Energy Sources in Middle-Latitude Synoptic-Scale Disturbances[1,2]

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ABSTRACT

Energy source terms in various types of mid-latitude synoptic-scale disturbances are examined with more than 3400 computed synoptic cases during a 5-year period over North America.

It is shown that cyclones and cyclone vicinities serve as the baroclinic energy source regions, although the released energy through the eddy conversion process may be transported to other regions for generation of the kinetic energy. In the development and mature stages of cyclonic disturbances the eddy energy conversion is very active both within the cyclones and their vicinities. When cyclones are occluded the cyclone vicinities lose their importance as the baroclinic source region. In contrast to cyclonic disturbances, anticyclonic disturbances destroy kinetic energy.

In intermediate type disturbances there is a significant generation of kinetic energy. However, there is no internal energy source through the eddy conversion in these disturbances, and they depend on imported potential energy for their kinetic energy generation.

1. Introduction

The importance of studying the energetics of mid-latitude synoptic-scale systems has been emphasized by various authors (e.g., Newton, 1970; Pearce, 1974; Petterssen and Smebye, 1971). Not only is it an essential link between theoretical research and practice in weather analysis and forecasting, but the problem is also fundamental in the development of meteorological science.

The majority of the recent energetics studies of mid-latitude systems were case studies of individual cyclones. Careful case studies of individual systems are required in the understanding of energy transformations that take place in the complex system of disturbances. However, the examination of selected cases alone is not sufficient when we delve into the roles of extratropical disturbances in the general circulation of the atmosphere. Complementing the detailed studies of selected cases, it is desirable to investigate the ensemble properties of various types of systems with a large data sample. It has been long recognized that in general synoptic-scale disturbances play a dominant role in energy transformations in the middle latitudes (e.g., Newell *et al.*, 1970; Oort, 1964; Palmén and Newton, 1969; Starr 1959; Wiin-Nielsen, 1959). By focusing our attention on the gross energy budget of various types of disturbances, the study of the specific roles of evolving, transient disturbances in the maintenance of the circulation in the middle latitudes will be facilitated.

In our preceding paper (Kung and Baker, 1975), the kinetic energy balance was computed over a defined continental area over North America for individual observation times twice-daily during a 5-year period. The computed energy budgets were then grouped into 11 predetermined categories of transient disturbances according to the flow pattern over the area. Through the examination of energy budgets in different groups of synoptic patterns, the kinetic energy balance of various cyclonic, anticyclonic and intermediate flow types were discussed.

Following that study of the kinetic energy balance, the problem of energy sources in relation to kinetic energy generation is pursued in this study for the various types of disturbances with the same set of data over a 5-year period. Whereas the study of kinetic energy balance is more concerned with the mechanisms by which these disturbances are maintained, an examination of energy source terms may give more information about the roles of these disturbances in the maintenance of the general circulation.

2. Energy source terms

The kinetic energy equation in the framework of primitive equations may be written in hemispherical polar coordinates as

$$\frac{\partial k}{\partial t}+\nabla\cdot\mathbf{V}k+\frac{\partial\omega k}{\partial p}=-\mathbf{V}\cdot\nabla\phi-E,\qquad(1)$$

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where $k=\frac{1}{2}\mathbf{V}\cdot\mathbf{V}$ is the kinetic energy per unit mass, $\mathbf{V}$ the horizontal wind vector, p the pressure, $\omega=dp/dt$ the vertical p velocity, E the dissipation, t the time, ϕ the geopotential and ∇ the horizontal del operator. The production of kinetic energy in the kinetic energy balance is presented by the cross-isobaric generation $-\mathbf{V}\cdot\nabla\phi$, and if Eq. (1) is integrated over the entire mass M of the atmosphere, we have

$$\frac{\partial}{\partial t}\int_M kdM=-\int_M \mathbf{V}\cdot\nabla\phi dM-\int_M EdM. \tag{2}$$

We may also have for the production term (see Kung, 1966)

$$-\int_M \mathbf{V}\cdot\nabla\phi dM=-\int_M \omega\alpha dM. \tag{3}$$

Eq. (2) states that for the entire mass of the atmosphere the maintenance and intensity of the general circulation depend on the balance between generation and dissipation of the kinetic energy. The kinetic energy is supplied through the conversion of the available potential energy, which is represented by the process $-\omega\alpha$ where α is the specific volume of the air. Eq. (3) states that for the entire mass of the atmosphere the measurement of the source term $-\omega\alpha$ will yield that of the generation.

When the kinetic energy balance in individual disturbances is to be investigated, however, the kinetic energy equation can only be integrated for a limited mass of the atmosphere, and all terms in Eq. (1) should be examined for different layers over a restricted region as we did in our preceding paper (Kung and Baker, 1975). To further study the energy sources for production of the kinetic energy in individual disturbances, the cross-isobaric generation term $-\mathbf{V}\cdot\nabla\phi$ for a layer of the atmosphere over a region may be expressed as

$$-[\mathbf{V}\cdot\nabla\phi]=-[\nabla\cdot\mathbf{V}\phi]-[\partial\omega\phi/\partial p]-[\omega\alpha]. \tag{4}$$

Square brackets on a dummy variable X per unit mass denote an area mean over a limited mass of the atmosphere, i.e.,

$$[X]=\frac{1}{gA}\int_{p_1}^{p_2}\int_A XdAdp, \tag{5}$$

where g is the acceleration of gravity, A the area of the region and $p_2>p_1$.

Terms on the right-hand side of (4) are three source terms related to the kinetic energy generation: $-[\omega\alpha]$ is the release of the available potential energy which is customarily regarded as the conversion of available potential energy to kinetic energy; and the horizontal and vertical flux convergences of potential energy, $-[\nabla\cdot\mathbf{V}\phi]$ and $-[\partial\omega\phi/\partial p]$, respectively, may be regarded as the redistribution of the released energy, relating the supply of kinetic energy to the pressure interactions at the boundaries.

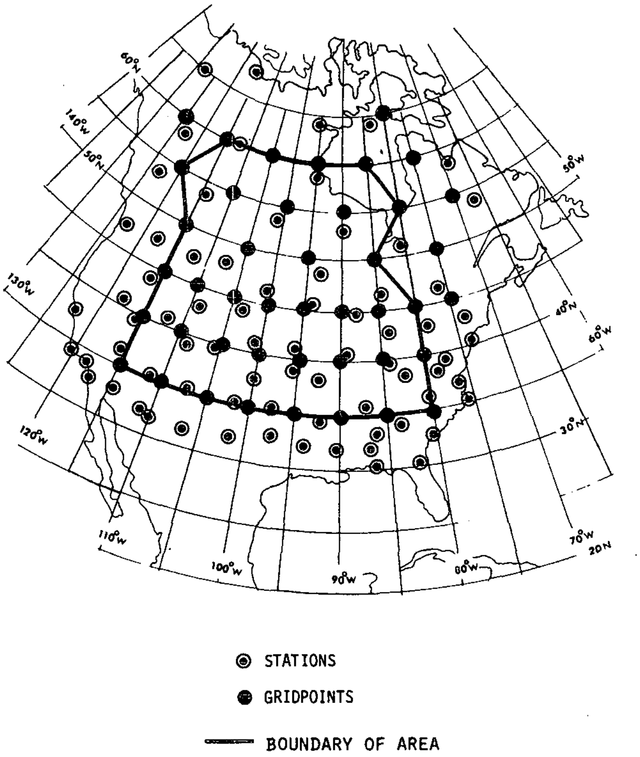

FIG. 1. Upper air stations and analysis grids.

For a limited region of the upper air network, like the defined continental area in this study (see Fig. 1), a convenient way to describe the spatial disturbance is to partition a meteorological variable into area mean and perturbation from the area mean. If the area mean value of a dummy variable X along an isobaric surface is defined by

$$\bar{X}=\frac{1}{A}\int_A XdA, \tag{6}$$

then

$$X=\bar{X}+X^*, \tag{7}$$

where the eddy quantity X^* is the perturbation or departure from the area mean $\bar{X}$ at any point in the area at that isobaric level. The adequacy and usefulness of this partitioning in the study of the large-scale energetics were verified by Eddy (1965) over North America and by Kung (1975) over the Marshall Islands area. With the definition of the area mean and spatial disturbances as in (7), Eq. (4) may be rewritten as

$$-[\mathbf{V}\cdot\nabla\phi]=-[\nabla\cdot\mathbf{V}\phi]-[\omega^*\alpha^*]-[\partial\omega^*\phi^*/\partial p]+RS, \tag{8}$$

where

$$RS=-[\bar{\omega}\bar{\alpha}]-[\partial\bar{\omega}\bar{\phi}/\partial p]. \qquad (9)$$

The horizontal transport term $-[\nabla\cdot\mathbf{V}\phi]$ measures the source of kinetic energy as the import of potential energy to the area through pressure interaction at the lateral boundary. The eddy conversion $-[\omega^*\alpha^*]$ and eddy vertical pressure interaction $-[\partial\omega^*\phi^*/\partial p]$ are the release of available potential energy and the vertical redistribution of the released energy within the synoptic-scale system by the eddies whose scales are resolvable with the defined upper air network. Effects of disturbances whose scales are larger than what are resolvable with the network are not explicitly measured in $-[\omega^*\alpha^*]$ and $-[\partial\omega^*\phi^*/\partial p]$, although the direct computation of $-[\mathbf{V}\cdot\nabla\phi]$ should give the measure of the actual cross-isobaric generation in the area. Therefore, the term RS is considered to be the residual source of kinetic energy from the larger scale processes which are not resolved with the given upper air network area. The defined area in this study (see Fig. 1) cannot resolve the eddy disturbances whose scales are larger than that of zonal wavenumber $n=10$. Therefore the internal baroclinic energy source in disturbances as represented by the eddy conversion $-[\omega^*\alpha^*]$ is the conversion in the short-wave range whose wavenumbers are $n=10$ and higher. A significant contribution to the eddy energy conversion from the longer waves whose wavenumbers are less than 10 may then be expected, since it has been well established that the intermediate-scale waves with $n=5$–8 are very active in energy conversion (Saltzman and Fleisher, 1960, 1961; Wiin-Nielsen, 1959). The residual source term RS, as seen in Fig. 7, is contributed from $-[\bar{\omega}\bar{\alpha}]$ since $-[\partial\bar{\omega}\bar{\phi}/\partial p]$ integrates out vertically. The vertical total of this residual terms RS should then represent the eddy conversion in the larger scale disturbances which cannot be resolved by the defined network data.

3. Data utilization and scheme of analysis

In our systematic energetics diagnosis of middle-latitude general circulation, we have been using the twice-daily upper air observations at 0000 and 1200 GMT over North America for a 5-year period from 1 May 1958 to 30 April 1963. These were from the MIT General Circulation Data Library, which were re-edited and recompiled at the University of Missouri–Columbia. The use of observed wind and geopotential data in energetics analysis is of major technical interest, and our long series of experiments and improvements have been reported previously (Kung, 1969, 1972, 1973, 1975; Kung and Baker, 1975; Tsui and Kung, 1976). In our preceding paper (Kung and Baker, 1975) the kinetic energy balance with Eq. (1) was computed for the 5-year period at each observation time. During the computation the intermediate output was retained for further computation in this study.

Among these retained data the cross-isobaric generation $-\mathbf{V}\cdot\nabla\phi$ and the vertical p velocity ω were computed at the upper air stations over North America (see Fig. 1). For the computation of $-\mathbf{V}\cdot\nabla\phi$, $\nabla\phi$ was evaluated by a least-squares fitting of the plane surface of geopotential utilizing the observed values at the station and surrounding stations, and then the scalar product of the observed wind $\mathbf{V}$ and the geopotential gradient $\nabla\phi$ at the station was obtained. For the kinematic estimate of ω, the 14-degree optimization scheme as described by Kung (1973) for North America was directly applied. Although the computations of $-\mathbf{V}\cdot\nabla\phi$ and ω are known for their technical difficulty, our analysis scheme seems to have yielded acceptable results for the energetics analysis as discussed in our previous papers (*loc. cit*). Since we utilize $-\mathbf{V}\cdot\nabla\phi$ and ω values retained in our preceding study (Kung and Baker, 1975), a specific discussion on the computational aspects of $-\mathbf{V}\cdot\nabla\phi$ and ω evaluations will not be repeated in this paper. Specific references may be made to Kung and Baker (1975) and Tsui and Kung (1976) in connection with the $-\mathbf{V}\cdot\nabla\phi$ computation, and to Kung (1972, 1973) in connection with the ω computation. During the preceding study the eastward and northward components of observed winds $\mathbf{V}$, the geopotential ϕ, and the ω were also interpolated at the grid points in Fig. 1 with the least-squares fitting of the plane surface.

The retained values of $-\mathbf{V}\cdot\nabla\phi$ are directly utilized in this study to obtain $-[\mathbf{V}\cdot\nabla\phi]$. The retained ω values at stations and temperature values from the original upper air observations are used together to compute the eddy conversion $-[\omega^*\alpha^*]$. The retained values of ω and ϕ at grid points are used to compute the eddy pressure interaction $-[\partial\omega^*\phi^*/\partial p]$. The direct computation of $-[\nabla\cdot\mathbf{V}\phi]$ is extremely difficult, because the magnitude of $\mathbf{V}\phi$ is too large in the upper troposphere to obtain a reliable estimate of $[\nabla\cdot\mathbf{V}\phi]$. It may be expected that $[\nabla\cdot\mathbf{V}\phi]$ is largely contributed from $[\nabla\cdot\mathbf{V}\phi^*]$, however, since $[\nabla\cdot\mathbf{V}\bar{\phi}]$ depends on $[\nabla\cdot\mathbf{V}]$ which is negligibly small for a continental size area. Therefore, in this study, $-[\nabla\cdot\mathbf{V}\phi]$ is substituted by $-[\nabla\cdot\mathbf{V}\phi^*]$, and $-[\nabla\cdot\mathbf{V}\phi^*]$ is evaluated by the line integral with the wind components and ϕ^* values at grid points on the boundary of the area (see Fig. 1). With values of $-[\mathbf{V}\cdot\nabla\phi]$, $-[\nabla\cdot\mathbf{V}\phi]$, $-[\omega^*\alpha^*]$ and $-[\partial\omega^*\phi^*/\partial p]$ for each synoptic observation, the residual source term RS is obtained as the residual term of Eq. (8).

The energy source terms are computed for each observation time, twice-daily during the 5-year period. After eliminating cases of sparse data coverage and missing observation times in the original data library, a total of 3468 synoptic cases are available for analysis in this study. This data sample is larger than the

TABLE 1. Eddy conversion $-[\omega^*\alpha^*]$ in units of W m^{-2} for different flow patterns.

Layer (mb)	C1	C2	C3	C4	C5	C6	Q1	Q2	A1	A2	UD	Mean
50–100	0.14	−0.02	−0.00	0.09	−0.02	−0.04	−0.07	−0.15	0.01	−0.07	0.01	−0.02
100–500	0.14	−0.04	−0.00	0.09	0.01	−0.07	0.04	−0.16	0.03	−0.03	−0.00	−0.01
150–200	0.04	−0.08	−0.01	0.04	0.05	−0.05	−0.02	−0.08	−0.00	−0.15	−0.02	−0.02
200–250	0.03	0.02	0.08	0.07	−0.01	0.01	−0.02	0.02	0.01	−0.11	−0.07	0.00
250–300	0.11	0.20	0.17	0.07	0.06	0.08	−0.00	0.05	0.07	−0.09	0.03	0.05
300–350	0.19	0.37	0.12	0.18	0.16	0.20	0.07	0.11	0.04	−0.06	0.04	0.09
350–400	0.24	0.41	0.13	0.24	0.23	0.24	0.13	0.15	0.05	−0.04	0.07	0.12
400–450	0.24	0.43	0.15	0.24	0.28	0.28	0.16	0.16	0.03	−0.03	0.06	0.13
450–500	0.20	0.39	0.11	0.26	0.27	0.29	0.18	0.16	0.03	−0.04	0.06	0.12
500–550	0.19	0.35	0.11	0.24	0.27	0.27	0.19	0.15	0.02	−0.02	0.06	0.12
550–600	0.19	0.31	0.11	0.23	0.27	0.25	0.20	0.13	0.01	−0.01	0.07	0.12
600–650	0.19	0.29	0.13	0.20	0.23	0.23	0.21	0.12	0.03	−0.01	0.08	0.12
650–700	0.19	0.27	0.13	0.20	0.22	0.21	0.21	0.13	0.05	0.00	0.09	0.13
700–750	0.19	0.23	0.13	0.19	0.22	0.20	0.20	0.14	0.05	0.02	0.10	0.13
750–800	0.14	0.18	0.12	0.17	0.20	0.19	0.17	0.13	0.05	0.03	0.10	0.12
800–850	0.08	0.14	0.09	0.14	0.14	0.17	0.15	0.11	0.05	0.03	0.08	0.10
850–900	0.01	0.08	0.06	0.07	0.07	0.15	0.13	0.09	0.02	0.03	0.06	0.07
900–sfc	−0.02	0.02	0.02	0.01	0.04	0.11	0.06	0.03	−0.00	0.01	0.02	0.03
Total	2.51	3.55	1.67	2.73	2.68	2.72	2.00	1.30	0.54	−0.56	0.91	1.40

2910 cases utilized in our preceding study of kinetic energy balance (Kung and Baker, 1975). Additional cases become available in this study by accepting cases whose vertical extents reach the upper troposphere but not the specified top level (50 mb in this study). The computed synoptic cases of energy source terms are grouped into the 11 predetermined categories of the prevailing flow pattern which were specified by Kung and Baker (1975) with a respective code as follows:

C1 A closed low at 500 mb and a developing cyclone at the surface
C2: A closed low at 500 mb and a mature cyclone at the surface
C3: A closed low at 500 mb and an occluded cyclone at the surface
C4: An open cyclonic wave at 500 mb and a developing cyclone at the surface
C5: An open cyclonic wave at 500 mb and a mature cyclone at the surface
C6: An open cyclonic wave at 500 mb and an occluded cyclone at the surface
Q1: A closed low at 500 mb but not cyclonic at the surface
Q2: An open cyclonic wave at 500 mb but not cyclonic at the surface
A1: An anticyclonic wave at 500 mb and an anticyclone at the surface
A2: A distinct ridge line recognizable at 500 mb and an anticyclone at the surface
UD: Neither distinctly cyclonic nor anticyclonic at 500 mb.

Typical 500 mb and surface synoptic patterns for recognizing the above categories are illustrated in Kung and Baker (1975). Types C1–C6 are various cyclonic patterns. Q1 and Q2 refer to quasi-cyclonic patterns which are cyclonic at 500 mb but not cyclonic at the surface. A1 and A2 are anticyclonic patterns. Those anticyclones whose existence are restricted in the lower troposphere are not considered as anticyclonic patterns in this classification. For instance, a "cold-core" anticyclone recognized at the surface may be associated with a trough at 500 mb in the region instead of an anticyclonic wave at 500 mb. The pattern is then the quasi-cyclonic type Q2 and not A2. A substantial number of cases whose 500 mb flow patterns are not clearly cyclonic or anticyclonic, or when more than one transient systems are present in the area without one particular system dominating, are classified as the unidentified type UD.

In classifying the computed cases according to the prevailing flow pattern in the area, the daily 500 mb and surface charts at 1200 GMT are utilized as described by Kung and Baker (1975). All distinct cyclonic cases in C1–C6 total 938, which is 27% of all 3468 available cases during the 5-year period. The distinct anticyclonic cases in A1 and A2 count 458 which is 13% of all available cases. The quasi-cyclonic cases in Q1 and Q2 sum up to 642 or 19% of all available cases, and the undefined cases of 1430 is 41% of all available cases. Note that this study involved a sufficiently large data sample for discussion of the gross energy budget of various categories of disturbances.

Computed values of energy source terms are averaged separately for 0000 and 1200 GMT observations within each of the 11 flow pattern categories. Budgets for 0000 and 1200 GMT are then averaged to eliminate the effect of the diurnal variation. To obtain the mean values for certain groups of combined flow types, the

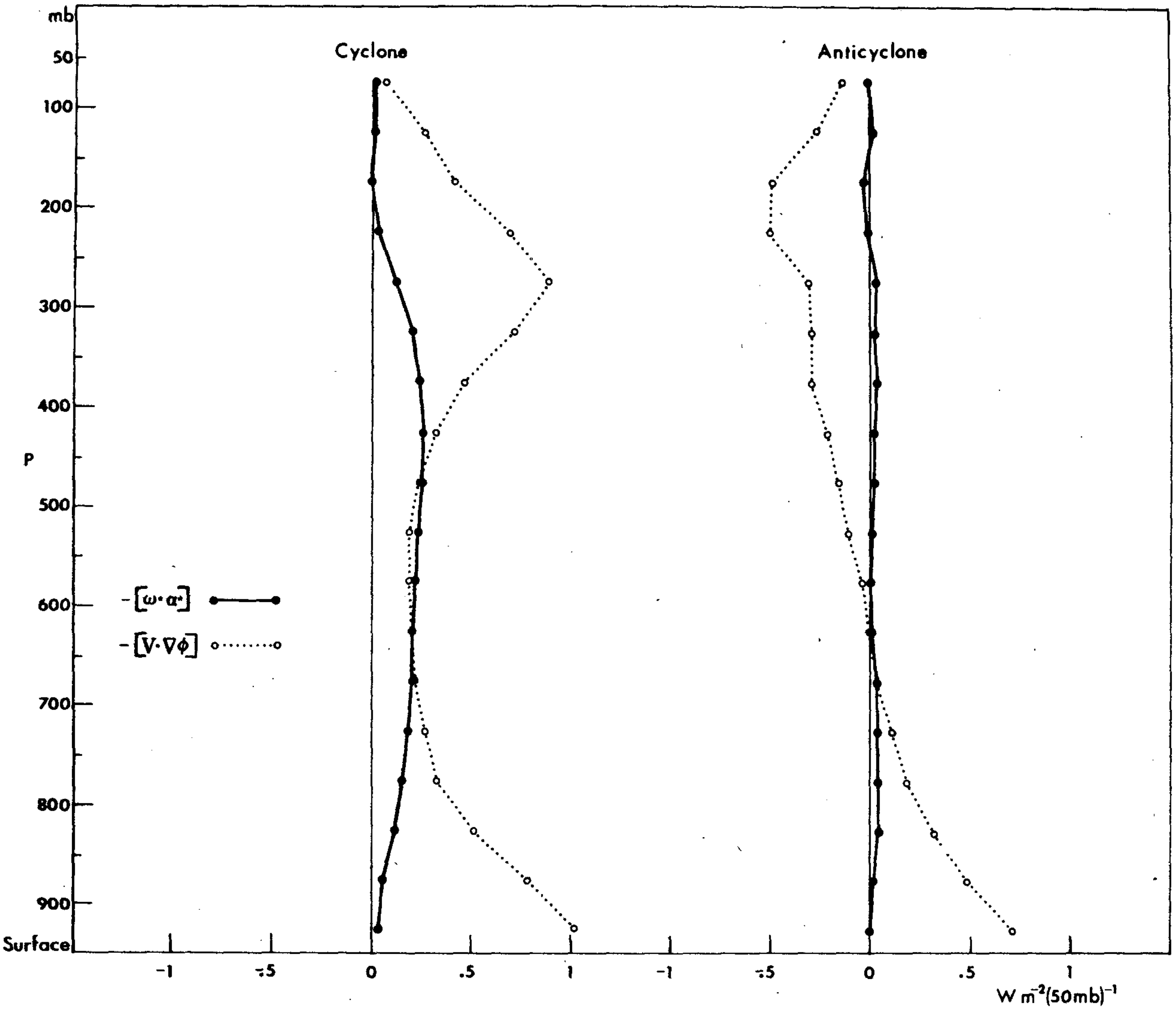

FIG. 2. Mean vertical profiles of the kinetic energy generation $-[\mathbf{V}\cdot\nabla\phi]$ and eddy conversion $-[\omega^*\alpha^*]$ for cyclonic and anticyclonic disturbances.

same procedure is followed with the total frequencies of synoptic cases in these combined groups.

Energetics computations with real atmospheric data involve a certain degree of uncertainty. Therefore, all discussions presented in this paper are restricted within what we consider as the reliable range of computational results. The reliability and stability of our computational scheme in this regard has been discussed in detail in our previous papers (Kung, 1975; Kung and Baker, 1975; Kung and Smith, 1974; Tsui and Kung, 1976).

4. Energy sources in cyclones and anticyclones

The eddy conversion $-[\omega^*\alpha^*]$ represents the internal release or supply of energy within the particular synoptic-scale system. Table 1 lists the mean eddy conversion within specified atmospheric layers for the 11 types of defined flow patterns. Although a comprehensive examination of all energy source terms in Eq. (8) in various groups of these flow types will be presented, Table 1 may serve as a useful reference in comparing the relative intensity of the eddy conversion.

Computed energy source terms and kinetic energy generation for all cyclonic cases and all anticyclonic cases are averaged in Table 2. Fig. 2 further compares the vertical profiles of the eddy conversion $-[\omega^*\alpha^*]$ and generation $-[\mathbf{V}\cdot\nabla\phi]$ in cyclones and anticyclones, and Fig. 3 compares those of the horizontal transport term $-[\nabla\cdot\mathbf{V}\phi]$ and eddy vertical transport term $-[\partial\omega^*\phi^*/\partial p]$.

The eddy conversion $-[\omega^*\alpha^*]$ in cyclonic disturbances indicates that the release of available potential energy takes place in the troposphere, with maximum

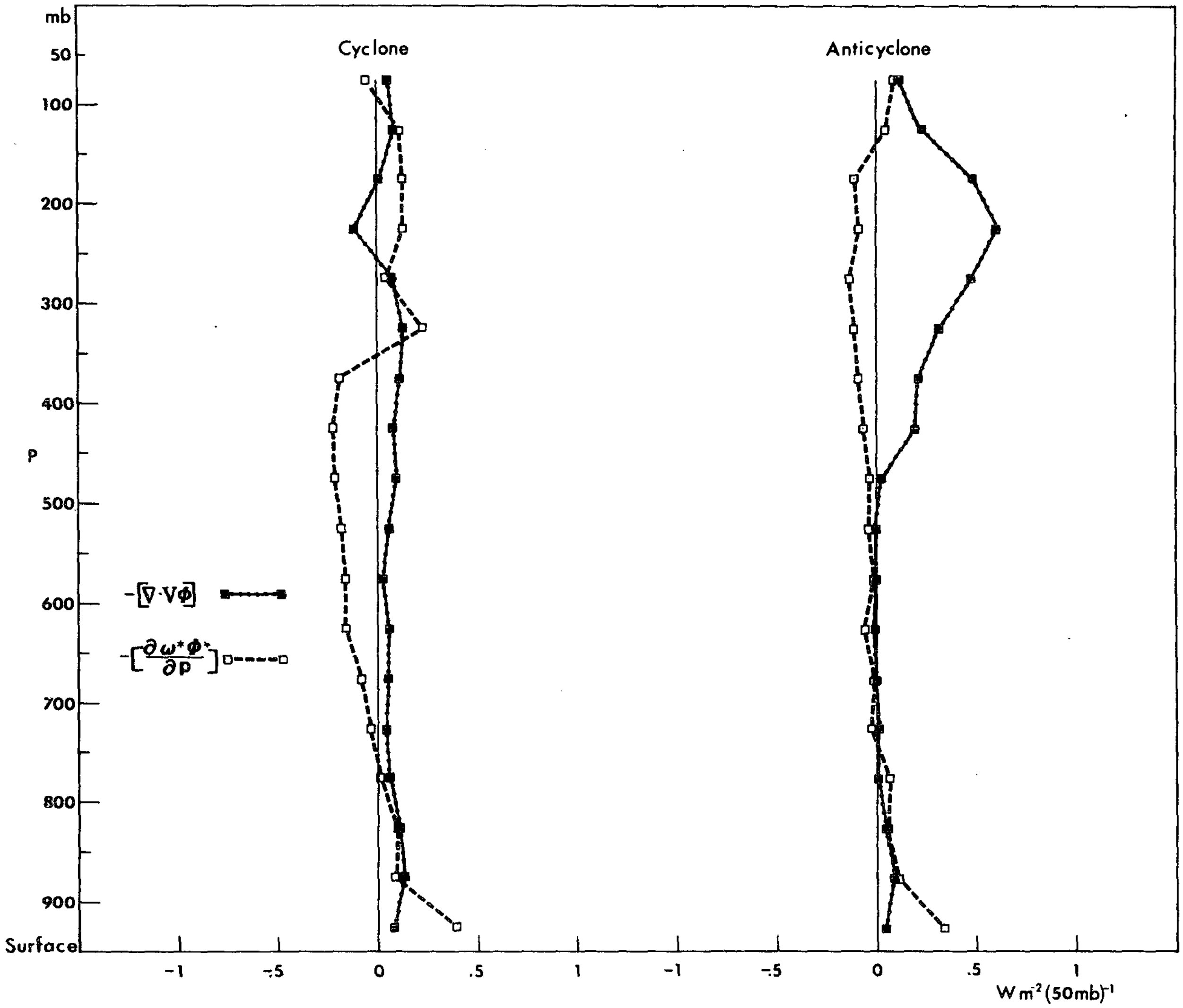

FIG. 3. Mean vertical profiles of the horizontal transport of potential energy $-[\nabla\cdot V\phi]$ and eddy vertical transport of potential energy $-[\partial\omega^*\phi^*/\partial p]$ for cyclonic and anticyclonic disturbances.

release in the mid-troposphere. The released energy is transported vertically through the eddy pressure interaction $-[\partial\omega^*\phi^*/\partial p]$ and imported to the upper and lower troposphere, contributing to the upper and lower tropospheric maxima of the cross-isobaric generation. The vertical total of *RS* is 4.25 W m^{-2}, indicating that the conversion due to disturbances in the wavenumber range of less than $n=10$ is about 1.6 times the measured eddy conversion $-[\omega^*\alpha^*]$ of 2.61 W m^{-2} within the observed short-wave range in the area. In view of the dominance of the medium-wave range over the short-wave range, this ratio seems to be reasonable. In a case study of a strong cyclone over North America, Eddy (1965) obtained 3.76 W m^{-2} of $-[\omega^*\alpha^*]$ in the scale range of disturbances between 6500 and 3000 km and 3.00 W m^{-2} in the smaller scale range of disturbances. This seems to be consistent with our overall averages of $-[\omega^*\alpha^*]$ and *RS*.

In addition to the eddy conversion in the observable and larger scale ranges, there is also a source of the horizontal transport of potential energy $-[\nabla\cdot V\phi]$ across the lateral boundary of cyclones. Its vertical total is 1.16 W m^{-2}, which is the secondary energy source imported from the surroundings for kinetic energy generation in the observed systems.

The examination of source terms in anticyclonic disturbances in Table 2 and Figs. 2 and 3 shows a marked difference from those in cyclonic disturbances. The vertical total of the eddy conversion of

TABLE 2. Kinetic energy generation and source terms in various groups of disturbances in units of W m^{-2}.

Flow pattern	Type	Layer (mb)	$-[\mathbf{V}\cdot\nabla\phi]$	$-[\omega^*\alpha^*]$	$-\left[\dfrac{\partial\omega^*\phi^*}{\partial p}\right]$	$-[\nabla\cdot\mathbf{V}\phi]$	*RS*
Cyclonic	C1, C2, C3 C4, C5, C6	50–100	0.07	0.01	−0.05	0.06	0.05
		100–350	2.95	0.37	0.64	0.22	1.72
		350–750	2.10	1.83	−1.25	0.50	1.02
		750–sfc	2.87	0.40	0.62	0.39	1.46
		Total	7.99	2.61	−0.03	1.16	4.25
Anticyclonic	A1, A2	50–100	−0.14	−0.00	0.08	0.11	−0.32
		100–350	−1.86	0.02	−0.34	2.12	−3.67
		350–750	−0.74	0.17	−0.36	0.42	−0.98
		750–sfc	1.76	0.11	0.62	0.18	0.85
		Total	−0.99	0.29	0.00	2.84	−4.12
Quasi-cyclonic (closed low at 500 mb)	Q1	50–100	−0.00	−0.07	−0.14	0.12	0.08
		100–350	1.99	0.07	−0.15	3.42	−1.35
		350–750	1.13	1.49	−0.25	1.66	−1.76
		750–sfc	2.03	0.52	0.23	0.21	1.07
		Total	5.15	2.00	−0.31	5.42	−1.96
Quasi-cyclonic (open cyclonic wave at 500 mb)	Q2	50–100	0.13	−0.15	0.25	0.47	−0.45
		100–350	3.89	−0.06	0.69	7.16	−3.90
		350–750	2.23	1.14	−1.40	4.28	−1.78
		750-sfc	2.30	0.36	0.35	0.79	0.79
		Total	8.55	1.30	−0.11	12.71	−5.34
Undefined	UD	50–100	0.07	0.01	−0.01	0.10	−0.03
		100–350	2.81	0.04	0.16	3.55	−0.94
		350–750	1.64	0.59	−0.47	1.94	−0.41
		750-sfc	2.01	0.27	0.50	0.28	0.98
		Total	6.53	0.91	0.17	5.85	−0.40

$-[\omega^*\alpha^*]$ is only 0.29 W m^{-2}, although the source from the horizontal transport $-[\nabla\cdot\mathbf{V}\phi]$ is 2.84 W m^{-2}, leaving the residual term *RS* as -4.12 W m^{-2}. The most significant character of the kinetic energy balance in anticyclones is the destruction of kinetic energy through cross-isobaric flow $-[\mathbf{V}\cdot\nabla\phi]$ in the upper and mid-troposphere as discussed in our preceding paper (Kung and Baker, 1975). The source terms in this study indicate that the limited internal baroclinic source and the imported source are not enough to offset the kinetic energy destruction caused by the negative conversion in the larger scale side of disturbances. The negative eddy conversion may be interpreted as the local contribution to the adiabatic destruction of kinetic energy in the synoptic-scale field of convection, returning it to the reservoir of the available potential energy.

Various investigators (e.g., Petterssen and Smebye, 1971; Smith, 1973; Vincent and Chang, 1975; Ward and Smith, 1976) have reported that cyclones show different energetics properties during various stages of their development. In our preceding report (Kung and Baker, 1975), different degrees of cyclonic and anticyclonic developments were shown to be reflected in the intensity of transformation rates involved in the kinetic energy balance. Source terms as presented in Tables 3 and 4 further reveal considerably different energetics properties among various stages of development of these disturbances.

Table 3 presents source terms of cyclonic disturbances averaged for three major stages of development and for two types of upper air flow patterns. Types C1 and C4 are recognized as developing cyclones, types C2 and C5 as mature cyclones, and types C3 and C6 as occluded cyclones. Synoptic cases of cyclones are also regrouped by types C1, C2 and C3 as those with a closed low at 500 mb, and by types C4, C5 and C6 as those with an open cyclonic wave at 500 mb. There is a significant production of kinetic energy in terms of cross-isobaric generation $-[\mathbf{V}\cdot\nabla\phi]$ in the developing and mature stages of cyclones with its maximum in the upper troposphere of 100–350 mb layer. The eddy conversion $-[\omega^*\alpha^*]$ is large at the developing stage, reaching its maximum at the mature stage in the mid-troposphere, and shows a decline as cyclones enter the occluded stage. There is some eddy conversion in the lower stratosphere of the 50–100 mb layer during the developing stage, but after the cy-

TABLE 3. Kinetic energy generation and source terms in various types of cyclonic disturbances in units of W m^{-2}.

Flow pattern	Type	Layer (mb)	$-[\mathbf{V}\cdot\nabla\phi]$	$-[\omega^*\alpha^*]$	$-\left[\frac{\partial\omega^*\phi^*}{\partial p}\right]$	$-[\nabla\cdot\mathbf{V}\phi]$	*RS*
Developing cyclones	C1, C4	50–100	0.08	0.10	−0.13	0.25	−0.15
		100–350	3.42	0.47	1.22	−0.48	2.21
		350–750	2.32	1.75	−1.18	−0.36	2.11
		750–sfc	2.65	0.34	0.65	0.32	1.34
		Total	8.47	2.67	0.56	−0.27	5.52
Mature cyclones	C2, C5	50–100	0.08	−0.02	−0.06	−0.11	0.28
		100–350	3.04	0.37	1.04	−0.48	2.11
		350–750	2.50	2.32	−1.82	0.43	1.58
		750–sfc	3.10	0.44	0.56	0.32	1.78
		Total	8.73	3.11	−0.28	0.15	5.75
Occluded cyclones	C3, C6	50–100	0.05	−0.02	0.02	0.13	−0.08
		100–350	2.52	0.30	−0.18	1.46	0.94
		350–750	1.50	1.33	−0.63	1.14	−0.33
		750–sfc	2.76	0.40	0.67	0.51	1.18
		Total	6.84	2.01	−0.12	3.23	1.71
Closed low at 500 mb	C1, C2, C3	50–100	0.03	0.01	0.02	−0.02	0.02
		100–350	2.66	0.42	0.17	−1.11	3.17
		350–750	1.75	1.74	−0.82	−0.11	0.94
		750–sfc	2.88	0.34	0.78	0.31	1.46
		Total	7.32	2.51	0.14	−0.93	5.60
Open cyclonic wave at 500 mb	C4, C5, C6	50–100	0.11	0.01	−0.12	0.13	0.08
		100–350	3.23	0.31	1.13	1.53	0.26
		350–750	2.44	1.91	−1.67	1.10	1.09
		750–sfc	2.87	0.47	0.47	0.46	1.47
		Total	8.65	2.71	−0.19	3.23	2.90

clones reach the mature stage $-[\omega^*\alpha^*]$ shows insignificant negative values. The pattern of eddy vertical transport $-[\partial\omega^*\phi^*/\partial p]$ changes obviously in the upper troposphere through the cyclonic development. It is a significant convergence in the 100–350 mb layer, but it becomes negative in the same layer in the occluded stage. The most significant change in the occluded stage occurs in the residual source term *RS* and the horizontal transport term $-[\nabla\cdot\mathbf{V}\phi]$. The conversion by the larger scale disturbances as represented by *RS* is the largest source for kinetic energy generation throughout the developing and mature stages, 5.52 and 5.75 W m^{-2}, respectively, accounting for 65 and 66% of the generation $-[\mathbf{V}\cdot\nabla\phi]$ in each stage. In the occluded stage, however, *RS* drops to 1.71 W m^{-2} which is only 25% of the generation in that stage, and the 3.23 W m^{-2} of horizontal import of potential energy $-[\nabla\cdot\mathbf{V}\phi]$ becomes the most important source of kinetic energy. During the developing and mature stage the vertical total of $-[\nabla\cdot\mathbf{V}\phi]$ in negligibly small.

The change in budgets as discussed above indicates an interesting temporal variation of energy sources in producing kinetic energy by cyclones throughout their development. In the developing stage the eddy conversion both in the short-wave range and in the longer wave range account for all of the sources of the kinetic energy generation, the latter being approximately twice the former. As cyclones enter the mature stage the eddy conversion intensifies, particularly in the short-wave range; the horizontal transport of potential energy also begins to function as a source, although it is still a small term at this stage. When cyclones are occluded the significance of eddy conversion in the longer wave range is drastically reduced, signifying a reduced importance of the cyclone vicinity as the energy source region; the kinetic energy generation is contributed most significantly by the horizontal import of potential energy and secondarily by eddy conversions in this stage.

The energy source terms in weak and strong anticyclones as represented respectively by types A1 and A2 are shown in Table 4. The general characters of anticyclones as presented in Table 3 are apparently intensified in strong anticyclonic disturbances A2. The eddy conversion $-[\omega^*\alpha^*]$ by the resolved scales of disturbances becomes negative throughout the depth of the atmosphere except for the lower troposphere. Most significantly the eddy conversion by larger scale disturbances as represented by *RS* becomes a large

TABLE 4. Kinetic energy generation and source terms in various types of anticyclonic disturbances in units of W m^{-2}.

Flow pattern	Type	Layer (mb)	$-[\mathbf{V}\cdot\nabla\phi]$	$-[\omega^*\alpha^*]$	$-\left[\frac{\partial\omega^*\phi^*}{\partial p}\right]$	$-[\nabla\cdot\mathbf{V}\phi]$	*RS*
Weak anticyclone	A1	50–100	−0.11	0.01	0.06	0.10	−0.30
		100–350	1.21	0.15	−0.12	2.14	−3.38
		350–750	−0.24	0.26	−0.32	0.65	−0.81
		750–sfc	1.71	0.11	0.58	0.21	0.81
		Total	0.15	0.54	0.20	3.10	−3.69
Strong anticyclone	A2	50–100	−0.24	−0.07	0.12	0.12	−0.41
		100–350	−4.11	−0.45	−1.07	2.05	−4.64
		350–750	−2.49	−0.14	−0.47	−0.32	−1.56
		750–sfc	1.92	0.09	0.76	0.08	0.98
		Total	−4.92	−0.56	−0.66	1.93	−5.63

negative value of -5.63 W m^{-2}; the import of potential energy through the horizontal pressure interaction also drops. These two factors indicate that anticyclones in middle latitudes are transient disturbances which effectively destroy the kinetic energy, with convective fields whose scales are larger than the short-wave range.

5. Energy sources in intermediate-type disturbances

The frequency of intermediate cases classified as Q1, Q2 and UD is high. Their total of 2072 cases during the 5-year period is 60% of the total available cases of 3468. In our preceding paper (Kung and Baker, 1975), it was reported that the pattern of kinetic energy balance in these intermediate type flows basically resembles that in cyclonic disturbances. However, when we break down the generation term $-[\mathbf{V}\cdot\nabla\phi]$ into source terms as listed in Table 2, the similarity between cyclonic and intermediate types no longer holds.

Quasi-cyclonic flows Q1 and Q2 that are cyclonic at 500 mb but not cyclonic at the surface have eddy conversion $-[\omega^*\alpha^*]$ in the middle and lower troposphere with a magnitude comparable to that in cyclonic disturbances. Yet the eddy conversions due to the larger scale disturbances as represented by *RS* are significant negatives in the quasi-cyclonic flows: -1.96 W m^{-2} for Q1 and -5.34 W m^{-2} for Q2. The energy source needed for the generation in support of Q1 and Q2 types of the flow is mainly through the horizontal transport of potential energy $-[\nabla\cdot\mathbf{V}\phi]$. In the unidentified cases UD, there is also a significant kinetic energy generation, but the source is mostly from the horizontal transport term $-[\nabla\cdot\mathbf{V}\phi]$. There is some eddy conversion $-[\omega^*\alpha^*]$ in these UD type disturbances, but it is not a major energy source. The eddy conversion from the larger scale side *RS* is an insignificant negative, indicating that the larger scale convective field associated with UD type flow patterns is not active in energy conversion This may be seen to a certain degree in a rather weak mean vertical motion associated with UD type flow pattern, although the ω field is not specifically listed in this report.

When comparing these intermediate type disturbances with cyclonic and anticyclonic disturbances, an interesting pattern emerges. There is a comparable energy generation in quasi-cyclonic and unidentified type flows to that in cyclonic disturbances. They do not destroy kinetic energy in the cross-isobaric flow as in anticyclonic disturbances. However, the source of the energy generation in these intermediate type flows is the horizontal import of potential energy and not the eddy conversion as is the case in cyclones. Actually the larger scale eddy conversion *RS* has a significant negative value for quasi-cyclonic flows and an insignificant negative value for the unidentified type. Thus as far as the internal baroclinic energy source of the eddy conversion is concerned, these intermediate cases are as limited as the anticyclonic type. In other words, the significant eddy conversion at short wave and longer wave ranges is only associated with clearly recognized cyclones, i.e., cyclones recognized from the surface through the depth of the atmosphere.

The horizontal transport term $-[\nabla\cdot\mathbf{V}\phi]$ shows an import of potential energy for all general categories of disturbances in Table 2, although there is a significant variation of its magnitude among different categories. It obviously is a regional characteristic. In this study, however, it has not been determined if it is due to meridional or zonal convergence, and consequently we cannot discuss the source region of this potential energy. However, it may be stated that in quasi-cyclonic and unidentified types of flows, where the supply of energy through the source of baroclinic conversion is limited or does not exist, the potential energy is supplied through horizontal pressure interaction for the generation of kinetic energy.

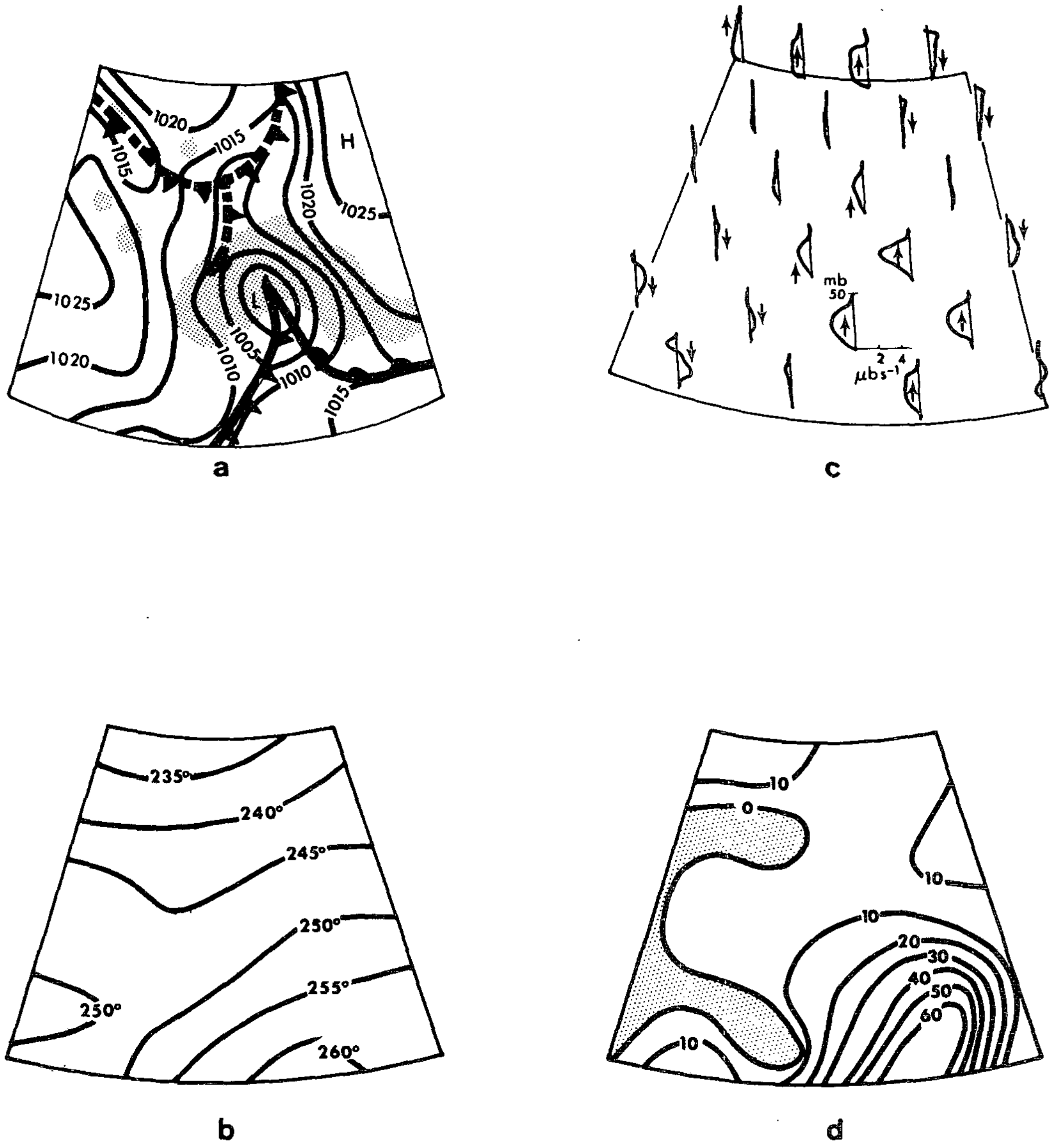

Fig. 4. Synoptic pattern and eddy conversion of 19 March 1963. (a) Surface chart. Pressure is in mb. Shading represents area of reported precipitation. (b) 500 mb temperature field in K. (c) ω profiles at analysis grids in units of $\mu b\ s^{-1}$. (d) $-\omega^*\alpha^*$ from the surface to 50 mb in units of $W\ m^{-2}$. Shading represents area of negative values. (a) is for 0000 GMT, and (b), (c), (d) for 0000 and 1200 GMT average.

6. Some examples of synoptic cases

Although the approach taken in this study is to examine the ensemble energetics properties of the synoptic-scale disturbances rather than to follow the development of individual systems as is done in case studies, some examples of synoptic cases may be appropriate to supplement the foregoing discussions. In the preceding report (Kung and Baker, 1975) four synoptic cases were arbitrarily chosen from four types of flow patterns, including 19 March 1963 for type C2, 20 March 1963 for C3, 2 June 1962 for A1, and 2 December 1960 for A2, to illustrate the spatial distribution of the vertically integrated value of the kinetic energy generation $-[\mathbf{V}\cdot\nabla\phi]$ in relation to the surface and 500 mb charts. The patterns of spatial distribution of the vertically integrated value of $-\omega^*\alpha^*$ from the surface to 50 mb are shown in Figs. 4–7 for the same four synoptic cases with the surface charts, the 500 mb temperature pattern and the fields of the vertical motion.

As pointed out by Johnson (1970), a statistical presentation of eddy energy components on a hemispherical or global diagnosis often conceals more drastic energy transformations that occur in individual systems in a limited horizontal extent. The gross energy budget analysis with a large sample of synoptic

FIG. 5. As in Fig. 4 except for 20 March 1963.

cases will also suffer from a similar shortcoming. With a budget analysis over a fixed observational area the advantages of following individual disturbances with the moving Eulerian method or quasi-Lagrangian method (see Kung and Smith, 1974) are limited, although in our approach a sufficiently large data sample in various types of disturbances allows us to examine gross energetics properties at various stages of their development. The problem is also compounded by the fact that except for exceptionally well-developed cyclones or anticyclones, in most cases there may exist more than one transient system within the defined continental area of the size utilized in this study. As illustrated in surface charts in Figs. 4–7 [see Kung and Baker (1975)] for their respective upper air patterns, although a dominating cyclonic or anticyclonic system can be recognized in the area thus enabling one to classify the synoptic case to a proper category, we also recognize partial existence of other types of disturbances in the area.

The distribution of the vertical totals of $-\omega^*\alpha^*$ in the area indicates the existence of both positive and negative eddy conversions (Figs. 4–7). These regions of positive and negative $-\omega^*\alpha^*$ also may show a concentration of very strong positive or negative conversion, as previously indicated in case studies by Eddy (1965) and Pearce (1974). Examination of $-\omega^*\alpha^*$ distribution in relation to 500 mb temperature and vertical p velocity in these figures confirms that the eddy conversion is distributed in the area according to the negative correlation of the temperature and ω. The 500 mb temperature field presented here

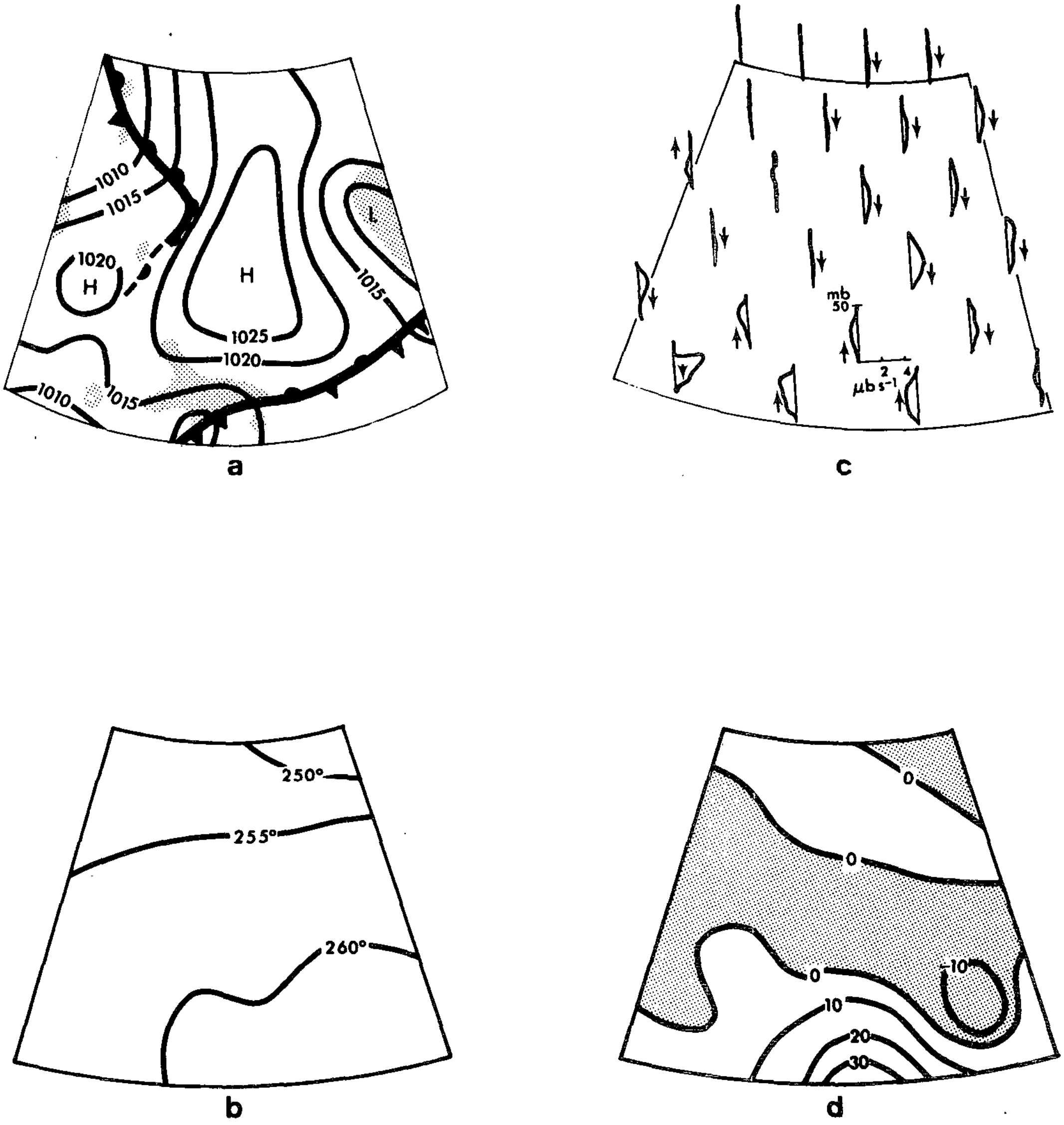

FIG. 6. As in Fig. 4 except for 2 June 1962.

as the eddy conversion is generally at its maximum in the mid-troposphere. The frontal systems associated with cyclonic disturbances indicate a significant variation in the temperature field and the existence of strong vertical motions; the concentrations of strong and negative eddy conversions are apparently observed in conjunction with well-developed fronts. Further systematic case studies of the energy budget with a large sample of cases will be revealing, but the possible effort involved will not be trivial.

In previous sections it was pointed out that the eddy conversion $-[\omega^*\alpha^*]$ in the short-wave range resolvable with the defined network area is rather small with a possible magnitude of $\sim$1–3 W m^{-2} (Tables 2–4). In the case of anticyclones it is even smaller or negative. However, examination of Figs. 4–7 clearly indicates that in the short-wave range, in which we commonly observe transient systems over the defined continental area, there are concentrated areas of strong positive and negative eddy conversions within the systems of the disturbances. Since these strong conversions of the available potential energy or destruction of kinetic energy mostly cancel each other out when an area average is taken, a rather weak value of conversion will be obtained as the mean for the particular synoptic case. By averaging these cases over a large sample, the ensemble statistics of $-[\omega^*\alpha^*]$ are expected to be even smaller than many of the single case means over the area. Contrary to the short-wave range, the longer wave range shows a much larger positive or negative conversion, as indicated by the *RS* term, except in UD type

FIG. 7. As in Fig. 4 except for 2 December 1962.

cases (Table 2). However, it is unlikely that the correlation of temperature and ω at the larger scale will show such a strong area concentration of positive and negative conversions as we observe in the short-wave range in Figs. 4–7.

7. Summary

An examination, over a 5-year period, of energy source terms over the defined continental area in various types of flow patterns and with a very large data sample of more than 3400 observational cases is revealing. Among the source terms examined in relation to the kinetic energy generation $-[\mathbf{V}\cdot\nabla\phi]$ are the eddy conversion $-[\omega^*\alpha^*]$, the eddy vertical pressure interaction $-[\partial\omega^*\phi^*/\partial p]$, the horizontal import of potential energy $-[\nabla\cdot\mathbf{V}\phi]$, and the residual source term *RS*. Terms $-[\omega^*\alpha^*]$ and $-[\partial\omega^*\phi^*/\partial p]$ are processes of short-wave eddies whose scale range is resolvable with the defined area. The term *RS* then represents the conversion by the longer wave disturbances whose scale is larger than the defined area. The transport term $-[\nabla\cdot\mathbf{V}\phi]$ is the energy source imported through the lateral boundary to the system. An estimate of these terms with upper air data, particularly that of $-[\nabla\cdot\mathbf{V}\phi]$ and *RS*, should be subject to a range of numerical errors. However, the meaningful qualitative comparison of ensemble statistics of these terms among different flow patterns is possible. All discussions presented in this paper are restricted to what are qualitatively revealed by these parameters.

Cyclonic disturbances are shown to release available potential energy through eddy conversion. However, the energy source terms of cyclonic disturbances, including eddy conversion, indicate distinct temporal variations throughout their development. In the developing and mature stage the eddy conversion in the short-wave and longer wave range is very large. At the mature stage the horigontal transport of potential energy increases. When cyclones reach the occluded stage, the eddy conversion in the longer wave range is substantially reduced and the imported potential energy becomes the major source of energy generation. This should mean the importance of the cyclone vicinity as the baroclinic energy source region, and its reduced importance as cyclones are occluded. In contrast to cyclones it is noted that there is a large negative eddy conversion in anticyclonic disturbances, particularly in the longer wave range. The kinetic energy destroyed by the cross-isobaric flow is then returned to the reservoir of the available potential energy through the associated large field of convection.

For the intermediate type of disturbances in the quasi-cyclonic and unidentifiable categories the kinetic energy is generated in cross-isobaric flow. However, in these intermediate types the internal baroclinic source of energy is not only limited, but the kinetic energy is also destroyed in the associated large-scale convection. Therefore they depend on the imported potential energy for the generation of kinetic energy. Comparing the intermediate types with cyclonic and anticyclonic disturbances may reveal that the cyclones, particularly the well-developed cyclones, and their vicinity are the part of the general circulation which serves as the baroclinic source regions of kinetic energy, even though the released energy may be redistributed through the horizontal pressure interaction to other parts of the system of the general circulation for the generation of the kinetic energy.

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