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Characteristics of the Upper Troposphere, Tropopause and the Lower Stratosphere over Trivandrum

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ABSTRACT. Using the data from radiosonde ascents at Trivandrum in the years 1948-51 and from afternoon pilot balloon ascents over Nagercoil in 1944-50 the structure of the atmosphere over Trivandrum with special reference to the upper troposphere, tropopause and lower stratosphere has been studied. Tables of temperatures and air densities are given and temperatures over Trivandrum are compared with those over Madras, Poona and Agra and at the same latitude over East Africa. Diagrams giving a composite picture of the wind and temperature distribution, four seasonal mean tephigrams and temperature-height curves for the ten ascents reaching the tropopause are also given and discussed. The patterns of wind distribution in January, April, July and October are compared with the four basic currents in the tropics classified by Riehl.

The chief results of the study are—

(*i*) The annual range of temperature is small and is maximum at the 200-100 mb level.

(*ii*) The tropopause occurs at or slightly above the 100-mb level and appears to be lower in June to October than in the rest of the year. The average counter-lapse of temperature in the lower stratosphere up to 20 km is -2°C km^{-1}.

(*iii*) The maximum lapse rate of temperature occurs between 300 and 200-mb levels. There is a marked decrease of lapse rate at the 150-mb level, about 2 km below the tropopause.

(*iv*) Winds with easterly components are the most predominant, westerly winds occurring mainly between surface and the 400-mb level during June to October. Easterly components are prominent and strong above the 300-mb level in June to October and increase in force with height up to the tropopause and decrease with height at higher levels.

(*v*) There is a large negative gradient of temperature between Trivandrum and Madras in the 200-100 mb region in all the seasons and to a lesser degree between Trivandrum and north India in winter and above the 600-mb level in summer. There is a positive gradient of temperature between Trivandrum and north India (Agra) in the SW monsoon season up to the 200-mb level, specially in the 500-300 mb region.

1. Introduction

The southernmost stations in India for which some data about the tropopause and lower stratosphere are available and are published (Ind. Met. Dep. Upper Air Data, 1946) are Madras and Bangalore except for the data from a solitary sounding balloon ascent at Trichinopoly (Lat. 10° 49′N, Long. 78° 42′E) on 14 December 1940 which penetrated into the lower stratosphere. This ascent reached a height of 22·98 km (pressure 33 mb, temperature 227° A) and showed Type I* tropopause at 15·61 km (pressure 112 mb, temperature 197° A). There was a well marked inversion of temperature above the tropopause, the average counter-lapse rate being 4·3° C km^{-1} between 16 and 22 km. Some characteristics of the tropopause over Madras in June to November have been briefly discussed by Sur and Ramakrishnan (1939) on the basis of 63 sounding balloon ascents made during 1932-35. A detailed study of the characteristics of the tropopause and the lower stratosphere over Madras-Bangalore in all the months of the year based on Madras sounding balloon data for the longer period 1932-40 and on Bangalore sounding balloon data in 1938-40 is being made by the first author separately.

A few sounding balloon ascents made at Trivandrum (Lat. 8° 29′N, Long. 76° 57′E) in July and August 1938 did not reach the tropopause. Radiosonde ascents with India Meteorological Department Fan-type radio-meteorographs have been made once daily at Trivandrum since 1948 but it is only in 1951 that some ascents reached the 100-mb

*The types of tropopause mentioned are according to the definitions adopted by the India Meteorological Department and given in the introduction to Upper Air Data Vol. XIII, Part B and higher levels and have provided some information about the tropopause and the lower stratosphere just above it. It is the purpose of this paper to examine the temperature data obtained from the radiosonde ascents at Trivandrum during 1948-51, specially those which reached the 100-mb and higher levels in 1951, together with the mean upper wind data, to get an idea of the characteristics of the upper troposphere, tropopause and the lower stratosphere over the station. As this station is situated near the southernmost tip of India, within 10°N of the equator, an examination of its upper air temperature and wind distribution will be of interest from the point of view of the general circulation of the atmosphere, up to and near the tropopause, in the tropics in a region subject to a monsoonal regime. It is hoped that the study will also be of some value in connection with the provision of meteorological information for the flight of jet aircraft over the Bombay-Colombo air route.

2. Data

In 1948-50, radiosonde ascents over Trivandrum did not reach the 100-mb level. In 1951, ascents on 62 days reached the 100-mb level and of these 14 reached higher levels, 6 reaching the 50-mb level. The highest ascent, on 8 October 1951, reached 21·41 km where the pressure was 45 mb and temperature 204°A. The radiosonde ascents were all made after sunset, the mean time of ascent being 2000 IST (1430 GMT), so that there was no question of the temperatures having been affected by direct solar insolation.

Table 1 shows the mean temperatures over Trivandrum at the surface and ten standard pressure levels based on the radiosonde ascents in 1948-51. Table 2 shows the seasonal mean temperatures for winter (January to March), summer (April-May), southwest monsoon (June to September) and northeast monsoon (October to December). Table 3 shows the difference between the seasonal mean temperatures of Trivandrum and those of Madras, Poona and Agra based on sounding balloon data. Table 4 gives the monthly mean air density over Trivandrum calculated from the data in Table 1, assuming a uniform relative humidity of 50 per cent except for surface for which the mean temperature and relative humidity at 1730 IST (1200 GMT) have been used.

3. Temperature and Lapse rate

Tables 1 and 2 show that the annual and seasonal variations in the upper air temperatures over Trivandrum are small. The annual range which is 2·6°C at the surface decreases to 1·9°C at the 600-mb level and increases thereafter slightly with height to 4·6°C at the 200 to 150-mb level (13 to 15 km) and becomes as much as 11·0°C at the 100-mb level (about 16·5 km). If the seasonal, instead of the monthly, mean temperatures are considered, the range decreases from 2·2°C at the surface to 1·1°C at the 600-mb level, increases thereafter to 2·8°C at the 300-mb level, then decreases to a minimum of 2·4°C at the 200 to 150-mb level and increases to 5·5°C at the 50-mb level.

Summer (April-May) temperatures are higher than winter temperatures up to the 150-mb level. Above that height, winter temperatures are higher. The lowest temperatures occur generally in the winter except that above the 200-mb level they occur in the northeast monsoon period. If June-July temperatures are considered as summer temperatures and December-January temperatures as winter temperatures, the difference between summer and winter temperatures is very small but the same type of variation is shown with the maximum range at the 300-mb level. The magnitude and type of variation is similar to that at Madras indicated in a recent study (Krishna Rao 1952) of upper air temperatures over India. Some upper air temperature data available for Ratmalana (Colombo) also show similar characteristics.

The chief features shown by the differences in Table 3 in the different seasons are indicated below—

Winter (January-March)—Trivandrum temperatures are generally higher than Madras, Poona and Agra temperatures, except from surface upto 850 mb at Poona and Madras and at 150-mb level and above over Agra, where temperatures are lower.

TABLE 1

Monthly Upper Air Temperatures (°A) over Trivandrum

Level (mb)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Range
50	T	211·0	202·7	—	—	—	201·4	—	—	—	205·5	—	—	
	n	*(1)*	*(1)*				*(1)*				*(3)*			
100	T	205·7	204·8	196·2	201·4	202·0	202·1	199·6	204·0	200·3	201·3	201·3	194·7	11·0
	n	*(3)*	*(5)*	*(6)*	*(11)*	*(4)*	*(7)*	*(5)*	*(2)*	*(4)*	*(9)*	*(6)*	*(3)*	
150	T	211·0	211·2	210·1	211·9	214·3	214·1	209·7	213·0	213·4	210·4	211·9	209·9	4·6
	n	*(6)*	*(19)*	*(23)*	*(21)*	*(8)*	*(16)*	*(15)*	*(6)*	*(13)*	*(14)*	*(8)*	*(7)*	
200	T	221·1	222·0	221·6	223·3	223·3	224·5	222·6	223·6	223·4	223·1	225·7	223·2	4·6
	n	*(36)*	*(54)*	*(76)*	*(61)*	*(58)*	*(54)*	*(43)*	*(38)*	*(36)*	*(28)*	*(15)*	*(14)*	
300	T	240·7	241·0	241·5	243·8	243·9	244·3	242·1	242·2	242·3	242·3	242·6	241·8	3·6
	n	*(96)*	*(97)*	*(108)*	*(82)*	*(80)*	*(74)*	*(100)*	*(104)*	*(84)*	*(87)*	*(73)*	*(83)*	
400	T	255·8	256·3	256·5	257·9	258·5	258·3	256·7	256·7	257·4	257·1	257·0	256·7	2·7
	n	*(119)*	*(104)*	*(114)*	*(81)*	*(82)*	*(75)*	*(111)*	*(112)*	*(100)*	*(97)*	*(95)*	*(97)*	
500	T	266·5	266·9	267·2	268·3	268·8	268·4	267·4	267·3	267·8	267·7	267·3	267·4	2·3
	n	*(120)*	*(109)*	*(118)*	*(84)*	*(82)*	*(78)*	*(114)*	*(115)*	*(105)*	*(103)*	*(96)*	*(103)*	
600	T	275·0	275·7	275·9	276·3	276·9	276·5	275·7	275·8	276·0	275·7	275·6	275·5	1·9
	n	*(120)*	*(111)*	*(120)*	*(85)*	*(86)*	*(77)*	*(117)*	*(119)*	*(113)*	*(107)*	*(102)*	*(107)*	
700	T	282·3	283·1	283·0	283·9	284·2	283·3	282·7	282·9	282·9	282·9	282·6	282·7	1·9
	n	*(122)*	*(110)*	*(122)*	*(85)*	*(90)*	*(81)*	*(118)*	*(122)*	*(114)*	*(115)*	*(105)*	*(114)*	
850	T	290·3	290·8	291·9	292·8	292·7	291·1	290·5	290·7	290·7	291·0	291·0	290·5	2·5
	n	*(124)*	*(110)*	*(121)*	*(88)*	*(92)*	*(85)*	*(122)*	*(123)*	*(119)*	*(119)*	*(107)*	*(117)*	
Surface	T	299·4	299·9	300·9	300·6	300·7	298·4	298·3	298·6	298·5	298·7	299·0	299·3	2·6
	n	*(124)*	*(112)*	*(124)*	*(90)*	*(93)*	*(88)*	*(123)*	*(123)*	*(119)*	*(120)*	*(109)*	*(121)*	

T—Temperature (°A) *n*—Number of observations

TABLE 2

Seasonal Upper Air Temperatures (°A)

Level (mb)			*Winter* (Jan-Mar)	*Summer* (Apr-May)	*SW Monsoon* (Jun-Sep)	*NE Monsoon* (Oct-Dec)	Range
50	..	..	206·9	—	201·4	205·5	5·5
100	..	..	202·2	201·7	201·5	199·3	2·9
150	..	..	210·3	213·1	212·5	210·7	2·4
200	..	..	221·6	223·3	223·5	224·0	2·4
300	..	..	241·1	243·9	242·7	242·2	2·8
400	..	..	256·2	258·2	257·3	256·9	2·0
500	..	..	266·9	268·5	257·7	257·5	1·6
600	..	..	275·5	276·6	276·0	275·6	1·1
700	..	..	282·8	284·1	282·9	282·7	1·4
850	..	..	291·0	292·7	290·7	290·8	2·0
Surface	..	..	300·1	300·7	298·5	299·0	2·2

TABLE 3

Difference between Seasonal Mean Temperatures (°C) of Trivandrum and those of Madras, Poona and Agra

Level (mb)	*Winter* Trivandrum *minus*			*Summer* Trivandrum *minus*			*SW Monsoon* Trivandrum *minus*			*NE Monsoon* Trivandrum *minus*		
	Madras	Poona	Agra	Madras	Poona	Agra	Madras	Poona	Agra	Madras	Poona	Agra
50 ..	0·5	1·5	—1·2	—	—	—	—6·8	—6·2	—8·1	—1·7	0·5	—3·4
100 ..	8·9	5·6	—0·2	6·8	7·5	2·5	6·0	6·3	6·0	5·2	4·5	—0·8
150 ..	7·0	4·1	—0·3	8·3	6·0	2·5	8·0	5·8	0·2	7·3	5·1	2·1
200 ..	4·4	1·7	2·6	3·4	2·4	2·2	4·4	1·6	—2·8	6·2	4·8	4·7
300 ..	2·2	2·4	6·7	3·4	2·9	6·0	1·1	—0·9	—5·6	1·8	1·4	4·1
400 ..	1·1	2·5	8·2	2·1	2·3	5·1	0·0	—1·5	—5·1	0·6	—1·4	4·3
500 ..	0·7	2·1	7·4	1·8	2·0	3·1	—0·4	—1·4	—4·1	0·1	0·4	4·7
600 ..	0·9	2·6	6·8	2·1	1·5	1·9	0·0	—0·6	—3·5	0·0	0·5	3·4
700 ..	1·5	2·3	6·1	0·9	—0·2	0·1	—0·4	—0·2	—3·7	0·5	1·2	4·0
850 ..	—1·2	—2·7	4·2	—4·0	—4·4	—5·8	—2·4	—2·8	—4·8	0·6	—0·3	2·3
Surface ..	0·3	—2·5	3·3	—1·7	—4·6	—7·5	—5·1	—2·5	—5·9	—1·0	0·2	2·0

TABLE 4

Mean Air Density in grams per cubic metre

Level (mb)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Range
50	83	86	—	—	—	86	—	—	—	85	—	—	—
100	169	169	177	173	172	172	174	171	174	173	172	179	10
150	248	248	249	247	244	244	249	245	245	249	247	249	5
200	316	314	315	312	312	311	313	312	312	313	309	313	5
300	434	433	432	429	428	428	432	431	431	431	431	432	6
400	545	543	543	539	538	538	542	542	541	541	541	542	7
500	653	652	651	648	647	648	651	651	650	650	651	651	6
600	759	757	755	754	753	754	756	756	755	756	756	756	6
700	862	859	860	856	855	858	860	859	859	859	860	860	7
850	1016	1014	1010	1007	1007	1014	1015	1015	1015	1014	1014	1015	9
Surface	1144	1139	1139	1137	1137	1148	1149	1147	1145	1147	1148	1144	12

Trivandrum temperatures are markedly higher than Madras and Poona temperatures in the 200 to 100-mb region and markedly higher than Agra temperatures between 850 and 300 mb. The difference between Trivandrum and Madras temperatures is highest (about 9°C) at the 100-mb level. Of the four stations, the highest temperature occurs over Poona from surface to 850 mb, over Trivandrum from 700 to 200 mb and over Agra at higher levels. The lower temperature is over Agra from surface up to 300 mb, then over Madras up to 100 mb and over Poona at 50-mb level.

Summer (April-May)—Trivandrum temperatures are lower below the 700-mb level and higher aloft. They are markedly higher than Madras and Poona temperatures at 150 to 100-mb levels and markedly higher than Agra temperatures at 400 to 300-mb levels. The highest temperature occurs over Agra from surface to 850 mb, over Poona at 700 mb and over Trivandrum at all other levels. The lowest temperature occurs over Trivandrum from surface to 850 mb, over Madras at 700 to 600 mb and 200 to 150 mb and over Agra at other levels.

Southwest Monsoon (June-September)—Trivandrum temperatures are lower up to 300-mb level and at the 50-mb level (*i.e.*, above the tropopause) and higher at other levels. At 200 to 100-mb levels Trivandrum temperatures are markedly higher than Madras or Poona temperatures. From surface up to 300 mb, Trivandrum temperatures are markedly lower than Agra temperatures.

The highest temperature is over Agra except at the 100-mb level where it occurs over Trivandrum. The lowest temperature is either over Trivandrum or Madras. Between 700 and 300-mb levels there is very little difference in temperature between Trivandrum and Madras.

Northeast Monsoon (October-December)—Trivandrum temperatures are generally higher specially in the 200 to 100-mb range. Trivandrum is much warmer than Agra at all levels up to 150-mb level and cooler at higher levels. It is markedly warmer than Madras and Poona from 200 to 100 mb. The highest temperatures occur generally over Trivandrum or Madras up to 150 mb and over Agra at higher levels. Above the 100-mb level (*i.e.*, at and near the tropopause) Trivandrum is cooler than Madras and Agra.

Table 3 shows that upper air temperatures over Trivandrum are higher than over Madras, Poona or Agra except that up to 300-mb level in the southwest monsoon season, up to 850-mb level in summer and in winter in respect of Poona and above the 100-mb level in the southwest and northeast monsoon seasons, they are lower. A large negative gradient of temperature (*i.e.*, temperatures decreasing with latitude) is shown in the 200 to 100-mb region between Trivandrum and Madras in all the seasons and to a lesser degree between Trivandrum and North India (Agra) in the winter and above the 600-mb level in summer. There is a fairly marked positive gradient of temperature between Trivandrum and North India (Agra) in the southwest monsoon season up to 200-mb level specially in 500 to 300-mb region.

It should be remarked that the difference between Trivandrum (radiosonde) and Madras (sounding balloon) temperatures at and above the 200-mb level are rather large and such large horizontal gradients of temperatures are not supported by winds at those levels in all the seasons. A comparison of the Trivandrum (radiosonde) temperatures with those shown for that latitude in Fig. 4 of the earlier paper (Krishna Rao 1952) on the upper air temperatures over India show that the Trivandrum temperatures are 2 to 5°C higher at and above the 200-mb level. A comparison of the Madras sounding balloon and Madras radiosonde temperatures also shows that while they more or less agree up to the 300-mb level, the radiosonde temperatures are higher by 2 to 5°C at the higher levels. It has been suggested that this may be due to the aneroid of the radiosonde meteorograph being too insensitive at pressures lower than 300 mb to give sufficient accuracy.

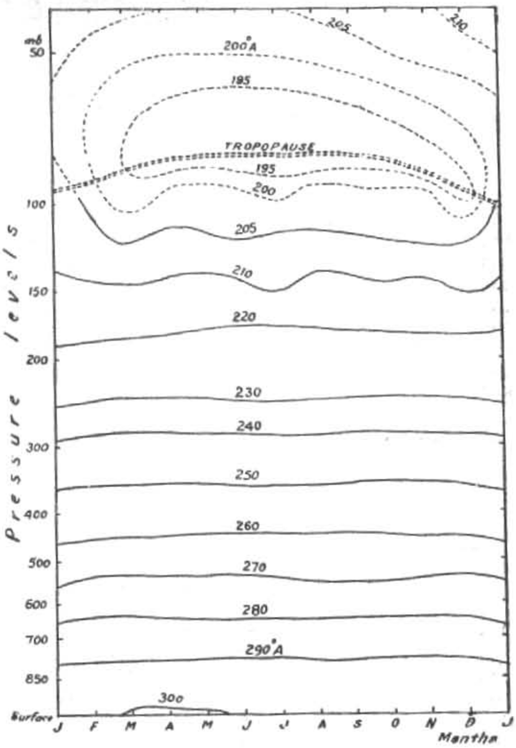

Fig. 1. Upper air temperatures over Trivandrum

Fig. 1 shows the isopleths of upper air temperatures over Trivandrum during the year and Fig. 2 the mean tephigrams of Trivandrum for the four seasons based on the data in Table 2. It is seen from Fig. 2 and Table 2 that up to the 700-mb level temperatures in winter and summer are higher than in the southwest monsoon and northeast monsoon seasons while at higher levels the tephigrams for the two monsoon

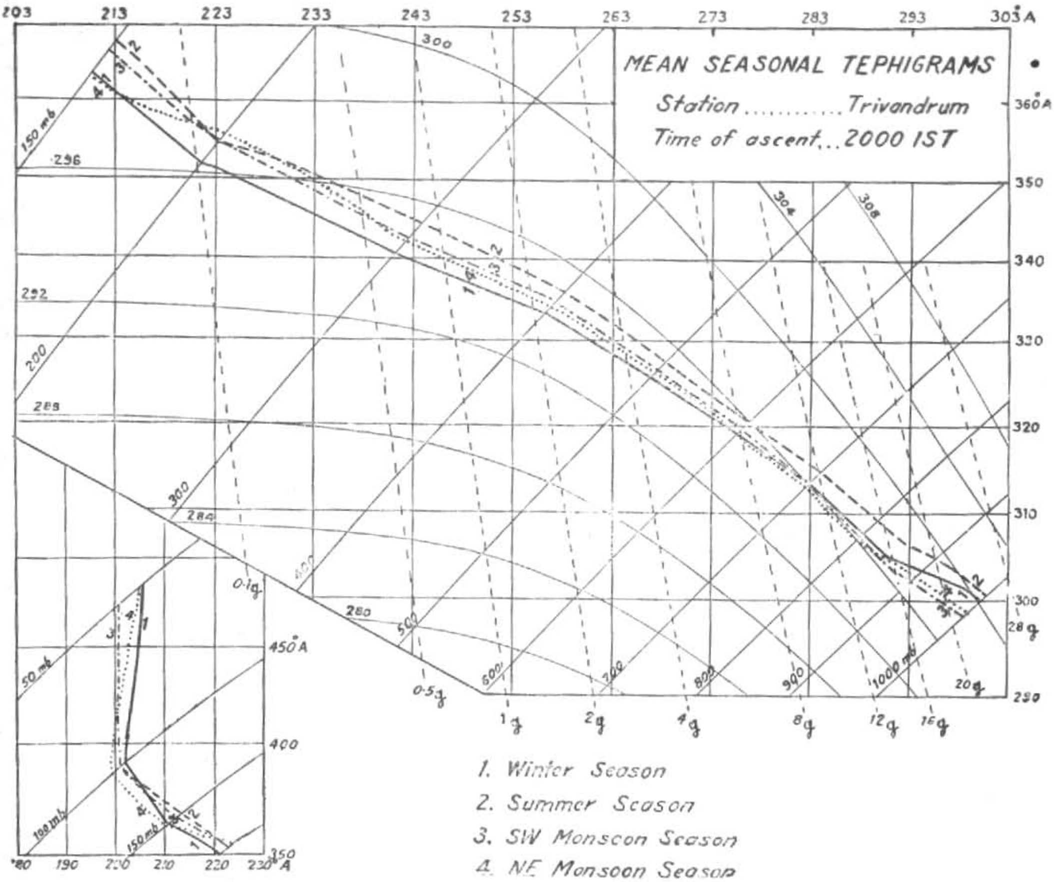

Fig. 2.

seasons lie between the summer and winter tephigrams. Above 150-mb level, winter temperatures are higher than summer temperatures. The tephigrams show that the lapse rate of temperature is maximum between 300 and 200-mb levels (*i.e.*, 10 to 12 km) and decreases appreciably at and above the 200-mb level. An examination of the tephigrams (not reproduced here) of the 62 ascents in 1951 which reached the 100-mb level shows that in a majority of the ascents there was a marked decrease in the lapse rate of temperature at the 150-mb level (about 14 km) about 2 to 2·5 km below the mean height of tropopause. The lapse rate immediately below the 150-mb level was 6 to 8°C km^{-1} while immediately above it, it decreased to 4 to 3°C km^{-1}. This feature is shown by other Indian stations also as will be seen from the diagram of upper air temperature lapse rates over India in summer and winter presented in the recent paper (Krishna Rao 1952). It is also interesting to note from Venkiteshwaran's (1952) recent studies that clear air turbulence occurs fairly frequently over Trivandrum in 300-250 mb region which is approximately the region in which the maximum lapse rate of temperature occurs.

It will be interesting to compare the temperatures over Trivandrum with those at the same latitude over East Africa and Arabia. In a recent report of the Meteorological Research Committee (Air Ministry, London), Frost (1952) has given meridional cross-sections of temperature and east and west components of winds along longitude

40°E for January, April, July and October up to 40-mb level. Comparing the temperatures at 8°N latitude from those cross-sections with the Trivandrum temperatures, it is found that they agree within 2°C up to the 200-mb level except that up to 850 mb in July the East African temperatures are much higher. At levels above 200 mb, East African temperatures are lower than Trivandrum temperatures. The tropopause appears to occur at about the same pressure level as over Trivandrum but the temperature at the tropopause is definitely lower.

4. Air Density

It is seen from Table 4 that air density over Trivandrum has only a small variation during the year. The variation is maximum at the surface, decreases slowly with height and is only about 5 to 7 gm per cubic metre at all levels from 700 to 150 mb. At the 100-mb level (*i.e.*, near the tropopause) the range increases and is about the same as at the surface. Maximum air density occurs generally in January and the minimum in April-May or June at all levels up to 150 mb with the exception that at the surface the maximum air density (in the evening and night) in the year occurs in July. This is because the surface temperature in July in the evening is 4 to 5°F lower than in January. The air density at the tropopause is about 170 to 150 gm per cubic metre. At the cruising height of "Comet" Jet airliner (*viz.*, 40,000 ft), the mean air density over Trivandrum is about 315 gm per cubic metre. It is interesting to note that the air density at the same height over England, in the lower stratosphere, is about 310 gm per cubic metre in summer and 280 gm per cubic metre in winter.

5. Characteristics of Tropopause and the Lower Stratosphere

Of the 62 radiosonde ascents which reached the 100-mb level in 1951, only 10 reached the tropopause. Details of these 10 ascents are given in Table 5 below.

TABLE 5

S. No.	Date	Highest point reached			Tropopause				Inversion at		
		Height (km)	Pressure (mb)	Temperature (°A)	Type	Height (km)	Pressure (mb)	Temperature (°A)	Height (km)	Pressure (mb)	Temperature (°A)
1	23-1-51	21·27	50	211·0	III	15·80	122	214·0	20·00		211·0
2	11-2-51	21·14		202·7	III	16·97	100	209·3	20·50		202·5
3	25-3-51	18·51	75	208·8	I	16·98	98	200·0	16·98	98	200·0
4	30-6-51	21·09	50	201·4	IV	16·93	100	203·8	18·40		201·8
5	1-9-51	17·26	90	201·0	I	16·45	103	194·5	16·45	103	194·5
6	16-9-51	16·85		197·3	II	16·29	110	198·3	—	—	—
7	19-9-51	18·25		201·4	III	16·95	100	203·7	—	—	—
8	8-10-51	21·41	45	203·9	III	18·00	81	198·5	18·75		197·8
9	9-10-51	20·95	50	205·0	III	17·85	85	201·2	18·80		200·2
10	14-10-51	20·63	50	209·5	I	17·05	98	195·0	17·05	98	195·0

A composite diagram showing the temperature-height curves (from 12 km upwards) for the above 10 ascents which reached the tropopause is shown in Fig. 3.

It is seen from Fig. 3, as also from Figs. 1 and 2 that, considering the year as a whole, the tropopause occurs between 16 and 17 km near about the 100-mb level at a temperature of about 200°A. The mean temperature at 20 km is about 205°A giving a mean inversion of about 2°C km^{-1} in the first 3 to 4 km above the tropopause. The lowest temperature recorded at the tropopause was 194·5°A at 16·45 km (103 mb) on 1 September 1951. The number of occasions when the tropopause was reached is too few to draw any final conclusions about the monthly or seasonal variation in the height of the tropopause or in the strength of the inversion above the tropopause. It would appear, however, that the tropopause occurs at a slightly lower height in June to September than in the other periods of the year. It is seen that of the 10 occasions, Type I tropopause with an inversion of temperature occurred only on 3 occasions, 2 in September and 1 in March.

In order to examine the variation of temperature with height in the upper troposphere and lower stratosphere with reference to the tropopause level, temperatures at every ½-km height above the tropopause (*Hc*) and for every 1-km height below the tropopause were tabulated for each of the 10 ascents listed in Table 5. Lapse rates of temperature in °C km^{-1} were then worked out and the results are shown in Table 6.

This provides a comparison of the lapse rates of temperature in the region of the lower stratosphere immediately above the tropopause with those in the troposphere immediately below. Although the number of occasions is too small to draw firm conclusions, it is seen that with Type I tropopauses the counter-lapse rates of temperature above the tropopause are of the order of 7 to 8° C km^{-1}. With Types III and IV tropopause, the counter-lapse rates above the tropopause are either small or there is a small decrease of temperature with height. The lapse rates of temperature in the upper tropospheres immediately below the tropopause are of the order of 2 to 5°C km^{-1} in the first kilometre and 4 to 5°C km^{-1} in the next 2 or 3 kilometres.

On 1 September 1951 when the radiosonde ascent at Trivandrum reached the tropopause at 16·45 km (pressure 103 mb, temperature 194·5°A), an ascent at Poona at about the same time reached the tropopause at 16·85 km (pressure 100 mb, temperature 198·5°A). The temperature-height curves of the two ascents are shown in Fig. 4. At Trivandrum, the tropopause was of Type I with an inversion of 8°C km^{-1} in the first kilometre above the tropopause. At Poona also the tropopause was of Type I, with an inversion of 7°C in 1·65 km above the tropopause, *i.e.*, a mean counter-lapse of 4·2° C km^{-1}. Although the tropopause over Trivandrum was slightly lower, the temperature at the tropopause was not higher but lower by 4°C. It is also seen that above 6 km, temperatures were higher over Poona than over Trivandrum up to the tropopause.

6. Upper Winds

Fig. 5 shows isopleths of the mean east and west components of upper winds based on afternoon pilot balloon ascents (1944-50) over Nagercoil, a station 40 miles to the south-southeast of Trivandrum and 10 miles to the northwest of Cape Comorin, the southernmost point of India. Winds over Nagercoil have been considered because the upper air temperature data refer to the evening hours and Trivandrum did not have afternoon pilot balloon ascents till very recently. Further, upper winds over Nagercoil are available up to much higher levels than over Trivandrum. Isopleths of upper air temperatures have also been shown in Fig. 5 which thus gives a more or less complete picture of the upper wind and temperature distribution over the extreme south India during the year up to about 20 km.

It is seen that winds with easterly components predominate. Westerly winds occur from the surface up to the 400 to 350-mb level (6 to 7 km) in June to October, upto the

TABLE 6

Lapse rates of temperature above and below the tropopause

Height (km)	Date (1951) Jan 23	Feb 11	Mar 25	Jun 30	Sep 1	Sep 16	Sep 19	Oct 8	Oct 9	Oct 14
	Lapse rate in °C km-1									
Hc+4½ to Hc+5	—0·6	..	..	..	..	..	..	..	..	..
Hc+4 to Hc+4½	—0·2	..	..	..	..	..	..	..	..	..
Hc+3½ to Hc+4	0·0	—0·4	..	2·0	..	..	..	..	..	..
Hc+3 to Hc+3½	0·4	0·0	..	2·2	..	..	..	—3·4	—3·6	—6·0
Hc+2½ to Hc+3	0·6	0·8	..	1·4	..	..	..	—3·0	—3·2	—5·6
Hc+2 to Hc+2½	0·8	1·2	..	—3·4	..	..	..	—2·4	—2·4	—5·0
Hc+1½ to Hc+2	1·2	1·4	..	—1·8	..	..	..	—2·2	—1·8	—4·0
Hc+1 to Hc+1½	1·4	1·8	—8·4	0·6	..	..	1·6	—1·4	—1·2	—3·4
Hc+½ to Hc+1	1·4	2·0	—7·2	1·6	—8·8	..	1·8	0·0	—0·4	—3·0
Hc to Hc+½	2 0	2·0	—1·4	2·0	—7·2	1·8	2·0	1·6	1·8	—1·4
Tropopause type	III	III	I	IV	I	II	III	III	III	I
Hc to Hc—1	2·2	3·3	5·5	4·2	5·6	6·7	3·0	2·5	2·2	3·0
Hc—1 to Hc—2	3·6	4·5	6·5	6·0	6·5	8·2	4·7	3·6	2·8	4·0
Hc—2 to Hc—3	6·2	5·0	6·9	6·7	7·0	7·8	5·8	4·2	5·4	5·1
Hc—3 to Hc—4	5·5	5·6	7·1	6·0	7·6	7·1	6·3	5·2	7·7	6·8

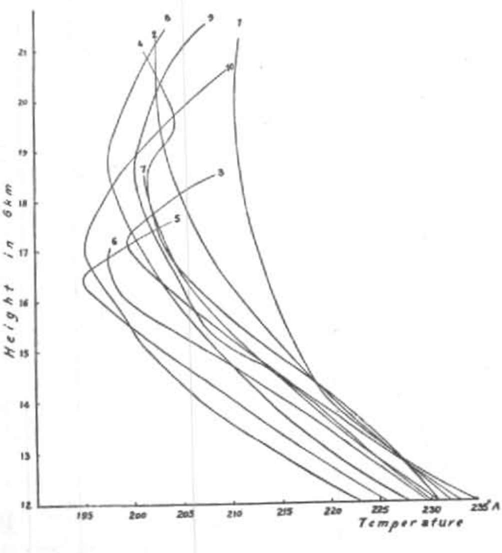

Fig. 3

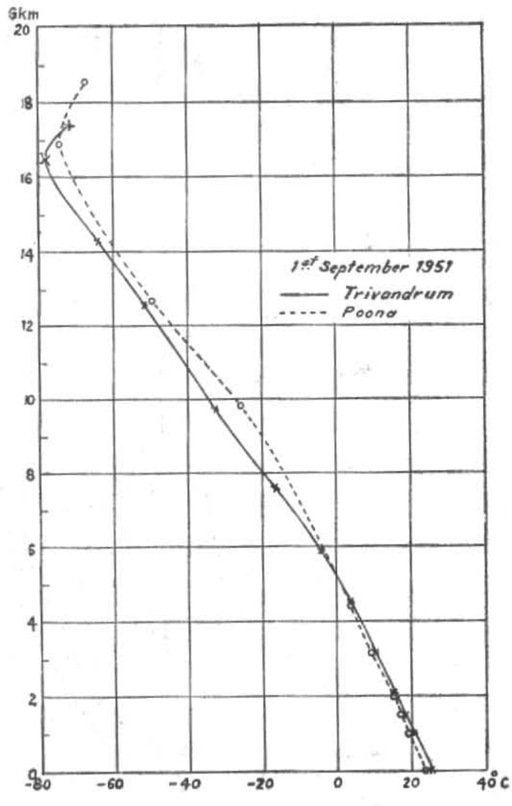

Fig. 4

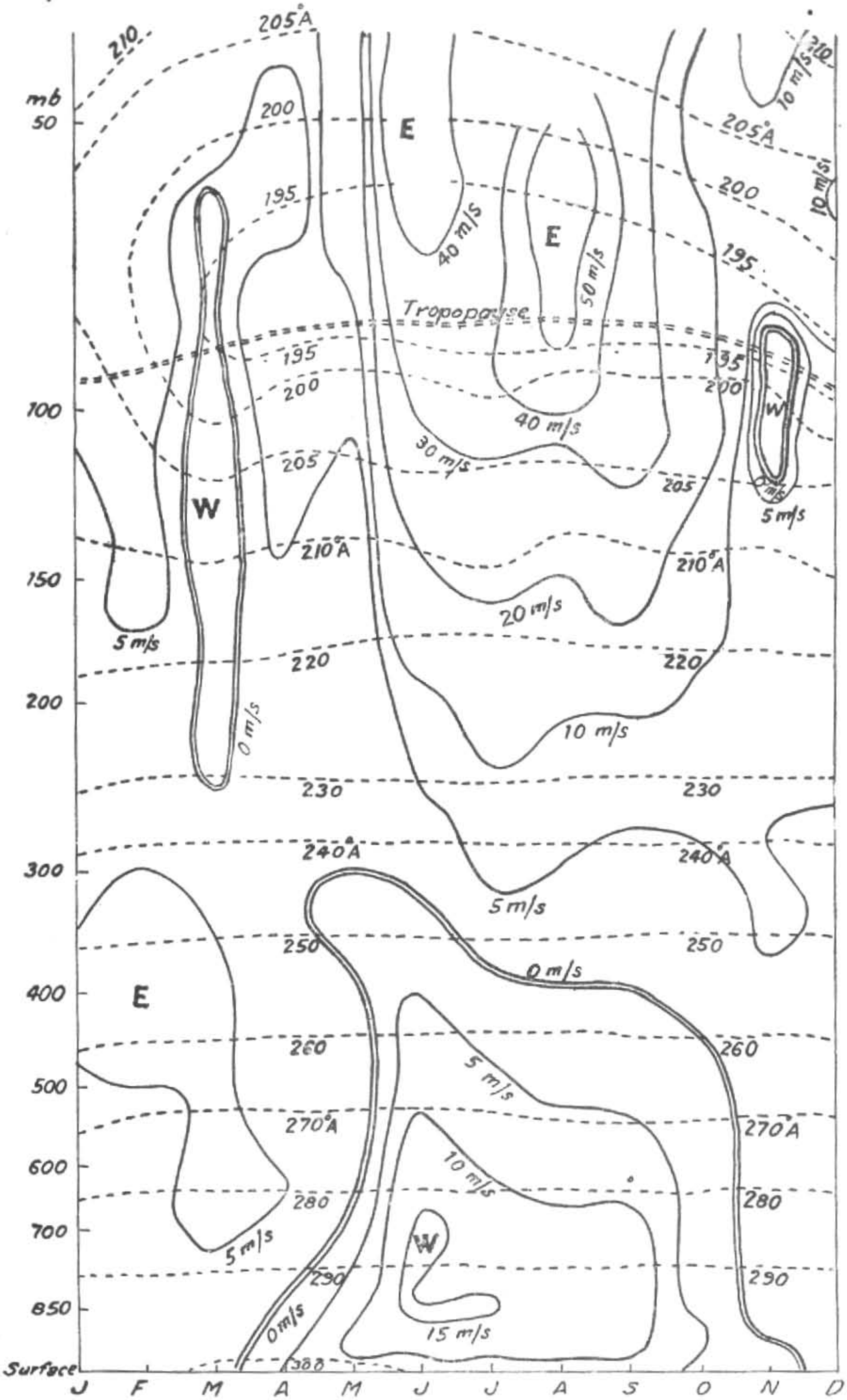

Fig. 5. Upper air temperatures and E-W components of winds at Nagercoil

650-mb level (3 km) in May, up to 850-mb level (1·5 km) in April and November and also at some higher levels above 200 mb in March, April and November. The strongest westerly components of 15 to 17 metres per second (about 35 mph), occur at the 850 to 700-mb level (1 to 2 km) in June—July. The westerly components generally increase in strength with height up to about 2 km and decrease at higher levels, reaching a minimum at the 400 to 350-mb level (6 to 7 km) in June to October. It is clear from this that the depth of the southwest monsoon current over the extreme south of India is about 6 to 7 km and is strongest at the 2-km level. In June, westerly components extend up to 7·5 km though it is very light at that level. In this connection, it is interesting to note (Ramanathan and Ramakrishnan 1939) that the depth of the southwest monsoon current increases as we proceed northwards from the southernmost point of India, is maximum (about 8 km) at about the latitude of Mangalore (13°N) and decreases as we go northwards. This is also shown in the meridional cross-sections (Krishna Rao 1952, Venkiteshwaran 1950) of east and west components along 78°E over India.

The easterly components are very prominent above the 200-mb level (12 km) in June to October when the westerly components are prominent in the lower levels from the surface up to 400-mb level. The easterly components which are about 10 to 13 m sec^{-1} at the 200-mb level increase in strength with height reaching a maximum of about 50 m sec^{-1} at about the 75-mb level (18 km) near about the tropopause and decrease in strength at higher levels. As pointed out in a recent note (Krishna Rao 1952) these very strong easterly winds constitute part of a normal easterly jet stream near the tropopause in the southwest monsoon season over South India between latitudes 7° and 18°N. Frost (1952) finds a similar easterly jet over Arabia and East Africa at the 100-mb level near the tropopause in July at about Latitude 15°N.

It is seen that at the tropopause winds are easterly throughout the year except for light westerly in March and November. The easterly winds are very strong during June to September, the mean speed ranging from 30 to 50 m sec^{-1} (*i.e.*, 70 to 110 mph). On individual days the easterly winds at the tropopause may reach speeds of 80 to 85 m sec^{-1}. The winds at the tropopause are lightest in November and March when they are westerly. In the region between 300 and 150-mb levels in which 'Comet' Jet aircraft will fly, winds are easterly except above the 200-mb level in March when they are light westerly. The highest mean speed of the easterly component in the region of 300 to 150 mb is about 25 m sec^{-1} and in individual cases it may reach 50 m sec^{-1}. It may be noted that the cruising height of the jet airliner is below the level of the normal easterly jet stream at the tropopause.

It will be interesting to examine the distribution of the north and south components of winds also. Such an examination shows that throughout the year, upper winds over Nagercoil do not have a southerly component up to the 400-mb level, not even during the southwest monsoon season. Southerly components occur generally above the 300-mb level. In the lower levels, the strongest northerly components of 5 to 8 m sec^{-1} occur in the 850 to 700-mb level in June to September. This is because in the lower levels up to 4 to 5 km there is a well marked anti-cyclonic ridge in the southeast Arabian Sea and the Indian Ocean to the southwest of Trivandrum and the winds over the Malabar coast are part of the circulation in the northeastern periphery of this anti-cyclone. This is supported by Hariharan's (1949) normal monthly contour charts at 850 and 750-mb surfaces.

Riehl (1950) has classified four types of upper wind circulation in the tropics in Fig. 5 of his paper "On the Role of the Tropics in the General Circulation of the Atmosphere". It is interesting to compare the upper winds over Trivandrum (Nagercoil) in January, April, July and October with Riehl's four types. Fig. 6 shows the east-west components of winds in January, April, July and October. It is seen that the wind distribution does not conform

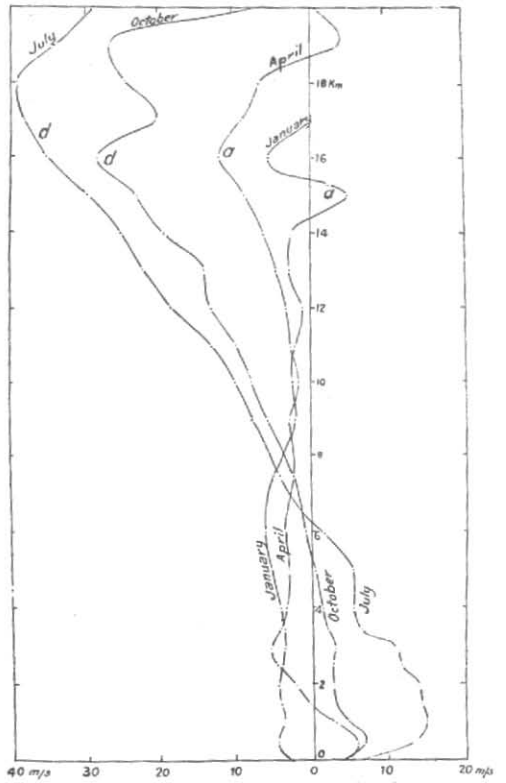

Fig. 6

to any one type throughout the year. The Riehl's type to which the wind distribution in each of four months conforms is mentioned by letters (*a*) to (*d*) of Riehl's classification. The wind distributions in July and October conform to type (*d*) and those in January and April to type (*a*). There are in fact only two types of wind circulation over Trivandrum, one of the southwest monsoon season, which Riehl would prefer to call the equatorial westerly type, and the other the equatorial easterly type. It is seen from Fig. 5 that there is a marked change in the wind distribution between April—May and June and between October and November. The change is both in wind direction and speed in the lower levels up to 400 mb and only in wind speed in the upper troposphere and near the tropopause.

The wind circulation over Trivandrum presented in this paper fits in fairly well with the maps of stream lines in the inter-tropical belt and with the diagram of wind speed and direction in the inter-tropical belt in longitude 80°E given by Brooks (1950) and others in their memoir on upper winds over the world. It does not, however, fit in with the diagram of planetary circulation in vertical planes given by Goldie (1950). His diagram shows that at latitude 8°N, westerly components occur between 6 and 24 km in winter and between 6 and 32 km in summer so that at the tropopause winds are westerly both in summer and winter. The present study shows that the winds over Trivandrum are predominantly easterly except in June to October below 400-mb level and that during that period the winds at the tropopause are not only easterly but very strong.

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