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Dynamics of the large-scale tropospheric circulation during summer monsoon and tropical droughts

S. T. AWADE, M. Y. TOTAGI, S. M. BAWISKAR and D. R. SIKKA
Indian Institute of Tropical Meteorology, Pune

सार — वर्ष 1967, 1972, 1973, 1974 एवं 1977 के अप्रैल से अगस्त तक के महीनों का 700 मि० बार एवं 300 मि० बार की भूविभव उच्चता के मासिक माध्यों का फोरिए विश्लेषण किया गया है । 1967, 1973 और 1977 के वर्ष अच्छे मानसून वर्ष तथा 1972 और 1974 के वर्ष सूखे के वर्ष थे । फोरिए गुणांकों से संवेग एवं संवेदी ऊष्मा के गमन एवं तरंग से तरंग और तरंग से जोन की अन्योन्य क्रियाओं की गणना तरंग संख्या डोमेन के रूप में की गई है ।

1 से 3 तक की संख्या वाली तरंगें अच्छे और खराब मानसूनी वर्षों में विरोधी गुणों को दर्शाती है । अच्छे मानसूनी वर्षों में उप-उष्ण-कटिबंधीय प्रदेशों के आरपार उत्तर की ओर संवेग का गमन अधिक होता है जबकि खराब मानसूनी वर्षों में संवेदी ऊष्मा का उत्तर की ओर गमन अधिक होता है । सूखे के वर्षों में उप-उष्टकटिबंधों में संवेदी ऊष्मा के अभिवाह का अपसरण अधिक होता है, जबकि अच्छे मानसूनी वर्षों में संवेग का अपसरण अधिक होता है । ऊपरी क्षोभमंडल में अच्छे मानसूनी वर्षों में मानसून के महीनों में तरंग से तरंग अन्योन्य क्रियाओं एवं तरंग से जोन के माध्य प्रवाह की अन्योन्य क्रियाओं के माध्यम से तरंग संख्या 1 एवं 2 अन्य तरंगों की तुलना में ऊर्जा के बड़े स्रोत हैं ।

ABSTRACTS. Fourier analysis has been used for monthly mean geopotential height for 700 mb and 300 mb levels for the months April through August for the years 1967, 1972, 1973, 1974 and 1977. The years 1967, 1973, 1977 are good monsoon years and 1972, 1974 are drought years. From the Fourier coefficients the transport of momentum and of sensible heat, wave to wave and wave to zonal interactions have been computed in wave number domain.

Waves 1 to 3 show contrasting features in years of good and bad monsoons. Northward transport of momentum across subtropical latitudes is large in good monsoon years while northward transport of sensible heat is large in bad monsoon years. In drought years there is large divergence of flux of sensible heat in subtropics, while there is large divergence of momentum in good monsoon years. In good monsoon years waves 1 and 2 are greater source of energy to other waves *via* both wave-wave interactions and wave to zonal mean flow interactions during monsoon months in the upper troposphere.

1. Introduction

Indian summer monsoon is a component of the planetary scale monsoon during the northern hemispheric summer season. Planetary scale monsoon is brought about and maintained by the redistribution of heat sources in which the differential heating between continents and oceans plays a dominant role.

In this study we wish to seek answers to the following questions :

(*i*) What is the year to year variability in the large scale dynamics of northern hemisphere on the monthly mean scale from spring season to summer season ?

(*ii*) Is the year to year performance of the Indian monsoon on seasonal scale (June-September) related to the large scale exchange of sensible heat, momentum and wave-wave and wave-zonal energy ?

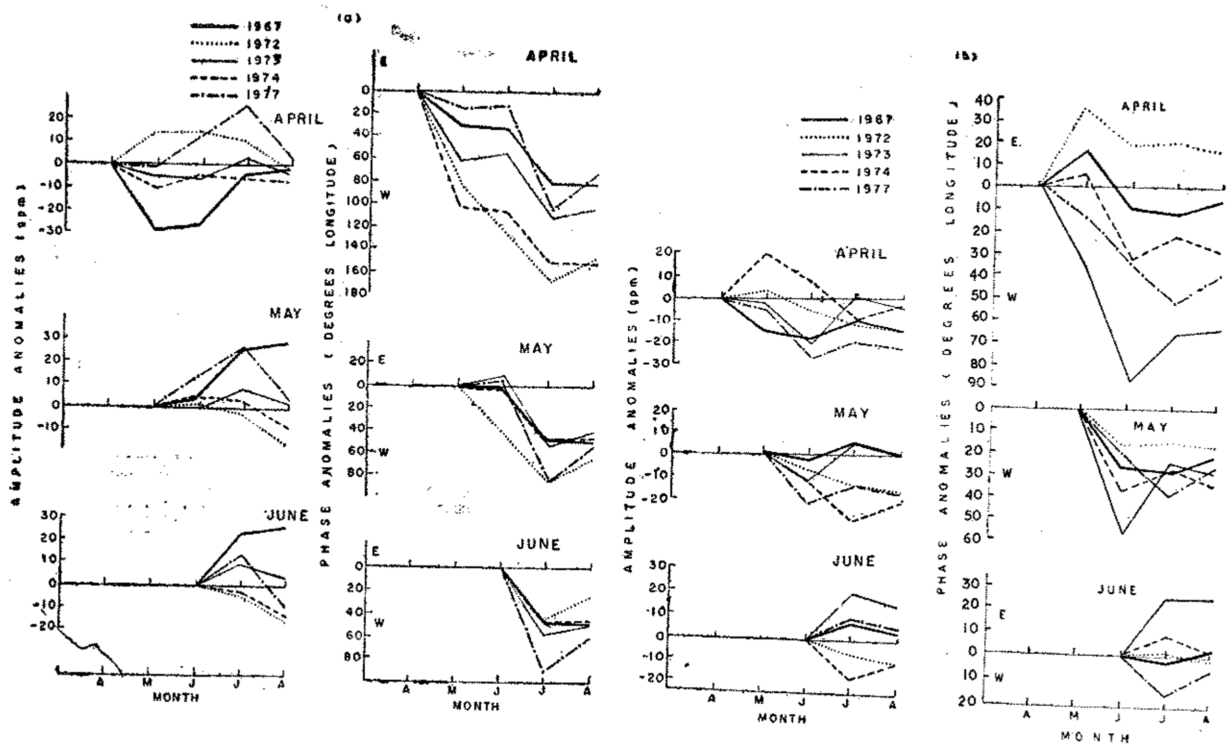
(*iii*) Are there any signatures in the exchange of these physical quantities during April or May (before the commencement of the summer monsoon) which foretell about the performance of monsoon rains ?

(*iv*) Alternatively does the poor performance of monsoon rain itself affect the large-scale energetics as the monsoon circulation is a major anomaly over the northern hemispheric general circulation ?

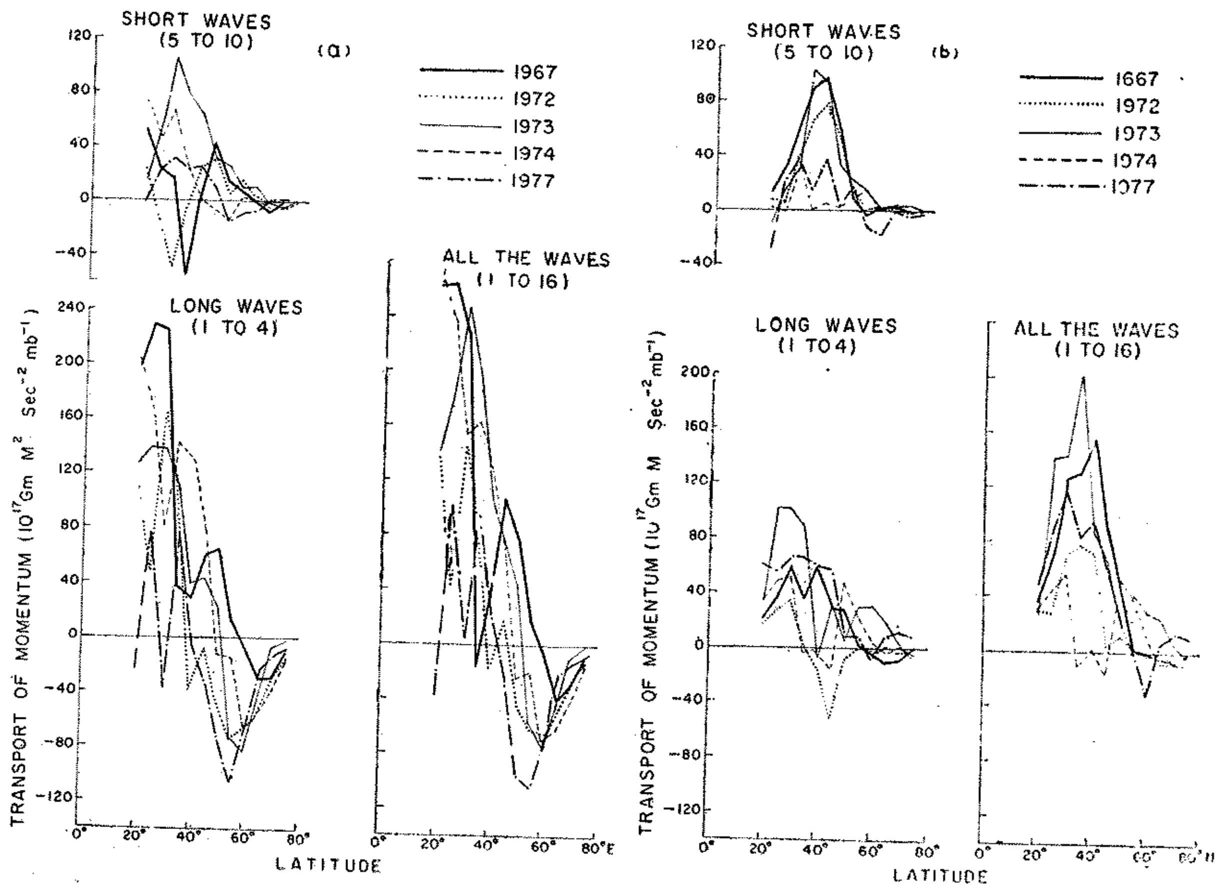
2. Data and method of analysis

Monthly mean northern hemispheric geopotential height data at the levels 700 mb and 300 mb for the years 1967, 72, 73, 74 and 77 for the months April to August have been subjected to Fourier analysis. Of these 1967, 73, and 77 correspond to good monsoon condition over India. The years 1972 and 74 correspond to drought years.

April and May are pre-monsoon months and June, July and August are monsoon months in India. The contour height data at 5 deg. latitude/longitude intervals is the basic data picked from charts published by



Figs. 1 (a & b). Amplitude and phase anomalies from a month for (a) Wave No. 1 at 30° N at 300 mb level and (b) Wave No. 2 at 300 mb across 30°N



Figs. 2 (a & b). Average meridional transport of momentum by standing eddies at 300 mb contributed by long, short and all the waves during period (a) April-May and (b) June-August

German Free University and the Russian Hydrometeorological Service. The height field is symmetrical with respect to the equator.

(a) Computation of flux of momentum and of sensible heat

We have used the geostrophic approximation for winds. We restrict our study to the region between latitudes 20 deg. N and 70 deg. N. The method of computation of these values is given below :

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

$$R_m = \sqrt{a_m^2 + b_m^2} \;;\; \epsilon_m = \frac{1}{m}\tan^{-1}\frac{b_m}{a_m} \quad (2)$$

$$[\overline{u}^* \overline{v}^*] = -\frac{g^2}{4\Omega^2 a^2 \sin^2\phi\cos\phi}\left[\overline{\frac{\partial z}{\partial\lambda}}^* \overline{\frac{\partial z}{\partial\phi}}^*\right] \quad (3)$$

$$\simeq \frac{g^2}{4\Omega^2 a^2 \sin^2\phi\cos\phi}\sum_{m=1}^{16}\frac{1}{2}m^2 R_m^2 \frac{\partial\epsilon_m}{\partial\phi} \quad (4)$$

$$\text{Flux of momentum} = \frac{2\pi a^2\cos^2\phi}{g}\int_{p_1}^{p_2}[\overline{u}^* \overline{v}^*]\,dp \quad (5)$$

$$[\overline{v}^* \overline{T}^*] = -\frac{g_p^2}{2\Omega a R\sin\phi\cos\phi}\left[\overline{\frac{\partial z}{\partial\lambda}}^* \overline{\frac{\partial z}{\partial p}}^*\right] \quad (6)$$

$$\approx \frac{g_p^2}{2\Omega a R\sin\phi\cos\phi}\sum_{m=1}^{16}\frac{1}{2}m^2 R_m^2 \frac{\partial\epsilon}{\partial p} \quad (7)$$

$$(R_m)_{500} = \frac{(R_m)_{300} + (R_m)_{700}}{2} \quad (8)$$

$$\left(\frac{\partial\epsilon_m}{\partial p}\right)_{500} = \frac{(\epsilon_m)_{300} - (\epsilon_m)_{700}}{300 - 700} \quad (9)$$

$$\text{Flux of sensible heat} = \frac{2\pi a\cos\phi}{g}\int_{p_1}^{p_2} c_p [\overline{v}^* \overline{T}^*]\,dp \quad (10)$$

WHERE,

- [ ] AVERAGE OVER LAT CIRCLE
- * DEVIATION FROM AVERAGE OVER LAT CIRCLE
- — MONTHLY TIME AVERAGE
- Ω ANGULAR VELOCITY OF THE EARTH
- R_m AMPLITUDE OF m^{th} WAVE
- ϵ_m PHASE OF m^{th} WAVE
- p_2-p_1 PRESSURES AT HIGHER AND LOWER LEVELS RESPECTIVELY

OTHER SYMBOLS HAVE USUAL MEANING

(b) Kinetic energy equation in the wave number domain

Using the same symbols as Saltzman (1970), the energy equation for eddy kinetic energy can be written as :

$$\frac{\partial K(n)}{\partial t} = -M(n) + L(n) + C(n) - D(n)$$

$$(n = 1, 2, 3, \ldots\ldots) \quad (11)$$

$K(n)$ gives the total KE in eddies of wave number n, $M(n)$ indicates the rate of transfer of kinetic energy between the zonally-averaged flows and eddies of wave number n. $L(n)$ indicates the flow of kinetic energy transfer to eddies of wave number n from eddies of all wave numbers.

The $C(n)$ term represents the conversion of eddy available potential energy to eddy kinetic energy for wave number n. Since data for vertical velocity is not available $C(n)$ is not computed. Similarly terms in $M(n)$ and $L(n)$ containing vertical velocities are not computed.

We have obtained these terms for two regions, *i.e.*, 20-40 deg. N and 20-70 deg. N.

TABLE 1

Monsoon performance

	Year				
	1967	1972	1973	1974	1977
Percentage departure or rainfall from normal	—0.3	—24.3	4.6	—12.2	4.9

3. Results

3.1. *Amplitude and phase*

Figs. 1 (a & b) give anomalies in amplitude and phases from a month for waves 1 & 2 at 300 mb level across 30 deg. N.

Waves 1 and 2 are prominent and contrast between good and bad monsoon years is prominent at 300 mb level across 30 deg. N. The enhancement in amplitude in each month is estimated with reference to previous months. In years of good monsoon activity, the enhancement for wave 1 is positive and large in June to August while in bad monsoon years it is negative.

The phase changes for wave 1 from April indicate that the ridge position moves more westward in bad monsoon years than in good monsoon years. The movement is similar from May but less westward. However, phase change from June shows more westward movement of ridge line in good monsoon years than in bad monsoon years.

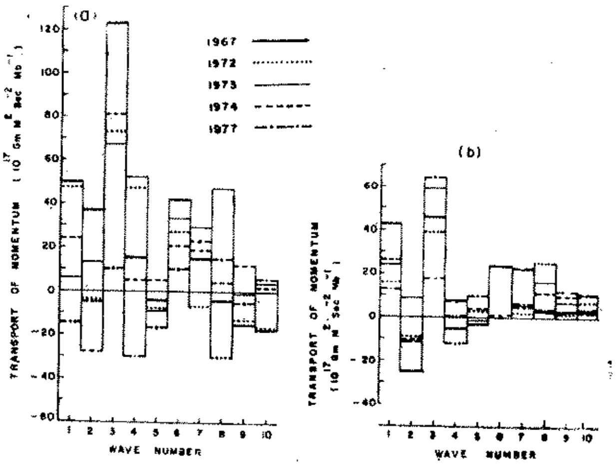
Amplitude anomalies for $m=2$ at 30 deg. N during June to August in comparison with May show similar trend as shown by wave 1 but less intense.

3.2 *Meridional transport of angular momentum during periods April to May and June through August at* 300 *mb level*

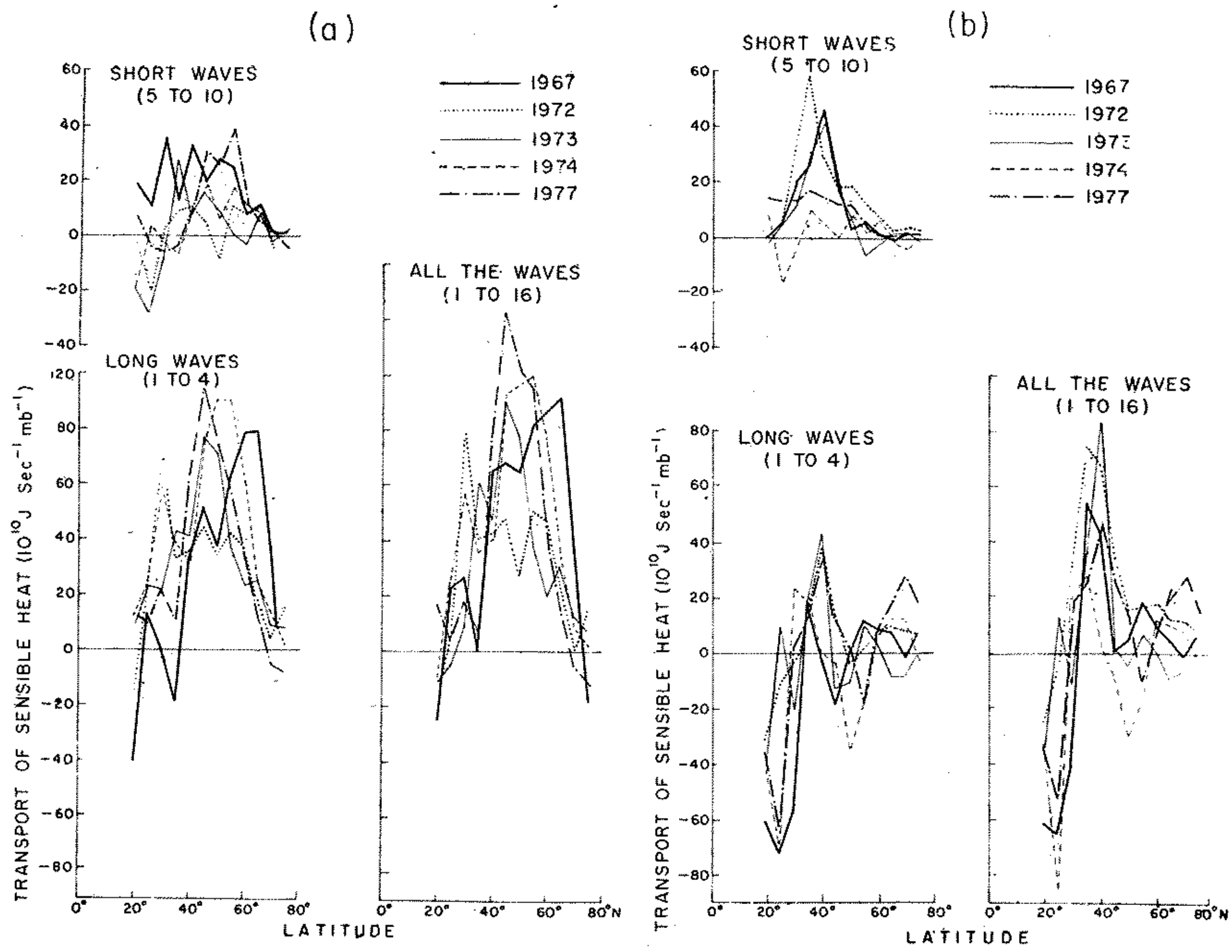
We have obtained the transport at levels 700 mb and 300 mb. However, the contrast is significant at 300 mb level. Hence we present the results for 300 mb level.

Fig. 2 and Table 2 give the transport during the periods April to May and June through August at 300 mb level contributed by long, short and all the waves. Fig. 3 gives the transport in wave number domain across 30 deg. N at 300 mb level.

The contribution by long waves (waves 1 to 4) to the momentum transport at 300 mb level is northward



Figs. 3 (a&b). Average meridional transfer of momentum by standing eddies as 300 mb across 30°N during (a) April-May and (b) June through August in wave number domain



Figs. 4 (a & b). Average meridional transfer of sensible heat by standing eddies at 500 mb contributed by long, short and all the waves during the period (a) April-May and (b) June-August

TABLE 2

Momentum transport across 30° N at 300 mb

Period and year	Waves 1-4	Waves 5-10	Waves 1-16
April to May			
1967	225	17	228
1972	163	—49	145
1973	137	105	245
1974	81	65	155
1977	—37	31	5
June through August			
1967	59	62	127
1972	34	39	69
1973	101	30	143
1974	52	34	57
1977	67	38	117

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

TABLE 3

Sensible heat transfer across 30° N at 500 mb

Period and Year	Waves 1-4	Waves 5-10	Waves 1-16
April to May			
1967	2	36	27
1972	71	3	79
1973	22	—9	10
1974	59	—3	57
1977	21	—6	18
June through August			
1967	—57	20	—39
1972	—4	36	31
1973	—21	12	—11
1974	23	—4	21
1977	2	13	18

Unit : 10^{10} J sec^{-1} mb^{-1}

between 20 deg. N and 40 deg. N during April to May. At 60 deg. N and beyond, the transport is southward. However, the transport during the year 1977 is southward across 20 deg. N to 70 deg. N (Fig. 2a).

The transport by short waves (waves 5 to 10) is generally northward at all latitudes. The transport by all the waves is northward between latitudes 20 deg. N to 40 deg. N. It is more northward in good monsoon than in bad monsoon.

Waves 1 to 4 are contributing significantly at subtropical latitudes to the momentum transport for all the years during April to May at 300 mb level (Fig. 3a). Larger waves (6, 7, 8) also contributed more northward transport in good monsoon years.

The contribution during June through August by long waves to the transport between latitudes 20 deg. N and 30 deg. N is northward and it is maximum across 30 deg. N (Fig. 2b). The transport is more northward in good monsoon years than in bad monsoon years. The contribution is southward at high latitudes (beyond 60 deg. N). However, the magnitude is small. There is a significant contribution by short waves at subtropical latitudes. The integrated effect of all the 16 waves shows more northward transport at subtropical latitudes (30 deg. N) in good monsoon years than in bad monsoon years. Our findings are qualitatively in agreement with those of Wiin-Nielson *et al.* (1964) who obtained northward transport of momentum at subtropics and middle latitudes in April and July at 300 mb level and southward transport at high latitudes.

Waves 1 and 3 are prominent at 30 deg. N during June to August in all these years (Fig. 3b). The transport by wave 3 is very much northward in good monsoon years than in bad monsoon years at this latitude. Wave 2 generally transports momentum southward. Waves 6 to 10 contribute to the northward transport in all these years.

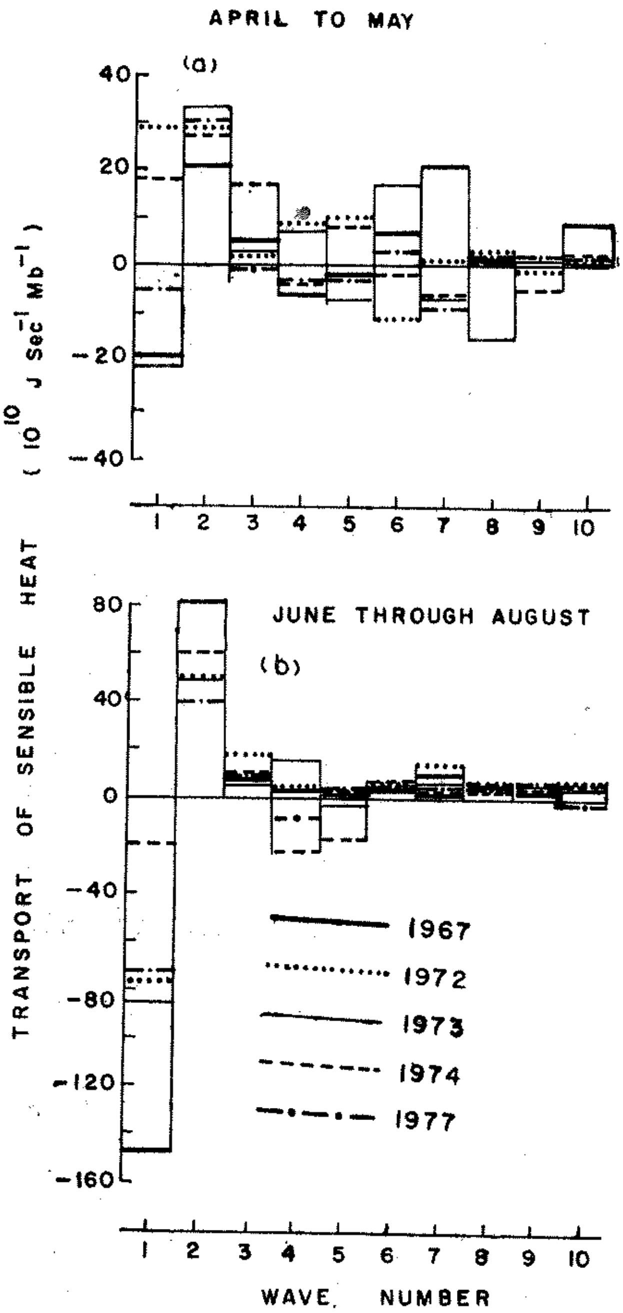
3.3. *Meridional transport of sensible heat during periods April to May and June through August at 500 mb level*

The transport of sensible heat was obtained using equation (10) at 500 mb level during pre-monsoon (April to May) and monsoon months (June through August) for waves 1 to 16 for various years. The transport by standing eddies contributed by long waves, short waves and all the waves are computed at 5-degree latitude interval from 20 deg. N to 70 deg. N. Fig. 4 and Table 3 give the transport by long, short and all the waves. Fig. 5 gives the transport in wave number domain across 30 deg. N at 500 mb. Fig. 6 gives the vertical tilt at 30 deg. N and 60 deg. N during July month for waves 1 and 2.

(*a*) *Transport during the period April to May at 500 mb level*

The transport of sensible heat by long waves during April to May is northward from 30 deg. N to 70 deg. N in all these years (Fig. 4a). It is significantly more northward at subtropics in bad monsoon years than in good monsoon years. The contribution by short waves is not significant except during the year 1967. The contribution by all the waves shows that at subtropics there is more northward transport in bad monsoon years than in good monsoon years. In bad monsoon there are two maxima, one at 30 deg. N and another around 55 deg. N. However, in good monsoon year there is one maximum around 50-60 deg. N.

Wave 1 at 30 deg. N during April to May contributes to the southward transport in good monsoon



Figs. 5 (a & b). Average meridional transport of sensible heat by standing eddies at 500 mb across 30° N in wave number domain

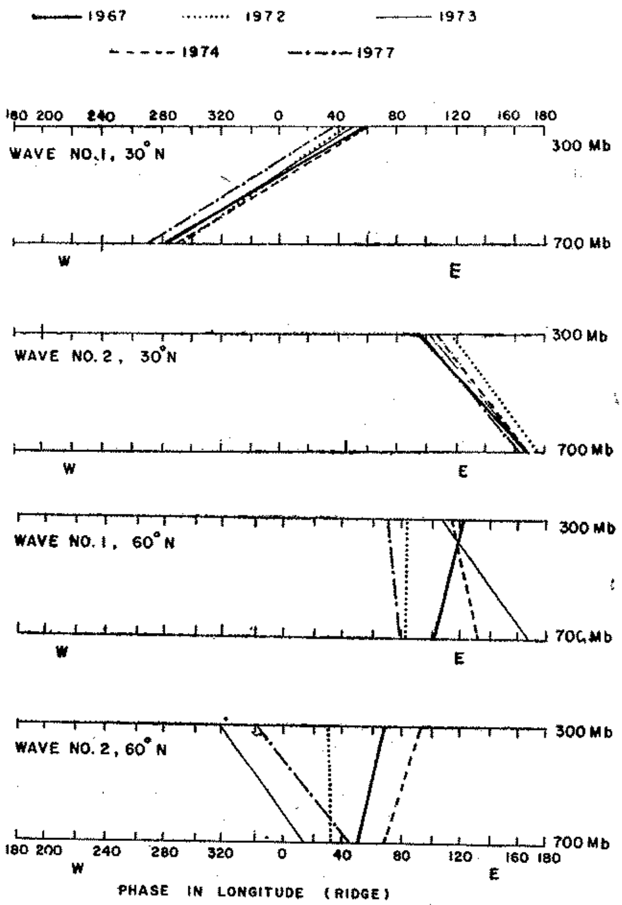


Fig. 6. Vertical tilt at 30° N and 60° N during July month

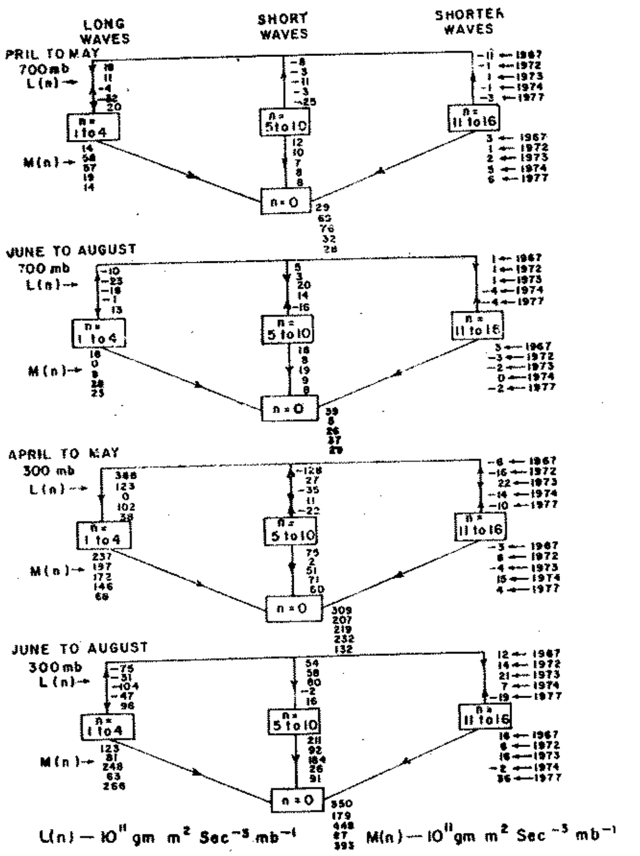


Fig. 7. Average energy exchange between waves $L(n)$, between waves and zonal flows $M(n)$, between 20° & 70° N due to long wave, and short wave and shorter waves during period April to May and June to August at 700 and 300 mb levels

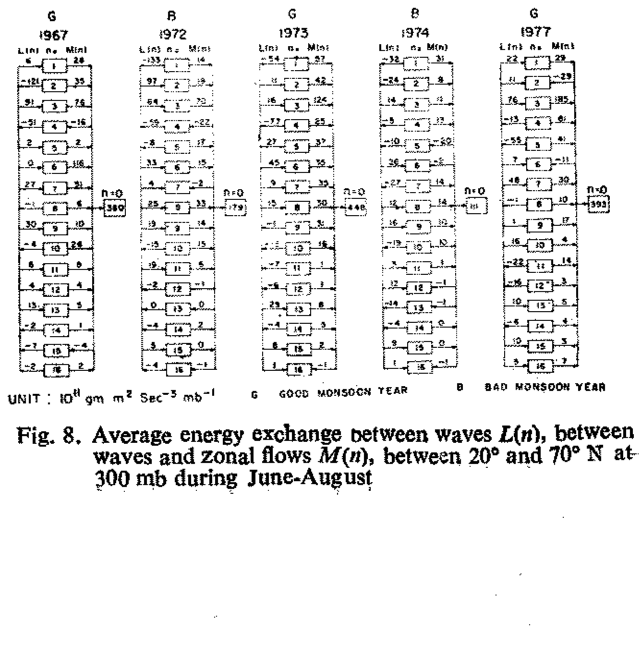


Fig. 8. Average energy exchange between waves $L(n)$, between waves and zonal flows $M(n)$, between 20° and 70° N at 300 mb during June-August

years but northward transport in bad monsoon years (Fig. 5a). The contribution by wave 2 is northward. Total contribution by other waves is small in all these years.

(*b*) *Transport during June through August at* 500 *mb level*

The transport of sensible heat by long waves (waves 1 to 4) between latitudes 20 deg. N and 30 deg. N is southward in all these years (Fig. 4b). It is more southward in good monsoon years than in bad monsoon years. It is northward at 40 deg. N and southward at 50 deg. N. Beyond 60 deg. N the transport is small.

The transport due to short waves (waves 5 to 10) is northward from 20 deg. N to 70 deg. N. The contribution by short waves is significant in the region 30 deg. N to 40 deg. N. At high latitudes the magnitude is small.

Integrated effect of all the waves (waves 1 to 16) at 20 deg. N gives southward transport. At 30 deg. N the transport is northward and it is more northward in bad monsoon years than in good monsoon years. At 40 deg. N the transport is northward. Beyond 40 deg. N, the contribution is small. There are two maxima. One stronger around 40 deg. N and another weak around 60 deg. N.

There is more divergence of heat from the subtropics in bad monsoon years than in good monsoon years. Bad monsoon activity is thus associated with divergence of heat and consequent weakening of meridional temperature gradient in the tropics in summer. In extratropics sensible heat flux devergence is larger in good than bad monsoon years.

Wave 1 across 30 deg. N contributes to southward transport during June to August (Figs. 5b and 6). It is more southward in good monsoon years than in bad monsoon years. Wave 2 contributes to northward transport in these years. Waves 3 to 10 contribute to northward transport.

3.4. *Wave-wave and wave-zonal energy exchanges during the periods April to May and June through August*

Fig. 7 represents the wave-wave and wave-zonal energy exchange contributed by long, short and shorter waves at 700 mb and 300 mb levels during the periods April to May and June through August. Fig. 8 depicts these energy exchanges contributed by each wave at 300 mb level during period June through August between latitudes 20 deg. & 70 deg. N. These values are more marked at 300 mb level than at 700 mb. We discuss in detail these exchanges at 300 mb level only.

(a) *Wave-zonal energy exchange during the periods April to May and June through August at* 300 *mb level*

Long waves (waves 1 to 4) and short waves (waves 5 to 10) transfer energy to zonal flow during periods April to May and June through August. During the period June through August long waves and short waves transport more energy to zonal mean flow. The contribution by shorter waves (waves 11 to 16) is insignificant. In earlier section we obtain northward transfer of momentum against U-gradient. This agrees with kinetic energy transfer from waves to zonal mean flow.

Waves 1, 3 and 4 contribute to zonal flow during the period April to May. Waves 1 and 3 contribute significantly to zonal flow during June through August. This agrees with Murakami (1981) for the regions (14.8 deg. N to 30.8 deg. N) at 200 mb level.

(b) *Wave-wave energy exchange during the periods April to May and June through August at* 300 *mb level*

Long waves (waves 1 to 4) receive the energy at 300 mb level from other waves *via* wave-wave interactions during the period April to May. However, there is no contrast in good and bad monson years. Short waves (waves 5 to 10) generally supply energy to other waves. Magnitude is small for shorter waves (waves 11 to 16). During the period June to August at 300 mb level, planetary scale standing waves 1 to 4 behave as source to kinetic energy to other waves. They lose more energy in good monsoon years than in bad monsoon years.

Waves 1 and 2 lose more energy to other waves, *via* wave-wave interactions and to zonal flow during the period June through August in good monsson years than in bad monsoon years. These waves are greater source for other waves and for zonal mean flow.

4. Conclusions

(1) Enhancement in the amplitude of waves 1 and 2 from pre-monsoon to monsoon months are larger in good than in bad monsoon years.

(2) The contrast is significant across 30 deg. N at 300 mb level.

(3) Northward transport of momentum in subtropics is weaker in drought years than in good monsoon years in pre-monsoon and monsoon months but sensible heat is larger in drought years than in good monsoon years. This may be of forecasting value.

(4) Waves 1 to 3 show contrasting features during years of good and bad monsoon activity.

(5) In drought years, there is large divergence of flux of sensible heat in subtropics while there is less flux of divergence of momentum when compared with good monsoon years.

(6) This leads to the weaker temperature gradient in the drought years than in good monsoon years. The westerly becomes stronger in mid-latitudes and easterly in tropics in good monsoon than in bad monsoon.

(7) In subtropics there is large divergence of flux of momentum and large convergence of momentum in mid-latitudes.

(8) Behaviour of sensible heat flux divergence in subtropics is in contrast with behaviour in extra tropics.

(9) During the period June through August long and short waves transfer more energy to zonal mean flow in good monsoon years than in bad monsoon years. They are greater source of kinetic energy to other waves in good monsoon years than in bad monsoon years.

(10) Major contribution of wave-wave and wave-zonal energy exchange is from the region 20 deg. N to 40 deg. N.

References

Lorenz, E. N., 1966, Computations of the balance of angular momentum and poleward transport of heat : Observational studies of the atmospheric general circulation, Scientific Report No. 2, Planetary Circulations Project, Dept. of Met. M. I. T., pp. 32-65.

Murakami, T., 1981, Summer mean energetics for standing and transient eddies in the wave number domain, *Monsoon Dynamics*, Edited by James Lighthill & Robert Pearce, Cambridge University Press, pp. 65-80.

Saltzman, B., 1970, Large-scale atmospheric energetics in the wave-number domain, *Rev. Geophys. Space Phys.*, **8**, 2, pp. 289-302.

Wiin-Nielson, A., Brown, J. A. and Drake, M., 1964, Further studies of energy exchange between the zonal flow and the eddies, *Tellus*, **16**, 2, pp. 168-180.