An analysis of wave structure near center of maximum turbulent kinetic energy

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(Manuscript received May 28, 1973)

ABSTRACT

An analysis is made of the wave structure near the center of maximum turbulent energy at 500 mb, Winter 1964. It is found that the kinetic energy of the zonal component is about twice that of the meridional component of the turbulent motion. The kinetic energy of the zonal component of the turbulent motion is essentially contributed by waves of low frequencies and by the interactions of waves of all frequencies. However, waves of all frequencies contribute to the kinetic energy of the meridional component of the turbulent motion. In the intermediate and high frequency ranges, contributions come mostly from interactions of waves of low frequency and the zonal mean motion, whereas in the low frequency range, contribution comes mainly from the ageostrophic motion.

1. Introduction

In a recent paper (Tsay & Kao, 1973), an investigation has been made of the spectral structure of atmospheric waves near a jet stream. It is found that near the maximum zonal mean motion, the kinetic energy of the zonal and meridional components of the wave motion is generally contributed by the nonlinear interactions between waves of various frequencies and with the mean zonal motion. It is also found that as waves travel eastward from the center of maximum zonal motion, the velocity amplitudes of waves of low frequencies grow at the expense of the kinetic energy of waves of higher frequencies. This suggests that center of maximum motion of the jet stream tends to excite wave motion of high frequencies, and that the kinetic energy of these waves is transferred to waves of lower frequencies through nonlinear interaction.

It was pointed out in the above mentioned paper, that a center of maximum kinetic energy of the turbulent motion occurs to the NE of the center of the maximum mean motion which confirms an earlier finding made by Kao & Hurley (1962). A question arises as to the mechanism for the maintenance of such a center of maximum turbulent kinetic energy. The purpose of this paper is to investigate this problem by analyzing the wave structure near the center.

2. Data and computations

The data used in this study were obtained from the 12-hourly 500 mb height and stream function analyses of the National Meteorological Center. The values of height and stream function were available over the portion of the Northern Hemisphere north of 17.5° N latitude on the NMC octagonal grid with a grid interval of 381 kilometers. The period from 0000Z 1 December 1963 through 0000Z 1 December 1964 was selected because the data available for this year was far more complete than the data available for other periods.

The stream function data were computed at the NMC through a finite difference solution of the balance equation

$$\nabla^2\psi = \frac{1}{f}\left\{\nabla^2\Phi + 2\left[\left(\frac{\partial^2\psi}{\partial x\partial y}\right)^2 - \frac{\partial^2\psi}{\partial x^2}\frac{\partial^2\psi}{\partial y^2}\right] - \nabla\psi\cdot\nabla f\right\} \quad (1)$$

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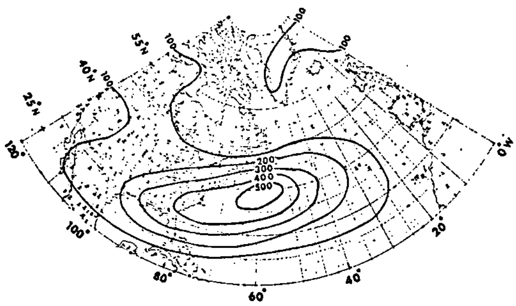

Fig. 1a. The distribution of the kinetic energy for mean motion in Winter 1964. (Unit: 10^4 cm^2 sec^{-2}.)

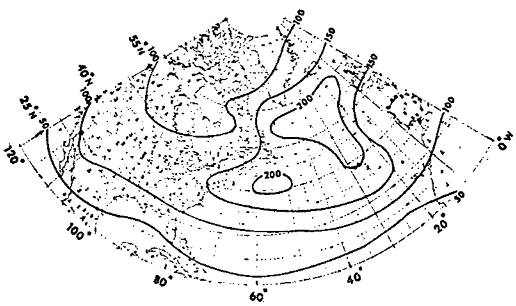

Fig. 1b. The distribution of the average kinetic energy for turbulent motion in Winter 1964. (Unit: cm^2 sec^{-2}.)

where f is the Coriolis force, Φ is the geopotential height of a pressure surface and ψ is the stream function. The balance equation is obtained by first taking the divergence of the equation of motion for nonviscous flow and then setting the divergence and its total derivative equal to zero. This permits us to define the stream function derived winds with

$$\mathbf{V} = \mathbf{k} \times \nabla \psi \tag{2}$$

where $\mathbf{k}$ represents the unit vector in the zenith direction.

The addition of divergent portion of the wind would make the study more realistic, but the velocity potential analyses were not immediately available. However, since this analysis is made at 500 mb, which is close to the level of nondivergence, the use of the nondivergence wind should be reasonable (Charney, 1948).

The wind data used in this study are derived from the stream function, and therefore represent only the horizontal part of motion. Furthermore, the vertical velocity resulting from the large-scale atmospheric motion is generally much smaller than horizontal motion (Phillips, 1963). Thus, for the computations involved in this work, the terms involving vertical velocity are neglected, and the energy equations (Tsay & Kao, 1973) may be expressed

Table 1. *Partition classification according to frequency*

Frequency, n (cycles/90 days)	Period, p (days)	Definition (frequency)	Symbol
0		Zero	0
1–10	9 to 90	Low	L
11 to 30	3 to 9	Intermediate	I
31 to 90	1 to 3	High	H

$$EUU(n) = \frac{T}{2\pi}\Bigg\{ \underset{\text{(U1)}}{U(-n)\frac{i}{na\cos\phi}\sum_m U(n-m)\,U_\lambda(m)}$$

$$+ \underset{\text{(U2)}}{U(-n)\frac{i}{na}\sum_m V(n-m)\,U_\phi(m)}$$

$$- \underset{\text{(U3)}}{U(-n)\,i\frac{\tan\phi}{na}\sum_m V(n-m)\,U(m)}$$

$$- \underset{\text{(U4)}}{U(-n)\frac{i}{n}f[V(n)-VG(n)]}$$

$$\underset{\text{(U5)}}{-\frac{i}{n}U(-n)\,G_1(n)}\Bigg\} \tag{3}$$

$$EVV(n) = \frac{T}{2\pi}\Bigg\{ \underset{\text{(V1)}}{V(-n)\frac{i}{na\cos\phi}\sum_m U(n-m)\,V_\lambda(m)}$$

$$+ \underset{\text{(V2)}}{V(-n)\frac{i}{na}\sum_m V(n-m)\,V_\phi(m)}$$

$$+ \underset{\text{(V3)}}{V(-n)\,i\frac{\tan\phi}{na}\sum_m U(n-m)\,U(m)}$$

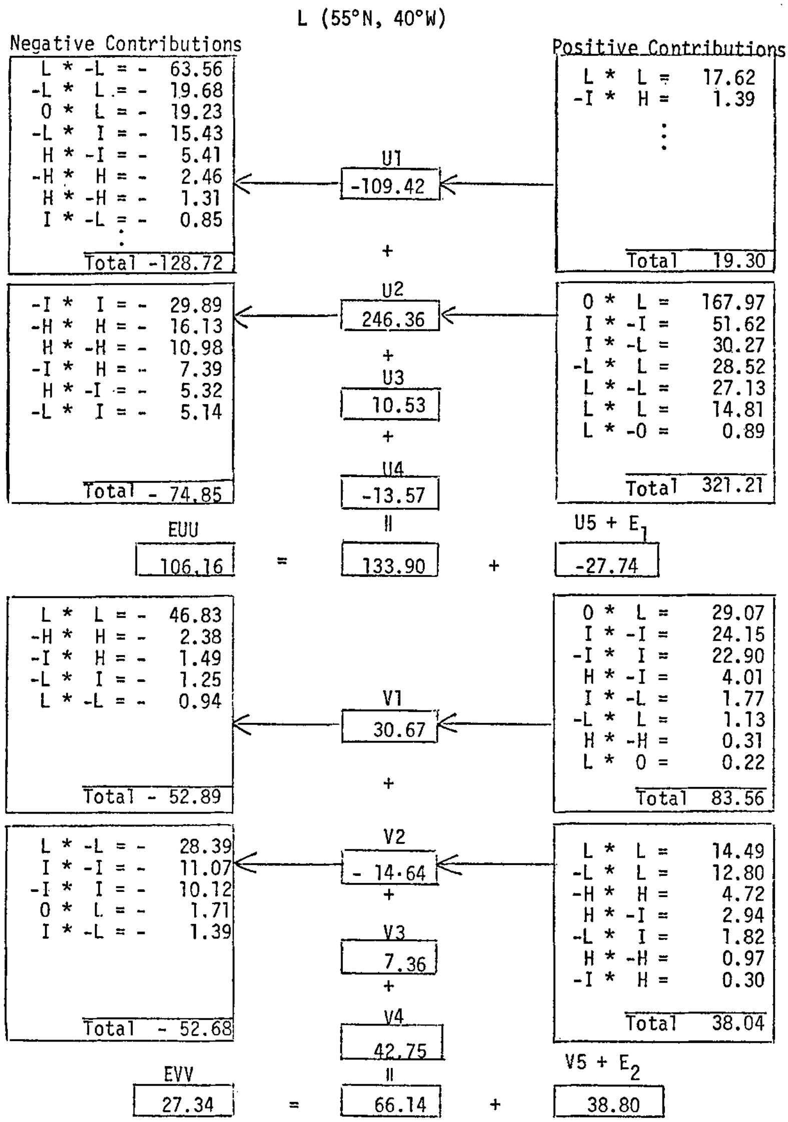

Fig. 2. Linear and nonlinear contributions to the kinetic energy spectra at 500 mb, Winter 1964 for L (55° N, 40° W).

$$+ V(-n)\frac{i}{n} f[U(n) - UG(n)]$$

(V4)

$$\left.- \frac{i}{n} V(-n)\, G_2(n)\right\} \qquad (4)$$

(V5)

The symbols below the terms on the right side of the equations are for future reference. The summations over m are from $-m_s$ to m_s, where m_s depends on the number of discrete time data points used, $m_s = 90$ cycles/(90 days) in this study. Summation is used here in place of integration with respect to m, because the transforms are computed for integral values of frequency. This is equivalent to assuming $q(t)$ to be periodic over the time period selected for the analysis.

The interaction terms involving derivatives

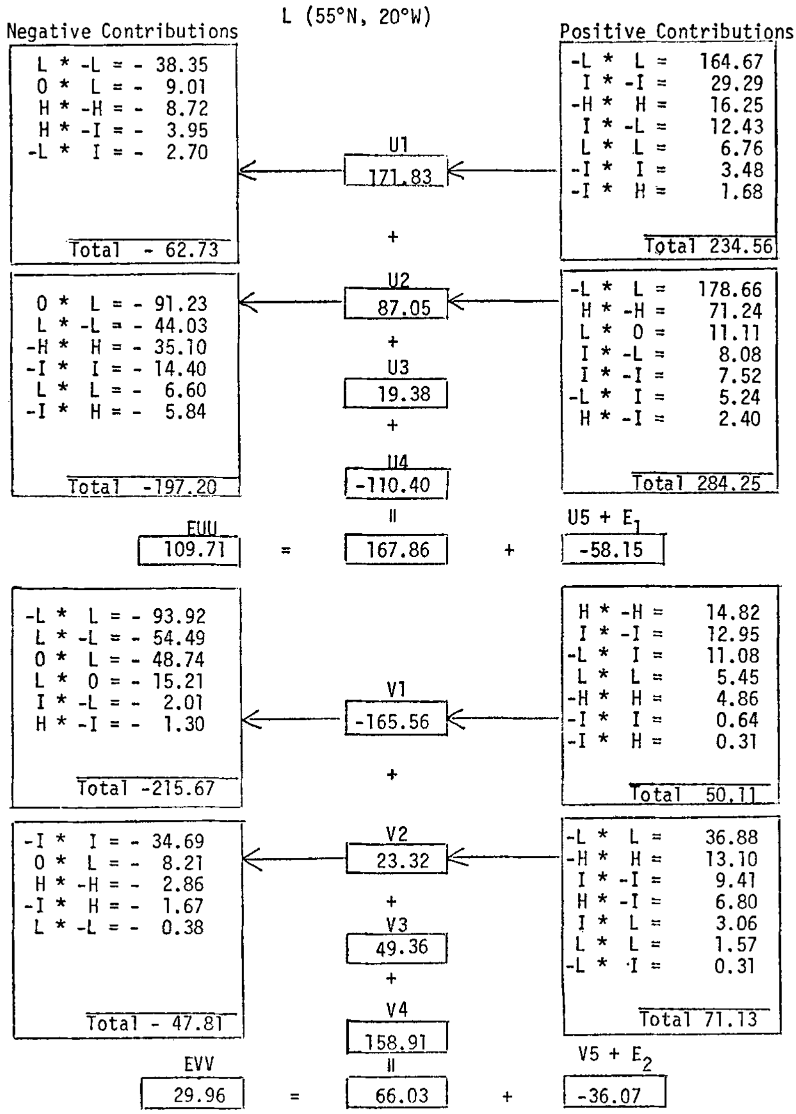

Fig. 3. Linear and nonlinear contributions to the kinetic energy spectra at 500 mb, Winter 1964 for L (55° N, 20° W).

with respect to longitude and latitude are computed by a centered difference with $\Delta\lambda = 10°$ and $\Delta\phi = 5°$.

To provide a reference for the study, the kinetic energy of the mean and turbulent motion in the region from 0° W to 120° W and from 25° N to 80° N for Winter 1964 has been computed and is shown in Figs. 1*a* and *b*. This region includes the American continent and Atlantic Ocean. It may be noted that the maximum of the kinetic energy of the mean motion is located on 55° N between 20° and 40° W. The northwest displacement of the maximum kinetic energy of the turbulent motion from that of the mean motion has earlier been observed by Kao & Hurley (1962).

3. The linear and nonlinear interactions

3.1. *General discussion*

The nonlinear interaction terms U1, U2, U3 in equation (3) and V1, V2, V3 in equation (4)

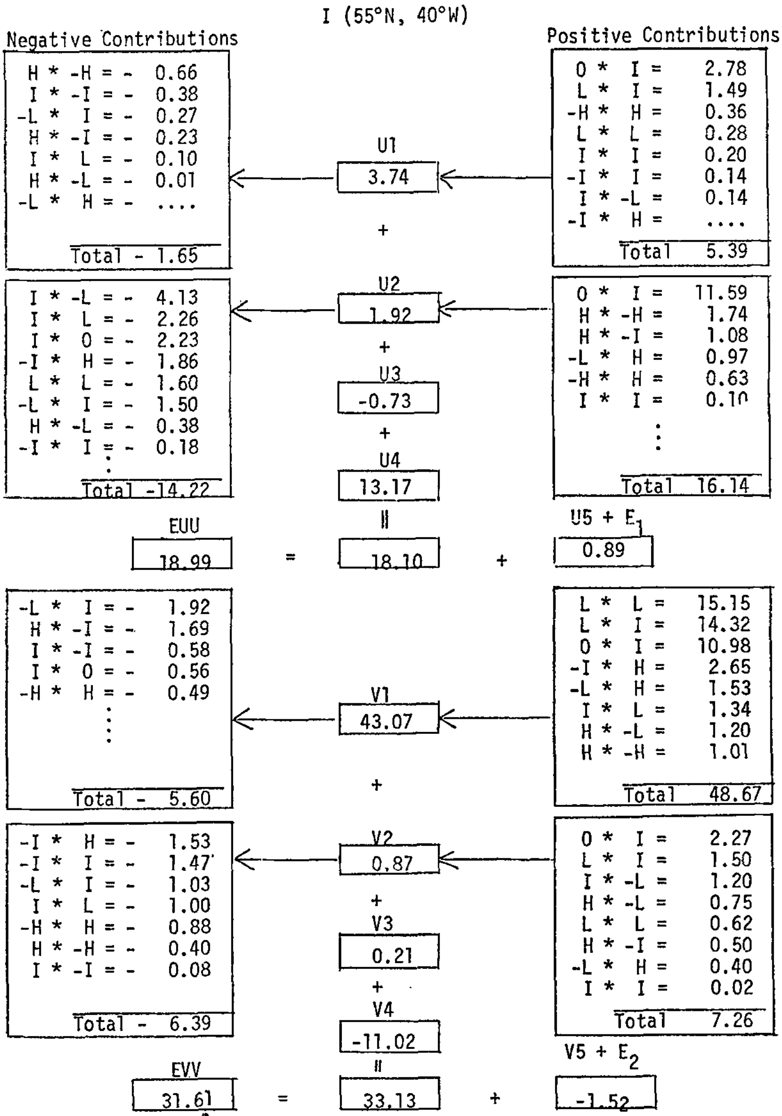

Fig. 4. Linear and nonlinear contributions to the kinetic energy spectra at 500 mb, Winter 1964 for I (55° N, 40° W).

involve sums of products of transforms for various frequencies in the form

$$\sum_{m=-m_s}^{m_s} Q(n-m)\,P(m)$$

It may be noted from these terms that, depending on the values of n, each term involves from 91 to 180 products of Fourier coefficients. Each product may be considered an interaction between a wave of complex amplitude Q, frequency $(n-m)$ and a wave of complex amplitude P, frequency m. For simplicity, we will say $(n-m)$ interacts with m. If m is allowed to vary over its entire range, the terms U1, U2, U3 and V1, V2, V3 represent the total contributions from all possible interactions. It may be noted that both $(n-m)$ and m could be negative. However, it can be shown (Appendix A) that the interaction of two given waves of frequencies

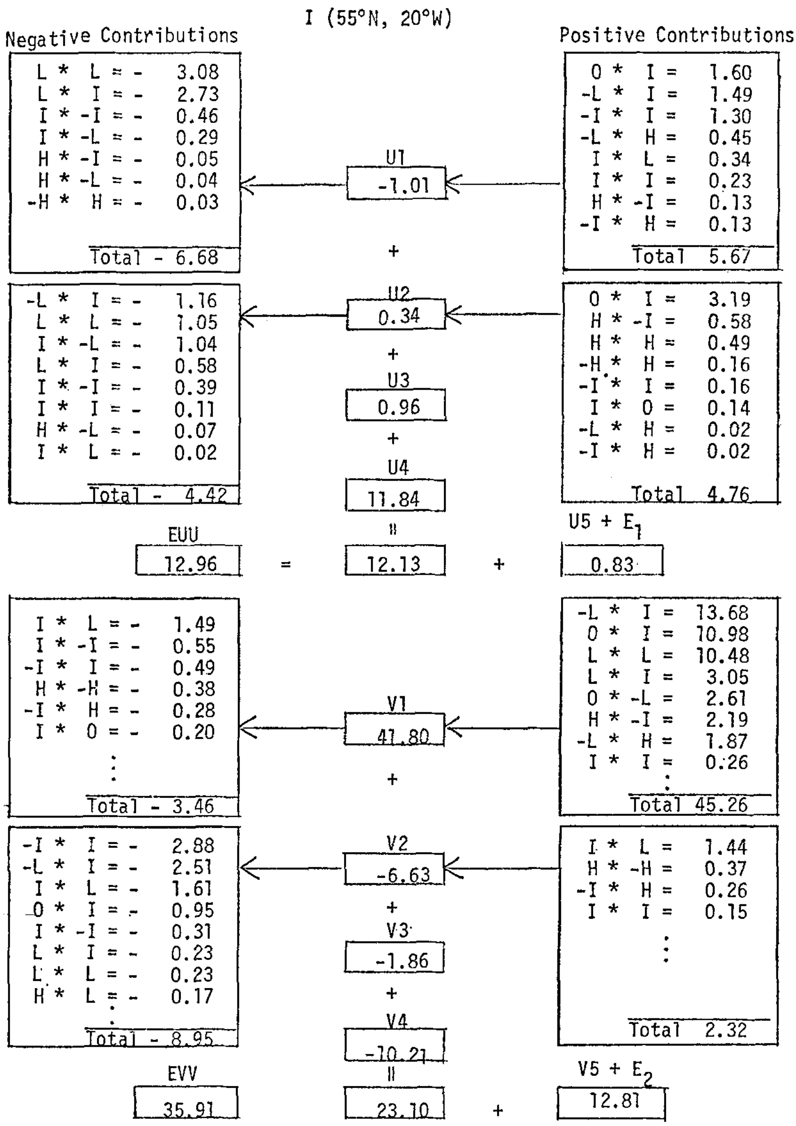

Fig. 5. Linear and nonlinear contributions to the kinetic energy spectra at 500 mb, Winter 1964 for I (55° N, 20° W).

k and j (if $k > j$) with their complex amplitude $Q(k)$ and $P(j)$ would result in two waves: one with frequency $k+j$, and with complex amplitude $Q(k)\,P(j)$, and the other with frequency $k-j$, and with complex amplitude $Q(k)\,P(-j)$. Therefore, the negative values of m (or $n-m$) represent the interaction of $|m|$ (or $|n-m|$) and $n-m$ (or m) and contribute to the frequency n with the amplitude $Q\,(|n-m|)\,P(-|m|)$ or $Q(-|n-m|)\,P(|m|)$. Since the interaction of waves of frequencies k and j results in two waves of frequencies $k+j$ and $k-j$, we will say k interacts with j and k interacts with $-j$ to distinguish them.

For the convenience of presentation, we classify the frequency range into stationary ($n = 0$), low frequency range ($n = 1$ to 10, i.e., period 9 to 90 days), intermediate frequency range ($n = 11$ to 30, i.e., period 3 to 9 days), and high frequency range ($n = 31$ to 90, i.e., period 1 to 3

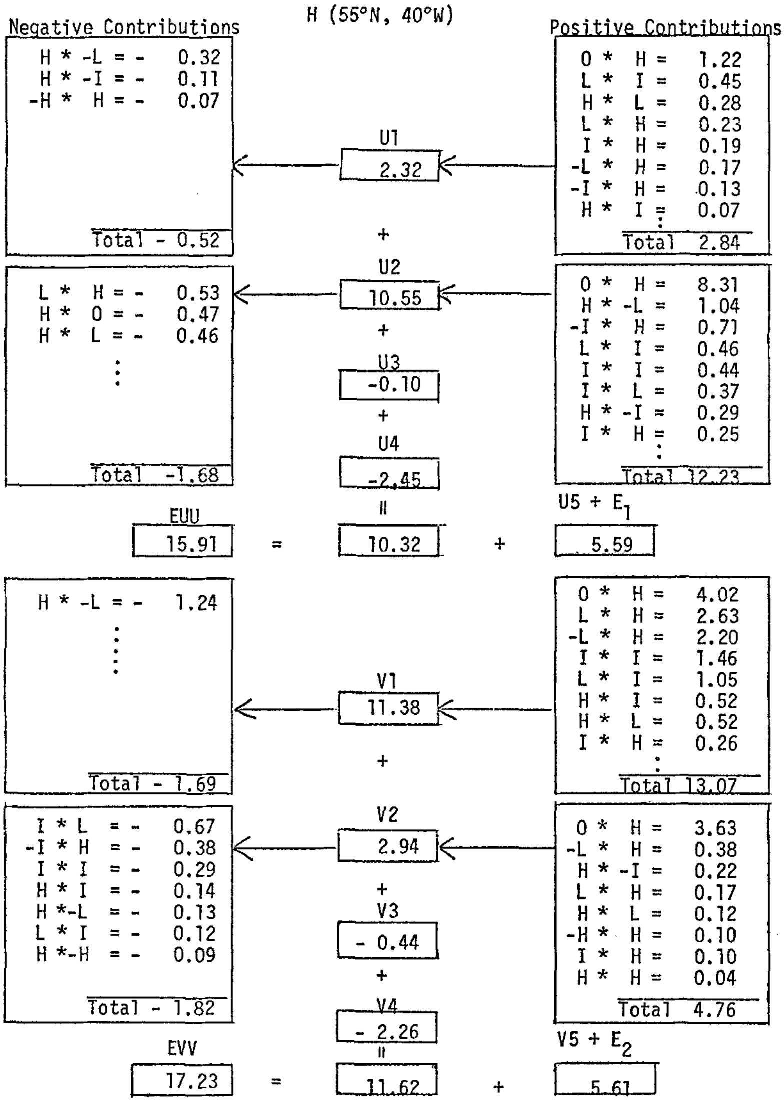

Fig. 6. Linear and nonlinear contributions to the kinetic energy spectra at 500 mb, Winter 1964 for H (55° N, 40° W).

days), as shown in Table 1. Since we use the negative frequencies, this classification contains 7 frequency categories. The interactions are designated by placing the frequency category symbols side by side with an asterisk separating them, for example, interaction between stationary and low frequency waves is denoted by $0 * L$.

Those terms in energy equation (3) and (4) are computed for the separate frequencies of each category. The results for each frequency are then summed over each category and presented in block diagram form, as shown in Figs. 2–7. In these figures, the total contributions of each of the terms in (3) and (4) are shown in the small blocks in the center of the diagram and labeled with the symbols for the terms they represent. The terms U1 and V1 represent the nonlinear interaction due to the zonal advection of the zonal and meridional components of kinetic energy, U2 and V2 the nonlinear interaction due to the meridional advection of the

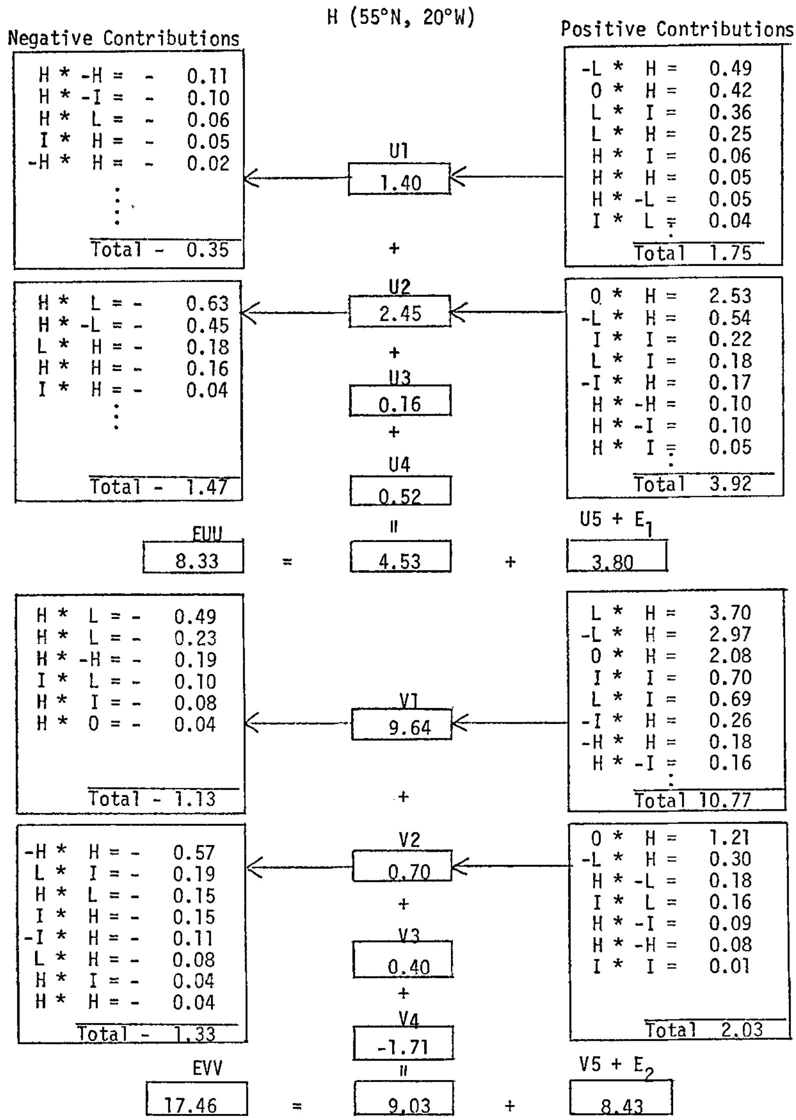

Fig. 7. Linear and nonlinear contributions to the kinetic energy spectra at 500 mb, Winter 1964 for H (55° N, 20° W).

zonal and meridional components of kinetic energy, U3 and V3 the effect of the earth's curvature, U4 and V4 the effect of ageostrophic winds. The ageostrophic terms represent contributions to the energy through the rate of work done by the pressure and Coriolis forces. They do not involve nonlinear interactions. All of the above terms are computed directly from the available pressure and wind data. The terms U5 and V5, however, cannot be computed directly because no data concerning the eddy stresses force of subgrid scales is available. The sums of the quantities U1 through U4 and V1 through V4 are displayed below the appropriate blocks. To the left of these sums are shown the sums of the spectral energy over the category. The difference between these two terms is displayed to the right and labeled $U5 + E_1$ and $V5 + E_2$. These quantities contain, in addition to the subgrid eddy stresses, the results of error in the data and computational error. The large blocks, connected with arrows to the small blocks labeled U1, U2, V1, and V2, contain positive and negative interactions contributing to the totals in the small blocks. A negative value for an interaction combination is interpreted as extractions to the spectral energy. Positive values are interpreted as contributions to the spectral energy. The figures at the bottom of the large blocks represent the total positive and negative contributions from all the interaction combinations.

The interaction computations have been made at the locations, 0°, 20°, 40°, 60°, 80°, 100°, and 120° W on 40° N for 500 mb, Winter 1964 (Tsay, 1972). We will only discuss the results at the locations near the jet stream (60° and 40° W on 40° N).

3.2. *Nonlinear interactions at locations in the area of maximum turbulent kinetic energy (40° and 20° W on 55° N).*

(*a*) *Low frequency category, L* (*Figs. 2 and 3*). At 40° W, 55° N, the nonlinear interaction term due to the meridional advection of zonal kinetic energy, U2, is the largest interaction term of zonal component of kinetic energy equation and $0 * L$ is the largest interaction combination. The secondary interactions of U2 involve positive contributions from $I * -I$, $I * -L$, $-L * L$ $L * -L$ and negative contributions from $-I * I$. The nonlinear interactions arise from the zonal advection of the zonal kinetic energy, U1 serves to extract energy in the low frequency range, in which the largest negative contribution comes from interaction $L * -L$. In the meridional component of the energy equation, V1 and V4 are the major terms and give positive contributions to the spectral energy. It may be noted that positive contributions to V1 come essentially from $0 * L$, $I * -I$, $-I * I$ and negative contributions come essentially from $L * L$. V2 which involves negative contributions from $L * -L$, $I * -I$, $-I * I$ and positive contributions from $L * L$, $-L * L$ serves to extract the kinetic energy from waves of the low frequency category.

At 20° W, 55° N, we see a completely different situation (Fig. 3). Both U1 and U2 contribute to the zonal kinetic energy, and $-L * L$ are the major interaction combinations for them. It is interesting to note that $0 * L$ of both U1 and U2 are negative, however, only $0 * L$ of U2

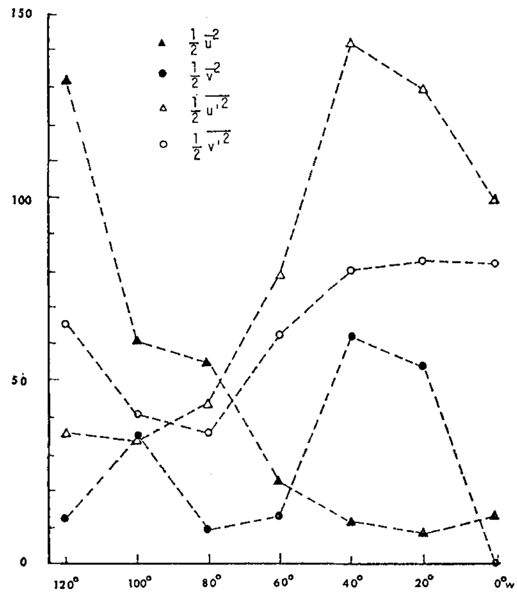

Fig. 8. Kinetic energy distribution 55° N, 500 mb, in Winter 1964.

is significantly large which indicates that there is a transfer of kinetic energy from the low frequency waves to the mean flow. The secondary interactions, other than $0 * L$ of U2, involve positive contributions from $H * -H$ and negative contributions from $L * -L$, $-H * H$. The ageostrophic effect U4 and eddy friction effect plus error, $U5 + E_1$ give large negative value and serve to extract the zonal kinetic energy. The kinetic energy of the meridional component mainly comes from the contributions of the ageostrophic term, V4. V1 gives a large negative value and serves to extract the spectral energy. It involves several large negative interaction combinations of the same order of magnitude, $-L * L$, $L * -L$, and $0 * L$. V2 and V3 give positive contributions, while $V5 + E2$ is negative.

(*b*) *Intermediate frequency category, I* (*Figs. 4 and 5*). In the intermediate frequency category, the ageostrophic term, U4, provides the main contribution to the zonal component of the spectral energy for both locations (40° and 20° W on 55° N). U1 at 40° W 55° N and U2 at both locations have positive contributions. $0 * I$ is the largest positive contribution for both U1 and U2 at these locations. The negative value of U1 at 20° W, 55° N is due to the larger negative

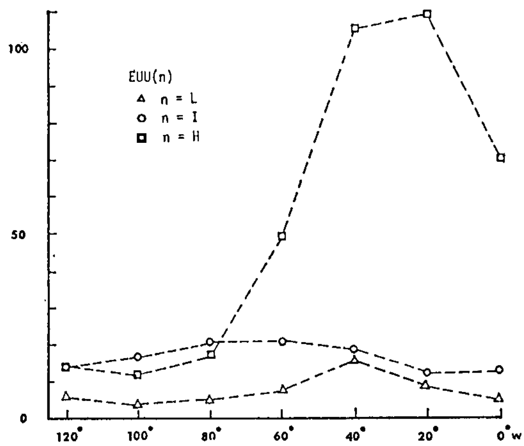

Fig. 9a. The distributions of energy spectra for zonal component of turbulent motion, EUU(n), on 55° N, 500 mb, in Winter 1964.

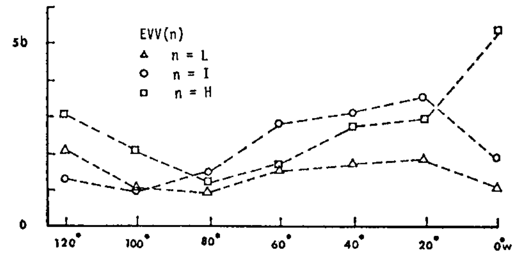

Fig. 9b. The distributions of energy spectra for meridional component of turbulent motion, EVV(n), on 55° N, 500 mb, in Winter 1964.

contribution by $L*L$ than the positive contribution by $0*I$. V1 is the major term for the meridional component of the spectral energy at both locations. V1 involves a number of interactions of the same order of magnitude: $L*L$, $L*I$, $0*I$ for 40° W, 55° N and $-L*I$, $0*I$, $L*L$ for 20° W, 55° N. V4 serves to extract energy at both locations.

(c) *High frequency category, H* (*Figs. 6 and 7*). In the high frequency category, U2 and U5 + E_1 contribute most to the spectral energy of the zonal motion at both locations. $0*H$ is the primary interaction combination for U2. U1, which has small positive values, contains several interactions of the same order of magnitude. V1 and V5 + E_2 contribute most to the spectral energy of the meridional motion at both locations. $0*H$, $L*H$, $-L*H$ are the major interaction combinations for V1 at both locations.

4. Spectral structure of atmospheric waves near maximum turbulent motion (55° N, 20°–40° W)

4.1. *Distributions of the kinetic energy of the mean and turbulent motions*

The distributions of the kinetic energy of the zonal and meridional components of the mean and turbulent motions at 55° N, 0°, 20°, 40°, 60°, 80°, 100° and 120° W for Winter 1964 are shown in Fig. 8. Near the center of maximum turbulent motion, the zonal component of the turbulent motion is about twice that of the meridional component of the turbulent and mean motion, and is almost one order of magnitude greater than that of the zonal component of the mean motion.

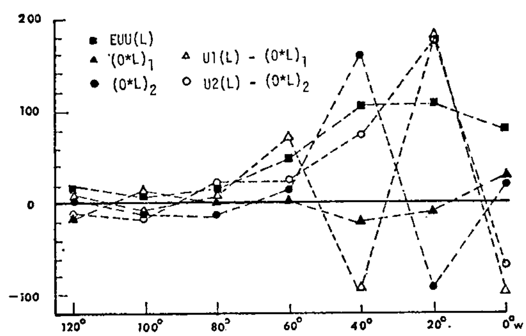

Fig. 10a. The distributions of the contributions of the nonlinear interactions to the kinetic energy spectra of zonal component of turbulent motion in low frequency range for 55° N, 500 mb, Winter 1964.

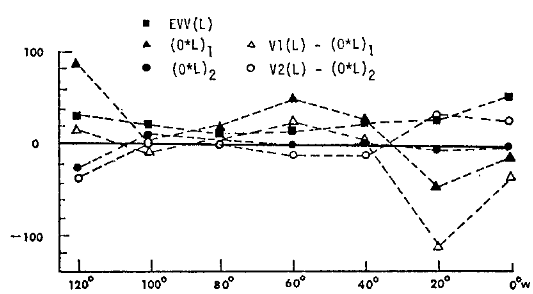

Fig. 10b. The distributions of the contributions of the nonlinear interactions to the kinetic energy spectra of meridional component of turbulent motion in low frequency range for 55° N, 500 mb, Winter 1964.

The kinetic energy of the zonal component of the turbulent motion and of meridional component of the mean motion shows a maximum between 20° and 40° W, whereas that of the meridional component of the turbulent motion shows a maximum between 0° and 40° W. The kinetic energy of the zonal component of the mean motion shows a minimum near 20° W. The maximum of the turbulent motion appears to be associated with the mean meridional motion in view of the similar distributions of the kinetic energy of the mean meridional motion and the zonal component of the turbulent motion as shown in Fig. 8.

4.2. *Distributions of the energy spectra in various ranges of frequency*

The distributions of the energy of the zonal and meridional components of the turbulent motion at 55° N in the ranges of high, intermediate, and low frequencies for Winter 1964 are shown in Figs. 9*a* and 9*b*, respectively. It is seen in Fig. 9*a* that the energy of the zonal component of the turbulent motion in low frequency range is about ten times that in the intermediate and high frequency ranges. The former shows a drastic increase from 80° W eastward and has a maximum between 20° and 40° W, whereas the latter varies little in the region. This indicates that the kinetic energy of the zonal component of the turbulent motion is essentially contributed by waves of low frequencies.

It is seen in Fig. 9*b* that the kinetic energy of the meridional component of the turbulent motion in the high, intermediate and low frequency ranges is of the same order of magnitude. The distributions of the energy in the intermediate and high frequency ranges are similar with a peak located between 40° W and 20° W, whereas the energy in the low frequency range increases from 80° W towards 0° W.

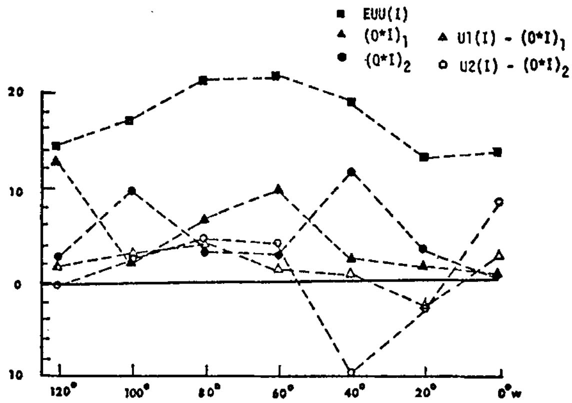

Fig. 11a. The distributions of the contributions of the nonlinear interactions to the kinetic energy spectra of zonal component of turbulent motion in intermediate frequency range for 55° N, 500 mb, Winter 1964.

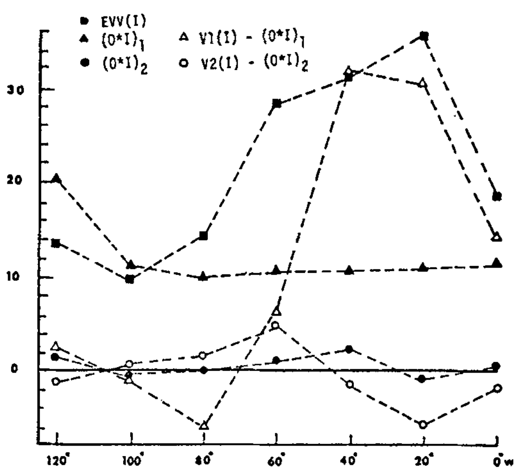

Fig. 11b. The distributions of the contributions of the nonlinear interactions to the kinetic energy spectra of meridional component of turbulent motion in intermediate frequency range for 55° N, 500 mb, Winter 1964.

4.3. *Contributions of the interactions to the energy spectra of the zonal component of the turbulent motion*

The distribution of the contributions of the nonlinear interactions among waves of various frequency ranges to the zonal component of the turbulent motion are shown in Figs. 10*a*, 11*a* and 12*a*. It is seen from these figures that the kinetic energy of the zonal component of the turbulent energy is essentially contributed by waves of low frequencies, which is primarily due to the interactions $(0 * L)_2$, U1 $(L) - (0 * L)_1$ and U2 (L) $- (0 * L)_2$. (See Figs. 2 and 3.) This indicates that the comparable small mean zonal motion (Fig. 8) contributes little to the zonal component.

It is seen in Figs. 11*a* and 12*a* that nonlinear interactions including the mean motion do contribute to the kinetic energy of the zonal components of the turbulent motion in both

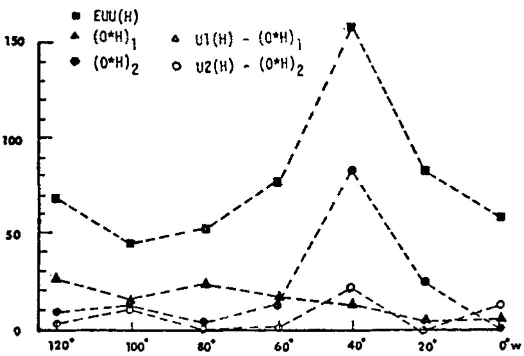

Fig. 12a. The distributions of the contributions of the nonlinear interactions to the kinetic energy spectra of zonal component of turbulent motion in high frequency range for 55° N, 500 mb, Winter 1964.

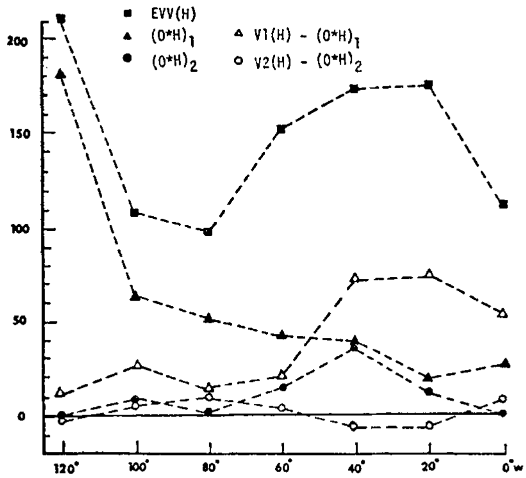

Fig. 12b. The distributions of the contributions of the nonlinear interactions to the kinetic energy spectra of meridional component of turbulent motion in high frequency range for 55° N, 500 mb, Winter 1964.

the high and intermediate frequency ranges, but they are not sufficient to account for the kinetic energy distribution as shown in the figures. It is, therefore, necessary to examine the distributions of the ageostrophic motion, Reynolds stresses, and the effect of the sphericity of the earth to the energy distributions. They are shown in Figs. 13*a*, 14*a* and 15*a*. It is seen in these figures that in addition to the contributions of the nonlinear interactions, ageostrophic motion contributes also to the energy in the intermediate frequency range, whereas the Reynolds stresses affect also the energy in the high frequency range.

4.4. *Contributions of the interactions to the energy spectra of the meridional component of the turbulent motion*

The distributions of the contributions of the nonlinear interactions, among waves of various frequency ranges, to the meridional component of the turbulent motion are shown in Figs. 10*b*, 11*b*, and 12*b*. The contributions of the ageostrophic motion, Reynolds stresses, and the effect of sphericity of the earth are shown in Figs. 13*b*, 14*b* and 15*b*. It is seen from Figs. 10*b* and 13*b* that $(0 * L)$ and the ageostrophic motion contribute most of the kinetic energy of the meridional motion in the low frequency range, $E_{vv}(L)$. The large contribution of the zonal motion in the low frequency range at 40° and 20° W to the intermediate and high frequency meridional turbulent velocity are shown in

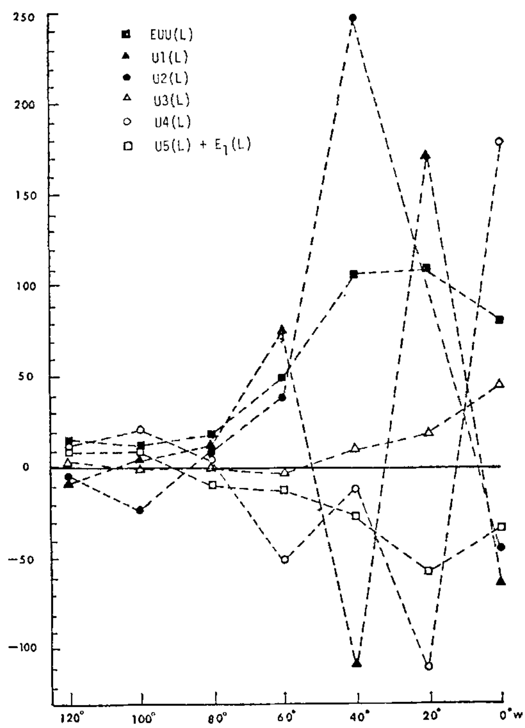

Fig. 13a. The distributions of the total contributions of individual terms in the energy equation of zonal turbulent motion in low frequency range for 55° N, 500 mb, Winter 1964.

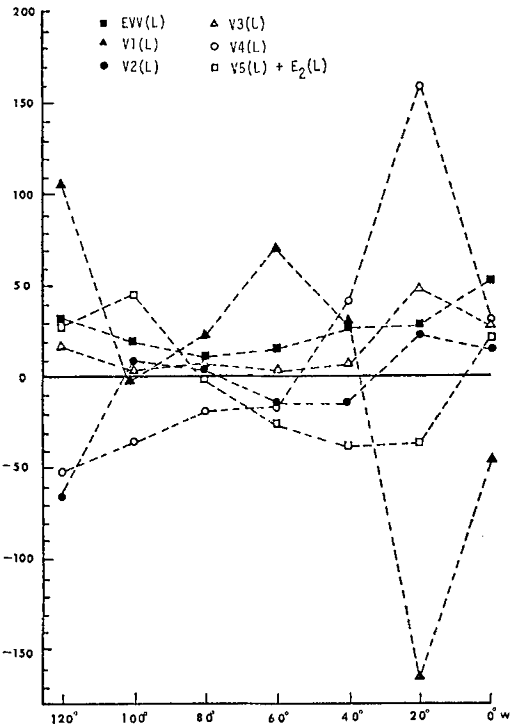

Fig. 13b. The distributions of the total contributions of individual terms in the energy equation of meridional turbulent motion in low frequency range for 55° N, 500 mb, Winter 1964.

Figs. 5, 7, 11*b* and 12*b*. They appear to be similar to microscale nonstationary turbulence produced by wind tunnel (Cheng et al., 1973), but are not seen at 40° N. Reynolds stresses contribute also to the energy in the high frequency range.

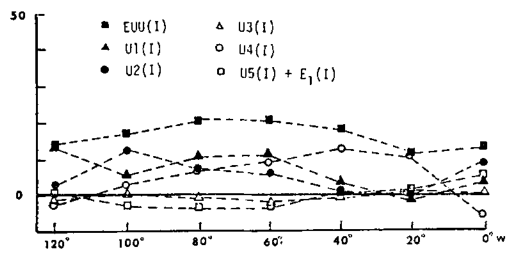

Fig. 14a. The distributions of the total contributions of individual terms in the energy equation of zonal turbulent motion in intermediate frequency range for 55° N, 500 mb, Winter 1964.

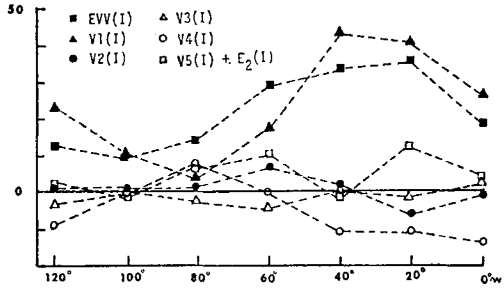

Fig. 14b. The distributions of the total contributions of individual terms in the energy equation of meridional turbulent motion in intermediate frequency range for 55° N, 500 mb, Winter 1964.

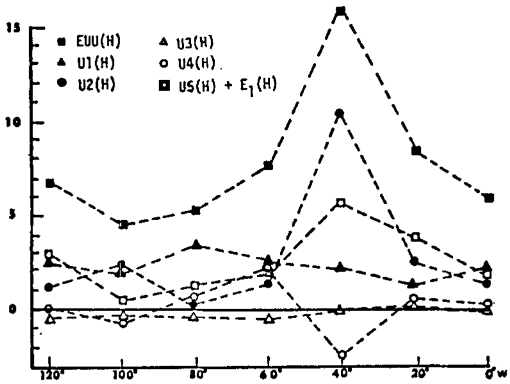

Fig. 15a. The distributions of the total contributions of individual terms in the energy equation of zonal turbulent motion in high frequency range for 55° N, 500 mb, Winter 1964.

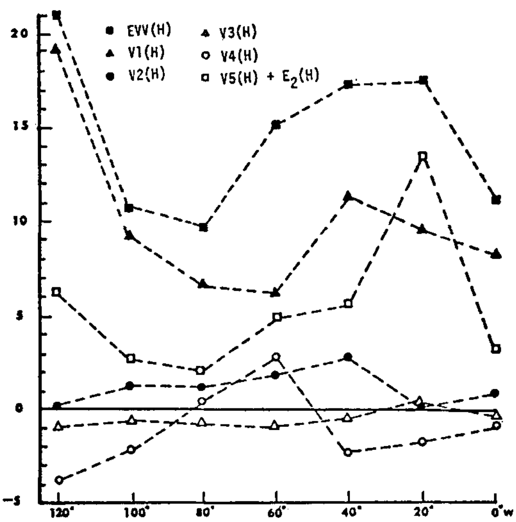

Fig. 15b. The distributions of the total contributions of individual terms in the energy equation of meridional turbulent motion in high frequency range for 55° N, 500 mb, Winter 1964.

5. Conclusion

An analysis of the distribution and spectra of the kinetic energy near the center of maximum turbulent kinetic energy indicates that the kinetic energy of the zonal component of the motion is about twice that of the meridional component of the turbulent motion. The kinetic energy of the zonal component of the turbulent motion is essentialy contributed by waves of low frequencies and by interactions of waves of all frequencies. However, waves of all frequencies contribute to the kinetic energy of the meridional component of the turbulent motion. In the intermediate and high frequency ranges, contributions come mostly from the interactions of waves of low frequency and the zonal mean motion, whereas in the low frequency range, the contribution comes mainly from the ageostrophic motion.

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АНАЛИЗ СТРУКТУРЫ ВОЛН ВБЛИЗИ ЦЕНТРА МАКСИМАЛЬНОЙ ТУРБУЛЕНТНОЙ ЭНЕРГИИ

Проделан анализ волновой структуры вблизи центра максимальной турбулентной энергии на уровне 500 *мб* зимой 1964 года. Найдено, что *кинетическая энергия зональной компоненты* примерно в два раза больше энергии меридиональной компоненты турбулентного движения. Существенный вклад в кинетическую энергию зональной компоненты турбулентного движения осуществляется за счет волн с низкими частотами и за счет взаимодействия волн всех частот. Вместе с тем волны всех частот вносят вклад в кинетическую энергию меридиональной компоненты турбулентного движения. В промежуточном диапазоне и при высоких частотах поступление энергии происходит, главным образом, за счет взаимодействия волн с низкой частотой и средним зональным движением, тогда как в диапазоне низких частот вклад в энергию вносит в основном агеострофическое движение.