551.510.52:551.58(54)

A case of very low latitude occurrence of the subtropical Jet Stream over the Indian region

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ABSTRACT. This paper is a case study of an unusual excursion of the subtropical jet stream into very low latitudes. From 18 December 1963, the subtropical jet stream began moving south from its normal position, roughly Bahrain to Delhi, consequent to the formation of a deep trough in the upper tropospheric westerlies, near Bahrain longitude. At 0000 GMT on 24 December 1963, the subtropical jet is located along Aden–Visakhapatnam, with Aden recording a maximum wind of 120 kts westerly, which is quite unusual. The vertical cross-section along longitude 80°E for 0000 GMT of 24 December 1963 shows clearly two jet streams, the subtropical jet stream core near Visakhapatnam, below the tropical tropopause and close to a break in the tropopause and another jet stream core, over Delhi, in the angle formed by the tropopause and an inclined front which does not extend below 500 mb.

1. Introduction

Koteswaram *et al.* (1953) found a mean westerly jet over the India–Burma region, during the winter months December to February, at 27°N and an altitude of 12 km, with an average speed of about 100 kts. Koteswaram and Parthasarathy (1954) found that the mean location of this jet is southernmost (25°N) in February. This is the subtropical jet stream appearing on almost all winter days on 300 and 200-mb charts of India as a narrow stream of strong westerly winds, generally near Delhi latitude. Wind speeds of 150 to 200 kts have been observed in the core of this jet stream (Koteswaram 1962). Fig. 1 shows the mean wind for December at the 200-mb level for the area under study (taken from Raman and Dixit 1964). The approximate location of the mean jet axis in December as could be inferred from the mean winds data is marked in the figure. The jet axis shows a mean trough between Bahrain and Karachi.

Krishnamurthy (1961) has studied the daily position of the subtropical jet stream axis on the 200-mb surface (the core of the subtropical jet stream lies normally near 200 mb) using data from all available upper air stations between equator and 45°N around the globe for the months December 1955 and January and February 1956. His findings are of special interest to this study.

It is seen (Reiter 1961) that the subtropical jet is connected with a 'tropopause break' and it lies below the higher, tropical tropopause, on the average about 150 km equatorward of the 'break line'.

An inclined front not extending below 500 mb is frequently encountered in subtropical jet situations. This front called the 'subtropical front' is observed by Mohri (1953, 1958) for the subtropical jet stream over Japan and Endlich and McLean (1957) for the North American area. The subtropical front (Newton and Persson 1962) having as its base the equatorward extension of the middle tropopause and sometimes extending as low as 500 mb, is occasionally as strong as the polar front. They also find that the subtropical jet frequently appears as two layers of maximum wind.

In this paper the author has presented a detailed study of a case of subtropical jet stream moving south to the very low latitude of Aden—Visakhapatnam on 24 December 1963 (0000 GMT) with Aden recording a maximum wind of 120 kts westerly, which is quite unusual. At the same time another jet stream core is situated above Delhi in the angle between the tropopause and an inclined front. This front extends downwards only up to 500 mb.

The stations whose data have been used in this study have been shown in Fig. 1. The stations (marked with a circle) used for the vertical cross-sections are all within a few degrees on either side of longitude 80°E. Stations Jaipur and Ambala are pibal stations and their data are used only for the wind cross-section of 1200 GMT on 18 December 1963. The main sources of data are the constant pressure charts of the Meteorological Office, Santacruz airport and the International Meteorological Centre, Bombay and the Indian Daily Weather Report (IDWR).

2. Upper air features on 18 December 1963 at 1200 GMT

Fig. 2 gives the 200-mb chart of 1200 GMT on 18 December 1963. The wind field east of 55°E is very much similar to the normal pattern shown in Fig. 1. Aden wind is stronger than the normal and Bahrain wind weaker. The jet core west of 55°E appears to have shifted a few degrees south

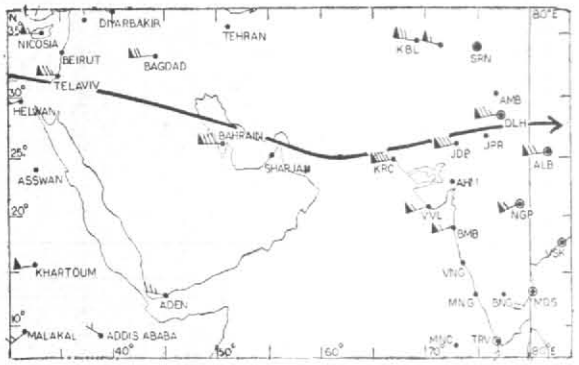

Fig. 1. Mean winds for December at 200 mb
(From Raman and Dixit 1964)

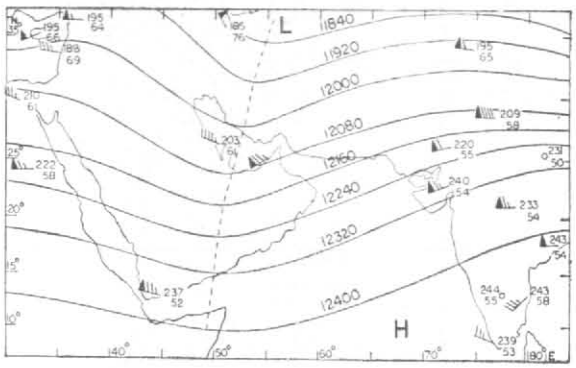

Fig. 2. 200-mb chart at 1200 GMT of 18 December 1963

of the normal position. There is a trough, east of Bahrain, shown by the dashed line. Between Trivandrum and Srinagar the wind speed gradually increases from 23 kts at Trivandrum, reaches a maximum of 89 kts at Delhi and then falls to 61 kts at Srinagar.

Fig. 3 gives the vertical cross-section of temperature along 80°E. The height in geopotential kilometre is used as the vertical co-ordinate. The reported tropopauses, as given in the IDWR are marked with a circle around the dot. The thick tropopause line is marked with the help of the isentropic lines on Fig. 4. Where actual tropopause reports are not available, the tropopause as inferred from temperature and potential temperature values is marked by thick dashes. Delhi has reported double tropopause, one at 11·92 km (206 mb) and the other at 14·63 km (134 mb). The coldest tropopause is over Vizag (—81°C). There is large temperature fall from Allahabad to Delhi above 6 km so that the isotherms from —25°C to —50°C dip sharply down from Allahabad to Delhi (The isotherms drawn in dashed lines are at intervals of 5°C). At 400 mb there is a fall in temperature of 5°C, at 300 mb a fall of 8°C and at 200 mb a fall of 7°C from Allahabad to Delhi.

Fig. 4 gives the vertical cross-sectiou of potential temperature. The isentropes are drawn at intervals of 10°K. The tropical tropopause is on the average around 380°K. The lower tropopause is around 335°K. The lower one may be called the polar tropopause or the extratropical tropopause, after Kochanski (1955), who has given the mean potential temperature θ values of tropopause surfaces in various latitude belts. According to him, in winter, for,

(1) the polar tropopause in latitudes 83–48°N $\theta = 302$°K

(2) the polar tropo pause in latitudes 46–36°N $\theta = 338$°K and

(3) the tropical tropopause in latitudes 46–09°N, $\theta = 393$°K

It may be seen that between 6 and 12 km the potential temperature falls rapidly from Allahabad to Delhi, so that the isentropes rise rapidly from Allahabad to Delhi. With the isotherms dipping sharply down and the isentropes rising sharply up from Allahabad to Delhi, one would expect the west wind to increase sharply with height from about 6 km between Allahabad and Delhi. This is seen in the wind cross-section given in Fig. 5. The maximum winds reported in IDWR are marked by crosses (It may be noted that maximum winds less than 30 mps — approximately 58 kts — are not reported). The double-dashed line marks the approximate position of the level of maximum winds. This line is approximately parallel to the tropical tropopause but a few kilometres below it. Single-dashed lines are the isotachs at intervals of 20 kts. It is seen that the jet core is at the break of the tropopause. This jet is the subtropical jet at its normal position over India. The maximum wind at Delhi is 260 degrees, 103 kts at 13·09 km. Unfortunately, the Allahabad ascent has given winds only upto 7·2 km.

3. Upper air features on 22 December at 1200 GMT

By 22 December, a deep trough has formed in the upper tropospheric westerlies (Figs. 6 and 7) and the subtropical jet, usually continuous around the earth, has got broken up. Bahrain is almost on the trough line. At 8·05 km at Allahabad wind is 260°, 88 kts (on the constant pressure charts where the wind observation has reached only say to 8·05 km, as at Allahabad in Fig. 6, the height of the wind observation is marked below the wind barb). From Figs. 6 and 7 one infers that the axis of the subtropical jet stream over India has moved south of its position on 18 December and the jet core may be placed between Allahabad and Nagpur. Nagpur wind ascent has reached a height of

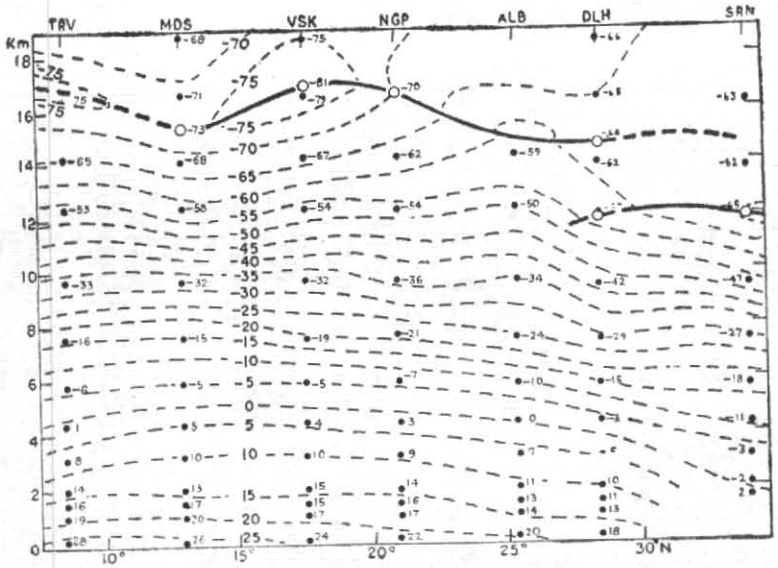

Fig. 3. Vertical cross-section of temperature along 80°E at 1200 GMT of 18 December 1963

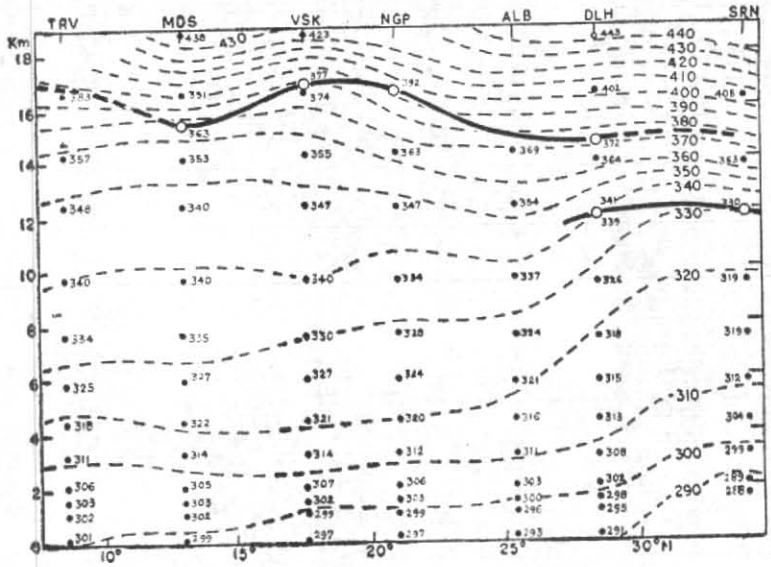

Fig. 4. Vertical cross-section of potential temperature along 80°E at 1200 GMT of 18 December 1963

12·55 km where it has recorded 250°, 129 kts. The wind observation at Visakhapatnam has reached a height of 21 km and a maximum wind of 270°, 89 kts is reported at 14·49 km. Delhi wind ascent has reached 14·1 km, the maximum wind being 270°, 116 kts at 13·72 km. From these it may be inferred that the jet core speed has increased considerably from 18 December to 22 December.

Air India Boeing flight (Bombay to Aden, Commander Mr. Zacharia and Navigator Mr. A. Varma, departure Bombay 0620 GMT and arrival Aden 1100 GMT on 22 December) has given a number of wind observations at flight level 350 (about 10·5 km). They are marked along Bombay–Aden route in Fig. 7. Each wind marked (with light lines and unfilled triangles) is a mean wind along the track between the dots marked on either side. The winds fit in very well with the contour analysis. These winds clearly show that the subtropical jet has moved considerably south of the normal position west of Bombay also. Aden has recorded a maximum wind of 273°, 78 kts at 13·42 km.

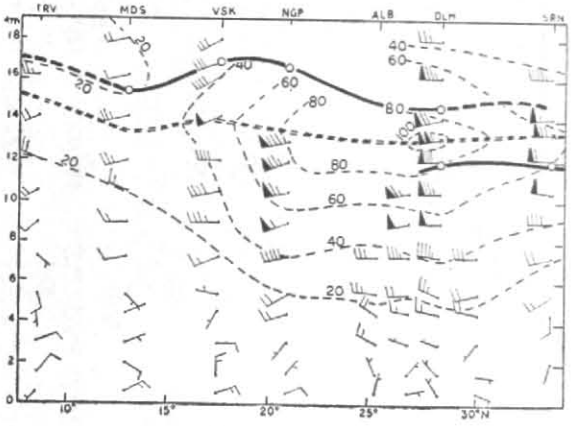

Fig. 5. Vertical cross-section of wind along 80°E at 1200 GMT of 18 December 1963

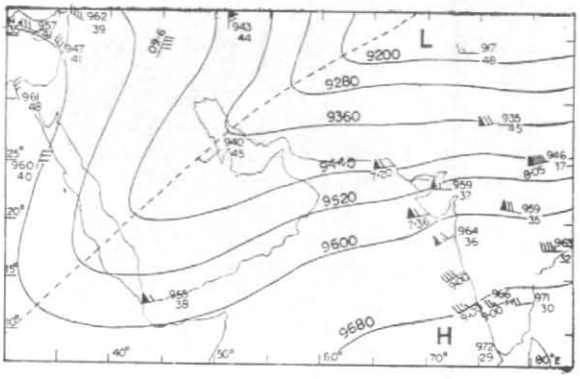

Fig. 6. 300-mb chart at 1200 GMT of 22 December 1963

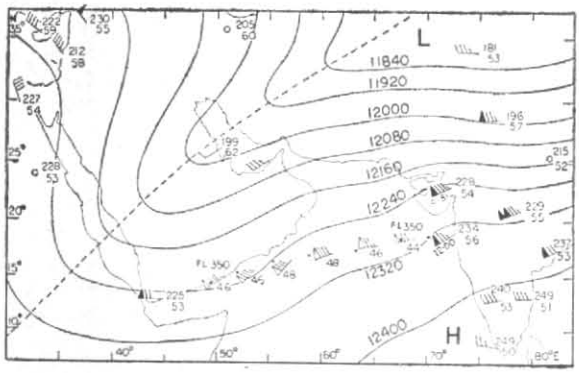

Fig. 7. 200-mb chart at 1200 GMT of 22 December 1963

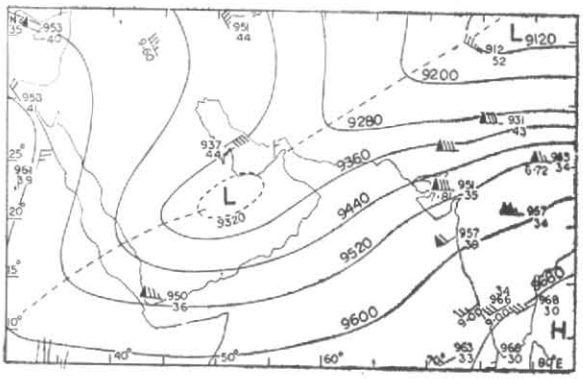

Fig. 8. 300-mb chart at 1200 GMT of 23 December 1963

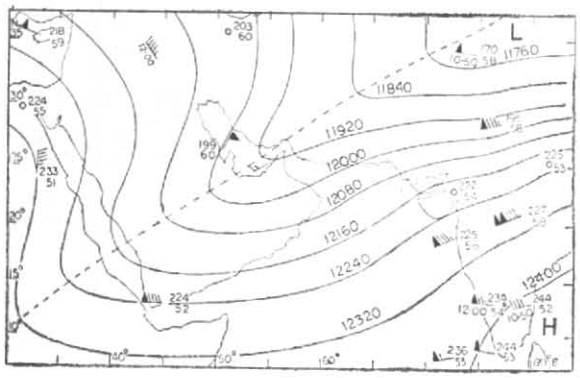

Fig. 9. 200-mb chart at 1200 GMT of 23 December 1963

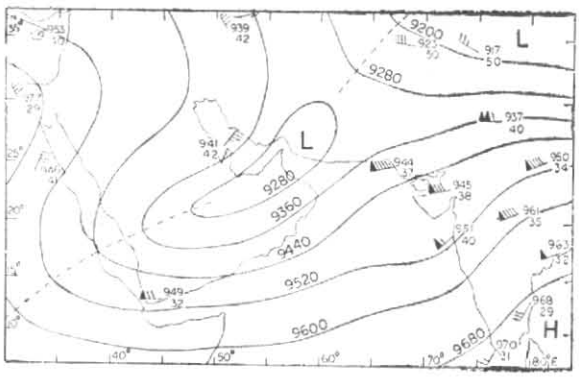

Fig. 10. 300-mb chart at 0000 GMT of 24 December 1963

4. Upper air features on 23 December 1963 at 1200 GMT

The trough near Bahrain at both 300 and 200 mb has deepened, as may be seen from Figs. 8 and 9. The trough line near Bahrain and north of it has shifted slightly eastwards with Bahrain 300 and 200-mb winds becoming strong northeasterlies on 23rd from weak southwesterlies on 22nd. Maximum wind at Delhi is 270°, 111 kts at 10·90 km and at Nagpur the last wind observed is 250°, 132 kts at 12·50 km. At Nagpur there is no change in wind speed from 200 mb (12·27 km) to 12·57 km; this may be taken as suggesting that the height of the maximum wind is close to 12·5 km. Aden maximum wind is 267°, 98 kts at 11·32 km. The wind observations show that the latitudinal position of the jet core over India has not appreciably changed during the 24-hour period since 1200 GMT on 22 December; but at Delhi, Nagpur, Aden and Vizag the level of maximum wind has come down appreciably. (Visakhapatnam wind observation of 1200 GMT of 23 December is not available, but the Visakhapatnam maximum wind at 0000 GMT of this date is 270°, 76 kts at 12·69 km). Trivandrum winds have strengthened with the station reporting a maximum wind of 290°, 65 kts at 13·66 km. On 22 December, at 1200 GMT, Trivandrum has not reported a maximum wind, but IDWR gives wind at 12·0 km as 290°, 45 kts and wind at 14·1 km as 280°, 44 kts.

5. The situation on 24 December 1963 at 0000 GMT

The 300 and 200-mb charts for 0000 GMT of 24 December 1963 are given in Figs. 10 and 11. Aden reports a maximum wind of 270°, 120 kts at 11·35 km. This may be compared with the December mean wind at 200 mb at Aden of 281°, 26·8 kts. The increase is considerable. Delhi maximum wind is 270°, 159 kts at 11·69 km. It is significant that Bombay and Ahmedabad have not taken part in the general strengthening of winds. Ahmedabad maximum wind is 240°, 91 kts at 9·21 km and Bombay maximum wind is 240°, 80 kts at 12·0 km. The 200-mb winds both at Bombay and Ahmedabad are, compared to other stations, less strong. The trough line near Bahrain has not changed much, in position since 1200 GMT on 23 December 1963. The winds show possible closed cyclonic circulations near Bahrain at 300 mb and may be even at 200-mb levels. In general, winds west of trough line continue to be weak except for a narrow meridional strip west of the line joining Bahrain and Tehran in Fig. 11. At Aden the 300-mb temperature has risen by 4°C in 12 hours since 1200 GMT of 23rd.

Around 0000 GMT of 24th, two aircraft have reported winds. On Cairo–Bahrain–Bombay route, Air India Boeing (Commander Mr. Hosali and Navigator Mr. Parulekar, departure Cairo

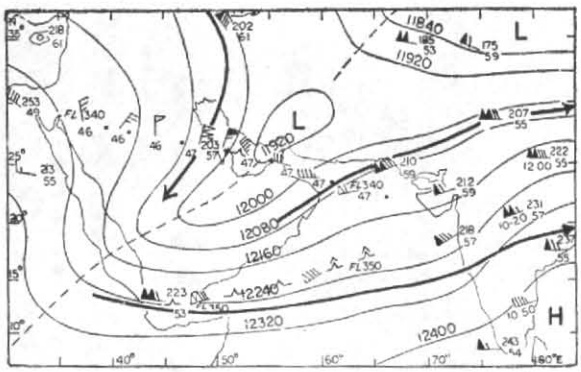

Fig. 11. 200-mb chart at 0000 GMT of 24 December 1963
Thick lines are jet stream cores

23rd, 2150 GMT and arrival Bombay 24th, 0302 GMT) has reported a number of sector mean winds. These winds show the troughing east of Bahrain. In the sector just west of Bahrain there is a very strong sector mean wind reported of 010°, 100 kts, at flight level 340. This observation is important. It agrees in direction and strength with Bahrain and Tehran winds at 200 mb. A jet core may be drawn here as shown in Fig. 11. The other aircraft is a jet aircraft of United States Air Force MATS, from Leopoldville to Bombay overflying Aden at flight level 350 (time of arrival at Bombay about 0200 GMT on 24th). On arrival at Bombay one of the crew members reported unusually strong winds and clear air turbulence encountered between Aden and Bombay. The two spot winds given in the oral debrief are marked in Fig. 11, one near Aden and the other at 60°E. The aircraft experienced continuous moderate clear air turbulence from Aden to 60°E and strong turbulence almost continuous from 60°E to 65°E. The times of these turbulence observations are quite close to the time of the synoptic charts at Figs. 10 and 11. These turbulence reports are from an area of very low Richardson Number (Joseph and Ranjit Singh 1966).

Fig. 12 gives the vertical cross-section of temperature roughly along 80°E. This cross-section is very much different from the cross-section of 18 December at 1200 GMT (Fig. 3). Here there are three tropopauses well supported by observations. Between 500 and 200 mb an inclined front may be seen. There is an isothermal layer between heights 2 and 4 km north of Allahabad, and a well marked inversion in the lowest levels from Visakhapatnam to Srinagar.

To study the structure of the inclined front tephigrams of Srinagar, Delhi, Allahabad and Nagpur were plotted. They are given in Fig. 13. The inversion in the lowest levels and the isothermal layer near about 3 km are seen. The double-dashed line marks the lower boundary of the layer

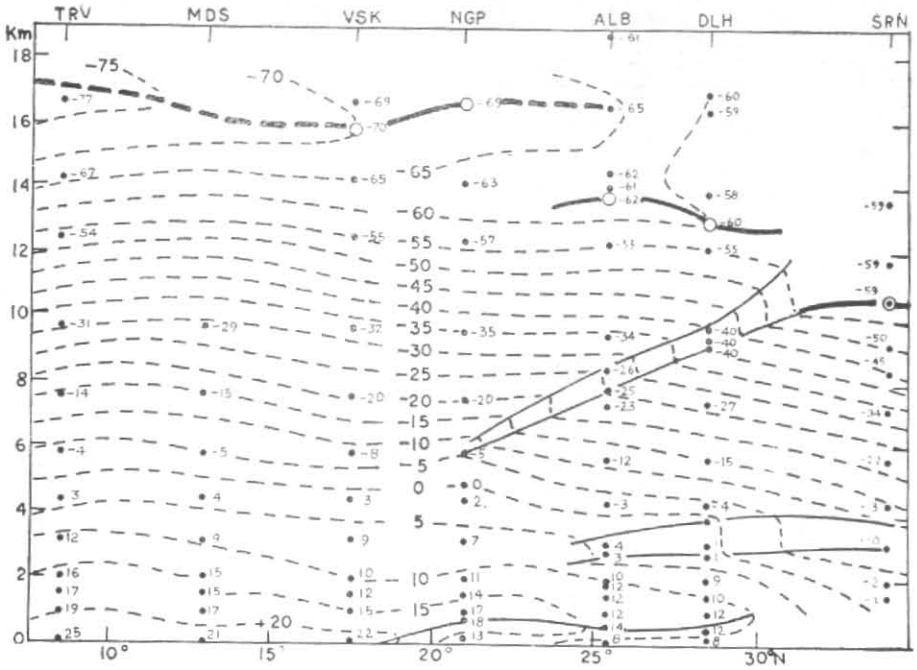

Fig. 12. Vertical section of temperature along 80°E at 0000 GMT of 24 December 1963

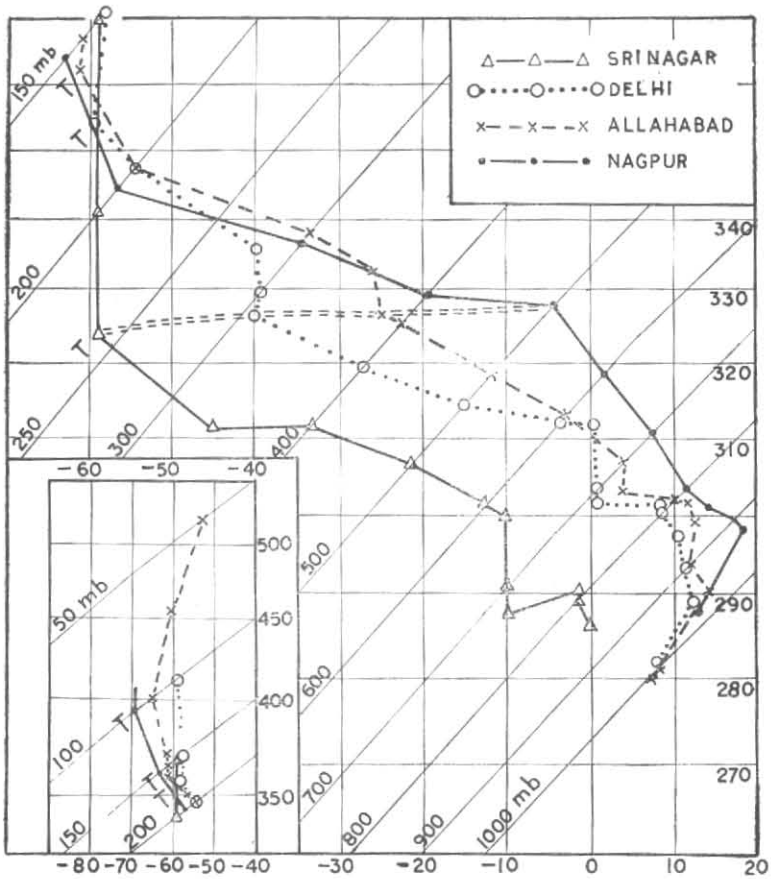

Fig. 13. Tephigrams of 0000 GMT on 24 December 1963

Double dashed line marks the lower surface of inclined front, T – Tropopause levels

corresponding to the inclined front. This double-dashed line is almost parallel to the lines of constant potential temperature. It is at a potential temperature of about 325°K. Nagpur does not show an isothermal layer; only a change of lapse rate is seen there. Fig 14 gives the vertical cross-section of potential temperature. The isentropes are drawn at intervals of 10°K except near the inclined front where they are drawn at intervals of 5°K (from 320°K to 340°K). The lower surface of the inclined front joins up with the tropopause over Srinagar, both of them lying close to the isentrope marked 325°K. The tropical tropopause at potential temperature of about 380—390°K may be seen, extending northwards upto about 25°N. The tropopause over Allahabad and Delhi has a potential temperature of about 355°K.

The vertical cross-section of wind at 80°E is given in Fig. 15. The tropopauses, fronts etc are marked in this figure also. The wind pattern is quite different from that of Fig. 5. The 60 and 80 kts isotachs show clearly that there are two distinct cores of high wind speeds. Maximum wind at Delhi is 270°, 159 kts at 11·69 km, at Srinagar 280°, 66 kts at 12·10 km, at Allahabad 270°, 130 kts (reported highest wind) and at Nagpur 250°, 105 kts at 10·20 km. As seen by the isotach analysis these maxima of wind belong to one jet. The rapid increase with height in wind speed at the inclined front is seen clearly at these four stations. Maximum wind at Trivandrum is 290°, 60 kts at 14·16 km and at Visakhapatnam it is 270°, 93 kts at 14·29 km. Madras wind ascent has given winds only upto 10·5 km. The wind maxima at Trivandrum and Visakhapatnam, as seen from the isotach analysis belongs to a separate jet, the subtropical jet which was traced in the preceding pages moving gradually south from its position on 18th over Delhi. Nagpur wind ascent has reached only upto 10·50 km. From the lie of the isotachs, the author feels that Nagpur winds after the maximum at 10·20 km would have weakened with height and then again increased to a second maximum around 15 km, corresponding to the jet over Visakhapatnam. The Delhi ascent, as seen in Fig. 16, shows such a secondary maximum near 18 km. Now, with the available details, the subtropical jet core can be placed just north of Visakhapatnam at 80°E and over Aden further west, with a core wind speed of about 100 kts near Visakhapatnam and 120 kts near Aden. The thick lines of Fig. 11 give the positions of the jet stream cores as visualised by the author from the contour analyses, cross-section analyses and the wind profiles in the vertical. There are two jet streams, one the subtropical jet stream which has progressively moved south from 18th to the position Aden to Visakhapatnam on 24 December and the other one around the deep trough near Bahrain, seen on the charts of 0000 GMT of 24 December 1963 and not on earlier charts. The comparatively less strong winds over Bombay and Ahmedabad lends supports to the picture of two jet stream cores over India. The subtropical jet stream has shifted south of its usual position by more than 10 degrees latitudes.

What type of jet stream is the one over Delhi? The inclined front is very much similar to the 'subtropical front' of Mohri (1953, 1958). Newton and Persson (1962) have given a schematic diagram of the fronts, tropopauses and wind field most persistently identified in the analyses of winter cases for the United States and Canada. They find that the subtropical jet frequently appears as two layers of maximum wind. The lower of these lies within the tropopause break and slopes downward south, often being closely identified with an isentropic sheet. The upper one always lies above the subtropical tropopause. Either of these may be stronger on a particular occasion, however, the upper layer always appears to be strongest in lower latitudes. Their schematic diagram shows the base of the subtropical front as a continuation of the middle tropopause. The polar tropopause is also marked in the diagram. In the case studied by the author, the base of the inclined front is a continuation of the polar tropopause. Could this inclined front be a truncated polar front and the jet over Delhi a polar front jet stream associated with the deep wave disturbance in the upper tropospheric westerlies? Riehl (1962) has presented two vertical cross-sections, one of wind and another of temperature showing tropopauses and fronts (on pages 35 and 36) of a case of a jet core south of latitude 30°N at 0000 GMT on 11 February 1958. These diagrams and the observations about them given in the paper are of special interest here.

Fig. 16 gives the tephigrams of 1200 GMT of 23 December 1963, for the same four stations as in Fig. 13. These tephigrams do not give any indication of an inclined front. As discussed earlier, there is only one jet present at 1200 GMT of 23rd over India, that is the subtropical jet near Nagpur. This leads one to think that all the developments seen at 0000 GMT of 24th took place during the 12 hours since 1200 GMT of 23 December.

6. Upper winds over Aden from 19 to 28 December 1963

Fig. 17 gives the vertical time-section of winds over Aden for 0000 and 1200 GMT from 19 to 28 December 1963. The maximum winds and tropopauses are also marked in the figure. The isotachs are drawn in dashed lines at intervals of 20 kts,

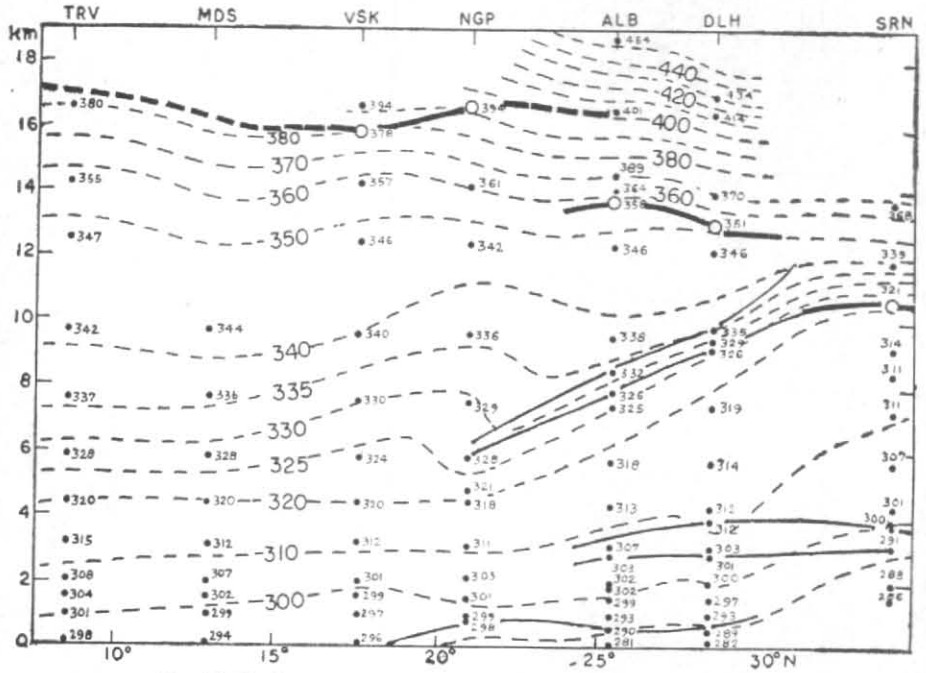

Fig. 14. Vertical cross-section of potential temperature along 80°E at 0000 GMT of 24 December 1963

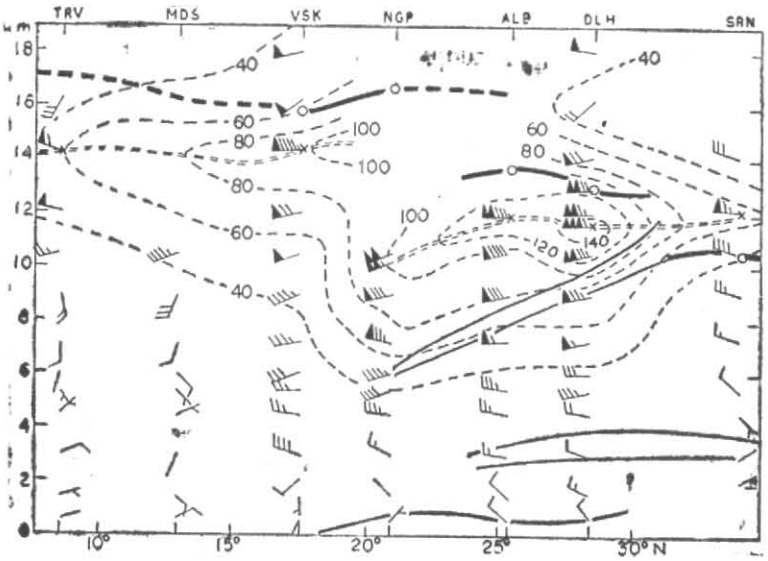

Fig. 15. Vertical cross-section of wind along 80°E at 0000 GMT of 24 December 1963

Double jet core structure may be seen

Slight smoothing is employed in drawing the isotachs. The upper winds strengthen twice over Aden during this period, once around 1200 GMT on 21 December and the other around 0000 GMT on 24 December. The double-dashed line gives the smoothed profile of the time variation in the height of the level of maximum wind over Aden. It is seen that from 19th this height decreases till about the time when Aden gets the first maximum (corresponding to a deep trough near Aden not discussed in this paper), then rises, and again falls to a level as low as 10·73 km near about the time Aden gets the second maximum (studied in this paper) and then rises rapidly up.

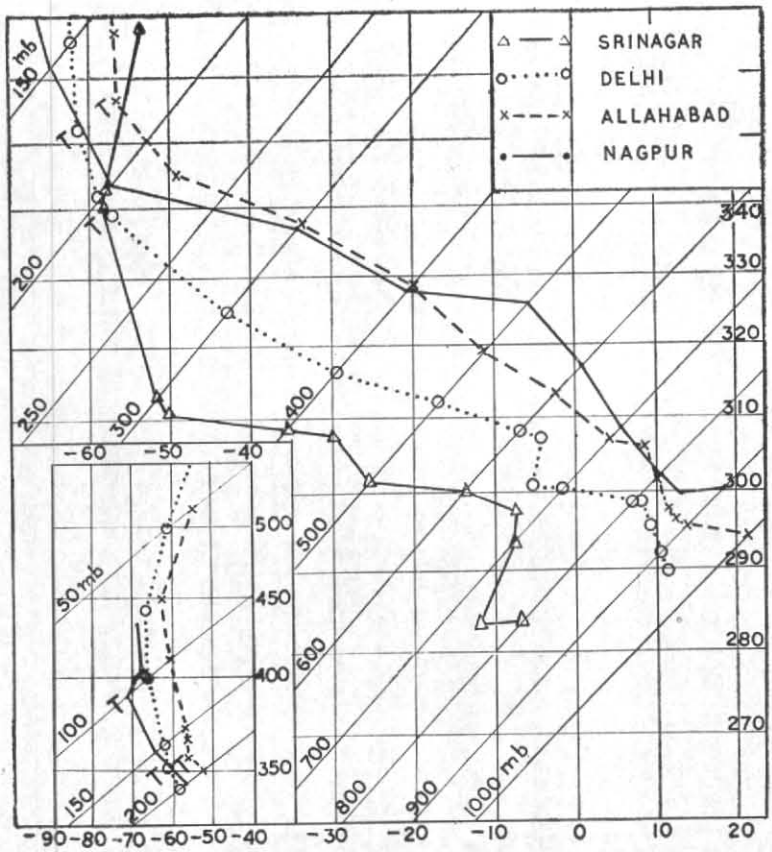

Fig. 16. Tephigrams of 12 GMT on 23 December 1963

T — Tropopause levels

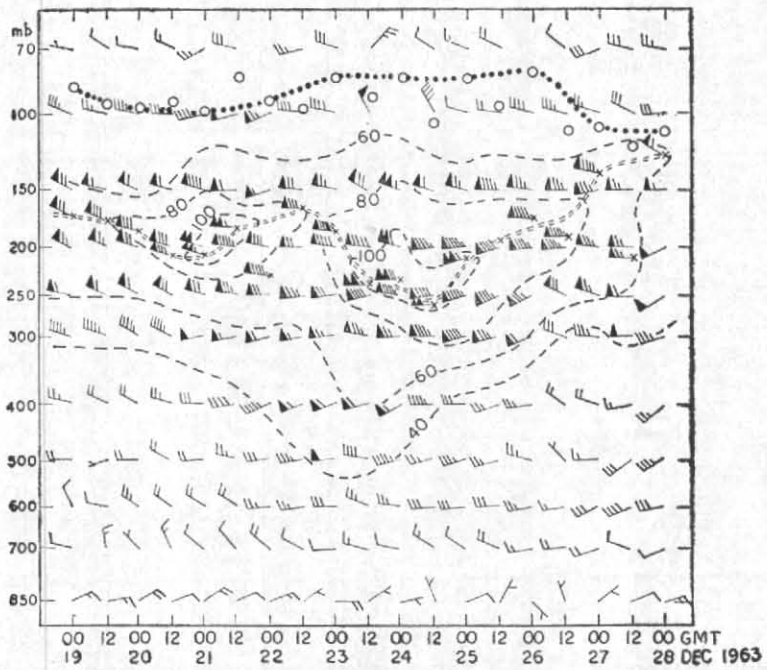

Fig. 17. Upper wind and tropopause over Aden during 19–28 December 1963

00 GMT tropopauses are joined by a line of dots. Dashed lines are isotachs in kts

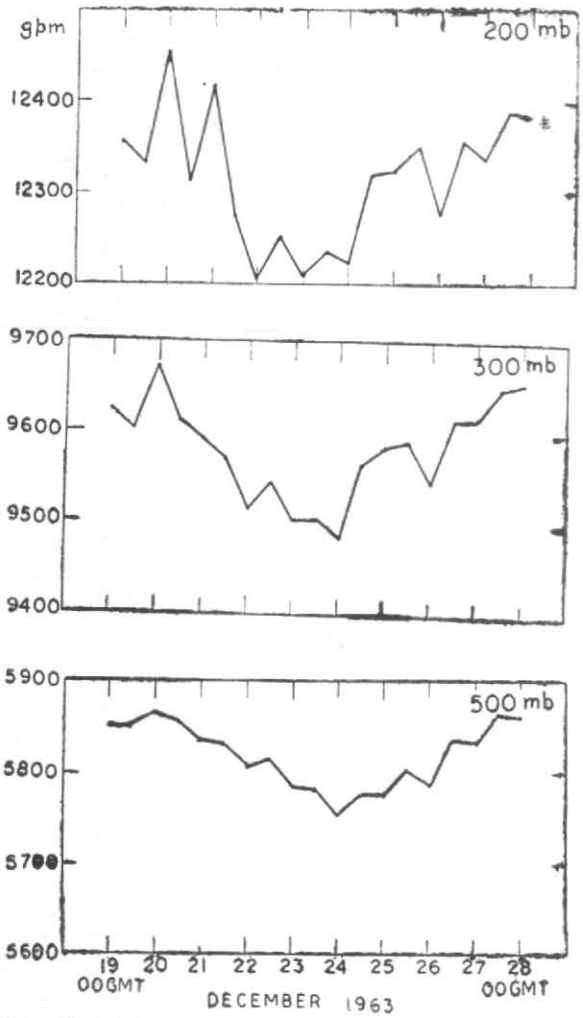

Fig. 18. Height (gpm) of 200, 300 and 500-mb surfaces over Aden during 19-28 December 1963 (00 and 12GMT)

The 0000 GMT tropopauses are joined by a smooth line of dots. It is seen that from 23 to 26 December the 0000 GMT tropopause is practically at the same height, almost 1 km higher than the tropopause level from 19 to 21 December.

Fig. 18 gives the height in geopotential metres of the 200, 300 and 500-mb surfaces over Aden during the period 19 to 28 December. On 24 December at 0000 GMT, the 500 and 300-mb height reached the lowest values. It is seen that the tropopause over Aden is very high during the period when contour heights of the millibaric surfaces are very low. The variation of the contour heights and the variation of the height of tropopause appear to be in opposite directions.

7. Acknowledgement

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