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Computation of the average precipitation over the western part of peninsular India during the summer monsoon from the continuity equation for atmospheric water vapour

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ABSTRACT

Water vapour fluxes computed across different walls of the triangular volume of peninsular India, bounded by Trivandrum, Bombay and Nagpur, were used to compute the net flux convergence on a monthly mean basis for the months June through September for the years 1967–72. The precipitation rates over the region were computed by using the flux convergence values and the equation of continuity for water vapour and were compared with the actual rainfall. The agreement between the computed precipitation and actual rainfall was found to be fairly close.

1. Introduction

Saha and Bavadekar (1973) computed the water vapour fluxes across different walls of the rectangular volume over the Arabian Sea during the summer monsoon months of 1963 and 1964 and suggested that the major influx of water vapour in the volume over the Arabian Sea was by the cross equatorial flow (i.e. across the wall 42°E to 75° E) and the major outflux was across the section wall parallel to the west coast of India (equator to 26° N).

The onshore fluxes over the west coast of India were further studied by Saha and Bavadekar (1977) for the 9 years 1964–72 for the summer monsoon months and were correlated with the rainfall along the west coast of India and also over peninsular India bounded by Trivandrum, Bombay and Nagpur. The correlation coefficients were 0.87 for the west coast section (Trivandrum to Bombay) and 0.85 for the peninsular region and these were statistically significant at the 1% level. In the present investigation precipitation values computed by the water vapour budget method for western peninsular India are compared with the actual rainfall over the region.

2. Continuity equation of the atmospheric water vapour

The equation of continuity of water vapour used for the computation of the average precipitation rate R_c for the western part of peninsular India is given as:

$$R_c = -\frac{1}{g}\int_{p_t}^{p_b} \nabla\cdot(q\vec{V})dp + E \qquad (1)$$

where

- g is the acceleration due to gravity
- q the mixing ratio of water vapour
- $\vec{V}$ the vector wind
- E the rate of evapotranspiration
- p_b, p_t the pressures at the bottom and top of the section wall, respectively.

The first term on the right-hand side represents the flux convergence of water vapour and contains the contributions due to time mean flow and transient eddies. The sum total of the flux convergence of water vapour and the evapotranspiration E is realized as the average precipitation over the region.

3. Data and methods of analysis

The positions of the radiosonde and pilot balloon stations used for the purpose of computations are shown in Fig. 1. As mentioned before, the data for the summer monsoon months June through September and for the years 1967 to 1972 were used for the computation of water vapour fluxes.

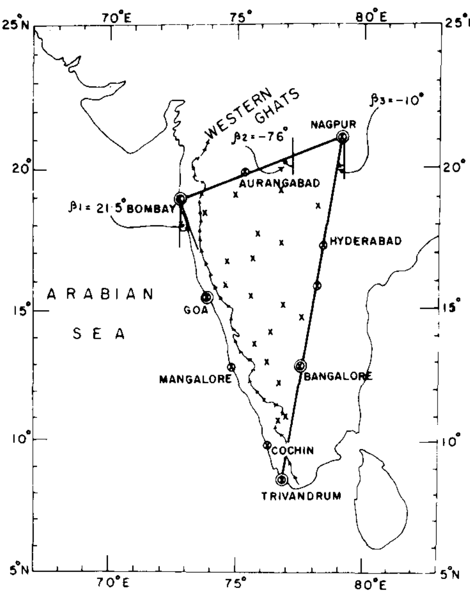

Fig. 1. Triangular portion of peninsular India showing the positions of the radiosonde, pilot balloon and rainfall stations.

The details regarding the sections of triangular region, height of the station above mean sea level, length segments, etc., are given in Table 1.

The top of the section wall was assumed at 450 mb and bottom at the surface of the earth. The pressure interval was 50 mb. The procedure for analysis to fill up the data gap for the moisture parameter, etc., is similar to that given by Saha and Bavadekar (1977).

3.1. *Calculations of moisture flux*

The water vapour fluxes are computed across the section walls of the triangular region (Fig. 1) of peninsular India. The expression for computing the net flux, F_n, normal to the section wall is

$$F_n = \frac{1}{g}\left[\sum_{p_t}^{p_b}\sum_{0}^{L}\{(\bar{u}\bar{q} + \overline{u'q'})\cos\beta + (\bar{v}\bar{q} + \overline{v'q'})\sin\beta\}\,\Delta L\,\Delta p\right] \tag{2}$$

where

- L is the length of the section
- ΔL convenient length segments
- Δp convenient pressure interval
- u, v components of the daily wind velocity, u positive towards the east and v positive towards the north
- β the angle of inclination of the section with the meridian.

Table 1. *Length of the segments used in three sections for the computation of water vapour fluxes*

Stations		Station height above m.s.l. in metres	RS/PB*	Length of segments in km	
Trivandrum to Bombay section	Trivandrum	64	RS	Trivandrum to 14° N	530
	Cochin	03	PB		
	Mangalore	22	PB		
	Goa	55	RS	14° N to Bombay	600
	Bombay	14	RS		
Bombay to Nagpur section	Bombay	14	RS	Bombay to 76° E	330
	Aurangabad	600	PB	76° E to Nagour	310
	Nagpur	300	RS		
Nagpur to Trivandrum section	Nagpur	300	RS	Nagpur to Hyderabad	370
	Hyderabad	600	PB	Hyderabad to Bangalore	450
	Bangalore	950	RS	Bangalore to Trivandrum	450
	Trivandrum	64	RS		

* RS—radiosonde station; PB—pilot balloon station.

Table 2. *Budget of moisture fluxes and actual precipitation (unit: 10^{13} kg day^{-1})*

Month		Year 1967	1968	1969	1970	1971	1972
June	FD	0.24	0.19	0.15	0.59	0.32	0.30
	E	0.16	0.16	0.16	0.16	0.16	0.16
	R_c	0.40	0.35	0.31	0.75	0.48	0.46
	R_a	0.44	0.44	0.41	0.55	0.52	0.41
July	FD	0.53	0.35	0.31	0.47	0.22	0.16
	E	0.17	0.17	0.17	0.17	0.17	0.17
	R_c	0.70	0.52	0.48	0.64	0.39	0.33
	R_a	0.66	0.64	0.58	0.48	0.41	0.40
August	FD	—	0.09	0.06	0.46	0.18	0.26
	E	0.16	0.16	0.16	0.16	0.16	0.16
	R_c	—	0.25	0.22	0.62	0.34	0.42
	R_a	0.27	0.25	0.27	0.62	0.34	0.20
September	FD	−0.02	0.16	—	0.10	0.28	0.10
	E	0.16	0.16	0.16	0.16	0.16	0.16
	R_c	0.14	0.32	—	0.26	0.44	0.26
	R_a	0.24	0.30	0.37	0.27	0.26	0.14

FD: Flux convergence; E: evapotranspiration; R_c: computed precipitation; R_a: actual precipitation.
— Not computed due to lack of data.

The other symbols are explained previously.

Bar and prime denote time mean (i.e. mean for the month) and eddy components, respectively.

Expression (2) can be split into two parts, giving the contributions due to time mean flow and transient fluctuations separately. The contribution due to transient fluctuations is very small and can be neglected.

With the help of computed fluxes normal to the section wall, the flux convergence term is obtained. These values are tabulated in Table 2. If the influx of the water vapour into the triangular volume is greater than the outflux, there is net flux convergence of water vapour and therefore the positive values are interpreted as flux convergence.

3.2. *Estimation of evapotranspiration*

The actual evapotranspiration E over the region was not readily available for the required period. The charts for the potential evapotranspiration PE over the Indian region have been prepared on a monthly basis (Rao et al., 1971). The average daily potential evapotranspiration was estimated from these charts for the monsoon months. The actual evapotranspiration E is obtained by comparing the actual rainfall R_a with potential evapotranspiration and using the following criteria:

$$E = PE; \quad \text{if } R_a > PE$$

and

$$E = R_a - \text{storage rate} - \text{run off} \quad \text{if } R_a < PE$$

In most of the cases R_a was found to be greater than PE, and hence the evaporation was assumed to be at the rate of PE. Year to year variations of E are thus disregarded in this study.

4. Results

From the computation of water vapour fluxes, it is observed that the influx into the area takes place across the sections Trivandrum–Bombay and Bombay–Nagpur. The major contribution is due to to the Trivandrum–Bombay section. The average daily fluxes in this section also show an increasing trend from June to July. The values drop in August and are lowest in September. This is consistent as far as the normal progress of the

Table 3. *Zonal and meridional components of water vapour fluxes for June 1971 and 1972* (*unit:* 10^5 *kg* m^{-1} *day*$^{-1}$)

	Zonal flux (positive towards east)				Meridional flux (positive towards north)			
	June 1971		June 1972		June 1971		June 1972	
	Mean	Eddy	Mean	Eddy	Mean	Eddy	Mean	Eddy
Trivandrum	396.4	−4.1	234.1	7.6	−137.3	2.1	−168.9	1.2
Goa	321.8	−0.7	138.5	6.5	−60.4	4.1	−36.0	11.0
Bombay	350.6	5.0	159.5	−1.9	82.9	8.8	71.8	12.6
Nagpur	255.5	−3.7	82.6	−14.0	−71.5	−4.9	−88.2	22.7
Bangalore	290.3	*	−130.7	*	0.9	*	34.4	*

* Not computed.

monsoon over the country is concerned and is found in almost every year except for the year 1971, when the maximum was found in June. The section Bombay–Nagpur is oriented more or less in the direction of the monsoon flow and has a small normal component to the section wall and hence does not show such systematic behaviour. The outflux given by the Trivandrum–Nagpur section shows systematic behaviour similar to the Trivandrum–Bombay section.

The section Trivandrum–Bombay was also investigated to find out the vertical distribution of water vapour fluxes in various layers from the surface to 450 mb. On an average the maximum contribution of 19% is made by the layer 900 to 850 mb. The layer from the surface up to 700 mb contributes 86% and only 14% contribution is due to the layer above 700 mb. The latter contribution, though insignificant (see also Section 4.2), is comparable to the magnitude of the precipitation.

4.1. *Zonal and meridional fluxes of water vapour*

Zonal and meridional components of water vapour fluxes, both due to time mean flow and transient fluctuations, are presented in Table 3 for the month of June for the years 1971 and 1972. The monsoon behaviour was contrasting in nature for these months. The progress of the monsoon during June 1971 was very rapid, except for the break period during the second week of the month. The monsoon, however, revived in the third week and advanced in north-west India by the last week. The advance of the monsoon during the year 1971 over different parts of the country was generally a week or 10 days ahead of the normal date of onset. In 1972, the south-west monsoon advanced temporarily over the south peninsula towards the end of the second week of May, but again retreated during the third week of May. It revived over Kerala by as late as 18 June. In general the advance of the monsoon over the peninsula and north-west India was delayed by 10 to 15 days in this year.

Comparing the zonal and meridional components of the fluxes, it is observed that the zonal flux was considerably smaller during June 1972 than in June 1971 at all the radiosonde stations. The eddy fluxes are generally small in magnitude. At Bombay the meridional flux is southerly and is weaker during June 1972, whereas the northerly meridional flux, shown by Trivandrum, strengthened in June 1972. Goa, which is in between the two stations, shows the northerly meridional flux to be weaker in magnitude than Trivandrum and Bombay. The orography on the west coast is probably responsible for the typical distribution of meridional fluxes as mentioned above.

4.2. *Flux convergence and precipitation*

The vertical profile of the flux convergence was obtained for all the years but they are presented only for the years 1971 and 1972 in Table 4. There is strong flux convergence in the lower layer up to about 850 mb followed by divergence aloft. the maximum value of flux divergence is near the 800 mb level and then decreases aloft rapidly and even changes sign with small fluctuations. The strong convergence in the lower layer is mostly due to the presence of the orographic barrier (Western Ghats) along the west coast of India.

Table 4. *Values of moisture flux convergence at different isobaric surfaces for the years 1971–1972 (unit: 10^{10} kg day^{-1})*

		Level											
Year		1000	950	900	850	800	750	700	650	600	550	500	450
1971	June		510	250	−076	−168	−089	−063	−033	+019	+021	−019	−009
	July		455	239	−093	−161	−101	−058	−041	−025	−011	−012	−002
	August		379	131	−119	−131	−087	−040	−002	+007	+007	003	001
	September		230	172	035	−064	−048	−035	−014	008	018	022	015
1972	June		232	165	−031	−049	−029	−018	005	001	−008	−010	−015
	July		477	245	−125	−225	−143	−046	−012	−010	−020	−022	−017
	August		393	119	−076	−081	−020	004	017	−020	−037	−017	−004
	September		096	042	−002	−017	009	008	−009	−014	−001	009	009

The west coast stations, therefore, always get more precipitation compared to the stations on the leeward side of the Ghats.

From the comparison of total influx and precipitation it is found that, on an average, about 13% of the total influx over the triangular volume is converted into precipitation. The contribution due to flux convergence is 8% and that due to evapotranspiration is 5%. These figures indicate that abundant moisture supply is available throughout the summer monsoon period but only a small fraction of it is converted into precipitation.

5. Concluding remarks

The budget method of computing the precipitation has some limitations. The limitations are due to the inadequate network of radiosonde stations over the region under consideration and also due to lack of knowledge of the actual evapotranspiration. The flux divergence term is the small difference of two large terms of total influx and outflux and requires proper and careful analysis of wind and mixing ratios. The computed precipitation rates, in spite of these limitations, are fairly close to actual rainfall.

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РАСЧЕТЫ СРЕДНИХ ОСАДКОВ НАД ЗАПАДНОЙ ЧАСТЬЮ ПОЛУОСТРОВА ИНДОСТАН ВО ВРЕМЯ ЛЕТНЕГО МУССОНА С ПОМОЩЬЮ УРАВНЕНИЯ НЕРАЗРЫВНОСТИ ДЛЯ АТМОСФЕРНОГО ВОДЯНОГО ПАРА

Потоки водяного пара через различные поверхности треугольного объема полуострова Индостан, ограниченного Гривандрамом, Бомбеем и Нагпуром, рассчитывались и использовались для расчетов полной дивергенции потока на основе среднемесячных данных для месяцев с июня по сентябрь 1967–72гг. Скорости осадков над этой областью вычислялись при использовании величин дивергенций потока и уравнения неразрывности для водяного пара и сравнивались с реальными осадками. Найдено довольно тесное согласие между вычисленными и реальными осадками.