A Kinetic Energy Analysis of the Meso $\beta$-Scale Severe Storm Environment

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ABSTRACT

An area of intense thunderstorms occurred within the special rawinsonde network collecting data on 20–21 May 1979, the fifth day of the Atmospheric Variability Experiment-Severe Environmental Storms and Mesoscale Experiment (AVE-SESAME). The data are at the meso $\beta$-scale, i.e., 75 km spacing and 3 or 1.5 h intervals. They are used to perform a kinetic energy analysis of the near storm environment. The mesoscale storm environment is characterized by cross-contour generation of kinetic energy, transfers of energy to nonresolvable scales of motion (negative dissipation), horizontal flux divergence and upward transport of energy. These processes are maximized within the upper troposphere and are greatest during times of strongest convection. Current mesoscale values are much larger than previous results based on synoptic-scale data.

Energy budgets are obtained at 3 h intervals from the routine National Weather Service rawinsonde network. A comparison of results from the same analysis region, but derived from the two different resolutions, reveals several common features. Complex vertical variations in winds (energy) over southeastern Oklahoma are also examined in detail. Motions not detected by the meso $\beta$-scale input data appear to play an important role in the energy balance of some layers. A sensitivity analysis is presented to quantify uncertainties in the energy budget terms.

1. Introduction

The study of energetics provides a fundamental approach for investigating the various scales of motion that occur in the Earth's atmosphere. Unfortunately, the scarcity of mesoscale data has limited most energy analyses to either the general circulation or synoptic-scale systems. Thus, relatively little is known about the energetics of important mesoscale phenomena, such as areas of intense convection, which are embedded within the larger-scale flow.

The synoptic-scale kinetic energy balance of extratropical cyclones containing convective outbreaks has been investigated by Fuelberg and Scoggins (1978), Vincent and Schlatter (1979), Robertson and Smith (1980) and Fuelberg and Browning (1983). Results have documented large conversions and transports of energy within the storm environments and have suggested that intense convection can alter the synoptic-scale kinetic energy balance through feedback mechanisms.

Few kinetic energy analyses have been performed on the mesoscale convective environment. Using meso $\alpha$-scale rawinsonde data [250 km spacings and 3 h intervals (Orlanski, 1975)] from the 1979 Atmospheric Variability Experiment-Severe Environmental Storms and Mesoscale Experiment (AVE-SESAME '79), Fuelberg and Jedlovec (1982) diagnosed kinetic energy variations associated with the Red River Valley tornado outbreak (10–11 April 1979). Many organized convective systems occur at the meso $\beta$-scale, having wavelengths of 20–200 km and periods from several hours to one day (Orlanski, 1975). The only energy budget studies of the meso $\beta$-scale storm environment appear to be those of McInnis and Kung (1972), Kung and Tsui (1975) and Tsui and Kung (1977). Their investigations utilized rawinsonde data from the National Severe Storm Laboratory (NSSL) having an average station spacing of 85 km and a time interval of 1.5 h. Although magnitudes of mesoscale energy processes varied considerably depending on the presence and strength of the convective storms, values in some cases were an order of magnitude larger than those reported at the synoptic scale.

The purpose of this paper is to examine the kinetic energy balance of the meso $\beta$-scale severe storm environment during the fifth day of AVE-SESAME '79 (20–21 May). In contrast to the three aforementioned mesoscale studies by Kung and associates, which emphasized a collection of days, the current investigation is a detailed analysis of a single 24 h period. The energetics are examined prior to, during, and after a convective outbreak over Oklahoma in order to relate energy fluctuations to storm activity. In addition, since data were simultaneously collected at both the synoptic and meso $\beta$-scale during AVE-SESAME V, we have a rare opportunity to compare the energetics of the same analysis region derived from different scales of resolution. It should be emphasized that our goal is to describe the storm environment rather than the individual convective elements.

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2. Methodology

a. Theoretical development

The theory used in large-scale energy analyses can be extended to the meso $\beta$-scale storm environment because both synoptic-scale motions and subsynoptic-scale motions outside of convective cells are quasihorizontal (Kung and Tsui, 1975). We used the kinetic energy budget equation for a fixed, limited volume in the isobaric coordinate system, which is given by Ward and Smith (1976) as

$$\frac{\partial K}{\partial t} = \int \int - \mathbf{v} \cdot \nabla \phi - \int \int \mathbf{v} \cdot \mathbf{k} \mathbf{v} - \int \int \int \frac{\partial \mathbf{w}}{\partial p} + \int \int \mathbf{v} \cdot \mathbf{F} \int \int k_0 \frac{\partial \rho_0}{\partial t},$$

where,

$$\int \int = \frac{1}{g A} \int \int \int dx \ dy \ dp,$$

$V$ is horizontal wind velocity, $\omega$ vertical motion in isobaric coordinates, $k = (u^2 + v^2)/2$ horizontal kinetic energy per unit mass, $K = \int \int \mathbf{k}$, $\phi = gz$ geopotential height, $F$ the friction force, $A$ the computational area and subscript zero surface values.

Local changes of kinetic energy, Term (A) above, are due to five energetic processes [Terms (B) through (F)]. Term (B) represents generation of kinetic energy by cross-contour flow. Terms (C) and (D) denote horizontal and vertical components of flux divergence, respectively. Term (F) represents variations in kinetic energy due to changes in mass of the volume being studied. In this study, surface pressure variations associated with the storm outbreak were much greater than the usual diurnal fluctuations. Nonetheless, the magnitude of Term (F) was found to be several orders of magnitude smaller than those of the other terms and will, therefore, not be considered further. Finally, Term (E) conceptually represents frictional processes. Since it cannot be adequately treated explicitly, it is computed as a residual to balance the other terms in (1). Thus, the residual represents not only frictional processes, but also transfers of energy between resolvable and unresolvable scales of motion (Smith and Adhikary, 1974), and possible errors from the calculations of the other terms. It is commonly called the “dissipation” term.

b. Data

The fifth period of AVE-SESAME '79 (AVE-SESAME V) extended from 1100 GMT 20 May through 1100 GMT 21 May. Meso $\beta$-scale rawinsonde data were gathered from 19 sites in Oklahoma and Texas (Fig. 1) at 3 h intervals. Special 1.5 h soundings were taken at 2130 GMT 20 May. The average station spacing was approximately 75 km. In addition, 23 National Weather Service (NWS) sites surrounding the mesonetwork (Fig. 1) also collected data every 3 h. These stations had the conventional synoptic-scale spacing of 400 km. Tabulated rawinsonde data at 25 mb intervals are given by Sienkiewicz et al. (1981), while additional details about AVE-SESAME '79 are found in Albery et al. (1979), Hill et al. (1979) and Barnes (1981).

c. Analytical procedures

Analytical procedures are based on Fuelberg and Jedlovec (1982). Since their specific application to

![Map of rawinsonde networks participating in the fifth day of AVE-SESAME '79. The top diagram shows synoptic-scale sites and the bottom gives the special network. Locations of the special sites are given in Fuelberg and Printy, 1983. Outlines (bottom diagram) indicate the $15 \times 13$ analysis region (outer), the overall energy averaging region (middle) and the subvolume encompassing the upper-level wind couplet (inner).]
the current period is described by Fuelberg and Printy (1983), only highlights will be presented here. The first step was to carefully check all rawinsonde data for abnormal characteristics. Special attention was given to soundings thought to have questionable geopotential heights and to those arising from sondes experiencing variable ascent rates (Sienkiewicz et al., 1981). The data that appeared erroneous and, therefore, were not used in subsequent calculations are listed by Fuelberg and Printy (1983). The data that were utilized appeared representative of the meso β-scale storm environment where hydrostatic conditions are assumed.

To account for nonsimultaneous sonde releases and variable ascent rates, data at each level were adjusted to a common time using a linear interpolation scheme similar to that of Fankhauser (1969). To generate values for missing data, linear time interpolation at individual stations was used if the interpolation interval was 6 h or less. Approximately 15% of the total soundings used during the 24 h period were created in this way. If the data gap was greater than 6 h, no values were prepared, and the missing data were retained. The effect of this procedure is to provide needed information in cases where it can reasonably be determined. Since only a small portion of the data was generated, however, the resulting energy budget is not overly influenced.

After obtaining the time consistent data set, the meso β-scale values were objectively analyzed onto a 15 × 13 grid of 25 km mesh length (Fig. 1) by using the Barnes (1964) procedure. Gridded data fields were obtained at the surface and at 50 mb intervals from 900 to 150 mb. Missing data were too prevalent at 100 mb to permit analyses. Sonde locations at individual levels were used instead of surface station locations. In order to suppress inherent data errors, winds at individual 50 mb levels were arithmetic averages of values at that level and those at 25 mb above and below. The resulting data grids retained approximately 32% of originally resolved amplitudes at 150 km wavelengths, and 82% at 225 km wavelengths (two and three times the average station spacing). For the separate synoptic-scale calculations, the NWS rawinsonde data were objectively analyzed onto a grid having a 127 km spacing. Procedures were similar to those employed for the special data. However, in this case, response values at wavelengths of 800 and 1200 km were approximately 65 and 90%, respectively.

The kinematic method was used to compute all vertical motions. The surface boundary condition included pressure tendency, cross-isobaric flow, and terrain-induced vertical motion. Profiles of ω were adjusted to zero at 150 mb using O'Brien's (1970) procedure. Except for 1100 GMT 20 May and 1100 GMT 21 May, time derivatives needed in (1) were obtained from finite differences using values before and after the current observation. Trial calculations using forward and backward differences revealed that values of neither ∂K/∂t nor dissipation (computed as a residual) were greatly affected by the procedure employed. Finally, both horizontal and vertical derivatives were obtained from centered finite differences.

d. Error analysis

Effects of random errors in the rawinsonde data on the derived energy parameters were quantitatively assessed using deliberately perturbed data sets. The procedures utilized in this analysis, as well as detailed results, are presented in the Appendix. Briefly stated, results indicate that our computational procedures greatly reduce the effects of the inherent errors. Thus, random errors should not have a significant role in the results that follow.

3. Weather conditions

Synoptic conditions at the beginning of the period (1200 GMT 20 May) are shown in Fig. 2. At the surface, a cold front extended from the Great Lakes into the Ohio River Valley. From there it became

![Figure 2](image_url)

**Fig. 2.** Surface and 300 mb National Meteorological Center (NMC) analyses for 1200 GMT 20 May 1979. Isotachs (dashed) are in m s⁻¹.
stationary, winding through central Oklahoma and into New Mexico. Conditions in the upper troposphere were dominated by a cutoff low centered just south of Arizona and a short wave trough over the upper Midwest. Jet maxima were located over the Iowa-Minnesota border and over northern Mexico; however, light winds were observed over Oklahoma and northern Texas. Radar summaries (not shown) revealed convection north of the front, in the middle Mississippi River Valley and extending into eastern Oklahoma. These storms had moved out of Oklahoma by 1500 GMT.

Constant pressure maps for the meso \( \beta \)-scale region are shown in Fig. 3, while radar summaries are given in Fig. 4. At 1700 GMT, just prior to convective development, the 850 mb chart depicts a low over the Texas Panhandle and a slight ridge over central Oklahoma. Winds were weak but exhibited considerable cyclonic turning. The 200 mb height contours showed no major perturbations, and the southwesterly flow contained little diffuseness.

Convection over Oklahoma began shortly after 1700 GMT. At 1935 GMT (Fig. 4), an area of intense storms with echo tops reaching 17.7 km (58,000 ft)

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**Fig. 3.** 850 (left panels) and 200 (right panels) mb analyses. At 850 mb, contours (solid) are in 5 m intervals; 00 denotes 1500 m. At 200 mb, contours are in 20 m intervals; 20 denotes 12,240 m. Isotherms (dashed) are in °C. Winds are in m s\(^{-1}\) with short barbs denoting 5 m s\(^{-1}\). Surface station locations are given by circles, although data at 200 mb are plotted at sounding locations (indicated by crosses).
over Oklahoma, while the strongest storms were situated south of the special network.

Constant pressure maps (Fig. 3) reveal significant changes in atmospheric structure accompanying the storm activity. At 850 mb, height falls of 20 to 40 m were common over southeastern Oklahoma between 1700 and 2130 GMT. The result was a pronounced trough over the special data region. Strong convergence was also evident. At 200 mb, heights at several stations rose approximately 50 m in the same 4.5 h period to produce a well-defined mesoridge at 2130 GMT. Winds exhibited pronounced diffusion and strongly ageostrophic flow. Fuelberg and Printy (1983) noted that vertical motions at 400 mb reached $-60 \mu \text{b s}^{-1}$ at 2130 GMT. They also documented the formation of a jet-level wind maximum poleward of the storms in the extreme northwestern corner of the data region. In southeastern Oklahoma, however, 200 mb winds decreased during storm development, whereas values at 400 mb nearly doubled; this latter feature will be explored further in Section 7. Finally, at 0200 GMT (Fig. 3) maps suggest that the region was returning to prestorm conditions.

Detailed descriptions of thermodynamic and kinematic variations on 20–21 May also are given by Fuelberg and Printy (1983). Although the current storm area was too small and too short-lived to be classified as a Mesoscale Convective Complex (MCC), they concluded that fluctuations in temperature, height and winds were consistent with those previously observed with the complexes (Maddox, 1980; Fritsch and Maddox, 1981a). In addition, mesoscale modeling studies (e.g., Fritsch and Maddox, 1981b; Chang et al., 1982, 1984; Fritsch and Brown, 1982) have suggested that observed changes in the storm environment of AVE-SESAME V were attributable to feedback mechanisms from the convection.

4. Composite area–time averaged energetics

Grid point values of the energy budget were averaged over the middle area shown in Fig. 1. Area-averaged results for the ten observation times then were combined to produce the composite area–time averaged budget given in Table 1. Kinetic energy content of the surface to 150 mb column is $11.99 \times 10^5 \text{ J m}^{-2}$, with the major contribution from near the jet stream level. All layers experience a net decrease of kinetic energy during the 24 h period, with the vertical total being $-5.41 \text{ W m}^{-2}$. Cross-contour flow provides the greatest source of kinetic energy to the region. The vertical total of $83.57 \text{ W m}^{-2}$ primarily results from contributions above 400 mb; however, a weaker secondary maximum exists in the planetary boundary layer.

Horizontal flux divergence and dissipation to unresolvable motions (negative values) are major sinks of kinetic energy. Column totals are $-47.39$ and
-41.62 W m\(^{-2}\), respectively. The vertical profile of dissipation is opposite to that of generation, i.e., maximum negative values near the jet stream level, weak dissipation in the midtroposphere and a secondary maximum near the surface. Significant horizontal outflow exists in the upper troposphere, whereas weaker inflow occurs in the middle layers. Velocity divergence is a greater cause of the upper-level energy outflow than is horizontal advection. Values of vertical flux divergence indicate an export of energy in the lower and middle layers, with significant import above 300 mb due to the widespread ascending motion. The nonzero column total occurs because vertical motions at 150 mb were zero and surface values were not.

It is informative to compare current results with those from previous investigations. Table 2 gives findings from Tsui and Kung (1977), hereafter denoted as TK, who computed energy budgets based on meso \(\beta\)-scale data from the NSSL network. Current results are most similar to those of TK’s four-day convective category. Cross-contour generation is the greatest source in each case. Values are comparable (about 85 W m\(^{-2}\)) even though the current level of energy content (11.99 \(\times\) 10\(^3\) J m\(^{-2}\)) is considerably smaller than that of the previous study (21.02 \(\times\) 10\(^3\) J m\(^{-2}\)). Tsui and Kung (1977) noted strong upward motions during periods of significant generation; a similar relation occurs during the current period. Energy dissipation during AVE-SESAME V (-41.62 W m\(^{-2}\)) is approximately half that obtained by TK (-95.99 W m\(^{-2}\)). Nonetheless, both values represent significant losses from the observed scale to either smaller or larger scales that are inadequately resolved by the data network. A difference between the two studies is the nature of horizontal transport. It was a weak source during TK’s periods (10.96 W m\(^{-2}\)), but a strong sink during the current study (-47.39 W m\(^{-2}\)). The contrast is especially pronounced in the highest layer. Two of TK’s four convective days contained

<table>
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<tr>
<th>Pressure layer (mb)</th>
<th>(K)</th>
<th>(\partial K/\partial t)</th>
<th>(-\nabla \cdot \nabla \phi)</th>
<th>(-\nabla \cdot kV)</th>
<th>(-\partial \omega k/\partial p)</th>
<th>(D)</th>
<th>(-\nabla \cdot \nabla k)</th>
<th>(-k \nabla \cdot \nabla V)</th>
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<td>2.35</td>
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<td>-1.79</td>
<td>-0.43</td>
<td>-0.04</td>
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<th>(K)</th>
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<th>(-\partial \omega k/\partial p)</th>
<th>(D)</th>
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<td>0.03</td>
<td>83.57</td>
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the strong upper-level horizontal export observed here, while the remainder exhibited inflow. Thus, unlike the other source–sink terms, it appears that mesoscale horizontal transport may vary greatly between cases. Since velocity divergence in the upper troposphere is characteristic of most convective outbreaks, differences in flux divergence are probably due to the advective component which is influenced by the locations of jet streams with respect to the network. It is important to note that these jet streams may be preexisting features of the large-scale flow, or they may be attributable to feedback processes from the convection itself (e.g., Fritsch and Maddox, 1981a; Fuelberg and Browning, 1983). Finally, the net effect of the various sources and sinks is to produce a slight decrease in kinetic energy during AVE-SESAME V, but a weak increase for the convective category.

Composite energetics of TK’s nonconvective group are weaker and differ considerably from the results of their convective periods and our current investigation (Table 2). The greatest contrasts are that supergeostrophic flow destroys kinetic energy during the nonconvective periods and that positive dissipation becomes a source of detectable energy. Tsui and Kung noted that their nonconvective cases occurred during anticyclonic conditions, but the synoptic-scale flow over Oklahoma during AVE-SESAME V is characterized by positive vorticity advection (Fig. 2). Regarding the frontal category, energy processes agree in sign with those of the present study, although magnitudes during AVE-SESAME V are much greater. This probably occurs because the convection on 20–21 May was more intense than during TK’s frontal periods.

Table 3 presents results from previous synoptic-scale studies of convective environments, current values, and those of TK. Energetics in the vicinities of two squall lines (areas approximately $1 \times 10^3$ km$^2$; see Fuelberg and Scoggins, 1978) are similar to, but weaker than, current values. Generation by cross-contour flow is the greatest source in both studies; horizontal outflow and negative dissipation are major sinks. On the other hand, both cases of Robertson and Smith (1980) differ considerably from results of AVE-SESAME V. Thus, it appears that the energy balances of synoptic-scale areas enclosing intense convection may vary greatly. However, results from AVE-SESAME V and TK imply that the near-storm environment may often be characterized by strong generation and negative dissipation.

5. Time variability of energetics

Previous studies have indicated that the kinetic energy budget undergoes major temporal variations that are related to the presence and strength of convection (McInnis and Kung, 1972; Kung and Tsui, 1975; Tsui and Kung, 1977; Fuelberg and Scoggins, 1978). Therefore, it is informative to relate current energy transfers to the life cycle of the enclosed thunderstorm activity. Figure 5 contains a time series of surface—150 mb totals and pressure-time cross sections of the various energy budget terms.

The special network region experiences decreasing kinetic energy content through much of the 24 h period. The vertical total drops greatest during the times of strongest convective activity (2000–0200 GMT) when values decrease by $4.4 \times 10^3$ J m$^{-2}$. The pressure–time cross section of the local derivative (Fig. 5) indicates that largest decreases occur above 300 mb. Interestingly, however, a center of increasing kinetic energy is located near 400 mb at 2000 GMT. This vertical variation agrees with findings of Vincent and Carney (1982), who observed decreases in jet-level winds accompanied by the formation of a midlevel wind maximum during the Red River Valley tornado outbreak (10–11 April 1979, AVE-SESAME

<table>
<thead>
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<th>Study</th>
<th>Scale</th>
<th>$K$</th>
<th>$\Delta K/\Delta t$</th>
<th>$-\nabla \cdot \nabla \phi$</th>
<th>$-\nabla \cdot k\nabla$</th>
<th>$-\partial \omega/\partial p$</th>
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<td>2 squall-line vicinities</td>
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<td>23.4</td>
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<td>54.0</td>
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<td>Palm Sunday 1965</td>
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<tr>
<td>Robertson and Smith (1980)</td>
<td>Synoptic</td>
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<td>3.5</td>
<td>39.4</td>
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<td>Jumbo 1974 outbreak</td>
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<td>convective region</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Tsui and Kung (1977)</td>
<td>Meso $\beta$</td>
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<td>4.6</td>
<td>89.4</td>
<td>11.0</td>
<td>0.2</td>
<td>-96.0</td>
</tr>
<tr>
<td>convective cases</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Current study</td>
<td>Meso $\beta$</td>
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<td>-5.4</td>
<td>83.6</td>
<td>-47.4</td>
<td>0.0</td>
<td>-41.6</td>
</tr>
<tr>
<td></td>
<td>1.5 and 3 h</td>
<td></td>
<td></td>
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</tbody>
</table>
Tsui and Kung observed increases in midtropospheric kinetic energy prior to peak storm activity, but, contrary to current results, strong decreases were not observed above 300 mb. The energetics associated with the current vertical variations in winds will be described in greater detail in Section 7. Finally, energy increases near 250 mb at 0800 GMT are due to the intrusion of a mesoscale wind maximum into the southern portion of the network region.

Vertical totals of cross-contour generation show major variations during the 24 h period (Fig. 5). Values range from $-11.6 \, \text{W m}^{-2}$ at the initial observation time to a maximum of 208.98 W m$^{-2}$ at 2130 GMT, when the storms are most widespread within the network region. By 0500 GMT, with the end of the convection, magnitudes decrease to near prestorm levels. Largest variability occurs above 400 mb. This extreme amount of upper-level generation is attributable to strongly divergent flow being superimposed on a mesoridge. Figure 3 shows that crossing angles at 200 mb are as great as 90°. In a recent study of the synoptic-scale storm environment, Fuelberg and Browning (1983) found that much of the cross-contour generation was due to the divergent wind component. Although quite large, values of generation observed in this study are not without precedent. Kung and Tsui (1975) reported a value of 110 W m$^{-2}$ based on five observation times of NSSL data, and the greatest value at a single time was 611 W m$^{-2}$ (McInnis and Kung, 1972). Even though these values are much greater than those observed in well-developed midlatitude cyclones diagnosed with synoptic-scale data (e.g., Petterssen and Smebye, 1971; Smith, 1973; Vincent and Chang, 1975; Chen et al., 1978), the mesoscale environments of intense convection embedded within the cyclones are probably characterized by the strong energetics diagnosed here.

Another interesting feature in the time series of generation (Fig. 5) is the area of weak cross-contour destruction in the middle troposphere near the time of peak convection (2130 GMT). Tsui and Kung (1977) found significant generation prior to and after thunderstorm activity, whereas destruction existed within virtually the entire column at peak convective intensity. They hypothesized that generation surrounded the intense storm area while destruction occurred within the area. For the present SESAME case, however, destruction is limited to the middle layers only and is much weaker. Thus, the findings of TK do not appear to represent all meso $\beta$-scale storm environments.

Figure 5 shows that dissipation also undergoes major fluctuations during the experiment period. Vertical totals are most negative at 2130 GMT, during the peak of the convective outbreak. The secondary minimum at 0800 GMT is associated with the jet intrusion. Patterns and magnitudes in the pressure–time cross section are the mirror image of those of generation, i.e., transfers to unresolvable scales (negative dissipation) corresponding to cross-contour generation and vice versa. The large values of dissipation confirm that the storm environment is a region of intense scale interactions. Although the residual is the least reliable budget term, the error analysis described in the Appendix indicates that the major variations observed here cannot be attributed to random data errors. The weak positive values in the middle troposphere, near 2130 GMT, are of interest. This unresolvable energy source may be due to meso $\gamma$-scale storm phenomena. Tsui and Kung observed a deeper and more intense area of positive dissipation during their convective cases, and it has been noted during synoptic-scale studies as well (Vincent and Schlatter, 1979).

Horizontal flux divergence provides a major energy sink during times of intense convection (Fig. 5). Magnitudes are greatest in the upper troposphere and are comparable to those of generation and dissipation. Large values of flux are attributable to strong horizontal gradients of kinetic energy and to velocity divergence, which reached $32 \times 10^{-3} \, \text{s}^{-1}$ at 200 mb (Fuelberg and Printy, 1983). The cross section of vertical flux divergence shows upward transport of energy. In this case, Fuelberg and Printy (1983) found that area-averaged vertical motion reached $-22 \, \mu \text{b s}^{-1}$ near 400 mb at 2130 GMT, while individual grid point values were in excess of $-60 \, \mu \text{b s}^{-1} (\sim 1 \, \text{m s}^{-1})$. Although current values of vertical flux based on mesoscale data are much larger than those observed in synoptic-scale cyclones, they are still smaller than those of the other budget terms.

Area-averaged calculations demonstrate that the storm environment contains intense energy conversions and transports which are maximized during the convection. Table 4 quantifies the budget at the time of most widespread storm activity. In spite of intense energy generation, the overall storm environment experiences decreasing kinetic energy content due to dissipation and horizontal export.

We believe that most of the energy variations are attributable to the convection because current results are consistent with those from previous mesoscale modeling studies (e.g., Fritsch and Maddox, 1981b; Chang et al., 1982, 1984; Fritsch and Brown, 1982). However, it is important to note that some budget terms, especially generation, began to change prior to the onset of the thunderstorms beginning shortly after 1700 GMT. Thus, these early fluctuations may be associated with atmospheric processes that created a suitable environment for the convection that followed. An additional consideration is diurnal variations in some energy parameters. Based on long-term synoptic-scale data, Kung (1967) noted that positive generation and negative dissipation were greater at 0000 GMT than at 1200 GMT. However, those diurnal fluctuations were quite small when compared with those
Fig. 5. Pressure-time cross sections of area-averaged kinetic energy budget terms. Units are $10 \text{ W m}^{-2} \text{ (50 mb)}^{-1}$. Surface to 150 mb totals are shown in the lower right section.
observed here; thus, the storm-induced changes should dominate strongly.

6. Synoptic-scale energetics

To the authors' knowledge, mesoscale energetics have not been directly compared with concurrent results at the synoptic scale. Kung and Tsui (1975) and Tsui and Kung (1977) presented mean and eddy kinetic energy budgets in which the eddy results reflected additional signals obtained by going from subsynoptic to meso $\beta$-scale resolution; however, calculations based on NWS sites were not reported. Our procedure with the synoptic-scale data was to average the grid-point energy values at 127 km intervals within a $6.4 \times 10^4$ km$^2$ area over Oklahoma. This domain agreed closely both in size and in location with the meso $\beta$-scale region shown in Fig. 1. The composite area–time averaged budget was then obtained from the nine 3 h observations—synoptic-scale data were not taken at 2130 GMT.

There are several similarities between the results from the two resolutions (Table 5). Values of energy content and the local derivative show close agreement. In addition, the cross-contour generation, negative dissipation and upward transport observed for the meso $\beta$-scale storm environment also characterize the larger-scale flow. An important contrast is that magnitudes at the finer resolution usually are considerably greater, especially in the upper troposphere. This is most evident for the generation term where the vertical total at the meso $\beta$-scale (83.57 W m$^{-2}$) is more than double that from the corresponding synoptic-scale data (30.62 W m$^{-2}$). The greatest contrast between the two budgets occurs with horizontal flux divergence: at the coarser resolution the vertical total is near zero, whereas the special network indicates strong export occurring mostly in the upper troposphere.

Figure 6 shows temporal variations of energy budget terms derived from the synoptic-scale data. Except for horizontal flux divergence, patterns have many similarities to those derived from mesoscale data (Fig. 5). Magnitudes from the NWS stations are much smaller, however, than those described earlier. The synoptic-scale network consistently fails to measure the strong export of energy from the storm environment. In addition, energy variations associated with the mesoscale jet intrusion at 0800 GMT are not detected.

Computational procedures must be considered when comparing the two budgets. Although different truncation errors occur when horizontal derivatives are calculated from the 127 and 25 km grids, we
believe that only a small part of the observed budget differences are due to this factor. Isopleths of the gridded data at the synoptic scale exhibit much smaller curvature than those at the finer resolution, and large-scale horizontal gradients are much weaker than those derived from the special network. Thus, if the synoptic-scale data had been objectively analyzed onto a 25 km grid mesh using the original synoptic-scale response curve for the Barnes technique (Section 2c), the resulting large-scale energy budget would probably be quite similar to that already presented.

Results from the two scales of data suggest that the synoptic network qualitatively resolves the convective influences on the hydrostatic environment, but that it does not adequately depict the magnitudes of higher order parameters such as generation and transport of kinetic energy. We believe that the enhanced magnitudes of these terms at the mesoscale are due in large part to the enhanced ability of the denser network to detect the strongly ageostrophic flow of the storm environment. Thus, current findings emphasize the importance of properly accounting for the effects of convection in large-scale numerical models. Fritsch and Brown (1982) noted that inadequate representations of mesoscale processes will cause large-scale model integrations to suffer cumulative errors that will limit their long-term predictability.

7. Vertical variations in wind

Vertical variations in horizontal wind speed are a fascinating aspect of the AVE-SESAME V period (Fuelberg and Pinny, 1983). Their horizontal maps of kinetic energy content for the 400–150 mb layer revealed energy decreases in southeastern Oklahoma during the first half of the experiment. More detailed analyses indicate, however, that these fluctuations are much more complex. Figure 7 is a time series of horizontal wind speed for Healdton, located in southeastern Oklahoma. Above 300 mb, speeds decrease slowly between 1100 and 1700 GMT, just prior to the onset of the convection. Winds then decrease by nearly 50% between 2000 and 2300 GMT when the storms are most widespread within the region, but values near 400 mb approximately double during the same 3 h period. As a result of the rapid fluctuations, the altitude of maximum wind speed drops almost 200 mb. By 0500 GMT, after the end of convection, the patterns return to near original configurations. Since corresponding changes are observed at several nearby stations, the variations appear in area-averaged values of $\frac{\partial K}{\partial t}$ (Fig. 5). Due to their large areal coverage, the fluctuations cannot be attributed merely to data uncertainties. Gradual decreases above 300 mb prior to 1700 GMT occurred before the onset of the convection, but the vertical couplet of rapid changes between 2000 and 2300 GMT may have been storm induced. Similar variations have been observed during AVE-SESAME I (Vincent and Carney, 1982).

To isolate energetics of the wind couplet from those of the remainder of the analysis region, grid point values of the energy budget were averaged over a fixed subvolume (1.5 x 10^4 km^2 area) in which the feature was most apparent (Fig. 1). Table 6 presents

![Fig. 7. Time series of horizontal wind speed for Healdton, Oklahoma. Units are m s^-1.](image)

FIG. 6. Time series of synoptic-scale energy budget terms integrated between the surface and 150 mb.
integrated budget totals for the 350–150 and 550–350 mb layers which contained the greatest energy decreases and increases, respectively.

Within the 350–150 mb layer, the original kinetic energy value of 7.63 × 10^5 J m^-2 at 2000 GMT drops nearly 50% to 3.95 × 10^5 J m^-2 at 2300 GMT. In agreement with results for the entire area (Fig. 5), conversions and transports are strongest at 2130 GMT, the time of maximum convective activity. At this time, generation and vertical flux convergence provide energy sources of 136.50 and 95.90 W m^-2, respectively, to the upper levels, but sinks by horizontal export (−130.45 W m^-2) and negative dissipation (−136.00 W m^-2) override the sources to produce the overall energy decrease. Relative contributions of the four budget terms are similar at all three times of intense convection.

Contrary to findings for the topmost layer, energy content between 550 and 350 mb increases during the 3 h period (Table 6). At 2000 and 2130 GMT, energy sinks by vertical flux divergence and horizontal export are counteracted by sources due to generation and positive dissipation. It is noteworthy that at 2000 GMT energy transfers from nonresolvable scales (33.15 W m^-2) are an even greater source of energy than is cross-contour flow (5.69 W m^-2). At 2130 GMT, the positive dissipation is only slightly smaller than generation. The energy balance changes somewhat at 2300 GMT when generation and horizontal import are in near balance with negative dissipation and vertical export.

The dissipation term is especially significant in producing differences between energy budgets of the two layers. As mentioned earlier, dissipation is computed as a residual; thus, its uncertainty is greater than that of the other terms. Nonetheless, sensitivity analyses suggest that random data errors are not the cause of positive values in the 550–350 mb layer (Appendix; Robertson and Smith, 1980; Fuelberg and Jedlovec, 1982). Although current dissipation values at 2130 GMT were based on δK/δt evaluated from centered 3 h time differences, similar results occur if uncentered 1.5 h differences are employed.

Large magnitudes of dissipation suggest that the near-storm environment is greatly influenced by processes which are not adequately resolved by the meso β-scale data network. Similar conclusions have been reported in previous diagnostic investigations of convective environments. Kornegay and Vincent (1976), for example, observed a strong relationship between synoptic-scale areas of positive dissipation and regions of intense convection. Their subgrid-scale source was most pronounced within the 700–300 mb layer, as were positive values of TK. Unlike this study, neither of the earlier cases exhibited the pronounced negative dissipation in the upper levels observed during SESAME. Based on the work of Moncrieff and Green (1972), Vincent and Schlatter (1979) suggested that positive values could be attributed to the transformation of potential energy on the cumulus scale to kinetic energy on the synoptic scale.

A somewhat different explanation for dissipation is based on eddy transport mechanisms. Ninomiya (1971a,b) found that major variations in winds near an area of intense thunderstorms were due to strong vertical convective transfer of horizontal momentum. Houze (1973) noted that these cumulus-scale vertical transports are as important as larger-scale vertical flux, even when longer time periods are considered. During the current SESAME case, meso γ-scale vertical motions within the deep convection could be “mixing” the air to produce an energy sink at the original jet level and a corresponding source at lower levels. Since these updrafts and downdrafts are not resolvable by the meso β-scale rawinsonde network, their net effect would appear in the dissipation term.

Finally, modeling results provide additional support for the hypothesis that convection can modify the surrounding horizontal winds via the dissipation term. Chang et al. (1982, 1984) compared fine-mesh forecasts of cyclogenesis that were prepared with and without latent heat release. Although their computational domain and grid length were much larger than those of AVE-SESAME V, the results are nonetheless qualitatively similar. First, they noted that latent heating diminished the upper-level jet stream while producing a lower-level jet. As a result, the preexisting large-scale wind pattern with pronounced vertical shear was changed to a smaller-scale pattern with strong horizontal shear. As a partial explanation for...
the wind variations, energy diagnoses showed that
latent heating enhanced dissipation to subgrid scales
in the upper levels, while producing less negative
values in the middle and lower troposphere. These
changes in dissipation were attributed to storm-in-
duced modifications to the diffusion process.

8. Summary and conclusions

A meso $\beta$-scale kinetic energy analysis was con-
ducted for a period of intense thunderstorm activity
that occurred over central Oklahoma during the fifth
day of AVE-SESAME '79 (20–21 May). Rawinsonde
data at 75 km spacings and either 3 or 1.5 h intervals
were used to examine energetics of the storm envi-
ronment prior to, during and after the convection.
Unlike previous meso $\beta$-scale energy studies which
emphasized a collection of days, the current investiga-
tion was a detailed analysis of a single 24 h period.

Area–time averaged energetics indicated that the
meso $\beta$-scale storm environment was characterized
by energy generation due to cross-contour flow, hori-
zontal flux divergence of energy, upward transport
by ascending motion and transfer of energy from
resolvable to nonresolvable scales of motion (negative
dissipation). Energy processes were maximized near
jet stream level. Results were similar to previous
findings of the mesoscale storm environment, but
considerably larger than those describing the synoptic-
scale environment.

The energy budget underwent major time fluctua-
tions. Maximum variability occurred above 400 mb,
centered about the time of greatest storm activity.
Strong upper-level generation at the times of convec-
tion was attributable to storm-induced divergent flow
being superimposed on a mesoridge. Energy decreases
occurred at the convection times because horizontal
export and dissipation to nonresolvable motions ex-
ceeded the generation.

A unique feature of AVE-SESAME V is that
rawinsonde data were collected simultaneously at
both the synoptic and meso $\beta$-scales, making possible
a comparison of the kinetic energy balance of the
same analysis region based on different scales of input
data. Results from the two resolutions were similar,
in that generation and dissipation dominated both
the mesoscale and synoptic-scale storm environments.
However, magnitudes at the finer resolution were
considerably larger, and the coarser network failed to
detect the enhanced horizontal-flux divergence within
the storm environment. Except for horizontal flux,
temporal trends of the two budgets were similar.

Finally, a complex vertical pattern of wind vari-
ations was observed above 600 mb in the southeastern
corner of the data network. Wind speeds near 200 mb
decreased approximately 50% during the 3 h
period coinciding with the most active storms, but
values near 400 mb nearly doubled during the same
interval. To explore this feature, an energy analysis
was conducted for a subvolume of the network in
which it was most pronounced. Results indicated that
vertical variations in the dissipation term contributed
greatly to the observed wind changes. Large magni-
tudes of dissipation suggested that the mesoscale
storm environment was greatly influenced by motions
that were inadequately resolved by the meso $\beta$-scale
network.

Energy relations during AVE-SESAME V are con-
sistent with those of previous storm-environment
studies. We believe that many of the observed energy
variations are due to feedback mechanisms from the
area of thunderstorms to the surrounding larger-scale
environment. Unfortunately, our understanding of
subsynoptic-scale phenomena and scale interactions
is very limited. Thus, many more theoretical, diag-
nostic and numerical investigations are needed.

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anonymous reviewers, which improved and clarified
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APPENDIX

Sensitivity Analysis

Uncertainties in rawinsonde data are due to random
and systematic errors. Our data handling and com-
putational schemes (Section 2c) should greatly reduce
the effect of errors on the energy budget calculations;
however, such effects will not be completely sup-
pressed. For this reason, it is imperative to determine
quantitative confidence limits for the derived param-
eters. Unfortunately, there is no effective procedure
to test for systematic errors; this type of uncertainty

<table>
<thead>
<tr>
<th>Pressure level (mb)</th>
<th>Wind direction (deg)</th>
<th>Wind speed (m s$^{-1}$)</th>
<th>Height (m)</th>
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<td>150</td>
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<td>200</td>
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</tr>
<tr>
<td>300</td>
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<td>21.0</td>
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<tr>
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<td>4.6</td>
<td>3.0</td>
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<td>3.5</td>
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<tr>
<td>900</td>
<td>2.0</td>
<td>1.0</td>
<td>4.1</td>
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Table A2. Area-averaged kinetic energy budget for 2130 GMT 20 May 1979. Values in parentheses are mean absolute differences between the original and ten perturbed budgets. The budget area consists of the overall energy analysis region shown in Fig. 1. All units of energy parameters are W m⁻², except for K which is 10⁵ J m⁻².

<table>
<thead>
<tr>
<th>Pressure layer (mb)</th>
<th>K</th>
<th>∂K/∂t</th>
<th>−V · ∇φ</th>
<th>−∇ · kV</th>
<th>−∂ωk/∂p</th>
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</thead>
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<td>(6.82)</td>
<td>(2.14)</td>
<td>(26.02)</td>
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<td>(2.14)</td>
<td>(2.10)</td>
<td>(5.91)</td>
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<td>(0.02)</td>
<td>(0.11)</td>
<td>(1.24)</td>
<td>(0.21)</td>
<td>(0.22)</td>
<td>(1.24)</td>
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<tr>
<td>Vertical total</td>
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<td>−26.65</td>
<td>208.98</td>
<td>−95.37</td>
<td>0.16</td>
<td>−140.42</td>
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<tr>
<td></td>
<td>(0.27)</td>
<td>(0.82)</td>
<td>(25.46)</td>
<td>(7.92)</td>
<td>(0.00)</td>
<td>(26.83)</td>
</tr>
</tbody>
</table>

was therefore not considered, nor were computational inadequacies such as truncation error evaluated. On the other hand, effects of random errors were documented using randomly perturbed data.

Our procedure was to add computer-generated random perturbations that simulated actual rawinsonde errors to the original time-adjusted 25 mb data at individual stations. Then, energy budgets were calculated from the perturbed data and compared with those derived from the original data. This technique is similar to that used by Robertson and Smith (1980) and Fuelberg and Jedlovec (1982). However, to the authors' knowledge, sensitivity analyses have not been reported for meso β-scale energy studies.

Perturbations were normally distributed about zero with standard deviations as a function of pressure (Table A1). Values for levels not shown can be obtained by linear interpolation. Because of the care taken in processing and checking the data, perturbations were restricted to two standard deviations from zero, which included about 95% of possible values. Since maximum convective activity and strongest energetics occurred near 2130 GMT 20 May, this observation time was chosen for the analysis. Ten versions of data, each with a different set of perturbations, were made for 2130 GMT. Analytical procedures (Barnes analysis, vertical motions, etc.) used with the perturbed data were identical to those used originally (Section 2c). By comparing the original and perturbed data grids, it was found that approximately 35% of the magnitudes of height perturbations introduced at the stations (Table A1) were removed by the Barnes analysis scheme. Since winds were filtered vertically before the objective analysis, approximately 55% of their introduced error was removed. Thus, our computational procedures have the desired ability to reduce errors within the data set.

Original budget values and mean absolute differences between the original and ten perturbed versions are given in Table A2 for the entire energy averaging region and in Table A3 for the limited area in the southeast (see Fig. 1). Results show that the generation and residual dissipation terms are most sensitive to random error, while terms representing energy content and vertical and horizontal flux divergence are the most reliable. With the exceptions of 700–400 mb dissipation over the entire area and 550–350 mb horizontal flux over the limited area, percentages of mean absolute difference to original values are less than 35%. At any particular level, one can have greater confidence in terms having large magnitudes than in those near zero.

To further investigate sensitivity of horizontal flux divergence, the term was separated into the components −V · ∇k and −kV · V, as done by Fuelberg and Jedlovec (1982). Thus, instead of using original estimates of velocity divergence, adjusted values, consistent with these needed to obtain adjusted vertical

Table A3. Integrated energy values for two layers of the subvolume enclosing the vertical wind couplet at 2130 GMT (see Fig. 1). Values in parentheses are mean absolute differences between the original and ten perturbed budgets. All units of energy parameters are W m⁻², except for K which is 10⁵ J m⁻².

<table>
<thead>
<tr>
<th>Pressure layer (mb)</th>
<th>K</th>
<th>∂K/∂t</th>
<th>−V · ∇φ</th>
<th>−∇ · kV</th>
<th>−∂ωk/∂p</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>350–150</td>
<td>5.46</td>
<td>−34.05</td>
<td>136.50</td>
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<td>95.90</td>
<td>−136.00</td>
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<tr>
<td></td>
<td>(0.18)</td>
<td>(0.90)</td>
<td>(17.14)</td>
<td>(12.79)</td>
<td>(8.15)</td>
<td>(18.45)</td>
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<tr>
<td>550–350</td>
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<td>10.46</td>
<td>39.68</td>
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<tr>
<td></td>
<td>(0.13)</td>
<td>(0.45)</td>
<td>(12.23)</td>
<td>(3.35)</td>
<td>(6.51)</td>
<td>(13.60)</td>
</tr>
</tbody>
</table>
motion, were employed (O'Brien, 1970). The advection component was not modified since analyses revealed that it was much less sensitive to data errors. Values of the new quantity (not shown), called “adjusted horizontal flux,” were similar to those of the original version (Table A2). For example, at 2130 GMT, their difference was only 0.7 W m⁻² for the 400–150 mb layer and only 0.2 W m⁻² for the total vertical column. This is less than 1% of the original values seen in Table A2. Thus, data errors that caused unadjusted vertical motion not to converge to zero at 150 mb do not have a major impact on the horizontal flux term.

REFERENCES


