The large-scale meridional transport of sensible heat in wavenumber frequency space

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ABSTRACT

The longitude-time co-spectra of the meridional transport of sensible theat across 20°, 40°, 60°, and 80° N at 100, 200, 500, and 850 mb for the summer and winter seasons of 1964 have been computed and analyzed. It is found that there exists a preferred spectral band in the wave-number frequency spectra at various latitudes, which indicates the wave-number frequency domain of interaction between the meridional velocity and temperature. In the middle latitudes, the spectral band is oriented in a domain extending from the region of low wave-numbers and frequencies to that of high wave-numbers and negative frequencies. In the high latitudes, the heat transport is confined to a domain of low wave-numbers and frequencies. In the lower latitudes, however, the transport is confined to a very narrow band centered near the zero frequency.

The total meridional transport of sensible heat at all four levels is mostly directed toward the North Pole, except at 20° N there is a weak equatorward transport of sensible heat at the 100, 200, and 850 mb levels. In the troposphere, the maximum heat transport is found to occur near 40° N, whereas in the stratosphere it occurs near 60° N.

It is also found that most of the poleward transport of sensible heat in both the troposphere and stratosphere is accomplished by the stationary and eastward moving, long and medium waves, and that the equatorward transport is mostly accomplished by the westward moving, low frequency waves. Most of the convergence and divergence of the meridional transport in the troposphere is the contribution of the transient waves, whereas in the stratosphere it is mainly the result of the stationary waves.

1. Introduction

One of the important studies of the large-scale atmospheric turbulence and transport processes is the analysis of power and cross spectra of the turbulent motion and transports in the atmosphere. The former, which deals primarily with the kinetic, potential, and internal energies, is basic to the understanding of the mechanism of turbulence. The latter, which concerns primarily the transport and conversion of energies, is fundamental in the maintenance of the general circulation in the atmosphere.

Studies of the large-scale turbulence in the free atmosphere have mostly been confined to either space or time spectra of the motion. The Eulerian space (longitude) spectra (Benton & Kahn, 1958; Eliasen, 1958; Kao, 1954; Saltzman, 1958; Barrett, 1961; Van Mieghem, 1961), the Eulerian time spectra (Van der Hoven, 1957; Chiu, 1960; Shapiro & Ward, 1960), and the Lagrangian time spectra (Kao, 1962, 1965; Kao & Bullock, 1964; Kao & Gain, 1968) of the large-scale motion in the atmosphere have recently been analyzed. These investigations have provided a great deal of information regarding the contributions of the large-scale atmospheric motion due either to the longitude- or time-eddies. In the atmosphere, however, motion at a point, which is generally nonstationary, is affected by eddies of various sizes and periods. To gain an insight into the mechanism of the large-scale atmospheric turbulence and transports, it is necessary to analyze the power and cross spectra in the wave-number frequency space.

The most general way of studying atmospheric turbulence is, of course, to analyze the motion in the wave-number frequency space. In a recent paper (Kao, 1968) a method for analysing the longitude time spectra in the wavenumber-frequency space has been devel-

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oped. The primary advantage of this method is that it permits analyses of transient waves in terms of their length-scale and phase-speed, and frequency and wavenumber spectra become special cases of the wavenumber-frequency spectrum. The relative importance of the forward and backward moving waves may, therefore, be evaluated. The longitude-time spectra of the meridional transport of sensible heat at 500 mb (Kao, Wendell & Noteboom, 1966), and at 100, 200 and 850 mb (Kao, Sagendorf & Tsay, 1969) have been computed. The purpose of this paper is to investigate the spectral characteristics of the meridional transport of sensible heat in the troposhere and stratosphere.

2. Analysis and data source

In order to make a spectral analysis of the large-scale atmospheric motion and transports in the frequency wave-number space, we make use of the following Fourier transform

$$Q(k, \pm n) = \frac{1}{4\pi^2}\int_0^{2\pi}\int_0^{2\pi} q(\lambda, t)\, e^{-i(k\lambda \pm nt)}\, d\lambda\, dt \quad (1)$$

where λ, t, k, and n are respectively the longitude, time, wave-number and frequency; $q(\lambda, t)$ is a real, single-valued function, which is piecewise differentiable in a normalized domain, $0 \leqslant \lambda,\ t \leqslant 2\pi$; Q is the complex coefficient of the Fourier transform. The positive and negative signs in front of n are designated to waves moving toward the west and east respectively.

For convenience of computations in this study we express

$$Q(k, \pm n) = Q_r(k, \pm n) + iQ_i(k, n) \quad (2)$$

where

$$Q_r(k, \pm n) = \frac{1}{4\pi^2}\int_0^{2\pi}\int_0^{2\pi} q(\lambda, t)\cos(k\lambda \pm nt)\, d\lambda\, dt \quad (3)$$

and

$$Q_i(k, \pm n) = \frac{-1}{4\pi^2}\int_0^{2\pi}\int_0^{2\pi} q(\lambda, t)\sin(k\lambda \pm nt)\, d\lambda\, dt \quad (4)$$

are respectively the real and imaginary part of the complex coefficient.

Consider the same conditions for another scalar function $s(\lambda, t)$ with a Fourier coefficient $S(k, n)$. It can be shown (Kao, 1968) that

$$\frac{1}{4\pi^2}\int_0^{2\pi}\int_0^{2\pi} s(\lambda, t)\, q(\lambda, t)\, d\lambda\, dt = \sum_{k=0}^{\infty}\int_0^{\infty}[E_{sq}(k, +n) + E_{sq}(k, -n)]\, dn \quad (5)$$

and that

$$E_{sq}(0, \pm n) = S_r(0, \pm n)Q_r(0, \pm n) + S_i(0, \pm n)\, Q_i(0, \pm n)$$

$$E_{sq}(k, \pm n) = 2[S_r(k, \pm n)Q_r(k, \pm n) + S_i(k, \pm n)Q_i(k, \pm n)],\ k \neq 0 \quad (6)$$

where $E_{sq}(k, +n)$ and $E_{sq}(k, -n)$ are the longitude-time cross spectra of s and q due to eddies of wave-number k and frequency n, moving toward the west and east respectively. Eq. (5) indicates that the total contribution of the product of s and q is equal to the cross spectrum of s and q integrated over all frequencies and over all wave-numbers. In (5) the summation of the product of complex coefficient S and Q with respect to the integer wave-numbers is the consequence of the cyclic distribution of $s(\lambda, t)$ and $q(\lambda, t)$ along latitude circles.

The cross spectrum of s and q due to the eddies of wave-number k and all frequencies, moving, respectively, toward the west and east is, therefore,

$$E_{sq}(k, \pm) = \int_0^{\infty} E_{sq}(k, \pm n)\, dn \quad (7)$$

and the cross spectrum due to eddies of frequency n and all wave-numbers, moving, respectively, in the direction of decreasing and increasing longitude is

$$E_{sq}(\pm n) = \sum_{k=0}^{\infty} E_{sq}(k, \pm n) \quad (8)$$

Therefore, the longitude- and time-spectrum are respectively

$$E_{sq}(k) = \int_0^{\infty}[E_{sq}(k, +n) + E_{sq}(k, -n)\, \mathrm{dn}$$

$$E_{sq}(n) = \sum_{k=0}^{\infty}[E_{sq}(k, +n) + E_{sq}(k, -n)] \quad (9)$$

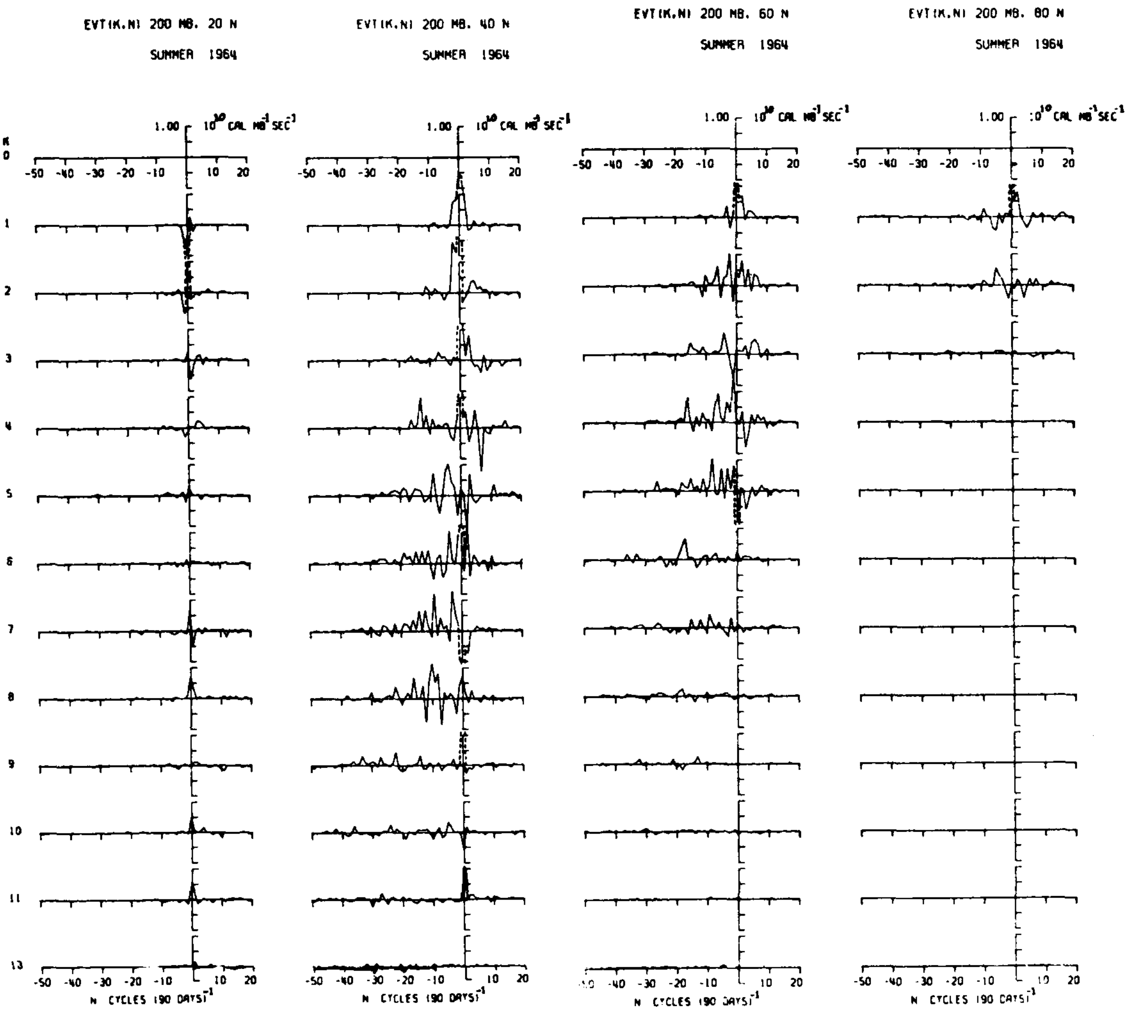

Fig. 1. Wavenumber-frequency spectra of the meridional flux of sensible heat at 200 mb, Summer, 1964.

The horizontal velocities used in this analysis are derived from the 1964 National Meteorological Center (NMC) stream function analyses at the 850 and 200 mb levels, and from the isobaric height field at the 100 mb level. The temperatures used are also obtained from the 1964 NMC analyses at 100, 200, 500, and 850 mb. The stream function, isobaric height and temperature distributions are available at 12-hr intervals except at the 100 mb level for the summer where a 24-hr interval was used. These functions are interpoated from the grid devised by the Joint Numerical Weather Prediction Unit (JNWP) onto the latitude circles 20°, 40° 60°, and 80° N at intervals of vive degrees of latitude.

The basic computation is the numerical calculation of the real and imaginary parts of Fourier coefficients for various variables. This involves the numerical evaluation of the integrals of (3) and (4) for $s = v$ and $q = T$. The data intervals used in the integration are five degrees of longitude and 12 hours except at 100 mb where 24 hours was used for the summer season. The time integrations are carried out over periods of 90 days for the winter and summer seasons of 1964, which are normalized to 2π. Computations of Fourier coefficients are carried out

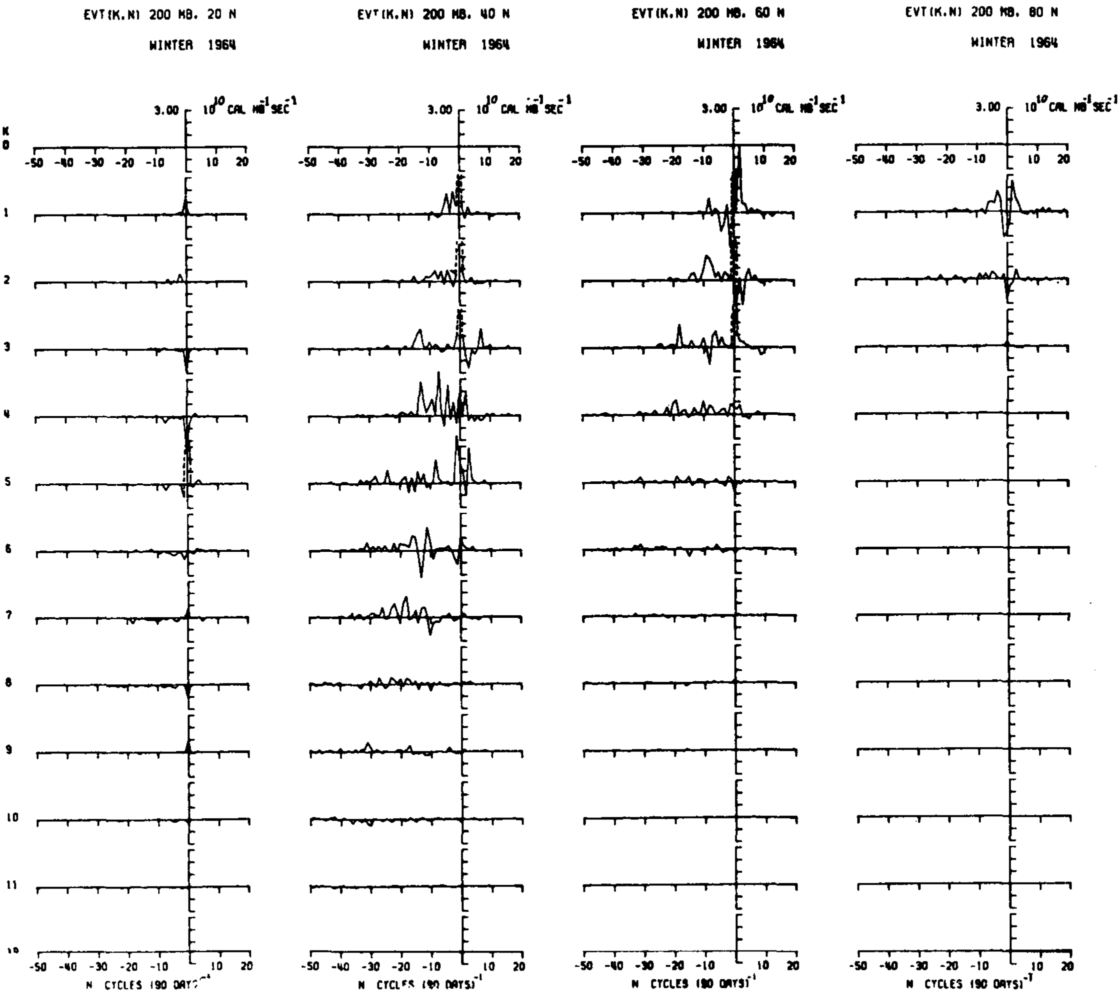

Fig. 2. Wavenumber-frequency spectra of the meridional flux of sensible heat at 200 mb, Winter, 1964.

for a wave-number range of 0 through 21, and for frequency range of 0 through 90 cycles per 90 days. The cross spectrums are computed with the application of Eq. (6) and with the use of the computed Fourier coefficients.

3. The wave-number frequency co-spectra of the meridional transport of sensible heat

The mean meridional flux of sensible heat over the Northern Hemisphere has been computed by White (1951, 1954) and Peixoto (1960). To investigate the effect of waves of various wave-lengths and frequencies on the meridional transport of sensible heat, the wave-number frequency co-spectra of the meridional heat flux will be analyzed. To do so, the longitudetime co-spectra of the meridional transport of sensible heat across 20°, 40°, 60° and 80° N, at 100, 200, 500 and 850 mb levels for the summer and winter seasons, 1964, have been computed with the use of Eqs. (3), (4) and (6) (Kao, Sagendorf & Tsay, 1969). Because of limited space, only the co-spectra of the heat transport at the 200 mb level for the summer and winter seasons are shown in Figs. 1 and 2. In these figures, the horizontal axis represents the frequency in unit cycles per 90 days and the vertical axis represents the spectral value of meridi-

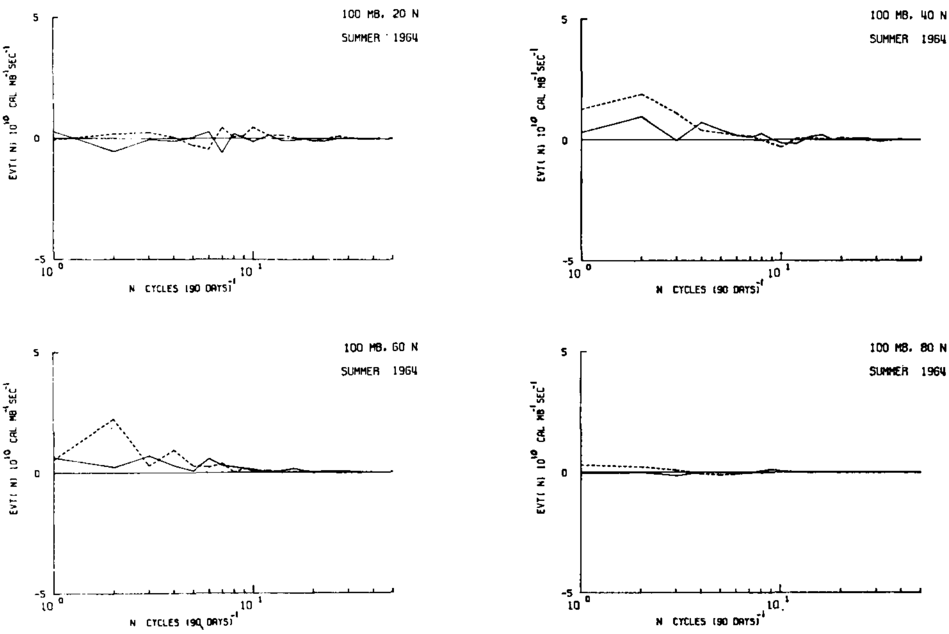

Fig. 3. Frequency spectra of the meridional flux of sensible heat at 100 mb, Summer, 1964. The solid and dashed curves represent respectively the contribution due to waves moving toward the east and west.

onal heat transport. It should be noted that the scales in Fig. 1 and Fig. 2 are not the same.

A striking feature in the co-spectra of the meridional sensible heat transport is that there exists a preferred spectral band at various latitudes, which indicates the wave-number frequency domain of interaction between the meridional velocity and temperature. In the middle latitudes, (40° and 60° N), the spectral band is oriented in a domain extending from a region of low wave-numbers and frequencies to a region of high wave-numbers and negative frequencies. In the high latitudes (80°), the heat transport is confined to a domain of very low wave-numbers ($k = 1$ and 2) and frequencies. In the lower (20° N) latitudes, however, the co-spectra is confined in a very narrow band centered near zero frequency. The change of the orientation of the spectral band with latitude may partially be explained by the increase in the Coriolis effect with increasing latitude on the wave motion in the atmosphere.

In both the troposphere (500 mb) and near the tropopause (200 mb) most of the heat transport occurs near 40° N, whereas in the stratosphere (100 mb) it shifts to near 60° N. In general, the transport in the winter is greater than that in the summer.

In the middle latitudes, most of the waves contribute to the poleward transport of sensible heat, except for a few slowly moving medium waves contributing to the equatorward transport of heat. In the low and high latitudes, the stationary and slowly waves contribute to most of the equatorward transport of heat in the atmosphere.

4. The spectrums of the meridional transport of sensible heat in the frequency and wavenumber domains

The distribution of the frequency spectrums of the rate of the meridional transport of sensible heat across 20°, 40°, 60°, and 80° N, at the 100, 200, 500, and 850 mb for the winter and summer seasons of 1964 are computed with the use of Eqs. (6) and (8). Because of limited space, only the spectrums at 100 and 850 mb are shown in Figs. 3 to 6. In these figures, the solid curves are the frequency spectrums of the transport contributed by waves moving from west to east, and the dashed curves are those contributed by waves moving from east to west. It is seen from these figures that most of the meridional transport of sensible heat is accomplished

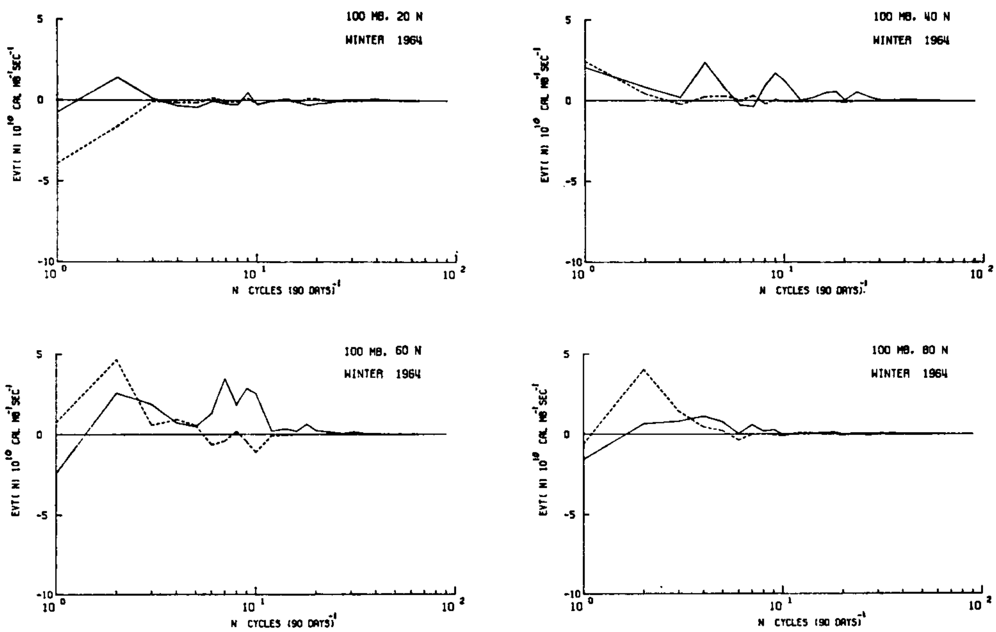

Fig. 4. Frequency spectra of the meridional flux of sensible heat at 100 mb, Winter, 1964. The solid and dashed curves have the same representation as in Fig. 3.

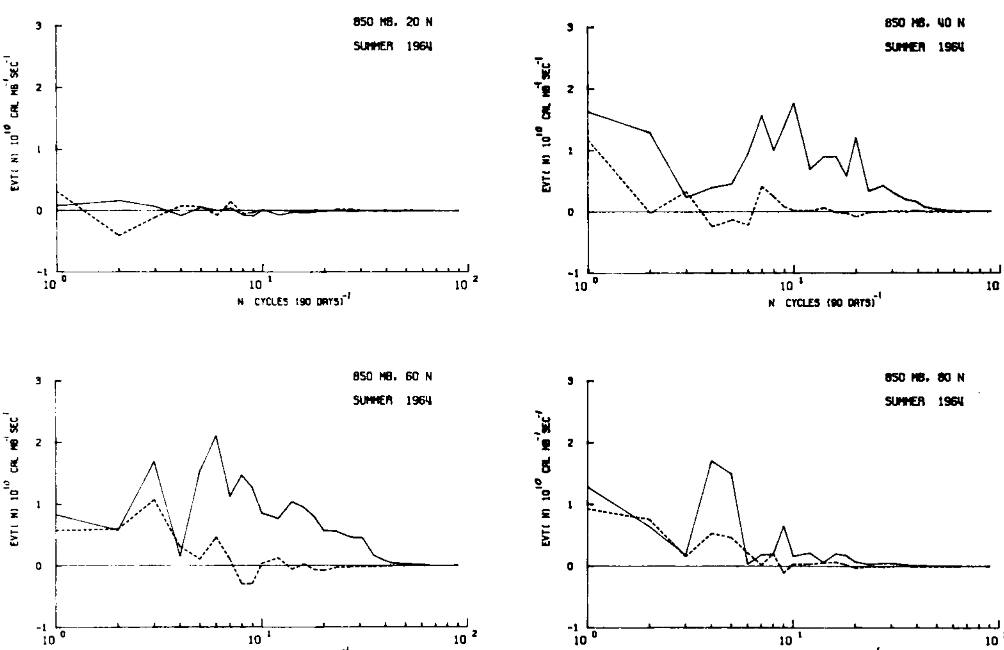

Fig. 5. Frequency spectra of the meridional flux of sensible heat at 850 mb, Summer, 1964. The soild and dashed curves have the same representation as in Fig. 3.

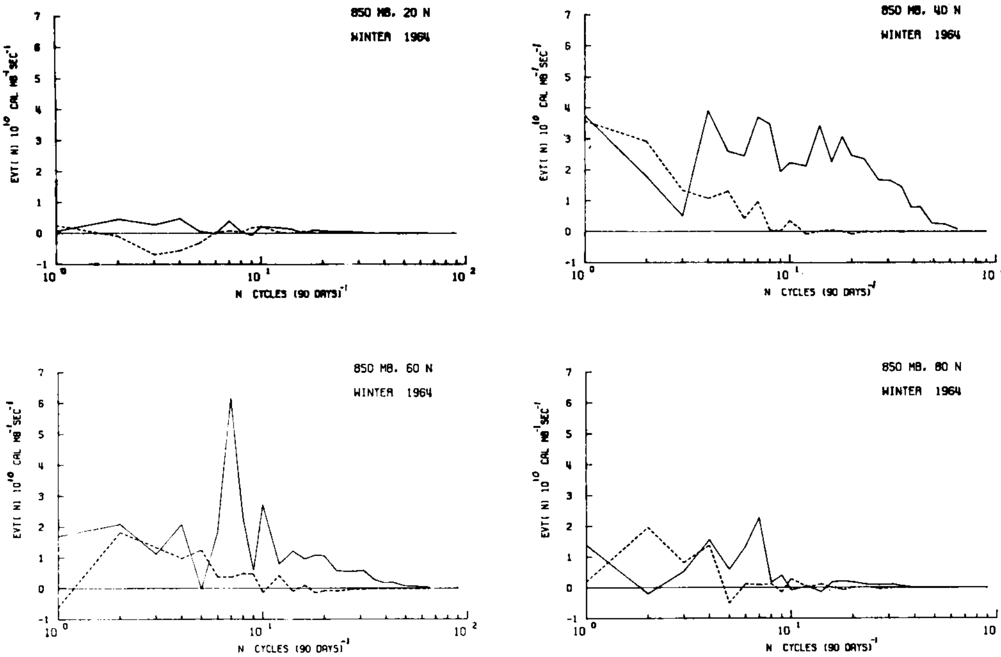

Fig. 6. Frequency spectra of the meridional flux of sensible heat at 850 mb, Winter, 1964. The solid and dashed curves have the same representation as in Fig. 3.

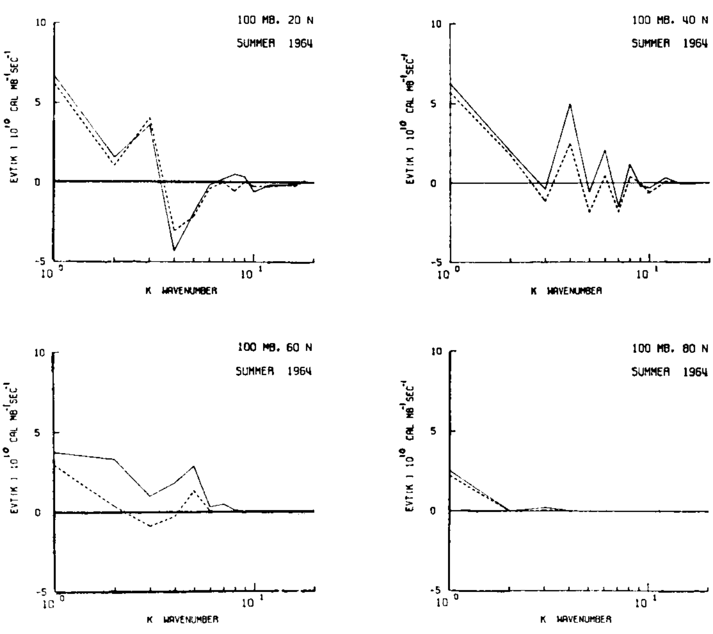

Fig. 7. Wavenumber spectra of the meridional flux of sensible heat at 100 mb, Summer, 1964. The solid curves represent the contribution due to the stationary and nonstationary motion, the dashed rvecus represent that due to the stationary motion only.

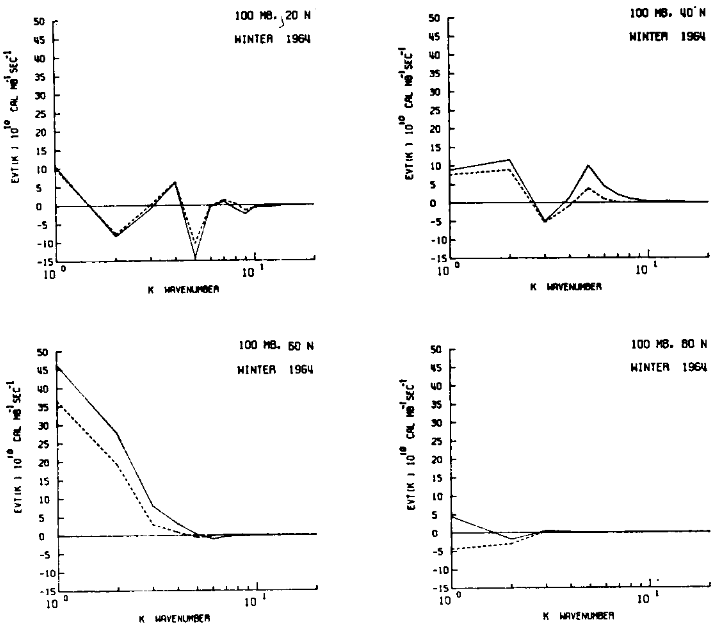

Fig. 8. Wavenumber spectra of the meridional flux of sensible heat at 100 mb, Winter, 1964. The solid and dashed curves have the same representation as in Fig. 7.

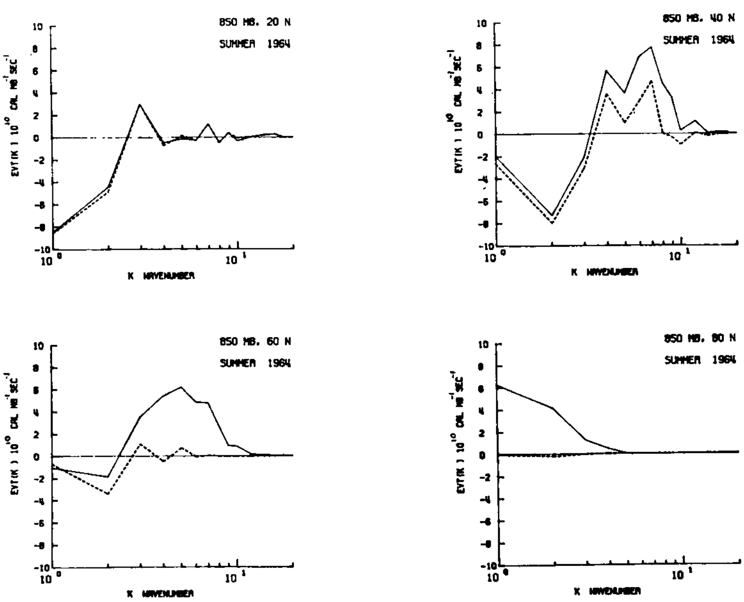

Fig. 9. Wavenumber spectra of the meridional flux of sensible heat at 850 mb, Summer, 1964. The solid and dashed curves have the same representation as in Fig. 7.

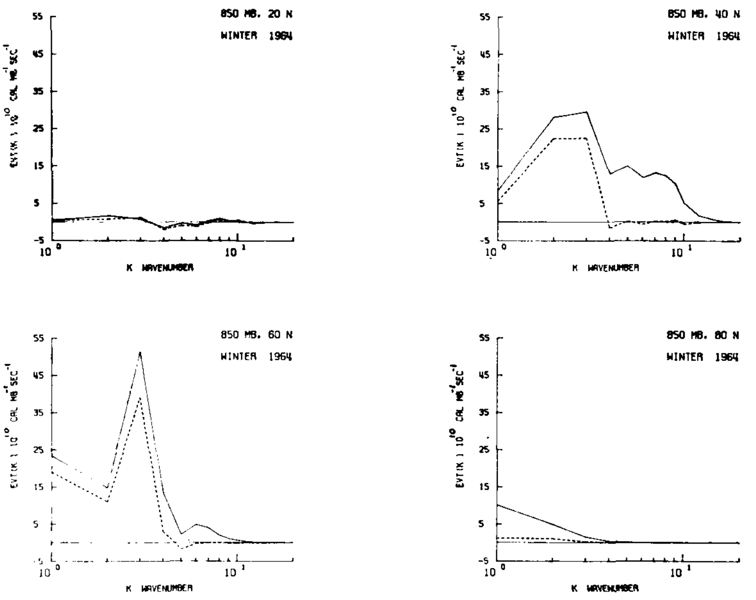

Fig. 10. Wavenumber spectra of the meridional flux of sensible heat at 850 mb, Winter, 1964. The solid and dashed curves have the representation as in Fig. 7.

by the medium frequency eastward moving waves and the low frequency waves moving both east and west.

It may be noted that most of the transport is directed toward the North Pole and is accomplished by the medium frequency waves. The rate of transport across the middle latitudes (40° and 60° N) in both the troposphere and stratosphere is greater than that across the low (20° N) and high (80° N) latitudes. In general, the rate of transport in the winter is greater than that in the summer, and the transport in the lower levels is greater than that in the upper levels. In the lower level near 850 mb most of the transport is accomplished by the medium frequency and stationary waves, whereas in the upper levels near 100 mb most of the transport is accomplished by the low frequency waves.

The distribution of the wavenumber spectrums of the rate of the meridional transport of sensible heat at 100, 200, 500, and 850 mb for the winter and summer seasons of 1964 are computed with the use of Eqs. (6) and (7), and those at 100 and 850 mb are shown in Figs. 7 to 10. In these figures, as a visual aid the points of line spectra are connected by solid and dashed lines. The solid lines represent the contribution to the transport due to both the stationary and moving waves, whereas the dashed lines represent that due to the stationary waves only. The space between the solid and dashed lines in these figures represents, therefore, the transport due to the contribution of the moving waves.

It is seen from the wavenumber spectrums that the poleward transport of sensible heat is greatest across the middle latitudes near 850 mb. In the winter, most of the poleward transport is accomplished by the medium and long stationary waves near 850 mb, whereas the equatorward transport is accomplished by the long waves near 100 mb. In the summer, most of the poleward transport is contributed by the medium waves, and the equatorward transport is contributed by the long waves near the 850 mb; in the stratosphere near 100 mb, however, both the medium and long waves contribute to the poleward transport of sensible heat. In general, the transport across the middle latitudes is greater than that across the low and high latitudes, and the transport in the winter is greater than that in the summer.

The meridional convergence and divergence of the heat transport across 20°, 40°, 60°, and 80° N have been computed and found to be primarily the contribution of the long stationary waves and the medium transient waves in the atmosphere.

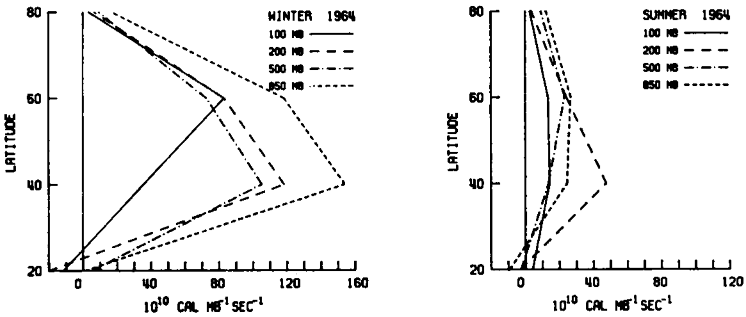

Fig. 11a. The meridional flux of sensible heat due to both the stationary and nonstationary motion.

5. The mean rate of meridional transport of sensible heat in the northern hemisphere

To obtain a general picture of the maintenance of the budget of the sensible heat in the atmosphere, the rates of the total transport of sensible heat across 20°, 40°, 60° and 80° N latitudes in the 100, 200, 500, and 850 mb for the winter and summer seasons of 1964 are computed and shown in Fig. 11*a*. It is seen from this figure that the total meridional transport of sensible heat at all four levels is mostly directed toward the North Pole, except at 20° N there is a weak equatorward transport of sensible heat at the 100 and 200 mb levels. It may be noted that the maxium poleward transport of sensible heat at the 100 mb level occurs near 60° N, whereas that at the 200, 500 and 850 mb levels occurs near 40° N. Therefore, there is a divergence of sensible heat transport between 20° and 60° N and a convergence between 60° and 80° N at the 100 mb level, whereas at the 200, 500, and 850 mb there is a divergence of the sensible heat transport between 20° and 40° N and a convergence of it between 40° and 80° N. The larger latitudinal region of the meridional convergence of sensible heat in the middle and high latitudes in the troposphere than that in the stratosphere indicates that in the middle and high latitudes in the troposphere there is a need for more import of sensible heat to compensate for the verticl heat transport and heat loss due to radiation than in the stratosphere. The rate of the total meridional transport of sensible heat across 20°, 40°, 60° and 80° N at the 100, 200, 500 and 850 mb levels in the summer season show a similar distribution as in the winter, except that the magnitude of the transport rate for the summer is less than 50% of that for the winter, and the maximum poleward transport of sensible heat at 850 mb shifts from 40° N in winter to 60° N in the summer. This indiactes the effect of the northward migration of the sun with respect to the earth in the summer season on the heat flux in the troposphere. In the stratosphere, however, the maximum poleward transport of sensible heat shifts from 60° N in the winter to 50° N in the summer. A similar result was obtained by Peixoto (1960).

To examine the mechanism for the meridional heat transport, it is convenient to express the rate of the total meridional heat transport as the sum of the transports due to the stationary and nonstationary waves, that is

$$\sum_k \sum_n E_{vT}(k, n) = \sum_{\substack{k \\ k \neq 0}} E_{vT}(k, 0) + \sum_{\substack{k \\ k \neq 0}} \sum_{\substack{n \\ n \neq 0}} E_{vT}(k, n),$$

since $E_{vT}(0, 0) = E_{vT}(0, n) = 0$. The values of the terms in the above equation at 100, 200, 500 and 850 mb for summer and winter seasons are plotted in Figs. 11*a*, *b*, *c* and are shown in the Table of the Appendix.

The distributions of the rate of the meridional transport of sensible heat across 20°, 40° 60° and 80° N latitudinal circles at the 100, 200, 500 and 850 mb due to the stationary waves in the winter and summer seasons of 1964 are shown in Fig. 11*b*. It is seen from this figure that the stationary waves provide a poleward transport of sensible heat at nearly all four levels and the four latitudinal circles. The exceptions are at 80° N in the winter and at the 500 and 850 mb level in the summer where there is a weak transport toward the equator. Again, the rate of the meridional transport in the winter is generally greater than that in the summer. However, the maximum poleward transport of sensible heat

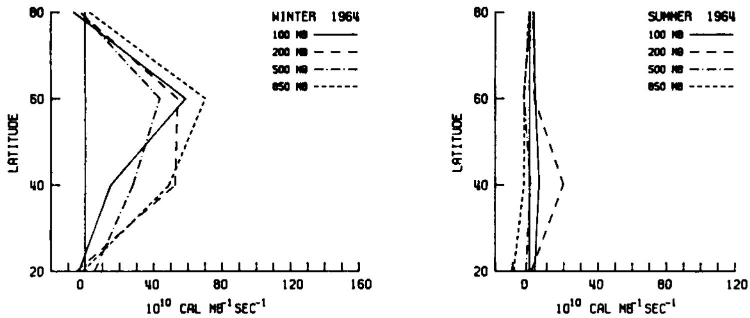

Fig. 11b. The meridional flux of sensible heat due to the stationary motion.

due to the stationary waves occurs near 60° N at the 100, 500 and 850 mb, whereas at the 200 mb level it occurs near 50° N. These indicate that the stationary waves provide a meridional divergence of sensible heat transport between 20° and 60° N and a convergence between 60° and 80° N at the 100, 500, and 850 mb, whereas at the 200 mb level the stationary waves contribute to a divergence of sensible heat transport between 20° and 50° N, but a convergence between 50° and 80° N.

The distribution of the rate of the meridional transport of sensible heat across 20°, 40°, 60° and 80° N latitudinal circles at the 100, 200, 500, and 850 mb due to transient waves in the winter and summer seasons of 1964 are shown in Fig. 11*c*. It is seen from this figure that transient waves contribute most of the poleward transport of sensible heat in the middle latitudes of the troposphere, and produce a maximum transport near 40° N at 200, 500 and 850 mb, and near 60° N at the 100 mb level. In the summer, the maximum transport at the 850 mb level shifts to 50° N, and in general the rate of the transport due to transient waves in summer is less than that in winter.

It may be noted from Figs. 11*b* and 11*c* that most of the convergence and divergence of the meridional transport of sensible heat in the troposphere is primarily the contribution of the transient waves, whereas in the stratosphere it is mainly the result of the stationary waves.

6. The latitudinal mean temperature distribution

We have found that the meridional sensible heat transport in both the troposphere and stratosphere is directed toward the North Pole, except in the low latitudes in the stratosphere where there is a weak transport of sensible heat toward the equator. To examine the relation between the meridional heat transport and the meridional gradient of temperature, the latitudinal mean temperature at the 100, 200, 500, and 850 mb levels for the winter and summer seasons are respectively shown in Fig. 12. It may be noted that in both winter and summer,

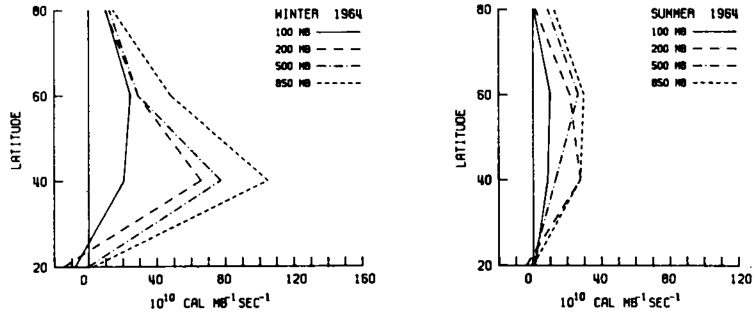

Fig. 11c. The meridional flux of sensible heat due to the nonstationary motion.

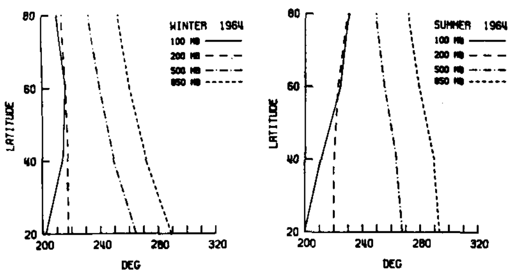

Fig. 12. The distribution of the latitudinal mean temperature.

the meridional gradient of the temperature in the troposphere is directed toward the North Pole, indicating that the sensible heat transport in the tropopshere is along the temperature gradient. In the stratosphere, however, the meridional gradient of temperature is directed toward the equator except north of 60° N in the winter where it is directed toward the North Pole. Therefore, the sensible heat transport in the stratosphere is mostly directed against the temperature gradient. A similar result was obtained by White (1954).

It is likely that there are two processes which result in this transport against the gradient of sensible heat in the stratosphere. The most obvious is the horizontal transport due to turbulent motion which may be along or against the temperature gradient. The second process that should be considered is the vertical transport of heat. It is likely that there is a downward transport from the stratosphere to the troposphere at high latitudes to compensate the heat lost by radiation in the lower levels.

7. Conclusion and summary

It is found that there exists a preferred spectral band in the wave-number frequency spectra at various latitudes, which indicates the wave-number frequency domain of interaction between the meridional velocity and temperature. In the middle latitudes, the spectral band is oriented in a domain extending from the region of low wave-numbers and frequencies to that of high wave-numbers and negative frequencies. In the high latitudes, the heat transport is confined to a domain of low wave-numbers and frequencies. In the lower latitudes, however, the transport is confined to a very narrow band centered near the zero frequency.

The total meridional transport of sensible heat at all four levels is directed, for the most part, toward the North Pole, except at 20° N where there is a weak equatorward transport of sensible heat at the 100 and 200 mb levels. In the troposphere, the maximum heat transport is found to occur neat 40° N, whereas in the stratosphere it occurs near 60° N. When the meridional sensible heat transport is compared to the latitudinal mean temperature gradient, it is found that the heat transport in the troposphere is directed along the temperature gradient. In the stratosphere, however, the heat transport is mostly directed against the temperature gradient.

It is also found that most of the poleward transport of sensible heat in both the troposphere and stratosphere is accomplished by the stationary and eastward moving, long and medium waves, and that the equatorward transport is mostly accomplished by the low frequency waves. Most of the convergence and divergence of the meridional heat transport in the troposphere is the contribution of the transient waves, whereas in the stratosphere it is mainly the result of the strationary waves.

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APPENDIX

Meridional transport of sensible heat across various latitudinal circles (10^{10} cal mb^{-1} sec^{-1})

Season	Level (mb)	Lat. (degree)	$\sum_k \sum_n E_{vT}(k, n)$	$\sum_{k \neq 0} E_{sq}(k, 0)$	$\sum_{k \neq 0} \sum_{n \neq 0} E_{sq}(k, n)$
Winter	100	80	3.4	−6.8	10.2
		60	83.2	58.6	24.6
		40	35.7	14.9	20.8
		20	−11.4	−3.6	−7.8
	200	80	6.8	−3.1	9.9
		60	83.0	54.0	29.0
		40	118.4	52.6	65.8
		20	−20.1	−5.3	−14.8
	500	80	9.4	−2.9	12.3
		60	72.7	43.6	29.1
		40	105.3	27.9	77.4
		20	5.3	5.5	−0.2
	850	80	16.8	2.4	14.4
		60	118.2	70.2	48.0
		40	154.0	49.1	104.9
		20	1.2	−1.4	2.6
Summer	100	80	2.7	2.2	0.5
		60	13.4	3.3	10.1
		40	14.4	5.7	8.7
		20	4.4	3.2	1.2
	200	80	3.6	2.1	1.5
		60	24.2	2.7	21.5
		40	47.6	19.9	27.7
		20	−2.9	1.1	−4.0
	500	80	9.1	0.4	8.7
		60	23.2	−3.3	26.5
		40	13.8	0.6	13.2
		20	−2.5	−1.9	−0.6
	850	80	12.1	−0.2	12.3
		60	26.8	−3.0	29.8
		40	24.6	−3.1	27.7
		20	−9.1	−9.2	0.1

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КРУПНОМАСШТАБНЫЙ МЕРИДИОНАЛЬНЫЙ ПЕРЕНОС ТЕПЛА В ПРОСТРАНСТВЕ ВОЛНОВЫХ ЧИСЕЛЧАСТОТ

Вычисляются и анализируются долготно-временные спектры меридионального переноса тепла через 20°, 40°, 60° и 80° с. ш. на 100-, 200-, 500- и 850-миллибаровых поверхностях для лета и зимы 1964 г. Найдено, что существует характерная спектральная полоса на различных широтах, указывающая на область волновых чисел и частот, при которых происходит взаимодействие между меридиональной скоростью и температурой. В средних широтах спектральная полоса ориентирована от области малых волновых чисел и частот к большим волновым числам и отрицательным частотам. В высоких широтах перенос тепла ограничен областью малых волновых чисел и частот. Однако в низких широтах перенос ограничен очень узкой полосой вблизи нулевой частоты.

Полный меридиональный перенос тепла на всех четырех уровнях в основном направлен к северному полюсу, за исключением 20° с. ш., где имеет место слабый перенос тепла к экватору на уровнях 100, 200 и 850 миллибар. В тропосфере максимальный перенос тепла имеет место вблизи 40° с. ш., тогда как в стратосфере — вблизи 60° с. ш.

Также найдено, что большая часть переноса тепла к полюсу как в тропосфере, так и в стратосфере осуществляется стационарными и движущимися на восток длинными и средними волнами, перенос к экватору осуществляется в основном движущимися на восток волнами низкой частоты.

Большая часть конвергенции и дивергенции меридионального переноса в тропосфере обязана вкладу нестационарных волн, тогда как в стратосфере она является, главным образом, результатом стационарных волн.