Indian J. Met. Hydrol. Geophys. (1978), **29**, 1 & 2, 163-169

551·553·21 : 551·511·32

Monitoring of semi-permanent troughs and ridges in relation to monsoon

G. C. ASNANI

University of Nairobi, Nairobi, Kenya

and

S. T. AWADE

Indian Institute of Tropical Meteorology, Poona

ABSTRACT. Two contrasting years (1967 and 1972) have been selected for intensive study in respect of large scale features of northern hemispheric contour field. In the present study, 700 and 300 mb mean monthly contours at different latitude circles at 5 degree interval, were subjected to Fourier analysis and horizontal and vertical tilts of troughs and ridges determined. At and north of 20°N, under quasi-geostrophic assumption, computations have been made to calculate meridional transports of momentum by tilted troughs and ridges at 700 and 300 mb levels and meridional transport of sensible heat at 500 mb level. The following chief results have been obtained.

(*i*) The differences in momentum transport during the two contrasting years were far more marked at 300 mb level than at 700 mb level.

(*ii*) In a year of good monsoon (1967), there was an anomaly of northward transport of momentum across sub-tropical latitudes while in a year of poor monsoon (1972), there was anomaly of southward transport of momentum across the subtropical latitudes, at 300 mb level.

(*iii*) During a year of good monsoon (1967), there was anomaly of southward transport of sensible heat across the sub-tropical latitude of 30°N at 500 mb level, while in a year of poor monsoon (1972), the anomaly was in the form of northward transport.

(*iv*) The anomalies in the transports of momentum and sensible heat during 1967 and 1972 were perceptible about a month before the onset of monsoon over India. If this be true also for other years which have not been studied here, then there is a possibility of foreshadowing large-scale behaviour of the Indian monsoon one month or so ahead of the arrival of the monsoon.

(*v*) In terms of the anomalies in meridional transports of momentum and sensible heat across the sub-tropical latitudes, we present a model of abnormal monsoon in India. If the summer tropical atmosphere is warmer (cooler) than normal, the monsoon rainfall over India is likely to be more (less) than normal. This is shown to be in broad agreement with what is presently known about the theory of monsoon and observations of short-period anomalies in the behaviour of the Indian monsoon.

We are aware that no firm conclusions can be drawn on the basis of study which extends to only two contrasting years. However, the study has led to the formulation of a model which appears physically sound and also which is in agreement with the well-known observations of short-period anomalies in the behaviour of the Indian monsoon. We can present it with some element of confidence.

2. Data

We used the monthly mean northern hemispheric constant pressure charts published by the Free University of Berlin for the years 1967 and 1972 (Scherhag and Miturbeiter 1967, 1972). The grid point values were picked at intervals of 5 degrees latitude and longitude from the equator to the north pole at levels 700 and 300 mb for each of the months April to August. The 72-grid point values at each latitude were subjected to harmonic analysis for wave numbers 1 to 16.

Under quasi-geostrophic approximation, the horizontal tilt of the troughs and ridges at 700 and 300 mb levels can be interpreted in terms of meridional transport of momentum. The veritical tilt between 700 and 300 mb levels can be interpreted in terms of meridional transport of sensible heat at 500 mb level. Since there can be valid objections to quasi-geostrophic approximation in the near-equatorial region, we confined ourselves to the region from latitude 20°N to 85°N.

The flux of angular momentum across a latitude circle by standing eddies is given by

$$\frac{2\pi a^2 \cos^2 \phi}{g} \int_{p_1}^{p_2} \left[\bar{U^*} \ \bar{V^*} \right] dp$$

where,

$$\left[\overline{U^*} \ \overline{V^*}\right] = - \frac{g^2}{4\Omega^2 a^2 \sin^2\phi \cos \phi} \left[\frac{\partial \bar{z}}{\partial \lambda} \ \frac{\partial \bar{z}}{\partial \phi} \right]$$

$$\approx \frac{g^2}{4\Omega^2 a^2 \sin^2 \phi \cos \phi} \sum_{m=1}^{16} \frac{1}{2} \ m^2 R_m^2 \ \frac{\partial \xi_m}{\partial \phi}$$

m is the wave number at latitude ϕ; R_m is the amplitude of the wave and ξ_m is the phase of the wave. Other symbols have the usual meaning. p_1 and p_2 are the pressures at the upper and lower levels respectively. Square brackets indicate zonal average; bar indicates time average and star indicates eddy quantity.

TABLE 1

Northward transport of angular momentum at 300 mb by standing wave numbers 1 to 4.

(Units : 10^{17} gm m^2 sec^{-2} mm^{-1})

Latitude	Period	1967	1972
40°N	April-May	57	−76
40°N	June-July	199	−64
30°N	April-May	451	325
30°N	June-July	186	63

The flux of sensible heat across a latitude circle due to standing eddies is given by

$$\frac{2\pi a \cos \phi}{g} \int_{p_1}^{p_2} c_p \left[\bar{V^*} \ \bar{T^*} \right] dp$$

where,

$$\left[\bar{V^*} \ \bar{T^*} \right] = - \frac{g^2 p}{2\Omega \ a R \sin \phi \cos \phi} \left[\frac{\partial \bar{z}}{\partial \lambda} \ \frac{\partial \bar{z}}{\partial p} \right]$$

$$\approx \frac{g^2 p}{2 \ \Omega \ a R \sin \phi \cos \phi} \sum_{m=1}^{16} \frac{1}{2} \ m^2 R_m^2 \ \frac{\partial \xi_m}{\partial p}$$

3. Results

For each month, we got several numbers representing meridional transports of momentum and heat by different wave numbers at different latitudes and we endeavoured to see if some coherent picture could emerge out of this multitude of numbers. The following results emerged.

3.1. *Meridional transport of angular momentum*

(*i*) The differences between the years 1967 and 1972 were far more marked at 300 mb level than at 700 mb level.

(*ii*) Planetary scale waves (wave numbers 1 to 4) contributed far more than smaller waves (wave number ⩾ 5) towards the transport of angular momentum.

(*iii*) Table 1 gives the northward transports of angular momentum at 300 mb level by wave numbers 1 to 4, during the periods indicated.

Between 1967 and 1972, there were marked contrasts at both the sub-tropical latitudes 30°N and 40°N. At 30°N, the transports were northward during both the years, but the transports

TABLE 2

Northward transport of sensible heat at 500 mb level at 30° N, by standing wave numbers 1 to 10

(Unit : 10^{10} Joules sec^{-1} mb^{-1})

Period	1967	1972
May	—25	74
June	—21	—8
July	—27	66
August	—63	36

were significantly more during 1967 than during 1972. At 40°N, even the directions of transport were different, being northwards during 1967 and southwards during 1972.

As stated in section 1 above, we do not have good "normal" values of meridional transports of momentum. Hoping that the "normal" values lie somewhere between the values of these two extreme years 1967 and 1972 we can speak of positive anomaly in the northward transport of momentum across sub-tropical latitudes during 1967 and negative anomaly during 1972. In other words, the anomaly consists of northward transport of momentum at 300 mb during 1967 and southwards transport during 1972.

(*iv*) This type of anomaly was seen during April-May, *i.e.*, before the onset of monsoon and persisted during the monsoon also.

3.2. *Meridional transport of sensible heat*

(*i*) Unlike the case of momentum transport, the contribution by wave numbers 5-10 is not very small compared to the contribution of wave numbers 1-4 in respect of sensible heat transport. The contribution by still larger wave numbers (11 to 16) is however negligible.

(*ii*) Table 2 gives the northward transports of sensible heat at 500 mb level at 30°N, by wave numbers 1 to 10, during the periods indicated.

Again there are marked contrasts during the years 1967 and 1972. At 30°N, the transport of sensible heat was mainly southwards during 1967 and northwards during 1972. As before, in the absence of good "normal" values of meridional transports of sensible heat, we hope that the "normal" values lie samewhere between the values of the two extreme years 1967 and 1972 and we can then speak of positive anomaly in the northward transport of sensible heat across sub-tropical latitudes during 1972 and negative anomaly during 1967.

(*iii*) This type of anomaly was seen during May, *i.e.*, before the onset of the monsoon and persisted during the monsoon also.

4. Model of the normal and the abnormal monsoon

In subsections 4·1 and 4·2, we present models of the normal and abnormal monsoon in India.

4.1. *Model of the normal monsoon in India*

4.1.1. Monsoon is essentially caused by the annual cycle of diabatic heating and cooling (Asnani and Mishra 1975).

(*i*) The summer heating causes :

(*a*) low pressure area in the lower troposphere and

(*b*) high pressure area in the middle and upper troposphere.

The low-level low pressure area generally coincides with the ITCZ/near-equatorial trough.

(*ii*) Frictional inflow into low pressure area and outflow from high pressure area causes vertical upwards motion.

(*iii*) In the presence of moisture, this upward motion causes monsoon rains.

4.1.2. This annual cycle of diabatic heating and cooling is accompanied by an annual cycle in all the elements of global circulation including :

(*i*) intensity of meridional cells (Equatorial cell, Hadley cells, Ferrel cells and Polar cells)

(*ii*) ITCZ/near-equatorial troughs, Sub-tropical ridge, Polar front } lying in near east-west direction

(*iii*) Semi-permanent troughs and ridges lying in near north-south direction.

4.1.3. These semi-permanent troughs and ridges along with the migratory systems of each season, including the monsoon season, act as transport agents for meridional exchanges of heat, momentum, moisture, etc between the tropical and extratropical regions. These transport agents maintain a delicate balance in the atmosphere.

4.1.4. In the tropics, semi-permanent troughs and ridges make much greater contribution in these meridional transports than do the migratory ones. In middle latitudes, the relative importance of the semipermanent systems and the migratory systems gets reversed.

4.1.5. No particular monsoon season is a "normal monsoon" season. The "normal monsoon" is an idealised season in which all weather elements, over all regions, at all times of the season, have the so-called "normal" values, equal to the arithmetic average of the time series at each place in the monsoon region.

In actual situations, we find more-than-normal rainfall in some places, less-than-normal rainfall at other places. Then we consider area averages and time averages and accept some reasonable departures, say ± 10 per cent from the normal as constituting the normal monsoon season.

What is true for rainfall is also true for all other meteorological elements like wind, temperature, humidity, cloudiness, sunshine, etc.

Anomalies in rainfall can easily be measured. The influence of anomalous rainfall on agricultural economics of tropical countries is so marked that in practice, anomalies in monsoon are denoted by anomalies in rainfall.

4.2. *Model of the abnormal monsoon in India*

4.2.1. If the summer tropical atmosphere is warmer than normal, the intensity of the following phenomena is more than normal :

(*a*) low pressure area in the lower troposphere,

(*b*) high pressure area in the middle and upper troposphere,

(*c*) vertical upward motion in the region of ITCZ/near-equatorial trough and

(*d*) rainfall in the region of ITCZ/near-equatorial trough.

4.2.2. If the summer tropical atmosphere is colder than normal, the intensity of these phenomena is less than normal.

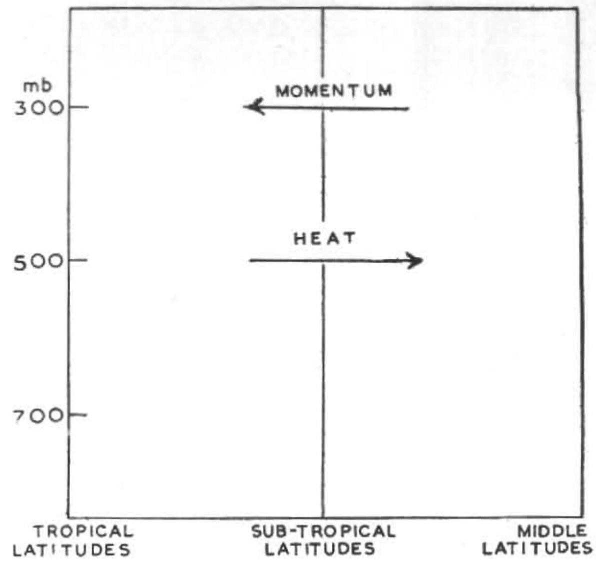

Fig. 1. Model of a drought summer monsoon in India in terms of anomalies in transport of angular momentum and sensible heat

4.2.3. This anomalous heating of the tropical atmosphere can come about by any one or more of the following anomalies :

(*i*) Anomalies in the in-coming solar radiation.

(*ii*) Anomalies in the albedo.

(*iii*) Anomalies in the out-going terrestrial radiation.

(*iv*) Anomalies in the meridional transport of sensible heat from the tropical regions to the extra-tropical regions.

(*v*) Anomalies in the sea-surface temperature.

4.2.4. In terms of anomalous transports of sensible heat and momentum, the model of a drought summer monsoon is given in Fig. 1. During a drought summer season, more than normal heat is transported from tropics to mid-latitude region across the sub-tropical region ($\sim$30°N) as shown in Fig. 1. This is accompanied by the following events :

(*i*) Monsoon "low" in the lower troposphere in southeast Asia has lower-than-normal intensity. There are positive pressure anomalies over India in respect of mean sea level pressure. The lower tropospheric westerlies over the south Indian Peninsula are weaker than normal. Lower tropospheric cyclonic vorticity is less than normal.

(*ii*) Upper tropospheric "high" over southeast Asia becomes less than normal in intensity. The upper tropospheric easterlies associated with the easterly jet stream may become weaker than normal. This ties well with the anomalous equatorial flux of westerly momentum across the sub-tropical latitude in the upper troposphere as shown in Fig. 1.

(*iii*) The intensity of the Hadley cell circulation becomes less than normal. Rainfall activity over the tropical plains becomes less than normal.

(*iv*) In association with excess heat going from tropics to middle latitudes, the temperature gradient between the tropical and extra-tropical regions is reduced. Zonal westerly flow in the middle latitudes becomes one of low zonal index and blocking highs. This also ties in well with the anomalous transport of westerly momentum from middle latitudes to the tropical regions as shown in Fig. 1, creating weaker-than-normal westerlies in middle latitudes and weaker-than-normal easterlies in the tropical upper troposphere. The anomaly in the tropical upper tropospheric easterlies is not confined to Indian region only but is clearly seen as far as East Africa. Table 3 shows the easterly component of upper tropospheric winds over Nairobi (01°18′S, 36°45′E) during July of 1967, 1972 and 1976. It may be remarked that although we chose 1967 as a year of good monsoon in India, the year 1976 was also equally a year of good monsoon in India.

The differences in Nairobi are most striking at 150 mb level which is close to the level of the easterly jet stream.

(*v*) Due to anomalies in the temperature and wind structure of the troposphere, the seasonal troughs and ridges in the tropical and sub-tropical troposphere find new geographical positions of quasi-equilibrium. In other words, there are anomalies in the positions and intensities of the seasonal troughs and ridges. These anomalies have their regional variations and can cause excess rainfall over limited areas while the over-all activity of the Hadley cell circulation becomes below normal.

TABLE 3

Easterly component (knots) of upper tropospheric winds over Nairobi during July

Level	Year		
	1967	1972	1976
100 mb	9·8	8·6	8·1
150 mb	29·5	0·0	32·7
200 mb	12·5	6·1	20·2

5. Short period fluctuations in the intensity of the Indian monsoon

Anomalies pointed out in section 4.2 above have generally been observed during the short period "strong" and "break" monsoon conditions over India. For example, break monsoon conditions over India are characterised by :

(*a*) shift of the monsoon trough towards the foot of the Himalayas in the lower troposphere and its disappearance in the middle troposphere (Ramamurthy 1969),

(*b*) displacement in the position and decrease in the intensity of the Hadley type circulation over the Indian region,

(*c*) southward penetration of middle latitude westerlies and western disturbances near north India (Pisharoty and Desai 1956),

(*d*) southwards shift of middle and upper tropospheric subtropical ridge over India (Rao 1976) and

(*e*) low index circulation over central Asia north of the Himalayas (Ramaswamy 1962).

It appears that the anomalies seen during short period are similar in nature to the anomalies seen in monthly mean charts during years of abnormal monsoon season as a whole.

6. Conclusions

(*i*) In the absence of accurate 'normal' global upper air patterns, a study of the global upper air patterns during contrasting years like 1967 and 1972 is an acceptable way to get an idea of the large-scale anomalies (departures from normal) in the global flow patterns.

(*ii*) Large-scale and persistent anomaly in the monsoon activity over India is just one symptom of the large scale and persistent anomalies in the global general circulation of the atmosphere.

(*iii*) During a year of poor monsoon season like 1972, there is an anomaly in the sub-tropical latitudes (~30° N) in the form of northward transport of sensible heat in the middle troposphere and southward transport of of westerly momentum in the upper troposphere. The reverse happens during a year of good monsoon in India like 1967.

(*iv*) In terms of these anomalies, a model of abnormal monsoon in India is presented. If the summer tropical atmosphere is warmer (cooler) than normal, the monsoon rainfall over India is likely to be more (less) than normal. This anomalous heating of the tropical atmosphere could come about by any one or more of the following anomalies :

(*a*) anomalies in the in-coming solar radiation,

(*b*) anomalies in the albedo,

(*c*) anomalies in the out-going terrestrial radiation,

(*d*) anomalies in the meridional transport of sensible heat from the tropical regions to the extra-tropical regions,

(*e*) anomalies in the sea-surface temperature, etc.

(*v*) The anomalies in the meridional transports of sensible heat and momentum during 1967 and 1972 were perceptible about a month before the onset of monsoon over India. If this be true also for other years which have not yet been studied, then there is a possibility of foreshadowing large-scale behaviour of the Indian monsoon one month or so ahead of the arrival of the monsoon.

(*vi*) The anomalies studied here are derived from the horizontal and vertical tilts of the seasonal troughs and ridges as seen on mean monthly charts. Study of the position and intensity of these troughs and ridges on charts averaged over periods smaller than a month is also likely to give us some insight into the mechanism of monsoon fluctuations over corresponding smaller periods.

REFERENCES

Asnani, G. C. and Mishra, S. K. 1975 *Mon. Weath. Rev.*, **103**, pp. 115-130.

Pisharoty, P. R. and Desai, B. N. 1956 *Indian J. Met. Geophys.*, **7**, pp. 333-338.

Ramamurthy, K. 1969 Some aspects of the 'break' in the Indian southwest monsoon during July and August, India met. Dep., FMU, Rep. **IV**. 18.

Ramaswamy, C. 1962 *Tellus*, **14**, pp. 337-349.

Rao, Y. P. 1976 *Southwest Monsoon*, India met. Dep. Met. Monogr., Synop. Met. 1/1976.

Scherhag, R. and Miturbeiter 1967 Institute of Meteorology and Geophysics, Free University of Berlin, Band **78**, Heft 1-12.

1972 *Ibid.*, Band **128**, Heft 1-12.

DISCUSSION

(Paper presented by G. C. Asnani)

J. SHUKLA : You have related momentum and heat transports over the whole northern hemisphere to monsoon rainfall over India. What has the whole hemispheric transport to do with Indian monsoon ?

AUTHOR : I regard the monsoon oscillation as global oscillation. Indian monsoon anomalies are related to the anomalies in the global circulation.

COMMENT

P.R. PISHAROTY : I am happy to see that the abnormalities in the trends of momentum and heat fluxes are noticeable in the months April-May.

AUTHOR : Thanks. I hope such features would be observed in other years. Then they would have forecasting value.