Dynamics of the stationary eddies in the lower stratospheric circulation in the wavenumber domain and monsoon activity*

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Abstract. Meridional transports of momentum and sensible heat have been computed using the Fourier coefficients of the geopotential heights at 50 mb and 30 mb levels for each month during the years 1972 to 1979. Seasonal variations in these transports and in the energy conversions $C(K_E, K_Z)$ and $C(A_Z, A_E)$ in the contrasting years of monsoon activity have been discussed. The transport and the conversion terms undergo annual variations only with winter maxima and summer minima.

Large northward transport of momentum and of sensible heat in the low latitude summer and in the high latitude preceding winter suggests a linkage between monsoon activity and high latitude stratosphere. Seasonal variations in the energy conversion terms $C(K_E, K_Z)$ and $C(A_Z, A_E)$ conform with the changes in the system in the years of widely differing monsoon activity both in low and high latitudes. Large conversion of energy from A_Z to A_E in low latitude summer indicates weakening of the existing meridional temperature gradient, in bad monsoon years.

Keywords. Stationary circulation; stratosphere; wavenumber domain; monsoon; meridional transport; seasonal variations.

1. Introduction

There are many studies (Oort and Rasmusson 1971; Wiin Nielson *et al* 1964; Holopainen 1965, 1967) on the eddy transports of momentum and of sensible heat undertaken as part of general circulation research. The momentum and sensible heat transports are closely linked with the atmospheric energetics. There are some studies connected with monsoon in relation to general circulation (Kanamitsu and Krishnamurti 1978; Awade *et al* 1981). They studied the meridional flux of momentum and sensible heat and found that there is contrast in these quantities during good and bad monsoon years. However, these studies have been restricted to troposphere. Recently Raja Rao and Lakhole (1978) and Thapliyal (1979) studied the stratospheric circulation with respect to the activity of the monsoon. They found that the activity of monsoon was closely linked with the circulation in the stratosphere and also with a time lag of a couple of months. The stratosphere is free from small perturbations existing in the troposphere induced by topographical and thermal forcings. The principal eddies in the stratosphere comprise planetary scale waves which can mostly be treated to reasonable accuracy by linear wave dynamics.

The Indian summer monsoon is a major anomaly on the general circulation. It is of interest to study these anomalies and their association with variation in the global flow patterns.

* A list of symbols appears at the end of the paper.

Table 1. Area weighted rainfall over Central India.

Year	Rainfall (mm)
1972	702
1973	1063
1974	773
1975	1080
1976	974
1977	999
1978	1035
1979	753
Mean	922

In this paper we present the results of the study of the meridional transport of momentum and of sensible heat and energy conversions at stratospheric levels, computed using the Fourier coefficients of the monthly mean grid point values of geopotential heights for the years 1972 to 1979. The primary objective of the study is to analyse the importance of seasonal and latitudinal variations in the meridional transport of momentum and of sensible heat and of various energy conversion terms from the point of view of monsoon activity. A year is classified as a good monsoon year, if the June to September rainfall in the central parts of India exceeds the normal rainfall in the same period (Raja Rao and Lakhole 1978). The years 1973, 1975, 1976, 1977 and 1978 were good monsoon years and 1972, 1974 and 1979 bad monsoon years in terms of rainfall over the central parts of India. Table 1 gives the area weighted rainfall over central parts of India.

2. Background

In an earlier paper (Raja Rao *et al* 1980) hereafter referred to as paper I, we have performed the spherical harmonic and Fourier analyses of the monthly means of geopotential heights at 50 mb and 30 mb levels for all the 12 months of the years 1972 and 1975 and obtained the amplitude and phases of waves 1 to 16. From the amplitudes and phases, the behaviour of the planetary waves was qualitatively estimated with respect to monsoon activity.

In the present paper we have quantitatively worked out the annual variations in the meridional transports of momentum and sensible heat for waves 1 to 16 and also the energetics at 10° interval of latitude, from 20° N to 70° N for 50 mb and 30 mb levels for all the years 1972 to 1979. (For the years 1978 and 1979, the 50 mb grid point values were not available and hence the heat transport and energy conversion $C(A_z, A_E)$ could not be calculated).

Observational studies resolving the transport into standing and transient eddy components (Oort and Rasmusson 1971; Kanamitsu and Krishnamurti 1978; Hirota and Sato 1970) have shown that standing eddies make substantial contribution to momentum and heat fluxes in the atmosphere. The standing eddies have been considered in the present study without prejudice to the role played by the transient eddies although we realise that the transient eddies play an important role.

3. Data and analysis

The gridpoint values of the monthly geopotential heights at 50 mb and 30 mb levels have been subjected to Fourier analysis. These grid point values have been picked up after the analysis of all the available radiosonde and rocket data and published by the German Free University, Berlin. The radiosonde data from USSR were submitted regularly only since April 1964. Hence, reliable data are available only since this time (Labitzke 1982). At present, these are the only reliable stratospheric data on global scale and they are being widely used by all workers. Here, these data have been used for harmonic analysis and from the harmonic coefficients amplitudes and phases for each month have been computed. The zonal winds have been derived at these levels using the geostrophic approximation which is valid north of 20° N. Hence we restrict our study to the region north of 20° only.

3.1. Momentum

In paper I the geopotential height Z along a latitude circle is expressed as

$$Z(\lambda) = \sum_{m=0}^{\infty} [a_m(\phi) \cos m\lambda + b_m(\phi) \sin m\lambda]. \quad (1)$$

The amplitude R_m and phase ε_m of the m th wave are given by

$$R_m = [(a_m)^2 + (b_m)^2]^{1/2}; \quad \varepsilon_m = \frac{1}{m} \arctan(b_m/a_m). \quad (2)$$

Following Lorenz (1966) we obtain the meridional transport of momentum

$$[U^* \bar{V}^*] = -\frac{g^2}{4\Omega^2 a^2 \sin^2 \phi \cos \phi} \left[\frac{\partial \bar{Z}^*}{\partial \lambda} \cdot \frac{\partial \bar{Z}^*}{\partial \phi} \right] \quad (3)$$

$$\approx -\frac{g^2}{4\Omega^2 a^2 \sin^2 \phi \cos \phi} \sum_{m=1}^{16} \frac{m^2}{2} \cdot R_m^2 \left(\frac{\partial \varepsilon_m}{\partial \phi} \right). \quad (4)$$

The square bracket indicates average over a latitude circle and the star, the deviation of a parameter from the latitude circle average. The bar represents the monthly time average, R_m and ε_m are amplitude and phase of the m th wave. The Greenwich meridian is reckoned as the longitude of phase zero.

From (3) and (4) it is clear that the meridional transport of momentum depends upon the tilt of the wave in the horizontal and on the kinetic energy of each wave. The momentum transport is northward (southward) if the tilt of the ridge line is in NE-SW (NW-SE) direction. The meridional flux of momentum across a latitude circle is given by:

$$\frac{2\pi a^2 \cos^2 \phi}{g} \int_{p_1}^{p_2} [U^* \bar{V}^*] dp, \quad (5)$$

where p_1 and p_2 are pressures at higher and lower levels. From (4), we can determine the contribution due to each component and add all the components to get the total contribution from all waves.

3.2. Sensible heat transport

We compute the meridional transport of sensible heat by differentiating equation (1) with respect to longitude and pressure and integrating over longitude. Hence we get (Lorenz 1966)

$$[\bar{V}^* \bar{T}^*] = - \frac{g^2 p}{2\Omega a R \sin \phi \cos \phi} \left[\frac{\partial \bar{Z}^*}{\partial \lambda} \cdot \frac{\partial \bar{Z}^*}{\partial p} \right], \quad (6)$$

$$\simeq \frac{g^2 p}{2\Omega a R \sin \phi \cos \phi} \sum_{m=1}^{16} R_m^2 \cdot \frac{m^2}{2} \left(\frac{\partial \epsilon_m}{\partial p} \right). \quad (7)$$

Using the amplitudes and phases at 50 mb and 30 mb levels thus computed, we obtain the amplitude and vertical tilt at 40 mb.

$$(R_m)_{40 \text{ mb}} \simeq \frac{(R_m)_{50 \text{ mb}} + (R_m)_{30 \text{ mb}}}{2}, \quad (8)$$

$$\left(\frac{\partial \epsilon_m}{\partial p} \right)_{40 \text{ mb}} \simeq \frac{(\epsilon_m)_{50 \text{ mb}} - (\epsilon_m)_{30 \text{ mb}}}{20 \text{ mb}} \quad (9)$$

Meridional transport of sensible heat thus depends upon the tilt of the wave in the vertical and on the kinetic energy of each wave. If the wave tilts eastward (westward) with increase of height, it transports sensible heat southward (northward).

The meridional flux of sensible heat across a latitude circle is given by

$$\frac{2\pi a \cos \phi}{g} \int_{p_1}^{p_2} C_p [\bar{V}^* \bar{T}^*] dp. \quad (10)$$

3.3. Energy conversions

The conversions from eddy kinetic energy into zonal kinetic energy, $C(K_E, K_Z)$ and zonal available potential energy into eddy available potential energy $C(A_Z, A_E)$ are given by

$$C(K_E, K_Z) \simeq \int [\bar{U}^* \bar{V}^*] \frac{\partial [\bar{U}]}{a \partial \phi} d_m, \quad (11)$$

$$C(A_Z, A_E) \simeq -g \int \frac{1}{\tilde{T}(\gamma_d - \tilde{\gamma})} [\bar{V}^* \bar{T}^*] \frac{\partial [\bar{T}]}{a \partial \phi} d_m. \quad (12)$$

The tilde indicates area average and double prime, the deviation from the area average. These terms have been computed in this paper.

4. Results and discussion

We have inferred in paper I that only waves 1 and 2 are prominent, therefore we have considered in the present paper the transports by the waves 1 and 2 separately and by all the waves (1 to 16). The latter represent the whole observed field and it is our purpose to compare the contribution of each of the waves 1 and 2 with the whole. The

computations have been made for 50 mb and 30 mb levels, but the results for 30 mb level only are presented here as those for 50 mb level are similar to the results of 30 mb level. We summarise below the seasonal features and the variation of transport of momentum and of sensible heat and energy conversion terms over the northern hemisphere with monsoon activity. 30°N represents sub-tropical latitudes and 60°N represents high latitude. As shown by Charney and Drazin (1961) under certain conditions tropospheric waves penetrate into the stratosphere and thus there is a vertical transport of energy in the planetary scale due to special structure of zonal winds in the vertical direction. It may be possible that during bad monsoon years, the vertical structure of the zonal winds change in such a way as to allow upward propagation of energy from troposphere to stratosphere. If this is true, the stratospheric circulation will be weak/strong resulting in weak/strong monsoon activity. For this purpose a critical examination of the zonal winds at various levels including the troposphere and the lower stratosphere has to be made and the vertical propagation of energy (following Charney and Drazin 1961) will have to be calculated. However, in the present study we restrict ourselves to only lower stratosphere and see how this behaves in good and bad monsoon years with respect to various parameters.

4.1. Meridional transport of momentum

Figures 1, 2 and 3 depict on a hemispheric scale, the annual march of the transports of momentum by waves 1, 2 and all waves (1–16) respectively for the period 1972 to 1979 at 30 mb level. Table 2 summarises the seasonal variation in the transports of momentum at low and high latitudes for good and bad monsoon years. The years 1972, 1974 and 1979 had bad monsoon activity whereas the years 1973, 1975, 1976, 1977 and 1978 had normal or above normal (good) monsoon activity. In table 2, mean winter values for any year represent the average of the values for December (of preceding year),

Figure 1. Momentum transport at 30 mb by $m = 1$. Positive values indicate northward transport and negative values (hatched) southward transport. Unit: $10^{17} \text{ g m}^2 \text{ sec}^{-2} \text{ mb}^{-1}$.

Figure 2. Momentum transport at 30 mb by $m = 2$. Positive values indicate northward transport and negative values (hatched) southward transport. Unit: $10^{17} \text{ g m}^2 \text{ sec}^{-2} \text{ mb}^{-1}$.

Figure 3. Momentum transport at 30 mb by $m = 1$ to 16. Positive values indicate northward transport and negative values (hatched) southward transport. Unit: $10^{17} \text{ g m}^2 \text{ sec}^{-2} \text{ mb}^{-1}$.

January and February (of the same year). In the case of 1972 winter, average of only two months (January and February) is considered. The mean summer value represents the average of the values for June, July and August.

4.1a. *Seasonal variation:* From these figures and table it is clear that in both low and high latitudes, the momentum transport by wave 2 and all waves is generally northward in winter. The values of meridional transport of momentum during summer are

Table 2. Meridional transport of momentum (unit $10^{17} \text{ gm}^2 \text{ sec}^{-2} \text{ mb}^{-1}$) at 30 mb for winter and summer months.

Lat.		Year	Winter			Summer		
			$m = 1$	$m = 2$	$m = 1 - 16$	$m = 1$	$m = 2$	$m = 1 - 16$
30°N	Good monsoon	1973	16.5	-2.1	9.3	-4.8	0.4	-3.5
		1975	13.5	4.3	17.4	-1.4	3.2	-0.4
		1976	8.6	0.2	6.9	-5.3	0.1	-3.7
		1977	6.2	7.8	37.1	-3.6	-0.2	-1.5
	Bad monsoon	1972	32.9	12.7	66.2	3.0	0.3	4.0
		1974	34.5	22.2	76.2	3.2	-0.2	3.0
		1979	-29.6	16.4	16.3	-0.7	0.6	-0.5
60°N	Good monsoon	1973	36.6	181.6	256.9	-1.6	0.4	-1.2
		1975	36.9	81.8	131.5	-1.3	-1.0	-2.4
		1976	9.0	144.6	169.0	1.6	-1.6	0.4
		1977	-43.6	29.3	3.2	0.3	-0.4	-0.1
		1978	152.9	6.0	180.9	0.2	-1.8	-1.6
	Bad monsoon	1972	-39.3	412.7	382.6	-0.6	-0.1	-0.8
		1974	-11.6	277.3	386.6	0.0	-0.4	-0.8
		1979	508.5	27.5	560.8	-1.0	-2.5	-4.3

considerably lower than the winter values suggesting that eddy transport plays a dominant role in the winter stratospheric circulation. In high latitudes during summer, the transport by waves 1, 2 and all waves is generally southward (however, there are 3 instances of northward transport in 1977 and 1978 for waves 1, and 1973 for wave 2, but these values are very low). In low latitudes during summer, transports by waves 1, 2 and by all waves are variable.

4.1b. *Monsoon activity:* Contrast between good and bad monsoon years is evident at low latitudes in summer and at high latitudes in the preceding winter. At high latitudes in winter preceding a bad monsoon, there is a large northward transport generally contributed by wave 2 (wave 1 for 1979). As is clear from figures 1 and 2, wave 2 in winter is significantly more intense than wave 1, around 50°N . In winter preceding a bad monsoon north of 60°N , wave 1 shows southward flux of momentum and wave 2 transports the momentum northward. In winter preceding a good monsoon year both the waves 1 and 2 transport momentum northwards and the intensity of wave 2 is less in winter preceding a good than in winter preceding bad monsoon years except in 1979. (This anomaly may be due to the intense stratospheric warming which started on 29 December 1978 and peaked on 25 February 1979). In summer at low latitudes, southward transport is larger in good than in bad monsoon years, here the contribution is largely from wave 1. Waves 1 and 2 in winter in high latitudes contribute to the northward transport and hence their contribution to the strengthening of the polar jet, as inferred from the values of $C(K_E, K_Z)$ in figure 7 and winds in figure 9 (Holton 1975). In the winter preceding a bad monsoon the strengthening of polar jet is more intense than in winter preceding a good monsoon and consequently winter westerlies preceding a bad monsoon are more intense (table 2). In lower latitudes, wave 1 plays an important role in defining the strength of the monsoon. The northward transport of momentum in low latitudes during summer leads to stronger summer easterlies in good than in bad monsoon years at 50 mb level (not shown). Stratospheric easterly jet in the low latitudes during the monsoon months gets enhanced. A close association exists between the strength of the jet and monsoon activity (Raja Rao and Jayanthi 1975).

4.2. Meridional transport of sensible heat

Figures 4, 5 and 6 represent the northern hemispheric annual march of the transport of sensible heat at 40 mb level by waves 1, 2 and all waves. Table 3 gives the summary of seasonal variations in the transports.

4.2a. *Seasonal variation:* In both low and high latitudes, the transport in winter is northward, contributed by both waves 1 and 2. But the high latitude transport is far larger than the low latitude one. At all latitudes, the summer values are much lower than the winter values, wave 1 contributing to the southward transport and wave 2 generally to the northward transport.

4.2b. *Monsoon activity:* At high latitudes in winter preceding a good monsoon, the northward transport of sensible heat is large by wave 1 and by wave 2 in winter preceding a bad monsoon. The integrated effect of all the waves indicates that in high latitudes in winter preceding a bad monsoon northward transport is generally large.

Figure 4. Sensible heat transport at 40 mb by $m = 1$. Positive values indicate northward transport and negative values (hatched) southward transport. Unit: $10^{10} \text{ J sec}^{-1} \text{ mb}^{-1}$.

Figure 5. Sensible heat transport at 40 mb by $m = 2$. Positive values indicate northward transport and negative values (hatched) southward transport. Unit: $10^{10} \text{ J sec}^{-1} \text{ mb}^{-1}$.

Figure 6. Sensible heat transport at 40 mb by $m = 1$ to 16. Positive values indicate northward transport and negative values (hatched) southward transport. Unit: $10^{10} \text{ J sec}^{-1} \text{ mb}^{-1}$.

But at low latitudes in winter preceding a good and bad monsoon, the contrast between the transports by waves 1, 2 and all waves is not clear.

In summer at high latitudes, the contrast between the transport in good and in bad monsoon years by waves 1, 2 and all waves is not conspicuous. But in low latitudes during summer there is larger southward transport by wave 1 in bad than in good monsoon years. The integrated effect of all waves also indicates larger southward transport in bad than in good monsoon years (table 3) at both low and high latitudes.

There is, therefore, a strong hint of a linkage between the monsoon activity and the transports of momentum and of sensible heat in high latitudes during the preceding winter and at low latitudes during summer.

4.3. Energy conversions between zonal flow and eddies

Figures 7 and 8 depict the annual march of $C(K_E, K_Z)$ at 30 mb level, $C(A_Z, A_E)$ at 40 mb level respectively. Table 4 summarises the seasonal and latitudinal variations in $C(K_E, K_Z)$ and $C(A_Z, A_E)$ in good and bad monsoon years.

The energy conversions $C(K_E, K_Z)$ and $C(A_Z, A_E)$ also reveal an annual variation with winter maxima and summer minima. Semiannual variation is not present in both the energy conversions. The conversion of kinetic energy is from K_E to K_Z during winter both at high and low latitudes. But during summer the conversion continues to be from K_E to K_Z at low latitudes, while at high latitudes it is generally from K_Z to K_E showing that the zonal flow is unstable. At low latitudes the summer easterlies are

Table 3. Meridional transport of sensible heat (Unit: 10^{10} J. sec⁻¹ mb⁻¹) at 40 mb for winter and summer months.

Lat.	Year	Winter			Summer		
		m = 1	m = 2	m = 1-16	m = 1	m = 2	m = 1-16
30°N	Good monsoon						
	1973	16.5	-2.1	9.3	-4.8	0.4	-3.5
	1975	13.3	4.3	17.4	-1.4	3.2	-0.4
	1976	8.6	0.2	6.9	-5.3	0.1	-3.7
	1977	6.2	7.8	37.1	-3.6	-0.2	-1.5
60°N	Bad monsoon						
	1972	13.6	5.1	21.5	-10.2	2.7	-6.2
	1974	9.4	-0.6	10.6	-7.3	1.6	-4.3
	Good monsoon						
	1973	293.0	286.0	569.0	-1.1	0.9	-0.7
	1975	310.0	224.0	530.0	-0.9	2.0	1.6
	1976	250.0	123.0	359.0	1.5	2.6	4.2
	1977	238.0	162.0	434.0	-1.4	-0.8	-2.3
Bad monsoon	1972	165.0	688.0	860.0	-1.6	2.5	-0.5
	1974	208.0	260.0	490.0	-3.6	1.0	-2.6

Figure 7. $C(K_E, K_Z)$ conversions at 30 mb. Positive values indicate $C(K_E \rightarrow K_Z)$ and negative values (hatched) $C(K_Z \rightarrow K_E)$. Unit: $10^{-2} \text{ m W m}^{-2} \text{ mb}^{-1}$.

Figure 8. $C(A_Z, A_E)$ conversions at 40 mb. Positive values indicate $C(A_Z \rightarrow A_E)$ and negative values (hatched) $C(A_E \rightarrow A_Z)$. Unit: $10^{-2} \text{ m W m}^{-2} \text{ mb}^{-1}$.

Table 4. Energy conversion terms $C(K_E, K_Z)$ and $C(A_Z, A_E)$ for winter and summer months (Units: $10^{-2} \text{ mwm}^{-2} \text{ mb}^{-1}$)

Lat.		Year	Winter		Summer	
			$C(K_E, K_Z)$	$C(A_Z, A_E)$	$C(K_E, K_Z)$	$C(A_Z, A_E)$
30°N	Good monsoon	1973	31.5	-1.9	2.0	0.7
		1975	33.6	-2.0	2.2	0.2
		1976	11.6	-1.4	3.0	0.7
		1977	20.2	-7.7	1.8	0.3
		1978	12.3	—	1.7	—
60°N	Bad monsoon	1972	10.0	-5.3	0.7	1.4
		1974	15.9	-2.0	3.2	1.8
		1979	0.6	—	-0.4	—
	Good monsoon	1973	43.5	160.4	-0.2	0.1
		1975	31.3	130.3	-0.2	-0.5
1976		108.0	230.9	0.1	-1.0	
1977		46.2	108.5	0.0	0.5	
1978		74.4	—	0.0	—	
Bad monsoon	1972	125.5	388.8	-0.1	1.1	
	1974	11.5	301.6	0.1	1.5	
	1979	194.2	—	-0.1	—	

intense, while in winter at high latitudes westerlies are intense. The energy conversion $C(K_E, K_Z)$ maintains the easterlies and westerlies in the respective regions.

At high latitudes in winter preceding a bad monsoon the conversion is from A_Z to A_E and it is large. In low latitudes during the winter preceding a good and bad monsoon year, the conversion is from A_E to A_Z but the contrast is not conspicuous. In both high and low latitudes the conversion is from A_Z to A_E (except in 1975 and 1976) during summer. In both high and low latitudes winter values are far higher than the summer values.

4.4. Winds

Wind field has been computed from geostrophic approximation, at intervals at 10° latitude for each month of all the years in the latitude range of 20°N to 80°N . Figure 9 plots the geostrophic wind field. The wind field indicates an annual variation with westerlies in the winter and easterlies in the summer months. The polar night jet is intense in the region of 55°N to 70°N in winter, more intense at 30 mb than at 50 mb. As we do not have a sufficiently long series of data any statistical significance test may not be meaningful. However, from the analysis we can get a hint that at high latitudes in winter preceding a bad monsoon, winds are stronger (> 0.03 km/s) than in the winter preceding a good monsoon (< 0.03 km/s).

By Fourier analysis of the grid point values of geopotential heights for the winter months 1963 to 1967, Hirota and Sato (1970) have computed the transport of momentum at 30°N and 60°N latitudes. Our results cannot be strictly compared with Hirota and Sato as they pertain to different periods. However, comparison of our

Figure 9. Zonal winds at 30 mb (m/sec). Positive values are westerlies and hatched areas are easterlies.

results for 1972 with the results of Hirota and Sato for 1965, both years of bad monsoon, shows that our values (29.2×10^8) of the momentum at 60°N for wave 2 are far higher than theirs (1.17×10^8). Comparison of our 1975 values with their 1967 values (both years of good monsoon activity) shows general agreement.

Thapliyal (1979) studied the lower stratospheric circulation of January in relation to summer monsoon over India. He observed that as early as January in 1972, 3 prominent circulation features (southern hemispheric trough, northern hemispheric trough and ridge) appeared, while during the month of January in a good monsoon year only a northern hemisphere ridge appeared between latitudes 40°S to 60°N .

Our computations have shown that at 30°N latitude, there is larger transport of momentum in the January preceding a bad monsoon year than in winter preceding good monsoon year. This is closely linked with the troughing and ridging he has observed. The two sets of results are complimentary to each other. Similar features have been noticed in winter at 60°N latitude also. These give a strong hint that the high latitude winter circulation patterns may be a good tool for forecasting of the following summer monsoon.

5. Conclusions

The primary conclusions of the study are summarised here: (i) In winter preceding a bad monsoon, in high latitude the amplitude of wave 1 or 2, northward transports of momentum and sensible heat by wave 2 and conversion from A_Z to A_E are all larger than in the winter preceding a good monsoon year, thus suggesting a linkage between monsoon activity and high latitude activity.

(ii) Large conversion of energy from K_E to K_Z in low latitude summer indicates intensification of the summer easterlies in good monsoon years. Conversion from K_Z to K_E in high latitudes in summer suggests barotropic instability.

(iii) In bad monsoon years large conversion of energy from A_Z to A_E in low latitude summer indicates the weakening of the existing meridional temperature gradient.

(iv) The transport of momentum and sensible heat and the Lorenz energy conversion terms exhibit only annual variation with winter maxima and summer minima. The seasonal variations in the conversion term $C(K_E, K_Z)$ is in conformity with the change in the wind systems.

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List of symbols

a	radius of the earth
a_m	cosine coefficient of longitudinal wave number m

A_E	Eddy available potential energy
A_Z	zonal available potential energy
b_m	sine coefficient of longitudinal wave number m
C_p	specific heat of dry air at constant pressure
d_m	element of mass
g	acceleration due to gravity
K_E	eddy kinetic energy
K_Z	zonal kinetic energy
m	number of waves along a latitude circle
p_1, p_2	pressure at higher and lower levels respectively
R	gas constant of dry air
R_m	amplitude of the m th wave
T	temperature
U, V	wind components along x and y directions respectively
Z	geopotential height
ε_m	Phase of m th wave
γ	environmental lapse rate
γ_d	dry adiabatic lapse rate
λ, ϕ, p	longitude, latitude and pressure respectively
Ω	angular velocity of earth
*	deviation from latitude circle average
[]	average over a latitude circle
—	monthly time average
~	area average
"	deviation from area average

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