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The thermal structure of troposphere, stratosphere and mesosphere over the equatorial India

K. S. APPU, K. SIVADASAN and V. NARAYANAN

Vikram Sarabhai Space Centre (T.E.R.L.S.), Trivandrum

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ABSTRACT. The thermal structure of the equatorial troposphere, stratosphere and mesosphere has been constructed based on the M-100 meteorological rocket sounding data at Thumba (8° 32′ N, 76° 52′ E). The upper air rocket temperature profile shows short and long term periodic variations. The Thumba actual temperature profile is found to be in good agreement within 2° C with the CIRA Model 1972 for 10° N in the stratosphere, but mesospheric temperatures over Thumba are lower by about 5° to 25° C. The results of harmonic analysis, lapse rate, sporadic warming are discussed, highlighting the characteristics of equatorial tropopause, stratopause and mesopause.

1. Introduction

As part of the Indo-Soviet collaborative agreement in upper atmospheric studies, M-100 meteorological rockets are being launched on every Wednesday during night time from Thumba (8° 32′N, 76° 52′E) since 9 December 1970. Atmospheric temperature data upto 80 km could be obtained from these launchings and are supplemented by radiosonde observations. The upper air temperature data for the period December 1970 to February 1977 (with an average of 4-5 soundings per month and total of 300 rocket flights) have been utilised in the present study. There is a gap of about 10 months in the data from July 1974 to April 1975 due to break in the M-100 rocket launching programme. Preliminary results have been reported earlier by Narayanan and Fedynski (1973). The India Meteorological Department has published a Monograph (1976) giving the monthly mean temperatures and standard deviation. George and Narayanan (1975) discussed the circulation pattern in the equatorial stratosphere and its relation with the circulations in the mesosphere and upper troposphere. The present study is in continuation of the above investigation with reference to the upper atmospheric temperature structure.

The main factors contributing to the systematic error in rocketsonde temperature measuring devices are aerodynamic heating, response time of the sensor and solar radiation effects. The solar radiation problem has been suppressed to a certain extent in the UK and USSR rocketsonde systems by launching during night time hours. The intercomparison results of various rocketsonde systems have been reported by Finger and Gelman (1975). Their conclusions on the compatibility of temperature data are quoted below citing the limitation and accuracy of temperature measurements above 45 km "........In some cases the temperature differences at the higher levels vary as a function of day and night. Specifically the French, UK, USSR and US temperatures upto 45 km taken during either day or night can be used confidently with regard to compatibility. Above that level adjustments increasing to about 15° to 20°C at 65 km would have to be applied in order to ensure compatibility between the USSR reports and those of the other countries......".

2. Data analysis

Detailed description of the M-100 meteorological rocketsonde payload system and accuracy of the temperature sensors are available in the Instruction Manual Vol. 46 published by the Central Aerological Observatory, U.S.S.R. (1976). Temperature measurements are done by Tungsten-Rhenium wire thermometers of 40 μ diameter. The RMS error in these measurements is 1.6°C at 40 km and 5.9°C at 60 km and 11°C at 80 km.

TABLE 1

Monthly mean temperature at Thumba during December 1970-February 1977

Ht. (km)	Jan N=6		Feb N=6		Mar N=5		Apr N=5		May N=5		Jun N=6	
	T	SD	*T*	SD	*T*	SD	*T*	SD	*T*	SD	*T*	SD
0	31	1.0	32	0.8	33	1.0	32	1.3	31	0.9	29	0.8
5	−1	1.1	−1	1.2	−2	0.8	−1	0.9	−1	0.4	−1	0.9
10	−38	4.4	−37	4.3	−36	1.9	−35	3.3	−35	3.7	−37	4.9
15	−77	3.5	−75	3.9	−75	1.6	−74	2.9	−74	3.0	−76	2.9
20	−69	3.8	−70	3.7	−68	3.2	−67	1.9	−67	1.2	−64	2.9
25	−55	2.4	−54	3.7	−54	1.9	−51	2.4	−50	1.0	−51	1.1
30	−43	2.4	−42	3.1	−42	1.6	−40	2.0	−39	1.3	−41	2.0
35	−34	2.4	−30	2.8	−29	2.0	−27	1.5	−26	3.0	−30	2.9
40	−23	2.1	−15	1.8	−14	2.7	−10	2.4	−14	2.7	−15	3.4
45	−14	1.4	−6	1.8	−7	2.1	−6	1.4	−8	2.4	−11	3.2
50	−12	3.7	−8	2.1	−11	1.5	−10	1.7	−13	1.7	−16	3.3
55	−25	6.3	−21	4.1	−26	2.2	−22	1.5	−27	1.8	−30	4.9
60	−45	7.1	−42	5.6	−45	3.5	−43	2.1	−50	4.6	−51	5.2
65	−62	6.4	−61	4.6	−61	5.5	−65	2.9	−70	3.9	−69	3.4
70	−71	7.4	−75	2.6	−75	5.8	−82	4.8	−83	3.5	−82	3.8
75	−73	9.0	−80	2.5	−82	5.5	−89	4.5	−88	5.0	−86	4.6
80	−83	9.9	−84	9.1	−89	5.8	−94	7.0	−92	8.6	−90	10.2

TABLE 1 (*contd*)

Ht. (km)	Jul N=5		Aug N=5		Sep N=5		Oct N=5		Nov N=5		Dec N=5		Mean
	T	SD	*T*	SD	*T*	SD	*T*	SD	*T*	SD	*T*	SD	
0	28	1.1	27	0.7	29	1.4	28	1.6	30	0.8	31	1.0	31
5	−1	1.2	−1	0.9	−1	1.2	−2	1.1	−1	1.0	−1	0.5	−1
10	−38	3.0	−37	2.1	−37	3.7	−36	1.5	−34	3.0	−36	3.4	−36
15	−75	2.4	−76	1.8	−76	1.9	−77	1.5	−75	2.9	−76	2.8	−74
20	−63	2.4	−64	1.8	−64	1.7	−67	2.9	−68	3.2	−67	2.8	−66
25	−51	1.4	−52	2.2	−52	1.3	−53	1.2	−53	1.5	−53	2.5	−52
30	−43	3.1	−44	1.9	−42	2.5	−40	2.1	−40	1.5	−41	1.5	−41
35	−33	3.1	−33	2.1	−28	3.1	−28	1.9	−27	2.5	−31	2.4	−28
40	−16	3.9	−17	2.8	−14	2.6	−14	1.0	−14	3.2	−17	2.0	−15
45	−11	3.5	−9	3.0	−8	1.8	−9	1.6	−9	2.3	−10	4.3	−9
50	−13	2.9	−12	3.7	−10	1.4	−10	2.4	−11	3.0	−12	5.4	−11
55	−27	1.6	−27	3.1	−22	1.8	−26	3.1	−25	0.8	−25	2.6	−25
60	−49	2.3	−47	4.0	−43	4.0	−45	4.0	−45	1.0	−43	2.5	−46
65	−67	2.3	−66	1.7	−65	4.0	−63	2.8	−64	2.0	−62	3.7	−65
70	−79	5.3	−80	3.2	−82	4.5	−78	3.6	−79	3.2	−74	4.6	−78
75	−81	6.1	−87	4.4	−89	4.5	−88	2.8	−86	2.8	−78	3.9	−84
80	−83	8.1	−95	8.5	−101	8.2	−98	9.2	−93	8.4	−83	9.4	−90

T—Temperature in °C, SD—Standard deviation, *N*—No. of observations (Monthly means)

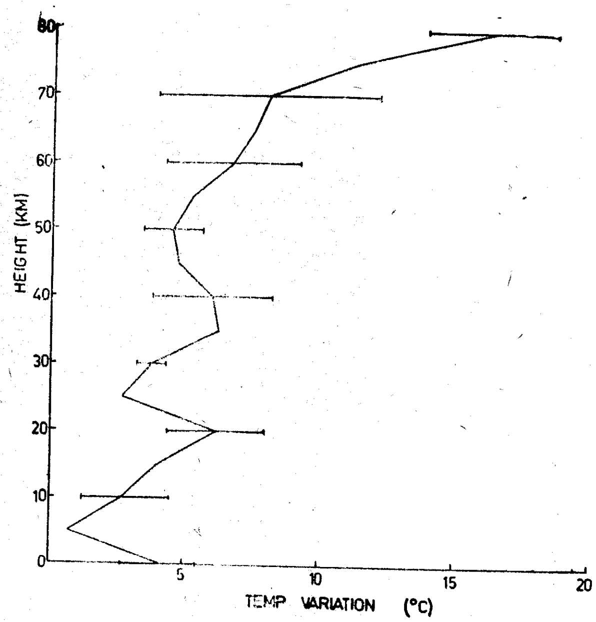

Fig. 1. Mean range of annual variation computed from seasonal means of 5 km interval

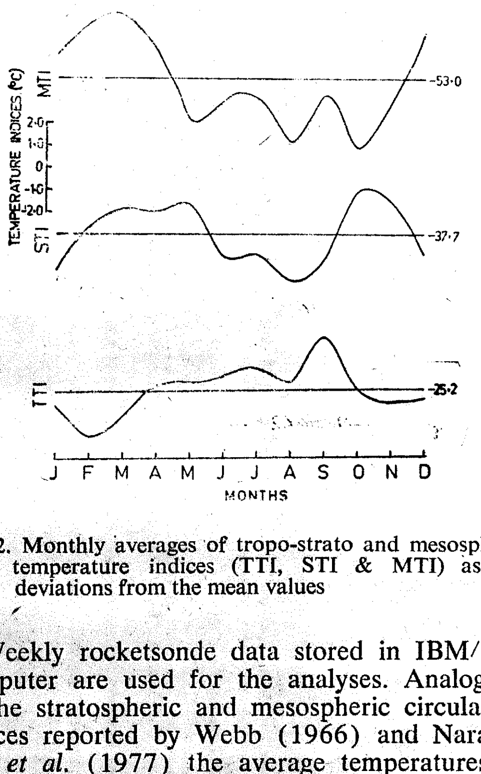

Fig. 2. Monthly averages of tropo-strato and mesospheric temperature indices (TTI, STI & MTI) as the deviations from the mean values

Weekly rocketsonde data stored in IBM/360 computer are used for the analyses. Analogous to the stratospheric and mesospheric circulation indices reported by Webb (1966) and Narayanan *et al.* (1977) the average temperatures of troposphere, stratosphere and mesosphere are computed and designated as Tropospheric Temperature Index (TTI), Stratospheric Temperature Index (STI) and Mesospheric Temperature Index (MTI). Wherever mesospause is not well defined the upper limit for MTI computation has been extended upto 80 km.

3. Results

3.1. *Diurnal variation*

To study the diurnal variation, eight M-100 rockets were launched from Thumba at 6 hours interval during a 48 hours period 18-20 August 1976 (Sasi and Reddy 1977, Narayanan 1977). The main features are :

(*i*) The ranges of diurnal variation in the tropospheric, stratospheric and mesospheric temperatures are 4°C, 12°C and 25°C respectively.

(*ii*) The maximum and minimum temperature in the mesosphere are found in the evening and early morning.

(*iii*) The maximum warming and cooling rate in the stratosphere and mesosphere appear to be of the order of 2°C and 4°C.

3.2. *Seasonal variation*

The monthly mean temperatures (from 0 to 80 km at 5 km interval) with standard deviation are given in Table 1. Fig. 1 shows the vertical profile of the mean temperature range of annual variation as derived from the seasonal mean values. The temperature changes associated with the seasonal variation in the troposphere, stratosphere and mesosphere are of the order of 3°C, 5°C and 9°C. *i.e.*, nearly 1:2:3 ratio.

The layer 20-25 km shows higher temperatures during summer while the 30-35 km layer exhibits warming during the equinox period. The upper stratospheric layer 40-45 km cools during winter. The entire mesosphere shows higher temperature during winter ranging from 5° to 20°C. This is a winter characteristic of the equatorial mesosphere. The least understood thermospheric region 75-80 km indicates cooler temperature during autumn.

3.3. *Temperature indices*

Fig. 2 presents the annual variation of TTI, STI and MTI over their annual mean values of 25° C, -38° C and -53°C. It is evident from Fig. 2 that the annual oscillations are significant in TTI and MTI, while semi-annual oscillation is predominent in STI. The annual variations in TTI and MTI are negatively correlated.

3.4. *Characteristics of tropopause, stratopause and mesopause*

Monthly means of tropopause, stratopause and mesopause heights and temperatures and their variations are presented in Fig. 3.

3.4.1. *Tropopause*

(*i*) The mean tropopause temperature and heights are –79.5°C and 16.4 km. In summer the tropopause temperature is higher by about 6°C.

(*ii*) The variations of temperature and height of tropopause with surface temperature is shown in Figs. 4(a) and (b). 1° C rise in surface temperature bring about 250 m increase in the tropopause height which corresponds to an average fall of 1°C in the tropopause temperature. It is interesting to note the steadiness of tropopause temperature when the surface temperature is above 32° C and when the tropopause height is above 17 km.

3.4.2. *Stratopause*

(*i*) The mean stratopause height is 45.6 km and temperature is —8° C. The stratospheric temperature shows a well marked semi-annual oscillation. The mean seasonal temperature values are -8.6°C in winter, -4.7°C in spring, -8.7°C in summer and -7.5°C in autumn. The cooling during summer and winter corresponds to the region of stratospheric semi-annual easterly circulation and warming during the equinoctial period to westerly circulation.

(*ii*) At the stratopause region occasionally double maxima in temperature are noticed. The details of such double stratopause are given in Table 2. Double stratopause is defined as the cases of two nearly equal maximum temperatures around the stratopause level separated vertically by a minimum of 3 km and a minimum temperature difference of 3°C between the maximum temperature and the temperature of the layer in between. Fig. 5(a) illustrates a typical case of double stratopause. The duration of double stratopause is normally one week. The average vertical distance etween the two stratopause heights is 7.6 km (±1.6 km). The average temperature difference is 5.4°C (±2.3°C). Rahmatullah and Jafri (1972) have reported the phenomenon of two maximum temperatures at the stratopause region over Sonmiani (25° 12′ N, 66° 45′E) during spring season. Over Thumba their occurrence shows no such seasonal characteristic, but their frequency is more in July and September.

3.4.3. *Mesopause*

The mean mesopause temperature is -84.5°C and height is 73.9 km. Mesopause temperature is higher during winter suggesting a reversal in the thermal behaviour, *i.e.*, in opposite phase with that at tropopause. The mesopause is cooler during the equinoxes and this corresponds to the beginning and the subsequent downward propagation of upper mesospheric easterlies into the upper stratosphere (Narayanan *et al.* 1977).

3.5. *Lapse rates*

Fig. 6 presents the mean lapse rate vertical profile. The average lapse rate in the troposphere, stratosphere and mesosphere are 6.7°C,—2.5° C

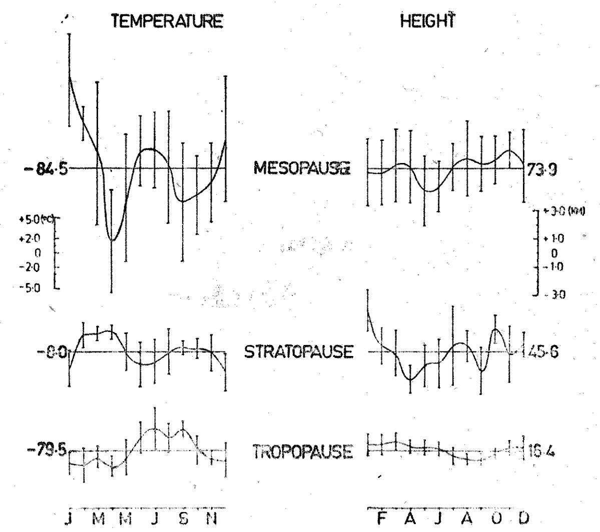

Fig. 3. Structure of tropopause, stratopause and mesopause computed from monthly means. Deviations from the long term mean values are plotted with standard deviation.

TABLE 2

Details of double stratopause cases during the period December 1970 to February 1977 at Thumba

Date of obsn.	Temp. and corresponding ht. of the two stratopause levels: Lower, Temp. (°C)	Lower, Ht. (km)	Upper, Temp. (°C)	Upper, Ht. (km)	Max. temp. diff.* (°C)	Vert. diff. between the two levels (km)
12-1-72	—14	42	—14	51	6	9
26-7-72	—9	42	—10	51	3	9
27-9-72	0	44	+1	50	11	6
2-5-73	—8	42	—9	47	3	5
18-7-73	—14	44	—13	50	4	6
5-9-73	—3	40	—5	50	5	10
28-11-73	—5	42	—3	50	6	8
19-11-73	—8	44	—9	50	3	6
14-7-76	—7	40	—9	48	7	8
1-9-76	—7	42	—9	51	6	9
Mean					5.4	7.6
S.D.					2.3	1.6

Total No. of observations : 10

*Max. diff. between the temp. at the stratopause levels and the layer in between (°C)

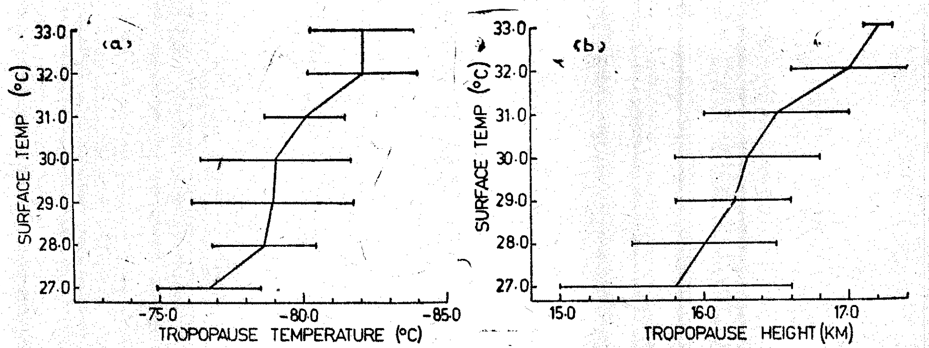

Fig. 4. Variation of tropopause temperature and height with the variation of surface temperature (at 1430 IST) as derived from the monthly data

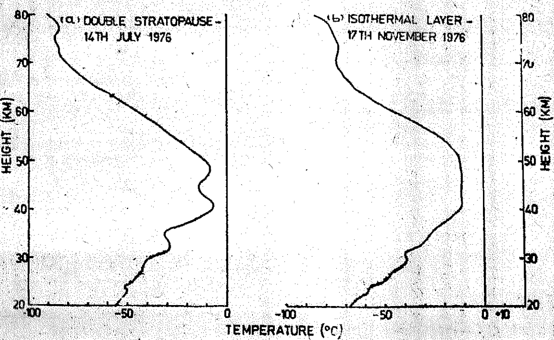

Fig. 5(a). A typical case of double stratopause occurred on 14 July 1976. The maximum difference of 7°C between the temperatures at the stratopause levels and the layer in between is observed in this case.

Fig. 5(b). A typical case of isothermal layer formed at the stratopause region on 17 November 1976. This case represents the isothermal layer having the maximum thickness of 7 km.

TABLE 3

Details of extreme lapse rates in upper troposphere, stratosphere and mesosphere region over Thumba during the period December 1970 to February 1977

Layer		Altitude (km)	S.D.	Lapse rate (°C)	S.D.	No. of obsn.
Upper troposphere		13	1.1	9.6	1.4	242
Stratosphere	I level	21	2.1	—6.9	1.9	159
	II level	35	3.1	—6.3	1.6	78
Mesosphere		59	3.3	5.4	1.2	253

and 2.4°C per km.

(*i*) The stratospheric average lapse rate has its maximum of the order of —2·7°C during spring. The mesospheric lapse rate is maximum 2.6°C during autumn which is followed by a minimum in winter.

(*ii*) Mean lapse rates have been computed for the layers 20-30, 30-40, 50-60 and 60-70 km. The layers 40-50 and 70-80 km are excluded since they are in the region of stratopause and mesopause. Both the lower stratosphere (20-30 km) and lower mesosphere (50-60 km) show higher lapse rate by 0.5°C per km except for the year 1976. There is an increase of the order of 0.5°C in the lapse rate in the lower stratosphere during the westerly phase of the quasi-biennial oscillation.

(*iii*) Table 3 gives details of extreme values of lapse rate corresponding to upper troposphere, stratosphere and mesosphere. Levels just below and above the tropopause, middle stratosphere and mesosphere exhibit extreme lapse rates 9.6°C,—6.9°C,—6.3°C & 5.4° C per km. Strong inversion layer above the tropopause has been reported earlier (Rayazanova and Khovstikov 1965).

3.6. *Isothermal layers*

Isothermal layers are formed around 26 km and 37 km in the stratosphere. Prominent isothermal layers having thickness of 2 km and more are included in the present analysis. Isothermal layers are also observed near the stratopause and mesopause region. As the stratopause and mesopause are normally confined to 1 to 2 km, only layers of thickness of 3 km and more are considered as isothermal layers. Table 4 gives the particulars of these 4 isothermal layers. Fig. 5(b) shows a typical isothermal layer of maximum thickness of 7 km near the stratopause region.

TABLE 4

Details of isothermal layers in stratosphere and mesosphere at Thumba during the period December 1970 to February 1977

Layer No.	Mean of the layer: isothermal (km)	S.D.	thick-ness (km)	S.D.	temp. (°C)	S.D.	No. of obsn.
First	26.4	2.5	2.1	0.3	—50.0	2.5	16
Second	37.1	2.9	2.4	0.7	—27.0	9.2	16
Third	46.5	2.4	3.8	1.2	—10.6	3.1	30
Fourth	74.1	1.9	3.4	1.0	—82.4	9.6	18

At times, isothermal layers are formed just below and above the stratopause, but the frequency is more for the above cases. At the mesopause it is formed mostly during early winter and at the stratopause mostly during early spring. These isothermal layers are short term phenomenon.

3.7. *Sporadic warmings*

Stratwarming is a much discussed subject in space meteorology since its discovery by Scherhag in 1952. Various authors have given different criteria for defining the higher latitude warming (Finger *et al.* 1974, Quiros 1975, Brobely 1975). In the present analysis warmings have been computed based on the deviation from the long term means calculated separately for different seasons. A layer of 4 km thickness with a deviation of 10°–20°C is considered as a minor warming. A deviation exceeding 20°C is called a 'major warming'. Earlier Mukherjee and Ramanamurthy (1972) have reported high level tropical winter warming.

3.7.1. *Minor warming*

Table 5 presents the details of the minor warmings which occurred in mesosphere over Thumba. Maximum number of cases observed is 6 during winter 1970-71 and 1976-77. Mean thickness of the minor warming layer is 8 km and mean increase in temperature is 13°C. As the maximum deviation in temperature is noticed at the centre of the layer on some occasions, the maximum warming temperature level could not be identified when the warmings are formed above 70 km, due to rocket performance limitation. Warmings occurring in mid-winter come under this category.

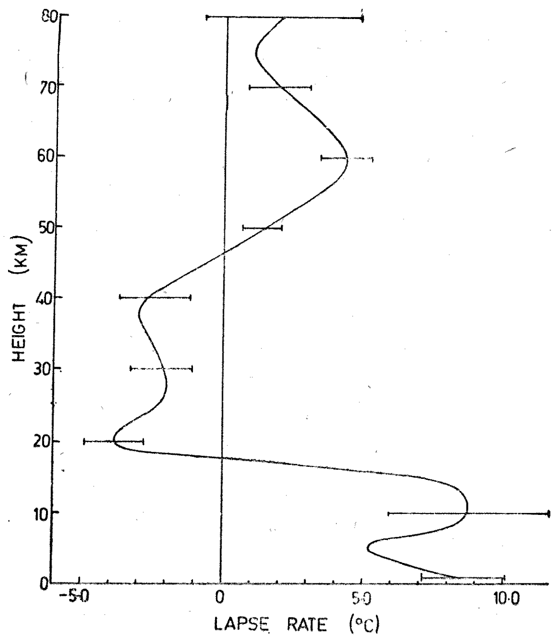

Fig. 6. Mean vertical profile of lapse rate 1 to 80 km at 5 km interval with standard deviation

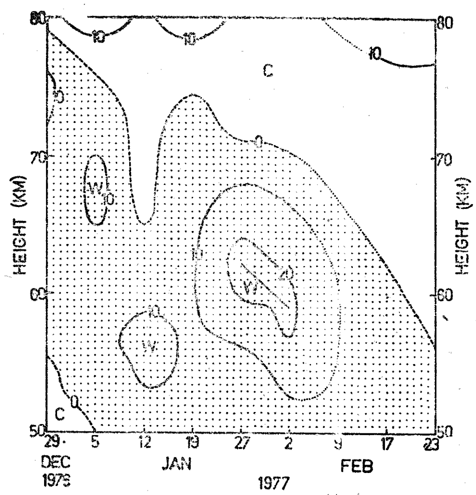

Fig. 7. A typical 'Major' warming during the winter 1976-77 in the mesospheric region. Deviations from the mean values are plotted for 1 km interval. 'W' represents warmings and 'C' cooling. Dotted line denotes absence of data. The straight line indicates the most intensive warming levels.

Inter-annual variation is noticed in the case of summer warmings. All the summer warmings during 1971 and 1972 are formed above 65 km with centres 76 and 75 km. It is below 65 km during 1973 and 1976 with centres 54 and 60 km. The duration of warming is mostly two weeks during winter and one week during other seasons. The winter warming of 1976-77 continued exceptionally for a period of one month.

TABLE 5

Details of the 'Minor' warmings in mesospheric region for different seasons at Thumba during the period December 1970 to February 1977

Year	Winter					Spring					Summer					Autumn				
	Mean temp. of warming layer (°C)	S.D.	Mean vertical thickness of layer (km)	S.D.	No. of obsn.	Mean temp. of warming layer (°C)	S.D.	Mean vertical thickness of layer (km)	S.D.	No. of obsn.	Mean temp. of warming layer (°C)	S.D.	Mean vertical thickness of layer (km)	S.D.	No. of obsn.	Mean temp. of warming layer (°C)	S.D.	Mean vertical thickness of layer (km)	S.D	No. of obsn.
1971	15	2.4	12	5.4	6	14	3.9	8	2.9	3	19	6.8	7	2.3	4	14	2.4	5	0.5	3
1972	14	2.5	5	1.5	3	11	—	7	—	2	14	2.4	9	3.4	3	12	—	7	—	2
1973	15	1.8	10	3.7	5	15	—	9	—	2	13	2.7	6	3.6	5	11	—	7	—	2
1974	11	—	4	—	1	13	2.2	9	3.2	5	—	—	—	—	—	—	—	—	—	—
1975	—	—	—	—	—	—	—	—	—	—	15	—	11	—	2	16	—	11	—	1
1976	13	—	9	—	2	12	—	9	—	2	11	0.8	6	1.3	4	12	—	9	—	2
1977	13	4.9	8	3.4	6	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

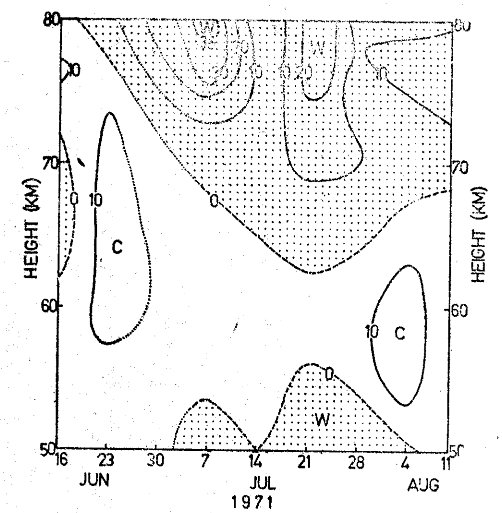

Fig. 8. The strongest 'Major' warming over Thumba during the period December 1970 to February 1977. Deviations from the mean values are plotted for 1 km interval. 'W' represents warmings and 'C' cooling. Dotted line denotes absence of data. The straight line indicates the most intensive warming levels.

3.7.2. *Major warming*

All the major warmings except one, occurred in the mesosphere. The average increase in temperature is 25°C. The average layer thickness is small, 4 km ; 6 km being the maximum during the late winter 1970-1971. The details of the major warmings are given in Table 6. A typical major warming occurred on 27 January 1977 is presented in Fig. 7. It appears that warming is propagated downwards from 62 to 59 km within a week and then completely disappeared after two weeks. The maximum increase in temperature is of the order of 22°C in this case.

The occurrence of major warmings is mostly during late winter. The most intensive major warming occurred during summer 1971 where the warming reached upto 40°C (Fig. 8).

3.7.3. *Warmings in stratosphere*

Unlike the mesosphere, minor/major warmings are rarely occurred in the stratosphere. Only one major warming took place during early winter 1970-71 at the stratopause region when warming reached 27°C. Two minor warmings have been noticed, one in mid-autumn 1971 and the other in early summer 1976, with an average increase in temperature of 11°C.

In the troposphere no considerable warming is observed. The recent investigation by Ramanathan (1977) indicates that stratospheric warming has subsequent feed back effect on troposphere of middle latitude. How far this affects the equatorial region is yet to be investigated.

TABLE 6

Details of the 'Major' warming in mesospheric region at Thumba during the period December 1970 to February 1977

S. No.	Date of obsn.	Vertical thickness of the warming layer		Mean temp. of warming layer	Max. warming temp. and corresponding level		The centre of warming layer	Period of warming
		Base (km)	Top (km)	(°C)	Temp. (°C)	Level (km)	(km)	(week)
1	4 Feb 71	61	67	22	31	62	64	1
2	17 Mar 71	71	75	27	30	75	Unknown (data upto 75 km)	1
3	7 Jul 71	75	80	33	40	80	Unknown	1
4	21 Jul 71	75	80	24	28	76	77	1
5	19 Jan 72	76	80	22	24	78	78	1
6	17 Jan 73	76	80	22	25	78	78	1
7	13 Mar 74	64	69	21	21	67	67	1
8	27 Jan 77	60	64	21	22	62	62	2

3.8. *Harmonic analysis*

The harmonic analysis (Fikhten Gol'ts 1970) results for the mean monthly temperature data at 1 km interval of the years 1971, 1972, 1973 and 1976 with 12 months as the fundamental period are discussed below with reference to the first three harmonics—annual, semi-annual and terrannual oscillations. The biennial oscillation characteristics have been reported earlier (Narayanan and Appu 1976). Fig. 9 shows the mean profiles of annual, semi-annual and terrannual oscillation characteristics — amplitude (°C) and phase (months). The amplitudes and phases of these oscillations for the individual years 1971, 1972, 1973 and 1976 are given in Table 7.

3.8.1. *Annual oscillation*

The most prominent annual oscillation with average maximum amplitude 5.4°C and extreme value of 7.4°C in 1973 is found in the mesosphere extending on an average layer of 15 km. The base of this layer shows a vertical shift for each year ; the base being 48 km in 1971, 54 km in 1972, 58 km in 1973 and 67 km in 1976. Maximum amplitude of this annual wave occurs between the 3rd week of February and 2nd week of March except for the year 1973, when it was leading by about 2 months.

The secondary maximum is in the stratosphere with average vertical thickness of 12 km with tropopause as base level. The maximum amplitude is 4.4°C at 18 km. The phase corresponding to the maximum amplitude is leading approximately by 2 months except in 1972 when it is lagging by 2 months. The maximum amplitude of the annual oscillation in the stratosphere and mesosphere has occurred at the same time in 1972 and 1973. In 1971 and 1976 the stratospheric temperature wave is leading by 3.9 and 5.2 months respectively showing approximately a phase reversal with the mesospheric temperature wave. Compared to the extra topical region where there is a phase reversal between the annual temperature waves in the mesosphere and stratosphere (Cole and Kantor 1974), the equatorial region shows an erratic behaviour which is to be studied in detail.

The two maximum amplitudes of the stratospheric and mesospheric temperature waves show a positive correlation coefficient of 0.8. In 1972 and 1976, the annual oscillation is prominent at 44 and 39 km with amplitudes 3.4° and 5.3°C nearly equal to the mesospheric annual temperature wave amplitudes.

3.8.2. *Semi-annual oscillation*

There are two regions of maximum amplitude

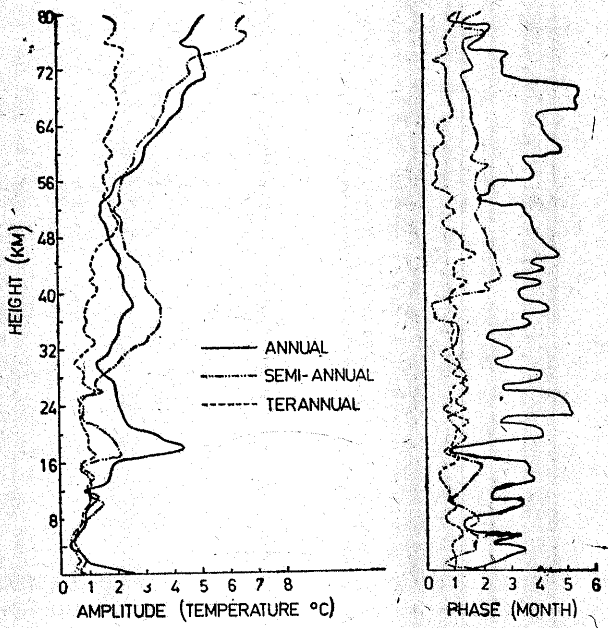

Fig. 9. Vertical profile showing the mean amplitude and phase of the annual, semi-annual and terrannual waves compiled from monthly values. Solid line for annual, dash and dot line for semi-annual and dashed line for terrannual waves.

for the semi-annual temperature oscillation. The most prominent one is in the mesosphere with average maximum amplitude 6.3°C with an extreme value of 9.6°C in 1971 at 76 km. The average vertical thickness of the semi-annual wave layer is 13 km which shows shifting upwards and downwards irregularly. During 1972, 1973 and 1976, the semi-annual wave is lagging by 1.2, 0.7 and 0.9 months while in the year 1971 it is leading by 1.1 months.

The secondary maximum of semi-annual temperature wave is in the middle stratosphere covering an average vertical layer of 12 km. The mean maximum amplitude is 4.1°C around 37 km. In 1972, 1973 and 1976 this wave has a leading phase of about one month while in 1971 it is lagging by about 1½ months showing a phase reversal with that in the mesosphere.

3.8.3. *Terrannual oscillation*

Terrannual oscillation in temperature has been reported earlier by Nastrom and Belmont (1975). This 4 month oscillation is very weak comparatively in temperature and is least discussed in literature. Terrannual temperature wave is prominent only in the layer 48-53 km except for 1971 where it is not at all significant in any of the layers. The mean maximum amplitude of terrannual wave is 2.6°C;3.5°C being the extreme value in 1973. In 1972 and 1976 this wave has a leading phase of 0.3 and 0.8 months while in 1973, it is lagging by 0.5 months. Even though this wave is less prominent, at certain levels it exceeds the amplitude of semi-annual wave by 5°C in the mesosphere and 0.5°C in the stratosphere.

3.9. *Comparison of TERA with CIRA Model 1972*

The Thumba Equatorial Reference Atmosphere (TERA) and CIRA profile for 10° N are presented in Fig. 10. In the stratosphere, they are in good agreement ±2°C. In the mesosphere, Thumba actual temperatures are lower by ±5° to 25°C. At the mesopause (76 km) again, agreement is somewhat good within 13°C. There is a difference of about 4 km between the stratospause levels of CIRA and Thumba, the level at Thumba being at lower altitude (46 km).

4. Summary

The main results of the present study are summarised below :

(*i*) The temperature changes associated with the short period variation in the troposphere, stratosphere and mesosphere are of the order of 4°C, 12°C and 25°C while they are of the order of 3°C, 5°C and 9°C for the long period seasonal variation.

(*ii*) The mean altitudes of the tropopause, stratopause and mesopause are 16.4, 45.6 and 73.9 km and the corresponding temperatures are –80°C, –8°C and –85°C respectively.

(*iii*) The average lapse rates in the troposphere, stratosphere and mesosphere are 6.7°C,

TABLE 7

Results of the harmonic analysis for the individual years

Ht. (km)	1971		1972		1973		1976	
	A	P	A	P	A	P	A	P
Annual oscillation								
0	2.9	1.3	2.3	1.5	3.1	1.6	1.4	1.3
5	0.5	4.0	0.7	0.2	0.6	2.2	0.3	5.4
10	0.5	0.5	0.6	2.7	2.4	2.4	0.5	2.9
15	1.1	3.0	1.3	3.9	3.0	2.2	1.7	0.1
20	3.3	1.4	2.6	4.5	4.7	0.7	2.9	5.7
25	1.4	3.9	1.9	4.8	2.1	4.3	2.6	5.9
30	1.7	2.0	0.9	5.5	0.6	2.0	1.9	0.2
35	2.1	5.9	1.7	5.0	1.3	3.9	3.6	0.2
40	0.5	1.8	2.3	3.8	1.7	1.2	5.5	5.2
45	1.0	4.8	3.1	4.8	1.0	5.9	3.3	3.8
50	2.6	4.2	1.7	4.6	0.8	5.9	1.7	0.3
55	4.3	5.2	1.6	2.0	1.3	0.5	0.8	2.0
60	5.1	5.3	2.7	5.9	3.6	5.6	0.8	2.9
65	4.6	5.4	3.4	4.7	5.8	5.6	2.6	0.1
70	3.2	6.0	4.0	4.9	7.0	6.0	4.7	5.2
75	3.8	0.5	3.8	0.2	7.3	0.1	5.0	5.4
80	3.7	1.0	4.5	1.7	7.3	0.9	5.1	1.4
Semi-annual oscillation								
0	1.4	0.2	0.4	1.7	0.7	2.6	0.6	2.2
5	0.7	1.0	0.2	0.0	0.3	2.0	0.3	0.5
10	0.6	1.2	1.6	1.4	1.8	0.2	1.5	0.7
15	0.9	0.7	0.9	2.3	0.6	2.2	0.2	3.0
20	1.5	2.4	2.2	0.6	1.6	0.7	1.5	0.8
25	0.6	2.8	0.6	0.5	0.5	1.0	1.5	0.7
30	0.8	1.2	3.0	0.5	2.9	0.6	1.8	0.7
35	2.9	0.5	2.2	2.8	4.5	0.1	4.1	0.6
40	3.7	2.9	1.8	3.0	3.5	2.9	3.4	0.2
45	2.6	2.5	2.5	2.3	2.5	2.5	2.7	2.5
50	2.5	2.1	2.9	1.6	2.8	2.2	0.9	1.7
55	1.8	2.2	1.2	0.6	3.2	2.1	2.7	2.2
60	3.4	2.0	0.4	1.3	2.8	1.6	4.2	2.4
65	4.5	1.5	2.5	2.1	3.4	1.0	4.3	2.3
70	7.7	0.7	4.1	2.3	3.6	0.3	2.1	2.3
75	8.9	0.4	6.8	2.5	5.5	2.7	2.5	0.2
80	7.4	2.9	7.8	2.7	3.5	2.8	5.8	0.3
Terrannual oscillation								
0	0.2	1.0	1.3	1.3	0.0	—	1.2	0.8
5	0.5	1.2	0.5	0.5	0.2	1.5	0.2	0.5
10	0.2	1.5	0.8	0.7	1.9	0.3	0.8	0.7
15	0.4	1.3	1.0	0.9	1.2	0.9	0.5	2.0
20	0.4	1.3	1.7	0.0	1.2	1.0	0.7	1.5
25	0.2	1.0	0.8	0.6	0.8	1.0	0.9	0.9
30	0.5	1.8	0.2	1.0	0.5	0.8	0.5	0.5
35	0.6	0.6	1.2	0.5	1.3	1.6	0.4	0.7
40	2.2	0.3	0.8	1.7	0.7	0.2	1.5	2.0
45	0.8	1.6	0.9	1.9	1.7	1.7	1.2	1.6
50	1.7	0.2	1.5	0.0	3.5	1.5	2.1	0.7
55	2.1	0.2	0.9	0.1	2.3	2.0	1.5	0.6
60	2.7	0.2	2.0	0.8	2.3	0.3	0.8	0.0
65	1.9	0.6	2.2	1.0	2.2	2.0	1.5	0.6
70	1.9	0.3	1.4	1.2	1.2	1.1	2.9	0.3
75	2.2	1.8	1.7	0.3	2.5	0.5	2.8	0.5
80	1.2	1.8	2.3	1.0	2.9	1.3	0.3	1.0

A—Amplitude temperature (°C) P—Phase (month)

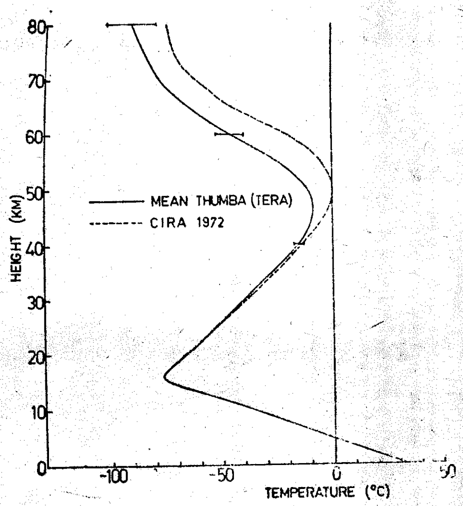

Fig. 10. Comparison of Thumba mean profile (5 km standard level data) with CIRA Model 1972 for 10°N. Solid line for Thumba and dashed line for CIRA. Error bars in the measurements are also plotted.

–2.5°C and 2.4°C per km. There is an increase of the order of 0.5°C per km in the lapse rate at 20-30 km (lower stratosphere) during the westerly phase of the quasi-biennial oscillation.

(*iv*) There are four isothermal layers centred at 26.4, 37.1, 46.5 and 74.1 km with average vertical thickness of 2.1, 2.4, 3.8 and 3.4 km. The corresponding temperatures are –50°C –27°C, –11°C and –82°C.

(*v*) 'Minor' and 'Major' warmings are observed in the mesosphere with average vertical thickness of 8 and 4 km and average temperature 13°C and 25°C. In the stratosphere mostly minor warmings are noticed.

(*vi*) Annual, semi-annual and terrannual oscillations are predominent in the mesospheric temperatures. Maximum amplitudes are 5.4°, 6.3° and 2.6 ° C. The stratospheric temperatures show significant annual and semi-annual oscillations of maximum amplitude 4.4°C and 4.1°C at 18 km and 37 km respectively.

(*vii*) There is a good positive, correlation (0.8) in time between the two maximum amplitudes of the annual waves in the stratosphere and mesosphere.

(*viii*) The Thumba actual temperature profile is in good agreement, within 2°C, with CIRA Model 1972 for 10° N for the stratosphere but mesospheric temperatures differ considerably. Thumba values are much lower by about 5° to 25°C over the range 50 to 80 km.

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