Meso-β Scale Perturbations of the Wind Field by Thunderstorm Cells

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15 September 1984 and 22 October 1985

ABSTRACT

Analysis of data from the high density storm-scale rawinsonde network of SESAME during the storm events on 2 May 1979 showed the existence of persistent and strong regions of tropospheric convergence and divergence which were detectable on the meso-β scale. In particular, mid- and upper-tropospheric divergence was superimposed over low-level convergence. The divergence, which had a maximum value of $4 \times 10^{-4} \text{s}^{-1}$, occurred well upward (75–100 km) as well as over the tornadic cells. To the south of the storm cells, the kinematic pattern is reversed with upper-level convergence superimposed over low-level divergence. Calculations indicate a vertical motion doublet with ascent ($-40 \mu \text{b s}^{-1}$) over the squall line and descent ($+40 \mu \text{b s}^{-1}$) approximately 70 km south of the squall line.

It is hypothesized that the above flow fields resulted from a combination of 1) blocking of tropospheric environmental flow by the storm cells, 2) anvil outflows, particularly from the tornadic cells; and 3) divergence from the exit region of the jet stream.

1. Introduction

Previous studies have documented the modification of environmental flow in the presence of intense convection, with emphasis on various scales of motion. Beebe and Bates (1955) and Newton (1963) showed that synoptic-scale, upper-level divergence is an important mechanism in triggering convective instability. A study of thunderstorms imbedded in a synoptic-scale system (Ninomiya, 1971) attributed upper-level divergence to persistent convective warming in the storm area. Similar results were shown by Maddox (1979) for mesoscale convective complexes. Fankhauser (1974) showed that the eventual effect of the presence of a squall line was strong diffuence of the flow aloft. From a detailed analysis of an Oklahoma squall line using National Severe Storms Laboratory upper air network data, Ogura and Chen (1977) stated that low-level convergence was responsible for the release of potential instability which contributed to the evolution of the squall line. Frisch and Maddox (1981) and most recently Fuelberg and Priney (1983) showed pronounced divergence in the upper troposphere, which appeared to have developed in response to a strong convective outbreak.

This note details the temporal and spatial changes in the divergence fields in the troposphere in response to severe storm evolution on 2 May 1979 during the Severe Environmental Storms and Mesoscale Experiment (SESAME) (Albert et al., 1979). The preliminary results presented here show the importance of a high density rawinsonde network in detecting meso-β scale [20–200 km, and several hours to one day, as described by Orlanski (1975)] kinematic features whose presence could not be discerned by the standard network of rawinsonde sites.

2. Storm overview and method of analysis

The severe storms which developed during the afternoon of 2 May 1979 were associated with a northeast-southwest oriented cold front, which at 1200 GMT (all times are GMT) was moving into northwestern Oklahoma, and a diffluent short wave trough at 500 mb over Oklahoma. By midafternoon, two tornadic storms developed quite rapidly along the cold front. Shortly after 2300, a northeast-southwest oriented cloud line began to develop to the southwest of the tornadic cells (Fig. 1). These clouds depict the initial stage of a developing squall line which during the next five hours moved southeastward across Oklahoma at $\sim 10 \text{ m s}^{-1}$. In contrast, the tornadic cells moved eastward at about 15 m s$^{-1}$ and always remained at the northeastern end of the line.

The storm-scale rawinsonde network (Fig. 2) as also described by Fuelberg and Priney (1983) provided the main data base to study the effect of the thunderstorms on the flow field. For reference, the tornadic storms were located in the northeastern part of the network. Station spacing was on the order of 80 km. Rawinsonde
releases began during the 2300 hour and continued through the 0500 hour on 3 May with a release schedule set at 90 min intervals. A total of 70 soundings was taken from 17 sites. In addition to the high temporal frequency of observations, the data were recorded with high vertical resolution (∼5–15 mb intervals).

Procedures to check for data quality and to evaluate space and time continuity of soundings are similar to those discussed in detail by Fankhauser (1969) and for another SESAME case study (Fuegberg and Printy, 1983); therefore, these techniques are only highlighted here. The expected errors in wind measurements increase with altitude; errors can be several meters per second at the 200 mb level. In order to eliminate any spurious data, the wind components were averaged at 50-mb increments. Balloon position (latitude, longitude, and height with respect to launch site) was computed for each sounding. Station positions could then be adjusted for balloon drift, which at the 200 mb level was often greater than 40 km. Rawinsondes were not released into active thunderstorms; therefore, approximately 60 to 85 percent of all possible launches occurred during a particular release period. This data discontinuity was a major factor in not applying Fankhauser’s (1969) linear interpolation technique to account for nonsimultaneous rawinsonde releases.

Divergence fields were computed for the surface and standard upper air levels of 850, 700, 500, 300, and 200 mb. Surface analyses included only rawinsonde data and used wind measurements between the first and second lowest sounding levels. The flow field was objectively analyzed by a technique developed by Barnes (1973). The Barnes scheme was selected because it is computationally efficient with a filter response function that can be determined a priori to provide

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**Fig. 1.** GOES visible image at 2304 GMT 2 May 1979 of tornadic storms and developing squall line.

**Fig. 2.** Storm-scale rawinsonde stations used in subsequent objective analysis. Box depicts the grid display region. Cross sections of various kinematic parameters are constructed along dashed line.
information only at the scales resolvable with a particular data distribution. Koch et al. (1983) have shown in detail that the scheme adequately recovers analysis details after only two passes through the data set. The above point was an important factor in the utilization of Barnes' scheme since data discontinuities necessitate that often a large search radius be used to insure that sufficient data influence is exerted at all grid points. The objective analysis scheme utilized here was part of an interactive software package which has been documented extensively by Koch et al. (1983). An $8 \times 7$ grid was employed in the analysis with the grid display area placed entirely within the data area to avoid attempted interpretation of the analysis in data-poor boundary regions. A grid spacing of 39 km, approximately 0.5 the average data spacing, was employed. This grid spacing was chosen based upon the criterion that the grid spacing must not be larger than one-half the data spacing in order to represent resolvable wavelengths (Peterson and Middleton, 1963). In addition, calculations of derivative quantities such as divergence are highly sensitive to grid length. An unrealistically noisy divergence field may result if the grid mesh size is too small. A measure of analysis quality was obtained from the calculation and interpretation of the field-averaged rms difference (rmsd) between the interpolated and observed fields. The rmsd provided a guide to the analyst to decide how much smoothing to accept in the final product. The $u$- and $v$-wind components formed the grid fields which were used in the centered finite-differencing approach to divergence calculations. Vertical motions were computed in three dimensions by the traditional kinematic technique and adjusted to zero at 100 mb by employing O'Brien's (1970) scheme.

3. Storm-environment interaction

a. Wind fields

A representative sequence of lower- and upper-tropospheric environmental flow is shown superimposed upon the 2334 GOES satellite image (Fig. 3). The surface wind field shows distinct confluence along the developing squall line. At this time, according to Heymsfield and Schotz (1985), the position of the cold front and squall line coincide. At 700 mb, the flow is predominantly southwesterly and confluence is not present. However, note that the winds at Shamrock (SHM) and Canadian (CAN) have a more southerly component than the other sites. The wind direction at Altus

Fig. 3. Composite GOES visible satellite image at 2334 GMT with surface, 700, 500, and 200-mb wind barbs plotted from the 2315 GMT sounding release time. A full barb equals 10 m s$^{-1}$. 
diffuence over the storm area, which persisted up to 200 mb. Particularly, note the directional shift between 500 and 200 mb at Gage (GAG) as the balloon drifts closer to the tornadic cells. Even more dramatic is the shift from southwesterly to westerly flow just south of the tornadic cells. In addition, the sites closest to the southern boundary of the anvil edge of the tornadic cells exhibit speeds (45–50 m s⁻¹) which are higher than the average 200-mb flow (35 m s⁻¹).

**b. Divergence and vertical motion fields**

The surface divergence field at 2315 (Fig. 5) shows that convergence generally exists along and behind the squall line. The 850-mb analysis is not significantly different from that at the surface, except for a northward shift in the convergence values. It is possible to account for this observed shift with the frontal slope toward the colder air, since the sounding at GAG shows the cold front in evidence at 800 mb (Heymsfield et al., 1983). At 700 mb, divergence is found 90 km upwind of the tornadic cells and is centered over the squall line. However, the squall line is in very early stages of development at this time (Heymsfield and Schotz, 1985), and thus should not have a large effect on the upper-level winds. At 500 mb, relatively strong divergence (1.5 × 10⁻⁴ s⁻¹) is now associated with the anvil outline of the tornadic storms. At 300 mb, a convergence cell has developed in the southeastern section of the grid. Both the divergence and convergence cells attain their maximum values (2.0 × 10⁻⁴ s⁻¹ and −2.5 × 10⁻⁴ s⁻¹, respectively) throughout the troposphere.

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at 200 mb. Additional divergence computations at 150 mb yield the same general pattern of divergence, but an overall decrease in magnitude.

At 0035 (Fig. 6), an expansion of the squall line anvil and surface convergence has occurred. At 850 mb, the convergence has weakened to approximately half the surface value. The flow field becomes increasingly divergent from 700 to 300 mb with the maximum values centered near the apex of the squall line. This position appears just to the east of the cold front-dryline intersection shown in the surface analysis (Heymsfield and Schotz, 1985). By 200 mb, the divergence maximum has shifted to a more easterly position near the tornadic cells. Convergence is also evident at 200 mb on the southeastern flank of the tornadic cells; however, its strength and areal coverage have weakened from 2315.

The 0210 analysis (Fig. 7) is probably most accurate because the squall line and cold front are centered in the network. The pattern at 0210 is consistent with earlier soundings, showing convergence up to approximately 850 mb and divergence above 700 mb increasing in strength up to 200 mb. The value of $+4.0 \times 10^{-4}$ s$^{-1}$ at 200 mb is the highest value attained throughout the sounding period. The upper-level convergence which was in evidence in the previous flow fields has weakened considerably and is far to the south of the thunderstorm complex as the complex generally progresses southward.

Though two additional release periods of rawin sondes were utilized to characterize this day, the unavailability of detailed satellite imagery hindered positioning of the squall line in relation to the divergence fields. However, a time-pressure cross section of di-
vergence (Fig. 8) at Hinton (HNT) yields additional aspects of the evolution of the flow fields. From approximately 2300 to 0000, upper-level convergence is superimposed over relatively shallow divergence. The time series of vertical motion (Fig. 9) shows sinking motion over HNT with a value of 10 \( \mu \text{b} \text{s}^{-1} \). Approximately two hours later, HNT experiences a dramatic reversal of the kinematic fields as the squall line passes this site. Corresponding to the vertical changes in divergence, upward vertical motion exists throughout the troposphere with a maximum of \(-40 \mu \text{b} \text{s}^{-1} \) at 500 mb. The strongest ascent occurs shortly after the squall line surface wind shift. Fuelberg and Pinty (1983) for the 20–21 May 1979 SESAME case depicted strong ascent throughout the troposphere with a maximum of \(-22 \mu \text{b} \text{s}^{-1} \) at 400 mb during the time of intense convection.

Spatial cross sections of divergence (Fig. 10) and vertical motion (Fig. 11) at 2315 along a northwest-southeast line (see Fig. 2) are constructed through the network. This cross section was chosen at this time, the squall line position was at Seiling (SEL). At the low levels, convergence is found at SEL and divergence exists ahead of the line at HNT. Strong upper-tropospheric (300–200 mb) divergence is found over SEL, but from HNT to Elmore City (EMC) strong upper-level (400–200 mb) convergence exists.

The vertical motion cross section shows upward motion throughout the troposphere over SEL, corresponding to the convective part of the squall line. A maximum value of \(-40 \mu \text{b} \text{s}^{-1} \) is found at the 300–200 mb levels. Strong downward motion exists well ahead of the squall line surface position. Maximum values of \(+40 \mu \text{b} \text{s}^{-1} \) at mid-tropospheric levels are centered over Chickasha (CHK). This result is similar to the mesoscale descent-ascent doublet observed by Sanders and Paine (1975) and Bradberry (1981), showing the descent above, or 10 km ahead of, the surface frontal position or radar echoes, respectively. Their ascent was on the order of 5 to 30 km behind the radar echoes and front, respectively. In our analysis, the...
maximum descent was approximately 70 km ahead of the squall line, though weaker downward motion exists closer to the squall line.

4. Speculations as to the causes of the kinematic fields

The storm-scale rawinsonde network of SESAME provided a unique data set to study the evolution of the wind, divergence, and vertical motion fields in the presence of intense convection. It is suggested that the following effects are responsible for the nature of the kinematic fields:

1) Tropospheric environmental winds are diverted around the convective cells of the squall line and tornadic storms. While the “obstacle effect” is certainly not a new observation (Newton and Newton, 1959; Barnes, 1970; Fankhauser, 1971), its documentation on the meso-β scale has not been widespread. The concept of obstacle flow has been refined by Rotunno and Klemp (1982). They demonstrated through linear theory that an axisymmetric updraft in a vertically sheared environment results in a pressure gradient aligned parallel to the shear vector, and a vertical vorticity couplet oriented normal to the shear vector. Rotunno and Klemp’s results show that the vorticity and pressure fields act to divert the environment air around the updraft rather than a solid object in classical obstacle flow

analogy. The formation of cyclonic and anticyclonic vorticity to the right and left of the updraft (i.e., looking downshear), respectively, suggests that environmental flow is increased on both sides of the updraft. Indeed, some increase in the environmental flow was found in the observations. However, analogies to either of the above models are complicated by the fact that the entire squall line and tornadic cells behaved more like the “obstacle” than any individual tornadic storm.

2) Upper-level environmental flow is diverted by the tornadic storm outflows. This process is supported by the independent hypothesis that the observed V-shaped pattern in infrared temperatures for the tornadic cells on 2 May (Heymsfield et al., 1983) is produced by strong divergence in the storm outflow. Using Doppler winds, Heymsfield et al. (1983) showed that divergence centers existed at upper levels of the tornadic storms with maximum values of $5 \times 10^{-3} \text{s}^{-1}$ and radii of at least 20–30 km. Three-dimensional model results of severe storm tops (Schlesinger, 1984) also indicate the large extent of thunderstorm outflows and the diversion of environmental flow around them.

3) Divergence is produced by the large-scale jet stream exit left region (Whitney, 1977). The jet stream was approximately at the 200-mb level and an isotach analysis (not shown) shows an area of maximum winds located to the south of the storms, straddling the Texas–Oklahoma border. Therefore, the position of the isotach maximum relative to the area of divergence at least qualitatively agrees with the work of Whitney.

Since the storm-scale rawinsonde releases did not begin until after the tornadic storm outbreak, we cannot unequivocally rule out that the divergence patterns are the result of an existing upper-level feature (e.g., short wave trough translating from the west). These results, though preliminary in nature, lend support to the employment of a high density network in conjunction with severe storm studies.

Acknowledgments. The authors would like to express their appreciation to the many helpful comments provided by Drs. Adler, Koch, and Simpson. Most of this research was performed while the senior author was a NASA summer faculty fellow. Appreciation is also extended to Kelly Wilson for typing the manuscript.

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