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A Study of Subsynoptic Scale Energy Transformations[1,2]

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ABSTRACT—Kinetic energy transformations from the viewpoint of energetics of the large-scale circulation are investigated with a series of subsynoptic scale radiosonde network soundings. Individual terms of the kinetic energy equation are evaluated along with the gradient form of the Richardson number.

A bimodal character of the vertical profile of kinetic energy generation having maxima in the upper and lower troposphere that is similar to what we observe in the general circulation-scale disturbances is observed in the subsynoptic scale disturbances studied. However, the inflow of kinetic energy into the area indicates that, on the average, more kinetic energy could be dissipated than generated even during intense thunderstorm activity. Large pulsations of kinetic energy generation and dissipation with time are observed. Extrema of upper level generation are observed to occur mainly in layers where the Richardson number is relatively low.

1. INTRODUCTION

Because the mesoscale processes represent the critical link between large-scale disturbance and small-scale turbulence, energetics of subsynoptic scale motions are important in the context of the general circulation research. Yet, this is still a new field open for investigation.

All scales of motion in the atmosphere are eventually related, but techniques of investigation that prove fruitful for a given scale will frequently fail for others. Mesoscale research relies heavily on case studies of individual episodes. Dynamical studies of the general circulation are generally based on broad assemblages of data arising from large networks or from the output of numerical experiments. The work presented here is an attempt to examine the subsynoptic scale kinetic energy transformations. Although methods of large-scale research are employed, the data used can be categorized as "mesoscale"—of a much smaller scale than is customary in this research field.

The data were gathered in April, May, and June of the years 1966 and 1967 by the National Oceanic and Atmospheric Administration's National Severe Storms Laboratory (NSSL) in Norman, Okla., using a radiosonde network of 10–11 stations located principally in southwestern Oklahoma (fig. 1). The soundings were initiated at times when thunderstorms were expected in the area. Because of the close spacing of the network stations, the resulting data offered an opportunity to study some aspects of energetics of subsynoptic scale motions during the period.

A general scheme of analysis, devised for radiosonde network data of this scale, is based upon the primitive equations of motion in the framework of the large-scale dynamics. Special features of the devised analytical scheme include the correction of systematic errors arising from the drift of the radiosonde balloons. The kinetic energy generation and the other terms of the kinetic energy equation are evaluated and discussed. As an aid to studying the vertical profiles of kinetic energy generation in relation to layers of turbulence, an area-mean version of the gradient form of the Richardson number is evaluated as a reference.

It must be noted that the network is too coarse to resolve details deriving from individual storm cells, although it has a much higher density than ordinary upper air networks, being confined to an area of less than 80,000 km^2. The use of radiosonde data from a network of this scale also involves certain technical difficulties. Although a very cautious attitude was maintained throughout the data editing and computation, this paper is best viewed as exploratory in nature. We want to emphasize that we do not try to trace individual mesoscale disturbances here, but that we are attempting to view the subsynoptic scale energy transformations as a link between large-scale circulation and small-scale turbulence.

2. BASIC FORMULATION

Radiosonde observation data form the basis for all calculations in this study; thus, the assumption of hydrostatic equilibrium is imposed at the outset. Since the data regime normally encompasses convective cells undergoing nonhydrostatic vertical accelerations, one must recognize that this assumption is a potential source of distortion. The degree to which the analytical model is made unrealistic can be determined only through independent measurements not themselves relying on the hydrostatic assumption.

Taking the scalar product of the horizontal wind vector and each term in the primitive equation of horizontal motion and applying the equation of mass continuity, we

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obtain the kinetic energy equation (Kung 1966, 1969). Integration over the area, A, of the observational network and application of the divergence theorem then produces the area mean kinetic energy equation:

$$\frac{\partial \bar{k}}{\partial t}+\frac{1}{A}\oint_c \mathbf{V}k\cdot\mathbf{n}ds+\frac{\partial \overline{\omega k}}{\partial p}=-\overline{\mathbf{V}\cdot\nabla\phi}-\overline{\mathbf{V}\cdot\mathbf{F}}$$

in which $\mathbf{V}$ is the vector of the horizontal wind, $k=(\mathbf{V}\cdot\mathbf{V})/2$, the kinetic energy per unit mass, t the time, p the pressure, ϕ the geopotential, $\omega=dp/dt$ the vertical p-velocity, $\mathbf{F}$ the vector of the frictional force per unit mass, ∇ the horizontal del operator along an isobaric surface, $\mathbf{n}$ the outward-directed unit vector normal to the boundary, s, of the network area, and the horizontal bar denotes the area mean of a quantity over the area A. Throughout this paper, the following notations will be used to represent terms in the above area-mean kinetic energy equation:

$$\mathrm{L}=\frac{\partial \bar{k}}{\partial t}=\text{local change of kinetic energy,}$$

$$\mathrm{H}=\frac{1}{A}\oint_c \mathbf{V}k\cdot\mathbf{n}ds=\text{horizontal outflow of kinetic energy,}$$

$$\mathrm{W}=\frac{\partial \overline{\omega k}}{\partial p}=\text{vertical transport of kinetic energy,}$$

$$\mathrm{G}=-\overline{\mathbf{V}\cdot\nabla\phi}=\text{kinetic energy generation,}$$

and

$$\mathrm{E}=\overline{\mathbf{V}\cdot\mathbf{F}}=\text{kinetic energy dissipation.}$$

These terms in the area-mean kinetic energy equation are integrated over each pressure layer using the hydrostatic relationship. To avoid cumbersome notation, vertical integrals will not be written for those energy variables.

The vertical velocity in isobaric coordinates is obtained kinematically by integrating the equation of mass continuity with respect to pressure; the boundary condition that $\omega=0$ is applied at the earth's surface.

Two important advantages of basing the analysis on the primitive equations should be noted: first, this approach requires a minimum of special restrictions, and second, it is in agreement with the fundamental numerical model used in general circulation research and numerical weather prediction.

To gain some insight into the potential for turbulence in a given layer, we obtained vertical profiles of the Richardson number (Ri). At present, even the meaning of the Richardson number in the free atmosphere is controversial. However, with the general recognition of the existence of turbulence in the free atmosphere that can be detected by radiosonde observations, the estimate of the Richardson number is an interesting problem. Panofsky et al. (1968) state that there is poor agreement between theory and observation. They note that radar soundings can show wind detail not available in the temperature soundings, which presents a smoothing problem; on the other hand, ordinary rawinsonde soundings generally oversmooth the wind data and systematically underestimate the shear. Reiter (1968) suggests that Ri is an increasing function of selected height interval Δz.

Despite these difficulties, we employ the Richardson number in this study to obtain a relative measure of the potential for atmospheric turbulence, but not to determine the value of a critical Richardson number separating growth and decay of the turbulence. Therefore, if a fixed interval Δz is selected, and if the rawinsonde soundings systematically overestimate Ri, then the shape of the vertical profile of Ri is still maintained and can provide a useful, if somewhat crude, measure of turbulence potential in the free atmosphere.

The gradient form of the Richardson number,

$$\mathrm{Ri}=\frac{g}{\theta}\frac{\partial\theta}{\partial z}\left|\frac{\partial \mathbf{V}}{\partial z}\right|^{-2},$$

is computed first for individual soundings and then in a mean form described in the next section.

3. DATA AND SCHEME OF ANALYSIS

All soundings used in this study were made by NSSL in southwest Oklahoma during spring 1966 and spring 1967, at the upper air stations shown in figure 1. The average separation between sites is about 85 km. This network was designed to operate during periods of significant convective activity, and so prior to expected stormy weather the network was activated simultaneously at all operable stations. These soundings were terminated at 100 mb, permitting an interval of approximately 90 min. to be maintained between releases. This nearly continuous operation was maintained until major convective activities had ceased. Compared with ordinary synoptic soundings, this set has much higher resolution in time and in space. The balloon position during ascent is accurately recorded. From the original NSSL data archive, a restructured magnetic tape was written that contains the information used as the basis for this study. This effort is detailed in Kung and McInnis (1969).

A total of 291 separate soundings from the restructured tape were utilized. In general, each sounding belongs to a "family" of nearby simultaneous soundings, and a series of families spaced at 90-min. intervals, called a "case," constitutes the essential data unit analyzed in this study. The soundings used here constitute nine separate cases, identified by the dates (CST) of initiation as follows:

4/22/66	(5 families, 41 soundings)
5/20/66	(7 families, 59 soundings)
5/31/66	(4 families, 39 soundings)
6/08/66	(8 families, 74 soundings)
5/20/67	(4 families, 22 soundings)
5/28/67	(5 families, 31 soundings)
5/30/67	(7 families, 60 soundings)
6/08/67	(3 families, 25 soundings)
6/10/67	(5 families, 40 soundings).

In most large-scale analyses, radiosonde soundings are treated as vertical probes occupying fixed positions with respect to the earth's surface. In this study, however, it

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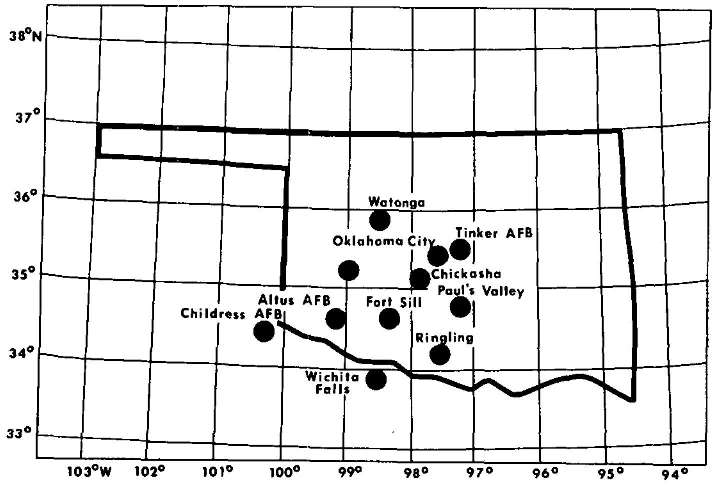

FIGURE 1.—National Severe Storms Laboratory 1966–67 mesoscale upper air network.

is necessary to determine each ballon's position in space and time for each reported level. Matters are further complicated by varying termination heights that cause recurring redefinitions of the reporting network geometry. All of these special requirements have been satisfied in a computer objective analysis program as described by McInnis (1970).

The estimation of the space variation of meteorological variables constitutes one of the fundamental technical difficulties in diagnostic studies with real atmospheric data because the data are of limited accuracy and are obtained from stations in an irregular configuration. The method chosen here was the representation of the space variation of a meteorological variable by a polynomial surface which best fits the data in the least-squares sense. If we have between 7 and 11 data points, we determine a smoothed quadratic surface; for six points, an unsmoothed quadratic surface. Below six, the computations are automatically shifted to determine either a smoothed plane, or in the minimal case of three points, an unsmoothed plane.

The generation term, $-\mathbf{V}\cdot\nabla\phi$, was estimated at each reporting station at each pressure level with the observed wind and partial derivatives of ϕ as approximated from the polynomial surface. An average value of $-\mathbf{V}\cdot\nabla\phi$ was than taken over all reporting stations as the estimate of the area-mean generation, G.

The vertical transport term, $\mathrm{W}=\partial\overline{\omega k}/\partial p$, was approximated by $\partial\bar{\omega}\bar{k}/\partial p$ since the area mean vertical velocity, $\bar{\omega}$, obtained from the horizontal divergence of the entire polygonal area, was the only vertical motion field computed. The estimate of the horizontal divergence field was based on the relationship

$$\nabla\cdot\mathbf{V}=\frac{1}{A}\oint_c \mathbf{V}\cdot\mathbf{n}ds.$$

Thus, in this study, evaluation of the two energy variables, horizontal outflow, H, and vertical transport, W, depended directly and indirectly on the evaluation of line integrals along the boundary of the polygon. For this, the values of $\mathbf{V}$ and k were interpolated along the polygon boundary using the computed polynomial surfaces of variables for each set of nearby simultaneous observations to evaluate line integrals.

The local change of kinetic energy, L, was evaluated at each level with $\Delta t=90$ min for the first and last observations of each case and with $\Delta t=180$ min otherwise.

In a diagnostic study of an exploratory nature like this one, it is essential to obtain the dissipation, E, without employing specific theories about the dissipation mechanism. Here, E was obtained as a residual term in the area-mean kinetic energy equation; indeed, until frictional processes in the atmosphere are better understood, this remains the theoretically valid procedure available with the least assumptions (Kung 1969, 1970).

Richardson numbers were calculated for the 500-m layer for each set of soundings. For this purpose, all original data were reinterpolated for 500-m increments. At each station, for the layer bounded by levels L and $L+1$,

$$\theta_L=(T_L+273°)\left[\frac{1000}{p_L}\right]^{0.286},$$

$$\bar{\theta}=\frac{(\theta_L+\theta_{L+1})}{2},$$

and

$$\mathrm{Ri}\approx\frac{500g(\theta_{L+1}-\theta_L)}{\bar{\theta}\{SP_L^2+SP_{L+1}^2-2SP_LSP_{L+1}\cos[0.017(DI_{L+1}-DI_L)]\}}$$

where SP_L and DI_L are the speed and direction of the wind at one particular station at level L. To obtain a value of Ri representative of the entire horizontal area A at a given level L, means of θ, $\partial\theta/\partial z$, and $\partial\mathbf{V}/\partial z$ were obtained over all n reporting stations, then combined to form Ri in the same manner given above.

A quantitative analysis of all errors inherent in the data and in the method of analysis will not be attempted. It should be noted that this data analysis shares a common difficulty with other general circulation research—the error components in space and time have a very complicated nature. Judgments of validity are therefore normally based on the degree to which the analyses appear systematic and on comparisons with other parallel but independent research efforts. Two papers by Kurihara (1960, 1961) and one by Kung (1969) bear specifically on these matters. In an affirmative sense, it should be recognized that the method of analysis we have used essentially eliminates methodical errors caused by the drift of the radiosonde balloons, and also that observed wind and geopotential data of this sample size should give a useful estimate of the terms in the kinetic energy equation.

Aside from the recognized error sources, there are others which are in some way particular to this study. Early in the data analysis, cases were found in which a

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TABLE 1.—*Kinetic energy variables averaged over all nine cases*

Pressure layer	$\bar{k}$	H	W	G	E
(mb)	(10^5 J·m^{-2})	(W·m^{-2})	(W·m^{-2})	(W·m^{-2})	(W·m^{-2})
Surface–900	0. 60	−1. 53	1. 33	7. 16	7. 36
900–800	0. 75	−0. 71	1. 39	3. 69	3. 01
800–700	0. 70	−0. 08	0. 66	−1. 19	−1. 77
700–600	1. 00	−3. 79	3. 78	−3. 42	−3. 41
600–500	1. 30	−5. 95	5. 15	−2. 38	−1. 58
500–400	1. 65	−1. 35	1. 97	−3. 92	−4. 54
400–300	2. 05	2. 19	−0. 20	−3. 24	−5. 23
300–200	3. 10	4. 25	2. 93	9. 88	2. 70
200–100	3. 40	−1. 91	−10. 37	17. 23	29. 51
Vertical totals	14. 55	−8. 88	6. 64	23. 81	26. 05

TABLE 2.—*Vertical totals of kinetic energy variables from the surface to 100* mb *for case 5/30/67 at each observation time*

Launch time	$\bar{k}$	L	H	W	G	E
(CST)	(10^5J·m^{-2})	(W·m^{-2})	(W·m^{-2})	(W·m^{-2})	(W·m^{-2})	(W·m^{-2})
1100	12. 91	59. 21	56. 69	−9. 73	34. 85	−71. 32
1230	16. 10	38. 66	− 0. 42	−3. 86	145. 24	110. 86
1400	17. 08	32. 23	− 14. 03	−9. 49	−206. 80	−215. 51
1530	19. 59	19. 49	− 33. 08	2. 35	610. 69	621. 93
1700	19. 19	16. 54	− 62. 86	6. 43	112. 28	152. 17
1830	20. 54	15. 76	− 33. 53	12. 98	90. 45	95. 24
2000	20. 50	−7. 83	−150. 62	61. 49	−48. 52	48. 44

particular station had reported pressure heights systematically at variance with our reconstruction of the synoptic field. Those situations were carefully checked, and suspicious soundings were eliminated from the analysis. Those reports which indeed are in error can most likely be traced to mistakes in reading surface pressure and errors in temperature readings. Another potential source of error is the variance in arrival time at a particular pressure level by the radiosonde balloons. In the analysis of standard operational synoptic soundings, these variances are usually neglected. It should be pointed out, however, that a 15-min launch time deviation could result in a displacement error of as much as 15 km for the position of a given balloon. The number of deviations this large were so few that they were ignored in the analysis and probably have had only minor influences on the computations.

4. KINETIC ENERGY BUDGET

Table 1 summarizes the kinetic energy variables $\bar{k}$, H, W, G, and E by 100-mb layers as the overall averages over the nine separate cases. These overall average values of area-mean kinetic energy $\bar{k}$, horizontal outflow H, vertical transport W, and generation G were obtained as the average of the time-mean values. The time-mean values were calculated separately in each case for the individual values originally computed for each family of near-simultaneous soundings for 20-mb layers from the surface to 100 mb. The dissipation E was obtained as the residual to balance the overall average values of H, W, and G in the kinetic energy equation. The local change, L, was neglected for its smallness in the overall averages.

From the profiles presented in table 1, we may roughly partition the atmosphere into three layers. In the bottom layer from the surface to 800 mb, we observe low kinetic energy, horizontal inflow and vertical outflow of kinetic energy, and positive generation and dissipation of kinetic energy. In the middle layer from 800 to 300 mb, there is an increase of kinetic energy, large horizontal inflow and vertical outflow, and negative generation and dissipation. In the top layer from 300 to 100 mb, the kinetic energy and generation and dissipation of the kinetic energy reach their maximum values, whereas the horizonal outflow (positive H) and vertical inflow (negative W) are indicated for this layer.

Turning to consideration of the general aspects of the calculated energy variables, we note a large variation, expecially near tropopause level. Table 2 presents the kinetic energy variables $\bar{k}$, L, H, W, G, and E, which are integrated from the surface to 100 mb, for case 5/30/67 at each observation time. The large variation in the vertical profile of G is also seen in figures 3, 4, and 5.

A cautionary note is in order before proceeding with further discussion of our computations. It must be stressed that the NSSL upper air network is still too coarse to allow us to trace the individual mesoscale events in the kinetic energy budget. Tempting though this exercise

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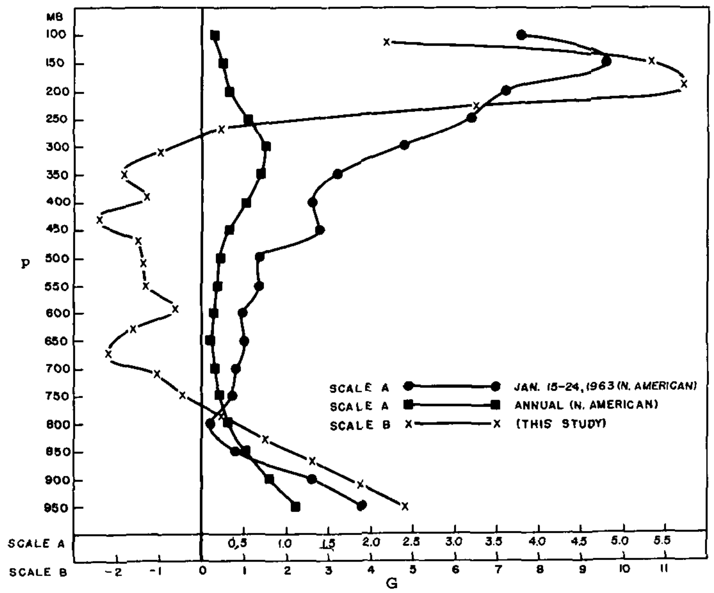

FIGURE 2.—Vertical profile of average kinetic energy generation, G, obtained in this study and those obtained by Kung (1966, 1969) over North America for a 5-yr period and during Jan. 15–24, 1963. Units are $W \cdot m^{-2} \cdot (50\ mb)^{-1}$.

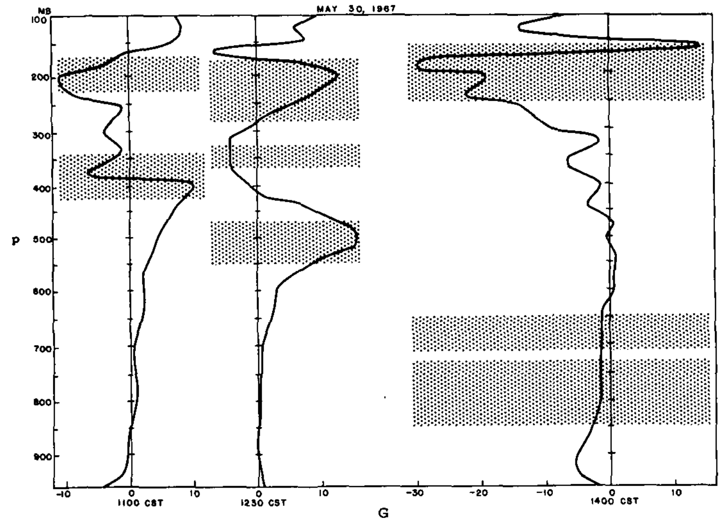

FIGURE 3.—Vertical profiles of kinetic energy generation, G, for case 5/30/67 at 1100, 1230, and 1400 CST observation times. The layers of $Ri < 1$ are indicated by shaded areas. Units are $W \cdot m^{-2} \cdot (20\ mb)^{-1}$.

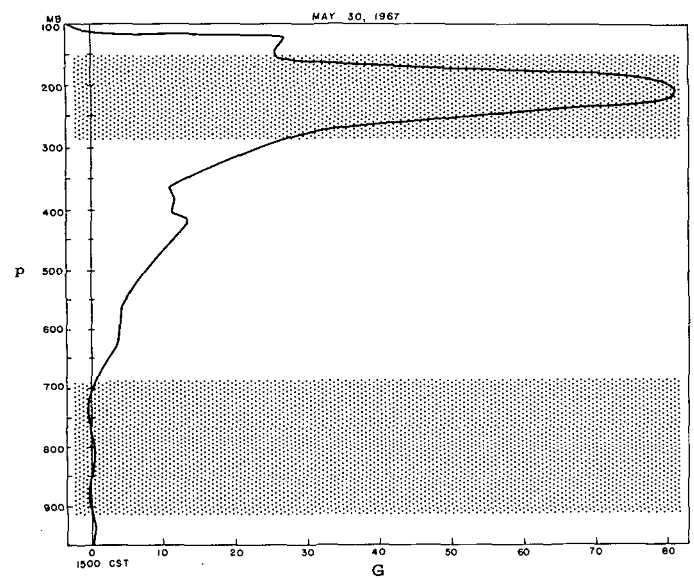

FIGURE 4.—Same as figure 3 for 1500 CST observation time.

may be, two important factors weigh against it. First, the length scale of thunderstorm activities is approximately two orders of magnitude smaller than the synoptic scale disturbances. Second, the NSSL soundings were deliberately launched in a manner to avoid penetration of active storm centers and therefore largely reflect the characteristics of the environmental air rather than the processes within the storms. Yet, the storm cells may function as the principal centers of mesoscale kinetic energy processes.

5. PROBLEMS OF ENERGY TRANSFORMATIONS

We know that for both individual synoptic scale cyclones and subsynoptic scale storms, kinetic energy is received from and returned to large scales of motion, although not much information is available about the direction of the net flow. Sechrist and Dutton (1970) recently examined the energy budget associated with a cyclone over the eastern United States. Among their findings, they note that the storm did extract high-level kinetic energy west of its center during its formative stages, then later it supplied kinetic energy to high levels east of the storm center. Much the same sort of exchange can occur between a well-organized squall line and its environment (Palmén and Newton 1969). This study likewise gives evidence of active kinetic energy transfer to and from larger scales of motion; note the alternation in signs of H and G in table 2.

The average of G over all nine separate cases is plotted in a vertical profile for 50-mb layers in figure 2 along with those of the general circulation scale previously given by Kung (1966, 1969). As seen in table 1 and figure 2, there is a positive peak of about 7 $W \cdot m^{-2}$ in the surface to 900-mb layer, and another positive peak of about 17 $W \cdot m^{-2}$ in the 200- to 100-mb layer. Normally, the midtropospheric winds are nearly geostrophic, resulting in small absolute values of generation for that region. However, storm interference with midlevel geostrophic flow could give rise to significant generation values in the middle troposphere as shown in figures 3, 4, and 5. The disappearance of midtroposphere generation in the mean over all cases is due to the balance with the negative generation in the time series.

The similarity of the average generation profile during thunderstorm periods to that of the general circulation

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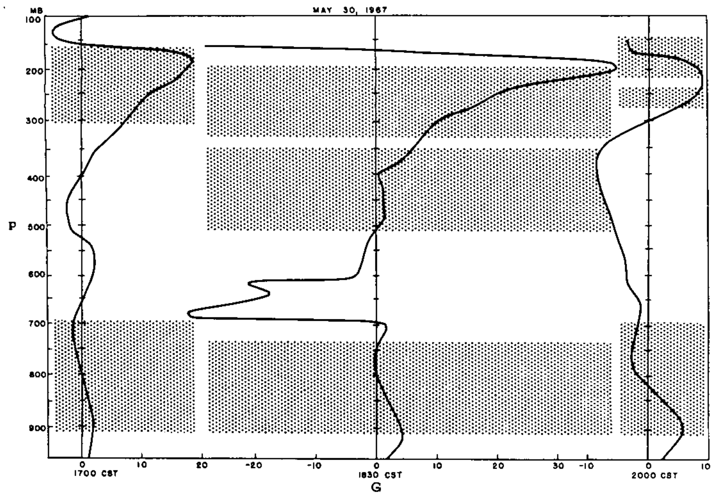

FIGURE 5.—Same as figure 3 for 1700, 1830, and 2000 CST observation times.

scale as shown in figure 2 is interesting, even though the average in this study is based on a small number of cases. Beyond their general similarity, we should note an important difference: whereas Kung (1966, 1969) and others have estimated the surface and tropopause-level generation peaks to be of roughly the same magnitude in the seasonal or annual mean, this study finds that on the subsynoptic scale the upper peak is more than twice as great as the lower peak on the average over all cases. In this regard, it is interesting to compare the overall generation profile with the one also shown in figure 2 that was calculated by Kung (1966) for the period Jan 15–24, 1963, when a strong cyclone system dominated the North American Continent. Kung's profile over North America during that period shows much greater generation in the upper troposphere than in the lower troposphere. The similarity in shape is suggestive of analogous energy processes on greatly different scales. There may be some indication in this study that thunderstorm activity can serve as a source of upper level kinetic energy generation on the subsynoptic scale. There is no evidence here, however, that the analogy can be extended to the transport terms. Whereas a significant amount of kinetic energy is transported out of the continental size cyclone as shown by Kung (1966) for the period Jan. 15–24, 1963, the horizontal transport H in this study shows inflow of kinetic energy to the area. This might suggest that the thunderstorm activity consumed energy supplied from the larger scales of motion in addition to that generated in the system itself.

As shown in table 2, the range of values of computed energy transformations is quite large. The range of those variations is, in fact, one to two orders of magnitude larger than most published values of kinetic energy conversion for global averages or continental approximations to the global averages. It is instructive to note the variation in values of these same energy parameters as obtained by Holopainen (1964) over a radiosonde network in the British Isles. His generation and dissipation values vary over a range of 200–300 $W \cdot m^{-2}$, in general exceeding the variation obtained in this study for the same layer. Certain computational uncertainties shall have been involved in these variations, but it is not surprising to find these variations in view of the possibly significant role of internal gravity waves above the lower troposphere.

As argued by Kung (1970), the dissipation E obtained as the residual should indicate the energy removed from the observation network scale, but does not necessarily represent the actual viscous dissipation processes.

In the overall average (table 1) and also in the majority at the individual observation times (table 2), the dissipation is a positive value one to two orders of magnitude larger than the global average or its approximations. It is also observed that, in this study, the dissipation tends to be noticeably larger than the generation due to large inflow of kinetic energy as indicated by H. This might suggest that severe turbulence phenomena of subgrid size perform active roles in addition to, or instead of, the uniform large-scale decay of the kinetic energy. The dissipative roles of clear air turbulence as suggested by Trout and Panofsky (1969) and that of cumulus convection as proposed by Gray (1969) are in line with this suggestion.

The generation profiles for each set of soundings in case 5/30/67 are given in figures 3, 4, and 5 along with the indication for the region of low Richardson number ($Ri < 1$). Acknowledging that the Richardson number computed in this study is only a crude indicator of the potential for atmospheric turbulence, it is nevertheless noteworthy that positive or negative peaks of the upper level generation are generally found in layers where Ri has a low value. Perhaps the high-level peaks of generation and dissipation occur in regions where the potential for subsynoptic scale "turbulence" is high. That the lower layers of the atmosphere have low values of Ri but no corresponding generation peaks may indicate that turbulent energy transfers are not detectable with observations of this scale in the lower troposphere.

6. REMARKS

The research reported in this paper was performed as one phase of the continuing diagnostic study of energetics of the general circulation supported by the Atmospheric Sciences Section, National Science Foundation, under NSF Grant GA-15952. As noted in the introduction, this study serves only as an initial investigation of subsynoptic scale energetics. Detailed examination of other aspects of the subsynoptic scale energy transformation is in progress from other angles of the problem and will be reported subsequently.

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