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Physical Properties of the Upper Atmosphere over India

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ABSTRACT. From available data from sounding balloon ascents and sound propagation experiments, the height-temperature curve for Central India from ground up to 100 km has been constructed. It is seen that the isothermal region which is found in the lower stratosphere over middle latitudes does not exist over India and that temperature steadily increases above the tropopause. This result is in agreement with Nazarek's conclusion from V-2 rocket soundings that the isothermal region does not exist over New Mexico in the lower stratosphere. The vertical distribution of pressure, temperature and density for levels above 10 km are discussed. Mean monthly geostrophic west wind components have been worked out for lat. 25°N approximately for levels between 10 km and 20 km and their variations are discussed. By comparison of Central Indian data with Central European data, west wind components during summer have been computed up to 100 km. The comparison indicates that the summer easterlies over North India in the troposphere extend upto about 30 km with strong westerlies aloft.

1. Introduction

A number of studies have been made in this country in the troposphere, with the aid of sounding balloon ascents till World War II and with radio-sonde data during recent years. Normals based upon sounding balloon ascents for some stations were published in 1942[1]. Daily radio-sonde data are available from 1944.

Due to the difficulties of balloons reaching heights above 25 km, not much data have been collected from the stratosphere. Since the development of jet and rocket flights has made it necessary to have a knowledge of the physical properties of the stratosphere, an attempt has been made in this paper to get an idea of these properties from available data.

2. Measurement of Stratospheric Temperatures

One of the most useful methods of obtaining temperature measurements in the upper stratosphere is by determination of sound velocities. Experiments in this direction were conducted in Europe and the U.S.A. In this country, the India Meteorological Department organised sound propagation experiments in the State of Madhya Pradesh (Central Provinces) in 1946-47, the results of which were published by Mathur[2]. He obtained temperatures in the stratosphere during the various seasons as shown in Table 1.

In addition to the propagation of sound waves, the study of trails of meteors by Lindemann and Dobson[3], atmospheric tides by Pekeris[4] and the distribution of ozone in the atmosphere by Gotz[5], Gowan[6] and Penndorf[7] have enabled them to calculate the probable temperatures at various heights in the stratosphere over Europe.

Recently V-2 rockets were used at White Sands, New Mexico, fitted with instruments for measuring pressure, temperature, ozone distribution etc. From the data collected by the V-2 rocket tried on 7 May 1947, pressure and temperature up to 120 km were determined by Best, Havens and LaGow[8]. In this ascent pressures at various heights were obtained and temperatures calculated from the slope of pressure curve and from *ram* pressure. Nazarek[9] calculated temperatures at various heights from the V-2 rocket pressure data by the application of the hydrostatic equation. Temperatures determined by different methods for the levels 40, 50 and 60 km are given in Table 2. The mean and extreme values calculated by the National Advisory Committee for Aeronautics (NACA) from all available data for NACA tentative standard atmosphere (1947)[10] are also given for comparison.

While the usual standard of accuracy for surface temperatures cannot be applied to these figures since the methods are rough

TABLE 1

Summer May-June 1946		Postmonsoon October 1946		Winter Jan-Feb 1947	
Height (km)	Temp. (°C)	Height (km)	Temp. (°C)	Height (km)	Temp. (°C)
42	51	34.1	39	38	54
			31	41.7	36
44	54	42	39	42	36
					43
45	43	43.5	49	44.5	38
			41	47	56
	44	44	51		
55	72	44.7	41	48.6	36
		55	54	54.5	51

and the calculations dependant on assumptions or implications, one may get from the table, the general order of values that may be expected at those heights. It may be seen that the Indian values compare favourably with other values and are within *NACA limits*.

Fig. 1 gives various height temperature curves between 20 and 60 km.

3. Vertical distribution of Temperatures over India

From the temperature values for various seasons, a mean temperature-height curve was constructed for the 34-55 km layer. Mean annual sounding balloon values for Poona and Hyderabad were used for the layer from ground to 20 km and the curve extended up to 26 km with Agra data worked out by Ananthakrishnan[11]. The curve for 26 to 34 km was extrapolated and an average height-temperature curve constructed. From ground to 55 km the temperature curve has the basis of actual observations. Beyond 55 km it has been extended on assumptions based upon data from NACA distribution and V-2 results.

A comparison with results obtained by other workers is given in Table 3.

One important feature of this comparison is the existence or otherwise of the isothermal layer above the tropopause. While the layer is noticeable in all European curves, it is not found in New Mexico, California and India. Nazarek has drawn pointed attention to this fact stating that his results are " disproving the belief that an isothermal layer exists over New Mexico from 15 to 35 km." The Indian values also support this conclusion since according to sounding balloon means, temperatures rise gradually from 17 to 26 km (201.2 to 221.5°A in February and 195.1 to 224.6° A in August at Agra according to Ananthakrishnan) while Mathur's values at 34 km (304 and 312°A) suggest a steady increase from 26 to 34 km. It thus appears that the existence of the isothermal layer in the lower stratosphere is a feature of the stratosphere in the higher latitudes (polar stratosphere) and is not present in the tropical stratosphere. This problem will be discussed elsewhere.

4. Distribution of pressure, density, etc.

Assuming a homogeneous atmosphere, the pressure at various heights may be

TABLE 2

Temperature of the upper atmosphere between 40 and 60 km

(W—Winter, S—Summer)

Method	Author	Temperature in degrees Centigrade		
		40 km	50 km	60 km
Sound	Whipple	10	60	—
,,	Duckert	40	70	—
,,	Gutenberg N. Germany (W)	70	80	75
,,	Gutenberg N. Germany (S)	-20	40	70
,,	Gutenberg California (W)	30	70	75
,,	Cox, Atanasoff, etc. Germany (S)	7	20	25 (55 km)
,,	Mathur India (S)	47	63	72 (55 km)
,,	Mathur India (W)	32	42	56 (55 km)
V-2 rocket	Best, Havens & LaGow N. Mexico	0	50	45
,,	Nazarek	–14	13	7 (Max. 35 at 55 km)
Meteors	Lindemann & Dobson	—	27 to 77	—
Atmospheric tides	Pekeris	–20	40	100
Ozone	Gowan O_3 alone	60	260	—
	O_3 water vapour (S)	0 to 20	90 to 120	—
	,, (W)	–30 to –120	30 to 70	—
,,	Penndorf	10	50 to 70	—
General	NACA Mean	0	60	60
	NACA Extremes	–80 to 80	—20 to 110	10 to 110

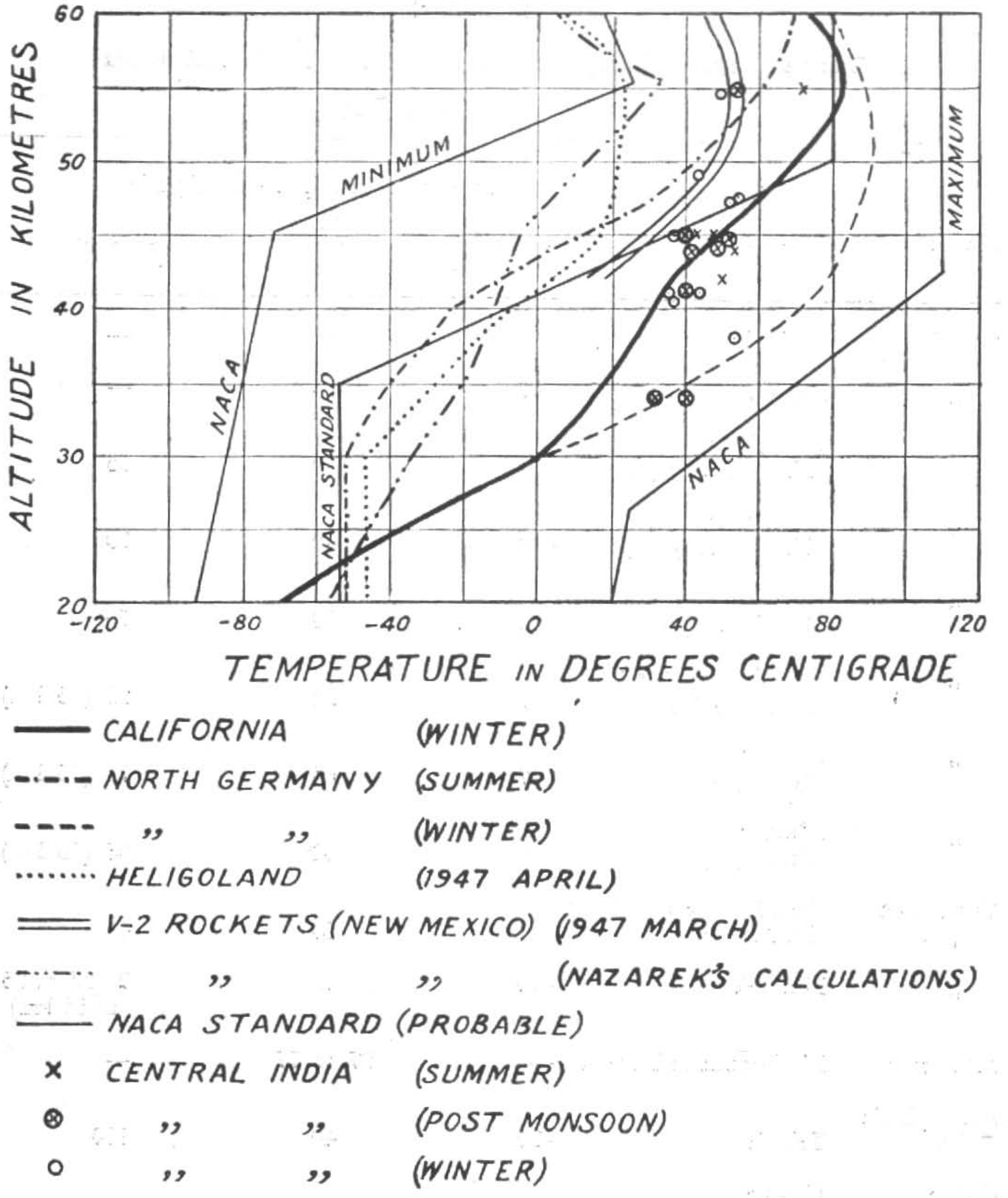

Fig. 1 Various Height-temperature Curves between 20 km and 60 km

calculated with the aid of the hydrostatic equation

$$\log p = \log p_0 - \frac{g}{R}\frac{\Delta h}{T_m}$$

Normal pressure values are available up to 20 km. The pressures at the higher levels up to 100 km were calculated with the aid of the above equation from the temperature values of Fig. 2. The variation of 'g' with height was also taken into account and pressures calculated for each 5 km interval.

Density is obtained from the equation

$$\rho = p/RT$$

TABLE 3

Author	Region	Tropospheric lapse rate in °C/km	Tropopause height in km	Extent of isothermal layer in km	Inversion (warm layer) rate of increase in °C/km	Top of warm layer in km	Lapse rate in the lapse layer in °C/km
Penndorf	Central Europe	7	10	30 to 35	6	50	4
Gutenberg	North Germany (Summer)	6	10	10 to 20	6 from 10 to 40 km and nearly isothermal from 40 to 60 km	55	—
	North Germany (Winter)	6	12	12 to 35	4.5	60	—
	California (Winter)	6	15	Nil	5 from 17 to 50 km	60	—
Cox, Atanasoff, etc., 1949	Germany (April)	7	12	12 to 30	6 from 32 to 42.5 km; slight rise about 1°C between 42.5 and 55 km	30—55	—
Best, Havens, 1947	New Mexico (March)	5	15	—	—	55	5(60—80 km)
Nazarek, 1950	New Mexico (March)	5	15	Nil	2.5 from 15 to 55 km	55	4(55—85 km)
Koteswaram	Central India	7	17	Nil	7 from 17 to 35 km; 1.7 from 35 to 55 km	60	—

The number of molecules per c c (Avogadro's number) at different heights is given by

$$N = \frac{\rho}{\bar{\mu}}$$

where $\bar{\mu}$ is the mean mass of air molecules.

Following Penndorf, the following values are used :

$$0 \text{ to } 50 \text{ km}: \quad \bar{\mu} = 47.8\times10^{-24} \text{ gm}$$
$$50 \text{ to } 100 \text{ km}: \quad \bar{\mu} = 48.6\times10^{-24} \text{ gm}$$

The mean free path of molecules λ is given by Tait's formula

$$\lambda = \frac{0{\cdot}677}{N\pi d^2}$$

where d is the molecular diameter. According to Landolt-Bornstein tables

$$d(O_2) = 2.98\times10^{-8} \text{ cm}$$
$$d(N_2) = 3.18\times10^{-8} \text{ cm}$$

Table 4 gives the average annual values of temperature, pressure, density in grammes per cubic metre, number of molecules per c c and mean free path of molecules at various heights up to 100 km over Central India. Curves showing variation of pressure, density and mean free paths with heights are given in Figs. 3,4 and 5. The pressure distribution at New Mexico from V-2 rocket results is also given for comparison.

5. Seasonal variations of Pressure, Temperature and Density at various levels

(i) *Up to 20 km*

Detailed variations of these three physical properties over Agra, Poona and Madras have been discussed by Ramanathan,[12] Ramanathan and Ramakrishnan[13] and Sur and Ramakrishnan[14] respectively. Fig. 6 illustrates these variations for Agra at different heights. The values of P and T have been taken from sounding balloon normals and ρ worked out. The 17 km level is also included in the picture since it happens to be the tropopause height.

Though rise in pressure in the higher levels in summer months is a general phenomenon the well-marked rise above 5 km over Agra

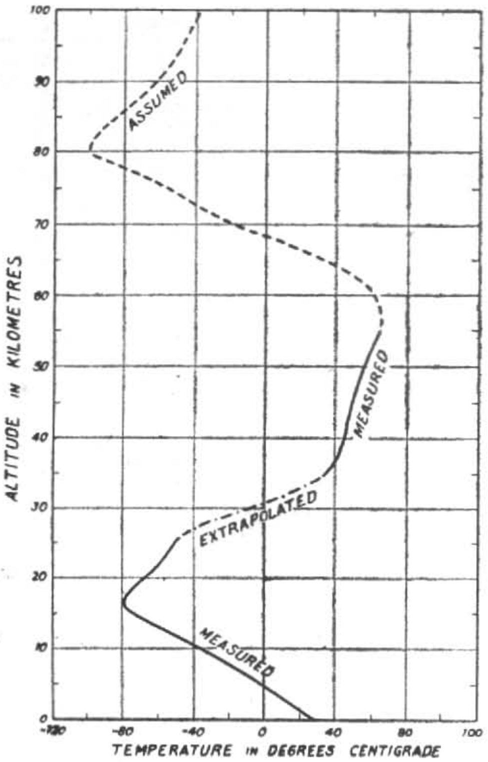

Fig. 2 Temperature Distribution

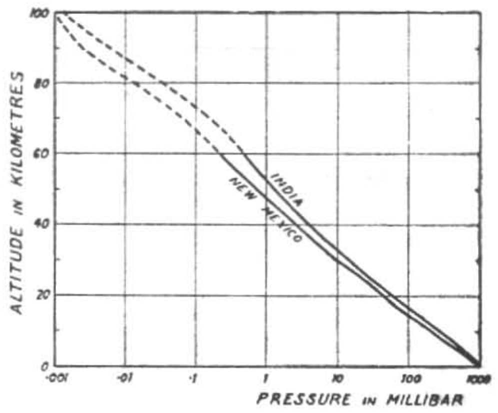

Fig. 3 Pressure Distribution

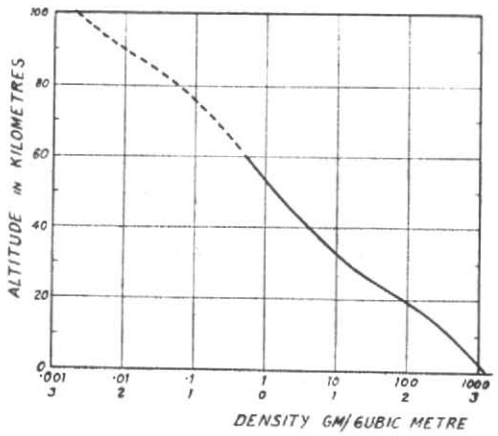

Fig 4 Density Distribution

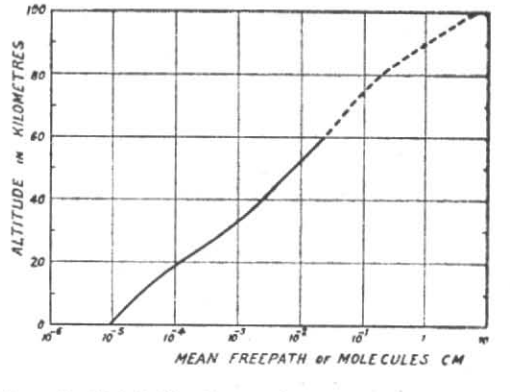

Fig. 5 Distribution of mean free path of molecules

The features of this mean temperature distribution curve are—

(i) Temperature lapse of about 7°C/km from ground to tropopause (17 km)

(ii) Absence of an isothermal layer above the tropopause

(iii) Temperature rise of about 7°C/km from tropopause up to about 35 km

(iv) Reduced temperature rise of 1.7°C/km between 35 and 55 km

(v) Lapse of 7 to 8°C/km between 60 and 80 km (from assumed values).

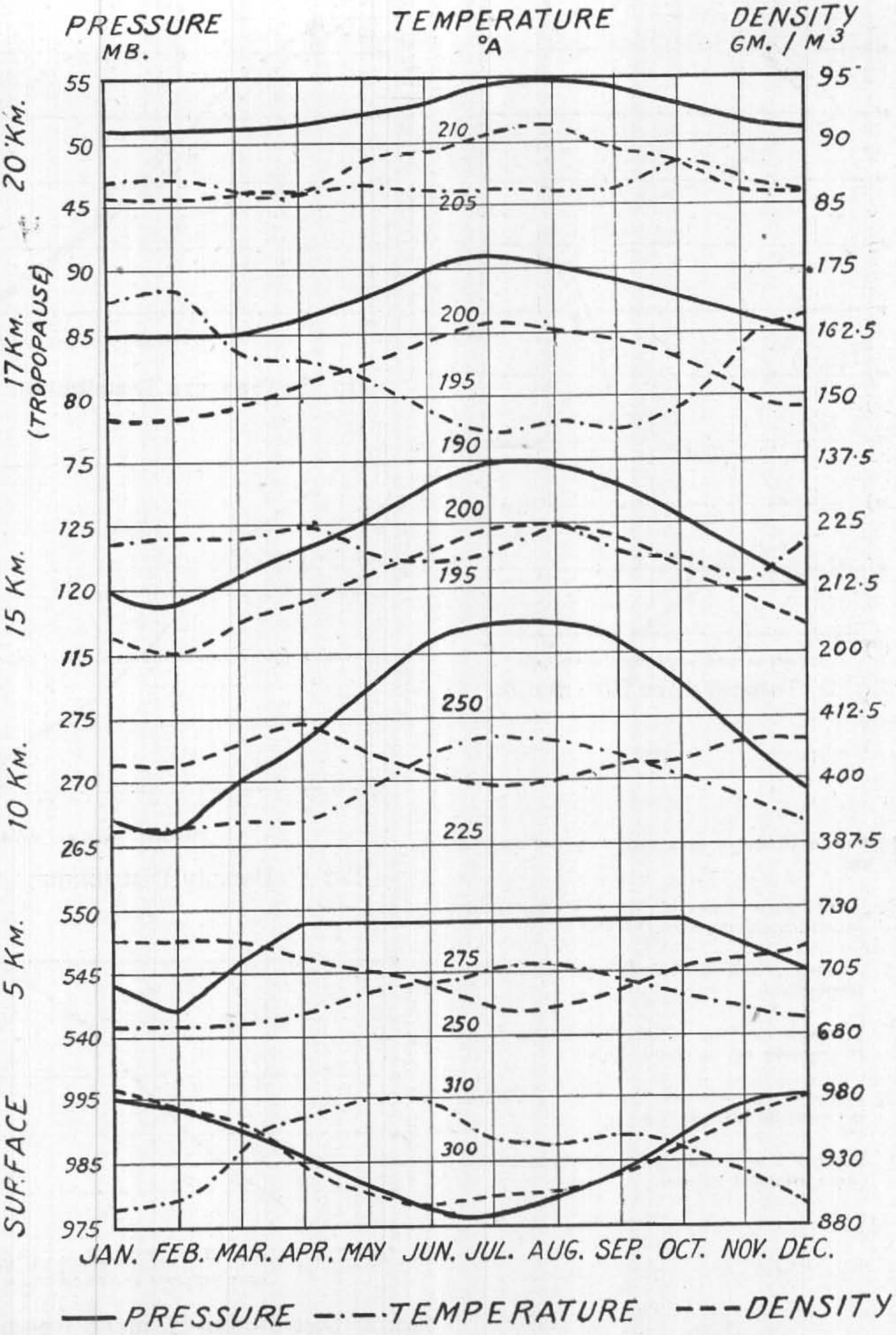

Fig. 6 Monthly variations of Pressure, Temperature and Density over Agra.

TABLE 4

Average values for the physical properties of the atmosphere over Central India

Height above sea level (km)	Temp. (^{0}A)	Pressure (mb)	Density (gm/m^3)	No. of molecules per c c	Mean free path of molecules
0	300	1013.3	1175	2.458×10^{19}	9.239×10^{-6}
5	271	542.3	696.3	1.456×10^{19}	1.559×10^{-5}
10	237	269.2	395.4	8.271×10^{18}	2.746×10^{-5}
15	199	118.0	206.4	4.317×10^{18}	5.260×10^{-5}
20	208	49.8	83.32	1.743×10^{18}	1.303×10^{-4}
25	222	22.6	35.42	7.411×10^{17}	3.066×10^{-4}
30	267	11.4	14.86	3.110×10^{17}	7.305×10^{-4}
40	317	3.69	4.05	8.474×10^{16}	2.681×10^{-3}
50	329	1.29	1.37	2.901×10^{16}	7.827×10^{-3}
60	333	0.47	0.49	1.014×10^{16}	2.241×10^{-2}
70	253	0.155	0.213	3.951×10^{15}	5.748×10^{-2}
80	173	0.032	0.066	1.329×10^{15}	1.710×10^{-1}
90	213	0.0056	0.0091	1.964×10^{14}	1.156
100	233	0·0013	0.0019	3.910×10^{13}	5.811

may be understood by remembering that the sub-tropical high pressure cells move to the north of Agra during the monsoon and move down to southern latitudes after the monsoon months. The seasonal location of these cells in the lower troposphere was discussed by the author and Chakravortty[15] from radio-sonde data and in the higher troposphere by Venkiteshwaran[16] from high-pibal data.

(ii) *At tropopause level*

Hess[17] has stated from his study of mean meridional cross sections along Long. 80°W, that the tropic tropopause is definitely lower in summer than in winter and estimates that it is clearly about 2 km lower. Willett[18] had found indication of this at Swan Island (Lat. 17°24′ N, Long. 83°56′W) and Hess finds evidence for the same from Swan Island right up to equator. Indian results have been examined with a view to detect any seasonal variation of the tropopause. Ananthakrishnan has given the following values (Table 5) for the heights of the tropopause over Agra. Hc_1 is the height at which lapse rate is less than 2°C/gkm and Hc_2 is the height at which it is negative. Tc_1 and Tc_2 are the corresponding temperatures. It may be seen that at Agra the variation of the height of tropopause tends towards an increase in summer months rather than a decrease. A similar conclusion may be drawn from the data of Poona-Hyderabad and Madras discussed by Ramanathan and Ramakrishnan and Sur and Ramakrishnan.

The variations of pressure, temperatures and densities at the tropopause level may be seen from Fig. 6. The summer cooling of

TABLE 5

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Hc_2 (gkm)	16.7	17.1	17.3	17.2	17.1	17.0	17.6	17.6	16.7	16.5	17.0	16.7
Tc_2 (°A)	202.3	201.2	199.8	197.8	197.3	196.8	195.1	192.2	193.9	193.0	196.4	201.4
Hc_1 (gkm)	15.7	16.3	16.3	16.7	16.5	16.6	17.0	16.5	16.4	16.2	16.0	15.7
Tc_1 (°A)	203.3	202.0	201.0	197.9	197.4	195.6	193.1	194.2	193.3	196.8	198.7	202.3

the tropopause over Agra is conspicuous, while over Poona-Hyderabad and Madras (for the months June-November) the seasonal variation of temperature at the tropopause is not appreciable. At Djakarta (Batavia), however, (Lat. 6.6° S, Long. 107°E) the opposite effect is observed [12]. The tropopause seems to lower in summer (June-August) by nearly 2 km (the drop being of the same order as noticed by Hess) and the tropopause temperature increases in summer and decreases in winter, as in the middle latitudes. Thus the seasonal variation of the tropopause appears to undergo a latitudinal change in the tropics. The probable cause of these variations will be discussed elsewhere.

(iii) *Above* 20 *km*

Data for levels above 20 km are very meagre. The explosion experiments in India showed that temperatures in May-June were generally higher than during winter (Jan-Feb). Mathur obtained a temperature of 72°C at 55 km in May-June as compared to 52° C in winter. Since the inversion (warm) layer in the stratosphere gets its heat by absorption of the incoming radiation from the sun by atmospheric ozone, it is to be expected that temperatures in this layer should be higher during summer than in winter. Murgatroyd [19] from sound propagation measurements found that the temerature at 45 km over England was some 40° C warmer in summer than in winter. According to Gowan's calculations, even the diurnal variation of temperature at 50 km should be the order of 25-30° C. Gutenberg's [20] curves for North Germany, however, show lower temperatures in summer than in winter between 25 and 60 km and consequently lower pressures in summer. Since Gutenberg's summer curve agrees with Penndorf's and also with the recent determination by Cox, etc. in Germany and Nazarek for Mexico, Gutenberg's winter curve for Germany showing higher temperature appears to be doubtful. The temperature values obtained by the above workers are given in Table 2.

From available evidence it appears that the seasonal variation of temperatures in India from winter to summer is a rise in the troposphere from ground to about 15 km, fall in the neighbourhood of tropopause, say between 15 and 20 km over north India and rise again between 30 and 60 km.

6. Upper winds

(i) 10-20 *km*

The mean geostrophic west winds between the latitudes of Poona and Agra were worked out for the levels 10 gkm, 15 gkm, 17 gkm (tropopause level) and 20 gkm, month by month. Since the values at higher levels are means of small numbers of observations, and may not be strictly comparable, it was found necessary to work out the pressure upwards from 10 gkm with the aid of the hydrostatic equation and the mean temperatures of the air columns between successive levels. Hess also had adopted a similar procedure while calculating the geostrophic west wind components along the 80°W meridional cross section. By this method it was possible to fill up some of the gaps in the normal sounding balloon values and get a more or less complete picture up to 20 km.

Table 6 gives the monthly mean geos-

TABLE 6

Mean geostrophic west wind velocities over India between Latitudes 20°N and 30°N

Height (gkm)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
10	mps	32	40	20	16	8	—8	—16	—16	—12	4	16	28
	mph	71	89	45	36	18	—18	—36	—36	—27	9	36	63
15	mps	27	43	18	17	5	—26	—29	—29	—24	—3	8	27
	mph	61	97	41	38	11	—59	—65	—65	—54	—7	18	61
17	mps	15	35	20	8	—5	—32	—30	—27	—21	—6	—3	17
	mph	34	79	45	17	—11	—72	—68	—61	—47	—13	—7	38
20	mps	4	17	6	4	—9	—23	—19	—12	—12	—1	—2	9
	mph	9	38	13	9	—20	—49	—43	—27	—27	—2	—4	20

trophic west wind velocities at different heights. Strong westerly winds in winter and easterly winds during the summer monsoon are clearly seen at all levels. The small easterly components indicated in October and November may be neglected. It is noticed that in winter the westerlies tend to increase in speed up to 15 km and decrease aloft up to 20 km whereas the summer easterlies increase up to the tropopause and decrease aloft. The mean summer and winter velocities are compared with those obtained by Hess for 80°W at 21. 6°N in Table 7. The general agreement between the two is satisfactory. Fig. 7 gives the seasonal curves for approximate wind velocities for different heights over north India. The velocities obtained by Venkiteshwaran for north India from high pilot balloon ascents are also given for comparison. While the winter curves agree, the summer (July-August) curves show a difference at higher levels, presumably because Venkiteshwaran's values are based upon very scanty number of observations.

(ii) *Above* 20 *km*

This is a region of scanty data. From pressures and densities over Central India computed for summer (May-June) and those calculated by Penndorf for Central Europe (summer), geostrophic west wind components have been worked out for higher levels and are given in Table 8. The values for 20 km computed by this method may be compared with the summer values obtained from sounding balloon data. The agreement is satisfactory. It

TABLE 7

Mean geostrophic west wind velocities at 22°N in metres per second

Heights (km)	Summer India 80°E	Summer America 80°W	Winter India 80°E	Winter America 80°W
10	—16	—9	36	17.5
15	—27	—17.5	25	25
17	—28.5	—25.5	10.5	18.5

TABLE 8

Mean geostrophic west wind velocities in summer between 20° and 50°N

Height km	Velocity mps	Velocity mph
20	-20.6	-46
30	-8.45	-19
35	39	90
40	107	240
50	141	317
60	265	596
70	304	684
80	210	473
90	137	388
100	0	0

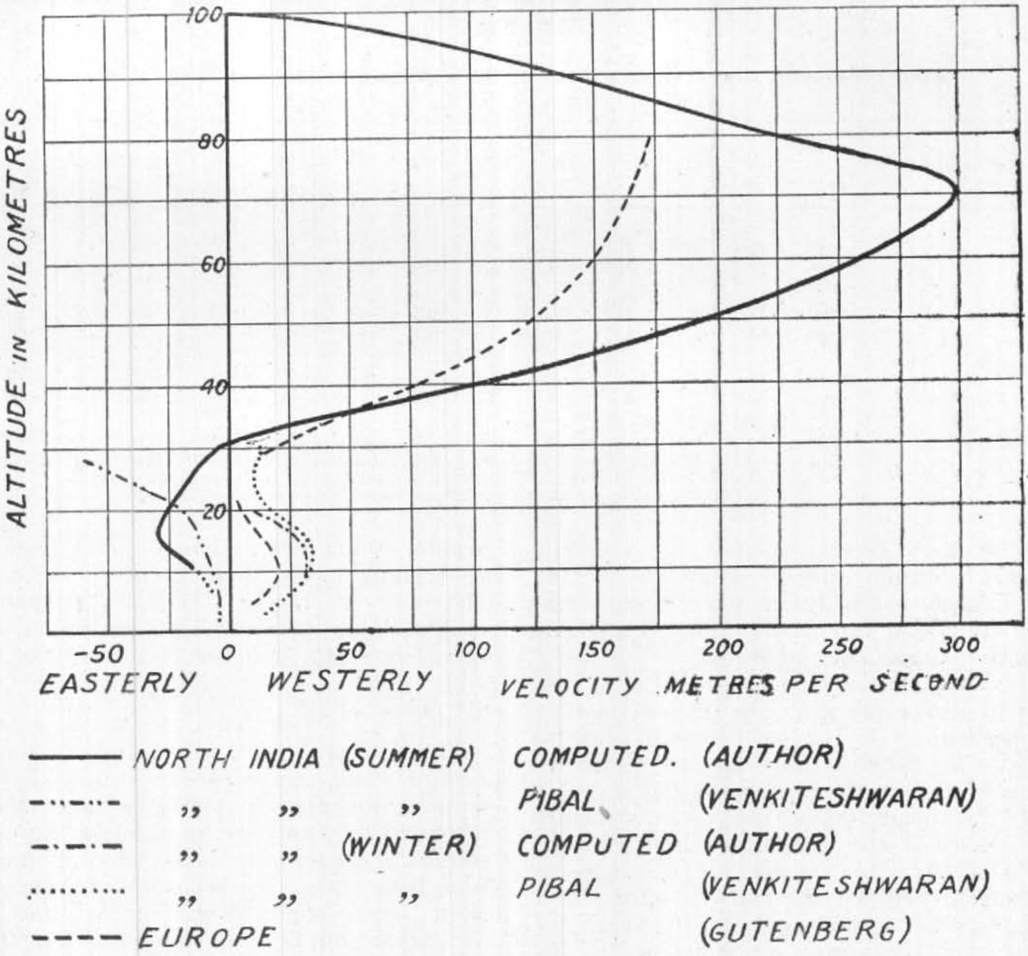

Fig. 7　Characteristics of wind velocities at various heights

is also seen that the easterly winds in summer extend up to about 30 km and change to westerlies aloft. From the few high pibal ascents available over some stations in India, Venkiteshwaran also reports that during summer months (July-August) easterlies are the most predominant winds at all levels above 20 km over India. At Peshawar, however, the one available observation up to 29 km indicated westerly winds up to 20 km and easterlies aloft. The mean easterly velocity of 8.45 mps calculated for winds at 30 km agrees with Venkiteshwaran's Peshawar value of 9 mps at 29 km, Murgatroyd and Clew's[21] observations that the wind at 30 km over Southeast England is predominantly easterly in summer, rising to some 13 mps (30 mph) and Gutenberg's [22] results over New Mexico.

No definite information regarding wind velocities is available for the region above 30 km for comparison with the values obtained in Table 8. Observations of movement of meteor trails (30 to 120 km) have produced contradictory results. Gutenberg in his general summary of the mean characteristic values of wind speed and direction for European latitudes indicates westerly winds upto 60 km reaching up to 150 mps and easterlies aloft. His data pertain to European latitudes and hence the easterlies in the levels up to 17 km in the Indian curves are replaced by westerlies which exist to the north of the subtropical high pressure cells as in the case of Peshawar cited by Venkiteshwaran. Between 10 and 30 km Gutenberg [20] indicates a reduction of speed, but has not mentioned the easterly components though he has referred to Johnson's [23] note in "*Nature*" on the direction and velocity of wind over England at an elevation of 30 km which reports easterly wind reaching 30 mph at that level. In his more recent observations with rawin-sondes over New Mexico (Lat. 32° N) Gutenberg [22] obtained easterly winds during summer above 18 km. Observations of movements of noctilucent clouds (80 km) have indicated easterly or northeasterly winds in summer at that level in Scandinavia and Canada.

Considering the fact that the Indian values for temperatures in the inversion layer (warm layer) have been found to be higher than those in European latitudes (by Penndorf or more recently by Cox and collaborators [24]), the pressure gradient in this layer should be towards the poles, thus giving rise to westerly winds between 20 and 50° N above 30 km as indicated in Table 8. It is possible that at the top of the lapse layer (which may be called *stratopause* on analogy with the *tropopause*) the temperature over the tropics may fall to values less than those over higher latitudes. Hence the tropical *stratopause* also may be pictured to be the coldest over the earth on analogy with its tropospheric analogue. With this temperature reversal at the *stratopause* there can be a wind reversal to easterlies above 80 km. This may account for the easterly winds in the polar regions at 80 km and the rapid decrease of the west components above 70 km in lower latitudes and the possible reversal to easterly above 100 km as given in Fig. 7.

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