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Evidence of deep convection as a source of synoptic-scale kinetic energy

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ABSTRACT

In a previous paper, Kornegay and Vincent (1976) calculated the kinetic energy budget during 12 hours in the life of a tropical depression over the United States. The dissipation term, calculated as a residual in the kinetic energy budget equation, was positive in areas of convective precipitation, prompting the authors to speculate that a subgrid-scale process, namely, deep cumulus convection, could supply kinetic energy to the synoptic-scale flow. That possibility is further examined here. The earlier case study is extended from 12 to 36 hours and additional evidence is presented, including a comparison with some theoretical results.

The case study involved a tropical depression, the remains of tropical storm Candy, and its interaction with a developing extratropical cyclone between 1200 GMT, June 24 and 0000 GMT, June 26, 1968. The kinetic energy budget is based upon multivariate statistical analyses of radiosonde observations. Areas of kinetic energy increase and positive dissipation (dissipation acting as an energy source) are roughly the same; they are marked by deep convection as evidenced by radar reports and precipitation amounts. The kinetic energy increase and positive dissipation are initially greatest in the 700–500 mb layer as the tropical depression and mid-latitude cyclone begin to interact. Twelve hours later, however, the largest increase in kinetic energy and greatest positive dissipation occur higher in the troposphere, from 500 to 300 mb.

1. Introduction

There is growing observational evidence that significant kinetic energy may appear in synoptic scales of motion as a result of energy transfer from subgrid scales of motion (e.g., Kung, 1970; McInnis and Kung, 1972; Smith, 1973a, b; Kung and Smith, 1974; Smith and Adhikary, 1974; Kung and Baker, 1975; Kung and Tsui, 1975; Vincent and Chang, 1975; Kornegay and Vincent, 1976; Ward and Smith, 1976; Chen and Bosart, 1977; Chien and Smith, 1977; Sheu and Smith, 1977; Tsui and Kung, 1977; Fuelberg and Scoggins, 1978). The evidence is based mostly on "positive dissipation" values computed as the residual term in the kinetic energy budget equation. In most cases, positive dissipation has been found in the upper troposphere, prompting speculation that eddy transport processes and turbulence associated with the jet stream are the most likely sources of energy. In a few cases, however, widespread deep cumulus convection seems to act as a source of synoptic-scale kinetic energy. McInnis and Kung (1972), Fuelberg and Scoggins (1978), Kornegay and Vincent (1976), Chien and Smith (1977) and Sheu and Smith (1977) have all found positive dissipation in the middle troposphere during intense convective activity; but only in the last three papers is it suggested that convection plays a role in the transfer of kinetic energy from subgrid-to-grid scales.

The purpose of the present paper is to focus attention on the role of deep cumulus clouds in producing grid-scale kinetic energy. This is accomplished by presenting results from an observational case study and by showing that these are in agreement with an existing theory on how cumulus cloud systems might act as a source of grid-scale kinetic energy. The case study concerns the interaction

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between a tropical cyclone and a developing extratropical cyclone over the United States. It has been previously discussed by Edmon and Vincent (1976), Kornegay and Vincent (1976) and Vincent et al. (1977).

Kornegay and Vincent (hereafter referred to as KV) found good correlation between areas of positive vertically integrated dissipation (budget residual term) and areas of intense convection. In addition, their vertical distribution of area-averaged dissipation showed a kinetic energy source for both systems in the 700–350 mb layer, arousing suspicion that a subgrid-scale phenomen, possibly convection, was producing grid-scale kinetic energy.

The KV study was limited to 12 hours because of the acknowledged difficulty in analyzing data subjectively at 19 pressure levels. Since the completion of that work, the period of investigation has been extended to 36 hours and new computations made based upon a multivariate statistical objective analysis scheme, developed by Schlatter (1975) at the National Center for Atmospheric Research (NCAR) and applied by Schlatter et al. (1976). The present paper uses this additional information, as well as new supporting evidence, to argue that deep cumulus convection acts to produce synoptic-scale kinetic energy. The period of this study begins 12 hours before and ends 12 hours after the KV period.

2. Data reduction

We computed objective analyses of geopotential height and wind in an area bounded by 48° N, 76° W, 28° N and 108° W every 12 hours from 1200 GMT, June 24, 1968, to 0000 GMT, June 26, 1968. We used a 2° latitude–longitude grid on each of nine pressure levels: 850 mb, 700 mb, 500 mb, 400 mb, 300 mb, 250 mb, 200 mb, 150 mb, and 100 mb. Surface variables were not analyzed; thus, the surface wind was assumed to be zero.

The objective analysis scheme used here differs in three ways from that described by Schlatter et al. (1976) and applied by Vincent et al. (1977): (1) it is regional rather than global; (2) the first guess is 12-hour persistence rather than a 12-hour numerical forecast; and (3) the height-height correlation is modeled by a damped cosine rather than a Gaussian curve.

3. Synoptic discussion

The synoptic conditions at each analysis time are depicted in the first four figures. Fig. 1 shows surface fronts, mean sea level pressure centers and present weather. Fig. 2 shows radar echoes. Fig. 3 shows the evolution of 500 mb geopotential height and temperature, and Fig. 4 the evolution of 500 mb vertical motion (ω). Vertical motion is calculated kinematically with O'Brien's (1970) adjustment scheme. The boundary conditions are that $\omega = 0$ at the earth's surface and at 100 mb.

Synoptic discussions of this case study may be found in KV, Sugg and Hebert (1969), and Edmon and Vincent (1976); only the highlights are mentioned here. At 1200 GMT, June 24, 1968, a warm-core tropical depression, the remains of tropical storm Candy, lies over central Texas, marked by a mixture of stable and convective precipitation, with the strongest convective activity just east of the system. Large-scale upward motion supports the observed precipitation pattern. Scattered showers and thunderstorms lie along a stationary front stretching from Utah to Michigan. Light continuous rain occurs over Montana, Wyoming, North Dakota and South Dakota in conjunction with cold air advection aloft and baroclinic wave development.

By 0000 GMT, June 25, the depression has moved to eastern Oklahoma. It still has a warm core but no longer exhibits a closed low-pressure center at 500 mb. A trough aloft has moved into the northwestern corner of the grid as cold air continues to flow into the area. Convective precipitation associated with both the tropical and the extratropical systems is widespread, again supported by large-scale upward motion. Downward motion at 500 mb occurs in the ridge over the eastern United States and between the tropical and extratropical waves. These areas are free of precipitation.

By 1200 GMT, June 25, the tropical depression is marked by a weak short-wave disturbance over western Illinois but it still retains a warm-core structure. In the west, continued cold air advection aloft has intensified the 500 mb trough, and a closed low has formed over South Dakota. Precipitation, primarily convective, remains widespread. It is difficult to separate the precipitation associated with the depression from that associated with the extratropical cyclone because the two

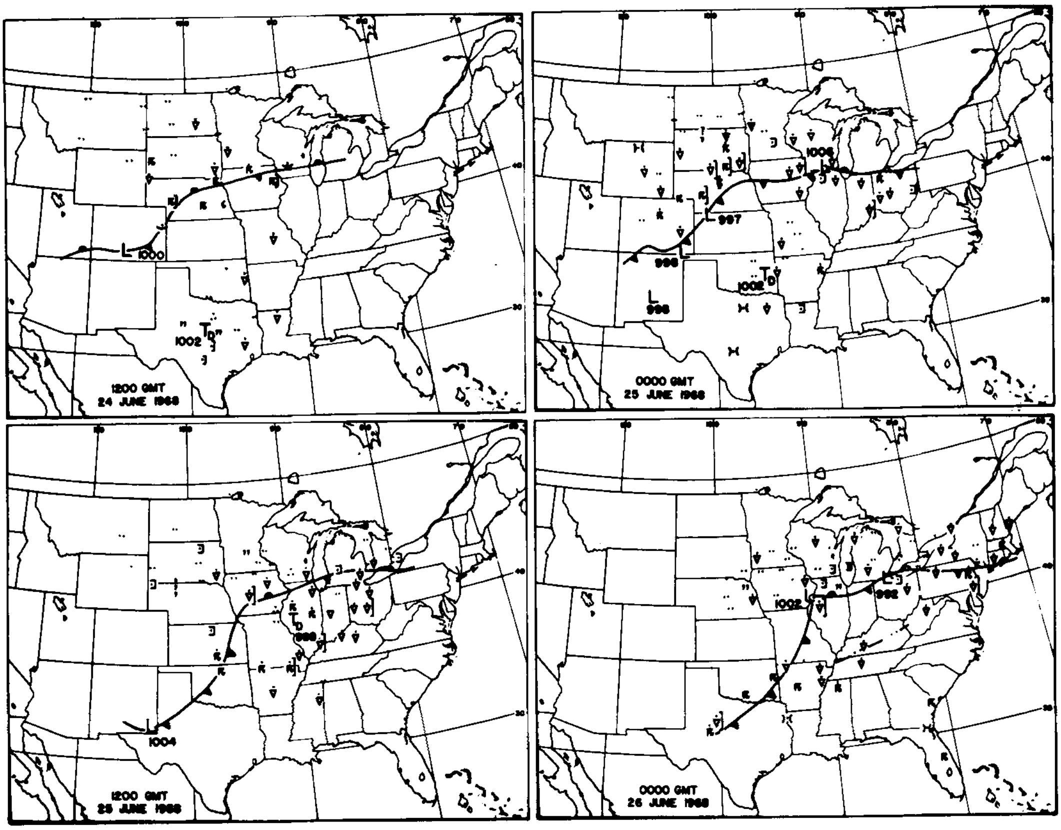

Fig. 1. Surface maps every 12 hours from 1200 GMT, June 24, to 0000 GMT, June 26. Shown are fronts, pressure centers with lowest pressure (mb) and type of precipitation reported at observing stations.

systems are beginning to interact. Radar echoes verify that convective activity is most pronounced where large-scale upward motion is at a maximum.

By 0000 GMT, June 26, the tropical depression has deepened into a wave on the frontal system over northern Ohio, but it still has a warm core. The extratropical system is now associated with a surface low near the Illinois–Iowa border. Convective precipitation still predominates, particularly in the northeast, along the cold front from Missouri to Texas and along the squall line in Kentucky. At 500 mb, pockets of warm air and strong upward motion occur with this convective activity.

4. Results

We have computed the kinetic energy budget for the limited area described in Section 2 using Smith's (1969) budget equation, which may be expressed symbolically as

$$DK = HF + G + VF + PS + D \qquad (1)$$

where DK is the time rate of change of kinetic energy, HF and VF are horizontal and vertical fluxes of kinetic energy into the volume, G is the generation of kinetic energy due to cross-contour flow, PS is the change in kinetic energy due to changes in surface pressure, and D is the dissipation term computed as a residual.

Vertical profiles of the area-averaged terms in the kinetic energy budget equation are shown in Fig. 5 for three 12-hour periods. PS was found to be two orders of magnitude smaller than the other terms and is not shown. The figure indicates that (1) kinetic energy is increasing; (2) horizontal flux acts as a sink, primarily in the upper troposphere; (3) kinetic energy is generated in both the lower and the upper troposphere; (4) kinetic energy is lost by the lower and middle troposphere and gained in

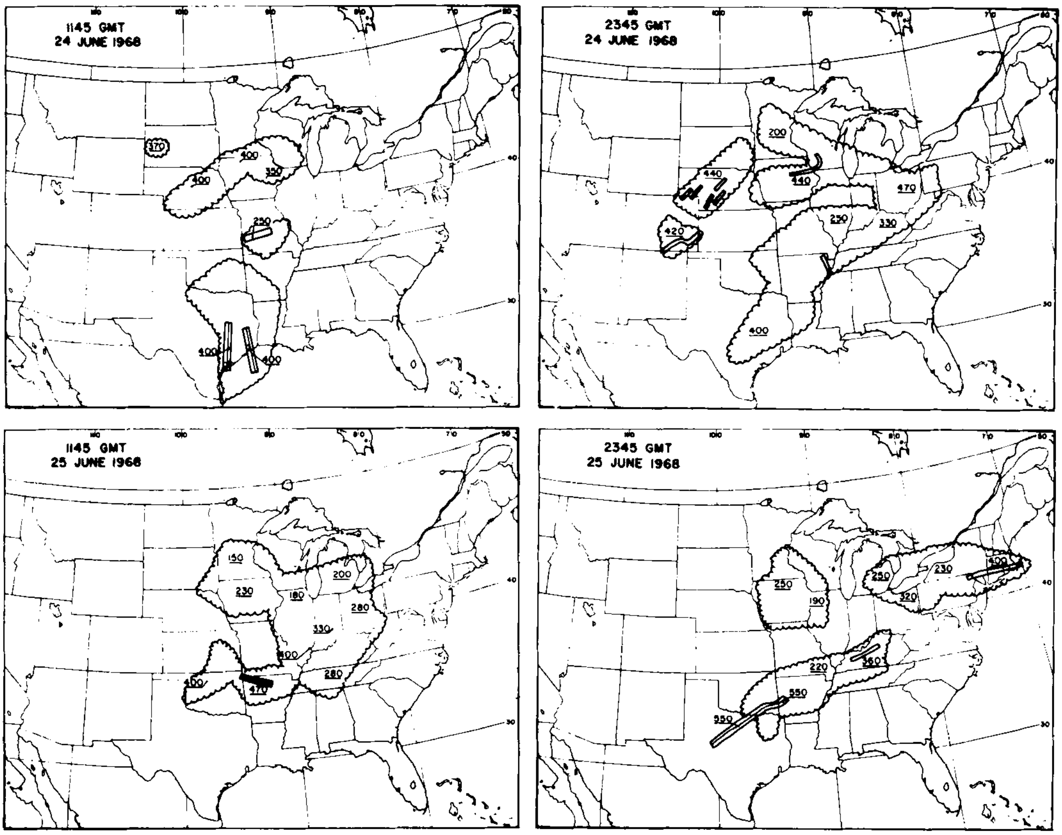

Fig. 2. Radar summary charts every 12 hours at 15 minutes before the synoptic times given in Fig. 1. Scalloped lines enclose convective area, solid lines indicate squall lines, numbers show maximum cloud tops in hundreds of feet.

the upper troposphere due to vertical flux; and (5) as in KV, dissipation acts as a source, primarily in the upper troposphere during the first 12 hours and in the middle troposphere during the last 24 hours.

A close examination of Fig. 5 shows that *DK* and *D* change roughly in parallel. Furthermore, since profiles of other terms change less than profiles of *DK* and *D* and are similar to those shown in *KV* for the middle 12 hours, we will concentrate on the *DK* and *D* terms.

Fig. 5 shows large increases in kinetic energy ($DK > 0$) in the 700–500 mb layer during the second 12-hour period and in the 500–300 mb layer during the third 12-hour period. The dissipation term exhibits similar behavior. Because of these similarities and the probable existence of deep convection in the 700–300 mb layer, we examined these terms more closely.

Maps of *DK* and *D* in the 700–500 and 500–300 mb layers and for each 12-hour period are presented in Figs. 6 and 7. In both layers maximum positive values of *DK* roughly coincide with those for *D*. Moreover, areas of positive *D* correspond to areas of deep cumulus convection, particularly over eastern Nebraska and South Dakota in conjunction with the developing extratropical cyclone during the first two periods, from eastern Oklahoma to Ohio in connection with the tropical cyclone during the latter two periods, and over Arkansas and Missouri ahead of the cold front during the third period. In all three examples, according to Figs. 1 and 2, convective activity is widespread, deep and persistent in the areas of positive dissipation. It appears that such convection *does* act as a source of synoptic-scale kinetic energy.

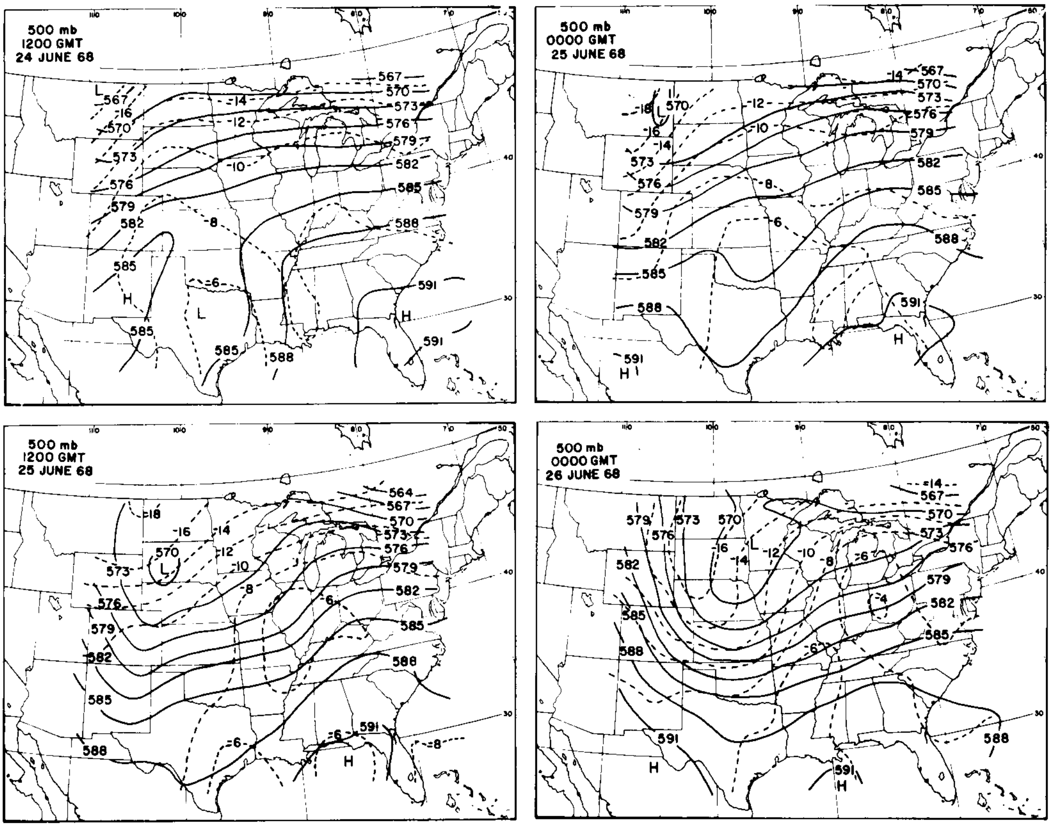

Fig. 3. Geopotential height (dam) and temperature (°C) at 500 mb for same synoptic times as in Fig. 1.

Kornegay and Vincent (1976) note that only a small fraction of the large-scale potential energy released in areas of deep cumulus convection is converted to synoptic-scale kinetic energy. Apparently, the fraction of the latent heat energy converted to kinetic energy is also small, as illustrated in Fig. 8. However, as shown later, the fraction of cumulus-scale potential energy transformed to large-scale kinetic energy is large. Fig. 8 compares the average rate of energy dissipation in the 700–300 mb layer with the average rate of latent heat release between 0000 and 1200 GMT, June 25. Grid-point values of latent energy are derived from hourly precipitation records for June 1968 (see Edmon and Vincent, 1976). Note that computed latent energy values are approximately two orders of magnitude larger than dissipation values. We assume that surface precipitation is representative of the latent energy released to the atmosphere in a column above a given grid point. The 700–300 mb layer, selected to illustrate dissipation, appears to be the layer most responsive to observed convective activity.

Fig. 8 shows good correspondence between released latent energy and positive dissipation, particularly in eastern Nebraska and South Dakota, and from eastern Oklahoma to Ohio. As noted previously, convective precipitation predominates in these two areas from 0000 to 1200 GMT, on June 25, although stable precipitation also contributes to computed latent energy estimates (Edmon and Vincent, 1976). Although there is no precipitation reported in the Texas and Oklahoma panhandles where positive dissipation occurs, hourly radar charts show scattered echoes with maximum tops of 14,300 m (47,000 ft) between

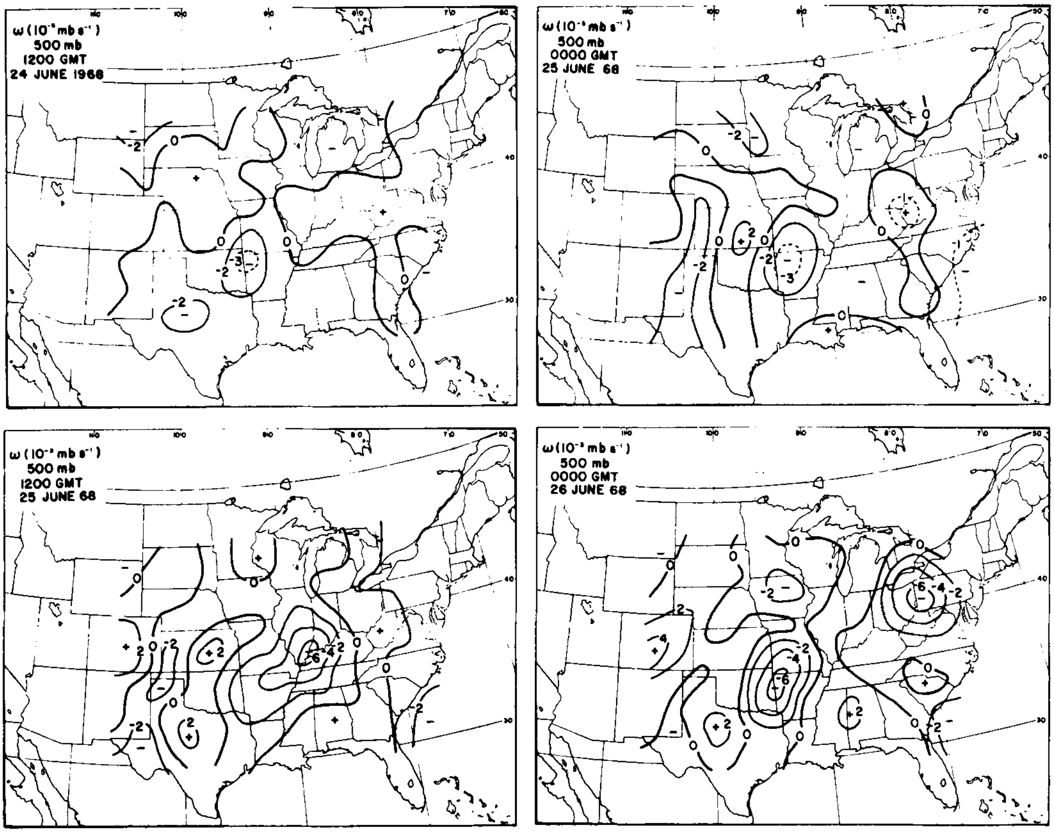

Fig. 4. Vertical motion (10^{-3} mb s^{-1}) at 500 mb for same synoptic times as in Fig. 1.

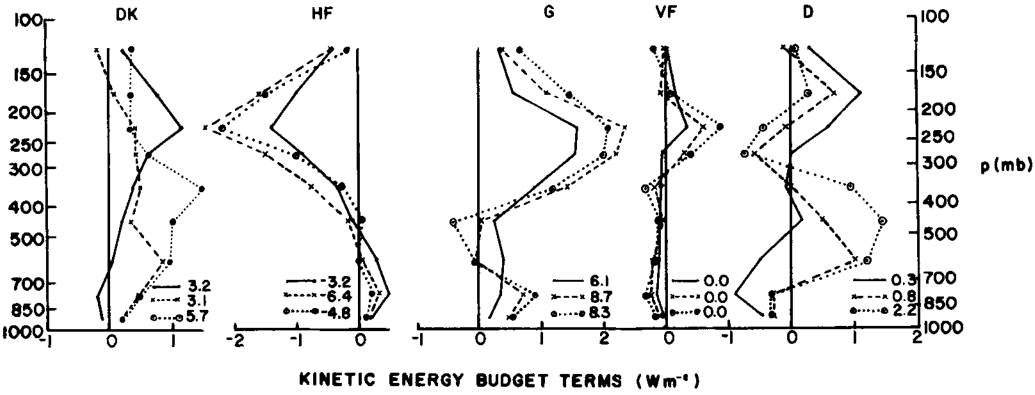

Fig. 5. Vertical distribution of area averages of kinetic energy budget terms for layers between analyzed levels (W m^{-2}) in eq. (1) for 1200 GMT, June 24, to 0000 GMT, June 25 (solid line); 0000 to 1200 GMT, June 25 (dashed line); and 1200 GMT, June 25 to 0000 GMT, June 26 (dotted line). Mass-weighted integrals given at bottom.

0445 and 0945 GMT. Positive dissipation is also evident over Ontario, Canada, but we have not attempted to examine Canadian precipitation data; thus latent energy estimates are not available there.

How is potential energy on a cumulus scale transformed to kinetic energy on the synoptic scale? The answer to this question is difficult to obtain and generally requires theoretical, as well as

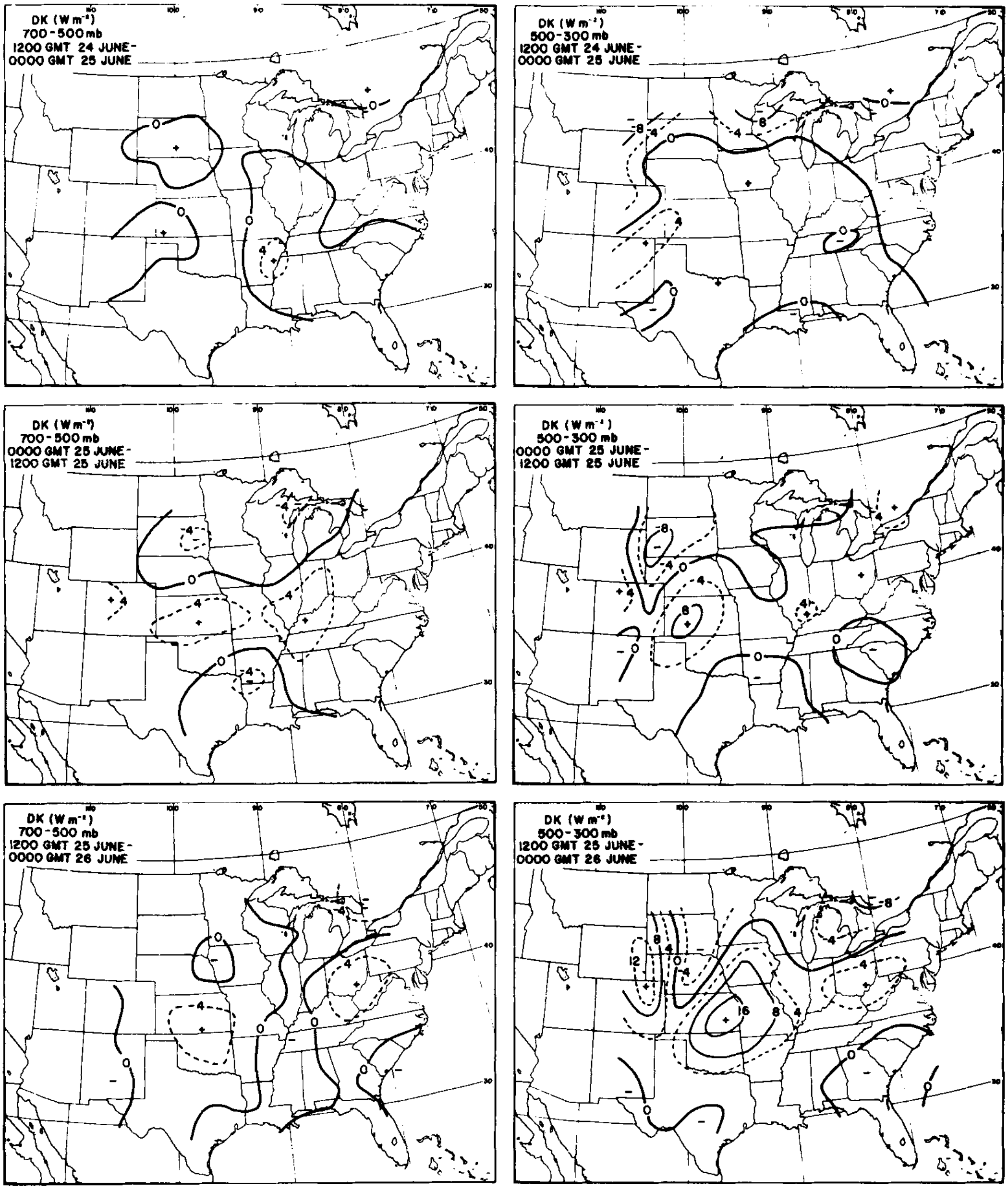

Fig. 6. Rate of change of kinetic energy with time (W m^{-2}) in the 700–500 mb and 500–300 mb layers for three 12-hour periods.

numerical modelling investigations. Only a few such investigations are relevant to the present paper. The most notable appears to be that by Moncrieff and Green (1972), expanded by Miller and Moncrieff (1978). In the first paper, in which a non-linear theory of steady, two-dimensional deep convection embedded in large-scale vertical shear is developed for mid-latitudes, it is shown that large-scale kinetic energy is often enhanced under conditions of large shear. In the second paper, two distinct models (mid-latitude and tropical) are discussed and a set of energy equations, relating

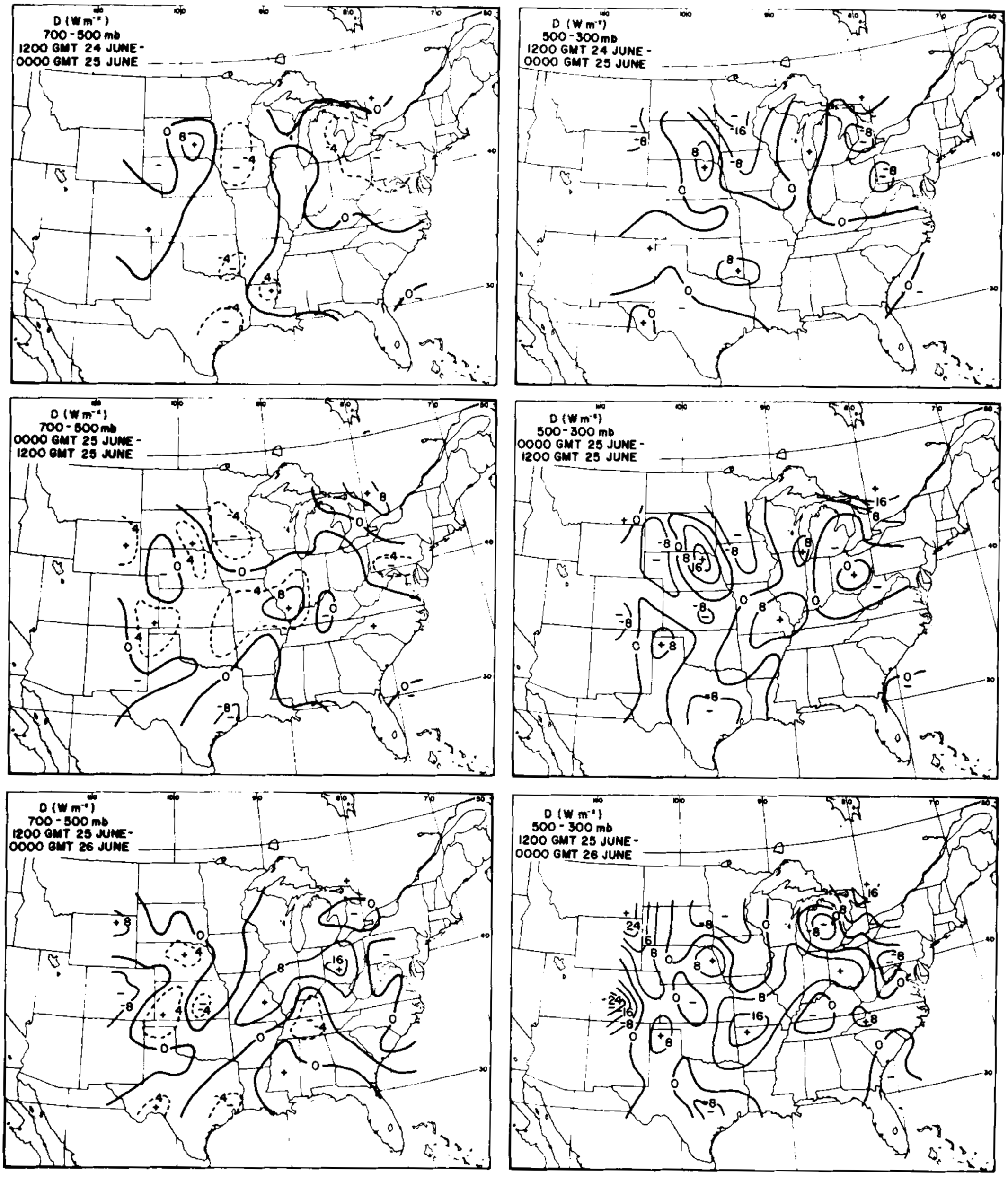

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Fig. 7. Same as in Fig. 6 except for kinetic energy dissipation (W m^{-2}) computed as the residual.

kinetic energy generation, work done by the pressure forces and net potential energy release, are derived for each model. It is shown that the contribution of potential energy released by deep cumulus convective overturning to large-scale kinetic energy is a function of the convective available potential energy (buoyancy due to difference between parcel and environmental lapse rates) and large-scale vertical shear in the cloud layer.

In the present study, Miller and Moncrieff's midlatitude model equations are used to estimate convective available potential energy (CAPE), as well as the fraction of this energy that is available to enhance large-scale kinetic energy, in the vicinity of

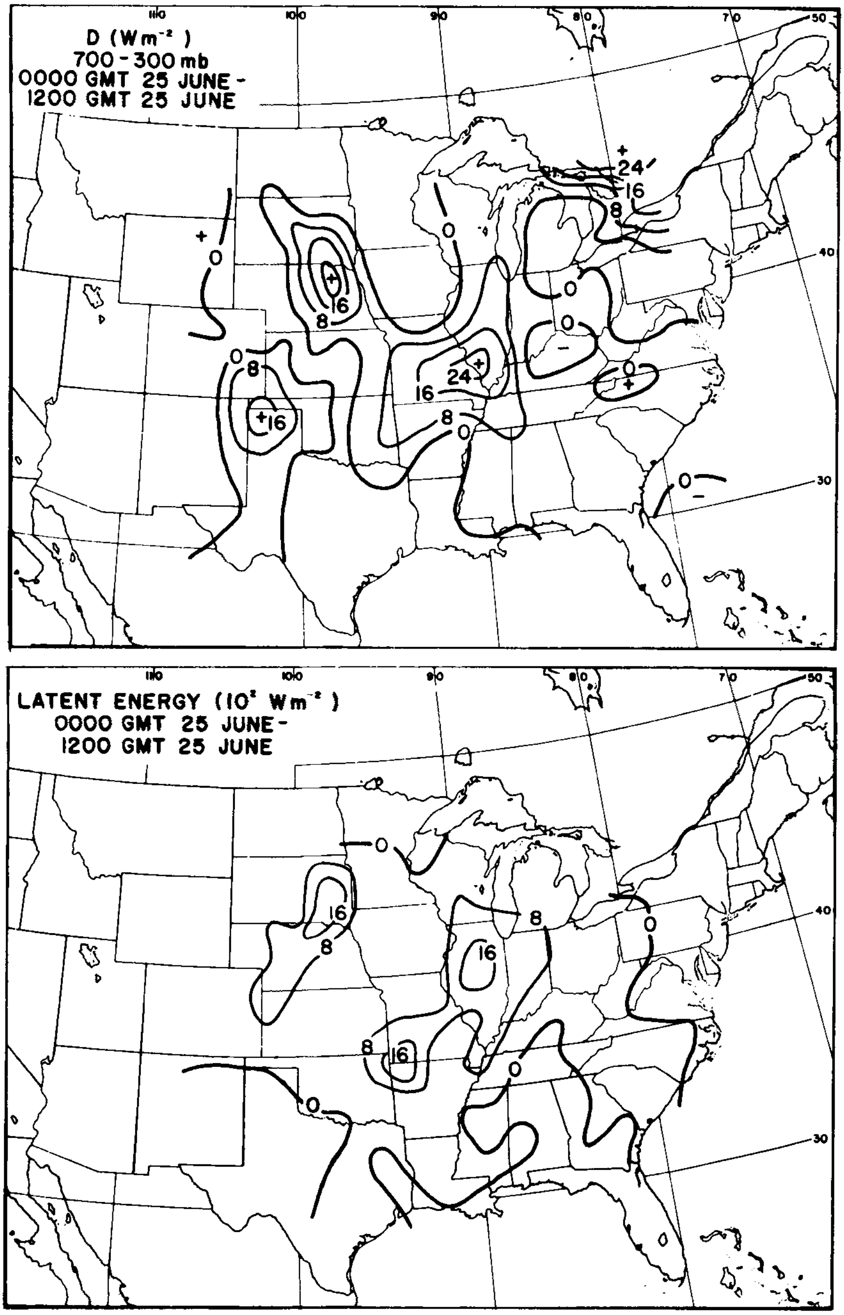

Fig. 8. Kinetic energy dissipation (W m^{-2}) in the 700–300 mb layer for 0000 to 1200 GMT, June 25, 1968 (upper panel), and latent energy released (10^2 W m^{-2}) computed from observed surface precipitation amounts (lower panel). Isopleths have not been drawn for negative dissipation, but values are available in Fig. 7.

the baroclinic zone over Nebraska for the period 0000–1200 GMT, June 25. Conditions there appear to be representative of the model assumptions. Figs. 1 and 2 show that at the beginning of this period widespread deep cumulus convection is occurring with cloud tops reaching

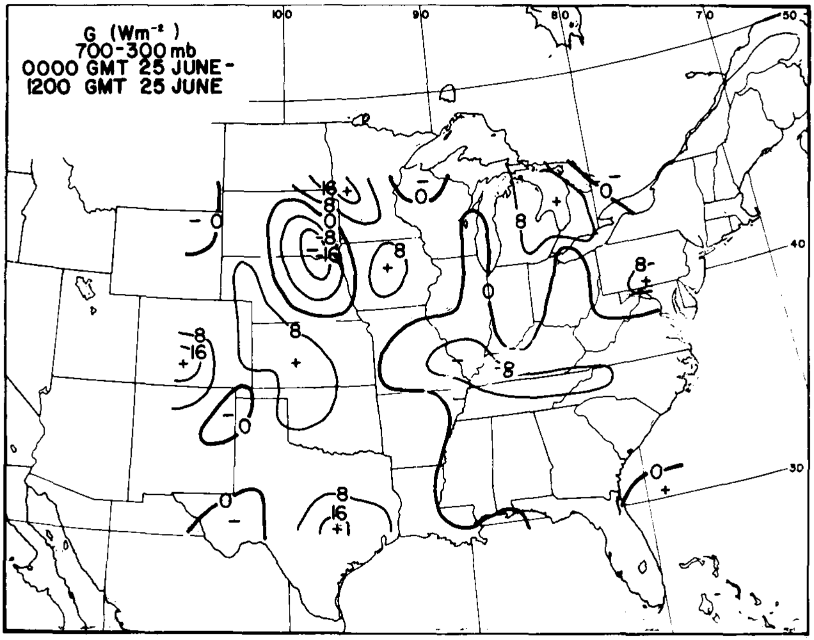

Fig. 9. Kinetic energy generation (W m^{-2}) in the 700–300 mb layer for 0000 to 1200 GMT, June 25, 1968.

13,400 m (44,000 ft), or about 175 mb. Edmon and Vincent (1976) noted that this area contained both large-scale moisture convergence and upward vertical motion, conditions which are favorable for the growth and maintenance of deep cumulus convection.

The average grid point value of CAPE in the vicinity of the area of maximum values of D and latent energy in Fig. 8 (eastern Nebraska) is 300 m^2 s^{-2} for the average surface(950 mb)-to-cloud top (200 mb) layer. The mean value of large-scale vertical wind shear in the cloud layer is about 30 m s^{-1}. Application of Miller and Moncrieff's equations yields a value of 59% for the portion of potential energy released by convection that is directly available to enhance large-scale kinetic energy. Thus, 41% remains to do pressure work. This compares well with the typical values of 62% and 38% given by Miller and Moncrieff.

We shall assume that the deep convection lasts for about 6 hours as it propagates across eastern Nebraska. Individual hourly radar reports verify this. Based on our 59% conversion factor, this yields an increase in large-scale kinetic energy due to the release of convective-scale potential energy in the 950–200 mb layer of approximately 62 W m^{-2}. This value compares favorably with the 700–300 mb values of D (maximum of about 30 W m^{-2}) over eastern Nebraska (Fig. 8), particularly since D is averaged over a 12-hour period, the latter half of which deep convection had subsided. Furthermore, if we assume that 1–2% of the total analyzed area is occupied by deep convection, we arrive at an area-averaged value of large-scale kinetic energy increase due to convection of about 1 W m^{-2}. This value is in good agrement with the mid-to-upper tropospheric values of D given in Fig. 5.

It could be argued that our results are questionable since they depend partly on residual estimates of D, and D contains errors in other terms in the kinetic energy budget equation. Errors can be classified as either systematic or random and include effects of data inaccuracies, physical and mathematical assumptions in the governing equations, and analysis and computational procedures. In particular, in the present study, it was shown that objectively analyzed winds tend to be "smoothed" toward geostrophic (Vincent et al., 1977). This was primarily evident in the short-wave troughs associated with the two areas of active convection.

The effect of errors is difficult to assess quantitatively. In two previous papers concerned with the present case study, KV and Vincent et al. (1977), it was found that magnitudes and subsequent interpretation of energy budget terms were not significantly altered by random fluctuations in the data. In the present paper, Fig. 9 shows that vertically integrated values of G, for the same layer and time period as for D in Fig. 8, are negative in areas of deep convection (where D and DK are positive). Thus, since our objectively analysed winds tend to under-estimate cross-contour flow angles, particularly in convection areas, G may in fact be more negative and D more positive than these results indicate.

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REFERENCES

Chen, T. G. and Bosart, L. F. 1977. Quasi-Lagrangian kinetic energy budgets of composite cyclone-anticyclone couplets. *J. Atmos. Sci. 34*, 452–464.

Chien, H. C. and Smith, P. J. 1977. Synoptic and kinetic energy analyses of hurricane Camille (1969) during transit across the southeastern United States. *Mon. Wea. Rev. 105*, 67–77.

Edmon, H. J., Jr and Vincent, D. G. 1976. An application of two tropical parameterization schemes of convective latent heat release in middle latitudes. *Mon. Wea. Rev. 104*, 1141–1153.

Fuelberg, H. E. and Scoggins, J. R. 1978. Kinetic energy budgets during the life cycle of intense convective activity. *Mon. Wea. Rev. 106*, 637–653.

Kornegay, F. C. and Vincent, D. G. 1976. Kinetic energy budget analysis during interaction of tropical storm Candy (1968) with an extratropical frontal system. *Mon. Wea. Rev. 104*, 849–859.

Kung, E. C. 1970. On the meridional distribution of source and sink terms of the kinetic energy balance. *Mon. Wea. Rev. 98*, 911–916.

Kung, E. C. and Baker, W. E. 1975. Energy transformation in middle latitude disturbances. *Quart. J. Roy. Meteor. Soc. 101*, 793–815.

Kung, E. C. and Smith, P. J. 1974. Problems of large-scale kinetic energy balance—A diagnostic analysis in GARP. *Bull. Amer. Meteor. Soc. 55*, 768–777.

Kung, E. C. and Tsui, T. L. 1975. Subsynoptic-scale kinetic energy balance in the storm area. *J. Atmos. Sci. 32*, 729–740.

McInnis, D. H. and Kung, E. C. 1972. A study of subsynoptic-scale energy transformation. *Mon. Wea. Rev. 100*, 126–132.

Miller, M. J. and Moncrieff, M. W. 1978. Models of deep convection and their large-scale interaction. *Report on the Workshop on the Parameterization of Cumulus Convection*, European Centre for Medium Range Weather Forecasts, Reading, England, pp. 48–72 and 187–199.

Moncrieff, M.W. and Green, J.S.A. 1972. The propagation and transfer properties of steady convective overturning in shear. *Quart. J. Roy. Meteor. Soc. 98*, 336–352.

O'Brien, J. J. 1970. Alternate solutions to the classical vertical velocity problem. *J. Appl. Meteor. 9*, 197–203.

Schlatter, T. W. 1975. Some experiments with a multivariate statistical objective analysis scheme. *Mon. Wea. Rev. 103*, 246–257.

Schlatter, R. W., Branstator, G. W. and Theil, L. G. 1976. Testing a global multivariate statistical objective analysis scheme with observed data. *Mon. Wea. Rev. 104*, 765–783.

Sheu, Y. T. and Smith, P. J. 1977. Kinetic energy budget analysis during a subperiod of the Air Mass Transformation Experiment 1975. *Mon. Wea. Rev. 105*, 1501–1507.

Smith, P. J. 1969. On the contribution of a limited region to the global energy budget. *Tellus 29*, 202–207.

Smith, P. J. 1973a. The kinetic energy budget over North America during a period of major cyclone development. *Tellus 25*, 411–423.

Smith, P. J. 1973b. Mid-latitude synoptic-scale systems: Their kinetic energy budgets and role in the general circulation. *Mon. Wea. Rev. 101*, 757–762.

Smith, P. J. and Adhikary, S. P. 1974. The dissipation of kinetic energy in large-scale atmospheric circulations. *Rev. Geophys. Space Phys. 12*, 281–284.

Sugg, A. L. and Hebert, P. J. 1969. The Atlantic hurricane season of 1968. *Mon. Wea. Rev. 97*, 225–239.

Tsui, T. L. and Kung, E. C. 1977. Subsynoptic-scale energy transformations in various severe storm situations. *J. Atmos. Sci. 34*, 98–110.

Vincent, D. G. and Chang, L. N. 1975. Kinetic energy budgets of moving systems: Case studies for an extratropical cyclone and hurricane Celia, 1970. *Tellus 27*, 215–233.

Vincent, D. G., Schlatter, T. W., Kornegay, F. C. and Edmon, H. J., Jr 1977. Comparison between the NCAR multivariate statistical objective analysis scheme and subjective analysis in a limited area. *Beit. z. Phys. d. Atmos. 50*, 272–283.

Ward, J. H. and Smith, P. J. 1976. A kinetic energy budget over North America during a period of short synoptic wave development. *Mon. Wea. Rev. 104*, 836–848.

ДАННЫЕ О ГЛУБОКОЙ КОНВЕКЦИИ КАК ИСТОЧНИКЕ КИНЕТИЧЕСКОЙ ЭНЕРГИИ В СИНОПТИЧЕСКИХ МАСШТАБАХ

В предыдущей статье Корнегэй и Винсент (1976) рассчитали бюджет кинетической энергии в течение 12 часов в эволюции тропической депрессии над Соединенными штатами. Диссипативный член, вычисленный как остаточный в уравнении бюджета кинетической энергии, оказался положительным в областях конвективных осадков, что побудило авторов высказать гипотезу о том, что подсеточные процессы, именно, глубокая кучевая конвекция, могут снабжать энергией течение синоптического масштаба. Эта возможность исследуется здесь далее. Анализ ранее исследовавшегося случая расширен с 12 до 36 часов и представлены дополнительные данные, включающие гипотезу о возможном механизме переноса энергии от подсеточных к сеточным масштабам.

Рассмотренный случай включает тропическую депрессию, остатки тропического урагана Кэнди и его взаимодействие с развивающимся внетропическим циклоном для периода между 12 часов 24 июня и 0 часов 26 июня 1968 г. универсального времени. Рассмотрение кинетической энергии основывается на многомерном статистическом анализе радиозондовых наблюдений. Области увеличения кинетической энергии и положительной диссипации (диссипации, действующей как источник энергии) приближенно совпадают; они отмечены присутствием глубокой конвекции, о чем свидетельствуют радарные наблюдения и количество осадков. Увеличение кинетической энергии и положительная диссипация первоначально наибольшие в слое 700–500 мб, по мере того, как тропическая депрессия и циклон средних широт начинают взаимодействовать. Однако спустя 12 часов наибольший рост кинетической энергии и наибольшая положительная диссипация наблюдаются выше в тропосфере, в слое от 500 до 300 мб.