551·513.1 : 551·553·21(–14)

Some characteristics of the Southwest Monsoon Circulation*

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(*Received 25 October 1960*)

ABSTRACT. The southwest monsoon is probably the largest local perturbation on the general circulation of the atmosphere. Meridional transport of mass, heat energy and angular momentum associated with the southwest monsoon circulation have been computed from the upper air data of Singapore, Nairobi, Madras, Bombay, Nagpur and New Delhi for July and August 1955. In view of the large airflow in lower levels across the equator in this period, mass exchange between the hemispheres is important. At Singapore and Nairobi, both near the equator, compensating southward flow exists at 200- and 600-mb levels respectively. There is still significant net flow northwards at Singapore and southwards at Nairobi, probably representative of the eastern and western sections of the monsoon circulation. In the southwest monsoon area due to the large cloudiness, the solar energy absorbed by the ground and the lower atmosphere decreases appreciably and is in a portion slightly less than the outgoing radiation. There is advective flux of heat from the north into this 'sink'. Necessity and evidence for transport of heat from summer to winter hemisphere is discussed. Angular momentum flows into the monsoon area from the north and more so northwards across the equator at Singapore.

1. Introduction

The southwest monsoon over the Indian sub-continent and neighbourhood is the largest local perturbation that is superposed on the general circulation of the atmosphere. The southwest monsoon circulation extends from 30° to 120°E and from the equator to 30°N. The wind-flow which in a corresponding oceanic area is mainly from the northeast is changed to some westerly flow, upto a height of 5 km to the south of 20° latitude. Monsoon circulations in other parts of the world are not so extensive either horizontally or vertically. Besides, the southwest monsoon circulation induces large flow of air across the equator. Even the northeast monsoon circulation over south Asia appears less prominent, since it does not reverse the normal flow pattern of low latitudes.

The general circulation of the atmosphere has been studied in recent years by Priestley (1951), Starr (1955) and others using measured temperature, humidity and wind data at upper levels. To balance between different latitudes the net gain of radiation from the sun and the angular momentum from the earth, heat must be carried across each of the bounding zones in latitudes 30—35° at the rate of 2×10^7 cal. cm^{-1} min^{-1} and angular momentum at $1{\cdot}0 \times 10^{34}$ g cm^2 sec^{-1} per year equivalent to a stress of $1{\cdot}8 \times 10^8$ dynes/cm. They have tried to find evidence and mechanism of such transport. In the southwest monsoon area the role of the tropics in the general circulation as a source of heat and angular momentum is disturbed. On account of the large cloudiness the solar radiation absorbed in the atmosphere is practically the same as the outgoing terrestrial radiation, if not in slight deficit. Angular momentum is lost by the atmosphere to the earth through friction on account of the surface winds having a westerly component. In view of these changes, the meridional transport of heat and angular momentum during the southwest monsoon has been studied (with the upper air data of Indian stations) using the technique introduced by Priestley. with the data of Singapore and Nairobi, the exchange of mass, heat and angular momentum across the equator is also discussed.

*Received originally on 18 February 1958 for the Symposium on 'Monsoons of the World'

2. Mass Transport across Equator

The meridional mass transport across a unit area fixed in the west-east vertical plane is ρv. Integrating vertically, the mass transport is

$$\int_0^\infty \rho\, v\, dz = \frac{1}{g} \int_0^{p_0} v\, dp, \quad \text{per unit length of the latitude.}$$

The mean meridional components at the various pressure levels indicate the mass transport across any latitude. In view of the known large flow across the equator in the lower layers, it is interesting to know the total mass exchange between the hemispheres in the monsoon area. In this area the equatorial region is mostly covered by sea and upper air data are lacking. However, temperature and wind data reaching upto 100 mb are regularly available from Singapore (1°20′N, 103°53′E) and Nairobi (1°18′S, 36°45′E) at the eastern and western ends of the monsoon circulation. Table 1 gives the mean northward component in the months of July and August 1955 at these stations.

At Singapore the northward transport decreases rapidly by about 700 mb and there is a marked counter-current above 300 mb. At Nairobi the return flow sets in at 600-mb level itself; but above 400 mb the pattern is irregular with other layers of northward flow. Integrating the mass transport between the station level and 100 mb, there is a mean northward flow of 0·7 knots in July and 0·2 knots in August throughout the column at Singapore and southward flow at Nairobi of 0·4 knots in July and 0·8 knots in August. These estimates suffer from not taking into account the flow above the 100-mb level. It thus appears that in the western portion of the southwest monsoon circulation there is a net mass flow southwards across the equator and in the eastern portion (east of 85°E) northwards. Upper wind roses of Addu Atoll published in the climatological charts of the Indian Monsoon area show greater frequency of north winds at 2 and 3 km in July and from 1 km upwards in August. This together with the wind roses of Indian stations west of 85°E suggests that the net flow southwards observed at Nairobi may be representative of the western portion of the monsoon circulation.

Napier Shaw's computations show that the mass of air in the northern hemisphere has a maximum at mid-winter and minimum at mid-summer. Compared to the total amount of air in a hemisphere of about 2700 billion tons, the range of variation is about ten billion tons. In a month there is a net flow of 1·6 billion tons of air across the equator. This is equivalent to total airflow across the equator of 2 nautical miles in a month throughout the vertical extent of the atmosphere. As against the monthly total flow of 2 nautical miles, the mean airflow observed at Nairobi and Singapore is about 0·5 nautical mile per hour. A flow of 1 knot across one degree length of the equator will transport in a month, the entire normal mass exchange between the hemispheres. Hence marked flow of air across the equator should be compensated by reverse flow at some other level or at some other point. It seems that in the southwest monsoon circulation the marked northward flow across the equator in the lower levels is compensated by a return current at higher levels. This return current sets in at the 600-mb level at the western end of the monsoon circulation, but only above 300 mb at the eastern end. The net southward transport in the western portion and northward flow in the east may together maintain balance.

3. Meridional Heat Transport

Tables 2 nd 3 show the meridional 'eddy flux ' of 'sensible heat' and latent heat in July and/or August 1955 at Singapore, Nairobi, Madras, Bombay, Nagpur and Delhi. Table 4 gives the eddy flux, integrated vertically upto the highest level for which data are available. Apparently owing to the small gradients of temperature and mixing ratio the eddy flux is mostly small. Only the eddy flux of latent heat at Delhi is large. This may be due to the greater horizontal gradient of mixing ratio in that region. At Bombay there is significant amount of northward transport of sensible and latent heat, but the much smaller values at Madras and Nagpur suggest that the figures for Bombay may not be representative of conditions to the east of the Ghats in the same latitude.

The advective flux of total energy is large and southwards at Delhi, Nagpur and Madras, but northwards at Bombay. The northward flow at Bombay seems a localized feature. Cursory examination shows that it is southwards also at Aden and Trivandrum, but northwards at Calcutta, Port Blair and Gauhati. It appears that to the west of longitude 85°E there is an appreciable energy transport southwards from the very hot regions of Central Asia, part of which spills across the equator. Owing to the very large cloudiness (about three quarter of the sky) in July in the Indian area, the amount of solar radiation reflected away by the clouds is large and radiation absorbed less. Simpson (1929) had shown that in a part of the monsoon area there is a net loss of radiation. Into this sink energy seems to flow from the north to the west of 85°E and from across the equator to the east of that longitude.

4. Meridional Transport of Angular Momentum

Table 5 shows the 'eddy flux' of angular momentum at Singapore, Nairobi, Madras, Bombay, Nagpur and Delhi.

Though mostly the eddy transport of angular momentum is small, at the level of the easterly jet, there is marked eddy transport northwards of angular momentum at both Singapore and Nairobi. This shows that stronger easterly winds are associated with more northerly component and *vice versa*. Owing to insufficiency of data, the conditions near the jet could not be examined for the Indian stations. Table 6 gives the values of zonal stresses both by eddy and advective flux integrated vertically upto the level upto which data are available.

There is a large transport of angular momentum northwards across the equator at Singapore, but it is negligible at Nairobi. At Delhi there is marked transport southwards. The values at Madras, Bombay and Nagpur may be appreciably modified by taking into account the conditions at the level of the easterly jet. Normally the area south of 30° latitude gains angular momentum from the earth which is transported northwards to compensate the higher latitudes for the momentum lost to the earth. During the southwest monsoon period over a quarter of the tropical belt easterly surface winds are replaced by westerlies and hence becomes a sink for angular momentum. It would appear that there is appreciable flow across the equator in the eastern portions and from the northerly latitudes to compensate for the loss of angular momentum in the southwest monsoon circulation. Eddy mechanism seems effective in transporting appreciable amount of angular momentum though not heat, even in tropical latitudes.

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TABLE 1

Mean northward speed (knot)

		Pressure level (mb)									
		850	800	700	600	500	400	300	200	150	100
Singapore	Jul	3·8		2·8	0·3	0·8	0·0	0·7	—2·4	— 9·7	—4·8
	Aug	6·2		0·3	— 0·1	2·5	0·3	—0·5	—7·8	—16·2	—2·5
Nairobi	Jul		3·4	1.5	— 7·7	—1·7	—1·0	1·5	5·3	0·6	0·3
	Aug		3·7	0·5	—10·3	—1·6	6·0	—0·1	0·5	— 5·2	—1·7

TABLE 2

$\overline{V'T'}$ (proportional to eddy flux of sensible heat)

(units of 10^2 Å × cm/sec)

			Pressure level (mb)										
			900	850	800	700	600	500	400	300	200	150	100
	1955												
Singapore	Jul	(03Z)		—0·1		1·4	1·2	1·0	0·7	0·3	0·5	—2·5	10·4
	Aug	(03Z)		—0·4		0·2	—0·9	—0·2	1·1	—0·6	0·3	—2·3	—2·3
Nairobi	Aug	(03Z)			—2·0	0·2	0·0	5·0	2·7	—1·8	1·5	3·3	4·4
Madras	Jul	(03Z)	0·6		—0·8	—0·4	1·1	—0·4	—2·1	0·6			
		(15Z)	1·3		0·3	—1·1	—0·7	0·0	—1·6	0·8			
Bombay	Jul	(03Z)	0·5		1·3	0·8	2·2	1·8	2·1	2·8	—3·1		
		(15Z)	1·2		0·9	2·6	2·6	1·2	—1·0	2·9	0·8		
Nagpur	Jul	(03Z)	0·4		—0·3	—0·1	—0·9	—0·5	—0·4	—0·8			
		(15Z)	—0·5		—0·3	0·0	0·0	1·0	1.5				
Delhi	Jul	(03Z)	—2·1		—1·9	—1·5	—0·7	2·6	0·2	2·7	0·3		
		(15Z)	—2·1		0·6	—1·1	1·0	6·9	5·3	—1·4	—0·1		

TABLE 3

$L/C_p \times \overline{V'x'}$ (proportional to eddy flux of latent heat)

(units of 10^2 Å × cm/sec)

		Pressure level (mb) 900	850	800	700	600	500	400
	1955							
Singapore	July		−1·0		1·4	2·3	0·9	−0·1
	August		−2·0		0·8	−0·2	−0·5	0·1
Nairobi	August			0·5	−1·0	0·9	−4·0	−1·4
Madras	July (03Z)	1·8		3·3	0·1	−1·0		
	(15Z)	0·3		−2·2	−0·2	0·8		
Bombay	July (03Z)	3·4		4·7	2·3	0·4		
	(15Z)	3·5		3·0	1·1	−1·3	0·2	
Nagpur	July (03Z)	1·9		−0·5	0·5	2·4		
	(15Z)	1·3		2·1	1·9	0·1		
Delhi	July (03Z)	3·3		6·1	9·2	11·4	5·8	
	(15Z)	4·4		2·9	4·4	13·2	2·4	

TABLE 4

Total northward eddy flux of heat

(units of 10^7 cal/cm × min)

	Singapore		Nairobi (August)	Madras (July)		Bombay (July)		Nagpur (July)		Delhi (July)	
	July	August		03Z	15Z	03Z	15Z	03Z	15Z	03Z	15Z
Sensible heat	0·09	−0·04	0·12	−0·02	−0·01	0·15	0·17	−0·03	0·01	−0·02	0·12
Latent heat	0·04	−0·06	−0·06	0·08	−0·02	0·18	0·12	0·06	0·09	0·50	0·33

TABLE 5

$\overline{V'u'}$ (proportional to northward eddy flux of angular momentum)

(units of 10^5 cm²/sec²)

		Pressure level (mb)										
		900	850	800	700	600	500	400	300	200	150	100
	1955											
Singapore	July		0·1		0·5	0·2	0·3	0·0	0·3	0·6	2·5	3·9
	August		—0·1		—0·5	0·4	0·1	0·0	0·5	1·0	3·2	0·8
Nairobi	August		—0·1		—0·2	0·4	—0·9	—2·7	—0·5	2·2	3·2	0·5
Madras	July	—0·2		—0·3	—0·2	—0·1	—0·1	—0·4	—1·1	—1·8		
Bombay	July	0·3		0·3	0·5	0·6	0·2	0·0	—0·2	—0·2		
Nagpur	July	—0·1		—0·1	0·0	—0·3	—0·6	—0·6	—0·5			
Delhi	July	—0·8		—0·5	—0·6	—0·2	—0·2	0·1	0·0	—0·3		

TABLE 6

Total zonal stress

(units of 10^8 dynes/cm)

	Singapore		Nairobi	Madras	Bombay	Nagpur	Delhi
	July	August	August	July	July	July	July 1955
By eddy flux	0·43	0·50	—0·05	—0·34	0·17	—0·19	—0·27
By advective flux	1·04	2·16	—0·04	—0·34	0·58	—0·39	—0·50