Indian J. Met. Hydrol. Geophys. (1975), **26**, 4, 443-454

551.501·7 : 551·513 (213)

Circulation pattern in the equatorial stratosphere and its relation with the circulations in the mesosphere and upper troposphere — Part I

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(*Received 25 September 1974*)

ABSTRACT. The zonal circulations in the equatorial stratosphere and mesosphere over the Indian Ocean region undergo cyclic oscillations having varying degrees of periodicity. The oscillation is biennial in the middle stratosphere (25-35 km) where westerlies interrupt the prevailing easterlies in alternate years. The period of one cycle of westerlies and easterlies decrease gradually, towards higher as well as lower levels, becoming semi-annual in the lower mesosphere and annual in the upper troposphere. The lower stratosphere is characterised by a thin stream of westerlies meandering around the globe within about 10° on either sides of the equator. Because of the seasonal north-south bodily shift of the entire stream, the Berson westerlies exist over Trivandrum only for about 8 months of the year. During this period the upper tropospheric easterly jet would be completely absent. Although the stratosphere is considered as a very stable region with the stratopause acting as a lid over it, the strato-mesospheric circulations are found to have some influence on the tropospheric monsoonal circulations.

1. Introduction

The upper air data obtained from the high altitude radiosonde ascents and rocketsonde ascents made at Thumba from December 1970 to December 1973 with M-100 (A) Series meteorological rockets supplied by USSR and those made by USSR research vessel *Voeykov* which participated in the MONEX-1973 programme over the Indian Ocean, have revealed features of the stratospheric and mesospheric circulations over the equatorial Indian Ocean region which may have significant influence on the onset, strength and withdrawal of the Indian monsoon over the country. In addition to the weekly rocketsonde ascents taken at Thumba from December 1970 onwards, a few special ascents were also made from Thumba in May 1973 and in November-December 1973. These additional ascents have provided unique upper air data at 2 to 4 days' intervals particularly during the crucial transition periods of onset of southwest monsoon and withdrawal of northeast monsoon from Kerala. The special characteristics of the circulation pattern at these significant levels are presented in this part of the paper.

In this study, the region of the stratosphere below stratonull (25 km) and above tropopause (17 km) is referred to as lower stratosphere, between 25 and 35 km as middle stratosphere and from 35 km to stratopause (45 km) as upper stratosphere. Narayanan and Fedynski (1973) found that the mean altitude of the stratopause over Trivandrum is at 45·2 km and the mean mesopause at 76·1 km. The region of mesosphere between 46 and 55 km is referred to as lower mesosphere, between 55 and 65 km as middle mesosphere and between 65 and 76 km as upper mesosphere.

2. Circulation pattern

Fig. 1 gives the vertical time-section of mean monthly zonal winds over Trivandrum computed from the rocketsonde data of Thumba for a 3-year period from December 1970 to November 1973 supplemented by high altitude radiosonde ascents. In the figure, the isotachs giving the salient features of the zonal circulation pattern over Trivandrum from the upper troposphere to the mesosphere are demarcated. The circulation pattern is broadly the same as that found by Kats (1970) and others by using rocketsonde data from the equatorial regions. The wind flow over Trivandrum in the middle stratosphere is predominantly zonal as found by Rao (1969) but in the upper stratosphere as well as in the lower mesosphere periodic meridional flow exists.

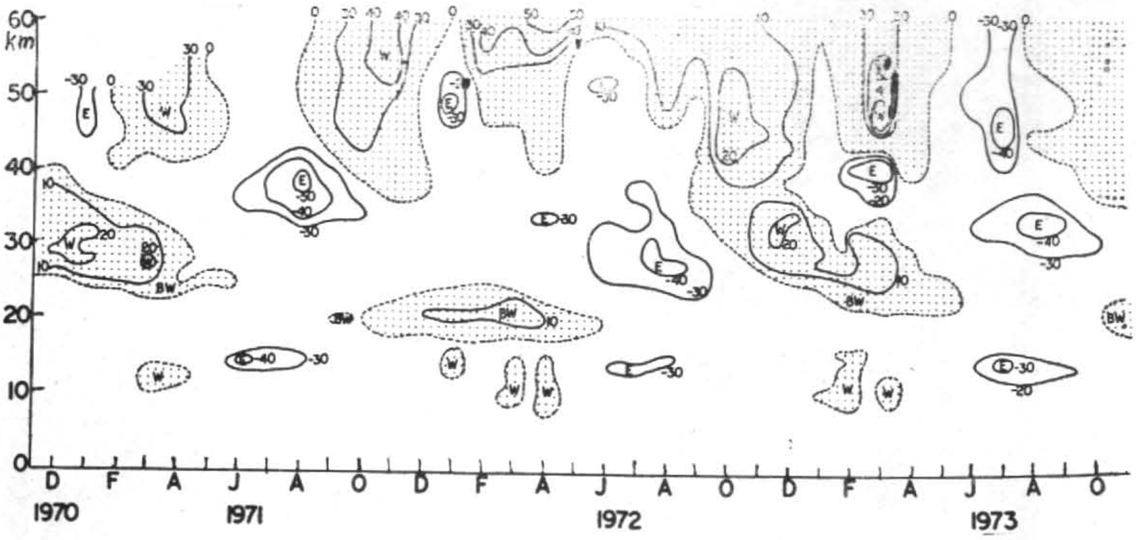

Fig. 1. Vertical time-section of monthly mean zonal winds (Thumba) for period December 1970 to November 1973

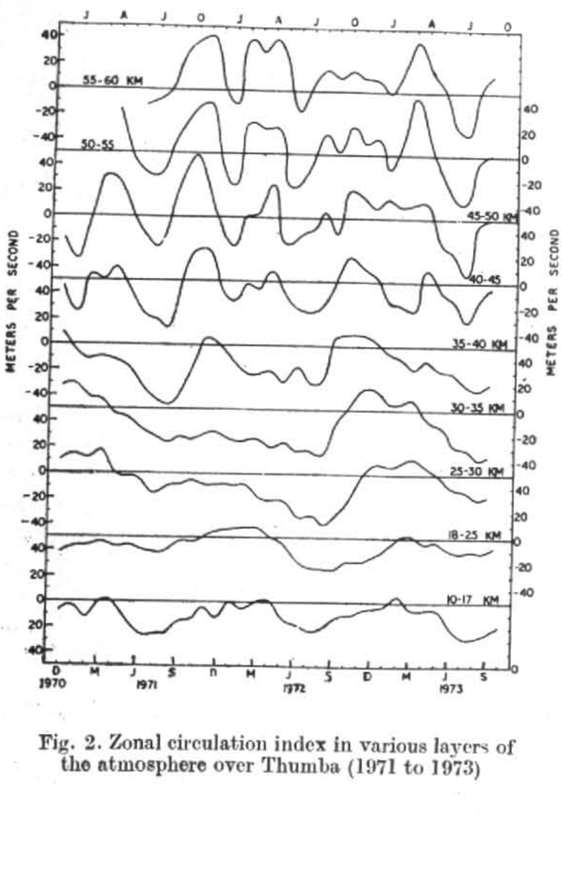

Fig. 2. Zonal circulation index in various layers of the atmosphere over Thumba (1971 to 1973)

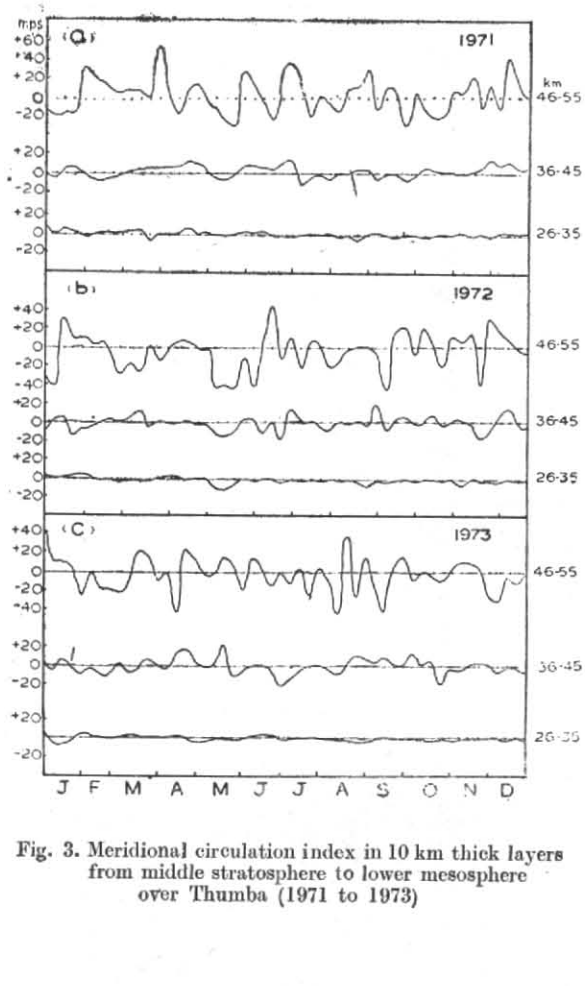

Fig. 3. Meridional circulation index in 10 km thick layers from middle stratosphere to lower mesosphere over Thumba (1971 to 1973)

3. Circulation Index

3.1. *Zonal Circulation Index*

Based on the mean monthly zonal components of winds at each kilometre level, the zonal circulation index for the various layers from 10 km to 60 km levels for the 3-year period (December 1970 to December 1973) have been computed by adopting Webb's (1966) criteria for stratospheric circulation index. The average duration of the consecutive cycles of reversal of current in the various layers are given in Table 1. The srmi-annual, annual, biennial oscillations of the circulations in the various layers can be clearly seen in the table. The result are also illustrated in Fig. 2.

It will be seen that in the layers of middle stratosphere (25 to 35 km a.s.l.) the westerlies and easterlies change biennially and in the layers within 10 to 17 km, they change annually. The transition from the biennial cycle above stratonull (25 km) to the annual cycle below the tropopause (18 km) takes place through a cyclic change of 15 months' period in the intermediate layer between the tropopause and stratonull. The layers above 40 km have oscillations of semi-annual period and the transition layer between 36 and 40 km levels has an annual period.

While the combined easterly-westerly oscillations in the middle stratosphere (25 to 35 km) have a biennial period, it is seen that the period is slightly more than 24 months as shown by the circulation index of 25 to 30 km layer. Other workers have found a 26 months' cycle for the stratospheric circulation over the Pacific Ocean area (Kats 1970). While in no layer of the atmosphere the westerly regime lasts for more than 6 months, the easterly regimes have very long durations in the upper troposphere and in the lower and middle stratosphere. In order to determine correctly the exact period of the oscillation over the Indian Ocean area, regular rocketsonde data over a much longer period is necessary.

3.2. *Meridional Circulation Index*

The meridional circulation index for each 10 km layer at the middle stratosphere (26-35 km), upper stratosphere (36-45 km) and lower mesosphere (46-55 km) based on the individual weekly rocketsonde data has been computed and the results for 1971, 1972 and 1973 are illustrated in Fig. 3 (a-c).

It will be seen that while the meridional transport of air in the middle stratosphere is negligible, there is a progressively increasing meridional flow as we go to higher altitudes. Meridional index of the order of 30-40 m.p.s. has been experienced in the lower mesosphere on certain occasions.

TABLE 1

Average duration of westerlies/easterlies in each cycle in the various layers

Layers (Ht. in km a.s.l.)	Duration in months		
	Westerly (W)	Easterly (E)	Full cycle (W+E)
56 – 60	4·75	1·25	6·0
51 – 55	3·75	2·5	6·25
46 – 50	3·5	2·75	6·25
41 – 45	2·2	4·2	6·4
36 – 40	3·0	9·0	12·0
31 – 35	5·5	18·5	24·0
25 – 30	5·5	19·0	24·5
18 – 24	5·5	9·5	15·0
10 – 17	1·0	11·0	12·0

In the higher latitudes, unidirectional meridional flow lasting for the entire season with only minor variations has been observed in the stratopause region (Webb 1966). But no such regular pattern of meridional flow has been observed over the equatorial region. The meridional fluctuations over the equatorial region are of shorter durations but of larger magnitudes.

Detailed characteristics of the equatorial circulation pattern, over the Indian Ocean area from upper troposphere to lower mesosphere are discussed in the following paras.

4. Characteristics of equatorial circulation pattern

4.1. *Circulation in upper troposphere (10-17 km)*

This is a region of easterly winds. The easterlies are interrupted periodically by short spells of narrow westerlies during January to April, the duration of each spell varying from a few weeks to about two months. Within the general easterly circulation, a narrow easterly jet stream prevails during southwest monsoon period, *viz.*, June to September, just below the tropopause (Koteswaram 1958, Mokashi 1971). Recently, Asnani (1973) reported meridional circulation in the summer monsoon over southeast Asia, according to which the equatorial cell separating the two Hadley cells of the two hemispheres gets elongated to the north and splits up into two sub-cells, one positioned over the equator and the other centred between 10° to 15° N. The location of Thumba is in the middle of these two sub-cells in the upper tropospheric circulation.

4·2. *Circulation in lower stratosphere (17-25 km)*

Berson Wind — The most significant feature of the circulation over Trivandrum in the lower

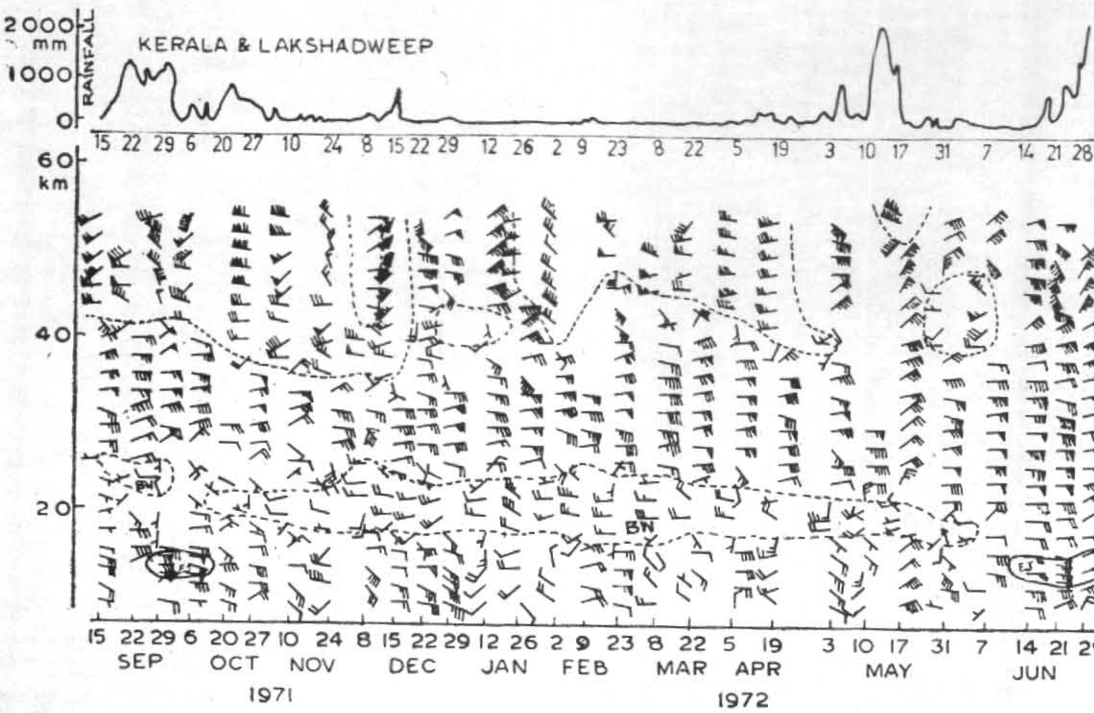

Fig. 4 (a). A typical Berson westerly stream as it existed over Thumba during 1971-72

stratosphere is the appearance of the westerly current every year at regular periodic intervals within the prevailing broad equatorial stratospheric easterlies. The westerly current occurring in the equatorial lower stratosphere is known generally as "Berson wind". According to Palmer (1954), the narrow stream of Berson westerlies has its axis usually near Lat. 2°N and extends through a latitudinal zone of not more than 7° on both sides of this axis. It was observed by him that the boundary between the Berson westerlies and the stratospheric easterlies varied from month to month and from year to year. For example, during the month of October 1952 the upper boundary of the narrow westerlies over the Marshall Islands (Lat. 5° N, Long. 165° E) was observed at 27 km, where as from January through May 1954, it was located at about 21 km. Modifications in the circulation scheme of Palmer have been pointed out by others based on subsequent wind data.

By utilising the large amount of upper air data from the central part of the Pacific Ocean which become available in subsequent years Kats (1970) made a detailed study. He found certain dissimilarities in the circulation patterns of two consecutive years. In 1961-1962 winter season, he found a narrow (6° to 7° wide) layer of stratospheric westerlies between 15 and 25 km level. In the previous year (1960-1961) easterlies instead of westerlies were situated in the same layer, and westerlies existed above 25 km level and also between 14 and 18 km levels. The westerly found below 18 km layer was assumed by him, as the Berson wind displaced to the troposphere.

According to Flohn (1960) westerlies of the lower equatorial stratosphere constitute a narrow isolated ring which is always observed between 20 and 25 km. But Kats (1970) from the observations over Pacific Ocean region found that westerlies of the lower equatorial stratosphere are not a constant feature and that they vary in the vertical due to the effects of the quasi-biennial oscillations in the lower equatorial stratosphere and in the horizontal due to seasonal (monsoonal) processes taking place in the extra-tropical stratosphere. Also, he concluded that a change from westerly into easterly flow (or *vice versa*) in the lower equatorial stratosphere is not due to seasonal causes.

Analysis of the recent wind data obtained from the rocketsonde and radiosonde ascents made at Thumba as well as those from MONEX-1973 ships show that, unlike what was noticed by Kats (1970) in the Pacific Ocean area, the short spells of narrow westerlies appearing in the upper troposphere over Trivandrum every year during January to April months, are distinctly different currents and are not part of the Berson westerlies of the lower stratosphere. The lower stratospheric westerlies have been found to extend upward into the

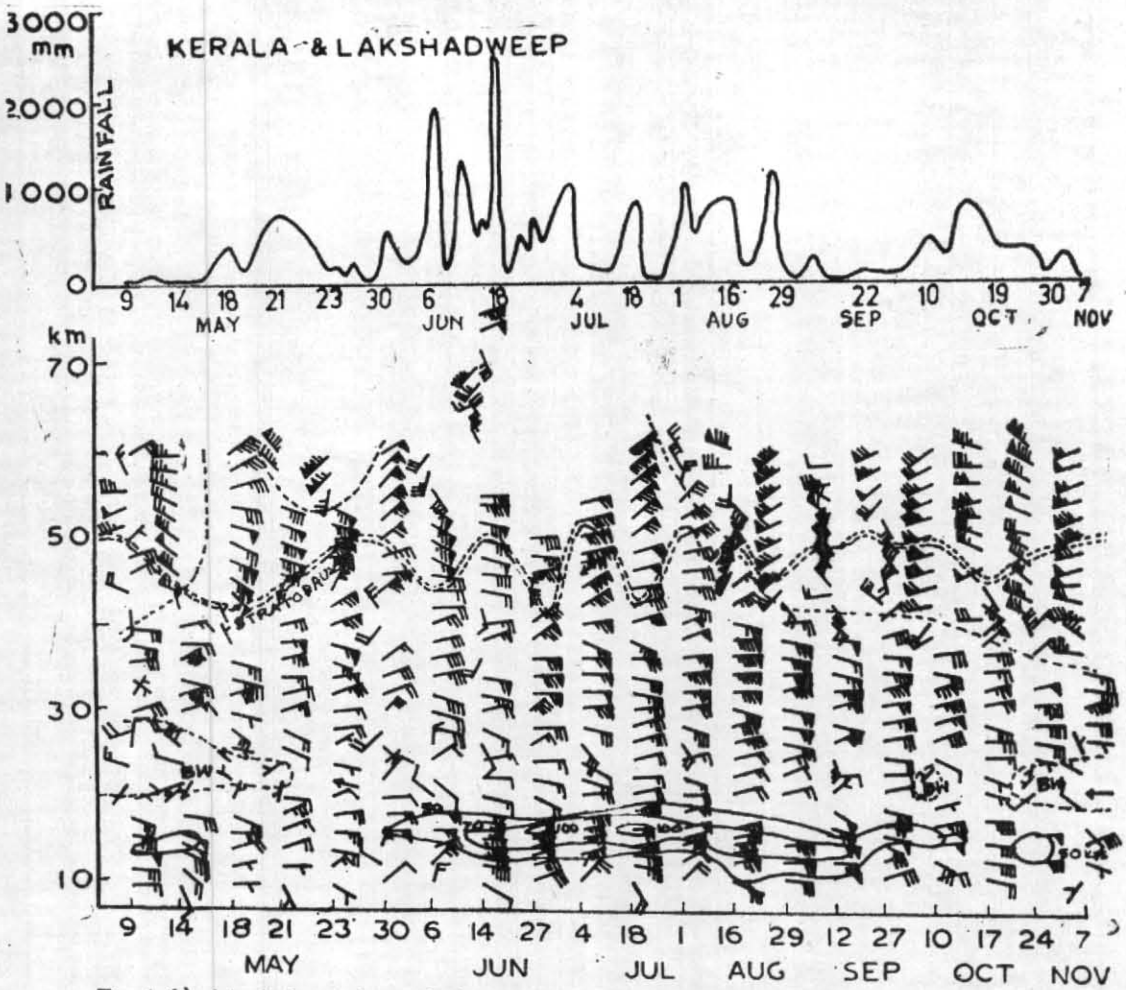

Fig. 4 (b). A typical upper tropospheric easterly jet stream as it existed over Thumba during 1973

middle stratosphere in alternate years rather than getting displaced downwards.

Some of the characteristics of the Berson westerlies over the Indian Ocean portion of the equatorial region studied by using the above data are presented diagrammatically in Figs. 4 to 6.

In Figs. 4 (a) and 4 (b) the vertical time-sections of two typical periods, one when Berson westerly stream existed in lower stratosphere over Trivandrum and the other when equatorial upper tropospheric easterly jet existed, are given.

In Figs. 5 (a) and 5 (b), the upper wind data obtained from the MONEX-1973 ships are plotted and presented suitably. Fig. 5 (a) gives the vertical time-section of the upper wind data over the equator within one degree on either side of Long. 50°E. Fig. 5 (b) illustrates the longitudinal variation in the upper winds over the Arabian Sea along the latitudinal zone of Trivandrum. The ships' rocketsonde ascent of 19 May 1973 taken from Lat. 8° and Long. 66°E and the rocketsonde ascents taken at Thumba from 14th to 23rd May 1973, have been utilised. The available high altitude radiosonde data from a ship in the neighbourhood of the rocket-ship and wind data from Minicoy also have been plotted in the diagram for obtaining an idea of the longitudinal variation during that period.

The vertical-time-sections of mean zonal winds for the year 1971 over Ascension Island, Kwajalein Island and Thumba are presented in Fig. 6.

The following characteristics of the Berson westerlies are evident from the above diagrams.

(*i*) The easterly jet in the upper troposphere and the westerly Berson current in the lower stratosphere appear to be two complementary circulation systems, one appearing over Trivandrum when the other disappears.

(*ii*) The Berson westerlies exist over the equatorial region of the Indian Ocean throughout the year. But over Trivandrum, they are seen only

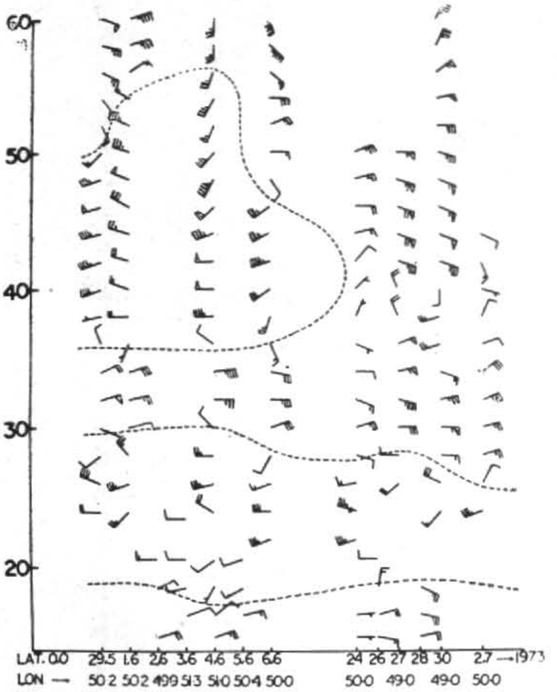

Fig. 5 (a). Vertical time-section of upper wind over the equator within a zone of one degree on either sides of Long. 50°E as obtained from MONEX-1973 ships

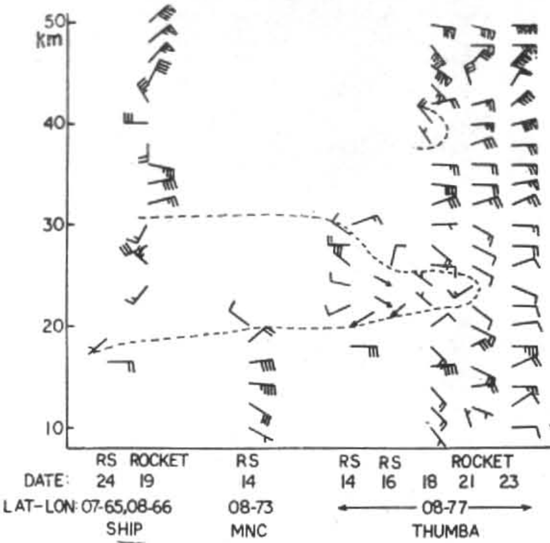

Fig. 5 (b). Winds over various longitudinal positions over the Arabian Sea along Trivandrum latitude during the second half of May 1973

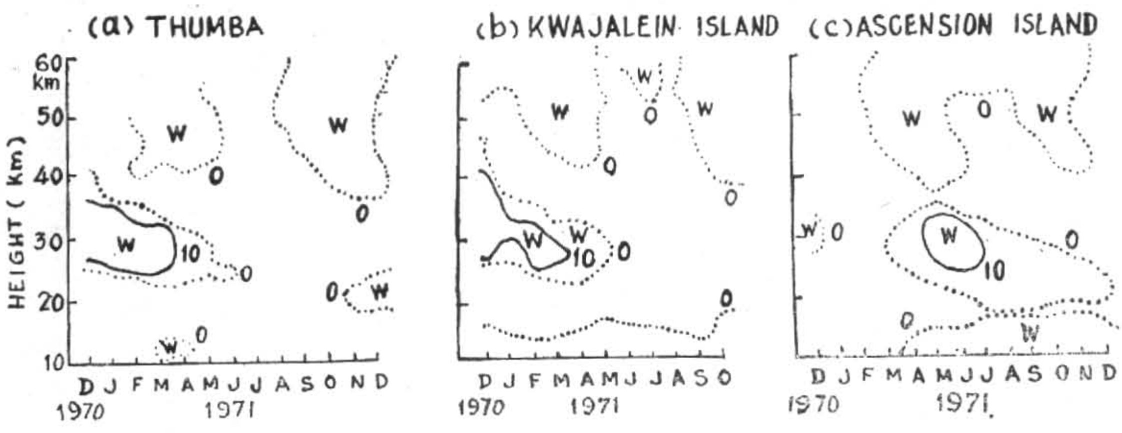

Fig. 6. Vertical time-sections of mean monthly zonal winds over Thumba (Lat. 8°32′N, 76°52′E), Kwajalein Island (8°44′N, 167°44′E) and Ascension Island (7°59′S, 14°25′W) during 1971

for about 8 months of the year and they are generally absent during the SW monsoon period. From Fig. 5 (a) it is evident that the Berson westerly current existed over equator even in June and July months, when it is generally absent over Trivandrum.

(*iii*) The lower boundary of the Berson westerly over the equator was found to remain uniformly between 17 and 19 km levels throughout May and June 1973, while the upper boundary lowered gradually from the end of May.

Over Trivandrum, the Berson current started weakening and decreasing in vertical depth after 14 May 1973. The upper boundary lowered to 24 km by the 18 May and the current disappeared by 21 May. But the rocketsonde data taken from the ship (Lat. 8° N and Long. 66°E) showed the upper boundary of the Berson current at 30 km even on 19 May 1973 (Fig. 5 b). Over the equator, between Longs. 49° and 57° E the upper boundaries of the Berson westerlies was found to be between 28 and 30 km levels from the end of May to the end of June 1973. It was

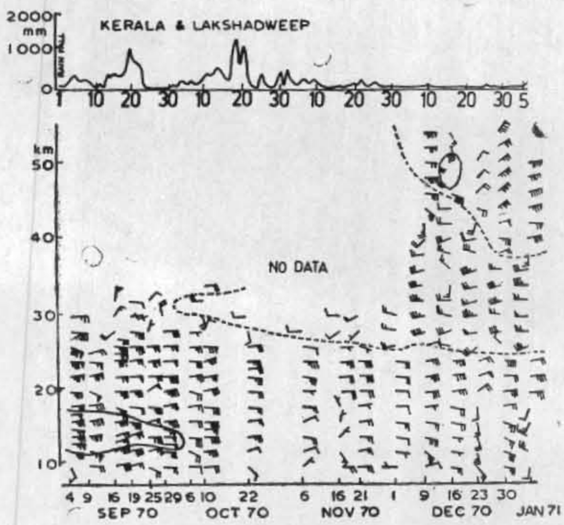

Fig. 7 (a)

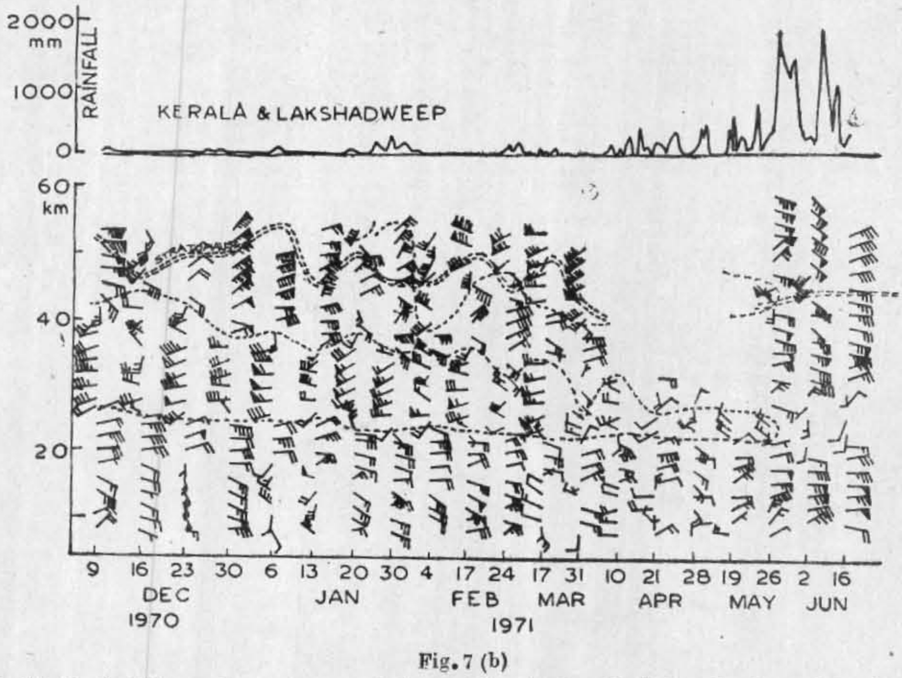

Fig. 7 (b)

Figs. 7 (a) & (b). Vertical time-sections of upper winds over Thumba from Sep '70 to Jan '71 and Dec '70 to Jun' 71

only by the first week on July 1973, that the upper boundary started descending below 26 km level in that region (Fig. 5 a). During mid-July, the upper boundary was found to be near 25 km level over the Bay of Bengal sector of the equator between Longs. 85° E and 88°E.

The changes described above suggest that the Berson westerlies get displaced gradually to the southern hemisphere when the Indian summer starts and that the displacement of the stream occurs earlier over the eastern portion than over the western portion of the Arabian Sea sector. This may account also for the southwest monsoon current advancing earlier over southeast Arabian Sea than over southwest Arabian Sea.

(*iv*) The layers in which Berson current exists over Trivandrum vary from year to year, with some similarities between the Berson currents of the alternate years. In the alternate seasons of 1970-1971 and 1972-1973, the lower boundaries appeared initially at comparatively higher levels and the upper boundaries remained merged with the mid-stratospheric westerlies. In both the seasons, the lower boundaries were between 25

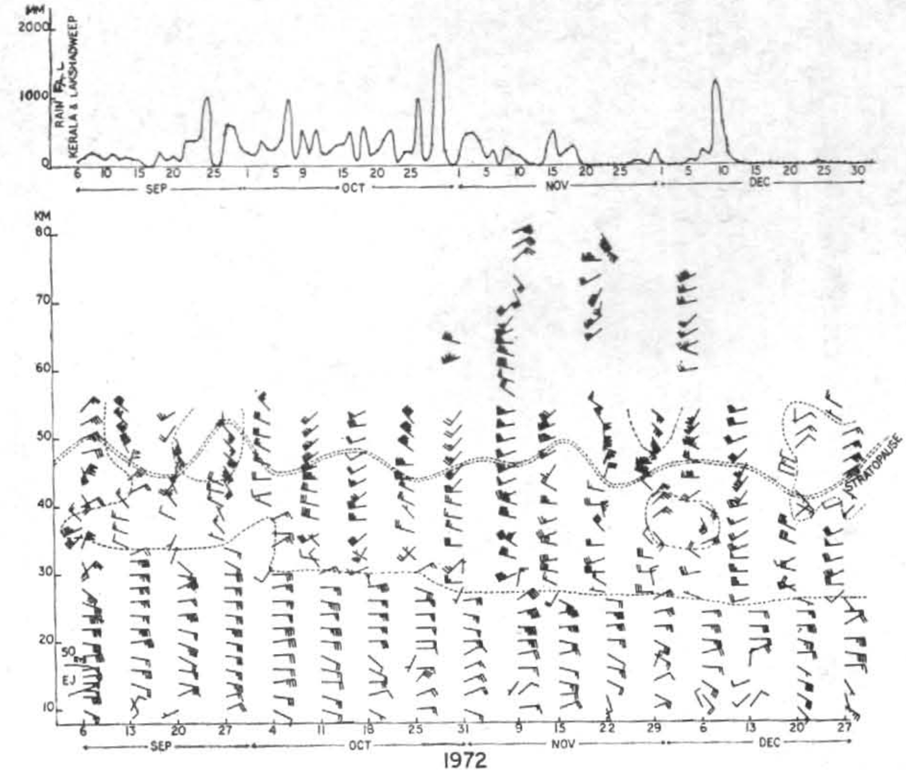

Fig. 7 (c)

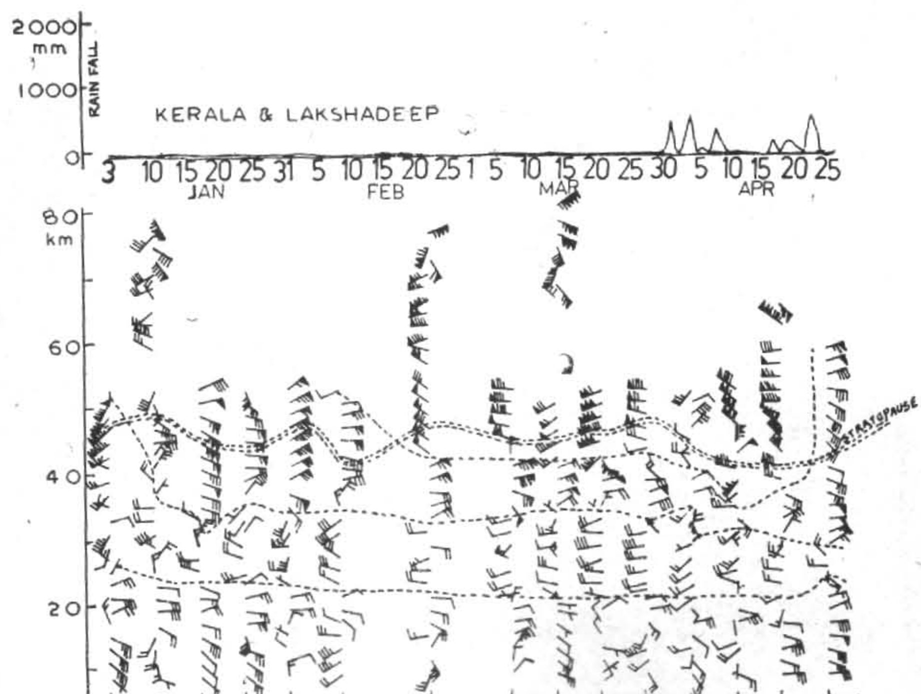

Fig. 7 (d)

Figs. 7 (c) & (d). Vertical time-sections of upper winds over Thumba from Sep-Dec 1972 and Jan-Apr 1973 and 30 km levels when the Berson winds made their appearance over Trivandrum in the month of October and they gradually lowered below 25 km by December and reached 20-22 km levels by March-April (Figs. 7 a to d). The upper boundaries remained merged with the lower layers of the biennial westerlies of the middle stratosphere till March-April. After April, when the mid-stratospheric westerlies disappeared, the upper boundaries of the Berson westerlies were found to be between 28 and 30 km levels (Fig. 7 a).

Similarly the Berson currents of 1971-1972 season and that of 1973-1974 season had almost identical characteristics in their mode of appearance over Thumba (Figs. 8 a and b). In 1971-72 season, the Berson westerlies existed over Trivandrum in the lower layers as a thin stream and remained confined more or less within the lower stratosphere, *i.e.*, between the tropopause and strato-null. During this season, the biennial mid-stratospheric westerlies were absent (Fig. 1) and the Berson westerlies had all their typical characteristics. Westerlies made their initial appearance over Trivandrum by middle of September 1971 and disappeared after 2 weeks. But they appeared again as a steady current by mid-October, near 20 km level. They had a maximum vertical depth of about 8 to 10 km from December 1971 to February 1972 (Fig. 4 a). The lower boundary remained more or less steady at 18 km level throughout the season.

(*v*) The average strength of the zonal components of the Berson current over Trivandrum during 1970 to 1973 period was generally of the order of 20-30 kt and the maximum speed experienced was of the order of 40 kt. But the ships' rocketsonde ascent made on 24 June 1973 from Long. 50° E over the equator reported westerly wind speed of 65 kt at 22 and 24 km levels (Fig. 5 a).

Considering the fact that this narrow stream of westerlies exist with strong easterlies surrounding it on all sides, it can be treated as a westerly jet stream counter-balancing the easterly jet stream of the upper troposphere.

(*vi*) A time-lag has been noticed between the appearance or disappearance of westerlies/easterlies over Thumba, Ascension Island, etc, situated on the periphery of either side of the equatorial zone. This is evident from Fig. 6.

The figure represents one of those biennial periods in which the westerlies appear in the mid-stratosphere and remain merged with the Berson westerlies in the lower stratosphere. It will be seen from the figure that, in the lower and middle stratosphere, while westerlies existed over Thumba during December 1970 to May 1971, easterlies prevailed generally over Ascension Island during the same period. Similarly, during the period when easterlies prevailed over Thumba (from May to September 1971) westerlies prevailed over Ascension Island. Over Kwajalein Island and Thumba, both situated nearly on the same latitude zone, the westerlies and easterlies prevailed more or less during the same periods.

The phase difference in the appearance and disappearance of westerlies over Thumba and Ascension Island is attributable to meridional oscillation of the lower stratospheric westerly current.

(*vii*) The manner in which the upper boundary of the Berson current over Trivandrum gradually increased and decreased in height would suggest that the vertical depth of the Berson stream was maximum along the central axis decreasing gradually towards the northern and southern boundaries.

(*viii*) It will be seen from Fig. 6 that during the transition periods of April-May 1971 and October to December 1971 the Berson westerlies existed simultaneously over both Trivandrum and Ascension Island. This is possible only if the Berson current extended horizontally to more than 8° latitude zone in either side of equator which would mean that it is slightly broader over Indian Ocean region than what was observed by others over the Pacific region. If the central axis of the stream is around Lat. 2°N as found by Palmer, the stream will have its northern boundary extending beyond 10°N during the period of its maximum displacement to the northern hemisphere.

A closer network of upper wind data over the equatorial region at more frequent intervals is required for making a more detailed study of this narrow westerly stream which meanders around the globe in the equatorial lower stratosphere.

From the above it is evident that the general pattern of zonal circulation in the lower stratosphere has certain amount of asymmetry about the equator as reported by Rao and Joseph (1971).

4.3. *Circulation in the middle stratosphere (25 to 35 km)*

This is a region of predominantly easterly circulation, having biennial characteristics. A biennial westerly circulation prevails over certain

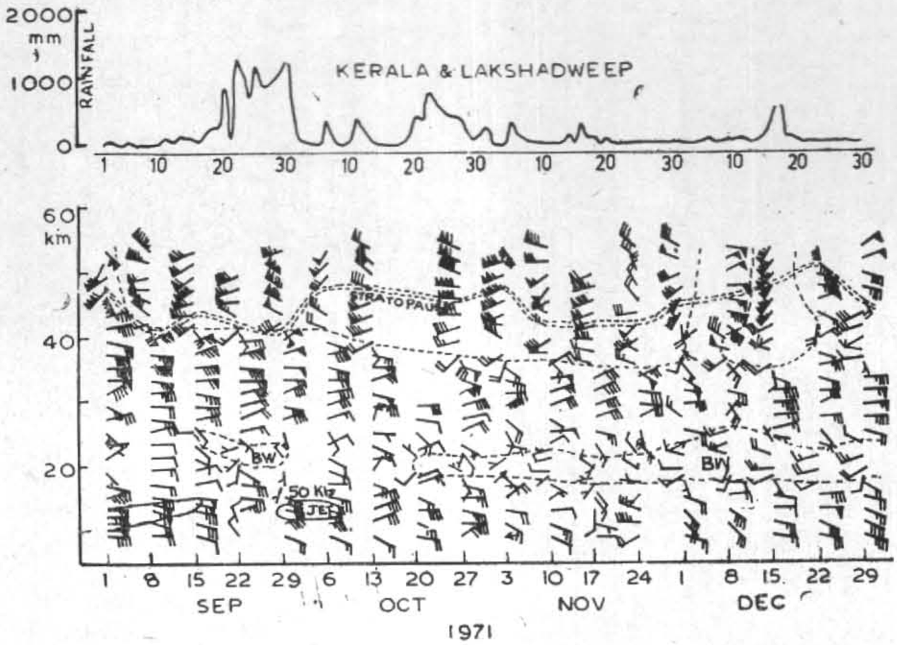

Fig. 8 (a). Vertical time-section of upper winds over Thumba from September to December 1971

Fig. 8. (b). Vertical time-section of upper winds over Thumba from Septembr 1973 to January 1974

layers of this region during September to April months of the alternate years. From October to December of these alternate years, westerlies cover the entire atmosphere over Trivandrum from lower stratosphere to lower mesosphere (Fig. 1). This is due to the combined effect of —

(*i*) The upper stratospheric westerlies in their semi-annual oscillation descending down into the mid-stratospheric westerlies in October-December quarter of the alternate years.

(*ii*) The upper boundary of the lower stratospheric westerlies (Berson westerly) in their annual oscillation penetrating into the mid-stratosphere in alternate years and remaining merged with the lower boundary of the mid-stratospheric westerlies.

The average zonal wind speed in the core of these westerlies above 30 km level is of the order of 30 m/s. It will be seen from Fig. 1 that a corridor of comparatively weak winds of less than 10 m/s exists around 35 to 40 km levels separating the core region of the middle stratospheric westerlies which too has a core region of average zonal wind speed of the order of 30 m/s.

In the 1970-71 season (October to April) these westerlies were prominent with average zonal components of the order of 10-20 m/s, reaching occasionally jet speed of 30-35 m/s in the core region. Owing to the quasi-biennial periodicity, these westerlies were absent in the 1971-72 season. They appeared again at the end of September 1972 and continued upto April 1973. The maximum speed of the westerlies was observed to be the same as in the previous biennial cycle (Fig. 1).

The appearance of broad and very strong easterly jet stream during June to October period is an annual feature of the middle stratospheric circulation. In the 1972 season (Fig. 1), the jet stream covered the entire middle stratosphere and even extended slightly into the lower stratosphere (*i.e.*, upto 23 km level) and well into the upper stratosphere (*i.e.*, upto 40 km level). The average strength of zonal wind component in the core region was of the order of 40-50 m/s. In the years 1971 and 1973, they covered only the upper portion of the middle stratosphere and lower portion of the upper stratosphere.

4·4. *Circulation in the upper stratosphere (35 to 45 km)*

The upper stratosphere over Trivandrum is characterised by well marked semi-annual oscillation with easterlies during winter (December, January and February) and summer (June, July and August) and westerlies in spring (March, April and May) and autumn (October, November and December). The pattern and shape of the in isotachs separating the westerlies and easterlies in the upper stratosphere and mesosphere would suggest that the westerlies in the upper stratosphere are due to the mesospheric westerlies penetrating downwards periodically.

The region 35 to 40 km appears to be closely linked with the semi-annual cycle above and the quasi-biennial cycle below through a well defined annual cycle.

The easterlies have a larger period than the westerlies and attain jet speeds with average zonal wind speed of the order of 30-50 m/s. These easterlies are stronger during the easterly phase of the quasi-biennial oscillation when zonal wind speeds of more than 80 m/s have been found in the core region on certain days.

4.5. *Circulation in the mesosphere (45 to 60 km)*

The semi-annual and other periodic variations of the zonal circulation in the equatorial mesosphere can be seen from Fig. 1.

It will be seen from the Table 1 that in the lower mesosphere region, the westerlies are of durations varying from 3 to 5 months followed by corresponding easterlies of shorter durations of 3 months to 1 month. The duration of westerlies gradually increase and that of the easterlies decrease towards the higher levels of the mesosphere. The total combined duration of two consecutive periods of westerlies and easterlies in the lower mesosphere is about 6 months, indicating a regular semi-annual cycle.

Very strong winds having average zonal components of more than 50 m/s are quite common in this region. Easterly and westerly winds of speed of the order of 200 kt are not rare. In March 1973, westerlies of speed of about 235 kt at 48 km (Fig. 7 b) and in July 1973 easterlies of speed about 200 kt at 47 km (Fig. 4 b) were observed.

From the above facts, it is to be concluded that the tropospheric circulation causing the Indian monsoon is influenced to a great extent by the equatorial strato-mesospheric circulations, particularly the Berson westerlies, unlike what was found by Flohn (1958). According to him "the planetary role of the Berson westerlies near the equator and the 20 km level is as yet not completely known, but they hardly seem to be related with the monsoon phenomenon".

It has been postutated by Raman (1971) that the near equatorial winter trough shifts to around Lat. 11°N in early summer and become dormant and lingers there during the rest of the summer. In autumn, this trough revives its activity and moves south. This trough, according to him, participates in a double oscillation and is different from the normal monsoon trough. The oscillation of the Berson westerly current in the lower stratosphere seems to have some relation with the above trough's oscillation.

For a proper understanding of the extent to which the above seasonal features in the tropospheric circulation are interlinked with the circulation pattern in the strato-mesospheric regions, a closer network of rocketsonde observations are needed. With the available data from Thumba, an attempt has been made to study the relation between the changes in the equatorial upper air circulation pattern and the changes in season and weather over the Indian Peninsula, with particular reference to Kerala. These are discussed in subsequent parts of this paper.

REFERENCES

Asnani, G. C. 1973 Meridional circulation in summer monsoon of south-east Asia, Res. Rep. RR-014, Indian Inst. Trop. Met., Poona.

Flohn, H. 1958 *Proc. Symp. Monsoons of the World*, India met. Dep., New Delhi, p. 73.

1960 Equatorial Westerlies over Africa, their extension and significance, Tropical Meteorological Proceedings, Nairobi.

Kats, A. L. 1970 Stratospheric and mesospheric circulation—IPST No. 5576, Israel Program for Scientific Translation, Jerusalem, Chapters I, II and IV.

Koteswaram, P. 1958 *Tellus*, **10**, p. 43.

Mokashi, R. Y. 1971 Mean axis of the Tropical Easterly Jet Stream, Rep. Symp, Trop. Met., Thumba.

Narayanan, V. and Fedynski, A. V. 1973 *J. Indian Roc. Society.*, **3**, p. 127.

Palmer, C. E. 1954 *Weather*, **9**, p. 341.

Raja Rao, K. S. and Joseph, K. T. 1971 *J. Appl. Met.*, **10**, p. 133.

Raman, C. R. V. 1971 Summer cloud organisation over northern Indian Ocean, Rep. Symp. Trop. Met., Thumba.

Rao., M. S. V. 1969 Stratospheric and mesospheric circulation in the equatorial region especially over South India, Ph. D. thesis, Univ. Kerala.

Webb, W. L. 1966 *Structure of the Stratosphere and Mesosphere*, Academic Press, New York and London, Chapter 4, pp. 141-145.