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Middle atmosphere dynamics and monsoon variability

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सार — ग्रीष्म मानसून ऋतु के दौरान भारत पर वर्षा की परिवर्तनशीलता निर्धारित करने में, उष्ण कटिबंधीय मध्य वायुमंडल में उच्च अक्षांश मध्य वायुमंडल के अन्तः वार्षिक परिवर्तनशीलता, निम्न अक्षांश समतापमंडलीय अंचलीय पवनों में द्विवर्षीवत दोलन जैसे मध्य वायुमंडल के कुछ गतिकीय प्राचलों की इन की भूमिका के अध्ययन का परीक्षण किया गया है। यह माना गया है कि बड़े ज्वालामुखीय विस्फोटों से समताप-मंडल में आने वाली गंधकीय गैसों की मात्रा जलवायु (वर्षा) को परिवर्तित कर देती है। इस शोधपत्र में इस दिशा में अभी तक किए गए कार्य को प्रस्तुत करने का भी प्रयास किया गया है।

ABSTRACT. Some dynamical parameters of the middle atmosphere such as quasi-biennial oscillation in the low-latitude stratospheric zonal winds, interannual variability of the high-latitude middle atmosphere and vertical motions in the tropical middle atmosphere are studied to examine their roles in determining the variability of rainfall over India during the summer monsoon season. It is believed that the amount of sulphurous gases released in the stratosphere from the great volcanic eruptions modifies the climate (rainfall). An attempt has also been made in this paper to present the work done so far in this direction.

1. Introduction

The coupling between the middle atmosphere and the tropospheric phenomenon forms an important part of the middle atmosphere programme (MAP) currently in progress. Severe distortion of tropospheric circulation over the United States associated with major sudden stratospheric warming events has been reported. Quiroz (1986) has shown that the stratospheric disturbances are accompanied by tropospheric blocking between 85 and 95 per cent of the time. The influences of the middle atmospheric parameters and their linkages with the tropospheric phenomena over tropics have been reported (Mukherjee *et al.* 1979). Also recently opinions have been veering strongly around the hypothesis, based on observational as well as theoretical studies, that the aerosols released into the stratosphere from the strong volcanic eruptions have the ability to modify the weather and climate.

The summer monsoon phenomenon is a spectacular seasonal tropospheric event sweeping over the Indian subcontinent and the southeast Asia. The objective of the present review is to project the usefulness of the different parameters of the middle atmosphere and their dynamics for understanding the variability of the summer monsoon rainfall over India, and the winter monsoon rainfall over Sri Lanka.

2. Results and discussions

The parameters of the middle atmosphere considered here are (*i*) low-latitude quasi-biennial oscillation (QBO) in zonal wind, (*ii*) interannual variability (IAV) in high-latitude zonal wind during winter, (*iii*) vertical motions in the tropical middle atmosphere and (*iv*) stratospheric aerosols released from the strong volcanic eruptions.

2.1. *Low-latitude stratospheric QBO and Indian summer monsoon*

The quasi-biennial oscillation in the lower stratospheric zonal wind over low latitudes is a major oscillation with a period of 26 months. A dominant QBO-spectral peak in the Indian monsoon rainfall has been reported by several workers. Monthly mean zonal wind data for 30 mb (about 25 km) for a low-latitude station Balboa (9° N, 80° W) during June-August and the mean percentage departures of the rainfall for the whole India during June to September for a period of 32 years (1951-1982) are considered to examine the relationship between them. The data for Balboa is considered because the station has a long-series of high-altitude radiosonde observations reaching up to lower stratosphere. Also the QBO observed in the lower stratosphere is a global phenomenon. Our investigation has suggested a relationship between the phases of the QBO and the rainfall activity over India (Fig. 1). About 15 per cent of the variability in the rainfall over India during the summer monsoon has been attributed to the pattern of the QBO (Mukherjee *et al.* 1985). Bhalme *et al.* (1987) have considered the zonal wind at 10 mb for the same station Balboa and further examined the relationship of the phases of the QBO with reference to the Indian monsoon rainfall and confirmed our findings.

Gray (1984) has shown a linkage of the phases of the QBO in the equatorial zonal wind with the frequency of the hurricanes forming in the Atlantic basin and the *El Nino* episodes. He has shown a negative correlation between the frequency of the hurricane activities and easterly phases of the QBO. Similar negative relationship of the hurricane, hurricane days and tropical storms with the moderate to strong *El Nino* has been indicated by Gray. Rasmusson and Carpenter (1983) have

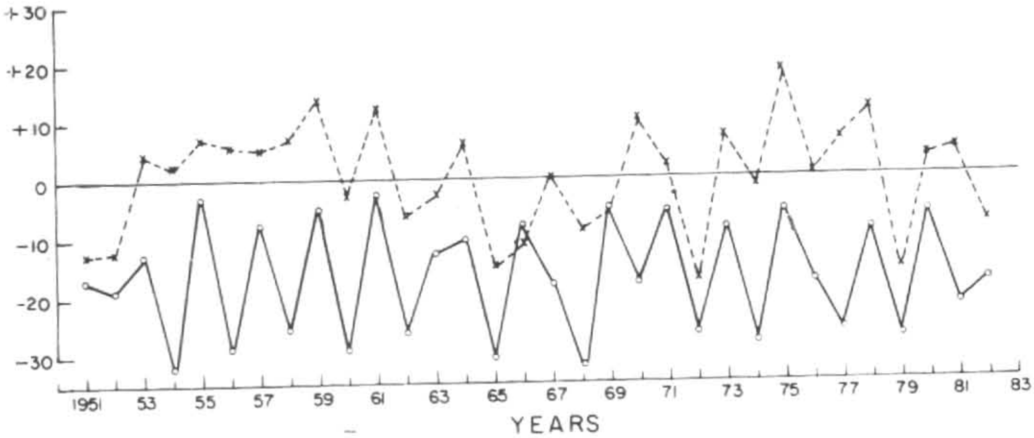

Fig. 1. Mean zonal wind (June-Aug) at 30 mb (ms^{-1}) for Balboa (9° N, 80° W) during 1951-82 (solid line) and percentage departures of rainfall (Jun-Sep ; dashed line)

TABLE 1

Frequency of cyclonic storms and depressions in westerly and easterly phases of QBO

S. No.	Year	Westerly phase	Ferque-ncy	Year	Easterly phase	Freque-ncy
1	1952	+8.0	8	1951	—20.0	4
2	1954	—4.0	4	1953	—16.0	2*
3	1955	—2.0	5	1956	—25.0	3
4	1959	+6.0	4	1958	—23.8	5*
5	1961	+1.3	2	1960	—15.8	7
6	1963	+9.8	8	1962	—22.0	4
7	1966	+5.3	8	1964	—9.0	6
8	1969	—4.0	5	1967	—16.0	6
9	1971	+0.1	7	1968	—20.0	4
10	1975	+6.0	10	1972	—21.0	8*
11	1977	+1.0	8	1973	—6.0	7*
12	1980	+2.0	8	1974	—25.0	6
13	1982	—2.0	6*	1976	—22.0	12*
14	1985	0.0	9	1978	—9.0	4
15				1979	—23.0	2
16				1981	—23.0	7
17				1983	—18.0	5*
Mean			6.6			5.4

Speed is in ms^{-1}. Asterisks indicates (*i*) moderate to strong and (*ii*) strong *El Nino* years. Westerly phase is from westerly to 5.0 ms^{-1} easterly and easterly phase is more than 5.0 ms^{-1} easterly.

also pointed out an association of the ENSO events with the Indian summer monsoon rainfall. But to our knowledge no concerted effort has been made till now to investigate the effect of the stratospheric QBO on the storms and depressions over the Indian seas. Using a long-series of data of the frequency of the occurrence of cyclones and depressions in the Indian seas, *i.e.*, in the Bay of Bengal and the Arabian Sea, and the zonal wind at 30 mb for Balboa during the post monsoon season (October-December) for 35 years (1951-1985), we have made a study to examine the effect of QBO modulation on the storm generating mechanism in the Indian seas. The study has indicated that the average number of the occurrences of the cyclonic storms and depressions over Indian seas per season (October-December) is 6.6 in the westerly phase (varying from westerly to 5.0 ms^{-1} easterly) and 5.4 in the easterly phase (more than 5.0 ms^{-1} easterly) as against 7.4 per year in the westerly phase and 5.2 per year in the easterly phase observed by Gray for hurricanes in the Atlantic basin. The frequency of occurrences of storms and depressions in Indian seas is shown in Table 1. The asterisk marks in the table indicate moderate to strong and strong *El Nino* years. If the storms and depressions occurring in the *El Nino* years are not taken into consideration then the average number of their occurrences will be modified to 6.6 in the westerly phase and 4.8 in the easterly phase per season. In this connection it should be mentioned that the data for 4 years (1957, 1965, 1970 and 1984) are not considered here as there are no changes in the frequency of the storms and depressions in these years as compared to their respective preceding years. It is noteworthy that out of 7 moderate to strong and strong *El Nino* years (1953, 1958, 1972, 1973, 1976, 1982 and 1983) considered in Table 1, only 1 moderate to strong *El Nino* occurred in the westerly phase (1982) and all the remaining 6 occurred in the easterly phase. An intriguing feature is to be noticed here that the frequency of the cyclonic storms and depressions in the Indian seas was more in every *El Nino* years but one in 1953. In the easterly phase of the QBO when the *El Nino* mostly occurred, the frequency of the storms and depressions was 6.5 per season in the *El Nino* years whereas it was 4.8 per season when the *El Nino* did not occur. The present study suggests that the storm generating mechanism in the Indian seas would be more favourable during the waning phase of the *El Nino* episodes, even though the QBO was in the easterly phase.

2.2. *Interannual variability of high-latitude middle atmosphere during winter and Indian summer monsoon*

Recent investigations on the middle atmosphere have given ample stress on the interannual variability (IAV) of the high-latitude stratospheric circulation during winter (Labitzke 1977, 1982; Wallace and Chang 1982). Also it has been suggested that the phases of the low-latitude QBO could modulate the interannual variability in the high-latitude middle atmosphere. Since a relationship between the phases of the QBO and the summer monsoon rainfall variability over India has already been established, it would be of interest to examine whether there exists a relationship between the interannual

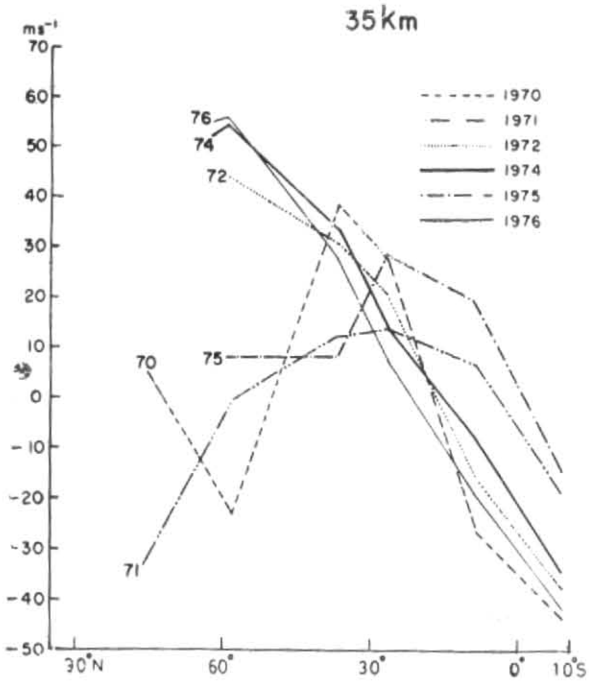

Fig. 2. Latitudinal distribution of zonal wind (ms^{-1}) at 35 km for January for 6 years (1970-1972) and (1974-1976)

variability of the high-latitude middle atmosphere during winter and the rainfall activity during the forthcoming summer monsoon over India. The rocketsonde temperature and wind data for the month of January, which typically represents the northern winter, for the 6-year period (1970-1972, 1974-1976) are considered here. The names of the stations and their geographical locations, for which data are available for the levels 25-55 km, are given below :

(1) Thule (76.6°N, 68.8°W), (2) Poker Flat (65.1°N, 147.5°W), (3) Fort Churchill (58.7°N, 93.8°W), (4) Wollops Island (37.8°N, 75.5°W), (5) Cape Kennedy (28.5°N, 80.5°W), (6) Fort Sherman (9.3°N, 80.0°W), (7) Kwajalein (8.7°N, 167.7°E) and (8) Ascension Island (8.0°S, 14.4°W).

The in-between year 1973 could not be considered in the analysis as the data for the month of January for that year were not readily available to us. The percentage departures of the monsoon rainfall of India as a whole, from its 32-year mean (1951-1982) for the entire country, were +10.6, +2.7, —17.8, —1.8, +18.9 and +0.1 during 1970, 1971, 1972, 1974, 1975 and 1976 respectively. Our study has broadly suggested that (*i*) the stable and strong polar night jet near 60°N in January have preceded weak to normal summer monsoon year, namely, 1972 (—17.8 per cent), 1974 (—1.8 per cent) and 1976 (+0.1 per cent) and (*ii*) early breaking of the polar night jet and presence of easterlies/weak westerlies near 60° N have preceded normal to strong summer monsoon years, namely, 1970 (+10.6 per cent), 1971 (+2.7 per cent) and 1975 (+18.9 per cent) respectively. The latitudinal distribution of the zonal wind at 35 km only for January for 6 years considered, is given here as an illustration in support of the above inferences (Fig. 2). It is also noticed from the analysis of the rocketsonde temperature that the north pole temperature at the middle atmosphere during January

TABLE 2

Mean warm and cold anomalies in the polar temperatures at 30 mb during December and January, position of 500 mb ridge at 75° E during April and percentage departures of rainfall during following summer monsoon

Winter years	Warm (+)/cold (—) anomaly (°C)	Ridge at 500 mb along 75° E during April	Summer years	Percentage departure of rainfall for entire India
1958-59	+2.3	16.0°N	1959	+13.8
1960-61	+7.8	15.0°N	1961	+12.4
1964-65	—3.7	14.0°N	1965	—15.0
1965-66	+5.3	13.5°N	1966	—11.1
1969-70	+11.8	15.8°N	1970	+10.6
1971-72	—5.7	11.0°N	1972	—17.8
1974-75	+3.3	17.5°N	1975	+18.9
1977-78	—2.7	14.0°N	1978	+11.9
1978-79	—1.7	12.5°N	1979	—15.4

was cold during 1972, 1974, 1976 and warm during 1970, 1971 and 1975. During the winter of December 1972 to March 1973 an early major warming occurred within the first week of January. This feature, on the basis of the results of the above analysis, would suggest better forthcoming summer monsoon over India. The percentage departure of the rainfall during the summer monsoon of 1973 was incidentally +7.3. This result has indicated that the early breaking of the stratospheric polar vortex may be conducive to the better performance of the forthcoming summer monsoon over India (Mukherjee *et al.* 1986). Wallace and Chang (1982) have shown an association of Southern Oscillation (SO) with the intensity of the stratospheric polar vortex. They have put forward an impressive evidence to show the linkage between "High/Dry (H/D)" winters and winters with strong polar vortex, and between "Low/Wet (L/W)" winters with weak polar vortex.

The mean monthly polar temperatures at 30 mb during winter (December-January) for a period of 26 years from 1955-1956 to 1980-1981 are analysed. The data are obtained from the Free Berlin University. The departures of the average temperatures of December and January for each winter from their 26-year mean are computed. The anomalies in the polar temperatures are then compared with the rainfall of those forthcoming summer monsoon years which have the percentage departures of rainfall more than +10 per cent and less than—10 per cent respectively. Table 2 shows the warm and cold anomalies during winter and the extreme cases of rainfall during the forthcoming summer monsoon. It can be noticed from the table that out of 5 occasions of excess rainfall (departures more than + 10 per cent) during 1959 (+13.8), 1961 (+12.4), 1970 (+10.6), 1975 (+18.9) and 1978 (+11.9), on 4 occasions *i.e.,* 80 per cent of cases strong monsoon activity was preceded by warm anomally in the north pole winter

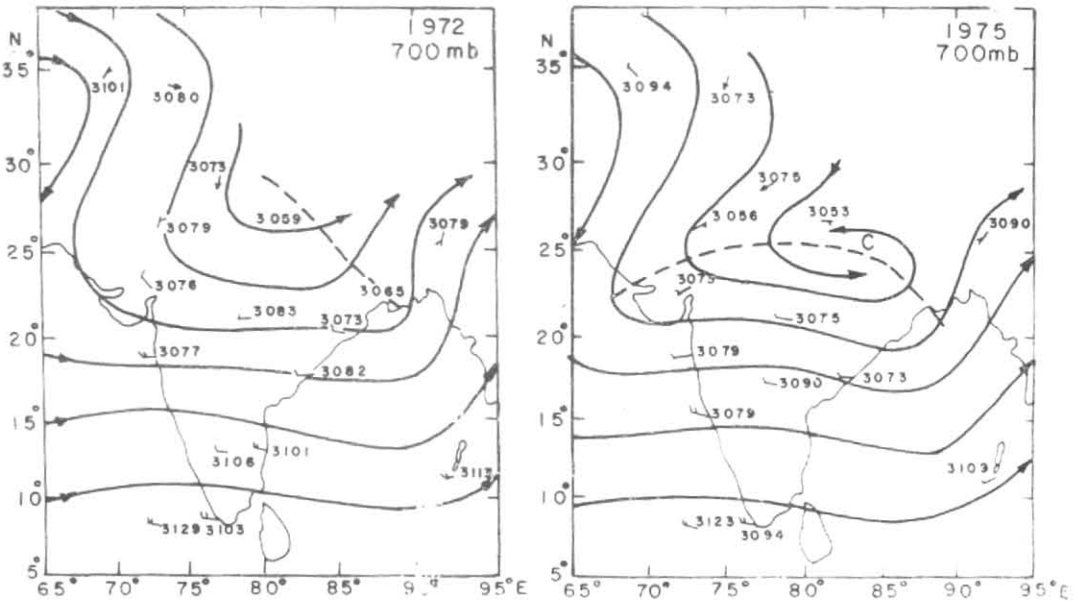

Fig. 3. Mean circulation at 700 mb during Jul-Aug for two contrasting summer monsoons, 1972 (very weak) and 1975 (very active). Full bar indicates 10 knot. Number indicates thickness in gpm.

temperature at 30 mb. Only on 1 occasion, *i.e.*, in 1978 the cold anomaly (in place of warm anomaly) in the polar temperature in the preceding winter was noticed. On 4 occasions of deficient rainfall (departures less than —10 per cent) during 1965 (—15.0), 1966 (—11.1), 1972 (—17.8) and 1979 (—15.4) on 3 occasions, *i.e.*, 75 per cent of cases weak monsoon activity was preceded by cold anomaly in the north pole winter temperatures at 30 mb. The position of the ridge at 500 mb at 75° E during April is also included in Table 2. An overall view of the table has revealed that the warm anomaly in the north pole winter temperature at 30 mb could be linked with the northward shift and the cold anomaly with the southward shift of 500 mb ridge during April. In this connection it should be mentioned that if the rainfall data are not subject to stratification in the above manner, one could not get a good relationship between warm/cold anomaly in the polar temperature at 30 mb during winter and the performance of the forthcoming monsoon in every occasion. However, the average of positive anomaly (+6.7°C) in the polar temperatures during winter is associated with the positive departures of rainfall (+3.6 per cent), and the average of negative anomaly (—4.1°C) with the negative departures of rainfall (—1.0 per cent).

2.3. *Conditions prevailing over tropical middle atmosphere during two contrasting monsoons, 1972 and 1975*

1972 and 1975 were the two summer monsoon seasons which showed strong contrast in the rainfall activity over India. The percentage departures of rainfall from the 32-year mean were —17.8 in 1972 and +18.9 in 1975. The mean circulation features for July and August at 700 mb showed that the axis of monsoon trough was in its normal position when the monsoon was very active (1975) but it was shifted towards the foothills of the Himalayas when the monsoon was very weak (1972) (Fig. 3). The phases of QBO for the mean zonal wind at 30 mb at Balboa (9°N, 80°W) for June to August were very strong easterly in 1972 and weak easterly (westerly phase) in 1975. At 50 km where semi-annual oscillation is dominant, a phase reversal occurred showing weak easterly/westerly in 1972 and strong easterly in 1975 during the same period. Such anomalies in the circulation features of the middle atmosphere was noticeable throughout the tropical globe (Mukherjee *et al.* 1981).

TABLE 3

Percentage frequency of occurrence of strong volcanic eruptions associated with different types of rainfall distribution at each station (values significant at 5 per cent level are denoted by asterisks)

Station	Group A (— —)	Group B (— +)	Group C (+ —)	Group D (+ +)
Jaffna	21.1	15.7	42.1*	21.1
Mannar	15.0	40.0*	15.0	30.0*
Trincomalee	25.0	40.0*	20.0	15.0
Anuradhapura	31.6*	31.6*	15.8	21.0
Maha Illuppallama	21.4	35.7*	7.2	35.7*
Puttalam	40.0*	35.0*	20.0	5.0
Batticaloa	30.0*	30.0*	25.0	15.0
Kurunegala	29.5*	23.5	23.5	23.5
Badulla	55.0*	10.0	15.0	20.0
Nuwara Eliya	50.0*	10.0	20.0	20.0
Colombo	30.0*	40.0*	5.0	25.0
Diyatalawa	46.7*	26.7*	13.3	13.3
Ratnapura	30.0*	40.0*	10.0	20.0
Hambantota	60.0*	15.0	15.0	10.0
Galle	35.0*	45.0*	20.0	0.0

TABLE 4

Types of rainall variation at different stations following strong volcanic eruptions

Month	Year	Group A (— —)	Group B (— +)	Group C (+ —)	Group D (+ +)
October	1869	7(3,6,9-11,14,15)	3(2,7,13)	—	—
June	1877	8(1,3,6,7,9,10,13, 14)	4(2,4,11,15)	—	—
August	1883	1(3)	3(6,13,15)	3(1,4,10)	5(2,7,9,11,14)
June	1886	—	2(7,11)	4(4,8,14,15)	7(1-3,6,9,10,13)
November	1899	4(4,7,9,15)	2(6,11)	5(1-3,8,14)	2(10,13)
May	1902	10(2,4,6,8-11, 13-15)	2(3,7)	2(1,12)	—
June	1911	1(5)	10(1-4,6-8,11, 13,15)	1(14)	3(9,10,12)
June	1913	1(12)	3(11,13,15)	8(1-4,6,7,9,10)	3(5,8,14)
April	1917	5(9,11,12,14,15)	2(3,13)	4(6-8,10)	4(1,2,4,5)
April	1918	4(9-11,14)	5(6-8,12,15)	1(3)	5(1,2,4,5,13)
August	1919	4(9-11,14)	1(3)	7(1,6-8,12,13,15)	3(2,4,5)
January	1932	12(2-7,9,10, 12-15)	2(8,11)	1(1)	—
May	1937	7(6-10,12,14)	8(1-5,11,13,15)	—	—
January	1951	12(1-8,10, 12-14)	1(9)	1(15)	1(11)
February	1952	7(1,6-8,13-15)	6(2-5,10,12)	1(9)	1(11)
March	1963	4(1,8,10,11)	10(2-6,9,12-15)	—	1(7)
September	1965	4(4,12,14,15)	7(1-3,6,10,11,13)	1(9)	3(5,7,8)
August	1966	4(4,9,12,14)	1(15)	9(1-3,5-7,10, 11,13)	1(8)
June	1968	1(13)	4(5,6,8,14)	2(7,15)	8(1-4,9-12)
October	1974	3(6,9,10)	7(2,4,5,7,12,14,15)	1(1)	4(3,8,11,13)

Station numbers are given in brackets

The coupling between mesosphere and stratosphere, and between stratosphere and troposphere constitute an essential part of the dynamics of the middle atmospheric processes. These couplings are often manifestations of the vertical motions in the different regions. The anomalous circulation noticed in the troposphere during the summer monsoon of 1972 and 1975 (Fig. 3) could give rise to the different modes of vertical motions in the tropical middle atmosphere. With this end in view, the vertical motions in the middle atmosphere over Thumba (8.5° N, 76.9° E) during June to August are computed by using weekly rocketsonde temperature and wind data. For computations of vertical motions (W), the thermodynamical equation :

$$\frac{\partial T}{\partial t} = \frac{1}{c_p} \frac{dH}{dt} - W(\Gamma - \gamma) - \mathbf{V}.\nabla_H T \quad (1)$$

with geostrophic assumption is considered. Under geostrophic assumption the advection term is given by:

$$\mathbf{V}.\nabla_H T = - \frac{fT}{g} V^2 \frac{\partial \theta}{\partial z} \quad (2)$$

where $\partial\theta/\partial z$ is the change of direction with height. The values of the diabatic term $1/c_p$ (dH/dt) at different levels are taken from Murgatroyd and Goody (1958). Γ and γ are the dry adiabatic and the environmental lapse rates.

The results of the computation of vertical motions within the Indian tropical middle atmosphere have suggested general prevalence of downward motion (subsidence). The range of variation in the absolute magnitudes of the vertical motions was 10.8 to 0.0 cm sec^{-1} in 1972 and 2.8 to 0.0 cm sec^{-1} in 1975. Also the upward vertical motion persisted for a longer period in 1972 than in 1975 (Mukherjee *et al.* 1984).

2.4. *Effects of strong volcanic eruption on rainfall*

Recent studies have suggested modification of climate by aerosols dispersed in the stratosphere by strong volcanic eruptions. Opinions have been veering strongly around the hypothesis, based on both observational (Sedlaceck *et al.* 1983) and the theoretical studies (*e.g.*, Pollack *et al.* 1976), that the amount of sulphurous gases released in the stratosphere from the great volcanic eruptions has an ability to modify the climate. Handler (1986) has pointed out that the Indian monsoon activity could be modulated by stratospheric aerosols released by volcanic eruptions.

Using a long-series of data of low-latitude volcanic eruptions with volcanic explosivity index (VEI) 4 or more and rainfall data of 15 Sri Lankan stations for a period of 112 years (1869-1980), we have studied the effect of volcanic eruptions on the northeast monsoon rainfall (Mukherjee *et al.* 1987). There are 25 low-latitude volcanoes recorded during 1869 to 1980. 3 volcanic eruptions are reported in both the years 1902 and 1966, and 2 in 1951. Their combined effect in each year are considered to arise from one volcano, reducing the number of volcanoes from 25 to 20. The rainfall for the northeast monsoon (October-December) for each station is classified into 4 groups according to the signs of the percentage departures of the rainfall for the two successive years. Stations with negative depatures of rainfall for two successive years following an eruption, are classified as Group A and is indicated by the sign (— —); stations receiving negative departures of rainfall in the first year and positive departures in the second year classified as Group B which is indicated by the sign (— +). Following the same line of argument Groups C and D are constituted and indicated by (+ —) and (+ +) respectively. A table (Table 3) is constructed to show the effect of the eruption of each volcano on the distribution of the rainfall received at different stations since 1869. The study has revealed that the 53-80 per cent of strong volcanic eruptions were associated with deficient rainfall at 14 out of 15 Sri Lankan stations during the following first and the first two successive northeast monsoon season (Table 4). Also 53-100 per cent of the stations received deficient rainfall during the first and the first two successive northeast monsoon seasons, following by 12 out of 20 strong volcanic eruptions. The study has suggested occurrence of deficient rainfall in the latitudes of the ITCZ, which is thought to be shifted further southwards from its normal position during northeast monsoon season due to weak solar radiation resulting from the dispersal of the volcanic aerosols in the stratosphere. The recent studies of Handler (1986) and the study conducted by us have led to the belief that the aerosols, particularly sulphuric acid particles, released in the stratosphere by strong volcanic eruptions play an important role in modifying climate and weather.

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