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Review Paper

Middle atmosphere Aerosols, Dynamics and Monsoon Variability: a Review

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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 stratospheric warming 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 into the stratosphere from the great volcanic eruptions modulates the climate (rainfall). The authors have made an attempt in this paper to present a review of the work done so far in this direction.*

Keywords: Middle atmosphere, interannual variability, stratosphere, Quasi-biennial oscillation.

Introduction

The coupling between the stratosphere and troposphere phenomenon forms an important part of the middle atmosphere processes. Severe distortion of troposphere circulation over the high-latitude associate with major sudden stratospheric warming events [1, 2, 3] has shown that the stratospheric disturbances are accompanied by troposphere blocking between 85 and 95 per cent of the time. The influences of the middle atmospheric parameters and their linkages with the troposphere phenomena over tropics have been reported [4, 5, 6, 7, 8 9, 10]. 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 [8, 9, 10].

Stratosphere For many years, climatologists have noticed a connection between large explosive volcanic eruptions and short term climatic change. At first, scientists thought that the dust emitted into the atmosphere from large volcanic eruptions was responsible for the cooling by partially blocking the transmission of solar radiation to the Earth's surface. However, measurements indicate that most of the dust thrown in the atmosphere returned to the Earth's surface within six months. Recent stratospheric data suggests that large explosive volcanic eruptions also eject large quantities of sulfur dioxide gas which remains in the atmosphere for as long as three years. In the last century, two significant climate modifying eruptions have occurred. El Chi chon in Mexico erupted in April of 1982, and Mount Pinatubo went off in the Philippines during June, 1991. Of these two volcanic events, Mount Pinatubo had a greater effect on the Earth's climate and ejected about 20 million tons of sulfur dioxide into the atmosphere. Researchers believe that the Pinatubo eruption was primarily responsible for the 0.8 degree Celsius drop in global average air temperature in 1992 [14, 15, 16, 17, 18, 19]. The global climatic effects of the eruption of Mount Pinatubo are believed to have peaked in late 1993.

The summer monsoon phenomenon is a spectacular seasonal troposphere 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.

Data sets considered: Monthly mean zonal wind data for 30 mb (about 25 km) for low-latitude stations Balboa (9° N, 80° W) and Tiruvanantapuram (8.19° N, 76.57°E) from June-August and the mean percentage departures of the rainfall for the whole India during June to September for a period of 55 years (1951-2006) are considered to examine the relationship between them. The rocketsonde temperature and wind data for the month of January, which typically represents the northern winter, for the 12-year period (1970-1972, 1974-1976, 2000-2003, 2005-2007 for stations (1) Thule (76. 6°N, 68. 8°W), (2) Poker Flat (65.1 N, 147 W), (3) Fort Churchill (58.7°N, 93 W), (4) Wollops

Island (37.8°N, 75 W), (5) Cape Kennedy (.28.N, 80 W), (6) Fort Sherman (9 .3°N, 80W), (7) Kwajalein (8.7°N, 167.7°E) and (8) Ascension Island (8 S, 14.4°W). are considered here to examine the interannual variability of the middle atmosphere and monsoon variability. From 1990 to 2009 temperature and wind data are collected for 30hpa from, Monthly Climatic Data for the World data. Rocket-sonde temperature data of the north- pole at 30 and 10 hpa levels are used to study the stratospheric warming at high latitudes. Using a long-series of data of volcanic eruptions with volcanic explosivity index (VEl) 4 or more and rainfall data of 15 Sri Lankan stations and 17 Indian stations for a period of 140 years (1869-2008), we have studied the effect of volcanic eruptions on the north east monsoon and south west monsoon rainfall.

Analysis methodology adopted: The mean zonal wind (June-August) at 30hpa for Balboa and Tiruvanantapuram for the available 55-year period (1951-2006) is considered. Since winds show variability in the stratosphere during September (transition month) data during June-August are considered to represent the characteristics of the winds in the lower stratosphere during monsoon. The mean percentage departures of the rainfall for India from its 55-year normal are calculated for each monsoon season (June-September). Rainfall in the country is recorded for subdivisions by the India Meteorological Department (IMD). The value of correlation coefficient between the rainfall departures of India and the mean zonal wind at 30hpa for Balboa and Tiruvanantapuram (June-August) for 1951-2006 calculated.

The three post-monsoon months, October – December comprises a period where most of the storms form over the Indian sea basins i.e. the Arabian Sea and Bay of Bengal. The frequency of cyclones and depressions for the 50-year period, 1951-2001 during each season which consists of the three months, October –December are collected from the publication on “Tracks of storms and depressions in the Bay of Bengal and Arabian sea” by India Meteorological Department. The mean zonal winds for 30hpa for Balboa and Tiruvanantapuram, during the same 50-year period are also considered. The weak easterly (speed up to 5 m/sec) and the westerly winds are considered together as the zonal wind in the westerly phase, the zonal winds in the easterly phase exceed a speed of 5 m/sec from the east in the present study. In order to examine whether the difference in the frequency of occurrence of storms and depressions over the Indian seas during the two phases of the QBO are significant , a non parametric statistical test known as the Mann-Whitney U Test has been applied.

The mean zonal wind and mean temperature for January from 25 to 55 km for the stations mentioned above are plotted at an interval of 5km from 25 to 55 km and analyzed. Using a long-series of data of volcanic eruptions with volcanic explosivity index (VEl) 4 or more and rainfall data of 15 Sri Lankan stations and 17 Indian stations for a period of 140 years (1869-2008), studied the effect of volcanic eruptions on the northeast monsoon and southwest monsoon rainfall The rainfall for the southwest monsoon (June-September) and 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 departures 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. Following Siegel (1956) a non-parametric sign test by taking into account a posteriori choice of statistics has applied to examine the statistical significance of the effect of the volcanic eruption on rainfall.

Results and Discussion

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) Stratospheric warming in high/low-latitude during winter and (iv) stratospheric aerosols released from major volcanic eruptions. 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 hpa for Balboa data during the post monsoon season (October-December), for 50 years (1951-2001), considered here to examine the effect of QBO modulation on the storm generating mechanism in the Indian seas.

Low-latitude stratospheric QBO and Indian summer monsoon: The QBO in the lower stratospheric zonal wind over low latitudes is a major oscillation with a period of 26 months. Several workers reported dominance of QBO spectral peak in the Indian monsoon rainfall [20, 21, 22, 23, 24, 25, 26, 27, 28]. Monthly mean zonal wind data for 30 mb (about 25 km) for low-latitude stations Balboa (9° N, 80° W) and Tiruvanantapuram(8.19° N, 76.57°E) from June-August and the mean percentage departures of the rainfall for the whole India during June to September for a period of 55 years (1951-2006) are considered to examine the relationship between them. The data for Balboa (has a long-series of high-altitude radiosonde observations reaching up to lower stratosphere) is considered up to 2001 and Tiruvanantapuram data is considered from 2001 to 2006. Also the QBO observed in the lower stratosphere is a global phenomenon. Mukherjee et al. (1985), Bhalme et al. (1987) [29,30] have considered the zonal wind at 30, 10 hpa for the same station Balboa and examined the relationship of the phases of the QBO with reference to the Indian monsoon rainfall Our investigation has revealed a relationship between the phases of the QBO and the rainfall activity over India (Figure 1). About 20 per cent of the variability in the rainfall over India during the summer monsoon has been attributed to the pattern of the QBO (r = 0.2).

Gray et al. (1984a), (1984b), (1993), (1993), (1997) [31, 32, 33, 34, 35], 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 Indian seas. Gray has shown a negative correlation between the frequency of the hurricane activities and easterly phases of the QBO. Similar positive relationship of the frequency of cyclonic storms and depressions forming in the Indian seas have shown an in phase relation with the westerly phase of the QBO [36, 37] Similar negative relationship of the hurricane, hurricane days and tropical storms with the moderate to strong *EI Nino* has been indicated [38]. They have also pointed out an association of the ENSO events with the Indian summer monsoon rainfall. Hirschberg and Fritsch, (1991) [39] have shown that, a relationship exists between stratospheric processes (especially temperature advection and density advection) and low-level pressure change in developing cyclones.

They found strong correlations between lower-stratospheric warming and sea level pressure fall. But 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 50 years (1951-2001), 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 6.2 in the westerly phase (varying from westerly to 5.0 ms-1 easterly) and 4.3 in the easterly phase (more than 5.0 m/s 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.

Speed is in m/s. Westerly phase is from westerly to 5.0 ms-I easterly and easterly phase is more than 5 .0 m/s easterly, 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 7.2 in the westerly phase and 4.3 in the easterly phase per season It is noteworthy that out of 8 moderate to strong and strong *El Nino* years (1953, 1958, 1972, 1973, 1976, 1982,1983 and 1991) considered in Table 1, only 1 moderate to strong *El Nino* occurred in the westerly phase (1982) and all the remaining 7 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* year 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 6.3 per season in the *El Nino* years whereas it was 3.83 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 favorable during the waning phase of the *El Nino* episodes, even though the QBO was in the easterly phase.

Interannual variability of high-latitude middle atmosphere during winter and Indian summer monsoon : Investigations on the middle atmosphere have given ample stress on the interannual *variability* (IAV) of the high-latitude stratospheric *circulation* during. Winter [40, 41, 42]. Also it has been suggested that *the* phases of the low - latitude QBO could modulate the interannual variability in the high-latitude middle Atmosphere [43]. Since a relation ship 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 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 12-year period (1970-1972,1974-1976, 2000-2003, 2005-2007) are considered here. The names of the stations and their geographical locations, for which data are available for the levels 25-35 km, up to 1990 are given below:
(1) Thule (76. 6°N, 68. 8°W), (2) Poker Flat (65.1 N, 147 W), (3) Fort Churchill (58.7°N, 93 W), (4) Wollops Island (37.8°N, 75 W), (5) Cape Kennedy (.28.N, 80 W), (6) Fort Sherman (9.3°N, 80W), (7) Kwajalein (8.7°N, 167.7°E) and (8) Ascension Island (8 S, 14.4°W).

From 1990 to 2009 temperature and wind data are collected for 30hpa from The Data book “Monthly Climatic Data for the World.”

Figure 2 Latitudinal distribution of zonal wind (ms-I) at 35 km and 30 hpa for January for 12 years (1970-1972), (1974-1976), (2000-2003) and (2006-2007).

The percentage departures of the monsoon rainfall of India as a whole, from its 50-.year mean (1951-2006) for the entire country, were+10.6, +2.7, -17.8, -1.8, +18.9 , +0.1, -6.9, -6.9, -18.3, 3.2, +0.5 and 5.7 during 1970,1971, 1972, 1974, 1975 and 1976, 2000, 2001, 2002, 2003 , 2006 and 2007 respectively. Our study has broadly suggested that *(i)* the stable and strong polar night jet near 60N in January has preceded weak to normal summer monsoon year, namely, 1972 (-17.8 per cent), 1974 (-1.8 per cent), 1976 (+0.1 percent), 2000(-6.9 percent)), 2001(-6.9 percent)) and 2002(-18.3 percent)) and *(ii)* early breaking of the polar night jet and presence of easterlies/weak westerly 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 percent), 2003 (3.2 percent), 2006(0.5 percent) and 2007(5.7 percent) respectively. The latitudinal distribution of the zonal wind at 35 km and 30 hpa only for January for 12 years considered, is given here as an illustration in support of the above inferences (Figure 2, Figure 2a) and temperatures for January at 30hpa (Figure 2b). It is also noticed from the analysis of the rocket-sonde temperature that the North Pole temperature at the middle atmosphere during January was cold during 1972, 1974, 1976, 2000, 2001, 2002 and warm during 1970, 1971, 1975, 2003, 2006 and 2007. These results have indicated that the early breaking of the stratospheric polar vortex may be conducive to the better performance of the forthcoming summer monsoon over India [34]. Wallace et al. (1982) [40] 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 (November -January) for a period of 53 years from 1955-1956 to 2008-2009 are analyzed. The data are obtained from the Free Berlin University. The departures of the average temperatures of December and January for each winter from their 53-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 -l0 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 9 occasions of excess rainfall (departures more than + 10 per cent) during 1959 (+ 13.8), 1961 (+ 12.4), 1970 (+10.6), 1975 (+18.9), 1978 (+11.9), 1983 (+13), 1988 (+19.3) and 1994(12.5) on7 occasions *i.e.*, 80 per cent of cases strong monsoon activity was preceded by warm anomaly in the north pole winter 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 10 occasions of deficient rainfall (departures less than -10 per cent) during 1965 (-15.0), 1966 (-11.1), *1972* (-17.8) , 1979 (-15.4),1982(-14.5),1986(-12.7),1987(-19.4),2002(-19.4),2004(-13.8) and 2009(-21.8) on 7 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 (+3.7°C) in the polar temperatures during winter is associated with the positive departures of rainfall (+14.1 per cent), and the average of negative anomaly (-4. 2°C) with the negative departures of rainfall (-16.1 per cent).

Effects of 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 [44] and the theoretical studies [45], that the amount of sulphurous gases released in the stratosphere from the major volcanic eruptions has an ability to modify the climate. Handler et al. (1986), Sedlacek et al. (1983), Lough et al. (1987), Lamurche et al. (1984), Millard et al. (2006) [46, 47, 48, 49, 50] 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 volcanic eruptions with volcanic explosivity index (VEl) 4 or more and rainfall data of 15 Sri Lankan stations and 17 Indian stations for a period of 140 years (1869-2008), we have studied the effect of volcanic eruptions on the northeast monsoon and southwest monsoon rainfall [14,16, 17, 18]. There were 30 volcanoes recorded during 1869 to 2008. 5 volcanic eruptions are reported in both the years 1902 and 1966, and 4 in 1951. Their combined effect in each year is considered to arise from one volcano, reducing the number of volcanoes from 30 to 25. The rainfall for the southwest monsoon (June-September) and 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 departures 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 29out of 30 stations during the following first and the first two successive monsoon seasons (Table 4). Also 53-100 per cent of the stations received deficient rainfall during the first and the first two successive monsoon seasons, following by 20 out of 25 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 monsoon season due to weak solar radiation resulting from the dispersal of the volcanic aerosols in the stratosphere. Studies of Handler et al. (1986) [46] 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.

Current status and future perspectives: Study of climate variations has assumed great importance now-a-days. Recently discovered Antarctic ozone hole and the aerosols injected into the stratosphere by the frequent volcanic eruptions in recent years could play dominant role in modifying the earth's climate. The authors intend to enhance the scope of the present research further to find out some middle atmospheric features that will be useful for studying the global climatic variability. Synthesis of the tropospheric and the middle atmospheric processes forms an important study of the middle atmosphere. More observational and theoretical studies should also be undertaken for better understanding of the different processes responsible for coupling of the troposphere and the middle atmosphere.

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Table 1
Frequency of cyclonic storms in westerly and easterly phases of QBO and mean zonal Wind anomaly at 30hpa (QBO m/s). Speed is in ms-I. Westerly phase is from westerly to 5.0 m/s easterly and easterly phase is more than 5 .0 m/s easterly N=34 years mean westerly = +3.395 cyclones/season = 6.2 N=25year mean easterly = -14. 984 cyclones /season = 4.3

1	1952	8	8	1	1951	+0.76	4
2	1954	-4	4	2	1953*	-16	2
3	1955	-2	5	3	1956	-25	3
4	1957*	6	8	4	1958*	-23.8	7
5	1959	6	9	5	1960	-15.8	5
6	1961	1.3	8	6	1962	-22	4
7	1963	9.8	8	7	1964	-9	5
8	1966	5.3	8	8	1965*	-14	7
9	1967	-1.2	6	9	1968	-20	4
10	1969	-4	5	10	1970	-15	5
11	1971	0.1	8	11	1972*	-21	6
12 13	1975 1977*	6 1.0	10 10	12	1973*	-6	6
14	1980	2	9	13	1974	-25	5
*15	1982*	-2	6	14	1976*	-22	10
16	1985	0.1	9	15	1978	-9	6
17	1986	-4.5	4	16	1979	-23	5
18	1987*	10.1	6	17	1981	-23	5
19	1988	3.2	9	18	1983	-5.7	2
20	1990	10	9	19	1984	-9.4	2
21	1992	+10.98	12	20	1989	-13.1	2
22	1993	-0.4	7	21	1991*	-7.5	6
23	1994	+3.3	6	22	1995	-7.1	3
24	1997	10.3	6	23	1996	-7.2	3
25	1999	+12.5	6	24	1998	-6	4
26	2001	0.4	5	25	2000	-9	2
27	1990	+10.4	7				
28	1992*	+10.98	12				
29	1993	-0.44	4				
30	1994*	+3.3	4				
31	1995	+4.9	7				
32	1997*	+10.3	10				
33 34	1999 2001	+12.5 +0.43	6 6				

Table 2
Mean warm and cold anomalies in the polar temperatures at 30 hpa during November to january, position of 500 hpa ridge at 750 E during April and Percentage departures of rainfall during following summer monsoon

Winter Warm Ridge at 500 hpa Summer Percentage Years	Warm(+) !cold (-) Anomaly^{0}C	Ridge at 500 hpa April Along 75°E	Summer Years	Percentage departures of Rainfall
1958-59	+2.3	16.0N	1959	+13.8
1960-61	+7.8	15.0N	1961	+12.4
1964-65	-3.7	14.0N	1965	-15.0
1965-66	+5.3	13. 5N	1966	-11.1

1969-70	+11.8	15.8N	1970	+10.6
1971-72	-5.7	11.0N	1972	-17.8
1974-75	+3.3	17 5N	1975	+18.9
1977-78	-2.7	14.0N	1978	+11.9
1978-79	-1.7	12.5°N	1979	-15.4
1981-82	-0.9	11.4 N	1982	-14.5
1982-83	2.3	14.5 N	1983	+13
1985-86	-5.9	11.5 N	1986	-12.7
1986-87	-7.2	12.6N	1987	-19.4
1987-88	3.8	15.8N	1988	+19.3
1993-94	1.4	16N	1994	+ 12.5
2001-2002	0.4	11N	2002	-19.2
2003-2004	0.2	14N	2004	-13.8
2008-2009	-6.1	11.2N	2009	-21.8

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 asterisk *)

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
Anuradj1apura	31.6*	31.6*	15.8	21.0
Maha				
IHuppallama	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 EIiya	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
Ahmedabad	29.5*	35.0*	25.0	20.0
Bengalore	50.0*	42.1*	15.9	13.3
Bhopal	31.6*	42.1*	16.8	10.0
Bombay	40.0*	35.7*	23.5	0.0
Cochin	40.0*	35.0*	24.2	20.0
Gopalpur	60.0*	20.2	21.0	2.5
Hyderabad	25.0	35.0*	35.0*	20.0
Jagdalpur	35.0*	35.7*	35.0*	13.3
Mangalore	35.0*	42.1*	35.0*	20.0
Goa	35.0*	20.1	29.5*	0.0
Kandla	60.0*	26.7*	10.0	10.0

Nagpur	25.0	35.7*	29.5*	35.7*
Pune	60.0*	20.0	22.0	20.0
Raipur	23.0	25.0	25.0	35.7*
Tiruchirapalli	35.7*	35.7*	28.1	20.0
Veraval	60.0*	24.9	26.5	13.3
Vishakhapatnam	35.0*	40.0*	24.5	20.0

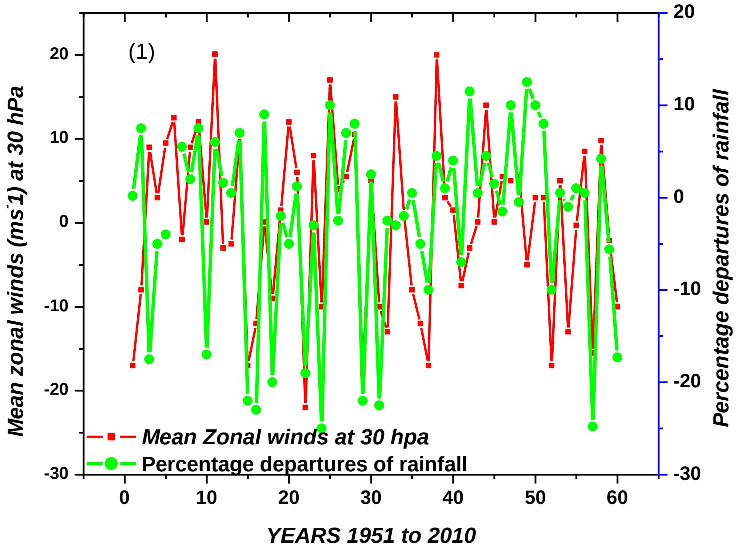

Figure 1: Mean zonal winds at 30mb (Balboa and Tiruvanantapuram) and percentage Departures of rainfall

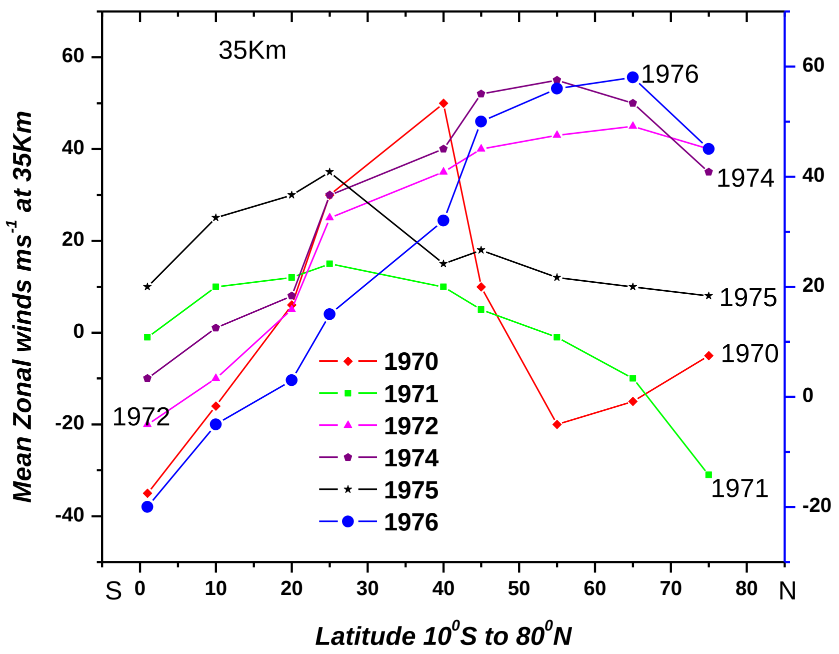

Figure 2: Latitudinal distribution of zonal winds (ms-1) at 35 Kms for January for 6 years (1970-1972) and (1974-1976)

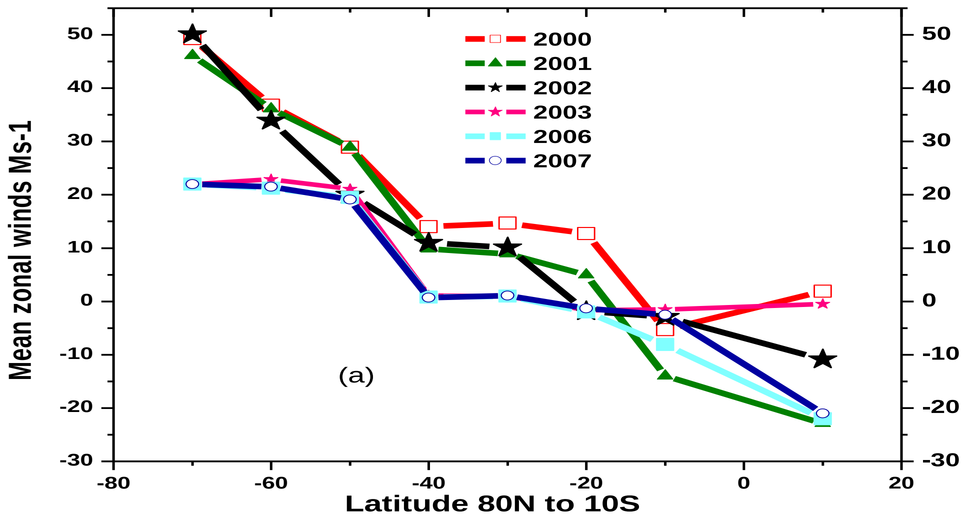

Figure 2a: Mean zonal winds (Ms-1) during January from 80N – 10S for 6-year period (2000-2003 and 2006 – 2007)

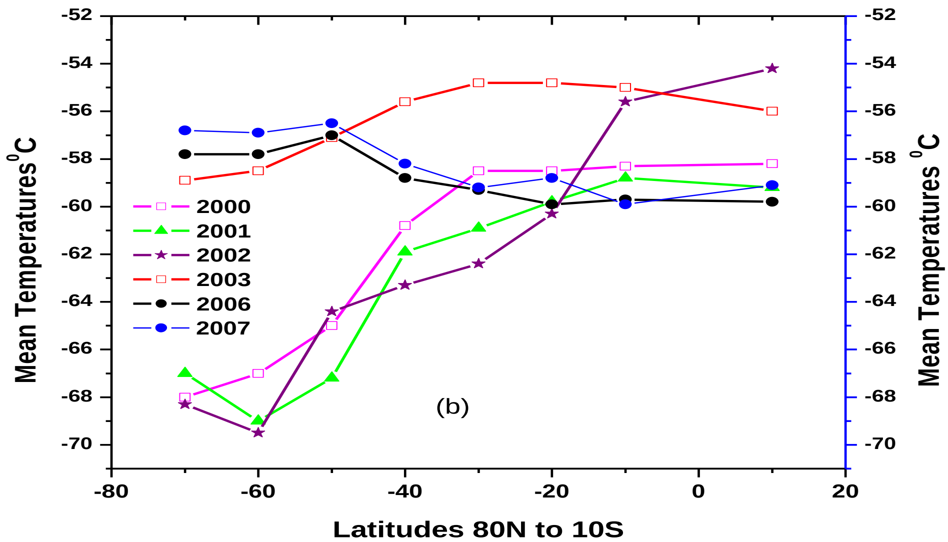

Figure 2b: Mean temperatures ^{0}C of January during 2000 – 2003 and 2006 – 2007 from 80N to 10S