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The meridional transport of momentum in the wave number regime during the contrasting monsoon years

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ABSTRACT. The momentum transport by the standing eddies are computed during a weak monsoon year (1972) and a strong monsoon year (1967) in the wave number regime for the months of April to August in the northern hemisphere at 700 mb and 300 mb levels.

The integrated effect of the first 16-wave numbers considered, indicate a more northward transfer of momentum at 300 mb level in a year of a good monsoon than a weak monsoon. The wave numbers 1 and 3 at this level contribute maximum northward transfer in the lower and middle latitudes during the period April to August, whereas the wave number 2 contributes southward transfer in both the years during this period (*i.e.*, April to August).

The comparison of monthly transport at 700 mb level for both the years does not indicate significant difference from each other. However, at 300 mb level, we find contrast in both the years in wave number regime. The wave numbers 1 to 4 are prominent. The wave numbers 1 and 3 are very prominent in the months April and June. The transport by the wave number 3 is very much northward in 1967 than in 1972 during April and June at all the latitudes. The transport is much above normal at 300 mb level in 1967 than in 1972 during April and June.

The results are compared with the results of other authors.

1. Introduction

Many investigators have worked on the wave number domain (Saltzman 1957, 1958, 1970; Saltzman and Peixoto 1957; Wiin Nielson *et al.* 1963, 1964 and Van Mieghem 1959). Following this approach, Keshavamurty and Awade (1974) studied the abnormalities associated with the drought in the summer monsoon.

It is recognised that the southwest monsoon regime over the Indian sub-continent is a part of the global general circulation. It is seen that in some years the monsoon rainfall is very good and in some years it is far below normal. The general circulation patterns in these contrasting years have been studied in the present paper in the wave number domain.

The momentum transport in the wave numbers in the northern hemisphere has been computed for the months April to August for the year 1967, a year of good monsoon and 1972, a drought year. These transport values are compared with the normal in order to evaluate the circulation pattern in contrasting years.

2. Method

We have expanded the height field in the Fourier series, using truncated series we get,

$$Z(\lambda,\phi,P) = \Big[Z(\phi,P) \Big] + \sum_{m=1}^{16} R_m(\phi,P) \times \times \cos m\,[\lambda - \zeta_m(\phi,P)] \qquad (1)$$

where m is a wave number in the horizontal, R_m and ζ_m are amplitude and phase respectively of the mth wave.

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Eqn. (1) can be put in the form

$$Z(\lambda,\phi,P) = \Big[Z(\phi,P)\Big] + \sum_{m=1}^{16} A_m(\phi,P)\sin m\lambda + $$

$$+ B_m(\phi,P)\cos m\lambda \qquad (2)$$

where,

$$R_m = \sqrt{A_m^2 + B_m^2} \qquad (3)$$

$$\zeta_m = \frac{1}{m}\tan^{-1}\frac{A_m}{B_m} \qquad (4)$$

We use geostrophic approximation for the wind. Following Lorenz (1966) and differentiating Eqn. (1) with respect to latitude and longitude, and summing over the longitudes, we get,

$$\Big[\bar{u}^*\,\bar{v}^*\Big] = \frac{-g^2}{4\,\Omega^2 a^2\sin^2\phi\cos\phi}\left[\frac{\partial \bar{z}}{\partial\lambda}\,\frac{\partial \bar{z}}{\partial\phi}\right]$$

$$= \frac{g^2}{4\Omega^2 a^2\sin^2\phi\cos\phi}\sum_{m=1}^{16}\frac{1}{2}\,m^2 R_m^2\,\frac{\partial\zeta_m}{\partial\phi} \qquad (5)$$

The flux of angular momentum across a latitude circle is given by $= \dfrac{2\pi a^2\cos^2\phi}{g}\displaystyle\int_{P_1}^{P_2}\Big[\bar{u}^*\,\bar{v}^*\Big]dp$ (6)

Here,

- [ ] zonal average
- * deviation from the zonal average
- — time mean
- a radius of the earth
- λ,ϕ latitude and longitude respectively
- g acceleration of gravity
- P_1 pressure in mb at a higher level
- P_2 pressure in mb at a lower level

We can find the contribution due to each component and add all the components to get the total contribution from all the waves. Thus the Eqn. (5) above gives the total momentum transport due to all the waves considered.

From above equation, it is clear that the momentum transport depends upon the tilt of the wave in the horizontal and kinetic energy of each component.

3. Data

The data here, used comprise the monthly mean values of geopotential heights on global scale published by the Free University of Berlin (Scherhag and Mitarbeiter 1967, 1972). The grid points were picked up at the intervals of 5 degree longitude and 5 degree of latitude from the equator to the north pole at the levels 700 and 300 mb for the months of April to August. The Fourier analysis was done for these data for the wave numbers 1 to 16.

4. Results and discussion

4.1. *Transport of momentum during the period April to August*

The transport of momentum was computed at 700 mb and 300 mb levels during the period (April to August) for wave number 1 to 16 for the years 1967 and 1972.

In order to understand the broad features, we obtained the transport of momentum due to the standing eddies contributed by long waves, short waves and all the waves separately, at latitudes 20°N to 70°N at intervals of 10° latitudes. This is presented in Fig. 1 and Table 1.

4.1.1. *Transport of momentum at 700-mb level*

A. *Contribution by long waves to the momentum transport*—The contribution by long waves (wave Nos. 1 to 4) to the momentum transport at 30°N at this level is southward in 1967, but northward in 1972. At 60°N, the transport is more southward in 1972 and very small in 1967. At other latitudes, small difference in the transport is observed in these two years.

B. *Contribution by short waves to the momentum transport*—The contribution by short waves (wave Nos. 5 to 10) to the momentum transport is northward in both the years at all latitudes; but there is small variation in these two years.

C. *Total contribution by all the waves to the momentum transport*—The contribution by all the waves (wave Nos. 1 to 16) at 700 mb gives the northward transport except at the lower and higher latitudes. However, the two years generally do not appear to be different.

TABLE 1

Meridional transport of momentum by standing eddies during the period April to August contributed by long, short and all waves

Lat. (°N)	Level (mb)	Wave Nos. 1-4		Wave Nos. 5-10		Wave Nos. 1-16	
		1967	1972	1967	1972	1967	1972
20	700	—96	—116	7	42	—55	—74
30		—32	77	46	18	70	81
40		160	156	45	38	204	207
50		80	34	26	48	90	84
60		0	—63	14	—4	15	—67
70		—34	—16	1	0	—33	—15
20	300	461	296	145	68	635	367
30		628	428	221	10	826	498
40		236	—121	297	286	548	180
50		211	—113	57	67	287	49
60		—24	—152	7	11	8	—131
70		—81	—67	2	—5	—80	—74

Unit : 10^{17} gm m^2 sec^{-2} mb^{-1}

4.1.2. *Transport of momentum at 300-mb level*

The contribution by long waves, short waves and all the waves show similar features though there are marked difference at some points. The transport of momentum is northward upto 50°N for wave Nos. 1-4 in 1967, but it is northward upto 30°N and southward beyond 30°N in 1972. The long waves contribute much more than the short waves.

The integrated effect of the first 16 waves numbers considered, indicate a more northward transport of momentum in a year of good monsoon than in a drought year at lower and middle latitudes. However, the transport is generally southward in both years at the higher latitudes.

The maximum transport during the period is at 30°N at this level.

4.2. *Transport of momentum in the wave regime during the period April to August*

Since there is marked difference at 300 mb, we shall discuss the transport at this level for various wave numbers.

The wave Nos. 1 and 3 at 300-mb level, contribute more northward transport in the lower latitudes in the years of good monsoon than the drought year. The wave No. 2, however, gives southward transport. It is more southward in 1972 than in 1967.

The wave Nos. 6 and 7 give more northward contribution in year of good monsoon (1967) than a weak monsoon (1972). The contribution at the higher latitudes is much smaller than the low latitudes. Fig. 2 illustrates the above inferences.

4.3. *Monthly variation of the transport of momentum by long waves, short waves and all the waves*

4.3.1. *Monthly transport of momentum at 700-mb level*

A. *Contribution by long waves to the momentum transport*—The transport of momentum by long waves (wave Nos. 1 to 4) is more southward in 1967 than in 1972 during July and August at latitudes 20°N and 30°N. The transport is northward in June 1967 but southward in June 1972 at 20°N. In April there is no significant difference in both the sets. However, the transport is southward in May 1967 but northward in May 1972.

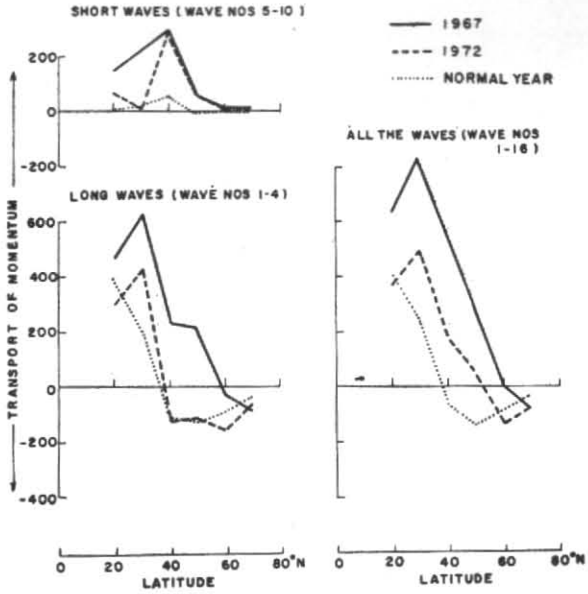

Fig. 1. Meridional transport of momentum (unit : 10^{17} gm m^2 sec^{-2} mb^{-1}) by standing eddies at 300 mb during the period April to August contributed by long, short and all waves

The transport at 40°N is northward in both the years, but there is no significant difference in these months.

The transport at 50°N is northward in all the months except in May. The transport in 1967 is generally more than in 1972. At 60°N and 70°N the transport shows similar features in these two years.

B. *Contribution by short waves to the momentum transport*—The transport is northward at 20°N during April to June and southward in July and August in both the years.

At 30°N, the transport is more southward in April 1967 than in April 1972. However, the transport is more northward during May to July 1967 than in 1972 in the same period.

At 40°N the transport is northward in 1967 during April to August. However, difference in two years is not significant.

At 50°N, the transport is generally northward in both the years but the difference is small.

At 60°N and 70°N the transport is negligible in these two years.

C. *Contribution by all the waves to the momentum transport*—The contribution by all the waves shows similar features as shown by the long waves.

At 20°N and 30°N, the transport is northward during April to June in these years, but southward in the remaining months.

At 40°N, it is northward in all the months in both the years.

At 50°N, it is northward in all months except in May, when it is southward in both the years.

At 60°N and 70°N, it shows similar features as shown by the long waves.

4.3.2. *Monthly transport of momentum at 300-mb level*

A. *Contribution by long waves to momentum transport*—Table 2 shows the monthly transport at 300 mb level at various latitudes. The

TABLE 2

Monthly meridional transport of momentum at 300-mb level by standing eddies contributed by long, short and all waves

Lat (°N)		Wave Nos. 1-4		Wave Nos. 5-10		Wave Nos. 1-16	
		1967	1972	1967	1972	1967	1972
20	Apr	293	112	48	32	360	155
	May	104	111	58	13	164	118
	Jun	36	72	43	13	82	88
	Jul	—22	—8	—12	1	—30	—7
	Aug	50	9	8	9	59	13
30	Apr	366	218	28	—92	363	171
	May	85	107	7	—7	93	119
	Jun	145	45	102	18	260	58
	Jul	44	18	55	66	115	90
	Aug	—12	40	29	25	—5	60
40	Apr	105	90	—12	4	102	87
	May	—48	—166	25	47	—22	—122
	Jun	172	—49	87	75	261	27
	Jul	27	—15	128	145	158	141
	Aug	—20	19	69	15	49	47
50	Apr	190	96	80	9	260	106
	May	—62	—189	—49	1	—111	—189
	Jun	93	—44	8	13	99	—31
	Jul	—13	—10	13	38	32	24
	Aug	3	34	5	6	7	41
60	Apr	66	7	38	12	109	24
	May	—80	—144	—38	—5	—118	—149
	Jun	20	—79	—9	3	13	—76
	Jul	2	45	9	2	13	47
	Aug	—32	19	7	3	—25	23
70	Apr	13	8	—4	0	9	7
	May	—70	—65	4	2	—67	—61
	Jun	—10	—28	0	—3	—10	—33
	Jul	—14	26	3	0	—10	—26
	Aug	0	—8	—1	4	—2	—13

Unit : 10^{17} gm m^2 sec^{-2} mb^{-1}

transport of momentum by the long waves at 20°N is northward in all the months (except July) in both the years. However, it is very much northward in 1967 than in 1972 during April.

At 30°N, the transport is northward in all months in these years. But the transport is more northward in 1967 than in 1972 during the months April, June and July, as depicted in Fig. 3 and Table 2.

At 40°N, the transport is more northward in 1967 than in 1972 in April, June and July. However, it is more southward in May 1972 than in May 1967.

At 50°N, the transport is more northward in 1967 than in 1972 during April and June but more southward in May 1972 than in May 1967.

At 60°N, it shows the same features as shown at 50°N.

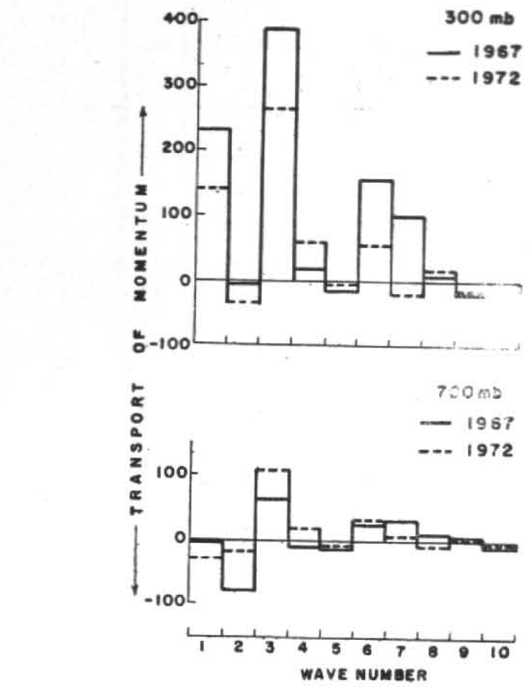

Fig. 2. Meridional transport of momentum. (Unit : 10^{17} gm m^2 sec^{-2} mb^{-1}) by standing eddies across 30°N during the period April to August in wave number regime

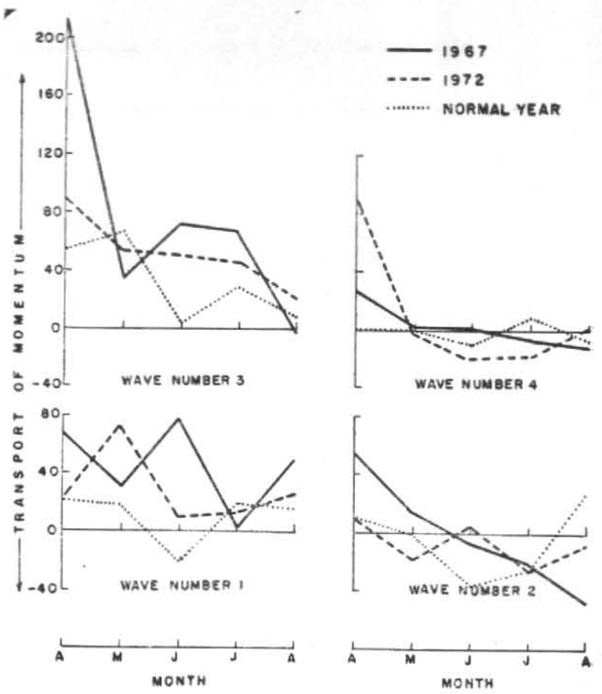

Fig. 4. Monthly meridional transport of momentum (unit : 10^{17} gm m^2 sec^{-2} mb^{-1}) by standing eddies across 30°N at 300 mb in wave number regime

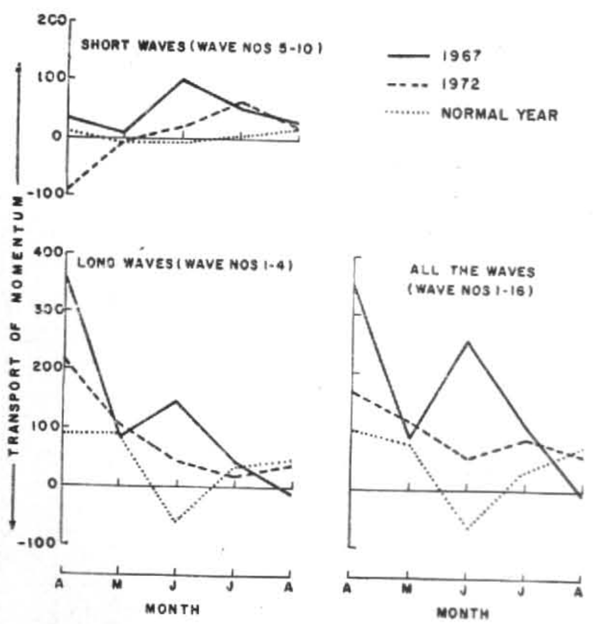

Fig. 3. Monthly meridional transport of momentum (unit : 10^{17} gm m^2 sec^{-2} mb^{-1}) by standing eddies across 30°N at 300 mb contributed by long, short and all waves

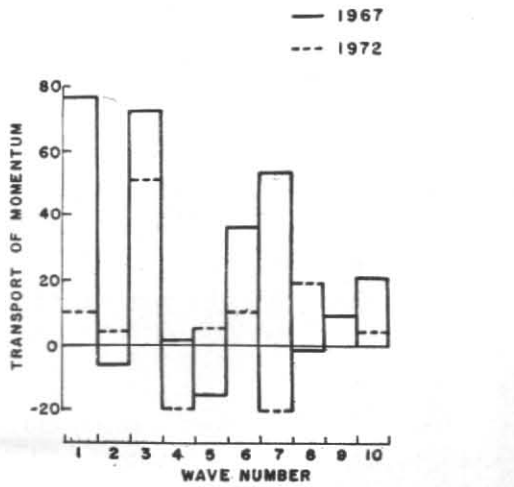

Fig. 5. Meridional transport of momentum (unit : 10^{17} gm m^2 sec^{-2} mb^{-1}) at 30°N by standing eddies in June at 300 mb in the wave regime

TABLE 3

Monthly meridional transport of momentum at 300-mb level by standing eddies in wave number regime

Lat (°N)		Wave numbers 1		2		3		4		5		6		7		8	
		1967	1972	1967	1972	1967	1972	1967	1972	1967	1972	1967	1972	1967	1972	1967	1972
20	Apr	177	35	−19	−31	131	102	4	6	−40	25	56	−5	−4	15	−5	0
	May	71	97	−6	−17	2	28	37	3	14	2	−1	11	42	3	16	1
	Jun	30	59	−5	−12	18	13	−7	12	1	−4	4	5	22	−4	11	11
	Jul	26	48	−23	−40	−35	−33	10	12	0	−5	−11	−7	2	4	−3	1
	Aug	48	4	−9	−23	−2	2	13	8	−2	1	−3	1	9	3	2	5
30	Apr	69	22	58	11	211	91	28	94	5	19	80	22	−2	−10	−11	−52
	May	31	72	15	−19	36	54	3	0	−13	−35	7	31	32	−4	3	−9
	Jun	77	10	−6	4	73	51	1	−20	−16	5	36	10	53	−20	−1	19
	Jul	3	13	−21	−24	68	46	−6	−17	0	2	31	−10	9	5	5	53
	Aug	49	26	−48	−8	−2	21	−11	1	6	7	4	1	7	8	10	4
40	Apr	−28	5	32	−9	117	11	−16	83	−111	−3	80	8	−3	−0	−2	−3
	May	−13	10	−7	−102	−4	−51	−24	−23	7	−43	1	8	6	1	13	−1
	Jun	31	−4	−5	−41	151	24	−5	−28	7	59	81	39	21	−2	0	2
	Jul	−6	−17	41	23	−7	−8	−1	−13	−6	15	144	−21	−1	38	−1	80
	Aug	−49	−3	27	54	11	11	−9	−43	5	−38	44	22	0	14	4	2
50	Apr	−13	6	69	11	173	12	−39	67	26	19	44	−2	−5	3	−1	0
	May	22	1	−29	−110	−13	−85	−42	5	−51	11	−7	4	4	−3	9	−15
	Jun	78	24	−71	−21	86	−17	0	−30	0	22	13	8	1	2	0	2
	Jul	−1	25	3	19	2	1	−17	−55	−4	5	23	0	0	11	1	17
	Aug	9	23	−16	41	−6	−24	+16	−6	4	−2	−1	9	3	9	−1	−7
60	Apr	20	−2	−3	−13	68	11	−19	11	16	12	2	1	24	0	−7	−1
	May	−3	−1	−70	−96	5	−49	−12	2	−16	−1	−9	0	−6	0	−4	−5
	Jun	36	19	−34	−68	26	−28	−8	−2	0	−2	−15	2	−2	−1	6	2
	Jul	−18	29	13	16	2	13	5	−13	−8	−6	6	2	12	2	0	1
	Aug	12	23	−19	20	−2	3	−23	−27	6	−3	3	1	1	2	1	0
70	Apr	−3	−8	17	3	−3	5	2	8	−2	0	−1	−1	0	0	−1	1
	May	−12	3	−48	−58	−5	−11	−5	1	4	1	0	0	0	0	0	1
	Jun	5	−2	−8	−5	−7	−21	0	0	0	−3	0	−1	0	1	0	0
	Jul	−22	21	12	3	−5	−2	1	4	0	−2	3	0	0	1	0	2
	Aug	−11	5	14	−22	5	7	−8	2	−1	−6	0	−1	0	0	0	3

Unit : 10^{17} gm m^2 sec^{-2} mb^{-1}

At 70°N, the difference is small in all months.

B. *Contribution by short waves to the momentum transport* — The contribution by short waves at 20°N is more northward in 1967 than in 1972 during April to June. In July the difference is small.

At 30°N, the transport is more northward in 1967 than in 1972 during April to August. The transport is even southward in April and May 1972 as seen in Fig. 3 and Table 2.

At 40°N, the transport is generally northward, but no appreciable difference is observed in both the years.

At 50°N, it is more northward in 1967 than in 1972 in April. However, it is more southward in 1967 than in 1972 in May. In other months, two years do not differ significantly.

At 60°N the transport is similar in all the months.

At 70°N the transport in both years is very small in all the months.

C. *Contribution by all the waves to the momentum transport*—The contribution by all the waves shows similar features as shown by long waves in all the months.

Our findings are qualitatively in agreement with the work of Wiin Neilson *et al.* (1964) who obtained northward transport of momentum at the lower and middle latitudes in April and July at 300-mb level and southward transport at the higher latitudes.

D. *Contribution by long waves during two month period*—The contrast seen during the total period clearly perceptible in the beginning of this period itself. As there could possibly have some long range forecasting value if such trends is observed in other years also. For example, the transport of momentum during the two month period April-May and June-July are shown below at 300-mb level at latitudes 30°N, 40°N, 50°N, 60°N. The contrast between the two years 1967 and 1972 is very clear.

Contribution (unit : 10^{17} gm m^2 sec^{-2} mb^{-1}) by wave Nos. 1-4 at 300-mb level are :

	30°N	*40°N*	*50°N*	*60°N*
Apr-May 1967	451	57	128	—14
Apr-May 1972	325	—76	—93	—137
Jun-Jul 1967	189	199	80	22
Jun-Jul 1972	63	—64	—54	—34

More years should be studied to confirm the trend.

4.4. *Monthly transport of momentum in the wave regime*

4.4.1. *Monthly transport of momentum at 700-mb level*

It is observed that the wave Nos. 1 to 4 are contributing maximum to the transport and the contribution by the wave Nos. 5 to 10 is less.

In the lower latitudes (20°N, 30°N) the wave Nos. 1 and 2 transport momentum southward in July and August, but it is northward at higher latitudes. The wave No. 3 is prominent and transport is northward. However, the two years do not seem to be much different.

4.4.2. *Monthly transport of momentum at 300-mb level*

Table 3 gives the monthly transport at 300-mb level. The wave Nos. 1 to 4 are prominent. The wave Nos. 1 and 3 are very prominent during April and June. The transport by the wave No. 3 at all latitudes is very much northward in 1967 than in 1972 during April and June.

The wave No. 2, however, transport momentum southward at the lower latitudes (20°N, 30°N) during June to August in these years. Fig. 4 and Table 3 illustrate the above inferences.

The transport of momentum at 20°N and 30°N due to wave Nos. 6 and 7 is more northward in 1967 than in 1972 during April to June (*see* Fig. 5 and Table 3). The wave No. 6 is more prominent in 1967 at 40°N which is shown in Table 3.

4.5. *Comparison with the normal year*

We have obtained the transport of momentum using 5-year normal height data from Free university of Berlin normal chart (Scherhag and Mitarbeiter 1969). We have used phase and amplitude values obtained earlier (Awade *et al.* 1975).

The transport of momentum at 300 mb in 1967 and 1972 is much more northward than the normal for most of the waves during the period April to August but its magnitude is small, for the year of drought in 1972.

The transport of momentum due to long, short and all the waves do not differ much from the normal at 700 mb. However, in comparison with the normal there was larger transport of northward momentum at 300-mb level in April and June 1967 than during the corresponding months of 1972.

The wave Nos. 1 and 3 are very much above normal at low latitudes in 1967 than in 1972 during April and June.

5. **Conclusions**

The study of meridional transport of momentum by standing eddies during the period April to August of 1967 and 1972 leads to the following conclusions :

(*i*) The difference in the transport of momentum between two years are far more marked at 300-mb level than at 700-mb level.

(*ii*) The planetary scale waves (wave Nos. 1 to 4) contribute far more than the smaller waves (wave Nos. ⩾5) towards the momentum transport.

(*iii*) The wave Nos. 1 and 3 are very much prominent in April and June at 300-mb level. The transport by the wave No. 3 is very much northward at this level in 1967 than in 1972 in the month of April and June at all latitudes.

The higher wave Nos. are prominent in a good monsoon year.

(*iv*) For the total period April to August there is much more northward transport of momentum in a year of good monsoon (1967) than in a year of poor monsoon (1972) at 300-mb level in the lower and middle latitudes.

(*v*) The contribution from wave Nos. 1 to 4 at 300-mb level at various latitudes in two months period April and May is more in 1967 than in 1972 and persist in next two month period June and July. This may be of some forecasting value.

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