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Daily spectral energy conversions of the global circulation during 10–27 January 1979

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ABSTRACT

The energetics of the daily wave activity over tropical and middle latitudes are examined for part of the first special observing period of FGGE using a modified version of ECMWF Level III-b analyses. Overall, the results are in good agreement with prior investigations. It is found that the eddy available potential (AE) is increased by sensible heat transport down the temperature gradient (CA) at all wavenumbers and that it is immediately converted to eddy kinetic energy (KE) through warmer air rising and/or colder air sinking (CE). Moreover, it is seen that this energy cycle takes place at each individual wavenumber, n, with the major contributions being due to $n = 2$–4 and $n = 6$–7. It is also seen that the wave-to-wave interactions are generally much less important than the remaining terms in the eddy energy budgets.

Special attention in this study is devoted to the southern hemisphere energetics. In the southern tropics, it is found that CE dominates over other conversion processes. The contribution from $n = 4$ accounts for the major portion of this conversion. It appears that latent heating in the south Pacific may be the main cause for the significance of this wavenumber 4 domination. In southern mid-latitudes, all conversion terms are equally important and the major contributions occur at intermediate wavelengths, $n = 6$–8. The energy cycle consists of a conversion of zonal available potential energy (AZ) to AE to KE to zonal kinetic energy (KZ).

1. Introduction

Several wavenumber studies have been conducted which emphasize global and/or hemispheric energetics over long time scales (e.g., Arpe et al., 1986; Awade et al., 1982; Chen, 1982; Chen and Lee, 1985; Kanamitsu, 1981; Kanamitsu et al., 1972; Kung and Baker, 1986a, b; Kung and Tanaka, 1983, 1984; Murakami, 1978; Saltzman, 1957, 1958, 1970; Singh, 1982a, b; Starr, 1968; and Wiin-Nielsen et al., 1964). However, in these studies, not much discussion was devoted to the southern hemispheric tropics, nor to the significance of tropical convection within the general circulation. The present study makes use of one of the special data sets collected during the global weather experiment (FGGE) to diagnose the energetics of the daily low and middle latitude wave activity that occurred over the globe during part of the experiment. Special attention is devoted to southern hemisphere energetics.

Recently, Huang and Vincent (1985) used a modified set of ECMWF FGGE Level III-b grid point analyses to diagnose the circulation features and energy conversions in the southern hemisphere during 10–27 January 1979. One of the dominant features during the period was the south Pacific convergence zone (SPCZ), a large-scale, quasi-stationary, convectively-active cloud band over the south Pacific ocean. Their study focused on the significance of the SPCZ on southern hemisphere energy conversions by partitioning the conversions into zonal and eddy (transient and standing) components. The mean state was examined for a 15-day period, 10–24

January, when the SPCZ was most active. After 24 January it dissipated. In addition, Huang and Vincent performed a zonal wavenumber analysis for wavenumbers 1–15 for the same 15-day period. The major findings of their study were: (1) the baroclinic conversion of eddy potential to eddy kinetic energy (CE) was the dominant conversion term in the tropics (0–30°S), and it was particularly important in the vicinity of the SPCZ; (2) wavenumber 4 dominated the CE conversion in the tropics, whereas wave numbers 5–8 dominated all the eddy conversions in middle latitudes (30–60°S); (3) one of the four waves in the CE ($n = 4$) conversion in the tropics coincided with the SPCZ, while the remaining three corresponded to the continental areas of Africa, Australia and South America; (4) during the last 3 days, when the SPCZ was decaying, the importance of the $n = 4$ contribution to CE was negligible.

In the present paper, the Huang and Vincent study is extended to include the day-to-day variations in the wave energetics and the effect of wave-to-wave interactions. Daily spectral energy conversions are shown not only for the southern hemisphere (0–60°S) but also for the global atmosphere (60°N–60°S) so that the southern hemisphere values can be placed in proper prospective. The southern hemisphere energy conversions are further partitioned into tropical (0–30°S) and extratropical (30–60°S) latitudes. In addition, the wave-to-wave energy exchanges are examined throughout the 18-day period, 10–27 January 1979.

A detailed description and discussion of the data sources used in this paper is given by Vincent (1982) and Huang and Vincent (1983, 1985) and will not be reiterated here. However, for the reader's convenience, a brief summary follows. The data set represents a modified version of the original ECMWF Level III-b analyses. It consists of daily-averaged values of: analyzed horizontal wind components and geopotential height; temperature (recomputed hydrostatically from analyzed heights); and vertical p-velocity (recomputed kinematically from the analyzed wind components with $\omega = 0$ at 1000 and 100 mb). Thus, all data are based on analyzed variables. The data are at standard pressure levels up to 100 mb and have been smoothed to horizontal increments of 5° latitude and longitude. The data set in this format is compatible with data sets used by other investigators who have computed general circulation energetics.

The spectral energetics results in this paper were derived using the one-dimensional wavenumber equations for available potential energy (APE) and kinetic energy in zonal and eddy form. These may be written in symbolic notation, after Saltzman (1970), as:

$$\frac{\partial \mathrm{AZ}}{\partial t} = -\sum_{n=1}^{15} \mathrm{CA}(n) - \mathrm{CZ} + \mathrm{GZ}, \qquad (1)$$

$$\frac{\partial \mathrm{AE}(n)}{\partial t} = \mathrm{CA}(n) + S(n) - \mathrm{CE}(n) + \mathrm{GE}(n), \qquad (2)$$

$$\frac{\partial \mathrm{KZ}}{\partial t} = \sum_{n=1}^{15} \mathrm{CK}(n) + \mathrm{CZ} + \mathrm{DZ}, \qquad (3)$$

$$\frac{\partial \mathrm{KE}(n)}{\partial t} = -\mathrm{CK}(n) + L(n) + \mathrm{CE}(n) + \mathrm{DE}(n). \qquad (4)$$

In the present study, all quantities represent integrals over the total mass of the atmosphere for each specified area and only contributions due to wavenumbers 1–15 are computed. Boundary fluxes are not included explicitly in these equations but some of them implicitly affect $L(n)$ and $S(n)$. AZ is the zonal APE; AE(n) the eddy APE at wavenumber n; KZ the zonal kinetic energy; KE(n) the eddy kinetic energy at wavenumber n; CA(n), CE(n), CK(n), and CZ are conversions of AZ to AE(n), AE(n) to KE(n), KE(n) to KZ, and AZ to KZ. $S(n)$ is the conversion of AE from all other wavenumbers to AE(n) and $L(n)$ represents conversion of KE from all other wavenumbers to KE(n). GZ, GE(n) are generations of AZ and AE(n); DZ, DE(n) dissipations of KZ and KE(n). If (2) and (4) are summed for $n = 1$–15, noting that

$$\sum_{n=-\infty}^{\infty} L(n) = \sum_{n=-\infty}^{\infty} S(n) = 0$$

for a closed region, a pair of equations is obtained which is identical to the energy equations in space domain (Oort, 1964) without boundary flux terms, assuming that eddy contributions from $n \geqslant 16$ are negligible.

2. Results and discussion

2.1. Global energetics

Daily variations of the wavenumber contributions to the global energy conversions that affect the AE(n) and KE(n) budgets, as given in (2) and (4), are illustrated in Fig. 1. With regard to the AE(n) budget, it is seen that CA(n) generally acts to increase the eddy available potential energy at all wavenumbers, while CE(n) acts to decrease it. Furthermore, both conversion quantities exhibit similar magnitudes and patterns, indicating a rapid response of the vertical heat transport conversion process to the horizontal heat transport conversion process. It appears that the available potential energy gained at any given wavenumber through horizontal temperature advection is immediately converted to kinetic energy at that wavenumber through thermally-direct vertical circulations. It is seen that wavenumbers 2–8 are responsible for nearly all of the CA(n) and CE(n) conversions throughout most of the study period, particularly the long waves ($n = 2$–4) and large synoptic-scale waves ($n = 6$–7). The remaining conversion term in (2), i.e., $S(n)$, is not as large as the other two conversions, but it does play a role in the AE(n) budget. Its main contribution also occurs in $n = 2$–8, and, at certain wave numbers, it shows a consistent pattern for several days. For example, at $n = 2$, $S(n)$ is negative throughout the period.

In the KE(n) budget, the CK(n) contribution generally is positive; it acts to convert eddy kinetic energy to zonal kinetic energy at most wavenumbers. The only exception occurs early in the study period when CK(n) is negative at $n = 2$ and 3. CK(n) is also found to be smaller than CE(n) and CA(n), especially for the first ten days when the SPCZ was quite active in the tropics. As for CE(n) and CA(n), the contributions by CK(n) are negligible at $n > 8$. The wave-to-wave interaction term in KE(n), i.e., $L(n)$, is seen to make an important contribution to the kinetic energy budget. As for $S(n)$, the temporal pattern of $L(n)$ at individual wave numbers is not always well organized. However, for $n = 2$–4, it is predominantly negative throughout the first half of the period. Furthermore, patterns of $L(n)$ and $S(n)$ are found to be very similar throughout the study period, as expected. This implies that active wave-to-wave interactions affect the conversions of both AE and KE.

A time series of each of the conversion terms which appear in (1)–(4), when summed over all wavenumbers ($n = 1$–15), is shown in Fig. 2. CA and CE are the largest contributors to their respective budgets and show a similar trend. Thus, as inferred earlier, the main energy flow is a rapid transfer from AZ to AE to KE. The conversion by the mean meridional circulations, CZ, is the same order of magnitude as CE and CA, and is always positive. This indicates a conversion of AZ to KZ and suggests that the Hadley circulation, which is stronger in the winter (northern) hemisphere, dominates over the Ferrel cell contributions in mid-latitudes of both hemispheres. The CK conversion is not as strong as the previously-mentioned conversions; however, it is always positive. This shows that KE is converted to KZ, and infers that the counter-gradient momentum transport found in the tropics dominates over the down-gradient transports which occur in middle latitudes of each hemisphere. Although the trend of CK appears to be in phase with that of CE, early in the period, it is not in phase after about 17 January. Thus, it is not obvious that the energy flow cycle noted above (i.e., AZ → AE → KE) continues directly from KE to KZ.

Finally, it is seen that the wave interaction conversion terms are nearly an order of magnitude less than the other conversion terms. This is not surprising, since these terms should be small after summing over waves, $n = 1$–15. To a certain extent, non-zero values of $S(n)$ and $L(n)$ indicate the noise level of the results, because errors in the computation of non-linear terms contribute to their values. However, other effects, such as boundary fluxes of heat and momentum across 60° N and 60° S, or through 100 mb, and interactions between waves of $n = 1$–15 and those of $n \geq 16$, can also influence these terms. Thus, the fact that they are relatively small provides us with a certain level of confidence regarding our results.

In their previous paper, Huang and Vincent (1985) examined the role of the SPCZ in the energetics of the southern hemisphere circulation. Because the SPCZ area was observed to be very active convectively during the period 10–24 January, they compiled time-averaged energy

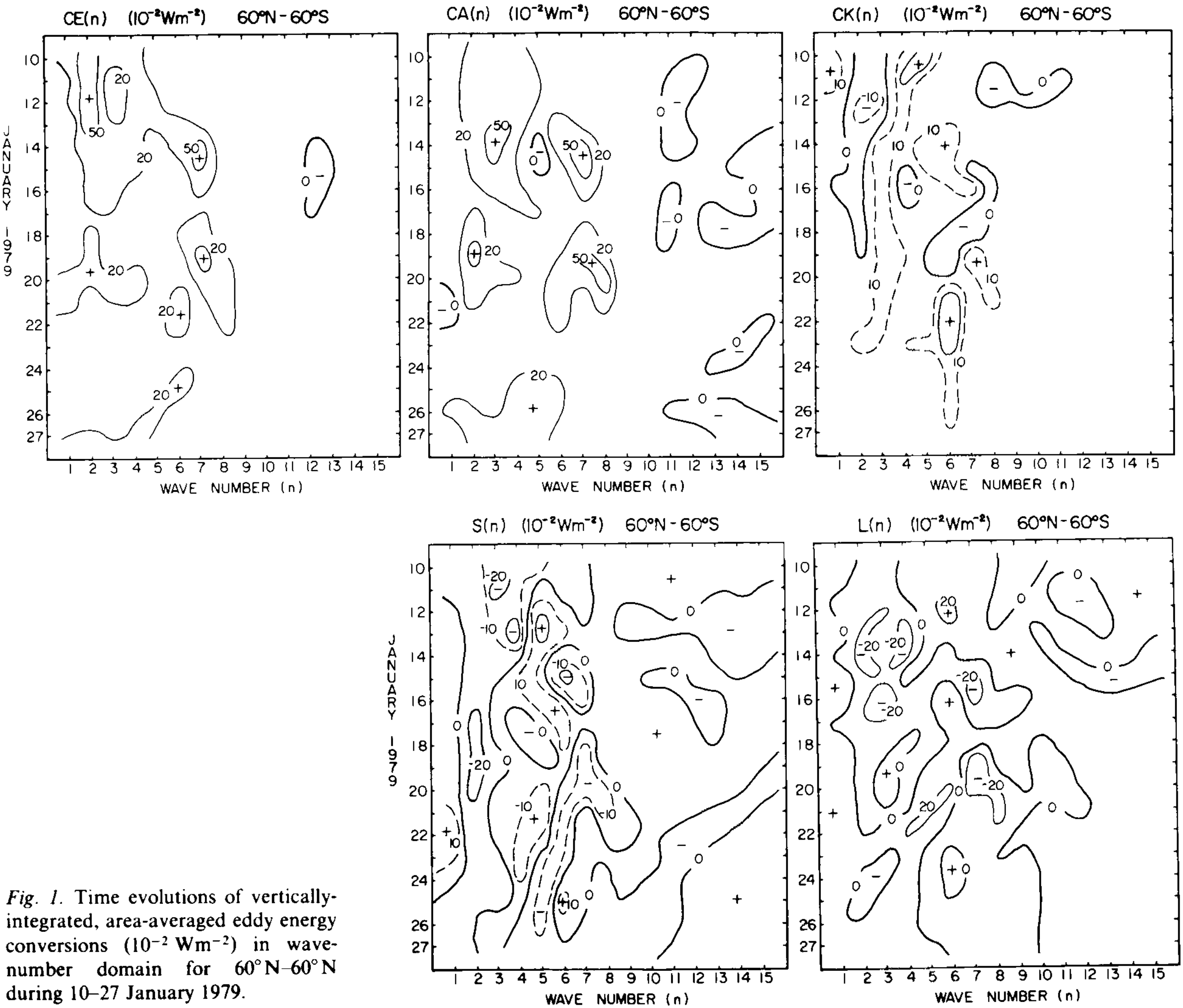

Fig. 1. Time evolutions of vertically-integrated, area-averaged eddy energy conversions (10^{-2} Wm^{-2}) in wave-number domain for 60°N–60°N during 10–27 January 1979.

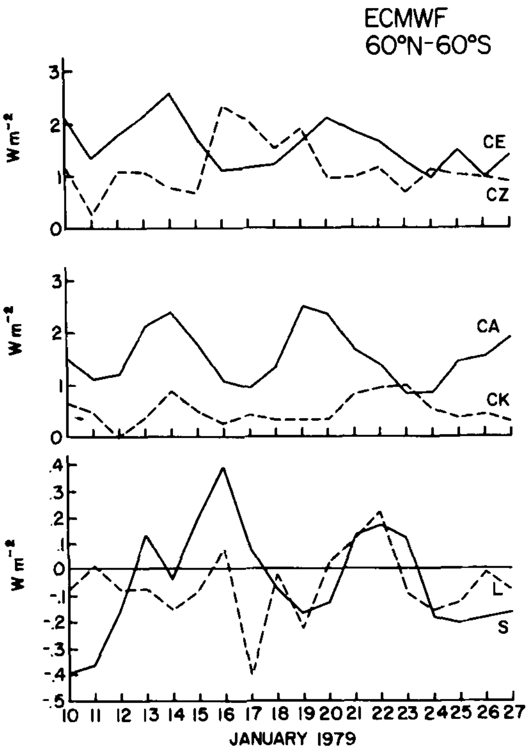

Fig. 2. Time evolutions of vertically-integrated, area-averaged energy conversions (Wm^{-2}), summed over all wavenumbers, $n = 1$–15 for 60°N–60°S during 10–27 January 1979. CE, CA and *S* are solid, CZ, CK and *L* are dashed.

quantities for that period. For consistency between their study and the present one, as well as for completeness in satisfying the objectives of this study, time averages were again compiled for the 15-day period, 10–24 January. Results of the time-averaged global conversions by wavenumber are shown in Fig. 3. As anticipated, CA(n) and CE(n) dominate over other conversions and the wavenumber distributions of both are essentially the same. The importance of wavenumbers 2–4 and 6–8, noted earlier in Fig. 1, is clearly evident. Also, as noted earlier, contributions by $n > 8$ are not very significant. In CK(n), only wavenumbers 3–6 make important contributions toward decreasing KE. These findings are very similar to those of Kung and Baker (1986a) for almost the same study period (compare with Fig. 12 of their paper).

The wave-to-wave interactions, $S(n)$ and $L(n)$, are qualitatively in good agreement with those given by Kung and Tanaka (1983). Wavenumber 1 receives energy from the other waves, while wavenumbers, $n = 2$–4, lose their energy to other waves. In Fig. 3, it is interesting to note the similarity between the distributions of wave contributions by $S(n)$ and $L(n)$. Recall that $S(n)$ and $L(n)$ are the conversions to a specific wavenumber for AE(n) and KE(n) by all other wavenumbers, whereas CA(n) and CK(n) represent the respective conversions to AE(n) and KE(n) by the specific wavenumber in question. Thus, horizontal wave transports of heat and momentum due to scale interactions tend to correspond with one another when their cumulative effect is considered for a particular wave. However, since the CA(n) and CK(n) distributions are not similar, the same transports do not necessarily cooperate to produce energy changes at a specific wavenumber.

A convenient summary, as well as a comparison between the present results and those by other investigators where similar spatial, tem-

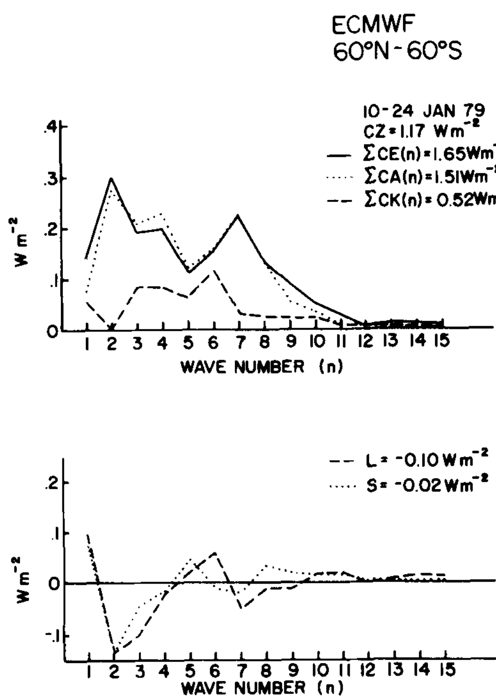

Fig. 3. Vertically-integrated, area-averaged energy conversions (Wm^{-2}) in wavenumber domain for 60°N–60°S, time-averaged for 10–24 January 1979 for reasons described in text.

Table 1. *Comparison of spectral energy contents (10^5 Jm^{2}) and conversions (Wm^{-2})*

(1) Kung and Tanaka (1983), 90°N–90°S, SOP-1, FGGE (1979)

	n = 1–3	4–9	10–15	Total
ECMWF				
AE	3.7	1.6	0.1	5.4
KE	2.9	3.1	0.7	6.7
CK	0.1	0.4	0.1	0.6
CA	0.7	1.2	0.1	2.0
CE	0.6	1.1	0.2	1.9
GFDL				
AE	3.9	1.6	0.3	5.5
KE	2.9	3.1	0.7	6.7
CK	0.1	0.2	0	0.3
CA	0.8	1.2	0.2	2.2
CE	1.1	1.7	0.6	3.4

(2) Kung and Baker (1986a), 90°N–90°S, SOP-1, FGGE (1979)

	n = 1–5	6–10	11–36	Total
GLA				
AE	5.2	1.0	0.6	6.8
KE	4.9	2.2	1.0	8.1
CK	0.3	0.3	0.1	0.7
CA	1.3	0.9	0.1	2.3
CE	1.4	1.1	0.5	3.0
GFDL				
AE	4.8	0.8	0.6	6.2
KE	4.4	1.8	1.2	7.4
CK	0.2	0.1	0.1	0.2
CA	1.4	0.7	0.3	2.4
CE	1.7	1.2	0.8	3.7

(3) Arpe et al. (1986), January 1981–85, 12-h forecasts at ECMWF

	n = 1–3	4–9	10–15	>15	Total
90°N–0					
AE	5.0	1.1	0.2	0.1	6.4
KE	5.4	3.6	0.7	0.3	10.0
CK	0.4	0.3	0	0	0.7
CA	1.7	1.3	0.1	0	3.1
CE	1.5	1.4	0.3	0.2	3.4
0–90°S					
AE	1.4	1.3	0.1	0.1	2.9
KE	1.8	2.8	0.5	0.2	5.3
CK	0.1	0.5	0.1	0	0.7
CA	0.2	1.0	0.1	0	1.3
CE	0.3	1.1	0.2	0	1.6

(4) Present study, 10–24 January 1979, ECMWF

	n = 1–3	4–9	10–15	Total
60°N–60°S				
AE	3.1	1.4	0.1	4.6
KE	2.7	2.9	0.4	6.0
CK	0.1	0.3	0	0.4
CA	0.6	0.9	0.1	1.6
CE	0.6	0.9	0.1	1.6
60°N–0				
AE	5.1	1.6	0.2	6.9
KE	4.0	2.8	0.4	7.2
CK	0.2	0.4	0	0.6
CA	1.2	1.3	0	2.5
CE	1.2	1.0	0.1	2.3
0–60°S				
AE	1.0	1.2	0.1	2.3
KE	1.4	2.7	0.3	4.4
CK	0.1	0.4	0.1	0.6
CA	0.1	0.8	0.1	1.0
CE	0.2	1.0	0.1	1.3

poral and wavenumber domains were used, is given in Table 1. The table shows mass-integrated, time-averaged values of the spectral distribution of eddy energy contents and conversions. The results presented are based on the following: (1) ECMWF and GFDL global data sets for SOP-1 of FGGE (Kung and Tanaka, 1983); (2) GLA and GFDL global data sets for SOP-1 of FGGE (Kung and Baker, 1986a); (3) ECMWF 12-h forecasts for the northern and southern hemispheres for the Januaries of 1981–85 (Arpe et al., 1986); (4) the present study using ECMWF (modified) data for the globe (60°N–60°S), northern hemisphere (60°N–0), and southern hemisphere (0–60°S) for part of SOP-1 (10–24 January, as in Fig. 3) of FGGE. In three of the four studies the wave compositing into long (n = 1–3), medium (n = 4–9), and short (n = 10–15) waves is identical. In Kung and Baker's study, the compositing is for slightly different wave groups (n = 1–5, 6–10, 11–36).

The results which are most ideally suited for comparison with the present results are those given by Kung and Tanaka (1983). In essence, the present results are a subset of those produced by them in their EMCWF data set, except that our ECMWF data have been modified, as discussed in Section 1. It is seen that the two sets of results are in good agreement, with the present set showing slightly smaller values in CA and CE, presumably due to the exclusion of the polar cap regions and, perhaps, the lower stratosphere. When comparing the present results with those of Kung and Baker (1986a), it is seen that the intensity of the energetics is greater in the GLA and GFDL analyses than in the ECMWF analyses. The main difference occurs in the CE-conversion where the ECMWF value is only about one-half that produced by the other two analyses. Several reasons could be responsible for this difference, namely, exclusions of the polar caps, lower stratosphere, and $n > 15$ contributions in the present study. Also, the Kung and Baker study, as well as the investigation by Kung and Tanaka, is for all of SOP-1, whereas the present study is only for about 1/4 of that period. It is worth noting that we recently obtained a set of GLA analyses for SOP-1 which we used to compute the energetics for the same wavenumbers and spatial and temporal domains as in the present study, except the GLA area was for 62°N–62°S. The GLA values for AE, KE, CK, CA and CE, in the same units as in Table 1, were: 5.2, 6.5, 0.6, 1.5 and 2.4. Comparing those to the present ECMWF values, reveals that the two sets of analyses yield similar results, with the possible exception of CE. Nevertheless, the GLA value of 2.4 Wm^{-2} is only 50% greater than the present value, whereas the global SOP-1 value was twice as large. In fact, it is seen that all of the energy quantities in the GLA results were larger in the global SOP-1 calculations than in the more restricted spatial and temporal calculations. This suggests that the exclusions in the present study, listed above, were responsible for many of the differences shown in Table 1.

Our southern hemisphere results can also be compared to those given by Arpe et al. (1986). Their ECMWF 12-h forecast values of energy contents and conversions during 1981–85 are in very good agreement with the present values, but are slightly larger. Again, this could be due to the exclusions in the present study that were noted above. In both studies, the total value of most energy quantities is greater in the northern hemisphere than its counterpart in the southern hemisphere, since the winter hemisphere circulations are more intense than those in the summer hemisphere. It is seen that the primary cause for larger values in the northern hemisphere is due to contributions by the long waves ($n = 1$–3). The intermediate ($n = 4$–9) waves appear to be as important in the southern summer as they are in the northern winter. Moreover, in the southern hemisphere these waves make a more significant contribution to the energy contents and conversions than do the longer waves. More will be said concerning the role of various waves in the southern hemisphere in Subsection 2.2 which follows.

2.2. *Southern hemisphere energetics*

Figs. 4 and 5 illustrate the daily variations of each of the energy conversion terms in (2) and (4) for wavenumbers 1–15 for the southern hemisphere tropics (0–30°S) and middle latitudes (30–60°S). In the tropics, Fig. 4 shows that CE(n) is greater than the other two conversion terms, especially at low wavenumbers. In particular, there is a significant positive contribution, indicating a conversion from AE(n) to KE(n), at wavenumber 4 during the periods 11–17 and 20–22 January when the SPCZ was most active. The only noteworthy contribution in the other two conversion terms occurs with regard to CK(n) at medium wavelengths during the middle part of the period. Wavenumber 4 is predominantly positive, indicating a conversion from KE(n) to KZ, and wavenumbers 6 and 7 are generally negative.

In extratropical latitudes, Fig. 4 shows that all three conversion terms are comparable in magnitude and each makes an important contribution to its respective budget. For all three, the largest contributions are due to wavenumbers 5–7 and each one exhibits a maximum from the middle to the latter half of the period. Furthermore, most values are positive. It appears that the maximum value of CE(n) occurs just after the maximum in CA(n) and just before the maximum in CK(n). This suggests that a rapid and significant flow (conversion) of energy takes place in the medium wave range as follows: AZ → AE(n) → KE(n) → KZ. Recall that when global conversions were examined, a rapid response for the latter transfer (i.e., KE(n) → KZ) was not clearly established.

The two wave-to-wave interaction terms, $S(n)$ and $L(n)$, are shown in Fig. 5. It is seen that these terms are smaller in the tropics than in mid-latitudes. In the tropics, however, their respective contributions are comparable in magnitude to the

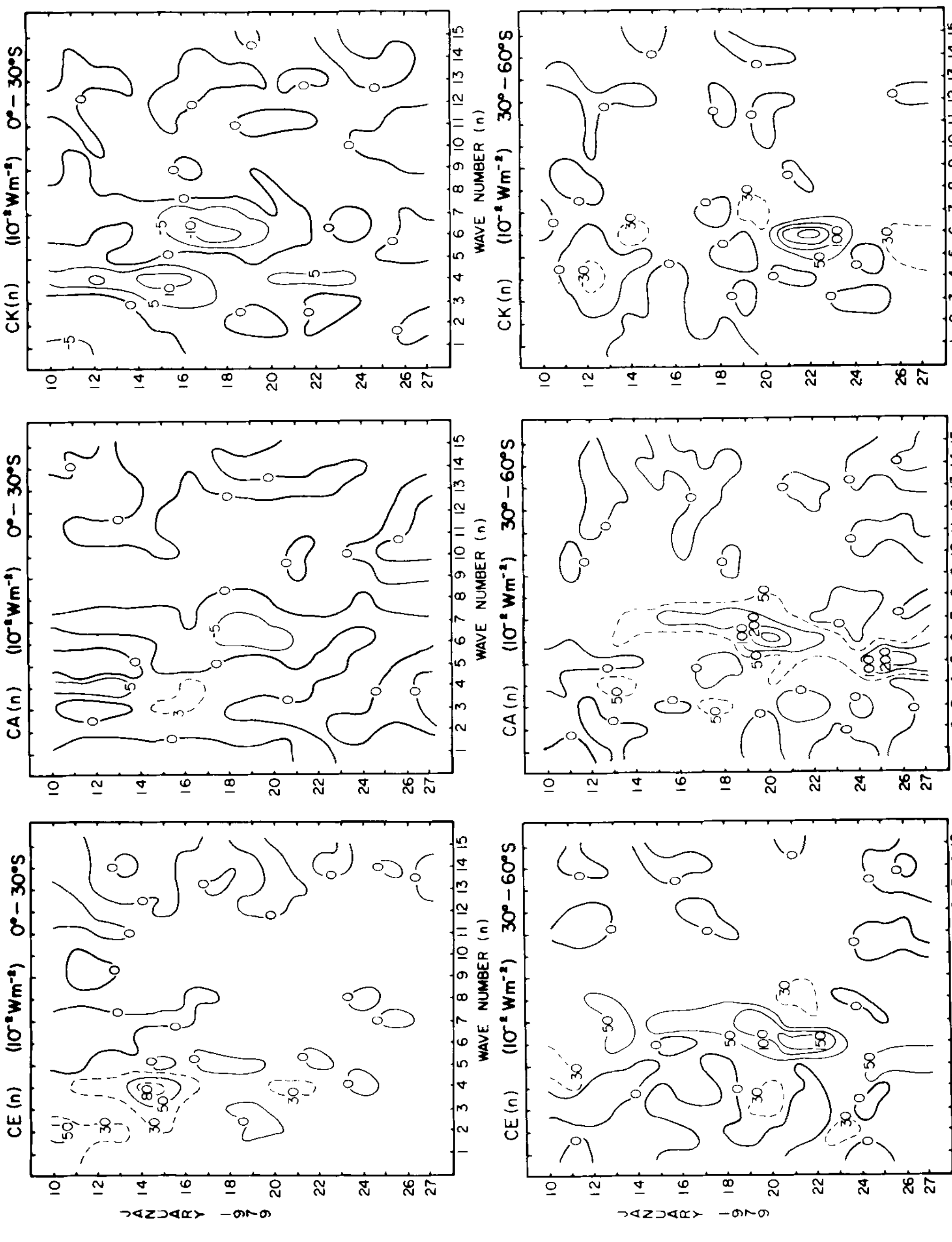

Fig. 4. As in Fig. 1, except for 0–30°S and 30–60°S.

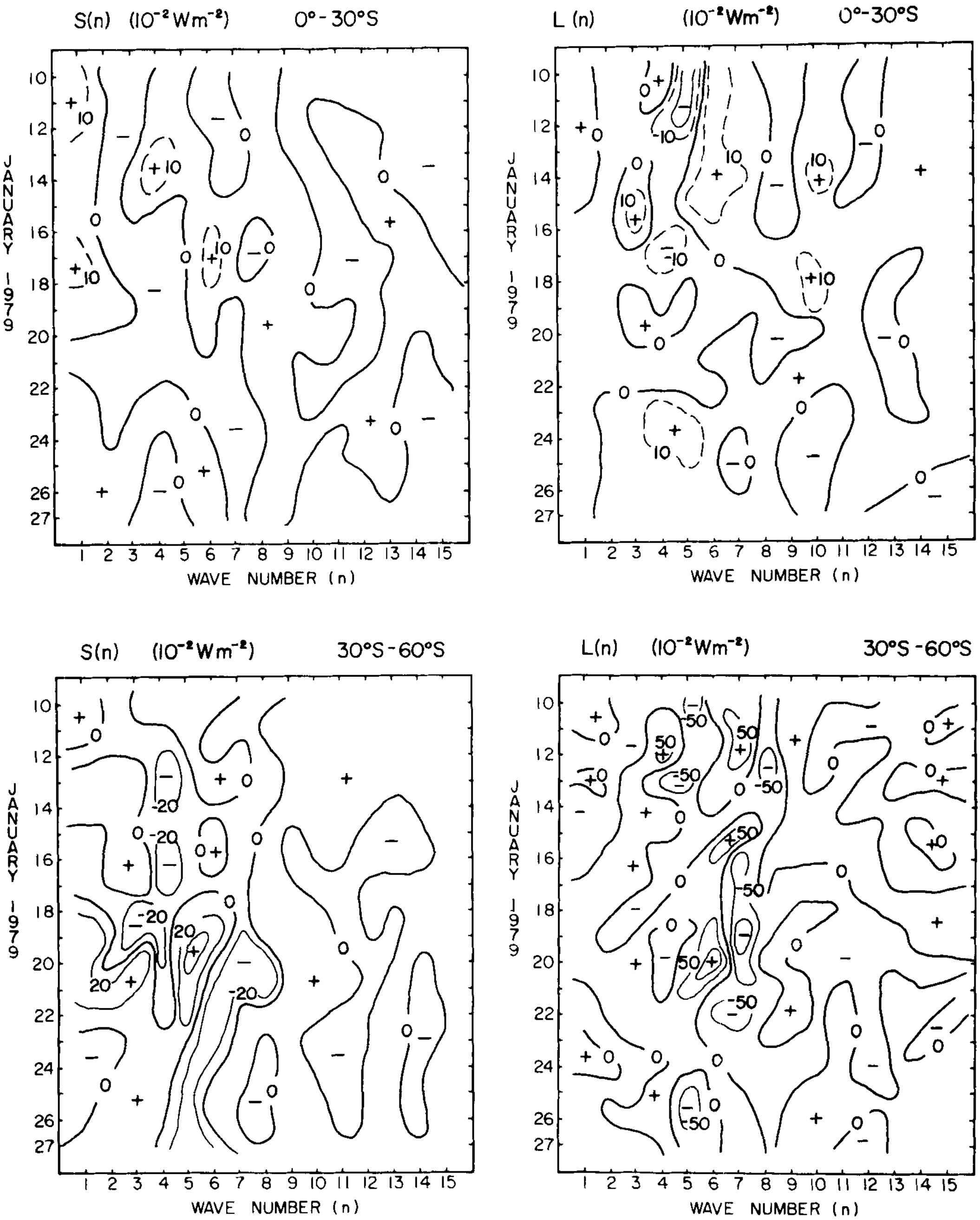

Fig. 5. Continuation of Fig. 4, for wave-to-wave interaction conversions.

corresponding conversion terms in the AE(n) and KE(n) budgets (i.e., CA(n) and CK(n)). Nevertheless, they are far less important when compared to the direct thermal circulations in the tropics represented by CE(n). In middle latitudes, $S(n)$ is small compared to CA(n), and $L(n)$ is often as large or larger than CK(n), but both $S(n)$ and $L(n)$ show similar patterns. This implies that

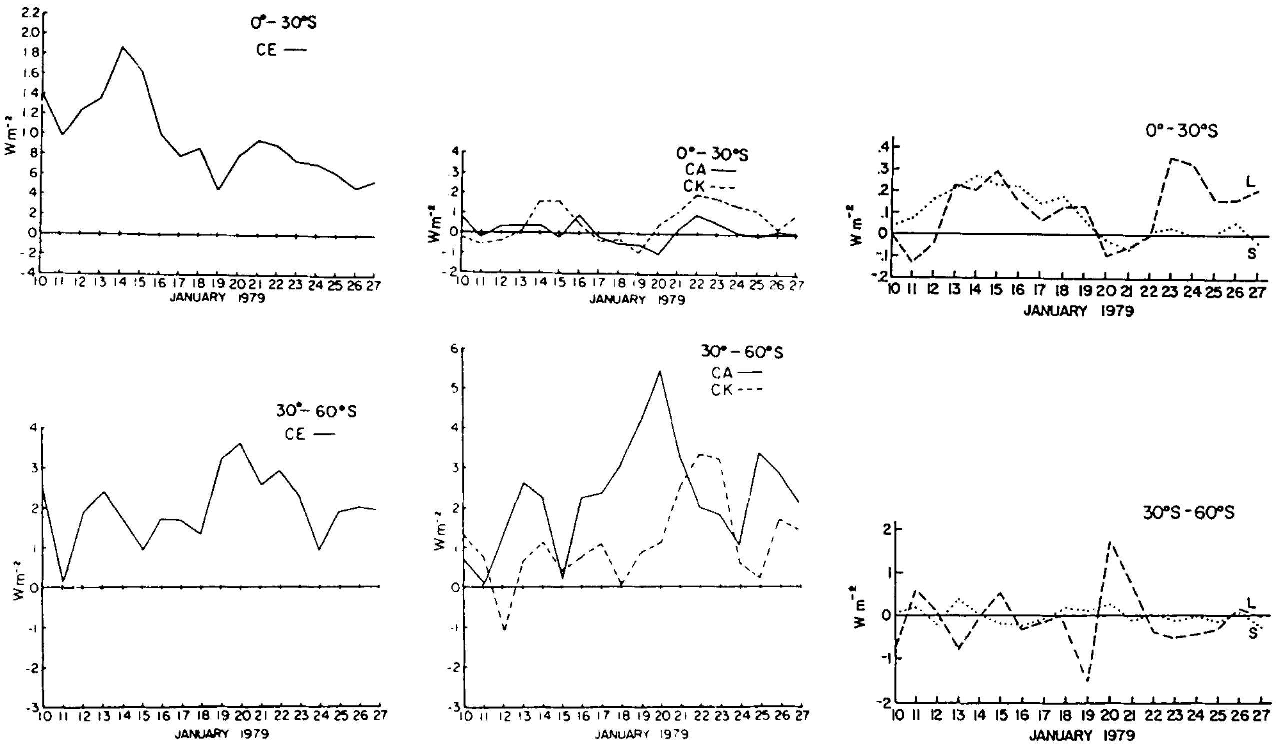

Fig. 6. Time evolutions of vertically-integrated, area-averaged eddy energy conversions (Wm^{-2}), summed over all wavenumbers, $n = 1$–15 for 0–30°S and 30–60°S during 10–27 January 1979. CE and CA are solid, CK and L are dashed, and S is dotted.

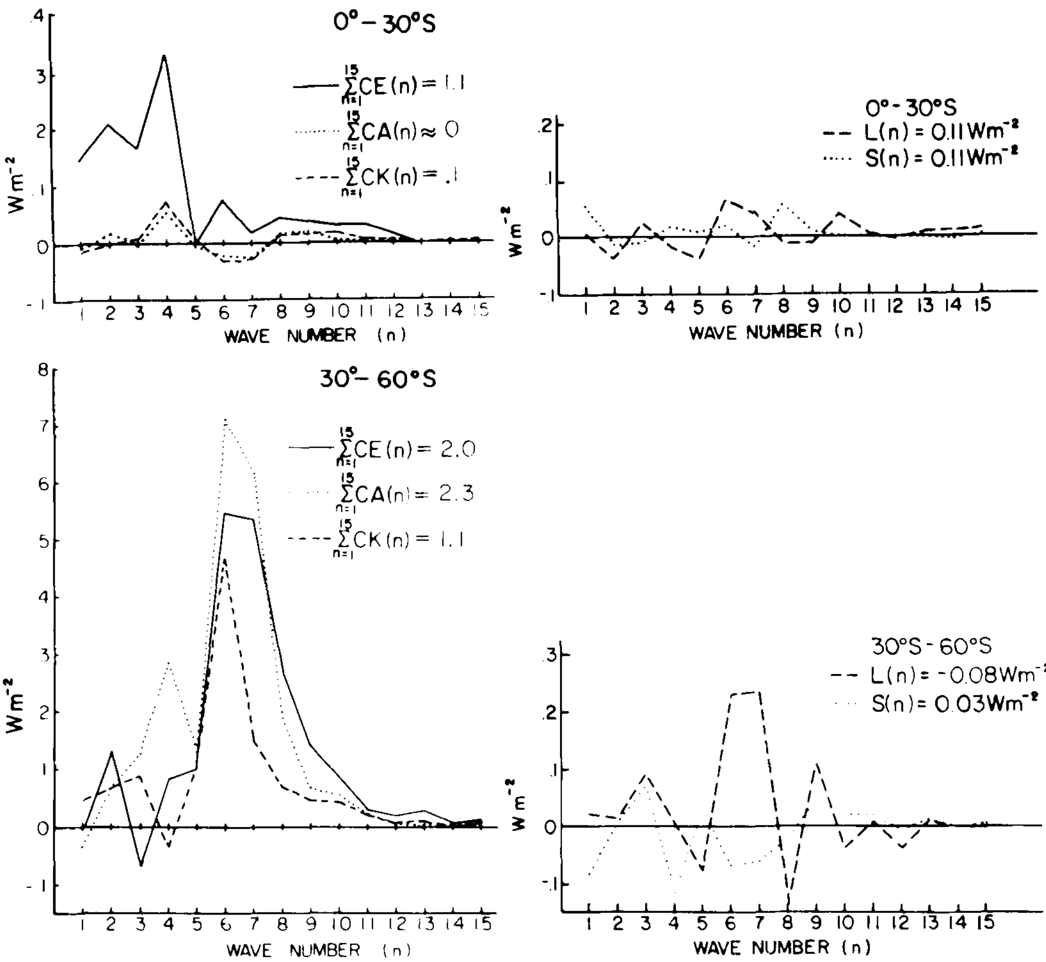

Fig. 7. As in Fig. 3, except for 0–30°S and 30–60°S, and CZ not shown.

wave-to-wave interactions are more active in conversions to KE(n) than in conversions to AE(n), which appears to be due to the presence of the jet stream and the less variable latitudinal temperature field in southern hemisphere mid-latitudes.

Daily variations of each of the five eddy conversions, summed over wavenumbers 1–15, are shown in Fig. 6 for the tropical and extratropical southern hemisphere. The only important conversion in the tropics is CE. It reaches a maximum on 14 January, then decreases gradually except for a slight increase near 21 January. This term is always positive, indicating that KE is increased at the expense of AE through warm air rising and/or cold air sinking.

In the extratropical region, as noted previously, all terms are important over most of the period except for the wave-to-wave interaction terms. CE and CA are both positive and show identical trends. This further substantiates the suggestion made earlier that there is an immediate response between the horizontal heat transport of warm (cold) air poleward (equatorward) and the thermally-direct vertical transport of heat. CK is also seen to be positive and seems to lag CE by one or, occasionally, two days. Since daily averages were used to compute all conversions, it is likely that some temporal smoothing occurred. Thus, it seems possible, as suggested earlier, that the energy transfers in southern hemisphere mid-latitudes between CA and CE and between CE and CK take place over a relatively short period of time (i.e., 1–2 days) and, furthermore, that the conversion process essentially follows a direct sequence of AZ → AE → KE → KZ.

The mass-integrated and time-averaged (10–24 January) results for each energy conversion are shown as a function of wavenumber for the tropics and extratropics in Fig. 7. As anticipated, CE(n) is the only important term in the tropics, and its significance is due to long waves. Wavenumber 4 accounts for approximately 30% of its total value. On a few of the days in the first half of the period, it was found that the $n = 4$ contribution was almost 50% (see Fig. 12 in Huang and Vincent, 1985). None of the results suggest that other waves (i.e., wave-to-wave interactions) are responsible for providing or concentrating their energy to wavenumber 4. Thus, it appears that this wavenumber 4 contribution is not due directly to dynamical wave interaction processes in the tropics. Recent model experiments by Kalnay et al. (1986) suggest that latent heating in the south Pacific may be an important factor in maintaining the significance of CE in the SPCZ. Because of the arrangement of the three continents in the tropical southern hemisphere, latent heating in the south Pacific may also be responsible for promoting the importance of wavenumber 4 in the CE-conversion process.

In middle latitudes, Fig. 7 shows that intermediate waves ($n = 6$–8) account for nearly all of the conversion with regard to CA(n), CE(n) and CK(n). This finding, together with the results shown in Figs. 5 and 6, verify that medium (synoptic-scale) waves are responsible for the aforementioned rapid conversion of AZ to AE, AE to KE, and KE to KZ. It is interesting to note that the peak in the baroclinic converison term, CE(n), which occurs at $n = 6$, 7, is in good agreement with the most unstable wavelengths according to Kuo's (1952) theory of baroclinic instabililty for middle latitudes. The only significant contribution from the wave interaction terms, is that by $L(n)$ at $n = 6$, 7. This result implies that other waves, both longer and shorter are combining their efforts to increase the eddy kinetic energy associated with these intermediate wavelengths, through momentum transport down the gradient of angular velocity. It appears that this scale interaction process offsets much of the loss of KE(n) due to the countergradient transport of momentum by CK(n) which maximizes at the same wavelength (i.e., $n = 6$, 7).

3. Acknowledgements

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