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Energy transformations associated with the synoptic and planetary scales during the evolution of a blocking anticyclone and an upstream explosively-developing cyclone

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ABSTRACT

Energy transformations associated with a wave system that included the development of a blocking anticyclone over the North Atlantic Ocean and the upstream explosive-development of an extratropical cyclone are studied for the period 17–21 January 1979. Included in the investigation are eddy kinetic energy (KE), release of eddy potential energy (CE), generation of eddy kinetic energy (GK), and exchange between eddy and zonal kinetic energy (CK). In addition, these quantities were partitioned into synoptic-scale, planetary-scale, and scale-interaction components. Results indicate that KE, which was about one-half of the total kinetic energy, was maintained by baroclinic conversion of potential to kinetic. Further, as released potential energy was being utilized to generate KE, a portion of the KE was barotropically converted to zonal kinetic energy. These transformations were dominated by the synoptic-scale component, in contrast to the authors' previously-reported height tendency results, which yielded significant contributions from both the synoptic and scale-interaction components. Thus, while changes in the mass field depended not only on the synoptic scale but also on the interactions between the synoptic and planetary scales, the corresponding changes in the eddy motion fields responded largely to synoptic-scale processes.

1. Introduction

Blocking anticyclones have been favored with a particularly abundant array of investigations in recent years. As a result, it is now known that while barotropic processes may be prominent in some cases (e.g., Thompson, 1957), the development of a blocking feature is often the result of baroclinic processes (e.g., White and Clark, 1975; Egger, 1978; Charney and Straus, 1980; Hansen, 1986) in which intense, upstream cyclones play a significant role (Green, 1977; Hansen and Chen, 1982; Mullen, 1987; Colucci, 1985, 1987).

Recently, Tsou and Smith (1990a, b, hereafter referred to as TSA and TSB) reported on a blocking anticyclone case over the North Atlantic Ocean. They concluded (TSA) that the block developed as a result of both synoptic/scale forcing and synoptic/planetary-scale interactions associated with an upstream, explosively-developing cyclone. The interactions noted were revealed through the forcing terms in the height tendency equation, with the horizontal vorticity advection assuming a dominant role. In addition, they noted (TSB) that the eddy kinetic energy was enhanced by baroclinic energy conversion and diminished by barotropic energy conversion. However, the contributions of the synoptic-scale, planetary-scale, and scale interaction components to these energy conversions were not considered. This elaboration of the energy conversions originally reported in TSB is then the objective of this paper.

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2. Data and synoptic discussion

The analysis fields used and computational procedures are discussed at length in TSA and TSB. It

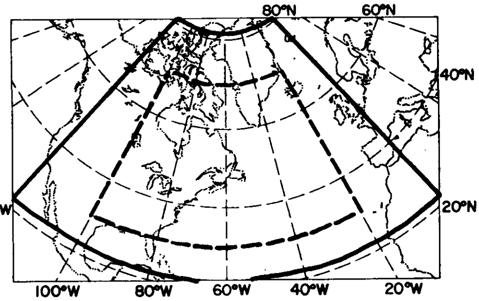

Fig. 1. The computational domain (area inside the heavy solid line) and the area averaging box for energy quantities (area inside the heavy dashed line).

will suffice here to note that the basic data fields are SOP-1 FGGE level III-b analyses provided by the Goddard Laboratory for Atmospheres on a 4° latitude by 5° longitude grid. The study focuses on the region from 0° to 120° W and 22° to 82° N during the period 17–21 January 1979 (Fig. 1).

Figs. 2 and 3 show the time evolution of the 500 mb height field and 250°K isotherm and the location of an associated surface cyclone that originated over Lake Michigan at 1200 GMT 17 January. In the initial 24-h period, a short-wave ridge downstream from the surface cyclone propagated eastward without significantly changing its amplitude. However, as the cyclone center passed the New England shore between 0000 and 1200 GMT 18 January, both the short-wave ridge and surface cyclone intensified and reduced their propagation speeds. The sea level pressure of the latter then dramatically decreased from 1002 mb to 971 mb, reaching a minimum value at 1200 GMT 19 January. By 0000 GMT 20 January, the slow-moving ridge became stationary and began to build northward. Over the remaining 36 h displayed, the ridge continued to amplify. A warm core high at 500 mb first appeared on 0000 GMT 21 January southeast of southern Greenland, followed 12 h later by the formation of a closed anticyclone over southern Greenland. This feature persisted in nearly the same location for the next week while diverting migrating cyclones to its west and south. Thus, it can be

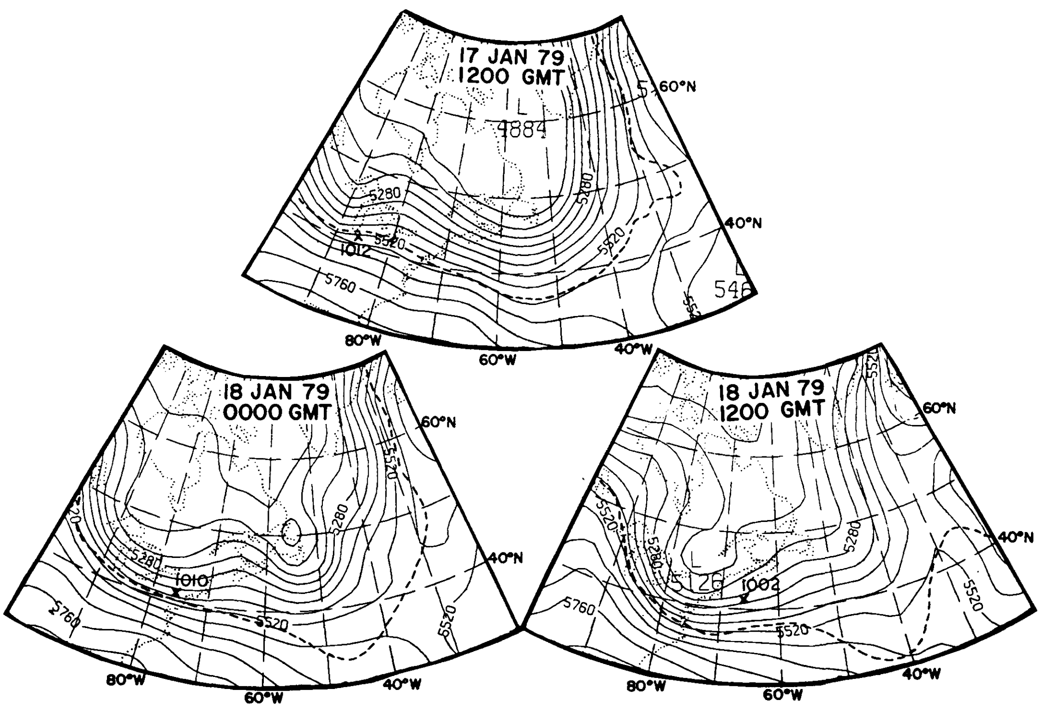

Fig. 2. 500 mb heights (solid, *m*, $\Delta z = 60$ m) and 250 K isotherm (dashed) for 1200 GMT 17 January through 1200 GMT 18 January 1979. "×" represents the location of the surface cyclone with central sea level pressure in mb.

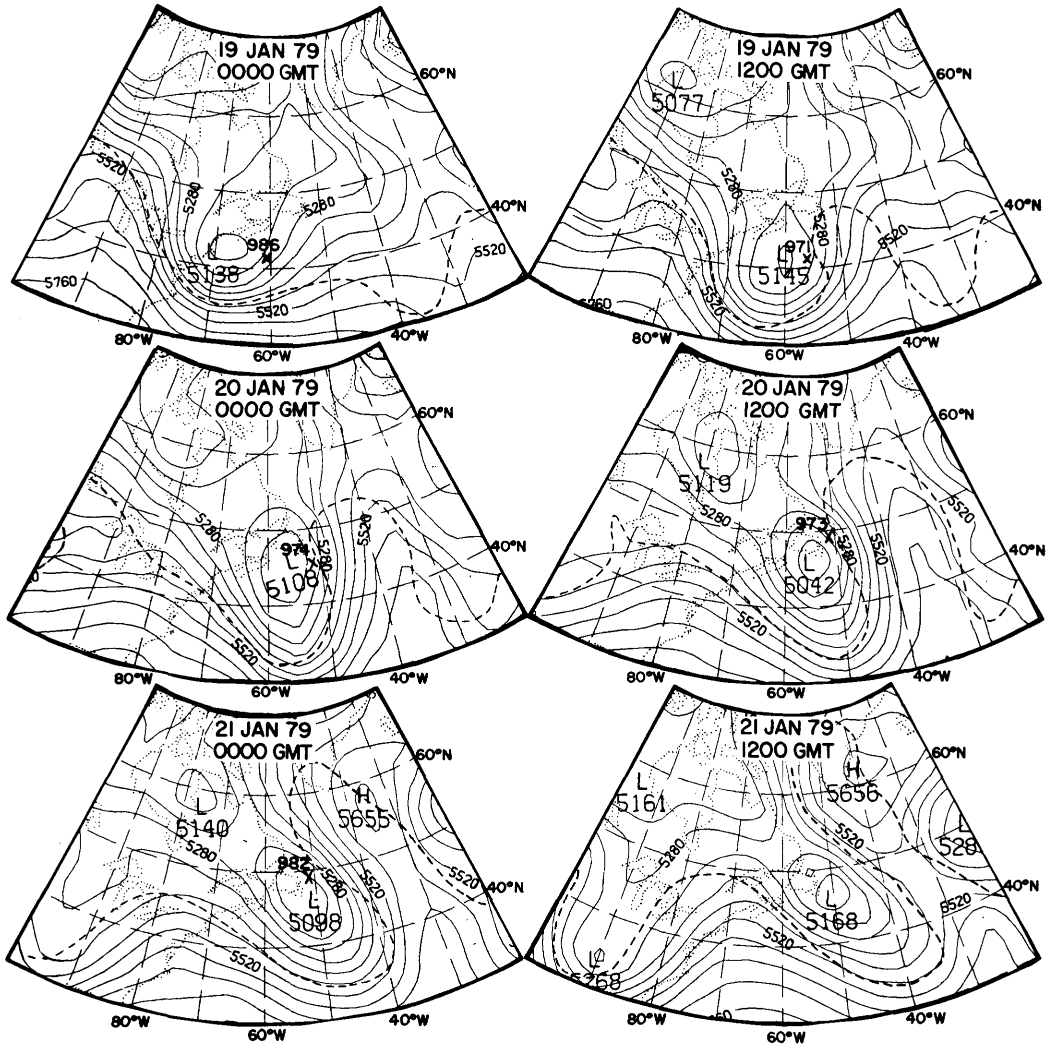

Fig. 3. As in Fig. 2 for the period from 000 GMT 19 January through 1200 GMT 21 January 1979.

properly regarded as a blocking anticyclone event. A more detailed synoptic discussion of this case is presented in TSA.

3. Energy equations

Following Robertson and Smith (1983) the horizontal eddy kinetic energy is given by

$$\mathrm{KE} = \frac{1}{g}\int_{p_t}^{p_s}\left[\frac{\overline{V'\cdot V'}}{2}\right]\mathrm{d}p, \qquad (1)$$

where V is the horizontal wind vector, p_t is 100 mb, p_s is the surface pressure, and g is the gravitational constant (9.8 m s^{-2}). The overbar corresponds to a local zonal average along each latitude over the interior domain in Fig. 1, the bracket is the latitudinal averaging operator, and the prime represents the departure of a given point from its zonal mean. Note that the zonal average and eddy quantities used here are not equivalent to hemispheric zonal and eddy quantities as used, for example, in hemispheric spectral energy diagnoses. In fact, the limited domain zonal average would be expected to contain information from those scales that are larger than the dimensions of the domain. In turn, the eddy quantities represented here can be interpreted as representing scales that are well-sampled within the limited domain studied, as suggested in Smith and Horn (1969). This is satisfactory because the domain was selected to be large enough to capture the blocking episode and the synoptic-scale waves that appear to be influential in the block development.

Since the matter of greatest interest is the baroclinic or barotropic energy conversion associated with the block development, the diagnosis of KE sources and sinks is restricted to the terms representing release of eddy potential energy (CE), generation of eddy kinetic energy (GK), and conversion between eddy and zonal kinetic energy (CK). Following Robertson and Smith (1983), these take the form, respectively,

$$\mathrm{CE} = \frac{1}{g}\int_{p_t}^{p_s} [\overline{\omega'\alpha'}]\,\mathrm{d}p, \tag{2}$$

$$\mathrm{GK} = -\frac{1}{g}\int_{p_t}^{p_s} [\overline{V'\cdot\nabla\phi'}]\,\mathrm{d}p, \tag{3}$$

$$\mathrm{CK} = -\frac{1}{g}\int_{p_t}^{p_s} [\overline{V'\cdot(V'\cdot\nabla)\,\bar{V}}]\,\mathrm{d}p - \frac{1}{g}\int_{p_t}^{p_s} \left[\overline{V'\cdot\omega'\frac{\partial \bar{V}}{\partial p}}\right]\mathrm{d}p, \tag{4}$$

where ω is the vertical motion in isobaric coordinates ($\mathrm{d}p/\mathrm{d}t$), α the specific volume, and ϕ the geopotential (gz). Note that CE is often referred to as the conversion of potential to kinetic energy, as was done in TSB. However, for open atmospheric systems, the released potential energy does not necessarily equal the generated kinetic energy (Smith, 1970). Thus, this paper provides an opportunity to expand the discussion of the baroclinic energy conversion for this case by examining both (2) and (3).

In addition, the quantities in (1)–(4) were partitioned into planetary-scale, synoptic-scale, and planetary/synoptic-scale interaction components. This was accomplished by replacing the eddy components of energy quantities by the sum of their planetary and synoptic-scale components. For example, the release of eddy potential energy (CE) can be partitioned into components as

$$\begin{aligned}\omega'\alpha' &= (\tilde{\omega}' + \omega^{*\prime})(\tilde{\alpha}' + \alpha^{*\prime})\\ &= \underset{(A)}{\tilde{\omega}'\tilde{\alpha}'} + \underset{(B)}{\omega^{*\prime}\alpha^{*\prime}} + \underset{(C)}{\omega^{*}\tilde{\alpha}' + \tilde{\omega}'\alpha^{*\prime}},\end{aligned} \tag{5}$$

where ($\tilde{\ }$) is the planetary-scale component and $(\ )^*$ is the synoptic-scale component. Thus, (A) is the planetary-scale release of eddy potential energy, (B) the synoptic-scale release of eddy potential energy, and (C) the release of eddy potential energy resulting from scale-interactions. The scale partitioning was accomplished using the procedure identified in TSA. In this the Barnes (1964) objective analysis procedure was used to partition the analysis fields into components based on the subjective observation that 500 mb height fields showed the preferred scale of the block to be 5000–6000 km and the synoptic waves to be 1500–3000 km. Thus, filter constants were chosen to yield a response function which retains 73% of the signal at 6000 km and only 11% at 3000 km. Interestingly, Kung and Baker (1986) found for the period of this study that hemispheric wave numbers 1 and 2 were representative of winter season blocking development, substantially larger scales than the 5000–6000 km dimension (equivalent to hemispheric wave number 5) identified in this paper. This may be explained by noting that while a local analysis may indicate a shorter wavelength, the placement of a major blocking high over the Atlantic and/or Pacific oceans will produce a strong hemispheric signal at wave numbers 1 and 2.

A positive (negative) value of terms (5A) and (5B) represents the gain (loss) of eddy potential energy by the planetary-scale or synoptic-scale flow as it vertically redistributes mass at the same scale. Warmer air rising and/or colder air sinking will release eddy potential energy for possible generation of eddy kinetic energy. A positive (negative) value of (5C) indicates that eddies gain (lose) potential energy by redistribution of mass through the interaction between planetary and synoptic-scale flow, i.e., either synoptic-scale ascent (descent) in the warmer (colder) planetary-scale environment or planetary-scale ascent (descent) in the warmer (colder) synoptic-scale environment.

Similarly, KE, GK, and CK can be partitioned into their planetary-scale, synoptic-scale, and scale-interaction components. Note that although CK involves triple products, the zonal wind is not affected by the scale partitioning. Thus, only the eddy products are involved in the scale-partitioning processes and the resulting terms are similar to the other energy quantities partitioned. A positive (negative) value for a GK component means that KE is being generated (destroyed) by cross-contour flow toward lower (higher) heights, while a positive (negative) value for a CK component means that zonal (eddy) flow is being converted to eddy (zonal) flow.

Finally, it should be noted that while TSA and TSB's height tendency diagnoses were restricted to 500 mb, the energetics diagnoses are represented as area-averaged (interior area of Fig. 1) statistics integrated from the surface to 100 mb.

4. General energetics results

Table 1 depicts the time variation of the total and eddy kinetic energy contents and their ratio during the development of the block. The total kinetic energy decreased from the initial time through 1200 GMT January 19 and then increased thereafter. However, the eddy kinetic energy began to increase 24 h earlier as the cyclone migrated across the east coast of the United States and explosively developed. The rate of increase of both the total and eddy kinetic energy were the greatest during the period from 0000 GMT 20 January, when the ridge became stationary, to 0000 GMT 21 January, when the closed high first appeared. On the whole, about 50% of the total kinetic energy was contributed by the eddy component. Clearly, the eddy contribution was greatest when the preexisting strong cyclone was coupled with the northward developing stationary ridge.

The time variation of the release of eddy potential energy (CE), the mechanical generation of eddy kinetic energy (GK), and the barotropic energy exchange between eddy and zonal kinetic energy (CK) are given in Table 2. CK was negative throughout the period of investigation, i.e., eddy kinetic energy was converted to the zonal flow. This indicates that the eddies were barotropically stable during the wave evolution, a result consistent with that of Chen and Shukla (1983). The loss of potential energy represented by the negative CE values and the corresponding increase in KE by the positive GK values indicate that KE was maintained by baroclinic energy conversion. This conversion was most vigorous during the explosive development phase of the cyclone and the amplification of the blocking ridge. Also, from the initial time until the end of explosive cyclone development, more potential energy was released than was required to mechanically generate KE by cross-contour flow. An export of excess potential energy to the surrounding environment would be required to balance the potential/kinetic energy exchange. This situation dramatically changed 12 h prior to the time at which the ridge became stationary when GK exceeded CE. This strong GK is consistent with the wind analyses shown in

Table 1. *Area-averaged, vertically-integrated total (K) and eddy (KE) kinetic energy and their ratio; units for K and KE are* 10^5 $J\,m^{-2}$

Date/time	K	KE	KE/K
17/12	29.9	14.1	0.47
18/00	28.3	13.6	0.48
18/12	26.7	12.0	0.45
19/00	26.5	12.5	0.47
19/12	25.2	12.8	0.51
20/00	25.5	13.7	0.54
20/12	27.1	14.7	0.54
21/00	29.1	16.0	0.55
21/12	29.7	16.5	0.56

Table 2. *Area-averaged, vertically-integrated release of eddy potential energy (CE), generation of eddy kinetic energy (GK) and barotropic kinetic energy exchange between zonal and eddy flows (CK); units:* $W\,m^{-2}$

Date/time	CE	GK	CK
17/12	−4.5	−2.7	−10.1
18/00	−1.8	8.9	−10.6
18/12	−4.3	0.6	−7.9
19/00	−7.7	0.9	−6.8
19/12	−8.4	11.2	−4.4
20/00	−7.9	15.3	−4.3
20/12	−6.4	8.8	−5.0
21/00	−7.1	13.8	−5.7
21/12	−8.3	20.6	−4.0

Figs. 11 and 12 of TSB, which show that strong cross-contour (ageostrophic) flow occurred in the vicinity of the ridge as it became stationary.

In summary, as noted in TSB, the energy in this case is baroclinically converted to KE from eddy potential energy and then barotropically to zonal flow. In addition, however, we note that the baroclinic conversion in the latter half of the period required additional potential energy input from the surrounding environment. The direction of energy flow is in agreement with Kung and Tanaka's (1983) global energetics study, although the work of Hartman and Ghan (1980) suggests that significant differences may exist between Atlantic and Pacific blocking episodes. Also, examining the local baroclinic and barotropic energy conversion for a blocking case using time mean/eddy analyses, Holopaninen and Fortelius (1987) found a baroclinic (barotropic) source (sink) of eddy energy.

5. Partitioned energetics results

Fig. 4 shows the time variation of eddy kinetic energy due to the planetary, synoptic, and planetary/synoptic-scale interaction components. When the short wave trough and ridge that eventually evolved into the block migrated eastward during the first 24 h, the planetary-scale KE was greater than the other components. Synoptic analyses (Fig. 2) show that the short wave was embedded in a dominant long-wave trough during

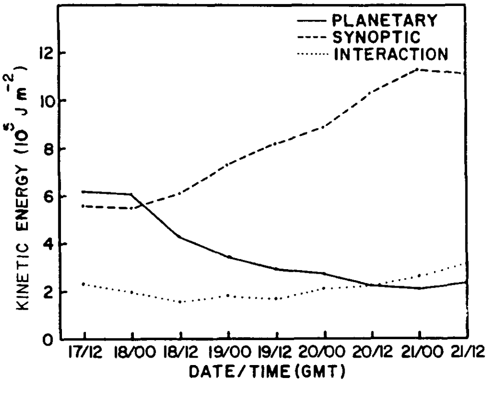

Fig. 4. Area-mean eddy kinetic energy ($10^5 \, J \, m^{-2}$) attributed to the planetary-scale, synoptic-scale, and synoptic/planetary-scale interaction components.

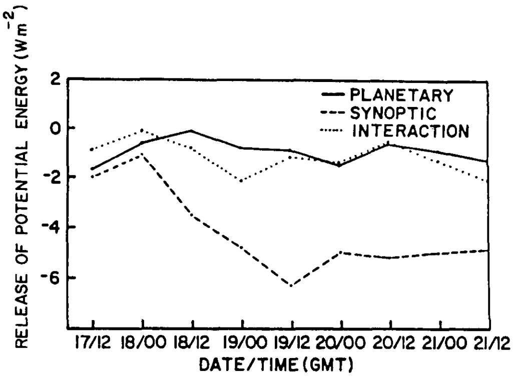

Fig. 5. As in Fig. 4 for the release of potential energy (CE, $W \, m^{-2}$).

this period. As the short-wave trough passed the east coast and rapidly deepened, the synoptic-scale component of KE increased while the planetary-scale component decreased. The synoptic component then continued to increase throughout most of the study period, reflecting the developing cyclone and downstream ridge feature. When the block finally formed during the last 12-h period displayed, the synoptic-scale KE decreased slightly, while the much smaller planetary-scale and scale interaction components increased. It is interesting to note that although the scale-interaction component of KE was small, it continued to increase after the surface cyclone reached maximum intensity at 1200 GMT 19 January.

Fig. 5 depicts the three components of CE. All components of CE were negative during the entire period, i.e., all components released eddy potential energy. All components were small in the beginning. However, during the explosive development stages of the cyclone, from 1200 GMT 18 January to 1200 GMT 19 January, the release of potential energy by the synoptic-scale dramatically increased, while the other two components remained small. This component reached its maximum at 1200 GMT 19 January when the surface cyclone reached its minimum pressure. The eddy component of the 500 mb vertical motion utilized in the calculation of CE at 0000 and 1200 GMT 20 January is shown in Fig. 6. We see that upward motion ahead of the trough and downward motion associated with the ridge were mainly attributed to the synoptic-scale component. Thus, the release of potential energy was more efficiently accomplished

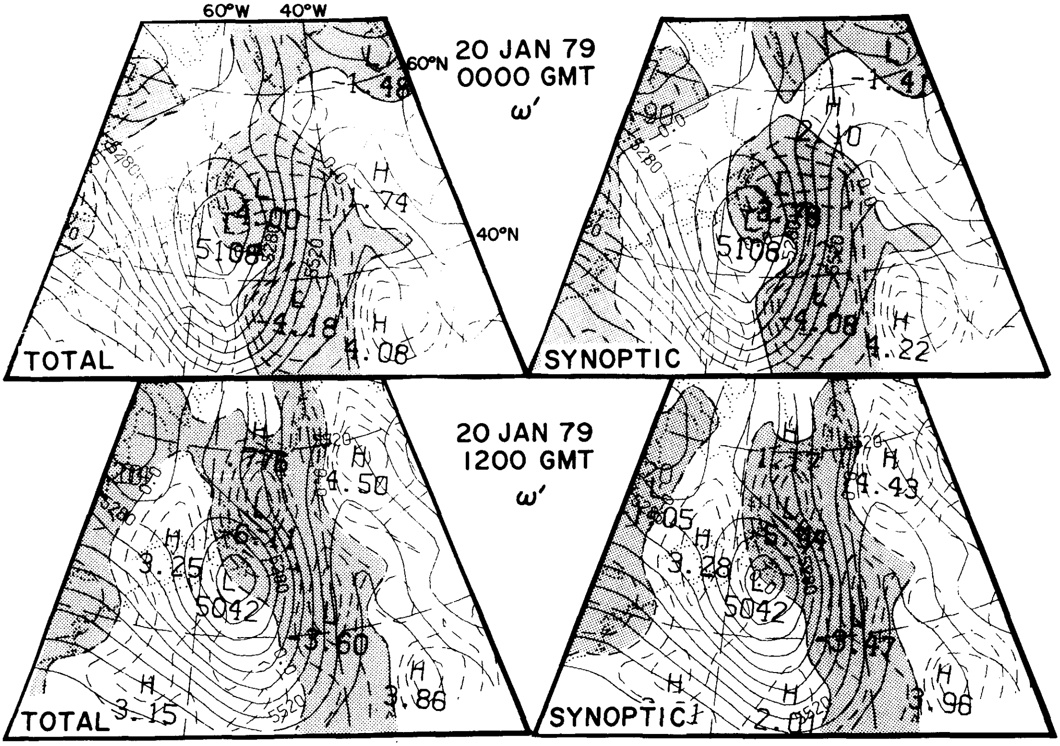

Fig. 6. The eddy vertical motion (dashed, μbar s^{-1}) attributed to the total and synoptic-scale components for 0000 and 1200 GMT 20 January. Upward motion regions are shaded.

by warmer air rising and/or colder air sinking at the synoptic scale than at the planetary scale.

Fig. 7 depicts the GK attributed to each component. The synoptic and planetary-scale components were positive, while the scale interaction was negative, i.e., synoptic and planetary-scale waves increased KE by cross-contour flow, while scale interaction decreased KE. The planetary-scale made the greatest relative contribution to GK before the surface cyclone reached maximum intensity. By 1200 GMT 19 January, the synoptic-scale component had dramatically increased and remained dominant throughout the remaining period displayed.

All three components of CK (Fig. 8) converted eddy kinetic energy to zonal flow. Much of the planetary-scale loss of KE to the zonal flow occurred before the ridge became stationary. Similar results were found by Chen and Shukla (1983). However, the loss of KE by the planetary-scale wave decreased sharply after the cyclone explosively developed on 1200 GMT 18 January. At the same time, the KE lost to zonal flow by synoptic-scale waves increased and became dominant after 0000 GMT 20 January.

The dominance of CE and CK at scales smaller than those associated with the blocking episode itself is consistent with the hemispheric spectral energetics results of Kung and Baker (1986). As noted earlier, they identified hemispheric wave-numbers 1 and 2 as the scales representative of blocking development. They then found that CE and CK were most prominent at smaller scales, including substantial contributions from wave-numbers 6–10. Their results also suggest that the KE of the longer waves was supplied by wave-wave interactions with the smaller scales. This upscale exchange of energy is also implied in Tanaka and Kung's (1988) Fig. 8. In this they note energy peaks at wave numbers 1 and 2

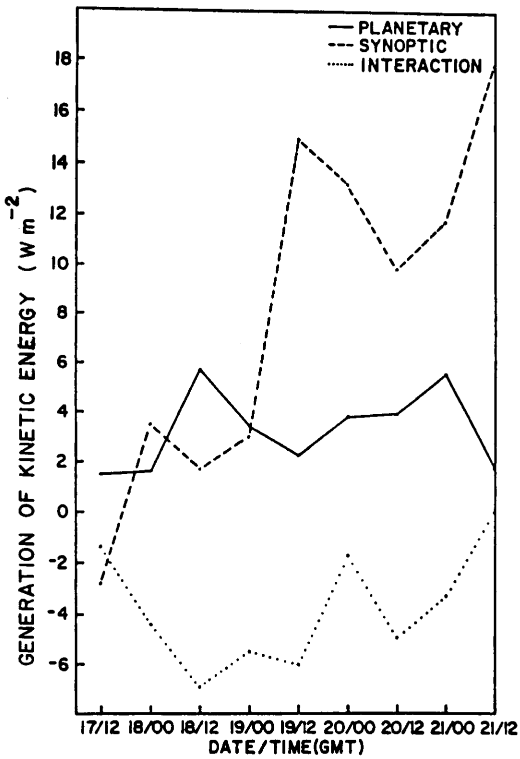

Fig. 7. As in Fig. 5 for generation of eddy kinetic energy (GK).

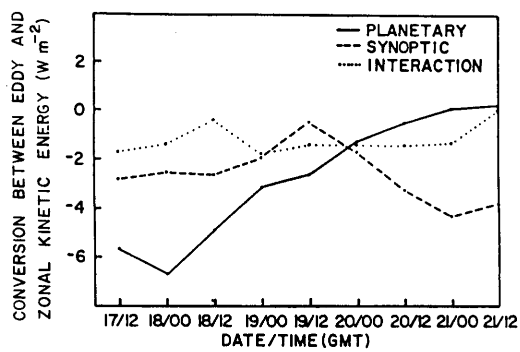

Fig. 8. As in Fig. 5 for conversion between eddy and zonal kinetic energy (CK).

during three blocking episodes, including the one discussed in this paper, which were preceded by energy peaks at wave numbers 3–15 five days earlier.

6. Summary

These results show that the eddy kinetic energy, dominated by its synoptic-scale component, increased as the wave features developed and was maintained primarily by baroclinic energy conversion. Both the release of potential energy and the corresponding generation of KE were large during the development of the surface cyclone and the block. The former was primarily attributed to the synoptic scale and reached its maximum when the cyclone reached maximum intensity. The latter was primarily a planetary-scale process initially, but then was dominated by the synoptic scale after the cyclone reached maximum intensity. Some of the kinetic energy converted through the baroclinic process was depleted by barotropic energy exchange from eddy to zonal flow. Much of this barotropic KE loss was attributed to planetary-scale processes before the ridge became stationary. However, as the ridge became stationary and the surface cyclone began to decay, the barotropic KE loss was primarily at the synoptic scale.

Finally, throughout the period investigated the synoptic/planetary-scale interaction components made only small contributions to the three energy transformations studied. This is in contrast to the TSA height tendency results, which showed that such interactions often dominated the height changes in both the height fall and height rise regions. This suggests that, while changes in the mass field depended on both the synoptic scale and the interactions between the synoptic and planetary scales, the corresponding changes in the eddy motion fields responded largely to only synoptic-scale processes. The reasons for this difference are not known.

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