On Upper Tropospheric Kinematics and Severe Weather Occurrence

RICHARD P. MCNULTY

National Severe Storms Forecast Center, Kansas City, Mo. 64106

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ABSTRACT

Upper tropospheric wind maxima and their associated divergence fields are examined in terms of severe weather occurrence. A two-part project is described. Part I involves examination of severe weather occurrences and divergence areas qualitatively evaluated in terms of upper tropospheric wind maxima quadrants and the curvature of the flow. Part II calculates synoptic-scale divergence directly from radiosonde wind data. These quantitative divergence estimates are compared with the location of upper tropospheric wind maxima, wave troughs and severe weather occurrence. It is concluded that regions of upper tropospheric divergence are present with the occurrence of severe weather and, in particular, with the occurrence of severe weather outbreaks. Several examples are presented to support the ideas discussed.

1. Introduction

Over 20 years ago, Beebe and Bates (1955) hypothesized that upper tropospheric divergence superimposed over low-level moisture, instability and convergence produce severe weather. These ideas were discussed in terms of crossing wind maxima at the 850 and 500 mb levels. As a result of that study and those of Lee and Galway (1956a, b, 1957, 1958), among others, severe weather forecasters have been using jet strength winds as a parameter in severe weather prognostication. The exact use of these high-speed winds, however, has been rather ill defined. The purpose of this paper is to examine the relationship between upper tropospheric wind maxima and severe weather occurrence, with particular emphasis on the divergence associated with the upper level flow. As an additional phase, the relationship of upper level and lower level wind maxima to severe weather events, as described by Beebe and Bates (1955), is reexamined in terms of 850 and 300 mb level data.

Several past investigations (Section 2) and the results of this study indicate the presence of synoptic-scale upper tropospheric divergence with severe weather occurrence. It is generally agreed that lower tropospheric convergence is also required, but the scale of this convergence is still to be determined. House (1958) and Beebe and Bates (1955) discuss the role of this divergence-convergence distribution in destabilization of the vertical column.

House (1958) and Riehl *et al.* (1954) indicate that 500 mb wind maxima do not accurately reflect the location of the jet and its branches during all seasons of the year. Ideally, the upper tropospheric jet should be used. But jet structure and location are often difficult to analyze accurately in an operational environment. Also, strong wind maxima are more easily located than jetlets.[1] These jetlets, which are often undetected between radiosonde observations, are often important in the severe storm environment.

The largest values of divergence in the upper troposphere are associated with jet-level wind maxima (Newton and Palmén, 1963). As a result, a study of the jet stream and upper tropospheric divergence naturally coincide. A two-part project has been undertaken. The first part involves examination of severe weather occurrence and divergence areas qualitatively evaluated in terms of upper tropospheric wind maxima quadrants and the curvature of the flow. Reexamination of the 850–300 mb relationship is also included here. The second part involves the calculation of synoptic-scale divergence directly from radiosonde wind data. These quantitative divergence estimates have been compared with the location of upper tropospheric wind maxima, wave troughs and severe weather occurrence.

2. Jets and severe weather

Ludlam (1963) shows that regions of severe weather activity are found along the mean monthly position of 500 mb wind maxima in various parts of the Northern Hemisphere. Conner (1956), by examining 30 major tornado days between 1945 and 1954, related areas of afternoon potential for severe storms to the morning 500 mb flow. He found the most likely area for tornado occurrence is within 325 km downstream and 480 km to the right of the 500 mb wind maximum for cyclonically curved flow. For zonal flow with multiple maxima

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[1] A jetlet is defined as a small region of jet-strength wind (*Glossary of Meteorology*, Amer. Meteor. Soc., 638 pp).

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along the flows, the highest probability of severe weather is to the right of the wind axis under the relatively weak flow between the maxima. This unpublished study was one of the first attempts to use upper level wind information in severe weather forecasting. Connor's results are not in conflict with the quadrant approach of Beebe and Bates (1955) or Newton and Newton (1959) (see below) if the subsequent movement of the 500 mb features between morning analysis, and afternoon and evening occurrence, is considered.

Newton and Newton (1959) noted that the maximum frequency of tornado and severe thunderstorm occurrence is under the left front quadrant of 500 mb wind maxima for a variety of flow situations.

Ramaswamy (1956) examined the effect of the subtropical jet stream on convection over the Indian subcontinent for 80 daily situations during the premonsoon period. Convection most frequently occurred with a combination of latently unstable moist air in lower levels and divergence in the upper troposphere (300 mb). The greater the intensity of 300 mb wind maxima, the more extensive and severe was the thunderstorm activity. Lee and Galway (1956a) investigated flow characteristics at the 200 mb level and found a correspondence between the presence of a wind maximum at that level and tornado occurrence.

In an unpublished study, Sanders (1971) quantitatively evaluated the divergence of the shear wind between the upper and lower troposphere. Over 80% of severe weather cases during the spring of 1970 occurred for positive values of shear divergence

$$[\nabla_2 \cdot \partial \mathbf{V}/\partial z = \partial(\nabla_2 \cdot \mathbf{V})/\partial z > 0].$$

House (1958) indicates that upper tropospheric divergence areas associated with severe weather are not always associated with a jet feature.

In recent papers, Whitney (1977) and Karst (1977) find that the diffluent region between the polar and subtropical jet streams, as indicated by satellite imagery, is a favorable location for severe weather. Skaggs (1967) statistically verifies the association between tornado days in the Texas, Oklahoma, Kansas region and the polar and subtropical jet streams.

Although the true low-level jet (LLJ) is not considered explicitly in this study, a brief summary of its relationship to severe weather over the Great Plains should be noted. Pitchford and London (1962) calculated the mean position of the LLJ over a 21-station network centered around Omaha. Widespread nocturnal convective activity was found to be associated with upward vertical motions downstream from the low-level maximum. Sangster (1967) also found that thunderstorm-related heavy rains occurred downstream from the surface wind maximum.

Bonner (1966) found thunderstorm activity originating in a region of strong ascent, downstream and to the left of the low-level wind maximum. The right rear of the LLJ was found to be a region of downward vertical motion and devoid of thunderstorm activity. Bonner concluded that the LLJ was not a cause of convective development but maintained an environment favorable for convective activity.

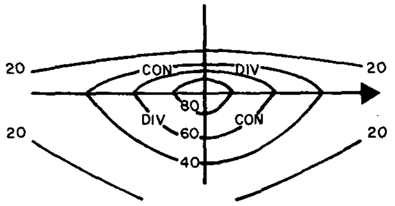

FIG. 1. Divergence-convergence pattern for a straight jet. Isotach values in knots.

3. Part I: Qualitative evaluation

Conscious of the analytical difficulties inherent in jet stream analysis and aware of the currently available operational charts, the 300 mb wind field has been chosen as representative of the upper tropospheric jet stream for Part I of this study. Note should be taken, however, that this study is analyzing only wind maxima, not the "jet stream." The term "jet stream" implies certain structural details of the wind field which have not been considered here. For example, the core of the jet stream is known to meander in the vertical as well as the horizontal direction. Examination of isotach analyses at more than one level, e.g., the 300 and 200 mb levels (available from National Weather Service facsimile networks), often shows differences in maximum wind location due to the vertical meandering of the core. Accurate depiction of the jet stream requires three-dimensional analyses of the wind field not available from pressure level charts.

Similarly, the reader is reminded that the 850 mb wind maximum should *not always* be interpreted as a low-level jet in the true sense of the term. An 850 mb wind maximum, especially during the spring season, can be a downward extension of an upper tropospheric jet maximum, not a true low-level phenomena (Riehl *et al.* 1954).

Kinematic analysis of atmospheric flow on a constant pressure surface is a basic technique of theoretical meteorology. The 300 mb divergence pattern in the vicinity of a wind maximum (Fig. 1) has been derived from analysis of the vorticity equation by Beebe and Bates (1955) and Riehl *et al.* (1954) among others. For synoptic-scale motions in the upper troposphere, the divergence term of the vorticity equation is approximately balanced by the vorticity advection. In particular, divergence is associated with positive vorticity advection (PVA) and convergence with negative vorticity advection (NVA).

Fig. 1 shows the divergence pattern for straight flow. Upper level divergence is found in the left front (LF)

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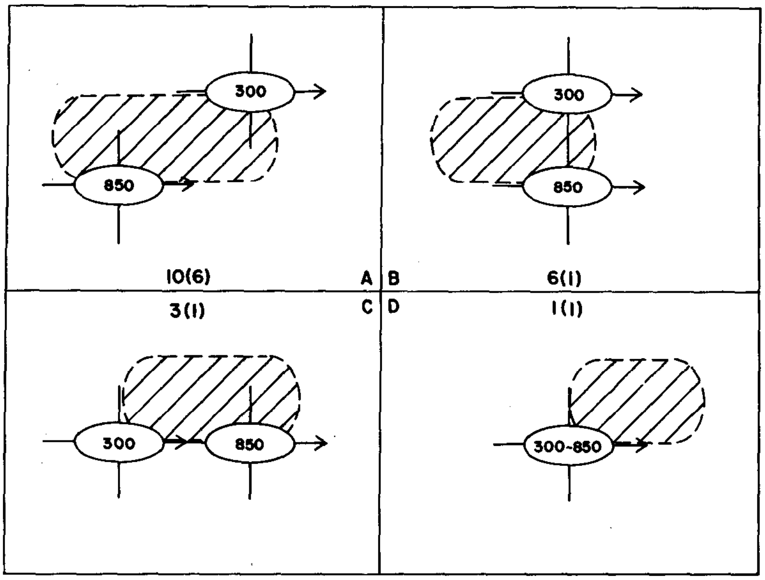

FIG. 2. The relationship between 850 and 300 mb isotach maxima (ellipses) and severe weather occurrence (hatched area). The number of cases from March 1976 data corresponding to each model are shown for any number of severe weather events and for outbreaks (parentheses).

and right rear (RR) quadrants of the wind maximum looking downstream, while upper level convergence is found in the left rear (LR) and right front (RF) quadrants. These patterns have been empirically verified by Part II of this study and through work done in association with Schaefer (1977).

If the flow represented in Fig. 1 is allowed to curve cyclonically, the positive relative vorticity on the left side of the axis is increased due to the addition of curvature. As a result, the divergence-convergence couplet on the left side is reinforced. On the right side of the axis, the shear and curvature are of opposite signs. Thus, the relative vorticity, the vorticity advection and the balancing divergence become qualitatively undefined. For anticyclonically curved flow, the couplet on the right side of the axis is reinforced while that on the left side is qualitatively undefined. Nevertheless, a qualitative estimate of the location of major divergence areas associated with strong 300 mb wind maxima can be obtained from an isotach streamflow analysis.

For low-level wind maxima, the atmosphere can no longer be considered inviscid and inertial terms are not negligable. Thus, a generalization as to expected convergence-divergence patterns cannot be obtained from such a simple kinematic analysis.

This study used a developmental data set of 61 cases from March 1976. March 1976 was particularly active for severe weather and was thought to give an appropriate mixture of occurrence and non-occurrence cases. Charts were prepared superimposing 850 and 300 mb isotachs, and the location of severe reports[2] occurring within 3 h either side of analysis time. The 300 mb data were taken from National Meteorological Center (NMC) facsimile charts. The 850 mb isotach patterns were hand analyzed. These charts were divided into 28 cases with severe reports occurring at map time (±3 h) and 33 cases with no severe reports at map time (±3 h). The no severe cases were further subdivided into ten cases where severe weather was reported in the 3–12 h period after analysis time and into 23 cases of non-occurrence of severe weather during that period. This subdivision allowed the effect of rapidly moving wind maxima to be incorporated into the analysis of severe weather not occurring near synoptic times. Data from the spring of 1977 and the last week of May 1973 have been used as an independent data set to qualitatively confirm the conclusions drawn from the March 1976 data.

As is aptly described by Miller (1972), parameters other than wind are also important for the occurrence of severe weather. As a result, each case was examined in terms of three synoptic scale parameters: low-level moisture, instability and upper divergence. It was assumed that if severe weather occurred, a fourth parameter, a source of low-level convergence of *unknown* scale, was present. It is possible that this low-level convergence is associated with the 850 mb wind maximum. But since this study is emphasizing upper level parameters, cases were not examined in detail to find the source of low-level convergence. These data demonstrated that the proper combination of these four parameters is sufficient to forecast severe weather on a regional scale.

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[2] Reports extracted from the Severe Local Storms Unit (SELS) log, a record of confirmed severe weather events maintained by NSSFC, Kansas City, Mo.

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4. Discussion of qualitative results

The March 1976 cases show that severe weather outbreaks [Galway (1977) defined an outbreak as 10 or more severe weather events] occur under regions of upper divergence inferred from 300 mb wind maxima. Divergence areas are more readily deduced from strong wind maxima normally observed during March and April than from weaker maxima often found later in the spring. Several examples of this relationship are presented in this section and in Section 5.

Examination of 850 mb data shows that severe weather occurs along or to the left of the 850 mb maximum, verifying the observations of Bonner (1966). SELS forecasters have also noted this relationship (R. H. Johns, personal communication). As a result, this axis can be used as a boundary for severe weather activity. Four basic patterns are observed in the March 1976 data. Composites showing the typical horizontal positioning of the 300 and 850 mb wind fields are given in Fig. 2. The ellipses represent the location of the isotach maxima while the hatched area represents the area of severe weather occurrence during the 6 h window noted above. These patterns best describe outbreaks of more than 10 severe weather events but are also valid for more isolated activity. The parallel orientation of the flow arrows in Fig. 2 does not imply that upper and lower level flows need be parallel. (Comment will be made on this below.) The arrows are intended to indicate the relative positions of the two maxima with regard to the 300 mb flow field. It was found that if the horizontal separation of the maxima was more than about 900 km, the two features did not interact and severe weather did not occur. Fig. 2 can be summed up, at least for types A, B and C by saying *as a general rule, severe weather activity occurs between the 850 and 300 mb wind maxima under areas of upper divergence.*

Beebe and Bates (1955) discuss the use of crossing upper (500 mb) and lower (850 mb) jets for tornado forecasting. Severe weather forecasters have adopted this concept in terms of crossing wind axes, but the detail of the upper divergent quadrant is often overlooked. This study shows that the divergent quadrant is important. Second, it was found that wind axes do not have to cross. *If parallel, or near parallel (relative flow angles less than 30°), upper and lower tropospheric flows superimpose divergence over low-level moisture, instability and convergence, no cross-over is necessary to generate severe weather.*

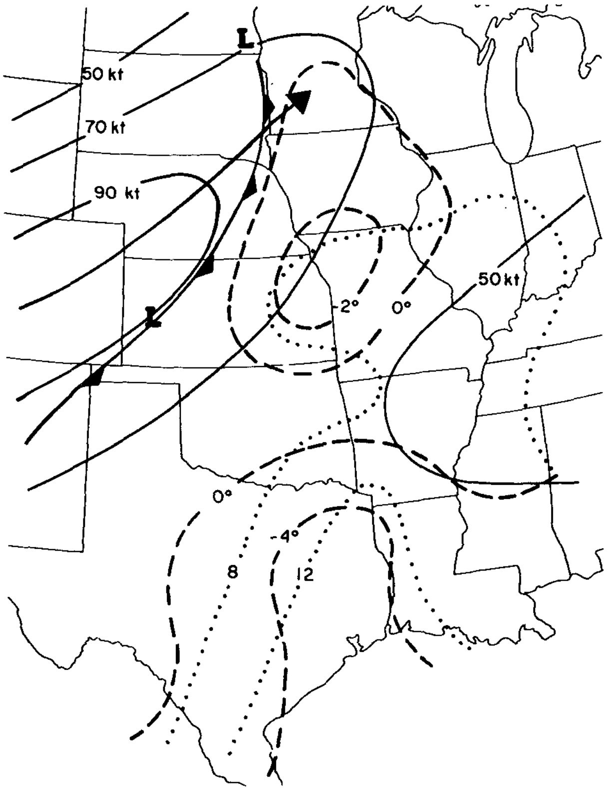

FIG. 3. Mean low-level mixing ratio (dotted, g kg^{-1}), lifted index value (dashed), surface front (barbs) and 300 mb isotachs (solid) for 0000 GMT 20 March 1976.

Up to this point the discussion has focused on the relative positions of wind maxima and their kinematics. Fields of mean low-level mixing ratio (lowest 100 mb) and SELS lifted index (LI) (Galway, 1956) were also examined for each case. Mean lower level mixing ratios of 7 g kg^{-1} or greater occurred for 75% of these cases, but values as low as 4 g kg^{-1} were found with severe events. Marginal instability values (LI's in the range of 0 to $+2$°C) were found to be sufficient if the wind flow indicated relatively strong kinematic divergence pattern in the upper troposphere.

The importance of moisture, instability and upper divergence to severe weather occurrence is shown by several of the non-occurrence cases. Often sufficient moisture and instability were present, but the upper tropospheric wind field did not provide the necessary divergence. Fig. 3 illustrates such a case. A tongue of moisture and instability extends northward from the Texas Coast to Iowa. A cold front (trigger mechanism) is moving eastward through the Northern Plains. Such a situation has potential for severe activity. However, the RF (convergent) quadrant of the 300 mb maximum is superimposed over the moisture and instability in northern Missouri and Iowa. During the subsequent 12 h, no severe weather was reported. This result is attributed to the lack of divergence aloft.

5. Operational application of qualitative results

The concept presented in the previous section can be applied in a multiplicity of situations. The two examples described below illustrate how a regional convective outlook can be prepared from the four basic parameters noted above.

Fig. 4 shows a case for 0000 GMT 13 March 1976.

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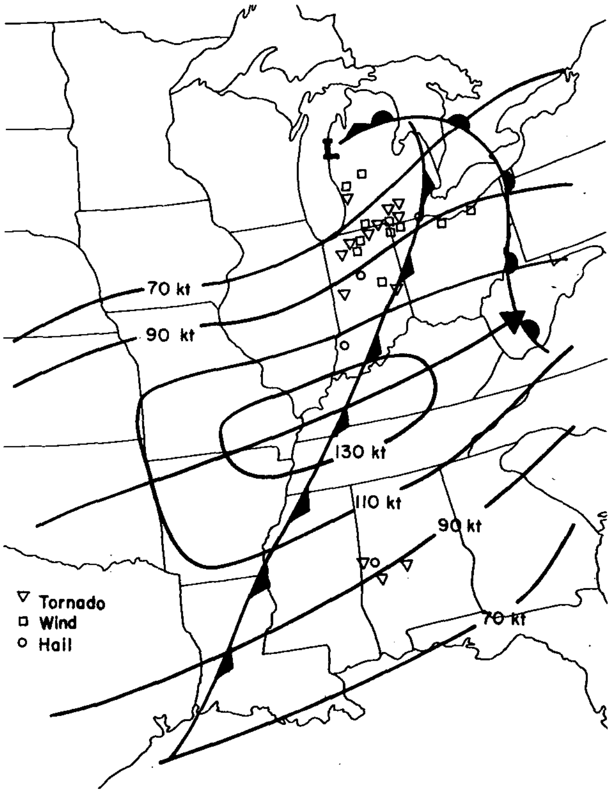

FIG. 4. Isotachs at 300 mb (solid) and surface frontal positions for 0000 GMT 13 March 1976.

The straight 300 mb flow implies upper tropospheric divergence in the LF and RR quadrants of the western Kentucky wind maximum. LI and mean mixing ratio values were found to be $+2°C$ and 4 g kg^{-1} over Indiana gradually changing to $-2°C$ and 12 g kg^{-1} over Alabama. A cold front moved across Illinois and Indiana during the afternoon, triggering the 24 severe weather events shown east and south of Lake Michigan. This activity began in Indiana about 2100 GMT and developed northward and eastward, reaching Ohio about 0100 GMT. Four severe events are also seen to occur in Alabama after 0200 GMT as the result of a squall line which formed in the RR divergent sector as the wind maximum progressed eastward.

The rapid movement of 300 mb wind maxima can have a strong influence on the occurrence of severe weather events. Fig. 5 illustrates a case for 2 April 1977. Fig. 5a shows a 300 mb wind maximum (solid lines) over the Texas Panhandle on the morning of the 2nd. At 1200 GMT, moisture and instability extend northward from the Gulf Coast to lower Michigan. At this time, the divergent quadrant of the 300 mb wind maximum was well west of the low-level instability. During the subsequent 12 h, the wind maximum moved rapidly northeastward (Fig. 5b), superimposing its LF quadrant over the marginally unstable ($LI \approx 0$) conditions around Lake Michigan. In response to these conditions and the triggering action of a rapidly moving cold front, an outbreak of tornadoes and severe thunderstorms began in southern Wisconsin around midday, progressing eastward during the afternoon and evening. In this type of situation, a good short-term (6–18 h) prognosis of the wind maximum location could be combined with recognition of thermodynamic conditions to outlook potential severe weather areas.

For the operational application of these concepts, it must be remembered that *upper divergence should be present at the time of occurrence of the severe weather*. As a result, the movement in time and space of wind maxima and low-level thermodynamic factors is one key to a successful forecast. At various time intervals downstream from the initial analysis, the various parameters can be superimposed to see if severe potential exists. For severe weather forecasting, 6 h time intervals would be best, but 12 h intervals are more readily available at present. Such prognoses can be obtained from either subjective methods or the NMC numerical products. This superposition of upper divergence (wind maxima) over low-level moisture, instability and convergence refines the forecast of severe weather in time and space.

6. Part II: Quantitative evaluation

The qualitative approach described in the previous sections provides the operational forecasters with a relationship between upper tropospheric wind maxima and severe weather occurrence. Although this approach can be used to infer areas of upper level divergence, two limitations should be noted.

First, without a well-defined maximum, it is difficult to accurately diagnose areas of divergence. This is especially true when the westerlies are weak, e.g., during the summer. Significant areas of divergence can exist in a weak flow field (House, 1958), but the lack of a wind maximum can preclude recognition of its presence.

Second, the qualitative approach restricts attention to a relatively small portion of the flow. If the flow is curved, for example, divergence can be inferred on only one side of the wind maximum. Other parameters favorable for severe weather may be present, but a lack of definition aloft complicates the forecast decision. A quantitative calculation of divergence, on the other hand, provides a complete picture.

Fields of mean divergence have been produced for the 61 cases from March 1976 described in Section 3, and for the major severe weather days of the spring and early summer of 1977. Divergence is calculated from the expression

$$\mathrm{DIV}=m^2\left[\frac{\partial}{\partial x}\left(\frac{u}{m}\right)+\frac{\partial}{\partial y}\left(\frac{v}{m}\right)\right]=\nabla_2\cdot\mathbf{V},$$

where m is the metric coefficient of the map projection used, while u and v are the horizontal velocity compo-

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nents in the x and y directions, respectively. In order to overcome inaccuracies inherent in using data from only one pressure level, a mean divergence value has been obtained by averaging through the 200 to 300 mb layer:

$$\overline{\mathrm{DIV}}=\frac{1}{p_2-p_1}\int_{p_1}^{p_2}\mathrm{DIV}\,dp, \tag{1}$$

where $p_1=300$ mb and $p_2=200$ mb.

Radiosonde wind data at 300, 250 and 200 mb have been interpolated for each pressure level to a 190.5 km grid covering the United States. The interpolation scheme is designed such that its response function decreases to 1% within four grid lengths [See Doswell (1976) for details of the interpolation procedure.] As a result, short-wavelength features (noise) have been minimized and the data smoothed to synoptic scale. Vertically averaged divergence is calculated for each grid point by using the trapezoidal rule to approximate the integral in (1):

$$\overline{\mathrm{DIV}}\approx\tfrac{1}{4}[\mathrm{DIV}_{300}+2\,\mathrm{DIV}_{250}+\mathrm{DIV}_{200}].$$

The 6 h window described in Part I was reemployed for the quantitative evaluation. It is realized that this window may introduce some unrepresentative values for severe weather occurring at the extremes of the time interval. Movement of jet-level features can change both the magnitude and sign of the divergence at the given location over a 2–3 h period. Nevertheless, a reasonable representation of the severe weather-divergence relationship should be obtained by the present method.

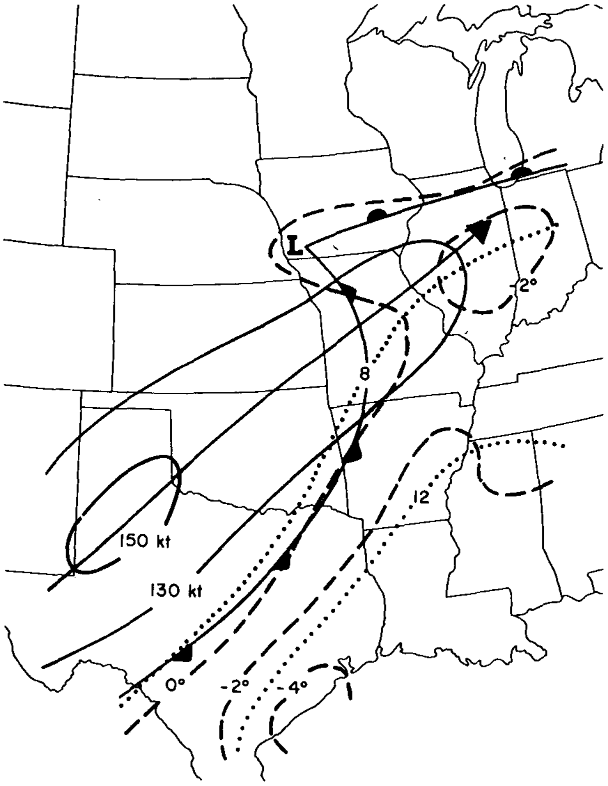

FIG. 5a. Surface weather pattern for 1200 GMT 2 April 1977. Notation as in Fig. 3.

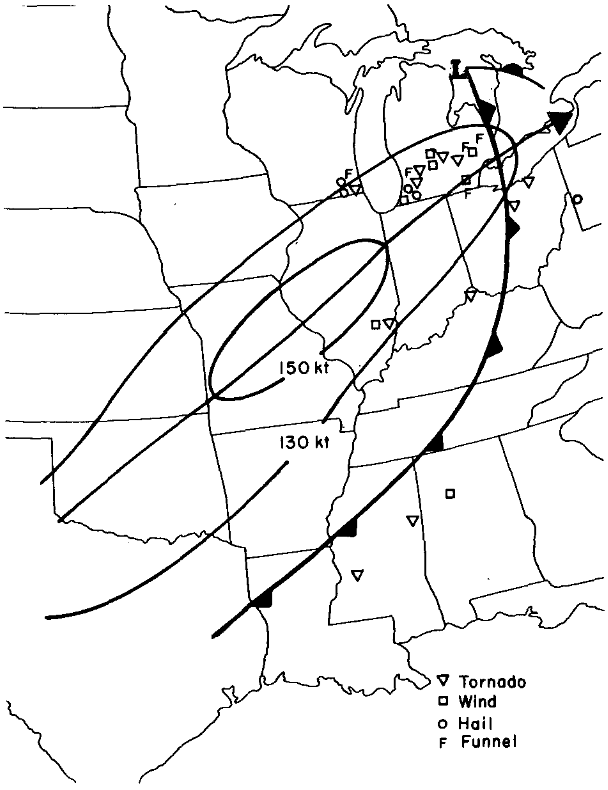

FIG. 5b. Isotachs at 300 mb (solid) and surface fronts for 0000 GMT 3 April 1977, and severe weather occurrences from SELS Log.

7. Discussion of quantitative results

To demonstrate that divergence values calculated in this study are consistent with previous theoretical and observational results, some comparison is in order. It must be realized, however, that the real atmosphere is much more complex than the simplified theoretical analysis presented in Section 3. As a result, a perfect match is not expected, but the major features deduced from theory should be evident. Attention is directed to Fig. 6. Fig. 6a superimposes the 300 mb contour and isotach fields for 1200 GMT 27 March 1976. The corresponding divergence field is shown in Fig. 6b. In agreement with the concepts of Bjerknes and Holmboe (1944), divergence is found downstream from the shortwave trough located over the upper Mississippi River Valley and convergence is found upstream. The divergence center over the Great Lakes is located in the RR quadrant of the anticyclonically curved wind maximum

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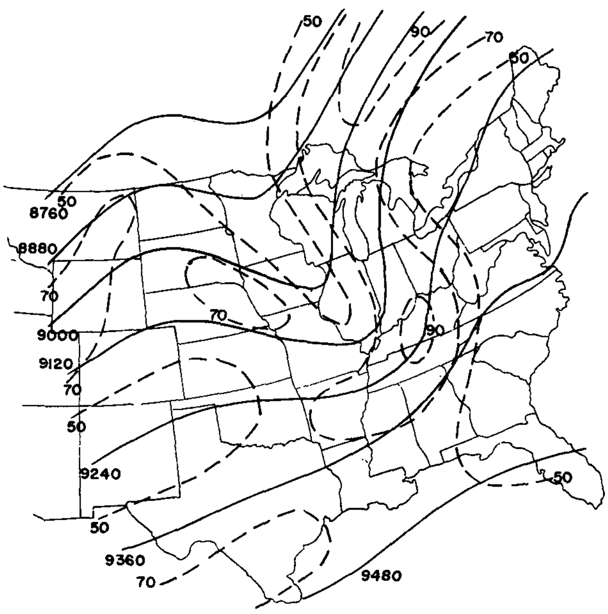

FIG. 6a. Contour field (solid, m) and isotachs (dashed, kt) at 300 mb for 1200 GMT 27 March 1976.

in east-central Canada. The wind maximum over Kentucky occurs in the sharply curved flow at the base of the upper Mississippi River Valley trough. As a result, qualitative comparison can be made only on the northern side of the axis. Divergence values are found in the LF quadrant (although rather weak) and convergence values in the LR quadrant, but no explicit divergence maxima are shown. This type of basic agreement between observation and theory is persistent throughout the data sample. Divergence fields have also been compared on a limited, qualitative basis with satellite cloud images and with vertical velocity fields (derived via an omega equation). These comparisons show good agreement and provide a high degree of confidence in the divergence analysis. Computed divergence magnitudes are in agreement with those of Landers (1956) for synoptic-scale flow.

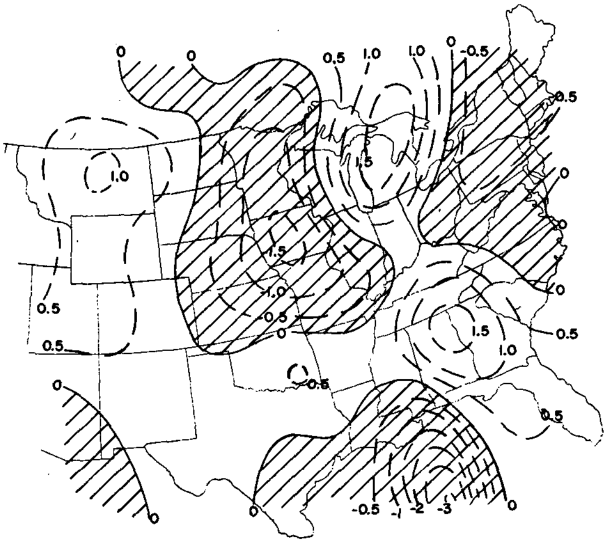

FIG. 6b. Mean divergence field for 200–300 mb layer (10^{-5} s^{-1}) for 1200 GMT 27 March 1976.

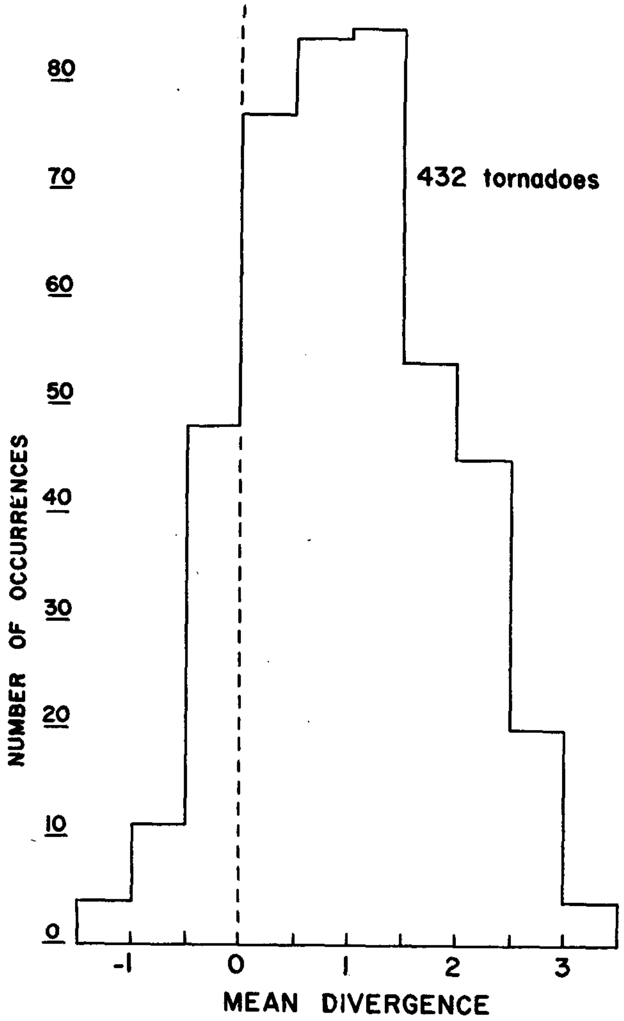

FIG. 7. Histogram of mean divergence in the 200–300 mb layer for tornadoes of March 1976 and February–June 1977.

Fig. 7 is a histogram of upper tropospheric divergence values associated with some 432 confirmed tornadoes which occurred within 3 h of analysis time during March 1976 and February–June 1977. The divergence values are concentrated between 0 and 2.5×10^{-5} s^{-1} (80%). Over 85% of the tornadoes occurred for positive values.

It is interesting to note that the majority of tornadoes occur for moderate and weak divergence values ($<2.5\times10^{-5}$ s^{-1}). Strong divergence values appear less favorable for severe weather occurrence. This dearth of tornadoes for divergence values $>2.5\times10^{-5}$ s^{-1} does not

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appear to be artificially imposed. Divergence values in the 2.5–4.5$\times10^{-5}$ s^{-1} range are not uncommon. Values larger than 4.5$\times10^{-5}$ s^{-1} are rare.

In support of the above assertion, reference is made to Fig. 8. The upper half of the figure gives the distribution of divergence at the point of tornado occurrence for the dependent data set of March 1976. Its characteristics are similar to those of the larger sample (Fig. 7). The lower portion of the figure shows the distribution of maximum divergence isopleth values. If a tornado occurred with an area of divergence, the value of the maximum isopleth associated with that area was tabulated and is represented graphically by the lower distribution. The fact that the lower distribution is shifted away from the upper distribution toward higher absolute values leads to the conclusion drawn above. This conclusion is further supported by the observation that over two-thirds of the tornadoes occurred in regions of divergence gradient, rather than inside the maximum divergence isopleth. Qualitative support comes from an observation by SELS forecasters (R. J. Williams, R. P. Darrah and C. L. David, personal communication). Tornadoes have been found, more often than not, to occur along the periphery of 500 mb PVA areas, not in the area of strongest PVA. Divergence areas in the upper troposphere should be highly correlated with PVA areas (see discussion, Section 3). Thus, the SELS observation implies higher probabilities of tornado occurrence away from the area of strongest divergence (PVA).

If the mean upper tropospheric divergence is interpreted as a measure of mid-tropospheric synoptic-scale vertical motion, it can be stated that weak to moderate upward vertical velocity is most favorable for severe weather. Strong upward vertical velocities apparently give a lower probability of significant convective activity. This result may be associated with the tendency of tornadoes to occur to the south and east of developing cyclones, away from the area of strongest upward vertical motion. On the other hand, strong synoptic-scale upward motion indicates widespread lifting of the air mass which while favoring widespread convection may somehow inhibit severe storm development which tends to occur with quasi-isolated convective elements. A definitive explanation for the lack of tornado activity with strong divergence values needs further investigation.

The above discussion supports the premise that upper level divergence is present with the occurrence of severe weather. Newton and Palmén (1963) observe that the largest divergence values are concentrated in the vicinity of upper tropospheric wind maxima. Bjerknes and Holmboe (1944) show that short-wave troughs are also a source of upper level divergence. As a result, a discussion of upper tropospheric flow must consider the interaction of these two features. O'Connor (1952) describes this interaction. Briefly, a wind maximum upstream from a trough tends to amplify the wave, while a wind maximum downstream from a trough weakens the wave and increases its downstream propagation speed.

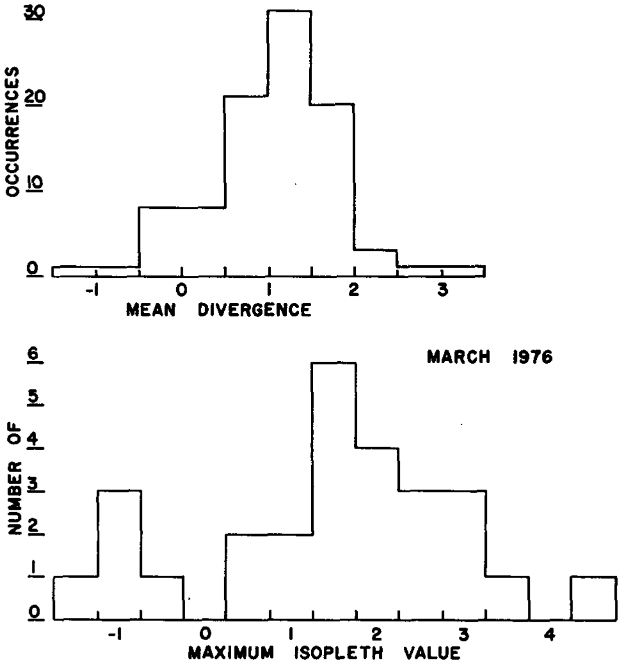

Fig. 8. Upper portion: as in Fig. 7 except for March 1976 only; lower: histogram of maximum isopleth values for severe weather situations (units: 10^{-5} s^{-1}).

SELS forecasters have operationally observed the controlling influence of upper level wind maxima and the importance of short-wave troughs to severe weather for many years (J. G. Galway, personal communication). Strong (1977) finds the presence of synoptic-scale short waves to be an important forecast parameter for large hail in Alberta. Several key parameters listed by Miller (1972) can be justified in terms of upper tropospheric divergence associated with short-wave/wind maximum pairs.

It is proposed that the upper tropospheric jet stream, the short-wave trough, or more often than not, the combination of the two features, are *the source of upper level divergence present with the occurrence of severe weather and, in particular, with the occurrence of severe weather outbreaks.* When this divergence becomes superimposed over low-level moisture, instability and convergence, severe weather probabilities increase.

8. Quantitative examples

Fig. 9 shows an example for 1200 GMT 30 March 1976. At 1200 GMT very unstable air (SELS LI's as low as −10°C) extended from eastern Texas to Mississippi. Stability values over Illinois and Indiana were around −4°C. A complex short-wave system is present

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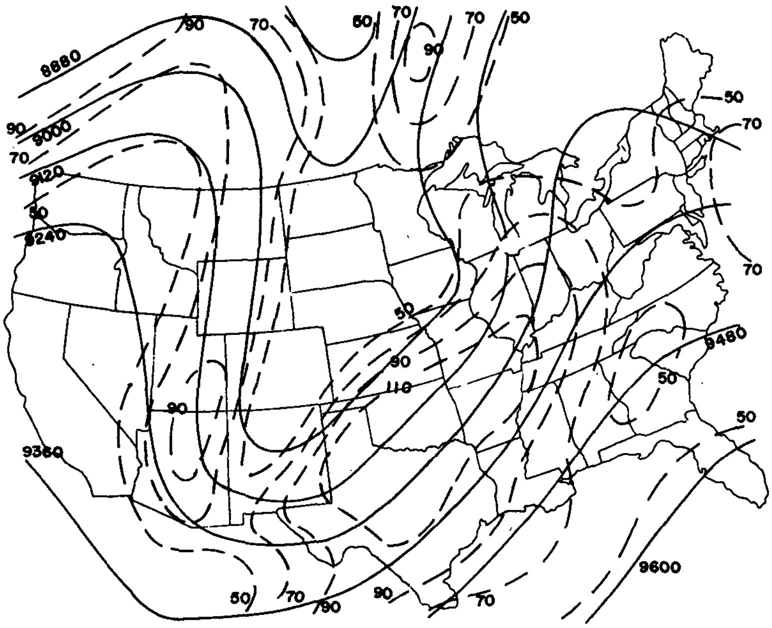

FIG. 9a. As in Fig. 6a except for 1200 GMT 30 March 1976.

over the central United States (Fig. 9a), while a strong wind maximum is found over Oklahoma.

The divergence analysis (Fig. 9b) shows a strongly divergent ridge over the Appalachian Mountains. Divergence is also found ahead of the short-wave trough over Illinois and in the RR quadrant of the wind maximum over eastern Texas.

During the 1200–0000 GMT period, the Oklahoma wind maximum moved rapidly northeastward. The strongest wind values at 0000 GMT (not shown) were found on the Michigan-Ohio border, but a secondary maximum stretched the isotach pattern southwestward into Arkansas. The short wave over Iowa moved through the Great Lakes during this period, and several severe weather events were reported in lower Michigan under the LF quadrant of the wind maximum.

In the RR quadrant of the wind maximum, severe weather is already occurring over east-central Texas at 1200 GMT. As the day progressed, the center of severe weather activity moved east-northeastward, spreading into northern Alabama by late evening. The divergence on the Texas coast also tracked east-northeastward,

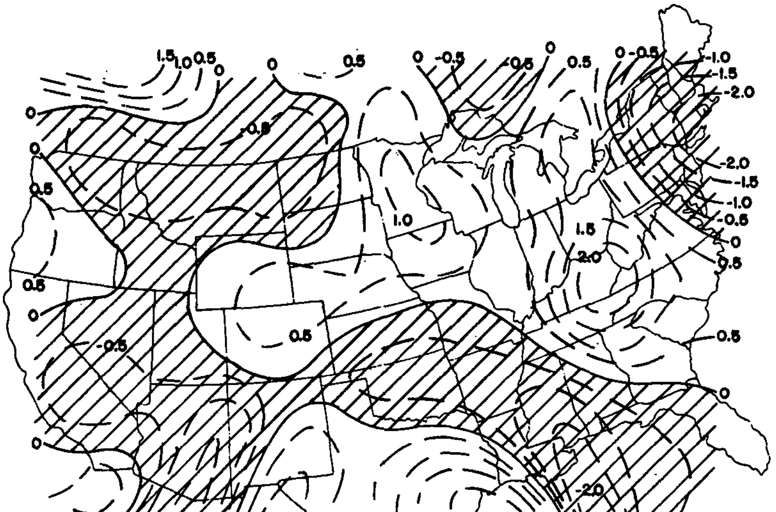

FIG. 9b. As in Fig. 6b except for 1200 GMT 30 March 1976.

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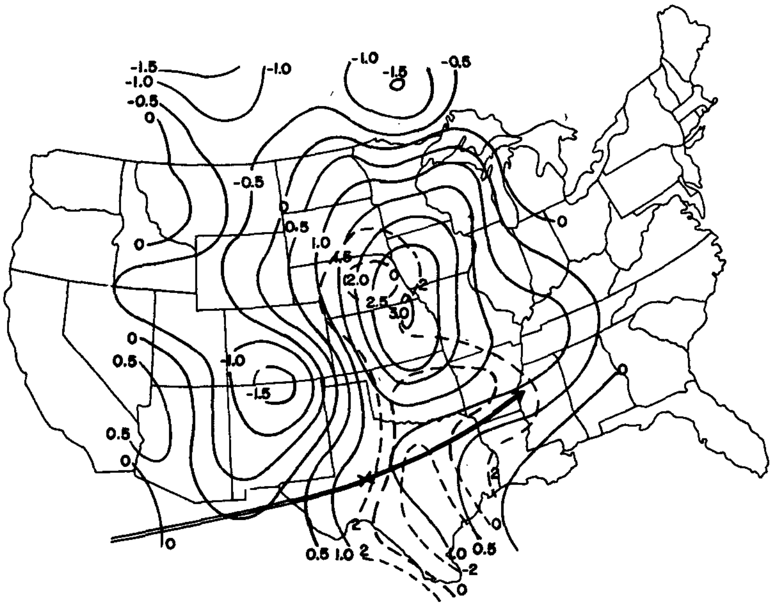

FIG. 10a. Mean divergence in 200–300 mb layer (solid, 10^{-5} s^{-1}) and SELS lifted index (dashed, °C); arrow is 300 mb axis of maximum wind; × is wind maximum center; 0000 GMT 3 March 1977.

remaining in the RR quadrant of the wind maximum. Recognition of this divergence area and its subsequent motion is one factor in forecasting the progression of the severe activity across the southeastern states.

This example illustrates an important point. The northern activity occurs with the passage of a short-wave/wind maximum pair, as is often the case. However, the activity on the Gulf Coast was not associated with a detectable short-wave trough. The divergence associated with the RR quadrant of the wind maximum is the only significant upper level feature present. *Even though a short-wave trough is often present with severe weather activity, a wind maximum alone can be the controlling feature in the upper tropospheric flow.* Such sources of high-level energy and divergence must not be overlooked in preparation of regional convective outlooks.

The intensity of upper tropospheric features relative to the intensity of the instability is important. House (1958) noted that, relatively speaking, stronger than average upper tropospheric divergence combined with weak instability (LI≈0) is as effective in producing severe weather as weak upper tropospheric divergence and strong instability. Fig. 10 illustrates both conditions. Fig. 10a shows a strong 300 mb wind maximum (>110 kt), strong divergence and weak lifted indices. Severe activity during the afternoon and evening started in western Kansas and spread through Oklahoma to the Dallas-Fort Worth area.

Fig. 10b presents a more summerlike situation. Moderate northwesterly flow covered the East Coast, north of the Carolina's. No well-defined short-wave troughs are present. Very unstable air covered the southeastern states. The weak divergence maximum over Ohio at 1200 GMT moved south-southeastward during the day, being located over Georgia at 0000 GMT. In response to this impulse from the north, isolated severe activity developed along a line from the Birmingham area to the Georgia Coast.

It is hoped that via some scheme such as a divergence analysis, recognition of significant upper tropospheric short-wave troughs, wind maxima, or more importantly, their combination, can be achieved. This recognition, when properly combined with other factors favorable

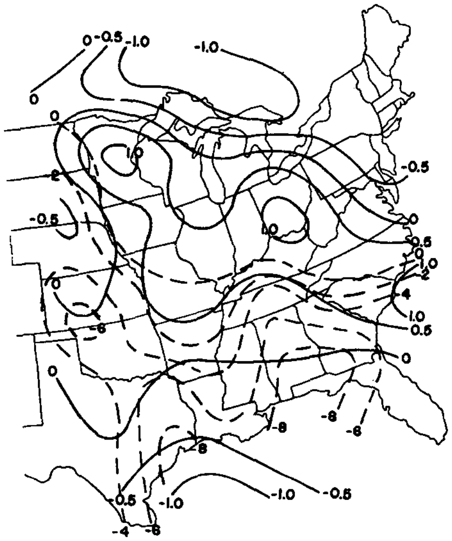

FIG. 10b. As in Fig. 10a except for 1200 GMT 22 June 1977.

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for severe weather occurrence, and when used in accord with the ideas presented in the last paragraph of Section 5, can lead to improved regional severe weather outlooks.

9. Summary

This study reemphasizes the importance of upper tropospheric wind maxima to severe weather forecasting. In particular, it has demonstrated both qualitatively and quantitatively that divergence is present in the 300-200 mb layer during severe weather activity. The divergent quadrant of wind maxima must be recognized and used in combination with low-level moisture, instability and convergence to define areas where severe thunderstorm and tornado activity may occur.

It is suggested that a quantitative analysis of divergence be used to identify upper tropospheric regions conducive to severe weather. The short-wave/wind maximum pair and occasionally, the wind maximum by itself, have been found to be a key parameter in severe weather forecasting. Marginal low-level instability and strong sources of divergence were found to be as effective in producing severe weather as very unstable low-level air and weak upper tropospheric features. Emphasis has been placed on the upper troposphere rather than the 500 mb flow because it is at these upper tropospheric levels that the controlling features of synoptic scale flow are found, not in mid levels.

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REFERENCES

Beebe, R. G., and F. C. Bates, 1955: A mechanism for assisting in the release of convective instability. *Mon. Wea. Rev.*, **83**, 1-10.

Bjerknes, J., and J. Holmboe, 1944: On the theory of cyclones. *J. Meteor.*, **1**, 1-22.

Bonner, W. D., 1966: Case study of thunderstorm activity in relation to the low-level jet. *Mon. Wea. Rev.*, **94**, 167-178.

Conner, W. C., 1956: Structure of the 500-mb jet in major tornadogenesis. U. S. Weather Bureau, Washington, D.C., 12 pp.

Doswell, C. A. III, 1976: Subsynoptic scale dynamics as revealed by use of filtered surface data. NOAA Tech. Memo., ERL-NSSL-79, Norman, Okla., 40 pp. [NTIS No. PB 265-433/AS].

Galway, J. G., 1956: The lifted index as a predictor of latent instability. *Bull. Amer. Meteor. Soc.*, **37**, 528-529.

——, 1977: Some climatological aspects of tornado outbreaks. *Mon. Wea. Rev.*, **105**, 477-484.

House, D. C., 1958: Air mass modification and upper-level divergence. *Bull. Amer. Meteor. Soc.*, **39**, 137-143.

Karst, O. J., 1977: Thunderstorm development in a jet stream diffluence zone. *Nat. Wea. Dig.*, **2**, 10-13.

Landers, H., 1956: On the magnitude of divergence and vorticity. *J. Meteor.*, **13**, 121-122.

Lee, J. T., and J. G. Galway, 1956a: Preliminary report on the relationship between the jet at the 200 mb level and tornado occurrence. *Bull. Amer. Meteor. Soc.*, **37**, 327-332.

——, and ——, 1956b: Progress report on upper level jets and their relationship to severe weather. U.S. Weather Bureau, Kansas City, Mo., 5 pp. [Available from National Severe Storms Forecast Center, Kansas City, Mo.]

——, and ——, 1957: Second progress report on upper level jets and their relationship to severe weather. U.S. Weather Bureau, Kansas City, Mo., 8 pp. [Available from National Severe Storms Forecast Center, Kansas City, Mo.]

——, and ——, 1958: The jet chart. *Bull. Amer. Meteor. Soc.*, **39**, 217-223.

Ludlam, F. H., 1963: *Severe Local Storms: A Review. Meteor. Monogr.*, No. 27, 1-30.

Miller, R. C., 1972: Notes on analysis and severe storm forecasting procedures of the Air Force Global Weather Central. Tech. Rep. 200 (Rev.), Air Weather Service, 190 pp. [Available Scott AFB, Ill.]

Newton, C. W., and H. R. Newton, 1959: Dynamical interactions between large convective clouds and environment with vertical shear. *J. Meteor.*, **16**, 483-496.

——, and E. Palmén, 1963: Kinematic and thermal properties of a large-amplitude wave in the westerlies. *Tellus*, **15**, 99-119.

O'Connor, J. F., 1952: Practical methods of weather analysis and prognosis. NAVAER50-1P-502, 192 pp. [Available NOAA Library, Rockville, Md.]

Pitchford, K. L., and J. London, 1962: The low-level jet as related to nocturnal thunderstorms over midwest United States. *J. Appl. Meteor.*, **1**, 43-47.

Ramaswamy, C., 1956: On the subtropical jet stream and its role in the development of large-scale convection. *Tellus*, **8**, 26-60.

Riehl, H., M. A. Alaka, C. L. Jordan and R. J. Renard, 1954: *The Jet Stream. Meteor. Monogr.*, No. 7, 100 pp.

Sanders, R. A., 1971: Frequency of severe weather with low-level convergence and upper level divergence. National Severe Storms Forecast Center, Kansas City, Mo., 5 pp.

Sangster, W. E., 1967: Diurnal surface geostrophic wind variations over the Great Plains. *Preprints 5th Conf. Severe Local Storms*, St. Louis, Amer. Meteor. Soc., 146-153.

Schaefer, J. T., 1977: On the applicability of the divergence equation to severe storm forecasting. *Preprints 10th Conf. Severe Local Storms*, Omaha, Amer. Meteor. Soc., 358-363.

Strong, G. S., 1977: Relating Alberta thunderstorms to synoptic short waves. Paper presented at 11th Annual Congress of Canadian Meteor. Soc., Winnipeg, 1-3 June.

Skaggs, R. H., 1967: On the association between tornadoes and 500 mb indicators of jet streams. *Mon. Wea. Rev.*, **95**, 107-110.

Whitney, L. F., 1977: Relationship of the subtropical jet stream to severe local storms. *Mon. Wea. Rev.*, **105**, 398-412.

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