Indian Journal of Radio & Space Physics
Vol. 25, June 1996, pp. 136-144

Climatology of the atmosphere up to 30 km over Thumba*

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Received 29 May 1995; revised 27 November 1995; accepted 30 January 1996

Wind and temperature data from surface to 30 km over Thumba for a period of 23 years from 1970 to 1992 are analysed. The long term mean pattern of the wind components and temperature as well as their monthly variations are studied. The prominent wave components present are identified and their amplitude and phase as well as their cycle-to-cycle variations are brought out. Also, the variations of the annual mean temperatures are worked out and vertical profile of these variation presented. The mean wind and temperature structure and characteristics of the quasi-biennial, annual and semi-annual oscillations in winds and temperature up to 30 km agree with the earlier results obtained from shorter data periods. Apart from this the present analysis reveals a rising trend in the annual mean temperature at all levels in the troposphere over Thumba. It is also seen that the monthly mean temperatures around 18 km are warmer by about 5K from the annual mean during the peak of the tropical easterly jet at around 15 km.

1 Introduction

Regular observations of the meteorological parameters of the middle atmosphere using M-100 rockets have been made from Thumba (8°32'N,76°52'E) since December 1970. High altitude balloon observations for wind measurements commenced at Thumba in April 1967. Temperature measurements using radiosonde (RS) instruments commenced in April 1970. The data collected from these balloon ascents for different lengths of time have been used extensively by various investigators to evolve the climatological reference profiles and to identify and bring out the characteristics of the long period oscillations in winds and temperature[1-6]. Sasi and Krishna Murthy[7] studied the characteristics of the quasi-biennial oscillation (QBO) both in zonal wind and temperature. Chakravarthy *et al.*[8] have updated the reference profile of temperature and winds and have shown that there has not been any change in the pattern of long period oscillation and temperature structure for the 20-80 km region. Most of these studies, which utilized the data collected at Thumba, extend up to 80 km, but do not cover the troposphere in full. Jain *et al.*[5,6] had included the Thumba balloon data also in their studies and obtained the mean profile and wave components for the zonal wind. Sasi and Sen Gupta[9] and Sasi[10] utilised the radiosonde temperature data of the troposphere also to compute a reference atmosphere for the Indian equatorial zone. The Thumba balloon data have also been used in the computation of the model atmospheric winds and temperature and in the study of long period oscillations in winds and temperature[10,11]. But in these studies, data up to 1986 only were used and the data were for shorter durations. Radiosonde data collection on a weekly basis, up to 30-35 km, has been continuing regularly at Thumba since April 1970. The data from these ascents, up to 1992, have been used here to confirm the results obtained by previous workers using smaller data base and to bring out the nature of temperature changes associated with established seasonal features of the mean zonal wind and also to study the nature of the annual mean temperature variation in the troposphere over Thumba.

*This paper was presented at the eighth National Space Science Symposium held during 20-24 December 1994 at Vikram Sarabhai Space Centre, Trivandrum.

2 Data and method of analysis

Weekly high altitude balloon ascents have been made regularly from Thumba to collect upper air data on winds at 1 km altitude interval. Radiosonde (RS) ascents commenced in April 1970. Two types of radiosonde instruments were used—one operating at 1680 MHz carrier frequency and the other operating at 1780 MHz. In the former type both Indian and American instruments were used, while only Russian instruments were used in the latter type. The time of observation was around 1430 hrs LT for most of these flights. The data available for the 23 year period since January 1970 were consolidated. Although some of these balloons had reached maximum altitude of up to 40 km, the number of ascents exceeding 30 km were less. Table 1 summarizes the monthwise data availability of winds and temperature for the 23-year period. Monthly mean values at 1 km altitude interval was computed for the zonal and meridional winds and temperature to get a time series of these parameters. For winds, the series of monthly means was continuous for the data length of 276 months. But for temperature, there was a long gap of 12 months from May 1975 to April 1976 and another gap of 7 months from May 1977 to November 1977. The 23-year means of wind components and temperature, for each of the calendar months from January to December, were also calculated at 5 km intervals from surface to 30 km and these are presented in Tables 2 and 3 for temperature and zonal winds, respectively, along with the corresponding values for 10°N from the COSPAR International Reference Atmosphere (CIRA) 1986 for comparison. The long term means of wind components and temperature at 1 km interval were obtained from the monthly mean of these parameters for the 23-year period. The profiles of these long term means with standard deviation are shown in Fig. 1[(a), (b) and (c)]. Cross-sections of the monthly variation of the zonal and meridional winds and temperature deviations are shown in Fig. 2[(a), (b) and (c)]. In the case of temperature, the deviations (ΔT) of the monthly mean value from the annual mean is used to construct Fig. 2(c). The monthly mean values of the zonal and meridional winds and temperature were used for further analysis. Part of the departure of the annual mean values from the monthly mean could be accounted for by the periodic variations. Since the data pertains to a single station only, temporal variations were studied using the time series of monthly mean

Table 1—Monthwise data availability with maximum altitude

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1970	4(34)	5(36)	4(33)	5(30)	5(33)	3(32)	4(37)	3(28)	9(33)	5(34)	6(31)	5(33)
1971	3(33)	4(34)	5(35)	5(36)	5(35)	5(34)	4(30)	4(32)	5(33)	4(34)	4(30)	4(30)
1972	3(33)	4(34)	5(34)	4(35)	3(35)	5(35)	4(33)	8(33)	8(31)	5(35)	8(32)	9(32)
1973	2(32)	3(31)	5(32)	4(35)	1(32)	2(30)	3(33)	4(34)	3(25)	1(25)	2(24)	2(25)
1974	3(32)	4(31)	4(32)	4(32)	5(35)	5(38)	6(35)	4(36)	4(36)	3(35)	3(33)	2(33)
1975	6(38)	9(33)	6(36)	6(37)	4(35)	4(35)	5(24)	3(27)	4(29)	4(33)	5(38)	5(35)
1976	3(18)	5(26)	6(29)	9(25)	10(35)	5(35)	4(37)	5(32)	6(35)	4(36)	6(37)	10(37)
1977	0(0)	0(0)	3(35)	3(35)	0(0)	0(0)	4(35)	4(35)	4(34)	3(33)	3(35)	5(34)
1978	3(34)	4(35)	5(28)	0(0)	9(34)	6(36)	7(35)	9(36)	5(34)	6(34)	7(32)	5(23)
1979	7(33)	7(29)	7(29)	6(30)	6(32)	6(30)	4(32)	8(32)	3(30)	0(0)	1(35)	4(36)
1980	9(36)	4(34)	4(35)	6(37)	4(35)	2(34)	4(34)	4(36)	4(35)	4(34)	1(35)	2(28)
1981	3(24)	2(22)	3(25)	4(24)	5(25)	5(34)	5(26)	4(35)	5(32)	4(35)	4(35)	5(34)
1982	3(33)	3(34)	5(29)	4(27)	4(30)	4(30)	5(25)	4(29)	5(28)	4(30)	4(28)	4(27)
1983	2(27)	4(27)	6(35)	2(31)	4(31)	6(31)	0(0)	5(31)	6(31)	4(31)	6(30)	5(31)
1984	2(30)	6(30)	4(30)	4(30)	6(31)	5(29)	5(31)	7(30)	4(31)	1(29)	3(30)	4(30)
1985	3(30)	7(33)	4(29)	4(30)	8(30)	7(31)	8(31)	5(30)	4(34)	5(34)	7(35)	6(32)
1986	6(34)	5(32)	6(33)	6(32)	2(33)	4(34)	6(32)	5(33)	2(29)	4(25)	1(23)	0(0)
1987	3(28)	3(27)	5(32)	5(30)	4(35)	4(26)	8(37)	3(34)	2(33)	3(35)	2(20)	0(0)
1988	1(32)	1(35)	4(36)	2(33)	4(38)	5(34)	4(34)	4(29)	3(33)	3(35)	7(33)	3(37)
1989	6(34)	6(36)	2(31)	0(0)	3(33)	5(33)	4(29)	4(32)	3(34)	4(33)	3(32)	3(32)
1990	0(0)	0(0)	0(0)	0(0)	11(35)	4(35)	3(33)	5(33)	5(30)	6(34)	7(33)	9(33)
1991	6(31)	6(33)	4(33)	8(35)	7(34)	3(35)	5(32)	4(32)	3(33)	4(33)	4(32)	2(29)
1992	2(31)	2(32)	2(31)	3(33)	8(32)	2(32)	4(32)	3(32)	2(32)	3(32)	3(31)	5(33)

Note: Numbers within brackets denote the maximum altitude reached for any ascent.

values. The missing data were filled using climatological mean values and by cubic spline interpolation. The time series thus obtained for all the three parameters were subjected to power spectrum analysis[12]. The maximum lag used was 132 months. The analysis was done for all the three parameters from surface to 30 km altitude at 1 km interval. Amplitude peaks corresponding to a period of 12 months (annual oscillation, AO) was prominent in the spectrum at 15 km for zonal

Table 2—Long term monthly mean of temperature for Thumba with corresponding values for 10°N from CIRA 1986

	Height km	Temperature (K) for the month											
		J	F	M	A	M	J	J	A	S	O	N	D
CIRA	0	300	300	300	301	301	301	301	301	301	301	301	300
THUMBA		304	305	306	306	305	302	301	301	303	303	304	304
CIRA	5	272	273	272	272	273	272	272	272	272	272	273	272
THUMBA		274	273	274	274	274	274	274	273	273	273	274	273
CIRA	10	239	239	239	239	239	239	239	239	239	239	239	238
THUMBA		241	240	241	242	243	242	241	241	241	241	241	241
CIRA	15	200	200	200	200	200	201	203	202	202	200	199	199
THUMBA		202	202	203	202	202	202	201	201	201	200	201	201
CIRA	20	205	205	205	206	207	209	209	209	209	208	207	206
THUMBA		205	204	204	204	206	207	209	209	208	207	206	206
CIRA	25	218	218	219	220	221	221	220	219	218	219	219	219
THUMBA		220	219	220	221	222	222	221	221	220	219	220	220
CIRA	30	228	229	230	230	231	230	229	228	230	232	231	229
THUMBA		230	229	231	234	235	233	231	231	231	232	232	231

Table 3—Long term monthly mean of zonal wind for Thumba with corresponding values for 10°N from CIRA 1986

	Height km	Zonal wind (m/s) for the month											
		J	F	M	A	M	J	J	A	S	O	N	D
CIRA	0	−5	−5	−5	−4	−3	−1	0	0	0	−2	−4	−5
THUMBA		2	2	2	1	2	2	3	3	3	2	1	1
CIRA	5	−2	−2	−3	−2	−3	−4	−4	−4	−4	−4	−4	−3
THUMBA		−3	−3	−4	−5	−1	6	5	6	3	0	−1	−6
CIRA	10	5	4	3	4	1	−5	−6	−7	−5	−3	0	2
THUMBA		−1	1	1	−1	−2	−6	−9	−10	−9	−6	−4	−3
CIRA	15	13	1	10	13	9	0	−5	−8	−5	−2	6	12
THUMBA		1	−1	3	−3	−13	−32	−36	−37	−29	−18	−7	0
CIRA	20	1	−1	−2	−1	−3	−9	−13	−15	−12	−10	−5	0
THUMBA		1	3	3	1	−4	−11	−16	−16	−12	−6	−3	−2
CIRA	25	−7	−8	−6	−7	−12	−17	−21	−22	−19	−17	−10	−6
THUMBA		−6	−3	−5	−8	−12	−18	−21	−20	−16	−13	−11	−6
CIRA	30	−11	−11	−8	−11	−18	−23	−27	−28	−23	−18	−8	−8
THUMBA		−5	−6	−13	−13	−17	−22	−24	−23	−16	−12	−5	0

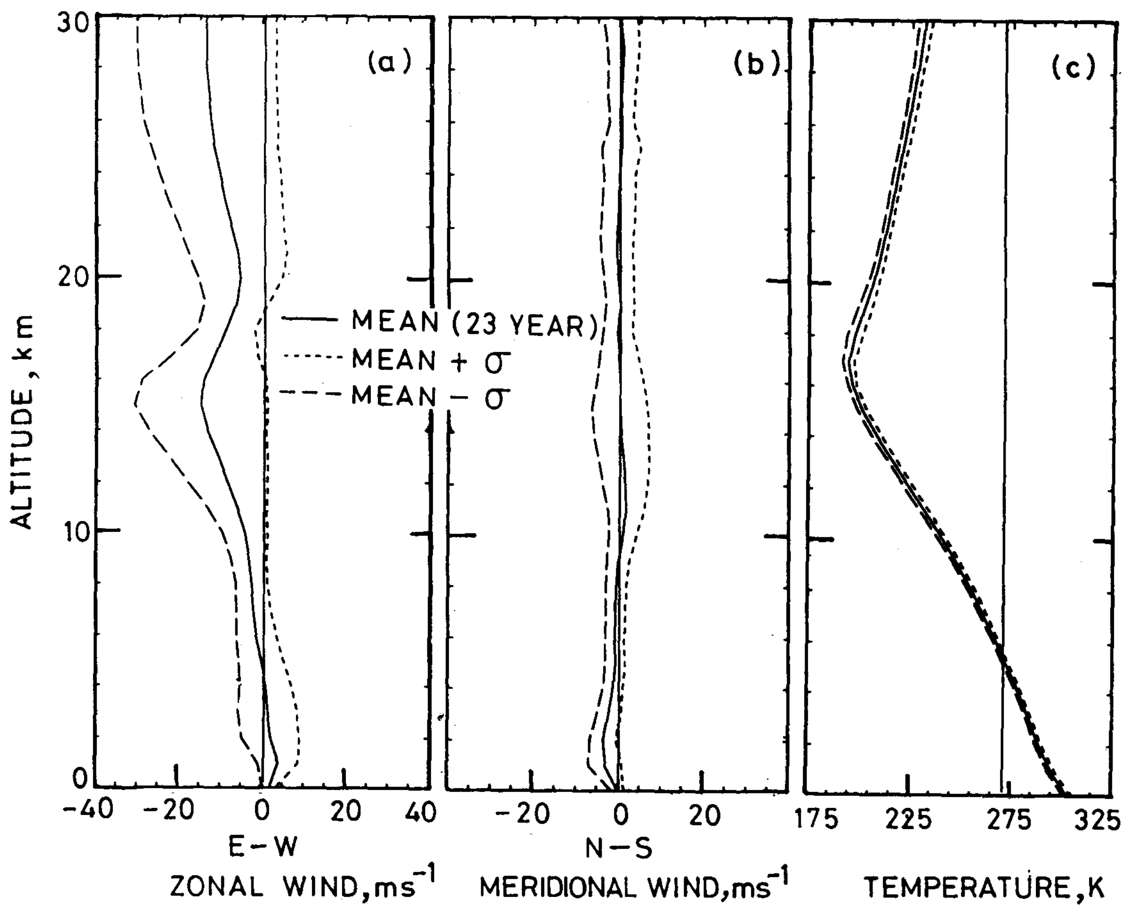

Fig. 1—Profiles of 23 years mean of (a) zonal wind, (b) meridional wind and (c) temperature along with mean +/-σ (standard deviation) on either side of the mean profile

wind at 18 km for temperature and at 14 km for meridional wind. Another amplitude peak was seen with a period of 28/29 months at 29 km for zonal wind and at 21 km for temperature, respectively. This is identified as the QBO. An oscillation with a period of 6 months (semi-annual oscillation, SAO) was also present at 16 km for the zonal wind and at 17 km for temperature. The QBO and SAO are detectable at 14/15 km in the meridional wind but they are weak. The amplitude spectrum at 5 km interval for the zonal wind is shown in Fig. 3. To extract the QBO component for a particular level, the long term mean values for each of the calendar months were subtracted from the respective values of the time series of monthly means and the new series of residuals thus obtained was subjected to harmonic analysis with a fundamental period of 29 months or 28 months as the case may be for wind components and temperature, respectively. This was repeated for all the remaining months. These mean values for each of the calendar months were subtracted from the individual monthly mean values to get a time series of residuals for each level. The series thus obtained was assumed to be devoid of contribution from AO and SAO. This series was subjected to harmonic analysis with the same fundamental period of 29 months or 28 months as the case may be for winds and temperature, respectively, to obtain the amplitude and phase of QBO. This was repeated for all the levels up to 30 km. Next, the contributions of QBO from the corresponding cycles were subtracted from the monthly mean values and from the resulting residual values 23-year mean value for each month was calculated for each level. Harmonic analysis was carried out on the set of 12 values thus obtained for each level, using a fundamental period of 12 months to get the amplitude and phase of the annual and semi-annual oscillations. Figures 4-6 show the amplitude and phase of these oscillations for the zonal wind, meridional wind and temperature, respectively.

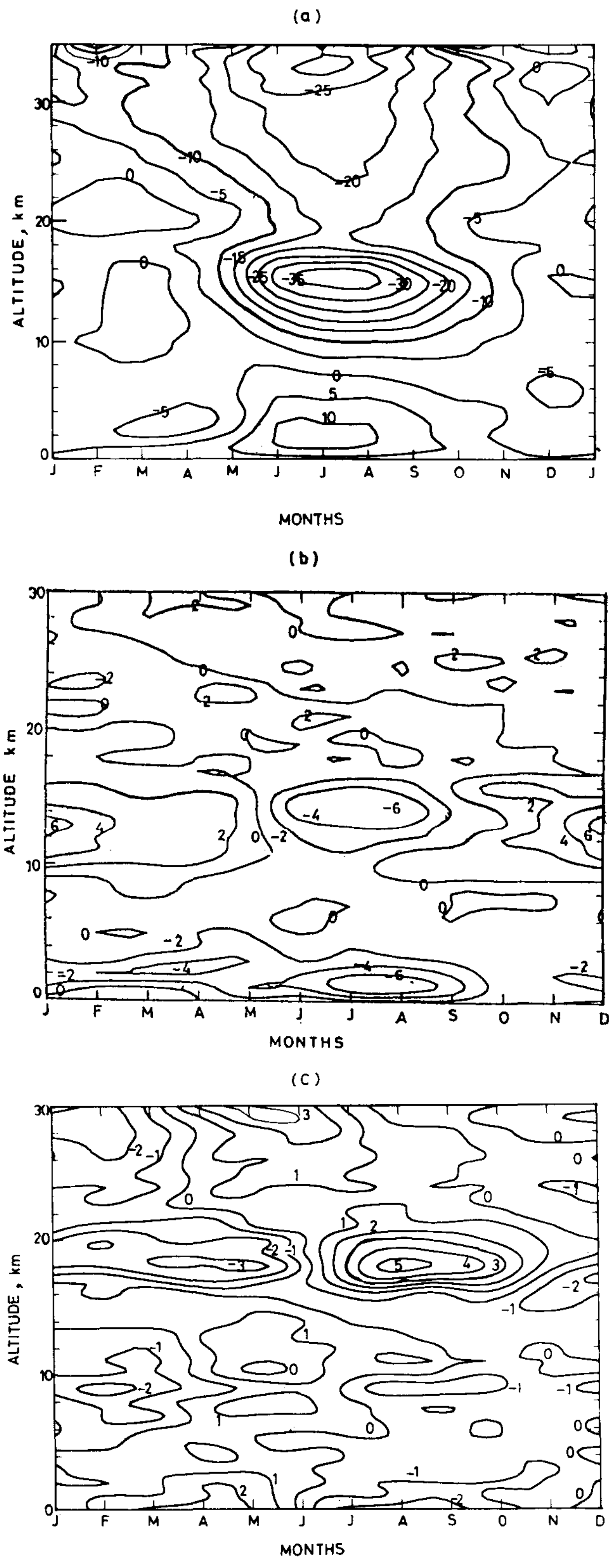

Fig. 2—Time-height cross-section of monthly mean (a) zonal wind, (b) meridional wind and (c) temperature deviation [In (a) and (b) wind velocities are in ms^{-1} with positive values representing westerlies/southerlies and negative values easterlies/northerlies. In (c) positive and negative values respectively represent warming or cooling in K]

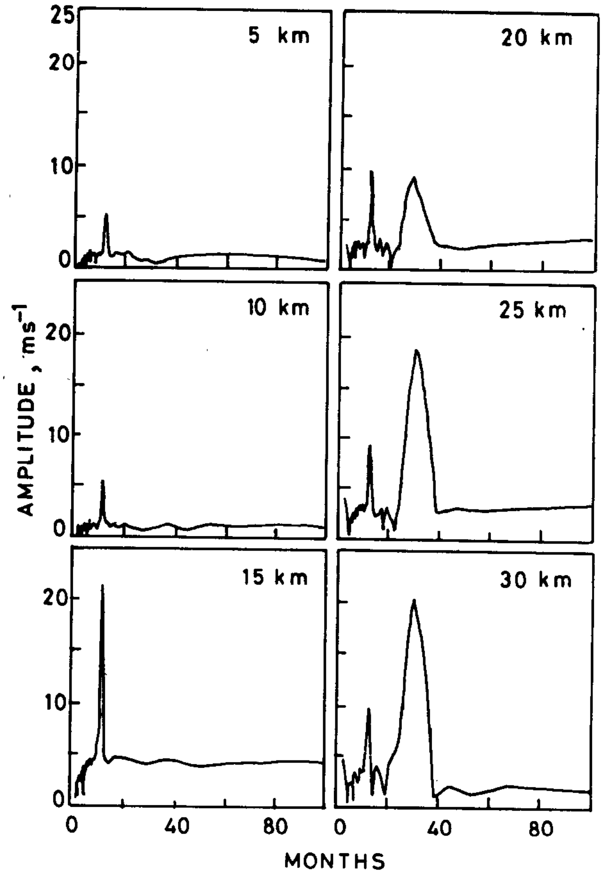

Fig. 3—Amplitude spectrum of zonal wind at 5, 10, 15, 20, 25 and 30 km

It is well known that the QBO period is not constant for the whole length of data and hence the contribution from QBO will vary from one cycle to the next. Therefore, harmonic analysis was done on the series of residuals for consecutive data periods of length 28 months for temperature and 29 months for winds so as to cover the whole data length. To examine the relation between solar activity and QBO, the monthly mean sunspot numbers corresponding to the QBO cycles were calculated from the Wolf sunspot counts supplied by the National Geophysical Data Centre, USA. These monthly mean sunspot numbers were plotted along with QBO amplitudes for the respective cycles at the level of their maximum amplitudes (29 km for zonal wind and 21 km for temperature) and are presented in Fig. 7[(a) and (b)]. Harmonic analysis was also done on each year of the continuous time series after eliminating the QBO contribution to study the inter-annual variation of the AO amplitudes. These variations for the zonal wind and temperature at their respective heights of maximum amplitudes (15 km for zonal wind and

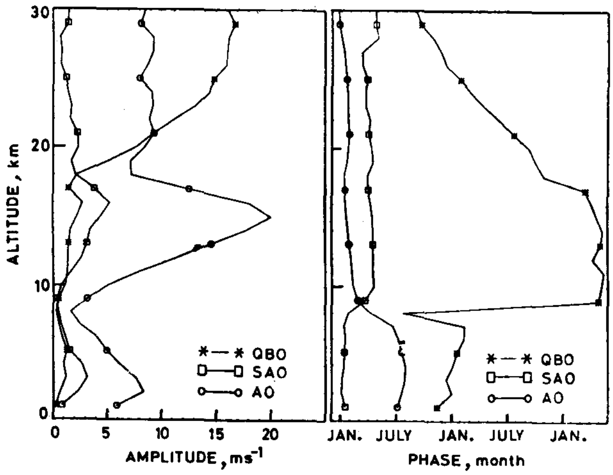

Fig. 4—Variation of amplitude and phase of QBO, AO and SAO of zonal wind with altitude

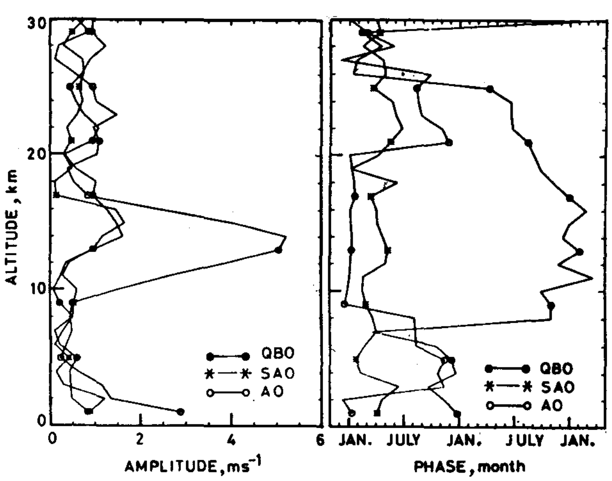

Fig. 5—Same as Fig. 4, but for meridional wind

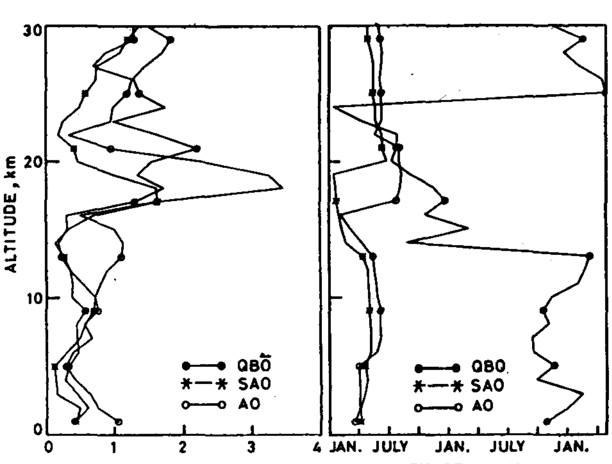

Fig. 6—Same as Fig. 4, but for temperature

18 km for temperature) are shown in Fig. 7(c) and (d)].

Finally, the nature of variation of the annual mean temperature was also investigated. The annual mean temperature was obtained as the mean of all observations for a particular level in a year. The annual mean temperature was plotted against year. Straight-line-fits of the data were made to get the trend in the data. Figure 8(a) shows the trend in the annual mean temperature for some selected altitudes (15,17 and 18 km). Slope of these straight lines which give the change in the temperature trend with altitude were obtained for all the levels up to 30 km. Figure 8(b) shows the variation of the temperature trend with altitude.

3 Results and discussion

The winds are predominantly zonal and Fig. 1(a) shows that the easterlies prevail except in the lowest layers where weak westerlies prevail.

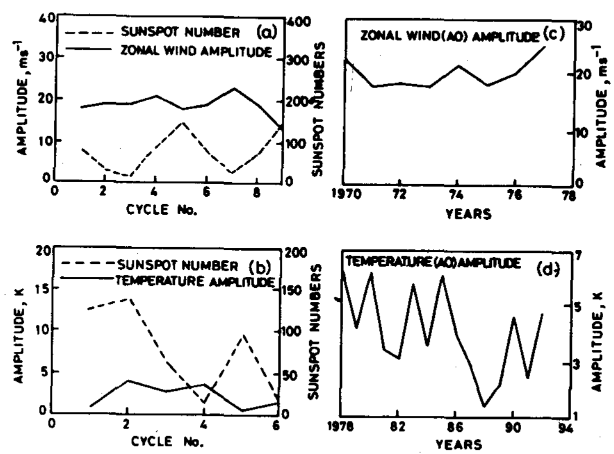

Fig. 7—(a) Variation of sunspot number and QBO amplitudes at 29 km for zonal wind, (b) variation of sunspot numbers and QBO amplitudes at 21 km for temperature, (c) variation of AO amplitudes at 15 km for zonal wind and (d) variation of AO amplitudes at 18 km for temperature

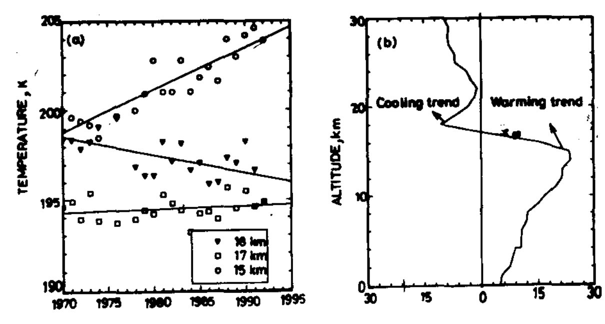

Fig. 8—(a) Trend in the annual mean temperature at 15, 17 and 18 km, and (b) variation of temperature trend with altitude

Figure 2(a) illustrates that the low level westerlies extend up to 8-9 km during the SW monsoon period with speed exceeding 10 mps at 2 km during June-August period. The tropical easterly jet (TEJ) with speed exceeding 35 ms^{-1} and appearing at around 15 km during the SW monsoon period, which is a well known feature of the SW monsoon, is very conspicuous in this diagram. Shallow weak westerlies are seen around 20 km and also in 9-14 km region and these disappear by April/May.

The meridional winds are generally weak with northerlies in the lower troposphere [Fig. 1(b)]. Cross-section of meridional wind [Fig.2(b)] reveals that southerlies are present in the upper troposphere except during the SW monsoon period. During this period the lower tropospheric northerlies extend above the tropopause.

The mean tropopause temperature is 194 K occurring around 17 km with a minimum (192 K) in April and maximum (197K) in July. It may be noted that CIRA 1986 gives 197K in January/February as minimum and 202K in July/August as maximum for 10°N. Cross-section of the temperature deviation [Fig. 2(c)] shows that the lower troposphere warms up during the months preceeding the summer monsoon. Subsequently the level of this warming shifts upward gradually and during the peak of the SW monsoon period this warming becomes more intense and shifts above the tropopause. At this time the warming exceeds 5K and is centered at around 18 km. Table 2 shows that temperatures are generally higher than the CIRA values, especially, the surface value from December to May. It has been reported earlier[10] that temperatures in the *Reference Atmosphere for Thumba* are higher than the corresponding values in CIRA for 10°N. This difference was attributed to difference in the measurement technique, longitudinal variability, tidal influence, solar cycle variations, etc. in the data used. Because of dominance of regional features, the winds in the lowest layers are not expected to match with the CIRA values. However, the large departure of the wind speed from the CIRA values up to 15 km, especially, during the monsoon months is noteworthy (Table 3).

A comparison of the cross-sections of zonal wind and temperature deviation [Fig. 2(a) and (c)] show that TEJ exceeding 35 ms^{-1} around 15 km is followed by a warming exceeding 5K around 18 km and the low level westerly jet exceeding 10 ms^{-1} around 2 km is accompanied by a cooling of more than 2K below 1 km.

The power spectrum analysis of zonal and meridional winds and temperature up to 30 km revealed amplitude peaks corresponding to AO and QBO. Sharp peaks in amplitude corresponding to AO were seen at about 15 km in zonal wind at 18 km in temperature and at 14 km in meridional wind. The spectral peak corresponding to QBO were seen at 29 km in zonal wind, at 21 km in temperature and at 14 km in meridional wind. The QBO had considerable spread which indicates the changing nature of the QBO period. Spectral peaks were weak for SAO. The amplitude spectrum of the zonal wind at 5 km interval up to 30 km is shown in Fig. 3.

The prominent oscillations of the zonal wind are shown in Fig. 4. In the zonal wind, AO is strongest[3,5,13,14] at 15 km. Maximum amplitude is 20 ms^{-1} with phase in February. This can be compared with CIRA 1986 for 10°N which gives a maximum amplitude of 11.3 ms^{-1} occurring at 14.3 km with phase in February. A secondary maximum with amplitude of 8.3 ms^{-1} and phase occurring in July is seen at 2 km as reported earlier[5,13]. The QBO predominates between 20 and 30 km with maximum amplitude of 16.8 ms^{-1} at 29 km. Earlier workers[5,7,8,14] have reported amplitudes varying from 15 to 20 ms^{-1} and periods in the range of 26-31 months for QBO at Thumba. The SAO is weak but almost follows the AO pattern with maximum amplitude of 5.2 mps at 16 km. The phase profiles of zonal wind (Fig. 4) clearly show the downward propagation of QBO phase at approximately 1 km per month from 30 to 18 km. The AO and SAO have nearly constant phase in February and April, respectively, above 9 km.

The amplitude of oscillations are weak for the meridional wind (Fig. 5). The AO has a maximum amplitude of 5.2 ms^{-1} at 14 km and a secondary maximum of 2.9 ms^{-1} at 1 km with both maxima having their phase in January.

For temperature (Fig. 6) the AO shows sharp peak in amplitude (3.4K) at 18 km with phase (max. warming) occurring in August. This is in conformity with Reed *et al.*[15] (for the level of maximum amplitude) and Sasi *et al.*[11] (for the six month difference in phase between the AO of zonal wind and temperature).

There is cycle-to-cycle variation both in the amplitude and the level of maximum amplitudes of the oscillations. The QBO amplitudes in the zonal wind are consistently predominant between 20 and 30 km. The maximum amplitude varies between 18.4 ms^{-1} and 25.5 ms^{-1} from one cycle to another in the height region of 25-30 km. This altitude corresponds to the level of maximum amplitude for the mean QBO. Many workers[16,17] have reported linkage between QBO and solar activity. Figure 7(a) shows the variation of the QBO amplitude of the zonal wind at 29 km along with the corresponding sunspot numbers obtained, as mentioned earlier, for 9 consecutive cycles covering the period from 1970 to 1992. For temperature, only 6 QBO cycles could be obtained, as there were some gaps in the data prior to 1978. Maximum QBO amplitude varies between 2.1 and 4.7K. Figure 7(b) shows the variation of QBO amplitude for temperature at 21 km (where the mean QBO amplitude is maximum) along with variation of monthly mean sunspot numbers corresponding to the 6 QBO cycles during the period 1978-1992. Figure 7(a) shows that the minima of the QBO amplitude for zonal wind coincide with the maxima of monthly mean sunspot numbers and vice versa for the second half of the 23 years considered. The corresponding diagram for temperature [Fig. 7(b)] does not show any such relation at 21 km.

The AO of the zonal wind is consistently strong at 15 km with amplitude of the order of 20 ms^{-1} [Fig. 7(c)]. For temperature, AO is very weak below 18 km. Maximum amplitude occurs between 18 and 20 km. Figure 7(d) shows the amplitude variation at 18 km for the period 1978-1992. Maximum amplitude exceed 8K at around 20 km in some years.

A rising trend in the annual mean temperature is seen at all levels in the troposphere. Figure 8(a) is the plot of the annual mean temperature at 15, 17 and 18 km. Straight-line-fit of the annual mean temperature shows positive slope for all levels in the troposphere with an average value of $\sim$0.13K per year and a maximum of 0.24K per year at 14 km. The trend reverses above the tropopause [Fig. 8(b)]. As it can be suspected that this observed warming could be due to uncompensated change in the measurement system as was demonstrated by Johnson and Gelman[18] for the cooling observed in the Western Hemispheric Rocket data for the 25-30 km region, the details of the radiosonde ascents used in this analysis were examined to see if the observed features could be attributed to the change in the radiosonde instruments used for data collection. As mentioned earlier, the data used pertain to radiosonde instruments of the 1780 MHz type (Russian RKZ-5 and MARZ versions) and the 1680 MHz type (Indian or American). The total number each of these two types of RS instruments used each year for collecting the temperature data is given in Table 4. For certain periods there were two ascents per week and then both the 1780 MHz and 1680 MHz types were used alternately. It can be seen that the trend persists even during these periods. Thus the observed trend does not appear to be attributable to the measuring instruments used.

Table 4—Yearwise distribution of types of radiosonde instruments used

Year	1680 MHz type	1780 MHz type	Total
1970	58	0	58
1971	47	6	53
1972	46	20	66
1973	29	0	29
1974	29	4	33
1975	5	0	5
1976	35	20	55
1977	0	9	9
1978	4	44	48
1979	12	45	57
1980	2	17	19
1981	0	50	50
1982	0	50	50
1983	10	33	43
1984	13	31	44
1985	21	45	66
1986	12	26	38
1987	2	26	28
1988	4	38	42
1989	27	15	42
1990	28	24	52
1991	21	32	53
1992	32	0	32

4 Summary

The mean winds over Thumba up to 30 km are predominantly zonal with westerlies in the lower troposphere and easterlies above, which are very much influenced by the low level westerly jet and the upper tropospheric easterly jet appearing during the SW monsoon periods. The mean tropopause temperature is 194 K and the mean tropopause height is 17 km. The AO is dominant below 20 km and QBO dominant between 20 and 30 km both in zonal wind and temperature. The SAO is weak. Also the oscillations (SAO, AO and QBO) are weak in the meridional wind. The combined strength of oscillations are weak at 7 or 8 km for winds and at around 5 km for temperature. There is a cycle-to-cycle variation both in the strength and altitude of maximum amplitude of these oscillations. The annual mean temperature shows a rising trend at all levels in the troposphere. The trend is maximum (0.24 K/year) at 14 km.

Acknowledgements

The authors wish to record their sincere thanks to the personnel of the Thumba Equatorial Rocket Launching Station (TERLS) especially of the Meteorology, Real Time Computer and Ground Support Facilities of TERLS for the balloon ascents, tracking and computation of the data. In particular, the efforts put in by Shri K S Santhikumar in consolidating the data and support received from Shri R Padmanabha Pillai, Shri Henry S Dsilva and Shri V Sreekanth in preparing the manuscript are gratefully acknowledged.

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