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Moisture flux and vergence of water vapour over India during drought and good monsoons

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सार — भारत में अनावृष्टि तथा अच्छे मानसून के दौरान जल-वाष्प अभिवाह तथा आर्द्रता के झुकाव की गणना की गई है। देश में कुल आर्द्रता झुकाव भी मालूम कर लिया गया है। 00 तथा 12 ग्री० मा० स० प्रेक्षणों के आधार पर अभिवाहों और झुकावों में दैनिक परिवर्तनों का मूल्यांकन किया गया है। इन दो वर्षों में प्राप्त परस्पर विरोधी लक्षणों पर विचार-विमर्श किया गया है।

ABSTRACT. Water vapour flux and vergence of moisture during drought and good monsoon seasons over India have been computed. The net moisture vergence over the country have been obtained. The diurnal variations in the fluxes and vergence based on 00 and 12 GMT observations have been evaluated. The contrasting features between the two years are discussed.

1. Introduction

According to the principle of conservation of mass, the water content in the atmosphere can neither be created nor destroyed. Any local change of water content can be brought out only through the addition or subtraction. The necessity for the transport of water content in the atmosphere arises from the fact that there are areas of excess precipitation over evaporation with a reversal of them in certain other parts of the world. The excess or deficit must be made of through the transport of water by atmospheric circulations, since there can be no significant inflow or outflow of water in the atmosphere as a whole (Starr *et al.* 1958). The transports may be in any one of the three phases, *i.e.,* solid, liquid or vapour and by zonal and meridional atmospheric circulations. Among the three phases the vapour phase is the most important.

In India, studies on the water vapour transport are reported by many authors (Raghunathan 1961, Pisharoty 1965, Sikka and Mathur 1965, Saha 1970, Saha and Bavadekar 1973, 1977; Ghosh *et al.* 1978, 1981; Bavadekar and Mooley 1978; Datta and Dewan 1975; Appa Rao and Ramanamurthy 1977). Some of the studies are confined to the Arabian Sea and west coast of India, whereas others have dealt with the main land India. In the present study, an attempt has been made to compute the water vapour flux over different parts of the country and the vergence of moisture over India during two contrasting monsoon seasons. The monsoon seasons of 1966 and 1967 are chosen to represent drought and good monsoon rains over the country (Appa Rao 1981) respectively.

2. Data used

Daily aerological data obtained from the eleven radiosonde stations of the country (Fig. 1) have been used for the study. Computations have been made at each station from surface/1000 mb to 650 mb at an interval of 50 mb. 00 and 12 GMT data are used to obtain the diurnal variations. The computations are carried upto 650 mb only. This is due to large scale missing data above 650 mb level and also rather small amount of water vapour content present in the atmosphere above 650 mb. This point is to be taken into consideration while discussing the results of the study.

3. Method of analysis

The method is mainly based on the studies reported by Starr *et al.* (1958, 1966), Peixoto (1960) and Parker (1970). The total horizontal flux of water vapour above a point on the surface of earth in (λ, ϕ, p, t) co-ordinate system has been computed. The two dimensional vector field is given as :

$$\mathbf{F}(\lambda, \phi) = \frac{1}{g} \iint q.\,\mathbf{V}\,dp\,dt \qquad (1)$$

where p is pressure in vertical co-ordinate, λ longitude, ϕ latitude, q specific humidity and t the interval of time. The respective zonal and meridional components are given as :

$$F_\lambda = \frac{1}{g} \iint q.\,u\,dp\,dt \qquad (2)$$

and

$$F_\phi = \frac{1}{g} \iint q.\,v\,dp\,dt \qquad (3)$$

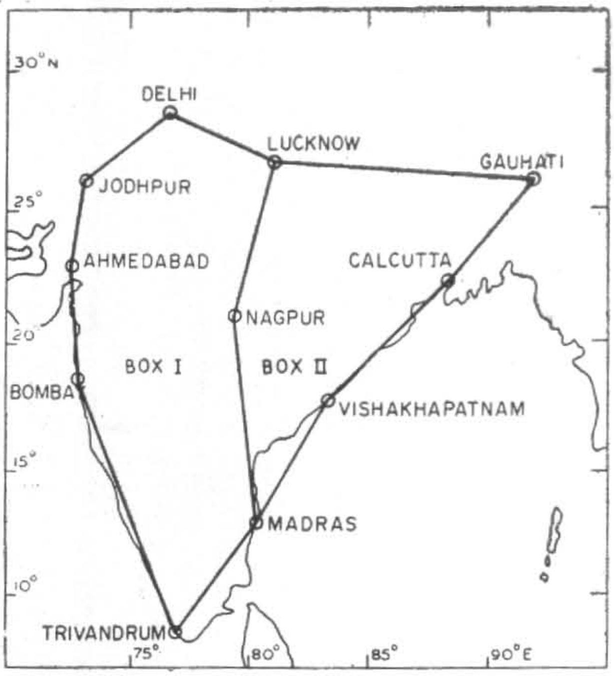

Fig. 1. Radiosonde stations constituting a triangular box

where 'u' and 'v' are zonal and meridional wind components, which are positive eastward and northwards respectively.

Eqns. (1), (2) and (3) are averaged with respect to time over the interval t the mean values are given as $\overline{F_\lambda}$, $\overline{F_\phi}$, where bar denotes

$$\overline{(\ )} = \frac{1}{t}\int (\ )\ dt$$

Eqns. (2) and (3) are further split-up to obtain mean and eddy components as :

$$F_\lambda = \overline{F_\lambda} + F'_\lambda$$

$$F_\phi = \overline{F_\phi} + F'_\phi$$

The transports by 'mean' or 'standing' fields are given as :

$$\overline{F_\lambda} = \frac{1}{g}\int \bar{q}.\ \bar{u}\ dp \qquad (4)$$

$$\overline{F_\phi} = \frac{1}{g}\int \bar{q}.\ \bar{v}\ dp \qquad (5)$$

and eddies as :

$$F'_\lambda = \frac{1}{g}\int q'.\ u'\ dp \qquad (6)$$

$$F'_\phi = \frac{1}{g}\int q'.\ v'\ dp \qquad (7)$$

The country is considered as a triangular box (Fig.1) with the west coast and east coast as entry and exit sides. The Himalayas are considered as lid, with an assumption that there is no inflow or outflow of the flux across the lid. This box is further subdivided into two parts along 80° E. The fluxes are computed resolving the wind components parallel and normal to each section of the box which are vertically integrated. The moisture outflow across 80° E in Box I is taken as the inflow into the Box II. While computing the net divergence or convergence from (into) any of the boxes, the inflow is assigned positive sign and the outflow negative sign. The net vergence in each box is obtained by summing up all the fluxes entering and leaving the sections of the box. The sections finally considered are as follows :

Trivandrum-Bombay, Bombay-Ahmedabad, Ahmedabad-Jodhpur, Madras-Nagpur, Nagpur-Lucknow, Trivandrum-Madras, Madras-Visakhapatnam, Visakhapatnam-Calcutta, Calcutta-Gauhati.

4. Results

(a) *Vertically integrated moisture flux*

The vertically integrated total moisture flux from surface to 650 mb crossing each side of the box have been computed with the help of station values. The orientation and the length of the each side of the box (based on individual cross sections) are taken into account in the final computations. The results obtained for 00 and 12 GMT data given in Table 1.

It is seen from the Table 1, that eddies over individual sections are generally small by one order of magnitude when compared to mean values. Between 1966 and 1967, considerable changes are seen in the mean daily fluxes along Trivandrum-Bombay, Nagpur-Madras and Madras-Trivandrum sections of Box I and along Nagpur-Madras and Visakhapatnam-Madras sections of Box II. The inflow, which is mainly from Bombay-Trivandrum section is higher in good year compared to drought year. This indicates that there is greater inflow of moisture from west coast into the country, during the good monsoon year. The inflow of moisture along the west coast of India (Trivandrum-Bombay-Ahmedabad sections) was about 0.83 units (29 per cent) more in 1967 over 1966 value.

(b) *Vergence of moisture flux*

Based on the fluxes crossing each side of the boxes, the total moisture vergence has been computed. It is seen that there is a net divergence in Box I and convergence in Box II during the two years under consideration. The good monsoon year shows higher divergence (0.356 units) in Box I and convergence (0.34 units) in Box II than the drought year. The net convergence by mean component is always higher by one or two orders of magnitude over the eddy in all cases, except during 00 GMT of 1966. Also, the mean net convergence of 1966 is small compared to 1967 in Box I, suggesting that there is more outflow in 1967

TABLE 1

Moisture flux across sections (in 10^{10} metric tons per day) during monsoons of 1966 & 1967

Cross-section	1966						1967					
	00 GMT		12 GMT		Mean day		00 GMT		12 GMT		Mean day	
	Mean	Eddy	Mean	Eddy	Mean	Eddy	Mean	Eddy	Mean	Eddy	Mean	Eddy
Box I												
TRV-BMB	2.050	+0.033	2.323	+0.073	2.186	+0.053	2.739	+0.056	3.096	+0.031	2.917	+0.043
BMB-AHD	0.747	+0.031	0.695	+0.040	0.721	+0.035	0.773	+0.005	0.864	—0.006	0.818	0.000
AHD-JDP	0.380	—0.010	0.311	—0.012	0.345	—0.011	0.230	—0.040	0.285	—0.024	0.257	—0.032
LKN-NGP	—0.612	0.002	—0.692	—0.023	—0.652	—0.012	—0.087	+0.002	—0.511	+0.044	—0.659	+0.023
NGP-MDS	—1.408	0.001	—1.464	—0.009	—1.436	—0.004	—2.054	+0.009	—2.256	—0.003	—2.155	+0.003
MDS-TRV	—1.245	0.021	—1.350	+0.001	—1.297	+0.011	—1.717	+0.000	—1.618	+0.003	—1.667	+0.001
Conv.	—0.088	0.078	—0.177	+0.070	—0.133	+0.072	—0.836	—0.032	—0.140	+0.045	—0.489	+0.038
Box II												
LKN-NGP	0.612	—0.002	0.692	+0.023	0.652	+0.012	+0.807	—0.002	0.511	—0.044	0.659	—0.023
NGP-MDS	1.408	—0.001	1.464	+0.009	1.436	+0.004	+2.054	—0.009	2.256	—0.003	2.155	—0.003
GHT-CAL	—0.010	+0.019	0.030	+0.033	0.010	+0.026	+0.113	+0.005	0.308	+0.024	0.210	+0.014
CAL-VSK	—0.604	+0.006	—0.405	+0.023	—0.504	+0.014	—0.678	+0.009	—0.231	+0.022	—0.454	+0.016
VSK-MDS	—1.040	—0.008	—1.017	—0.008	—1.028	—0.008	—1.719	—0.007	—1.609	—0.012	—1.664	—0.009
Conv.	0.366	+0.014	0.764	+0.080	0.566	+0.048	0.577	—0.004	1.235	—0.013	0.906	—0.005

Ahmedabad-AHD, Bombay-BMB, Calcutta-CAL, Gauhati-GHT, Lucknow-LKN, Madras-MDS, Nagpur-NGP, Trivandrum-TRV, Visakhapatnam-VSK.

TABLE 2

Diurnal variation of water vapour flux (in 10^{10} metric tons per day), 1200 GMT-00 GMT

Cross-section	1966		1967		1967-1966	
	Mean	Eddy	Mean	Eddy	Mean	Eddy
Box I						
TRV-BMB	+0.273	+0.040	0.357	—0.025	0.084	—0.065
BMB-AHD	—0.052	+0.009	0.091	—0.011	0.143	—0.020
AHD-JDP	—0.069	—0.002	0.055	+0.016	0.124	0.019
LKN-NGP	—0.080	—0.025	0.296	+0.042	0.376	0.067
NGP-MDS	—0.056	—0.010	—0.202	—0.012	—0.146	—0.002
MDS-TRV	—0.105	—0.020	0.099	+0.003	0.204	+0.023
Conv.	—0.089	—0.008	0.696	0.013	0.785	0.022
Box II						
LKN-NGP	0.080	+0.025	—0.296	—0.042	—0.376	—0.067
NGP-MDS	0.056	+0.010	0.202	+0.012	0.146	+0.002
GHT-CAL	0.040	+0.014	0.195	+0.019	0.155	+0.005
CAL-VSK	0.199	+0.017	0.447	+0.013	0.248	—0.004
VSK-MDS	0.023	—0.000	0.110	—0.005	0.087	—0.005
Conv.	0.398	+0.066	0.658	—0.003	0.260	—0.069

over 1966. For the whole country it is a net convergence in both the years. The difference in the values of convergence between the drought and the good monsoon years is small unlike those in the individual boxes.

(c) *Diurnal variation*

00 and 12 GMT values are used to compute the diurnal variations in the flux and the vergence values. The values are given in Table 2. The values are smaller by one order of magnitude compared to the fluxes observed at the synoptic hours. This is particularly so along the west coast, where strong monsoon westerly current exists. The inter annual variability in flux, when considered for the whole country (given in the last two columns of Table 2) is highest along the Lucknow-Nagpur and lowest along Trivandrum-Bombay sections. The net convergence values are comparable in magnitude to those of the fluxes in the boxes. Large variations along Calcutta-Visakhapatnam section may be due to the wind variations.

5. Discussion

The role of moisture flux and the convergence values related to Indian monsoons have been studied by many. Pisharoty (1965) showed that the monsoon current is from the northern hemisphere and the flux is mainly from the Arabian Sea. On the contrary, Saha (1970) indicated that 60 to 70 per cent of monsoon air and moisture is from the southern hemisphere. Saha and Bavadekar (1973) pointed out that cross equatorial

TABLE 3

Daily water vapour flux in 10[10] metric tons computed by various workers, crossing west coast of India

Authors	Moisture	Remarks
Raghunathan (1961)	7.5	Strong monsoon spell
Pisharoty (1965)	5.8	Strong monsoon month (July)
Saha & Bavadekar (1977)	2.75	Mean of nine monsoon seasons
Ghosh *et al.* (1978)	(a) 2.53	Active spell } along 50° E
	(b) 2.45	Weak spell } along 50° E
Present study	(a) 2.92	Good monsoon season 1967
	(b) 2.19	Deficient monsoon season 1966

flux of water vapour on an average is 30 per cent larger than the evaporation over the Arabian Sea. Ghosh *et al.* (1978, 1981) showed that the variations of water vapour flux across the west coast of India are independent of the fluxes across equator and extreme west Arabian Sea. Their study indicated that the important changes in the monsoon circulation takes place over the Arabian Sea but not in the southern hemisphere. Saha and Bavadekar (1977) obtained significant correlations between the fluxes and the rainfall along the west coast of India. These studies suggest that the moisture entering the west coast is an important factor for Indian monsoon rainfall. The moisture flux across the west coast of India computed by different authors for different seasons or spells are given in Table 3. The results indicate that the values are of the same order but differ from the active to weak spells of the monsoon. Datta and Dewan (1975) studied the water potential based on the net moisture influx over India. They observed an increase of moisture by 15 per cent in 1967 (good monsoon year) and decrease of the same by 29 per cent in 1965 (drought year) over the normal value. The present study suggests that the moisture flux along the west coast (mainly Bombay-Trivandrum section) is important. The results obtained now are for two complete seasons (June to September) which consist of weak and strong spells of monsoon activity. They are quite comparable with the mean value obtained by Saha and Bavadekar (1977) based on nine monsoon seasons. The drought year (1966) showed a decrease of moisture by 28 per cent and good year (1967) an increase of moisture by 44 per cent over mean of nine years respectively. Also a strong monsoon month like July (Pisharoty 1965) can contribute 50 per cent of the moisture flux transported during whole season.

In case of mean convergence, the values are higher by nearly three and half times in Box I and by two times in Box II in good year compared to the drought year. Diurnal variations are also higher in the two boxes during the good year.

6. Conclusions

The moisture flux and convergence over India during a pair of contrasting monsoon seasons have been worked out.

The flux by the mean component is highest along the west coast of the country. The contribution by eddies is small compared to the mean fluxes. The good monsoon year is associated with higher convergence and prominent diurnal variations, compared to the drought year.

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References

Appa Rao, G. and Ramanamurthy, Bh. V., 1977, Water vapour transport and vergence patterns over India during two contrasting summer monsoons, *PAGEOPH*, **115**, p. 491.

Appa Rao, G., 1981, Atmospheric energetics over India during drought and normal monsoons, *Mausam*, **32**, p. 67.

Bavadekar, S. N. and Mooley, D.A., 1978, Computation of the average precipitation over the western part of peninsular India during the summer monsoon from the continuity equation for atmospheric water vapour, *Tellus*, **30**, p. 537.

Datta, R. K. and Dewan, B. N., 1975, A study of water potential over India during Monsoon Season, Proc. Second World Congress, IWRA, New Delhi, p. 493.

Ghosh, S. K., Pant, M.C. and Dewan, B. N., 1978, Influence of Arabian Sea on the Indian summer monsoon, *Tellus*, **30**, p. 117.

Ghosh, S.K., Pant, M.C. and Dayal, V., 1981, Air and water vapour transports associated with a Bay of Bengal depression during Monex-79, ICSU/WMO GARP, International Conference on early results of FGGE and large aspects of its monsoon experiments, Florida, USA, p. 11.

Parker, A.E., 1970, An observational study of the meriodional flux of energy and angular momentum in the troposphere and lower stratosphere at latitude 30°N using 1958 IGY data, *Geophys. Memoir*, London, **15**, No. 113.

Peixoto, J.P., 1960, On the global water balance and the hydrological cycle, *Tropical meteorology in Africa*, Munitalp foundation, Nairobi.

Pisharoty, P.R., 1965, Evaporation from Arabian Sea and the India southwest monsoon, Proc. Symp. Met. IIOE, Bombay, p. 22.

Raghunathàn, K.R., 1961, An investigation into the southwest monsoon, Thesis, submitted to Poona Univ. (*Unpublished*).

Saha, K.R., 1970, Air and water vapour transport across the equator in the western Indian Ocean during the northern summer, *Tellus*, **22**, p. 681.

Saha, K.R. and Bavadekar, S. N., 1973, Water vapour budget and precipitation over the Arabian Sea during the northern summer, *Quart. J.R. met. Soc.*, **99**, p. 273.

Saha, K.R. and Bavadekar, S.N., 1977, Moisture flux across west coast of India and rainfall during southwest monsoon, *Quart. J. R. met. Soc.*, **103**, p. 370.

Sikka, D.R. and Mathur, M.B., 1965, Transport of a water vapour over Arabian Sea during active monsoon situation, Proc. Symp. Met. Results of IIOE, Bombay, p. 55.

Starr, V.P., Peixoto, J. P. and Livadas, G.C., 1958, on the meridional flux of water vapour in the northern hemisphere, *Geo. Phys. Appl.*, **39**, p. 174.

Starr, V.P. and Saltzman, B., 1966, Observational studies of the atmospheric general circulation, MIT, Rep. No. 2, Mass., USA.