High-Level Warmings, Winds and Indian Summer Monsoon

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ABSTRACT

Temperature and wind data for the troposphere, stratosphere and mesosphere obtained from rocketsonde/radiosonde/rawin observations made at a tropical station (Thumba, 8°32′15″N, 76°51′48″E) during five summer monsoons (1971–73, 1975–76) with differential monsoon activity were examined.

There is agreement between the occurrence of high-level warmings and monsoon activity in four out of five monsoons studied. There were no warmings in the year with very weak monsoon activity. The temperatures of the stratopause and the tropopause were significantly warmer in 1972 when the monsoon was very weak than in other years when the monsoon was active or very active.

There is a high positive correlation between the monsoonal activity (precipitation departure from normal over Indian subcontinent) and the 25 km mean zonal wind, and a strong negative correlation with the winds near 16 and 50 km. The change in the sign of correlation coefficient was due to the observed phase change with altitude of the quasi-biennial oscillation.

The study indicated the possibility of a relationship between stratospheric quasi-biennial structure and the Indian monsoon rainfall.

1. Introduction

A complete knowledge of the characteristics of warming and cooling phenomena in the upper stratosphere is valuable for the study of synoptic-scale events in the troposphere (Labitzke, 1965; Julian, 1965; Scherhag, 1969; Trenberth, 1973; Quiroz, 1977; Houghton, 1978; Schoeberl, 1978). Studies of the stratospheric warmings over the tropics are sparse. Earlier studies undertaken using limited rocket data for a tropical station (Thumba, 8°32′15″N, 76°51′48″E) indicated association of high-level warmings with 1) tropospheric events (Mukherjee and Ramana Murty, 1972) and 2) monsoon activity (Mukherjee and Ramana Murty, 1976). A more extensive study has been undertaken using rocket temperature data and radiosonde and rawin data for the 5-year period 1971–73 and 1975–76. The results of the study are presented below.

2. Analysis and classification

The analysis of rocketsonde data for five summer monsoon seasons (1971–73 and 1975–76) was carried out with the objective of detecting significant differences in the warmings of the upper atmosphere vis-à-vis monsoon activity. The M-100 Soviet rocket data for Thumba (8°32′15″N, 76°51′48″E) were used. No rocket data are available for the summer monsoon season of 1974. The temperature and wind data of the troposphere obtained from the radiosonde and rawinsonde observations made at 1200 GMT at Trivandrum (8°29′N, 76°57′E) were also considered in the study. The classification of warmings and monsoon activity and details of other analyses adopted in the study are given below.

a. Warmings of the stratosphere/mesosphere

An occasion characterized by a rise in temperature of ≥15°C from the preceding sounding, the interval between two consecutive soundings being about 7 days, is considered as a case of warming.

A warming is classified as strong or weak depending on whether the thickness of the warming layer is >5 km or ≤5 km, respectively. The details of the cases of strong warmings observed during the five summer monsoon seasons are given in Table 1. The time sections of temperature of the stratosphere–mesosphere were analyzed and two typical cases, one each for a very weak (1972) and a very active (1975) monsoon condition, are shown in Fig. 1.

The temperature sensor used for the Soviet rocketsonde is a tungsten-rhenium wire, 40 μm in diameter. The probable mean-square error in determining the atmospheric temperature with this sensor is 3°C at 40 km, 5°C at 50 km and 7–10°C at 60–80 km (Mukherjee and Ramana Murty, 1972). The Mann-Whitney U test and the Wilcoxon matched-pairs signed-ranks test (Siegel, 1956) were used for evaluating the differences of the various parameters during different years.

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TABLE 1. Details of warmings observed during different years.

Year	Date	Height of warming layer (km)	Maximum warming (°C)
1971	30 Jun	55–65	21
	18 Aug	49–55	21
1972	—	no warming	—
1973	4 Jul	49–60	28
	16 Aug	54–63	26
1975	30 Jul	60–71	22
	20 Aug*	56–61	19
1976	11 Aug	59–68	21

* Temperature profile of 20 Aug was compared with the profile of 6 Aug due to unavailability of data for 13 Aug.

b. Tropopause and stratopause temperatures

In order to examine the association between the events of the stratosphere and troposphere the mean temperatures of the tropopause obtained from radiosonde observations, and of the stratopause obtained from rocketsonde data for the period June–August and for the month of May, were analyzed and are given separately in Table 2. The mean temperatures at the 200 mb level during July–August obtained from the radiosonde observations from 19 Indian stations as extracted from *Monthly Climatic Data for the World*, published by the National Climatic Center, were also considered in the study and the results are given in Table 3.

c. Circulation characteristics in the stratopause region, and winds in the lower stratosphere and at 100 mb

For the study of circulation patterns in the stratopause region the stratospheric circulation index (SCI), which is a measure of the mean zonal/meridional winds, for a 10 km thick layer around the stratopause was computed (see Webb, 1966). The monthly values of zonal SCI for the period May–August are given in Fig. 2. Also, zonal winds at 25 km and 100 mb are shown in Fig. 2 and the mean

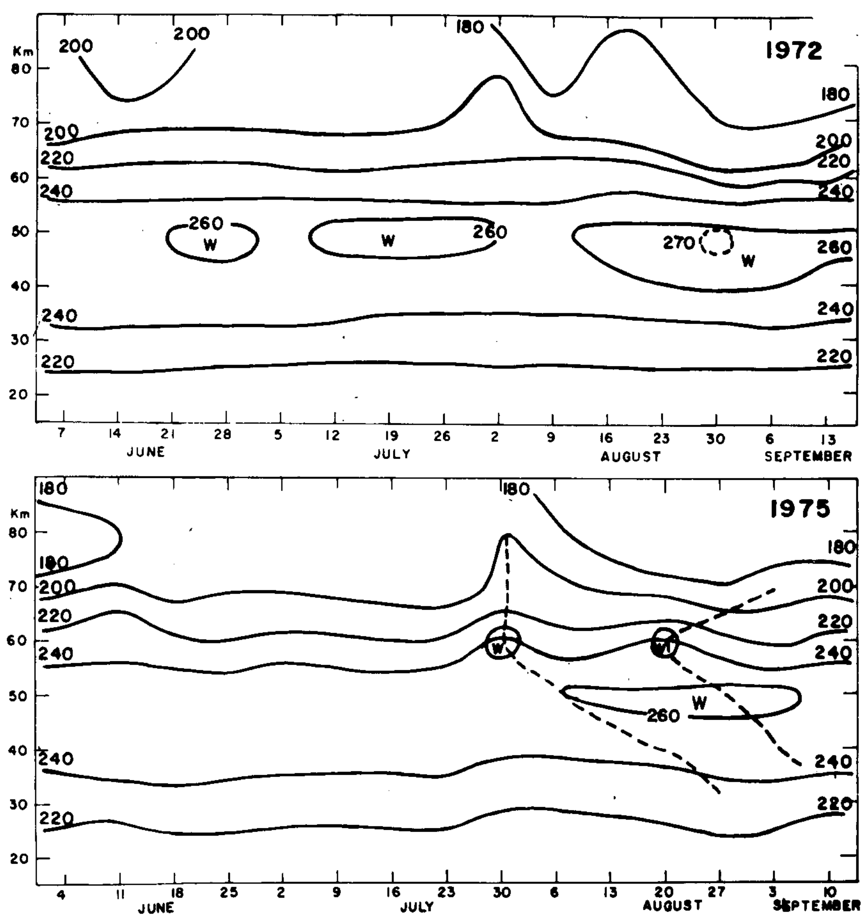

FIG. 1. Time sections of temperature (K) during two contrasting summer monsoons, June–August: 1972, very weak; 1975, very active.

TABLE 2. Temperatures (°C) of stratopause and tropopause during different years.

Year	Stratopause		Tropopause	
	May	Summer monsoon	May	Summer monsoon
1971	−6.1	−6.5	−81.7	−79.7
1972	−4.7	−3.7	−77.7	−78.5
1973	−9.9	−8.9	−80.7	−80.0
1974	—	—	−83.4	−80.4
1975	−12.0	−12.6	−83.5	−80.1
1976	−5.3	−5.8	−80.1	−78.6

values for the summer monsoon season are given in Table 4.

Time sections of the winds in the stratospheric and lower mesospheric regions for Thumba for the period 1971–73 and 1975–76 were analyzed and the charts for a very weak (1972) and a very active (1975) monsoon condition are shown in Fig. 3.

d. Monsoon activity

The summer monsoon sets in over extreme southwest India toward the end of May and the rainfall moves up along the west coast in about 10 days. During the four-month period of the summer monsoon ~75–90% of the annual rainfall is received in most parts of the country. The characteristics of the summer monsoon circulation and the monsoon rainfall have been reviewed (Ananthakrishnan, 1977).

The rainfall in the country is recorded in 35 meteorological subdivisions and reported by the India Meteorological Department (IMD). The details of the meteorological subdivisions over the Indian subcontinent were described by Jagannathan and Bhalme (1973). The monsoon activity is classified by the authors based on the rainfall distribution and the mean synoptic conditions in the country. The percentage departures are worked out from the normal rainfall for the period 1901–70 and also from the 6-year average rainfall for the period under study (1971–76), and the values are given in Table 5. When the percentage departure exceeded the value ±10 it was classified as a very active or a very weak monsoon condition. Since there was no agreement in 1976 between percentage departures obtained from normal and 6-year average data, the activity of the monsoon during 1976 could not be classified under any of the categories.

TABLE 3. Mean temperatures (July–August) at 200 mb during different years.

Year	Temperature (°C)
1971	−50.7
1972	−50.3
1973	−49.5
1974	−50.6
1975	−49.4
1976	−52.6

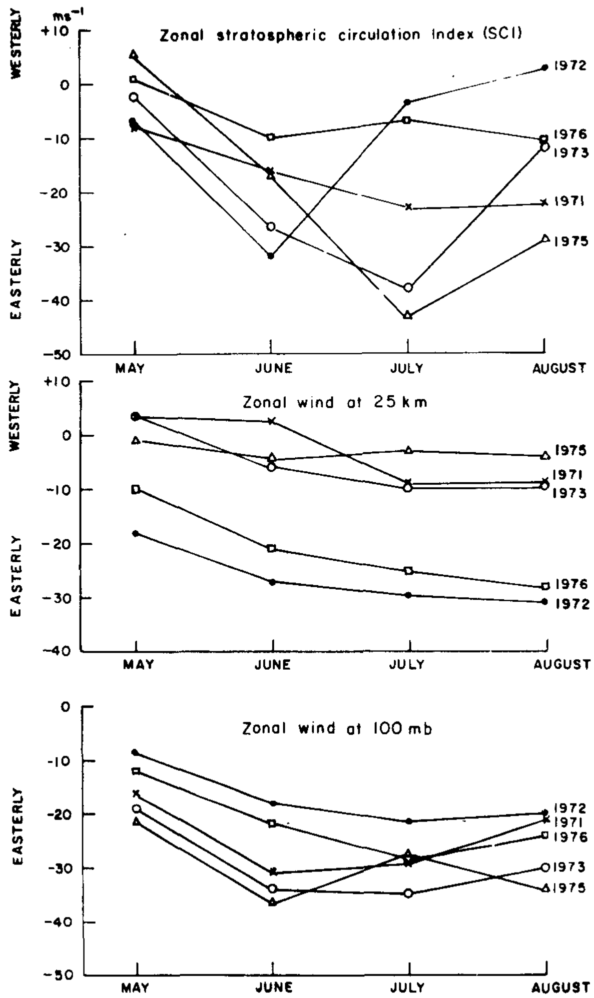

FIG. 2. Mean values of zonal stratospheric circulation index (SCI), zonal wind at 25 km level and zonal wind at 100 mb.

TABLE 4. Values of zonal stratospheric circulation index (SCI), and zonal wind at 25 km and 100 mb during different years.

Year	SCI ($m\ s^{-1}$)	Zonal wind 25 km ($m\ s^{-1}$)	Zonal wind 100 mb ($m\ s^{-1}$)
1971	−21.3	−6.0	−26.6
1972	−7.7	−29.8	−20.0
1973	−25.7	−8.4	−33.2
1974	—	—	−28.4
1975	−29.9	−3.4	−31.8
1976	−9.3	−24.5	−24.1

Minus signs indicate easterly winds.

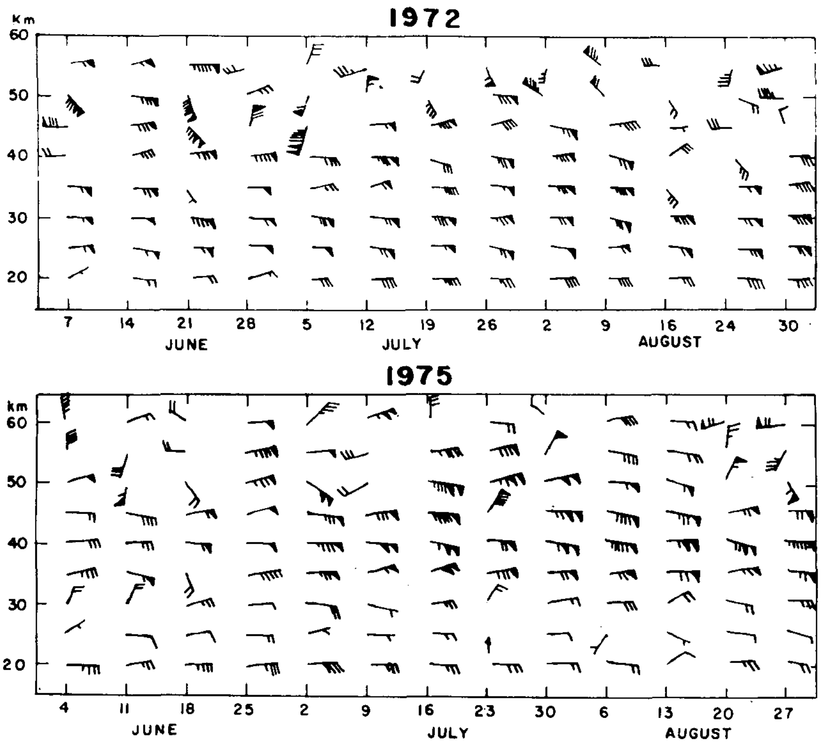

FIG. 3. Time sections of wind during two contrasting summer monsoons, June–August: 1972, very weak; 1975, very active.

The mean circulation characteristics at 700 mb for different years were examined using the upper air data for July and August months obtained from *Monthly Climatic Data for the World*. The results of the two years (1972 and 1975) of contrasting monsoon activity are given in Fig. 4. The monsoon trough was located in its normal position during 1975 when the monsoon was very active, whereas it was shifted toward the foot of the Himalaya (northward shift) during 1972 when the monsoon activity was very weak. During 1971, 1973 and 1976 the monsoon trough was more or less at its normal position with an occasional southward shift. Since the circulation characteristics during 1976 did not differ from those which existed in 1971 and 1973, while they did differ from those of 1972, it is difficult to classify the monsoon activity during 1976 either as weak or strong.

TABLE 5. Percentage departures of Indian subcontinent rainfall during the summer monsoon.

Year	Departure from normal (1901–70) (Jun–Sep)	Departure from 6-year average (1971–76) (Jun–Aug)	Monsoon activity
1971	+3.6	+2.9	Active
1972	−26.1	−20.2	Very weak
1973	+2.9	+4.7	Active
1974	−0.6*	−3.2	Weak
1975	+14.4	+12.5	Very active
1976	−2.6	+3.0	Inconclusive

* Based on data for Jun–Oct as summer monsoon activity continued up to October.

3. Results

a. Warmings and monsoon activity

A simple comparison of the occurrence of warmings and the monsoon activity during different years was made and the results are given in Table 6. There is agreement in four out of the five monsoon seasons. In 1976 the agreement is not clear, even though the mean synoptic conditions and the percentage departure of the 6-year rainfall indicated such a possibility. In view of (i) the small data sample with a gap in 1974, (ii) weekly resolution in rocketsoundings and (iii) limitation in the accuracy of temperature measurements above 60 km (Section 2a), it is recognized that the observed association between warmings and monsoonal activity could not be accepted as real. However, the results would be of significant interest to research workers in the field.

Out of five summer monsoon seasons studied, 1972 and 1975 are the two contrasting years with very weak and very active monsoon conditions, re-

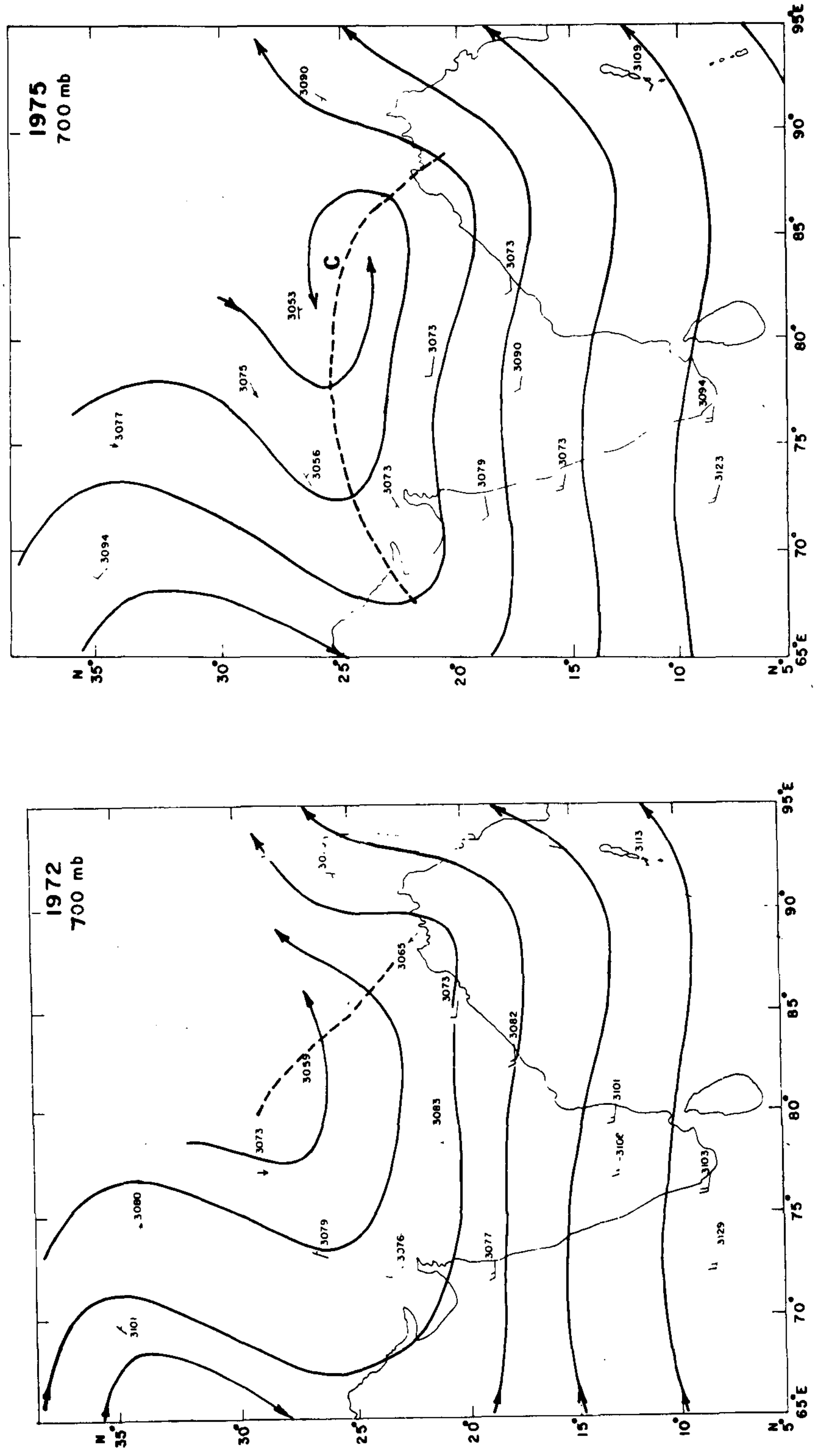

FIG. 4. Mean circulation pattern at 700 mb during July–August for two contrasting summer monsoons: 1972, very weak; 1975, very active. Full bar indicates 10 kt. The numbers indicate thickness (gpm).

TABLE 6. Details of warming and associated monsoon activity.

Year	Number of warmings	Classification of monsoon activity	Agreement
1971	2	Active	Yes
1972	none	Very weak	Yes
1973	2	Active	Yes
1974	—	Weak	—
1975	2	Very active	Yes
1976	1	Inconclusive	?

spectively. An examination of the stratopause and the tropopause temperatures during the above two years of contrasting monsoon activity showed significant differences. The temperatures of the stratopause and the tropopause were significantly warmer in 1972 than in 1975 (Table 2). The difference in stratopause temperatures between the two contrasting years is 7.3°C during May (significant at the 6% level) and 8.9°C during the summer monsoon season (significant at the 0.1% level). Similarly, the difference in tropopause temperatures is 5.8°C during May and 1.6°C during the summer monsoon season. The above differences are significant at the 0.1% level.

An examination of the mean radiosonde temperatures at 200 mb during July–August showed that during 1972 and 1975, the years of contrasting monsoon activity, the temperatures were significantly different. The temperatures during 1973 and 1975 were warmer than those during other years (Table 3). The rocketsonde temperatures also exhibited strong warming conditions during 1973 and 1975. However, there is no systematic relation between warmings and the 200 mb temperatures during other years.

b. *Stratospheric circulation index (*SCI*), and zonal winds at 25 km and at 100 mb*

The zonal stratospheric circulation index and the zonal winds at 25 km and at 100 mb were examined for an understanding of the characteristics of the wind field prevailing during the years of contrasting monsoon activity. The zonal SCI, by and large, showed an easterly component during the months May–August (Fig. 2). The zonal SCI in July and August was weak and contained easterly/westerly components in 1972, whereas it was strong and easterly in 1975. The difference between the SCI's of 1972 and 1975, the years of contrasting monsoon activity, is 22.2 m s^{-1} (significant at <2% level). The values of SCI were high during 1971 and 1973, even though they were less than the value in 1975, the year of very active monsoon circulation. The value was minimum during 1972 when the monsoon activity was very weak. The value during 1976 was more than in 1972, the difference not being significant.

A quasi-biennial oscillation (QBO) of the wind at 25 km was noticed. Active or very active monsoon conditions were associated with a weak easterly/westerly zonal wind, and very weak monsoon activity with a strong easterly zonal wind. The zonal wind was weak easterly/westerly during 1975 when the monsoon was very active, and was strong easterly during 1972 when the monsoon was very weak (Fig. 2). The value of the easterly wind at 25 km was strongest in 1972 and weakest in 1975 (Table 4), the difference, 26.4 m s^{-1}, being significant at the 0.1% level. During 1976, the zonal wind was strong easterly but weaker than that in 1972, the difference between the two years being significant at <1% level. This observation suggests that the activity of the monsoon during 1976 could be different from that of 1972.

The zonal wind at 100 mb was easterly during the summer monsoon. The active monsoon conditions were, by and large, associated with strong zonal winds and vice versa (Fig. 2). The difference in the zonal wind between 1972 and 1975 is significant at the 0.1% level. The values during 1972 and 1976 are also significantly different (<1% level), indicating that the monsoon activity during 1976 is different from that of 1972.

c. *Association between precipitation departure over Indian subcontinent with other specified meteorological parameters*

The possible association between monsoonal activity (precipitation departure from normal over the Indian subcontinent) and other specified meteorological variables was examined and the correlations are given in Table 7. There is a high positive correlation (+0.89) between X (precipitation departure) and Y_2 (25 km mean zonal wind), and a strong negative correlation with the winds near 16 km (100 mb) and 50 km (SCI). The change in the sign of the correlation coefficient is readily understood when one takes into account the observed phase change with altitude of the QBO. The precipitation departure and the zonal wind ($\bar{U}$) at 25 km are shown in Fig. 5. The value of $\bar{U}$ for 1974 at Kwajalein (~8°42′N, 167°42′E) was used since data for Thumba (8°32′15″N, 76°51′48″E) were not available. Evidence of QBO variation in the long-term monsoonal activity is also seen from the work of Jagannathan and Bhalme (1973) where a dominant QBO spectral peak in Indian subcontinent monsoonal precipitation was noticed. The above study corroborates the indicated relationships of the present study. It is interesting to note that a relationship between precipitation and some of the meteorological parameters is indicated as high as 50 km. Also, the indicated relationship of the monsoonal activity with temperature at the tropopause (Y_5) and the stratopause (Y_4) but not at 200 mb (Y_6) are rather intriguing.

TABLE 7. Correlation (r_{xy}) between precipitation departure over Indian subcontinent with other specified meteorological parameters.

Year	X percentage departure from normal	Y_1 SCI (m s^{-1})	Y_2 $\bar{U}$ (25 km) (m s^{-1})	Y_3 $\bar{U}$ (100 mb) (m s^{-1})	Y_4 T(stratopause) (°C)	Y_5 T(tropopause) (°C)	Y_6 T(200 mb) (°C)
1971	+3.6	−21.3	−6.0	−26.6	−6.5	−79.7	−50.7
1972	−26.1	−7.7	−29.8	−20.0	−3.7	−78.5	−50.3
1973	+2.9	−25.7	−8.4	−33.2	−8.9	−80.0	−49.5
1974	−0.6	—	—	−28.4	—	−80.4	−50.6
1975	+14.4	−29.9	−3.4	−31.8	−12.6	−80.1	−49.4
1976	−2.6	−9.3	−24.5	−24.1	−5.8	−78.6	−52.6
r_{xy}		−0.85	+0.89	−0.84	−0.87	−0.72	+0.23

4. Discussion

An investigation of the rocketsonde temperature data for five summer monsoon seasons not only corroborated the authors' earlier finding of the occurrence of stratospheric warmings in the tropics (Mukherjee and Ramana Murty, 1972) but also revealed that warmings could be correlated with the characteristics of the monsoon activity, vis-à-vis temperatures of the stratopause and the tropopause, high-level zonal wind. The monsoon activity and the temperature of tropopause and stratopause were associated. The temperatures were minimum during 1975 when the monsoon was very active, and maximum in 1972 when the monsoon was very weak.

The observed agreement between warmings and monsoon activity in four out of five summer monsoon seasons indicates the possibility of a relationship between warmings in the tropical upper stratosphere and the convective processes in the troposphere. However, it is to be recognized that the data used in the present study are too meagre to establish any definitive relationship between warmings and monsoon activity, especially in the absence of any linking physical mechanism. Numerical studies suggested an association between stratospheric warmings and sudden increases in the amplitude of the planetary waves in the troposphere (Matsuno, 1971; Holton, 1976). It was postulated that cell eddies, commonly referred to as planetary waves, which formed in the troposphere through baroclinic, orographic and diabatic processes, would propogate vertically and affect the stratospheric circulation (Schoeberl, 1978). Also, it was pointed out that in lower latitudes the diabatic heating source in the troposphere would generate global-scale propagating waves in the equatorial stratosphere (Holton, 1972). The present study indicated that the stratospheric/mesospheric warmings occurred mostly during the months of July and August, when the monsoon activity would be at its peak. Since the diabatic processes would be substantial during active monsoon conditions (Selvam *et al.*, 1980), the possible influence of its effect on the stratospheric circulation and warmings could not be ruled out. The time section of temperatures and winds shown in Figs. 1 and 2 indicate the possibility of such a mechanism. The time sections of temperatures shown in Fig. 1 indicate that the warmings appear to have their origin in the upper stratosphere/mesosphere region and also contain propagation modes in the vertical. This inference lends support to the physical mechanism discussed above.

The activity of the monsoon appears to be associated with the zonal SCI and the zonal wind at 25 km. The value of SCI was lowest during the year 1972 when the monsoon was very weak, and highest during the year 1975 when the monsoon was very active. The zonal wind at 25 km was highest during 1972 and lowest during 1975. The zonal wind at 100 mb was lowest during 1972, and the value during 1975 was significantly higher than 1972 even though not the highest. A numerical study of the upper wind fluctuations during the summer monsoon suggested

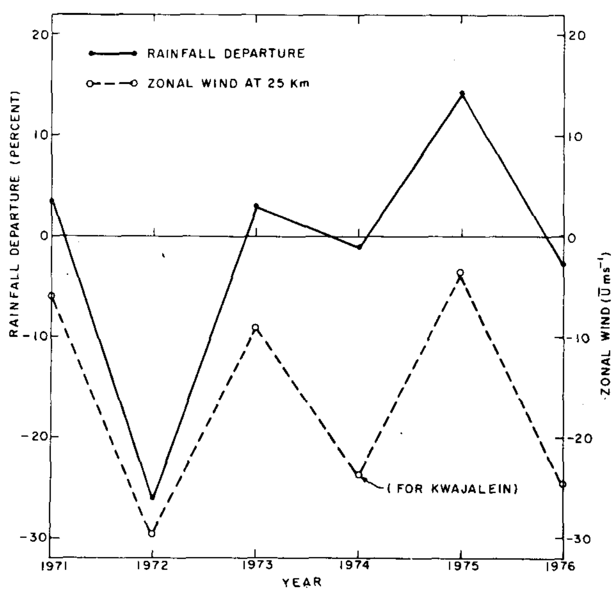

FIG. 5. Mean zonal $\bar{U}$ (June–August) at 25 km and precipitation departures from normal (June–September) during different years. The value of $\bar{U}$ for 1974 is based on 12-month running means of Kwajalein.

that increases in diabatic heating could cause intensification of the upper tropospheric easterlies (Murakami and Frydrych, 1974). Also, it has been reported that the circulation characteristics near 200 mb and the monsoon activity are correlated (Thiruvengadathan, 1972). The variations noticed in the zonal winds at 100 mb and the warmer temperatures observed at the 200 mb level during the years of active (1973) and very active (1975) monsoon conditions suggest that the warmings in the upper stratosphere could be related to convective processes in the troposphere.

The study has revealed an apparent relationship between stratospheric quasi-biennial structure and the Indian monsoon rainfall, which is of significant interest. The zonal wind at 25 km showed a QBO with strong easterly component during 1972 and 1976, and weak easterly/westerly components during 1971, 1973 and 1975. The westerly phase of the QBO in the lower stratosphere was generally manifested by the weakening of the easterly winds, as the prevailing winds in the stratosphere during the summer monsoon were broadly easterly. It was observed that the occurrence of the Kelvin and Yanai-Maruyama (mixed Rossby-gravity) waves was closely associated with alternating regime of the QBO (Appa Rao and Ramana Murty, 1976). Since Kelvin and mixed Rossby-gravity waves are associated with the large-scale dynamics of the equatorial stratosphere (Holton, 1975), it would be worthwhile to investigate further the QBO of the winds in the stratosphere vis-à-vis monsoon activity especially in view of the work of Jagannathan and Bhalme (1973), who showed a dominant QBO spectral peak in Indian monsoon rainfall. Such an investigation may help to identify the physical mechanism explaining the relation between warmings in the stratosphere and convective processes in the troposphere.

5. Conclusion

A study of the temperature and wind data of the troposphere, stratosphere and mesosphere for tropical station Thumba during five summer monsoon seasons with differential monsoon activity suggested the following:

1) There is agreement between the occurrence of warmings and monsoon activity in four out of the five monsoon seasons studied. There were no warmings in the year with very weak monsoon activity.

2) The temperatures of the stratopause and the tropopause were significantly warmer in 1972 when the monsoon was very weak than in other years when the monsoon was active or very active.

3) There is a high positive correlation between the monsoonal activity (precipitation departure from normal over the Indian subcontinent) and the 25 km mean zonal wind, and a strong negative correlation with the winds near 16 and 50 km. The change in the sign of correlation coefficient was due to observed phase change with altitude of the QBO.

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