Energy Analysis of Convectively Induced Wind Perturbations

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ABSTRACT

Budgets of divergent and rotational components of kinetic energy (K_D and K_R) are examined for four upper level wind speed maxima that develop during the fourth Atmospheric Variability Experiment (AVE IV) and the first AVE-Severe Environmental Storms and Mesoscale Experiment (AVE-SESAME I). A similar budget analysis for a low-level jet stream during AVE-SESAME I also is performed. Special radiosonde data at 3 or 6 h intervals and mesoscale horizontal spacing (AVE-SESAME I only) are a major advantage to the cases selected. Previous studies have attributed the development of upper level wind maxima during AVE IV to the presence of mesoscale convective complexes. They appear to be similarly formed, or at least enhanced, during the SESAME case; however, strong pre-existing dynamics and less reliable wind data make the determination more difficult. The energetics of the four upper level speed maxima is found to have several similarities. The dominant source of K_D is cross-contour flow by the divergent wind, and K_D provides a major source of K_R via a conversion process. Conversion from available potential energy provides an additional source of K_R in three of the cases. Horizontal maps reveal that the conversions involving K_D are maximized in regions poleward of the convection, i.e., where the speed maxima form.

Low level jet development during AVE-SESAME I appears to be assisted by convective activity to the west. Enhanced low level convergence produces conversion from available potential energy to K_D and then to K_R. These aspects are similar to those occurring in the upper-level speed maxima.

1. Introduction

Areas of intense convection commonly are accompanied by variations in horizontal and vertical winds. For example, forecasters recognize upper and lower level jet streams as frequent precursors of severe weather (e.g., Miller 1972). Other wind variations occur as a storm complex interacts with its larger scale environment. One example is upper level speed maxima that develop north of storm complexes (Ninomiya 1971a,b; Fritsch and Maddox 1981a; Fuelberg and Jedlovec 1982; Wetzel et al. 1983). Conversely, wind speed minima have been found south of Mesoscale Convective Complexes (MCCs) by Fritsch and Maddox (1981a). Furthermore, in the immediate vicinity of active convection, diminished upper level winds and enhanced middle level winds (effectively reducing vertical shear) were noted by Vincent and Carney (1982) and Fuelberg and Printy (1983, 1984).

Wind variations may be examined through kinetic energy analyses, and numerous studies have presented kinetic energy budgets for regions encompassing convective outbreaks (e.g., Tsui and Kung 1977; Fuelberg and Scoggins 1978; Vincent and Schlatter 1979; Robertson and Smith 1980; Fuelberg and Jedlovec 1982). Although each of these papers considered the total wind, Carney and Vincent (1986a,b) partitioned the flow into a synoptic scale component and its difference between that detected by a special mesoscale network. Furthermore, Fuelberg and Browning (1983) considered relative contributions of divergent (V_D) and rotational (V_R) winds to the total kinetic energy balance of upper air wind maxima located north of two MCCs. They found that V_D was an important component of their energy budgets.

This paper examines divergent (K_D) and rotational (K_R) kinetic energy budgets for subvolumes enclosing wind perturbations during two cases. The first, the 10–11 April 1979 day of the Atmospheric Variability Experiment—Severe Environmental Storms and Mesoscale Experiment (AVE-SESAME I), is ideal for study because of meso α-scale data availability and the variety of observed wind phenomena. The second case includes two MCCs occurring on 24–25 April 1975 (AVE IV). The current study is an extension of Buechler and


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Fuelberg (1986, hereafter referred to as BF) in which KD and KR budgets were shown for the entire AVE IV and AVE-SESAME I networks, but not for the wind maxima described here.

2. Theory

The KD and KR budget equations have been given for closed systems by Chen and Wiin-Nielsen (1976), and for limited volumes in terms of streamfunction and velocity potential by Krishnamurti and Ramanathan (1982). The current study uses BF's formulation for open systems which utilizes \( V_R \) and \( V_D \).

A brief derivation begins with Helmholtz's theorem, i.e.,

\[
V = V_R + V_D,
\]

and by defining kinetic energy per unit mass (\( k \)) as \( k = \frac{1}{2} V \cdot V \). Similarly, \( k_D = \frac{1}{2} V_D \cdot V_D \) and \( k_R = \frac{1}{2} V_R \cdot V_R \).

Application to (1) produces

\[
k = k_D + k_R + V_R \cdot V_D.
\]

The kinetic energy of an atmospheric volume in isobaric coordinates is given by

\[
K = \int \int k,
\]

where

\[
\int \int = \frac{1}{gA} \int \int \int dx dy dp,
\]

\( g \) is the acceleration of gravity, \( A \) is the computational area, and \( dp \) is the pressure interval. Similarly,

\[
KR = \int \int k_R, \quad KD = \int \int k_D,
\]

thereby allowing (2) to be written as

\[
K = KR + KD + \int \int V_R \cdot V_D.
\]

\( \int \int V_R \cdot V_D \) (hereafter referred to as VRVD) integrates to zero in a global domain, but not necessarily in a limited region. Taking the time derivative of (6) yields

\[
\frac{\partial K}{\partial t} = \frac{\partial KR}{\partial t} + \frac{\partial KD}{\partial t} + \int \int \frac{\partial V_R \cdot V_D}{\partial t}.
\]

The final budget equations derived by BF are

\[
\frac{\partial KD}{\partial t} = \int \int - V_D \cdot \frac{\partial V_R}{\partial t} - \left[ \int \int - f (v_R u_D - u_R v_D) \right] + \int \int - \frac{\partial k_R}{\partial p}
\]

\[
\frac{\partial KR}{\partial t} = \int \int - V_R \cdot \frac{\partial V_D}{\partial t} + \int \int \frac{\partial k_R}{\partial p} + \int \int V_D \cdot F,
\]

and

\[
\frac{\partial KR}{\partial t} = \int \int - V_R \cdot \frac{\partial V_D}{\partial t} + \int \int - f (v_R u_D - u_R v_D)
\]

where \( \omega = dp/dt \), \( f = \) Coriolis parameter, \( f = \partial v_R / \partial x - \partial u_R / \partial y \), \( \phi \) is geopotential and \( F \) is frictional force.

A schematic depicting the various processes of (8) and (9) is shown in Fig. 1, where "A" represents the reservoir of available potential energy and lines connecting reservoirs denote conversions. The four terms enclosed by brackets in (8) and (9) represent conversions between KR and KD since they appear in both equations with opposite signs, an often used guideline in energetics (e.g., Smith 1970). Terms AF and Az depend on relative orientations and magnitudes of \( V_R \) and \( V_D \). Chen (1975) has provided a physical interpretation by noting that \( V_D \) horizontally transports fluid elements having given angular momentum. Then, to

Fig. 1. Schematic of rotational and divergent kinetic energy budgets for an open domain. See (8), (9), and the text for an explanation of symbols.
satisfy conservation of angular momentum, the exchange of fluid elements produces a tangential force. The work of this force on the tangential (rotational) motion is the integrand of Af and Az. Terms B and C also qualify as conversions. Chen (1975) observed that $V_D$ produces vertical motion yielding a momentum exchange between levels. Term B describes the vertical exchange of rotational momentum while Term C describes the divergent component. This redistribution may enhance or diminish conversions by Af and Az. Total conversion between KD and KR, the sum of the four components, is denoted by $C(KD, KR)$ in Fig. 1.

Conversions among A and KD and KR due to cross-contour flow, frequently called generations by baroclinic and barotropic processes, respectively (Chen and Wiin-Nielsen 1976), are represented by GD and GR. HFD and HFR denote horizontal flux divergence of total K by $V_D$ and $V_R$, while VF is vertical flux divergence of K and affects only KD since $\omega$ arises from $V_D$. Dissipation terms DD and DR represent frictional processes as well as transfers of energy between resolvable and unresolvable scales of motion. They are calculated as residuals and therefore also contain the accumulation of possible errors from other terms in their respective equations. Finally, Terms INTR and INTD arise from $V_R \cdot V_D$ in (6) due to the open system being studied. Although difficult to interpret physically, we chose the term "interaction" because they represent energy transfers between KR and KD due to the presence of the other component. For example, KR can be enhanced or diminished by the complementing/interfering influences of $V_D$ through INTR.

Buechler and Fuelberg showed that Af $\approx$ GD because $V_R$ closely follows the height contours, thereby approximating the direction, but not necessarily the magnitude of the geostrophic wind ($V_R$). Thus, signs of Af and GD will agree in areas where directions of $V_R$ and $V_K$ are similar.

We now compare the energetics of global and limited atmospheres. When (8) and (9) are integrated over the entire mass of the atmosphere, flux terms HFD, HFR, and VF will vanish. Similarly, GR, INTD, and INTR will integrate to zero globally. Finally, in (7), Term DVRVD is zero in a global atmosphere.

3. Data and computational procedures

Data and computational procedures are identical to those of BF; therefore, only highlights will be presented here. The AVE-SESAME I period extended from 1200 UTC 10 April to 1200 UTC 11 April 1979 and encompassed the south-central United States. The Wichita Falls, Texas, tornado was the major event occurring during this highly baroclinic case which included many features common to severe storm outbreaks, e.g., strong low and upper level jets, an intense cyclone, and associated fronts. Rawinsondes provided meso $\alpha$-scale resolution every 3 h, enabling detailed analysis of various storm-related features. Conditions at the beginning of the period are shown in Fig. 2, while additional details about the data and synoptic situation can be found in Carlson et al. (1980), Moore and Fuelberg (1981), and Fuelberg and Jediovoc (1982).

In contrast, AVE IV exhibited weak synoptic forcing, but two MCCs did develop, reaching peak intensity near 0600 UTC on each day of the experiment (24–25 April 1975). Synoptic-scale rawinsonde data at 3 or 6 h intervals provided good temporal resolution of wind fluctuations that have been attributed to the storms (Maddock et al. 1981). Figure 3 shows conditions at the first sounding time, while in-depth synoptic discussions can be found in Fuelberg and Scoggins (1978) and Fuelberg and Browning (1983).

Eighteen levels of objectively analyzed data were produced at each observation time in both cases (the surface and 50 mb intervals from 900–100 mb). Vertical motions were obtained by the kinematic method using the O'Brien (1970) procedure to adjust values to zero at 100 mb. Additional information about methodology can be found in Wilson (1976) and Fuelberg and Scoggins (1978) for AVE IV and in Fuelberg and Jediovoc (1982) for AVE-SESAME I.

The horizontal wind was separated into its divergent

![Image](image-url)

**Fig. 2.** Synoptic conditions at the beginning of the AVE-SESAME I experiment (1200 UTC 10 April 1979). Heights are in decameters with isolachts (top) in m s$^{-1}$ and sea level pressures in 4 mb increments.
their detailed study, jet level charts similar to those of Maddox (1979) are presented in Fig. 4. The plotted winds are maximum reported values at or above 400 mb. To isolate areas of greatest variability, horizontal maps of the three hourly change in kinetic energy (DK) for the 400–100 mb layer are shown in Fig. 5. Most of the fluctuations observed in the jet charts (Fig. 4) also are evident in Fig. 5; however, differences are attributable to the integration of DK over the layer.

The jet chart (Fig. 4) at the first observation time (1200 UTC 10 April) reveals strongest winds (reaching 60 m s\(^{-1}\) near 200 mb) associated with the subtropical jet stream over southern Texas. Directions are basically westerly; however, as the experiment progresses, they shift to a more southerly orientation. The relative isotach minimum over central Texas remains nearly stationary through 1500 UTC although speeds increase over most of the domain resulting in widespread positive DK (Fig. 5). These kinetic energy changes (Fig. 5) in the prestorm environment are less than 55 W m\(^{-2}\).

The first major convection begins just south of the Texas–Oklahoma border near 1735 UTC (Fig. 4). The speed minimum over central Texas is no longer evident, but is replaced by a relative maximum near 175 mb that moves generally eastward and decreases in strength through the next 12 h. The developing convection is located between areas of increasing K at 1500–1800 UTC (Fig. 5).

Winds over Oklahoma suddenly intensify greatly (e.g., from 45 to 65 m s\(^{-1}\) at Gage) between 1800 and 2100 UTC with the increasing areal coverage of convection (Fig. 4). Pressure–time cross sections at Gage (GAG) and Oklahoma City (OKC) (Fig. 6) show that these variations are most prominent near 200 mb. In terms of kinetic energy, increases greater than 80 W m\(^{-2}\) occur northeast of the most intense storms (Fig. 5), while there are decreases to their southwest, corresponding to the speed minimum on the jet chart (Fig. 4). The newly developed speed maximum appears to move into Kansas at 0000 UTC 11 April (Fig. 4), although this is somewhat speculative due to the absence of a key wind report for northern Kansas at 2100 UTC. Decreases in both speed and vertically integrated kinetic energy (Fig. 5) are evident over northern Oklahoma between 2100–0000 UTC. A second, but weaker area of energy increases occurs near the convection that spawns the Wichita Falls tornado near 0000 UTC, while there are energy decreases over central Texas as the subtropical jet diminishes. The most pronounced variation between 0000 and 0300 UTC is the decrease in winds and energy over Kansas that is associated with the exit of the first wind perturbation from the domain.

Continued storm development occurs over Texas and Oklahoma between 0000 and 0600 UTC, and jet level isotach patterns (Fig. 4) undergo striking changes. Specifically, between 0300 and 0600 UTC, winds strengthen as much as 35 m s\(^{-1}\) over the panhandles.

4. Upper level wind variability

Complex upper level wind variations are a fascinating aspect of the AVE-SESAME I period. To facilitate and rotational components using the Endlich (1967) scheme. Trial energy budget calculations were made using \(V_D\) that had been adjusted for consistency with vertical motion and divergence from the O’Brien (1970) scheme. Since there was no major effect on results, however, the original form of \(V_D\) was employed in the computations reported here. Horizontal and vertical derivatives were computed using centered finite differencing where possible, while time derivatives were calculated as differences between consecutive sounding times. Energy budget terms were integrated over 50 mb layers, and, for calculating DD and DR as residuals, terms not involving time derivatives were averaged over consecutive times.
Fig. 4. Jet level charts for the AVE-SESAME I period where flags represent 50 m s$^{-1}$ and long (short) barbs denote 10 m s$^{-1}$ (5 m s$^{-1}$). Maximum winds (m s$^{-1}$) at or above 400 mb are plotted and analyzed. Radar echoes (VIP 3 level or greater) also are shown (scalloped).
Fig. 5. Local change of kinetic energy (EK) for the 400-100 mb layer during AVE-SFAME I. Values are W m⁻². Radar echoes (VIP 3 level or greater) indicated by shading, are for the ending time of each 1 h period. Outlined regions are for energy budgets presented in Fig. 9.
of Texas and Oklahoma, and associated positive DK exceeds 100 W m$^{-2}$ (Fig. 5). Strongest winds occur near 300 mb (Fig. 6). Conversely, jet level winds over eastern Oklahoma weaken approximately 10 m s$^{-1}$, resulting in a vertically integrated kinetic energy decrease reaching $\approx 80$ W m$^{-2}$. The maximum/minimumcouplet of energy changes for this period is similar to that observed between 1800 and 2100 UTC, but with a different orientation.

Storms develop east of Midland, Texas, at approximately 0300 UTC, and a positive center of DK is located nearby for the 0300–0600 UTC period (Fig. 5). Strongest winds at 0900 UTC are 80 m s$^{-1}$ at Midland (Fig. 4). Between 0600 and 0900 UTC, DK greater than 120 W m$^{-2}$ (Fig. 5) continues northwest of the convection that now stretches from Illinois into southwest Texas. Finally, at 1200 UTC 11 April, strongest winds are centered over the Texas-Oklahoma border (Fig. 4).

The pronounced wind/energy fluctuations occurring between 1800–2100 UTC and 0300–0600 UTC (Figs. 4–5) now will be examined in greater detail. The following paragraphs describe our hypothesis that the fluctuations are not due solely to advection of preexisting features, or due to data uncertainty, but instead can be at least partially attributed to feedback from the storm areas.

Based on Fig. 2 and the previously cited references for synoptic discussions, it is clear that a major jet streak is located over northern Mexico at the start of the experiment period. Its role in producing the observed wind speed variability must be examined. Figure 6
contains pressure-time cross sections of wind speed for four stations in southwestern Texas that are upwind of the sites exhibiting the major fluctuations: El Paso (ELP), Marfa (MRF), Midland (MAF), and Del Rio (DRT). The 65 m s\(^{-1}\) value seen over western Oklahoma at 2100 UTC (Fig. 4) is not observed prior to that time at Marfa. Although El Paso, Midland, and Del Rio have speeds near 60 m s\(^{-1}\) at 1800 UTC, values at stations between Gage and Midland (e.g., Amarillo, Childress and Morton, Texas) never reach 60 m s\(^{-1}\) prior to 2100 UTC (Fig. 4). Also, rather than exhibiting the oscillations of 10–20 m s\(^{-1}\) that are observed over Oklahoma, winds at the upwind sites before 2100 UTC are relatively constant. Thus, speed fluctuations near the Texas-Oklahoma panhandles at 2100 UTC do not appear to be due to convection, with the larger-scale jet streak still located southwest of the area.

Concerning the 0000–0600 UTC period, the 80 m s\(^{-1}\) value observed over western Oklahoma at 0600 UTC (Fig. 4) is not observed previously in the upwind sites (Fig. 6). However, the jet streak over northern Mexico (Fig. 2) could have moved northeastward into the area during the 18 h period, and the convection might have amplified values within the streak from those observed upwind.

The role of data limitations in producing the wind fluctuations also must be considered. Kurihara (1961) and Fuelberg (1974) have shown that uncertainty in rawinsonde-derived winds is inversely proportional to pressure and sonde elevation angle. In the current case, elevation angles above 300 mb frequently are less than 10° over Oklahoma and southwestern Texas (Arnold et al. 1981), and resulting root-mean-square errors were estimated to reach 15 m s\(^{-1}\) for speed and 20° for direction. Our own examination of the current soundings, however, suggests that these values probably are the extreme limit and are only infrequently encountered. Although this type of uncertainty is usually considered to be random in character, Fig. 4 indicates that most of the isochot and DK features described earlier have reasonable continuity and coherence. Furthermore, computational procedures used to calculate DK should lessen the influence of the error that is present. Specifically, the winds at 50 mb intervals used to obtain K and its budget terms were arithmetic averages of values 25 mb above and below (Fuelberg and Jedlovec 1982). Since the effect of low sonde elevation angle is to produce large vertical variations in horizontal speed (Fuelberg 1974), this filtering, as well as the vertical integration of filtered winds to produce K (e.g., for the 400–100 mb layer) should help to suppress the effect of speed uncertainty.

To assess the role of rawinsonde data error on patterns of DK, a sensitivity analysis was performed. The procedure was identical to that employed by BF and Fuelberg and Jedlovec (1982) and similar to those of Robertson and Smith (1980) and Vincent and Chang (1975). Briefly stated, wind errors were simulated by introducing computer generated random perturbations into the original soundings, i.e., before any filtering or the objective analysis. Ten different sets of perturbed soundings were prepared with assumed errors reaching 10 m s\(^{-1}\) at the highest levels. The altered soundings then were used as though they were original data. To quantify the sensitivity of DK patterns in the 400–100 mb layer, linear correlation coefficients between the original and ten perturbed fields were calculated. Results ranged between 0.71 and 0.84 (not shown), but even the field having the lowest correlation showed good visual similarity with the original (not shown). Thus, we believe that the DK fluctuations observed near the convection are real and not due primarily to wind error. Although the role of missing wind observations in producing the DK fluctuations was not examined formally, Figs. 4–5 suggest that it too is not a major factor.

The second case to be examined, 24–25 April 1975 (the AVE IV Experiment), was one of the initial MCC cases to be documented (Maddox 1979; Maddox et al. 1981). Therefore, only highlights of the wind variations are presented here. On each of two days, an MCC reached maximum intensity near 0600 UTC. Jet level charts for these and nearby times are shown in Fig. 7 (only 6 h data were available), while Fig. 8 contains fields of DK integrated over the 400–100 mb layer. At 0000 UTC, i.e., prior to greatest convection on each day, there is no pronounced jet activity; however, as the storms intensify during the next 6 h, winds north of the convection increase as much as 20 m s\(^{-1}\) forming pronounced speed maxima. Rates of energy increase (DK) reach 60 W m\(^{-2}\) on each day (Fig. 8). For the 0000–0600 UTC period on 24 April, the region of greatest positive DK is located over Michigan, at the northern edge of the storms, but it subsequently moves to northern Illinois by 1200 UTC. Since all convection over the area develops at approximately the same time, initial effects from the southern region of storms possibly are overwhelmed by the shortwave in the area (Fig. 3). Decreasing winds and energy on both days generally are located southwest of the positive centers as observed in a composite study of MCCs (Fritsch and Maddox 1981a). One should note that these wind/energy fluctuations are similar to those for the SESAME case (Figs. 4–5).

Cold air advection into the upper level lows could produce in situ development of the wind maxima. In both cases, however, an examination of thickness and temperature patterns provides little support for that hypothesis. Instead, the apparent local developments observed during AVE IV and AVE-SESAME I appear to be linked to storm related processes. In this regard, mesoscale numerical models have reproduced the wind maxima observed near MCCs and have been a valuable tool toward understanding their formation. For example, Fritsch and Maddox (1981b) and Fritsch and Brown (1982) have demonstrated the importance of
latent heat release and associated vertical motion. Other numerical simulations of convectively induced wind perturbations include Chang et al. (1982, 1984). Concerning the AVE IV period, Maddox et al. (1981) modelled the case with and without latent heat release and concluded that observed atmospheric variability was consistent with feedback from the storm complexes.

Unlike the AVE IV period, it is more difficult to confirm suspected relationships between convection and wind variations during AVE-SESAME I because there is a well-defined preexisting jet stream along with other strong dynamic features. Nonetheless, the wind fluctuations are similar to those modelled and observed previously, albeit at a reduced scale. Also, Fuelberg and Printy (1983, 1984) observed similar changes at a still smaller scale, i.e., based on sonde data at 75 km spacing. Furthermore, even though the storm areas during AVE-SESAME I do not meet the size and duration requirements of MCCs (Maddox 1980), environmental changes in addition to the winds are consistent. For example, there is cooling at 200 mb over the storm region (not shown), and there are systematic variations in nearby vertical motion, low level convergence, and upper level divergence (Moore and Fuelberg 1981).

Numerical modeling with and without latent heat release is required to verify our hypothesis relating the SESAME wind fluctuations to the convection. Unfortunately, to the authors' knowledge none of the various model studies of 10–11 April 1979 has examined the upper level wind perturbations in detail (Benjamin and Carlson 1986; Kalb 1985; Kaplan et al. 1982; Zack and Kaplan 1987). However, Anthes et al. (1982) do briefly mention an “anticyclonic mesoscale jet” with a speed of 39 m s⁻¹ that was modeled at 300 mb along the Red River Valley, just north of a forecast convection area. Although forecast winds were too weak, the authors noted similarity to actual conditions and the observations of Ninomiya (1971b) and Maddox et al. (1981).

To summarize, available results do not conclusively establish a cause–effect relation between the convection and wind fluctuations during AVE-SESAME I. Nonetheless, even though part of their development likely is due to dry processes, the intense convection should have at least provided an added mechanism for further strengthening.

5. Upper level energetics

To further explore the upper level wind perturbations, KR and KD budgets were computed for the 400–100 mb layer. Budget areas for the perturbations are indicated in Fig. 5, where IN21 denotes the region of increasing speed between 1800 and 2100 UTC 10 April and IN06 is a corresponding region for 0300–0600 UTC 11 April. The energy terms originally were calculated on horizontal grids encompassing the two net-
works; thus, the subvolume budgets simply are averages of grid values on or within the outlined regions. Results are shown schematically in Fig. 9 while the key is in Fig. 1.

The maximum contribution to K at 400–100 mb in either area of increasing winds is provided by KR (Fig. 9). On the other hand, VRVD accounts for less than 10% of K, and KD less than 2%. Increasing K (i.e., DK) is very large in each case due to the selection criteria for the limited regions. Although the change in KD (DKD) is very small, the presence of V_D is felt through interaction term DVRVD which comprises approximately 40% of DK.

Energy conversions and transports affecting KD are nearly identical in regions IN21 and IN06 (Fig. 9). For example, the dominant source of KD is cross-contour conversion from A (13.14 W m\(^{-2}\) for IN21 and 30.94 W m\(^{-2}\) for IN06). Also, the greatest sink of KD is conversion into KR (9.60 and 32.25 W m\(^{-2}\), respectively). Finally, sinks by dissipation (DD) and horizontal export (HFD) are nearly balanced by the source from vertical motion (VF). In spite of these major transports and conversions, KD changes little, thereby confirming its role as a “catalyst” in converting A into KR (Chen and Win-Nielsen 1976).

Considering the KR budgets (Fig. 9), sources greatly dominate the sinks. The greatest sink is dissipation (DR), while the loss through INTR indicates that V_D can detract from KR in a way that is not ordinarily considered a conversion. A similar, but less significant effect occurs in the KD budget. As noted earlier, these terms integrate to zero in a global domain. The greatest source of KR is horizontal import (HFR), with smaller contributions by conversions from A (Term GR) and KD [Term C(KD, KR)].

Additional insight into C(KD, KR) is obtained by considering its four components (Table 1). As found previously in hemispheric (Chen and Win-Nielsen 1976) and monsoon (Krishnamurti and Ramanathan 1982) studies, Term Af is the greatest contributor in both areas of positive DK, while Terms Az and B are either the second or third greatest, depending on the case. Since Af is positive, positive Az indicates cyclonic flow, whereas ascending motion over the area (see Fig. 7 of Moore and Fuelberg 1981) contributes to negative B. Term C is the smallest of the three entries.

The importance of V_D to the energy balance of the speed maxima can be estimated through the procedure.

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**Table 1. Average of conversion terms C(KD, KR) for limited regions enclosing developing wind speed maxima. Locations of limited regions are shown in Figs. 5 and 8. Values are in W m\(^{-2}\) where positive represents transfers from KD to KR.**

<table>
<thead>
<tr>
<th>Region</th>
<th>Layer (mb)</th>
<th>Af</th>
<th>Az</th>
<th>B</th>
<th>C</th>
<th>C(KD, KR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN21</td>
<td>400-100</td>
<td>9.48</td>
<td>1.17</td>
<td>-1.26</td>
<td>0.21</td>
<td>9.60</td>
</tr>
<tr>
<td>IN06</td>
<td>400-100</td>
<td>21.83</td>
<td>15.27</td>
<td>-6.40</td>
<td>1.65</td>
<td>32.35</td>
</tr>
<tr>
<td>IN24</td>
<td>400-100</td>
<td>19.61</td>
<td>-2.55</td>
<td>-4.17</td>
<td>0.16</td>
<td>13.05</td>
</tr>
<tr>
<td>IN25</td>
<td>400-100</td>
<td>18.43</td>
<td>-6.72</td>
<td>-1.33</td>
<td>-0.99</td>
<td>9.39</td>
</tr>
<tr>
<td>LLJ</td>
<td>SFC-700</td>
<td>6.98</td>
<td>-0.64</td>
<td>-2.27</td>
<td>-0.10</td>
<td>3.97</td>
</tr>
</tbody>
</table>

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**Table 2. Kinetic energy budgets for the 400–100 mb layer of developing wind speed maxima after omitting the divergent wind component. Locations of limited regions are shown in Figs. 5 and 8. Values are in W m\(^{-2}\).**

<table>
<thead>
<tr>
<th>Region</th>
<th>Layer (mb)</th>
<th>DK–DK'</th>
<th>DK</th>
<th>DK'</th>
<th>HFRR</th>
<th>GR</th>
<th>DR</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN21</td>
<td>400–100</td>
<td>16.88</td>
<td>51.49</td>
<td>34.61</td>
<td>41.77</td>
<td>20.38</td>
<td>-27.54</td>
</tr>
<tr>
<td>IN06</td>
<td>400–100</td>
<td>24.93</td>
<td>38.19</td>
<td>13.26</td>
<td>77.83</td>
<td>1.78</td>
<td>-66.35</td>
</tr>
<tr>
<td>IN24</td>
<td>400–100</td>
<td>-4.72</td>
<td>15.34</td>
<td>20.06</td>
<td>-12.60</td>
<td>9.84</td>
<td>22.82</td>
</tr>
<tr>
<td>IN25</td>
<td>400–100</td>
<td>6.41</td>
<td>20.90</td>
<td>14.49</td>
<td>3.91</td>
<td>-9.63</td>
<td>20.21</td>
</tr>
<tr>
<td>LLJ</td>
<td>SFC–700</td>
<td>10.21</td>
<td>21.27</td>
<td>11.06</td>
<td>2.29</td>
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<td>-4.70</td>
</tr>
</tbody>
</table>
Fig. 10. Horizontal field of $V_y$ at 0600 UTC 11 April for the 300 mb level. Isopleths contours of geostrophic and mean sea level pressure are superimposed. Other panels are horizontal fields of energy budget terms (W m$^{-2}$) for the -400-300 mb layer at 0600 UTC 11 April (or 0300-0600 UTC for D/V/ID). Radar echoes (VIP level or greater) are also shown (scalloped).
of Chen et al. (1978) in which no conversions or interactions involving it are permitted. Table 2 gives results for IN06 and IN21 where DK', indicating omission of $V_D$, is computed as a residual from the three rightmost terms. The symbol, HFRR, denotes $-\nabla \cdot k_R V_R$. Since DK - DK' can be interpreted as the deficit in the rate at which energy is supplied by neglecting $V_D$, it is clear that omission would seriously underestimate the increasing K. For example, in region IN06, DK would be only 13.26 W m$^{-2}$, instead of the observed 38.19 W m$^{-2}$, a difference of 24.93 W m$^{-2}$. Thus, as noted by Chen et al. (1978) and Fuelberg and Browning (1983), it is vitally important that numerical models seeking to represent storm–environment interactions accurately portray the divergent wind.

The $V_D$ plays an integral role in the wind perturbations; therefore, it is instructive to consider its horizontal patterns as well as those of related budget terms. Figure 10 contains these fields at 0600 UTC 11 April. Since precipitation rates during the current case frequently exceed 6 mm h$^{-1}$ (Fuelberg et al. 1985), it is not surprising to find a pronounced $V_D$ pattern at 300 mb (Fig. 10). Specifically, upper tropospheric flow is directed outward from the storms over southeastern Oklahoma. Although changes in KD (DKD) were found to have little impact on DK (Fig. 9), variations in DVRVD were significant. In fact, Fig. 10 shows that its pattern is similar to that of DK (Fig. 5).

The energy analyses (Fig. 10) indicate that regions northwest of the convection are preferred for the development of upper level speed maxima. For example, generation of divergent kinetic energy (GD) in that area averages 30.94 W m$^{-2}$ within IN06 (Fig. 9). The location of positive GD depends on the orientation of the convection with respect to the flow. In the current case, with convection parallel to the winds (Figs. 2, 4), KE generation occurs to the left when looking downstream. Conversely, there is destruction southeast of the storms where K is decreasing (Fig. 5). In addition to enhancing $V_D$, convection has been found to induce higher pressure in the upper troposphere (e.g., Fritsch and Maddox 1981a; Fritsch and Brown 1982; Fuelberg and Printy 1983), also leading to the couplet of positive/negative GD. During the current case, however, it is very difficult to locate these height variations. Considering the direct conversion between KD and KR, i.e., C(KD, KR) in Fig. 10, patterns of the Af component are very similar to those of GD because $V_R$ approximately parallels the height contours (see explanation at end of section 2). Thus, areas where $V_D$ acts to increase KD by conversion from A also are areas where KD is converted to KR.

Patterns of Term Az (Fig. 10) are similar to those of Af since there is strong positive vorticity over the domain. Vorticity is greater than f along the border of New Mexico and the Texas Panhandle, causing Az to exceed Af. Since maximum Az in this region is comparable to maximum Af over northern Oklahoma, it is clear that Az can play a major role in the overall conversion within localized co-located regions of strong vorticity and divergence. This significance of Az contrasts with findings for the hemispheric scale where it was found to be negligible (Chen and Wiin-Nielsen 1976).

The B component of C(KD, KR) will be negative (positive) in regions of ascent (subsidence) (Fig. 10) because $k_R$ increases with height through most of the 400–100 mb layer. Thus, strong ascent in the convective areas leads to conversion from KR to KD (i.e., negative values). Conversely, there is subsidence and conversion to KR centered over the Oklahoma panhandle where the speed maximum is developing (Fig. 5). The negative entry in Table 1 results from the majority of IN06 being located within the area of negative B. Patterns of Term C are not shown because magnitudes are very small (Table 1). Therefore, since B is smaller than Af and Az, the latter two terms dominate the field of overall conversion [C(KD, KR) in Fig. 10] in which the main feature is a center of KD to KR transfer that is approximately co-located with the region of increasing winds (IN06 in Fig. 5). As noted earlier, this also is the location of maximum GD conversion from A to KD. Thus, the area northwest of the storms is where maximum available potential energy is converted into rotational kinetic energy. Southeast of the storms where K is decreasing (Fig. 5), there is an opposite energy cycle, i.e., C(KD, KR) transforms KR into KD, and GD converts KD into A.

Energetics of the wind perturbations associated with the two MCCs of AVE IV (Fig. 11) will be compared with those of AVE-SESAME I (Fig. 9). The two limited regions (IN24 and IN25) are shown in Fig. 8. Unfortunately, the speed maximum that developed between 0000 and 0600 UTC 24 April (Fig. 8) was located on the northern edge of the data domain where the objective analyses are less reliable. However, since winds north of the MCC continued to increase between 0600 and 1200 UTC in a more interior location, that region is used for the discussion that follows.

Energy conversions and transports for the speed maxima during AVE IV (Fig. 11) have both differences and similarities with those of AVE-SESAME I (Fig. 9). Kinetic energy content for the 400–100 mb layer still is dominated by KR, and once again, the large positive time derivatives of KR and VRVD constitute a major percentage of the overall K increase (DK is 15.34 and 20.90 W m$^{-2}$). The change of KD is comparatively small and positive for IN25 but slightly negative for IN24, perhaps because the nearby MCC already had begun to weaken.

With the KR budgets (Fig. 11), dissipation (DR) is the greatest source, suggesting energy transfer from unresolved to grid scale motions (Smith and Adhikary 1974; Vincent and Schlatter 1979). Conversion from KD [Term C(KD, KR)] again is an important source while cross-contour generation by $V_R$ is a source to
IN24, but a sink to IN25. Other common sinks to both experiments are HFR and INTR. A closer examination of C(KD, KR) (Table 1) shows that Af again is dominant. Since the wind perturbations develop anticyclonic flow (Fig. 7), apparently a common occurrence with MCCs (Fritsch and Maddox 1981a), Az is negative and somewhat smaller than Af. Ascending motion again causes negative B while Term C continues to be small. The overall conversion from the four components is toward increasing KR at the expense of KD, similar to that found for the SESAME regions.

The KD budgets (Fig. 11) are dominated by the source from cross-contour generation. Thus, as observed with IN06 and IN21, A is transformed into KR via KD whose value changes little. Vertical transport from lower levels still is a significant source to KD in the 400–100 mb layer while KD sinks are due to C(KD, KR) (discussed earlier), horizontal export, and INTD. Dissipation is positive in one area and negative in the other. Finally, if Vf were eliminated from consideration (Table 2), the increasing K observed in IN25 would have been underestimated by 6.41 W m⁻². On the other hand, there would have been an overestimate on 24 April. This surprising result may be due to the decreasing storm intensity that was noted earlier.

The above comparisons emphasize that no unique balance of energy sources and sinks characterizes the apparently convectively induced upper level wind maxima. Of course, convection itself may form in a variety of thermal, moisture, and flow fields. On the other hand, the major common aspect to the energetics is strong conversion from A to KD to KR.

6. Low-level jet stream

Low-level jet streams (LLJs) commonly are associated with severe storm outbreaks (e.g., Bonner 1966; Miller 1972). Fuelberg and Jedlovec (1982) calculated the K budget for a low level jet during AVE-SESAME I; however, to the authors' knowledge, no other energy studies have been performed, including none of KR and KD.

The evolution of the LLJ during AVE-SESAME I can be seen in Fig. 12 which gives the strongest reported wind between the surface and 700 mb at each station. Corresponding maps of integrated DK are shown in Fig. 13. At 1500 UTC (Fig. 12), there is no well defined jet axis, and most speeds are less than 20 m s⁻¹. By 1800 UTC, strongest winds stretch from New Mexico into Kansas; however, Moore and Fuelberg (1981) noted that this southwesterly flow near 700 mb probably is a downward extension of the upper level jet (Fig. 4). An area of southerly flow reaching 22 m s⁻¹ begins to develop over central Texas and Louisiana by 1800 UTC, with corresponding DK as great as 15 W m⁻² (Fig. 13), and this region appears to be the incipient LLJ. Energy increases continue at 2100 UTC when DK exceeds 20 W m⁻² near the Red River Valley and strongest winds are 25 m s⁻¹ at approximately 800 mb. Speeds increase during the ensuing hours, reaching 32 m s⁻¹ at 0000 UTC and 37 m s⁻¹ at 0300 UTC, after which time they decrease slightly. Greatest DK is 60 W m⁻². The jet axis moves eastward throughout the period, being located over Arkansas at the final time.

Area averaged energy budgets of the LLJ were based on grid points where DK > 15 W m⁻² in the surface–700 mb layer. There were no such points in the 1200–1500 UTC period (Fig. 13), and we did not go beyond the 0000–0300 UTC interval because considerable positive DK extended outside the analysis area. Only contiguous grid points comprising the jet were included. Since the budgets were very similar at the four times, results were combined into a single diagram (Fig. 14).

As observed with the AVE-SESAME upper level speed maxima (Fig. 9), KR within the LLJ (Fig. 14) comprises approximately 90% of K, with KD and VRVD each only contributing about 5%. Similarly, DK consists mostly of DK (71%), but 25% is from DVRVD and 4% from DKD. The nature of the KR energy budget also is similar to that of the upper level maxima, i.e., sources are provided by GR, HFR, and C(KD, KR), with sinks by INTR and DR.

There are several differences between KD budgets of the upper and lower level wind maxima (Figs. 9, 14). Since there is ascending motion over both areas, VF is a sink to the LLJ, and there is horizontal energy...
Fig. 12. Low-level jet charts for the AVE-SEASAME I period. Maximum winds between the surface and 700 mb are plotted and analyzed in m s$^{-1}$, where flags represent 25 m s$^{-1}$ and long (short) bolds represent 5 m s$^{-1}$ (2.5 m s$^{-1}$). Radar echoes (VIP level or greater) also are shown (scalloped).
FIG. 13. Local change of kinetic energy (DK) for the surface–700 mb layer during AVFM/ESAME I. Values are W m$^{-2}$. Radar echoes (VIP 3 level or greater) also shown (scallop).
Fig. 14. Energy budgets for the LLJ in the surface–700 mb layer. See Fig. 1 for key. K, KR, KD, and VRVD are in $10^4$ J m$^{-2}$, while all others are in W m$^{-2}$. The domain for averaging included grid points (Fig. 13) where DK > 15 W m$^{-2}$; see text for further details.

The overall nature of energy conversions is similar for the upper and lower regions (Figs. 9, 14). Specifically, divergent generation from A is the greatest source of KD, and KD is an important source of KR via C(KD, KR). Table 1 shows that A is the greatest contributor to the conversion which is similar to that aloft. Similarly, Term B, describing the vertical exchange of rotational momentum, is the greatest negative contributor. It should be noted that the LLJ does not possess a well defined level of maximum speed at many sites. Instead, values often increase rapidly just above the surface and then remain nearly constant through 700 mb. KD again acts as a type of “catalyst” since its own value changes little (Fig. 14). If $V_D$ were not present (Table 2), DK would be underestimated by 10.21 W m$^{-2}$, having only 52% of its observed rate of increase. Thus, $V_D$ is important to the developing low level speed perturbation as it is to the upper level variety. Finally, to complete the energy conversion process of Fig. 14, cross-contour flow by $V_R$ is the greatest source to KR.

Horizontal maps of selected energy budget terms at 0000 UTC (Fig. 15) indicate that the LLJ is a center of energy conversion for the surface–700 mb layer. The panel containing $V_D$ and height contours at 700 mb reveals an opposite orientation to that found in the 400–100 mb layer (Fig. 10). Specifically, low-level convergence encompassing the convection over the Red River Valley causes $V_D$ southeast of the storms to flow in the direction of lower heights, thereby generating KD, whereas the reverse occurs to the northwest (Fig. 15). Moore and Fuelberg (1981) noted strong surface pressure falls in the convective region (their Fig. 8), and these would enhance cross-contour flow and GD. It is not clear, however, what portion of the falls is attributable to latent heat release in the way described by Ninomiya (1971b) and Aubert (1957). Although peak GD (30 W m$^{-2}$) is less than one-third that observed at the upper levels (140 W m$^{-2}$, Fig. 10), it approximates the total conversion (GD + GR) observed in the upper levels of some major cyclones (e.g., Ward and Smith 1976). Finally, concerning KD-KR conversion (Fig. 15), patterns of A and again are similar to those of KD, and it dominates the overall conversion [C(KD, KR)] although the influences of B and A also are evident.

Ninomiya (1971b) proposed a synergistic relationship between low-level jet streams and convective activity based on observed data. Applicability to the current case is supported by mesoscale modelling results (Anthes et al. 1982; Zack and Kaplan 1987) and by limited observational evidence. During the current SESAME period, the hypothesized process begins with the LLJ transporting heat and moisture northward and helping establish the low level convergence that “triggers” storm formation. The convergence already present then appears to be enhanced by the storms (see Fig. 7 of Moore and Fuelberg 1981). Thus, even though the LLJ may be linked to its upper level counterpart since it begins to form before the convection (Uccellini and Johnson 1979), storm enhanced $V_D$ and divergent generation may be significant factors leading to further LLJ development. The strengthened jet, in turn, may assist future storm development. An analysis of isentropic effects induced by convective heating is needed to confirm this hypothesis for the AVE-SESAME I period.

7. Summary and conclusions

Wind perturbations associated with two cases of intense convection have been examined. In the upper troposphere, speed maxima were observed poleward of storm areas while minima were located to their south. Three-hourly mesoscale radiosonde data during the SESAME case revealed wind perturbations at smaller scales than can usually be documented with routine observations. Although advection of a preexisting major jet streak into the area and data uncertainty were factors in explaining the observed variability, continuity of the speed centers and their relation to the storm areas suggest that they were at least partially induced by the convection. Although strong preexisting forcing during the SESAME period makes it difficult to separate storm effects from those attributable to dry processes, similar storm/environment interactions have been observed previously, and they have been modeled numerically.
Fig. 15. As in Fig. 10, except at 0000 UTC 11 April for the 700 mb level and the surface-700 mb layer. Radar echoes (VIP level or greater) also are shown (shaded).
Budgets of KR and KD were used to better understand the upper level speed maxima. Although KD was only a small fraction of total K, it played a major role in the overall energy balance. In fact, if $V_D$ had been omitted from the budget, the rate of energy/speed increase would have been greatly reduced. In the areas of increasing speeds, it was found that available potential energy was converted into KR via KD, with KD acting as a “catalyst.” This is similar to that observed at the global scale (Chen and Wiin-Nielsen 1976). The conversion from A to KD occurred because of cross-contour flow by $V_D$ (Term GD). North of the storms, near the speed maxima, $V_D$ was streaming outward of the convective region, and height gradients were enhanced. Thus, GD was maximized. Conversion from KD to KR can be attributed to four component processes; however, in the region of increasing speeds, it was dominated by Term Af whose patterns and signs were similar to those of GD.

A low-level jet stream occurring during the AVESESAME case also was examined using the energy budget approach, and its energetics was greatly dependent on $V_D$. Once again, cross-contour flow by $V_D$ toward lower heights converted A to KD, and the conversion from KD to KR was dominated by Term Af. Although the LLJ began to form prior to the convective outbreak and appeared to be coupled to the upper-level jet stream, its later development may have been aided by storm initiation. That is, the convection located west of the LLJ produced enhanced low level convergence and divergent flow as well as height falls, thereby creating greater GD and Af which were energy sources to the KR maximum, i.e., the LLJ.

Energy budget analysis is one of several ways by which convection can be observed to influence its environment. New mesoscale data sources such as satellites, Doppler radar, and profilers are beginning to add greatly to our knowledge of the various interplays between scales. It is an exciting period for meteorology.

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