionally found the depth of the mixed-layer and the eastward component of the low-level flow to be related to convective intensity over the High Plains.

The final two independent variables included in our statistical analysis, the divergence and the vor-

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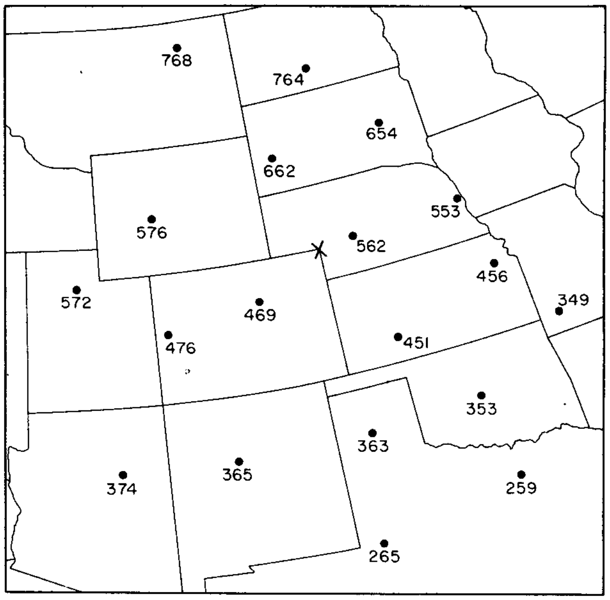

FIG. 1. Stations from which wind data was used for input to wind field analysis. × marks grid point nearest NHRE area.

ticity at 300 mb, are indicators of synoptic-scale forcing. Numerous synoptic studies including those of Endlich and Mancuso (1968) and McNulty (1978) have emphasized the importance of such field variables to severe thunderstorm development. In the present study, winds at several pressure levels including 300 mb were extracted from the North Hemisphere data tabulations (1972, 1973, 1974) for the 19 stations shown in Fig. 1 at 0000 GMT (1700 MST) on all declared hail days for which representative sounding data are available from the NHRE network. The eastward and northward wind components have been interpolated from the stations to a 2° latitude by 2° longitude (222 km by 170 km) grid using a scheme developed by Barnes (1964). The divergence and vorticity are readily calculated from the gridded wind components using centered-finite differences over two grid distances. The divergence and vorticity estimates for the grid point nearest the NHRE area (shown by an × at 41°N, 102°W in Fig. 1) are used in this study. Preliminary examination of the corresponding divergence and vorticity values for the 400 and 700 mb levels revealed some superiority of the 300 mb level results; thus, only the 300 mb data has been incorporated into our final statistical analysis.

TABLE 1. Definitions and units for independent variables.

Variable	Definition	Units
w	Mean mixing ratio in the first 50 mb above ground.	g kg^{-1}
NETE	Net energy for a parcel (having the characteristics of the mean environment over the lowest 50 mb) after lifting from the lifting condensation level to the top of the positive energy area.	10^3 J kg^{-1}
NEGE	*Absolute value* of the negative energy for a parcel (having the characteristics of the mean environment over the lowest 50 mb) after lifting from the lifting condensation level to the level of free convection.	10^3 J kg^{-1}
SHEAR	Magnitude of the vector wind shear from the lifting condensation level to the top of the positive energy area.	10^{-3} s^{-1}
h	Depth of the mixed layer estimated by several objective schemes applied to vertical profiles of potential temperature.	km
u	Mean eastward component of the wind over the lowest kilometer.	m s^{-1}
DIV	Divergence at 41°N, 102°W estimated by finite difference from gridded 300 mb winds.	10^{-6} s^{-1}
VOR	Vorticity at 41°N, 102°W estimated by finite difference from gridded 300 mb winds.	10^{-6} s^{-1}

It should be noted that computation of the isobaric divergence is difficult and very sensitive to data deficiencies (e.g., see Schmidt and Johnson, 1972). In the present case, one or more observations are missing from the tabulations on ~75% of the days. The resulting errors of the divergence estimates are difficult to estimate, but are probably of consequence as discussed in Section 4.

While a direct indicator of hailstorm severity such as the total hail mass over the NHRE area is attractive for use as dependent variable, the difficulties experienced in estimating this basic quantity from limited observational material preclude its use (see Crow *et al.*, 1979). We choose instead an area integral of the radar reflectivity, Q45, defined as

$$Q45 = \iint Z dA dt,$$

where Z is the radar reflectivity factor, A area and t time. The integration is carried out only inside the 45 dBZ reflectivity contour and inside an 80 km by 80 km region centered over the NHRE area. Further discussion of Q45, its computation, relationship to other radar-measured variables, and to hail parameters may be found in Foote *et al.* (1979) from which our Q45 data is taken.

Preliminary analysis reveals that the Q45 distribution is highly skewed. To facilitate application of significance tests this distribution is partially nor-

TABLE 2. Results of forward-step regression analysis.

		Variance (%)			Partial correlation coefficients of independent variables with TQ45							
Step	Variable added	Total explained	Improvement over preceding step	t	w	u	NEGE	SHEAR	VOR	NETE	H	DIV
1	w	35.6	35.6	5.10	0.60	−0.52	0.09	0.17	−0.27	0.45	−0.14	0.16
2	u	39.9	4.3	−1.82	—	−0.26	0.26	0.15	−0.13	0.20	0.06	0.11
3	NEGE	46.9	7.0	2.43	—	—	0.34	0.13	−0.07	0.28	0.09	0.10
4	SHEAR	50.0	3.1	1.66	—	—	—	0.24	−0.18	0.18	−0.09	0.08
5	VOR	51.5	1.5	−1.15	—	—	—	—	−0.17	0.13	−0.02	0.09
6	NETE	52.0	0.5	0.66	—	—	—	—	—	0.10	−0.06	0.04
7	H	52.4	0.4	−0.55	—	—	—	—	—	—	−0.08	0.03
8	DIV	52.4	0.0	0.08	—	—	—	—	—	—	—	0.01

malized by the transformation

$$\mathrm{TQ45} = \ln(\mathrm{Q45} + 3).$$

All further statistical analysis is done using TQ45.

The eight independent variables are combined with the dependent variable TQ45 using both forward and backward step multiple-linear regression analysis applied to the sample of 50 days for which all data are available. For a recent discussion of this method and its limitations, the reader is referred to Mahrt and Pierce (1980). In the present application, the results of the backstep procedure duplicated those of the forward step so only the latter are presented in the next section.

3. Results

The final regression equation obtained by including all variables is

$$\begin{aligned}\mathrm{TQ45} &= 2.26 + 0.49w - 0.26u + 14.44\ \mathrm{NEGE}\\ &\quad + 1.93 \times 10^{2}\ \mathrm{SHEAR} - 9.5 \times 10^{-3}\ \mathrm{VOR}\\ &\quad + 0.67\ \mathrm{NETE} - 0.24H + 1.38 \times 10^{-3}\ \mathrm{DIV}.\end{aligned}$$

It is evident that severe convection in the NHRE area is favored by large low-level mixing ratio, low-level easterly winds, large negative parcel energy and strong vertical wind shear. Little statistical significance may be attached to the other variables, as will be shown later. This combination of all independent variables explains 52.4% of the variance of TQ45.

The relative importance of the independent variables may be inferred from the reduction of variance at each step in the forward regression which is shown, together with the incremental improvement as each variable is added to the model in Table 2. Evidently only trivial improvement results from the addition of more than four variables to the model. The table also shows the t-statistic for each variable when it is added to the model. Following addition of shear to the model, no variable shows a t value above 1.3 which corresponds to the 90% level on the Student-t distribution for 40 degrees of freedom. Taking a somewhat more conservative approach, we note that the t value at the 95% level is 1.68. We conclude, therefore, that the most reasonable statistical model obtained from our analysis is

$$\mathrm{TQ45} = 0.61 + 0.66w - 0.27u + 11.51\ \mathrm{NEGE}.$$

The Q45 estimates provided by this model explain 47% of the TQ45 variance in our sample. Unfortunately, the sample size is too small to divide to allow testing on an independent set of data.

4. Interpretation

While the preceding analysis provides a potentially useful index of storm severity and documents a degree of environmental control over storm severity, physical interpretation of the results is uncertain. For example, we may inquire, "Why does net energy appear to be unimportant?" Clearer interpretation of the results is facilitated by examination of the partial correlation coefficients (Table 2) and correlations between pairs of independent variables (Table 3).

It is evident that a rather high correlation exists between NETE and TQ45 ($r = 0.45$). However, w is more strongly correlated with TQ45 ($r = 0.60$) while w and NETE are significantly correlated. Thus, the importance of NETE drops greatly after w is in the model. Apparently, variations in stratification play a secondary role in the value of NETE. On the other hand, negative energy increases in importance as w is added to the model. A plausable explanation for this behavior is that *given* high moisture, storms will be more severe if there is a strong capping inversion (large negative energy). This line of reasoning is supported by the positive correlation between NETE and NEGE. However, this correlation is too weak to allow more than highly tentative conclusions.

Despite the high correlation between low-level moisture and easterly flow, the latter retains some significance even after w is in the model. East winds not only advect moisture into the NHRE area, but

TABLE 3. Correlation coefficients between pairs of variables.

	TQ45	w	u	NEGE	SHEAR	VOR	NETE	H	DIV
TQ45		0.60	−0.52	0.09	0.17	−0.27	0.45	−0.14	0.16
w			−0.59	−0.19	0.08	−0.28	0.53	−0.32	0.12
u				0.30	−0.13	0.36	−0.14	0.26	−0.11
NEGE					−0.28	0.36	0.25	0.51	0.03
SHEAR						−0.17	0.11	−0.40	−0.02
VOR							−0.13	0.07	−0.29
NETE								0.10	0.19
H									−0.04
DIV									

also correspond to upslope motion and may be associated with favorable synoptic situations such as a low pressure or trough system to the west. For example, low-level easterly flow exhibits some correlation with 300 mb vorticity and is presumably even more correlated with low-level dynamics.

Mixed layer depth participates in conflicting roles and cannot be used to predict storm severity. For example, increasing mixed layer depth is associated with increased NEGE but decreased low-level moisture (Table 2) probably through entrainment-drying.

While the 300 mb divergence is poorly correlated with TQ45 at all stages of the regression analysis, there is evidence of its physical significance. Dividing the hail days into two samples based on TQ45 results in a mean 300 mb divergences of $+7.9 \times 10^{-6}$ s^{-1} for days with above median TQ45 and -1.9×10^{-6} s^{-1} for the below median group. However, the corresponding standard deviations are 13.1 and 16.8 (10^{-6} s^{-1}) respectively.

More complete illustration of the significance of the 300 mb divergence is found in Fig. 2 showing the differences between the mean divergence and vorticity in the above-median and below-median TQ45 samples. The most striking feature evident in these analyses is that, within the resolution of the analysis, the maximum divergence increment is found directly over the NHRE area. Furthermore, the mean vorticity differences indicate that the vorticity is more cyclonic upstream of the area (the mean 300 mb wind at 41°N, 102°W is from 271° at 14 m s^{-1}) on the above-median TQ45 days. A similar analysis for the 700 mb level (not shown) indicates a distinct band of greater *convergence* across the NHRE area, approximately coincident with the region of enhanced *divergence* at 300 mb. Furthermore, the 700 mb vorticity is more cyclonic over northeastern Colorado on the high TQ45 days. For example, at the grid point nearest the NHRE area, the mean relative vorticities for the two samples are $+6.1 \times 10^{-6}$ s^{-1} for high TQ45 days and -1.4×10^{-6} s^{-1} for low TQ45 days.

We believe that these physically consistent results indicate that synoptic scale forcing is an important factor conditioning the hailstorm environment. However, a substantial random error component in our estimates of the divergences (and, to a lesser degree, the vorticity) results in poor correlation between daily values of the kinematic variables and TQ45. It is only when this random error component is filtered out by averaging over days with high and low TQ45 that the significance of the divergence and vorticity fields becomes evident.

5. Conclusions

The above study indicates that NHRE area thunderstorms are most severe (in terms of integrated radar return) with moist low-level easterly flow and significant low-level negative parcel energy. Vertical wind shear is somewhat less important here even though it may be instrumental in determining the type of hailstorm (Browning, 1977). The influence of shear at different levels and the direction of shear with respect to flow direction are worthy of additional study.

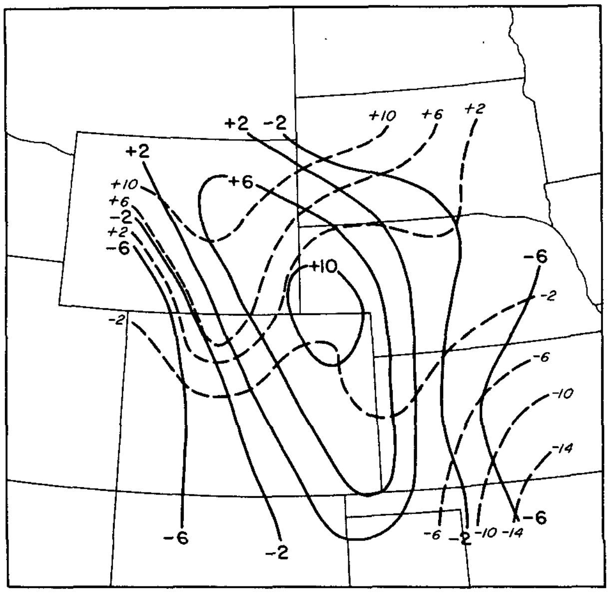

FIG. 2. Mean increment of divergence (solid) and vorticity (dashed) (10^{-6} s^{-1}) for above median TQ45 days over below median TQ45 days.

Of further interest is that much of the variance of storm intensity remains unexplained by the regression model. This may be due, in part, to instrument or analysis errors or to an imperfect relationship between integrated radar return and hailstorm severity. Furthermore, the literature is replete with studies indicating a large variety of factors which may influence thunderstorm development and severity. Unfortunately, in a statistical model the number of independent variables which can be included is severely limited by the sample size.

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