substantial negative deviations in total ozone across a wide span of latitudes from the Antarctic to 20° N, but outside the Antarctic, pronounced deficits generally did not appear until late 1982. They found annually recurring deficits in the region 65° N to 45° N and deficits with a biennial component between 45° N and 20° N. In the southern middle latitudes deficits were observed from late 1985. The two tropical stations, Kodaikanal and Huancayo showed rather small deviations on the year-to-year time scale, consistent with their low variability during their base period 1969–1973.

Newell and Selkirk[10] came to the conclusion that (1) the reductions in the total ozone are highly seasonal in nature both in the Antarctic and elsewhere, where they occur in the cold winter months, (2) as tropospheric ozone has generally been increasing in recent years, the observed decreases in column ozone in a particular region and season are the result of changes in the stratospheric ozone balance, due to either decreased photochemical production, increased photochemical destruction, transport changes or some combination of these three.

Conclusion

The only conclusion, which can be made about long-term trends in averaged column ozone in the tropics, is that there is no identifiable systematic decrease that can be ascribed to anthropogenic causes. There appears to be a steady decrease after 1982 at some stations but whether it is caused by volcanic eruptions or solar activity or large scale atmospheric dynamics cannot be discerned with any degree of confidence.

The latest results demonstrate an undoubted chemical cause in the destruction of ozone by atmospheric chlorine in the Antarctic, but also point to special climatic conditions as the reason why depletion occurs so severely in the Antarctic and so little elsewhere. Although there are still many unresolved questions, and the tropics may be spared the fate of the middle and high latitudes, there is an urgent need to stop further flooding of the atmosphere with CFCs and other pollutants.

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Ozone vertical distribution in the tropics

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In recent years several rocket campaigns have been conducted at Thumba (8.5° N) to study the vertical distribution of ozone over the tropics. Measurements have been made up to an altitude of about 65 km both during daytime as well as night-time. These measurements have not only delineated the basic characteristics of the mean vertical distribution of ozone over a tropical site, but also revealed some new features on the photochemical and dynamical control on ozone at stratospheric and mesospheric altitudes.

THE importance of ozone in the chemistry and radiation balance of the earth's atmosphere has been recognized for a long time. However, in the past two decades there has been an upsurge of interest in atmospheric ozone studies as a result of the recognition of the possibility of a long-term depletion of the global ozone overburden due to catalytic chemical reactions involving several trace gases of the NO_x, ClO, and HO_x families, some of which are due to anthropogenic activities[1–3]. This danger has been highlighted by the discovery of the Antarctic Ozone Hole[4,5] which is an extreme manifestation of the ozone depletion problem. While the Antarctic Ozone Hole has received adequate attention, significant ozone depletions are already evident in the Arctic and even in Northern hemisphere mid-latitude regions[6] emphasizing the global nature of the phenomenon. Recently the recognition of the importance of tropospheric ozone as a greenhouse gas[7] and the possibility of increase in surface and tropospheric ozone[8,9] has added a new dimension to the problem. These developments have necessitated a more accurate description of the global ozone distribution both in the horizontal as well as in the vertical. The need to detect a long-term trend due to anthropogenical influences predicted to be of the order of a few per cent per decade[10,11] in the presence of much larger short-term changes due to natural causes calls for a much higher level of precision and accuracy in the ozone-measuring systems than what was existing prior to the seventies. A number of programmes were undertaken during the seventies and the eighties to evaluate the different ozone-observing systems. Ground-based, rocket and balloon as well as satellite-based intercomparison and validation campaigns were undertaken with a view to obtaining an improved data base which can be used for photochemical process-related studies as well as long term trend-detection studies of atmospheric ozone.

Ozone in the tropics

The tropical region holds special interest for research in ozone and atmospheric chemistry. It contributes more than 50% to the global budget of the trace gases that are involved in the chemistry whether they are of photochemical or biogenic origin. Most of the global ozone is actually produced in the tropics and the middle and high latitude abundances are controlled by transport from the tropical regions, the vertical uplift and the meridional and subsequent downward transport. Hence there is a great deal of interest in studying the processes that control the distribution of ozone in the tropics and their subsequent transport to middle and higher latitudes. The tropics also provide diverse perturbations of dynamical origin and the relative importance of photochemistry and dynamics in determining the ozone vertical distribution in the tropics has become an important topic for research.

The ozone measurement programme in India has a rich history. Systematic observations of ozone from a network of Dobson spectrophotometers have been in progress in India since the IGY. The present Indian Dobson network consists of six stations, four of which are maintained by India Meteorological Department at Kodaikanal (10° 13' N, 77° 28' E), Pune (18° 31' N, 73° 31' E), New Delhi (28° 35' N, 77° 12' E) and Srinagar (34° 05' N, 74° 50' E) and the other two at Mt. Abu/Ahmedabad (24° N, 73° E) and Varanasi (25° 19' N, 85° 52' E) being maintained by the Physical Research Laboratory (PRL), Ahmedabad and the Institute of Geophysics of the University of Varanasi respectively. Both total ozone and vertical distribution measurements by the Umkehr technique are being made from this network of stations on an operational basis. A balloon ozonesonde system was developed[12,13] by the India Meteorological Department and regular balloon soundings are being made from Trivandrum (8.5° N), Pune and New Delhi since the early seventies. The Regional and National Ozone Centre located at New Delhi ensures participation in the Dobson intercomparison, calibration with travelling standard lamps[14] and the balloon ozonesonde intercomparisons that are being organized by WMO.

Rocket ozonesonde programme at Thumba

Rocket ozonesondes capable of measuring the vertical distribution of ozone up to altitudes of about 65 km or more were developed at PRL, Ahmedabad[15,16] and at the National Physical Laboratory (NPL), New Delhi[17]. After a few sporadic measurements from the Thumba rocket range, an intercomparison experiment was conducted in collaboration with the CAO of Soviet Union in March 1983 and a large scale campaign in December 1987 for the diurnal variation studies. These campaigns involved a number of measurements with different rocket ozonesondes, balloon ozonesondes coordinated with groundbased total ozone and Umkehr observations[18-20]. Recently another campaign was undertaken at Thumba as a part of the International Programme—Dynamics Adapted Network for Atmospheric Studies (DYANA)—with the objective of studying different aspects of dynamics and the impact on trace gas distribution in the middle atmosphere. While the data from the 1990 campaign are still under analysis, the earlier experiments have yielded significant new information on the ozone vertical distribution in the tropics and its variabilities.

Mean vertical distribution over Thumba

Figure 1 shows the mean vertical distribution of ozone over Thumba based on a large number of rocket measurements. The rocket data extend from an altitude of about 20 km to about 65 km. The profile is extended to lower altitudes using the Trivandrum ozonesonde observations. The horizontal bars represent the standard deviation. The ozone concentration decreases from a value of 0.8–1.0×10^{12} molecules per cc near the surface until a minimum value of $(1$–$2) \times 10^{11}$ molecules per cc in reached around 15 km level. Above this level ozone concentrations increase rapidly with increasing altitude. The ozone maximum is attained at an altitude

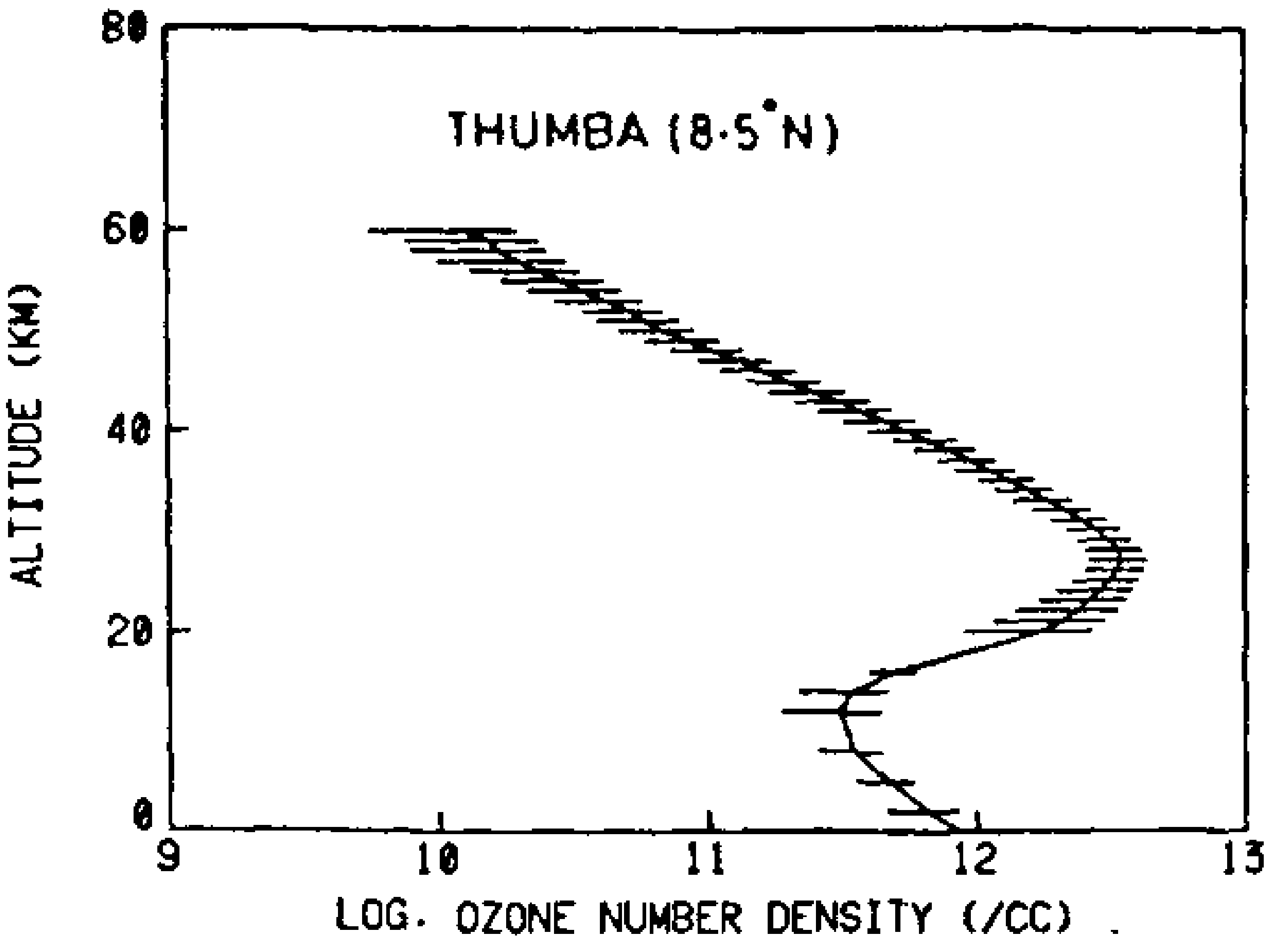

Figure 1. Mean vertical distribution of ozone over Thumba (8.5° N) based on about 25 rocket measurements. The horizontal bars correspond to the standard deviation of the measurements.

of 27 ± 1 km with a number density of $3.75 \pm 0.78 \times 10^{12}$ molecules per cc. Above about 30 km altitude the ozone number density decreases with increasing altitude with a scale height of about 5 km. The earlier data[20] based on Trivandrum balloon ozonesondes and Kodaikanal Umkehr observations had indicated the ozone maximum to be at 24–25 km altitude level with number densities of about 4.5×10^{12} molecules per cc. During the March 1983 Intercomparison experiment[19] thirteen rocket ozonesondes from India and Soviet Union, both optical and chemiluminescent type, flown at different times of the day and night indicated the level of the ozone maximum to be at 27 ± 1 km. Hence there was a definite disagreement between the rocket ozonesondes on the one hand and the balloon ozonesondes and the groundbased Umkehr data on the other with regard to the altitude of ozone maximum at the low latitude site, Thumba/Trivandrum which needed to be resolved.

After careful examination of the rocket and balloon data collected during the 1983 intercomparison experiment it was realized that the anomaly arises out of the fact that the balloon does not penetrate the actual ozone maximum during most of its ascents and the balloon data analysis procedure involves an extrapolation of the data beyond the level of the balloon burst. It was further suggested[19] that for a correct evaluation of the ozone vertical distribution and number densities from the balloon measurements at a tropical site like Thumba the balloon must reach a peak altitude exceeding 30 km. Further, Umkehr analysis cannot give an accurate estimate of the peak layer since the individual layers are roughly 4.5 km thick and the analysis gives only mean layer amounts. Interestingly the Umkehr layers 4 and 5 correspond to the altitude region 20–24.5 km and 24.5–29 km respectively. The mean layer ozone amounts for these two layers are taken at the central altitudes of 22 km and 27 km respectively. Hence a smoothly constructed profile based on such data would give the maximum at an intermediate altitude which happens to be around 24–25 km. This is due to the profile construction technique and does not necessarily represent the true picture.

The December 1987 ozone campaign at Thumba

During December 1987, a second major campaign was undertaken at Thumba to further investigate the basic characteristics of the vertical distribution of ozone over the tropics and also to study the day to night variations in ozone concentrations at different levels in the stratosphere and mesosphere. Twenty-two M-100 rockets, nineteen of them equipped with ozonesondes and three with standard met. payloads and four balloon ozonesondes (IMD) were flown in three salvos, the first a test series on 3 December 1987 and the second and third on 5/6 December 1987 and 7/8 December 1987 in diurnal series, including both daytime and night-time launchings. Twelve rockets carried optical ozonesondes, six Indian and six Soviet, and three chemiluminescent heterophase and four gas phase chemiluminescent sensors from the Central Aerological Observatory (CAO) of USSR. Table 1 gives the details of the launchings.

Table 2 shows the details regarding the ozone maximum obtained from the PRL rocket ozonesondes and IMD balloon ozonesondes. All the balloons reached peak altitudes exceeding 30 km and very good agreement was found between the rocket and balloon data not only regarding the altitude of the ozone maximum but also regarding the ozone number densities.

In Figure 2 the mean Thumba profile is compared with balloon ozone measurements made from Hyderabad (17.5° N) with a suntracking multichannel UV photometer which is, in principle, similar to the rocket ozonesonde and yields absolute values of the ozone concentrations[21] and also the model midlatitude ozone profile. The ozone peak over Hyderabad is found to be at 24 km which is lower than the peak level over Trivandrum but higher than that over mid-latitudes and the maximum ozone number density increases from Thumba to Hyderabad and to mid-latitudes. These observations are qualitatively consistent with the familiar picture of the ozone transport from the tropics to the mid-latitudes via an uplift in the tropics and a meridional and downward transport in mid-latitudes and further validate the considerations of the previous paragraph.

Table 1. Rocket and balloon sounding programme for the December 1987 Indo-Soviet ozone campaign at Thumba

Time IST (h)	Type of payload	Instrument	Institution
I Series: 3 December 1987: (Test series)			
0600	Balloon	Electrochemical ozonesonde	IMD, India
0751	Rocket	Optical ozonometer	CAO, USSR
0851	Rocket	Gasphase chemiluminescent ozonesonde	CAO, USSR
1805	Rocket	Optical ozonometer	CAO, USSR
1930	Rocket	Standard met. payload	ISRO and CAO
II Series: 5,6 December 1987: (Day-night series)			
0600	Balloon	Electrical ozonesonde	IMD, India
0742	Rocket	Optical ozonometer	CAO, USSR
0850	Rocket	Optical ozonesonde	NPL, India
1200	Balloon	Electrochemical ozonesonde	IMD, India
1340	Rocket	Gasphase chemiluminescent ozonesonde	CAO, USSR
1520	Rocket	Optical ozonesonde	PRL, India
1640	Rocket	Optical ozonesonde	NPL, India
1807	Rocket	Optical ozonesonde	CAO, USSR
1937	Rocket	Standard met. payload	ISRO and CAO
2145	Rocket	Heterophase chemiluminescent ozonesonde	CAO, USSR
2315	Rocket	Optical ozonesonde	PRL, India
0037	Rocket	Gasphase chemiluminescent ozonesonde	CAO, USSR
0400	Rocket	Optical ozonesonde	PRL, India
III Series: 7/8 December 1987: (Day-night series)			
1400	Balloon	Electrochemical ozonesonde	IMD, India
1522	Rocket	Optical ozonesonde	PRL, India
1810	Rocket	Optical ozonesonde	CAO, USSR
1930	Rocket	Standard met. payload	ISRO and CAO
2130	Rocket	Heterophase chemiluminescent ozonesonde	CAO, USSR
2334	Rocket	Heterophase chemiluminescent ozonesonde	CAO, USSR
0105	Rocket	Optical ozonesonde	PRL, India
0325	Rocket	Gasphase chemiluminescent ozonesonde	CAO, USSR

Table 2. Rocket and balloon data on the ozone maximum obtained during the December 1987 campaign at Thumba.

Sensor	Time (h)	Maximum altitude (km)	Ozone no. density (cm^{-3})
5 December 1987			
Balloon (IMD)	0600	26.4	4.19×10^{12}
Balloon (IMD)	1200	26.8	3.55×10^{12}
Rocket (PRL)	1520	27.0 ± 0.5	4.22×10^{12}
Rocket (PRL)	2315	26.0 ± 0.5	4.05×10^{12}
7/8 December 1987			
Rocket (PRL)	0105	27.0 ± 0.5	4.1×10^{12}
Balloon (IMD)	1400	27.0	4.4×10^{12}
Rocket (PRL)	1522	27.0 ± 0.5	4.4×10^{12}

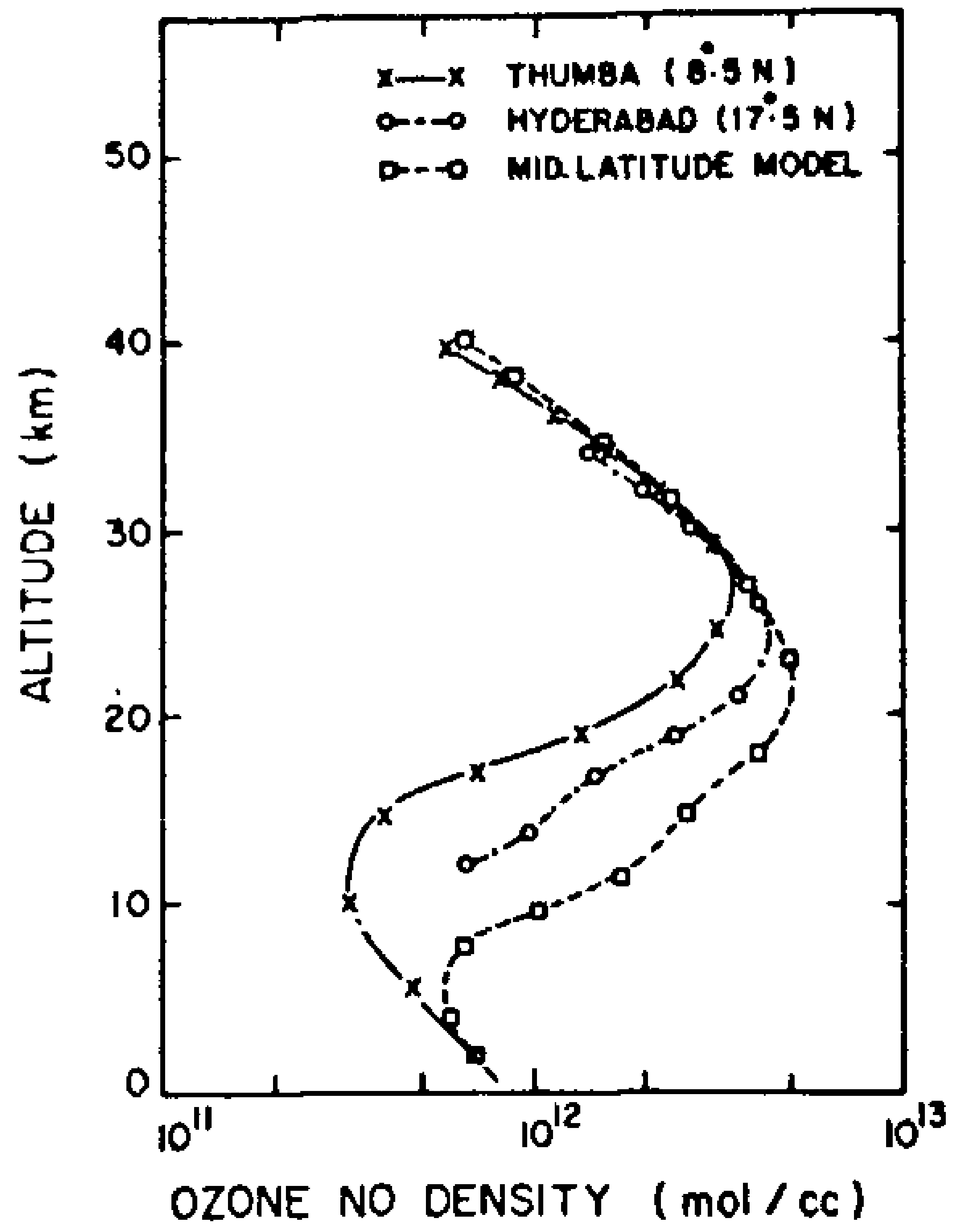

Figure 2. Ozone vertical distribution over Thumba compared with the balloon-borne optical ozonesonde measurements over Hyderabad (17.5° N) and mid-latitude model of Krueger and Minzner[26].

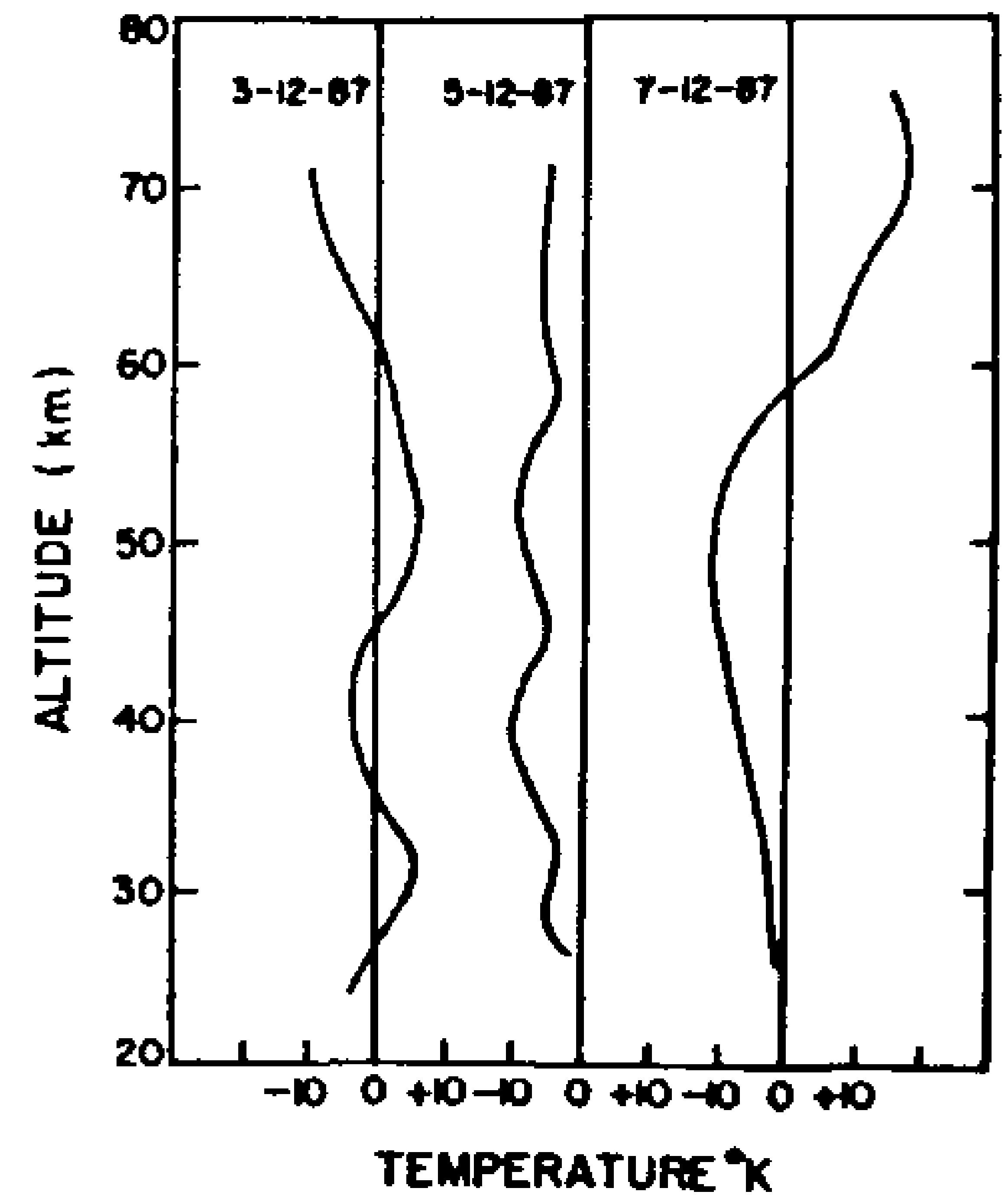

Figure 3. Temperature fluctuations in the stratosphere and mesosphere over Thumba on 3, 5 and 7 December 1987 based on meteorological rocket measurements.

Dynamical perturbations on the ozone vertical distribution

Another interesting feature of the December 1987 campaign results is on the effect of meteorological disturbances on the ozone vertical distribution. The campaign period was meteorologically highly disturbed. There was a deep depression in the Bay of Bengal during 3–5 December. Even though the depression did not develop into a storm, the temperature structure on 3 and 5 December showed wave-like perturbations at all heights on 5 December. On 7 December, there was a large wave at altitudes above 60 km region (Figure 3). The ozone distribution obtained from the rocket flight on 5 December at 1520 h IST also showed wave-like perturbations. In order to study this feature in greater detail, the ozone number densities were converted into mixing ratios. Wave-like perturbations are more clear in the mixing ratio profile (Figure 4) and the features correspond well with the features on the temperature profile of Figure 3. The amplitudes are in the range 12% to 16%. Even though meteorological effects are known in the total ozone number densities and the ozone profile at lower levels, this is probably the first evidence for the penetration of such effects on ozone concentrations at higher altitudes in the stratosphere and mesosphere.

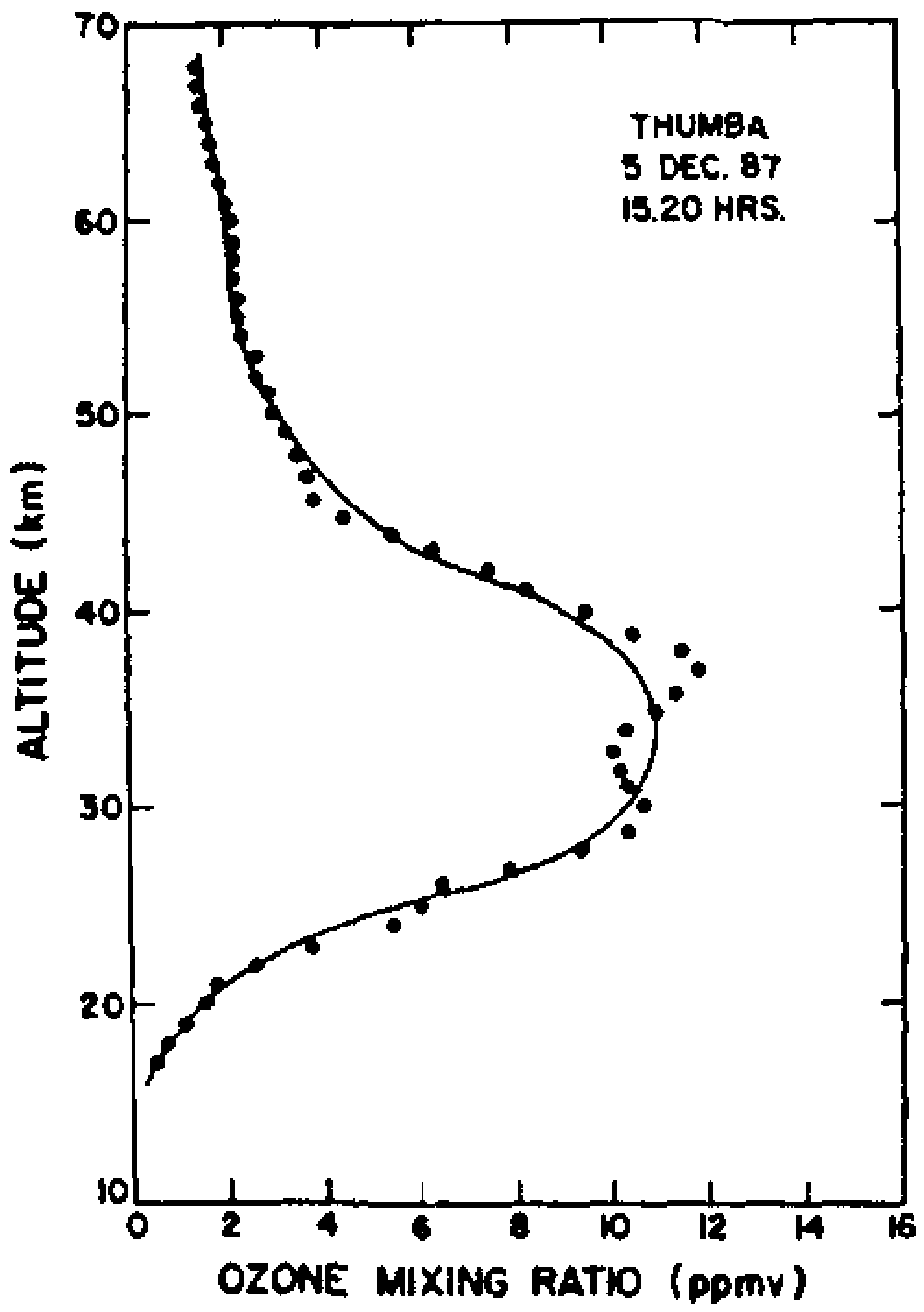

Figure 4. Ozone mixing ratios measured on the rocket flight of 5 December 1987 at 1520 hrs showing wave-like perturbations in the 25 to 60 km altitude region.

Day–night variation

The rocket flights of the December 1987 campaign were mainly in two salvos, one on 5 December 1987 and the other on 7/8 December 1987 and these were aimed at a study of the day to night variations in the ozone vertical distribution. Four rockets were flown from PRL, and two were flown in daytime and two during night-time. The data are shown in Figure 5. The daytime profile of 5 December used in Figure 5 is a smoothed version of the actual data so that the day to night changes can be studied free from the wave-like perturbations due to the dynamical effects. It is seen from Figure 5 that the ozone concentration increases from day to night at all altitudes above ~ 40 km. The percentage increases range from a few per cent to about 10 per cent in the 40–45 km region reaches values of a few tens of per cent in the 50–55 km region. Above ~ 60 km the increase is much larger and can reach values of 50%.

Table 3 shows a comparison of the 1987 data on day to night changes with the results from the March 1983 campaign and model predictions[22–24]. The observed increases at all heights in the 40–55 km altitude region

Table 3. Day to night changes in ozone concentrations over Thumba measured on 5 December 1987 and 7/8 December 1987 compared with results from the March 1983 campaign at Thumba and model predictions.

Altitude (km)	5 December 1987 (%)	7/8 December 1987 (%)	March 1983 (%)	*Theory* (%)
40	–	28	16	–
45	12	15	28	2–3
50	30	40	32	6–12
55	36	–	45	20–25
60	50	–	56	50
65	55	–	–	–

*Herman[22], Pallister and Tuck[23], Vaughan[24].

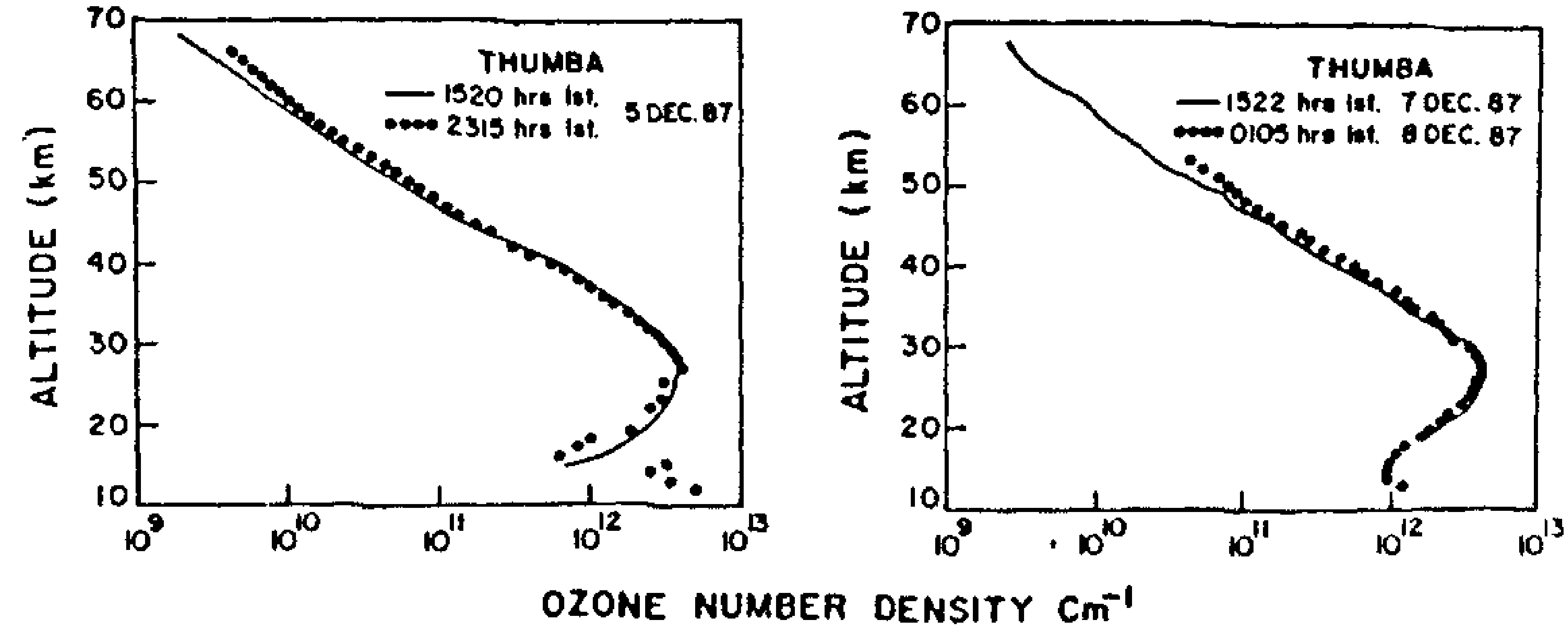

Figure 5. Day to night changes in ozone vertical distribution from the PRL rocket flights conducted on 5 December 1987 and 7/8 December 1987.

are larger than predicted by models. Further, the data of Figure 5 show a definite day to night decrease in the altitude region below 40 km. The decrease is of the order of 5% to 10% and current model predictions are only for altitudes above 40 km and the observed decreases remain to be explained.

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A statistical analysis of total ozone data at four Indian stations

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Total ozone data are being recorded at a number of Indian stations for over three decades. However, doubts have been recently raised on the consistency and dependability of Indian data. A recent US report omitted Indian data from the global analysis and the UMO even suggested that Indian data may need to be adjusted to correspond to global data. It was therefore felt that a statistical analysis of monthly means of total ozone data available for Indian stations may help in an appreciation of the consistent nature of the data.

Data availability

The periods of data available at the four stations, Kodaikanal, New Delhi, Varanasi and Mount Abu/Ahmedabad are listed below:

Kodaikanal from 1960 to 1988. Six months' data for March 1972, April 1976 and 1978, November 1981 and December 1978 and 1980 were missing.

New Delhi. 1960–1970 and 1975–1988.

Varanasi from 1964 to 1988. Of these, data for 13 months were missing, viz. January 1986, February 1986, March 1982 and 1986, April 1974, 1982 and 1986, May 1982, July 1987, November 1981, 1985 and December 1981 and 1985.