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Study of the jet stream over India and to its north in winter : Part I

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ABSTRACT. Characteristics of the jet streams over India and to its north in winter were studied with the daily vertical cross-sections (1200 GMT) along 75°E from 8°N to 60°N for the period 1 to 15 February 1967. It was observed that there are three separate jet cores present in this latitude belt on most of the days, located on an average at 43°N, 31°N and 23°N. Of these three, the most stable and persistent one is the second which is located between Delhi and Srinagar, at 200-mb level with an average maximum speed of 140-150 kt. The one to its south is weaker and quite variable in location as well as altitude. The jet at 31°N, therefore, has been called the primary sub-tropical jet over India and its characteristics studied. Based on this study, a model cross-section has been prepared for this STJ. The descriptions of the STJ at 23°N and also of PFJ (Polar Front Jet) at 43°N are included.

1. Introduction

Chowdhury (1950) studied the upper winds at longitude 75°E using the radiosonde data of the winter of 1946 and noted the existence of two jet streams over India, one at about latitude 31°N and the other at latitude 15°N at the 200-mb level. Koteswaram *et al.* (1953, 1954) studied the jet streams over India during the winter as well as the pre and post-monsoon seasons with the help of radiosonde data and showed that there is a sub-tropical jet stream (STJ) over India throughout the period, October to May, with a mean latitudinal position 27½°N. It is at its southernmost position in February, *i.e.*, at latitude 25°N, and northernmost position at latitude 29°N in May and located at a height of about 12 km with a mean wind maximum of 53 mps. Later studies of the sub-tropical jet stream with the help of wind as well as temperature data brought to light many details of its structure and characteristics. Mohri (1953) and Endlich and McLean (1957) showed the presence of a sub-tropical or 'jet-stream' front below the core of this jet. Defant and Taba (1957, 1958) claimed that the STJ lies in the break between two tropopauses, the middle and the sub-tropical, similar to the PFJ which lies between the middle and polar tropopauses. Newton and Persson (1962) confirmed this finding of Defant and Taba but noted that the sub-tropical tropopause was very much attenuated at times. They also found that —

(*a*) In general two cores of the strongest wind are found, one lying in the break between the middle and the sub-tropical tropopauses and the other often lying over the sub-tropical tropopause (average altitude 200 mb). Attached to both these cores are the layers of maximum wind (LMW).

(*b*) Some times there is only one core lying in the break between the two tropopauses and two LMWs attached to it on the anticyclonic side and one on the cyclonic side.

Bannon (1954) also in a study of winds at Habbania and Bahrein noted that "the level of maximum wind falls southwards through the strong wind belt" and that "the stream is found to be broad and without horizontal gradients". Serebreny *et al.* (1962), however, state that the STJ is not a broad band but consists of more than one wind maximum. According to them, the main core is located above an isotherm of —15°C at the 500-mb level. Some times another core is found to the south, above an isotherm of —11°C (at 500 mb) and occasionally a third one at —6°C (500 mb). They note that the STJ complex may cover a great latitudinal span.

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TABLE 1

Subtropical Jet stream over India — location and speed of the core

Date (Feb 1967)	Height of the core (mb)	Location of the core Lat. (°N)	Maximum wind (kt) reported at Srinagar (at Ht. m)	Maximum wind (kt) reported at Delhi (at Ht. m)	Maximum Geostrophic wind (kt)	Maximum core speed estimated (kt)	Remarks
1	240	32	122 (10860)	111 (11130)	25	140	
2	210	31·5	123 (11390)	105 (7980)	104	160	PFJ approaching
3	160	32·5	87 (9130) (no data above)	146 (9860)	250	200	Merging with STJ
4	210	31	107 (10550)	132 (9800)	96	160	
5	250	33	170 (10240)	147 (11070)	67	170	
6	210	30	112 (9940)	145 (11270)	75	150	
7	210	30·5	124 (9620)	145 (11270)	143	160	PFJ approaching
8	175	32	97 (11640)	128 (9920)	145	140	PFJ approaching
9	140	31	106 (11770)	137 (11390)	176	180	PFJ merges
10	135	31·5	85 (11390)	142 (12380)	229	180	Process complete
11	180	31	63 (12390)	130 (10330)	84	140	
12	250	32	88 (9750)	105 (11770)	10	100	
13	250	30	97 (12940)	100 (9870)	50	100	
14	170	31	110 (13400)	128 (11730)	71	140	
15	150	30	74 (13140)	107 (14440)	67	120	
Total	2940	469·0				2240	
Average	196	31·3				150	

Koteswaram (1953) noted the intrusion of PFJ into the country in association with strong western disturbances in winter. Koteswaram (1957) also stated that there were quite frequently two separate cores over the country. Singh (1964) showed that the STJ over India has one or two cores. When it has one core, it normally has two well developed LMWs on the anticyclonic side. But when there are two separate cores, the LMWs are not so prominent. He also showed the existence of 'Jet-stream front' below the jet. Recently Joseph (1969) showed the existence of two separate cores over the country in association with a deep trough in the westerlies approaching from the west. Gupta (1968) noted the existence of three jets on one occasion, the southern-most of which was located at about 8°N.

These few case studies point to the fact that the day-to-day structure of the sub-tropical jet stream over India is quite complex and may include one, two or three separate cores and many other features which are not clear as yet. Koteswaram (1957) pointed out the need for day-to-day study of the jet stream over India emphasising its importance for the prognostication of its location, strength and movement. An attempt has been made in this paper to study the jet stream over India on a day-to-day basis for a period of 15 days in February 1967.

2. Data

Daily vertical cross-sections along longitude 75°E for 1200 GMT observations were prepared from 1 to 15 February 1967 covering latitudes 8°N to 60°N. The Russian data utilised for extending the cross-sections northwards were available only for 700, 500, 300 and 200-mb levels leaving all other details which were so desirable. Radiosonde/Rawin stations in India whose data were used for this study are—Trivandrum (8°29′N, 76°57′E), Ernakulam (9° 56′N, 76°14′E), Bangalore (12°58′N, 77°35′E), Bombay (19°07′N, 72°51′E), Ahmedabad (23°04′ N, 72°38′E), Jodhpur (26°18′N, 73°01′E), Delhi (28°35′N, 77°12′E) and Srinagar (34°05′N, 74°50′ E). Extra Indian stations used are—Horog 38954 (37°31′N, 71°31′E), 51709 (39°30′N, 76°E approx), Dzlalabad 38613 (40°30′N, 73°E), Alma Ata 36870 (43°14′N 76°56′E), Balhas 35796 (46°54′N, 75°E), Karganda 35394 (49°48′N 73° 08′E), Pavlodar 36003 (52°17′N, 76° 57′E), Taromask 28698 (54° 56′N 73° 24′E) and Aleksan Drovskoe 23955 (60°26′N 77°52′E).

Besides, pilot balloon data along this longitude were also utilised. Morning (00 GMT) data were used wherever evening observations were absent.

The choice of the month of February was with a view to get the jet stream at its southernmost position (*vide* Koteswaram, at 25°N in the mean) so that it could be located in an area of dense data.

3. Analysis

The accuracy of radiosonde observations over India, particularly in the higher levels is rather low. The accuracy of wind reports from rawin observations too is not very good, particularly in the jet stream region. Experience shows, however, that the wind observations at higher levels are much more reliable than the temperature observations. The characteristics of the jet core, therefore, were determined with the help of both temperature as well as wind observations taking care to eliminate the error if any in the data. The height of the core was fixed at or slightly below the intersection point of the temparature curves which showed the maximum temperature gradient. The isotachs were drawn at 20kt intervals. The core speed was decided from considerations of temperature gradient in the region, the height of the core and the configuration of the isotach pattern.

It was found that on most of the days there were three separate jet cores in this latitude belt *i.e.*, 8°N to 60°N. Of the three, one was invariably situated between Srinagar and Delhi and showed very little variation in its location from day-to-day. It was mostly stronger than the other two (Fig. 1). There was another core to the south of it at about the latitude of Ahmedabad (Lat. 23°N) in the mean, which was more variable in position, weaker in speed and on certain days absent. The third was to the north of the country between Lat. 40° and 50°N. Of the two jet cores over India the one between Srinagar and Delhi was considered as the 'Primary sub-tropical jet' and the one to its south as the 'Secondary sub-tropical jet'. The jet to the north of Srinagar was of the 'Polar front type' and has been called by this name in this paper. The study of the primary STJ forms the subject of this paper. The other two are only briefly mentioned. They will be discussed in a separate paper.

3.1. *Primary Sub-tropical Jet*

Table 1 gives the height location and the core-speed of this jet as well as the reports of maximum wind at Srinagar and Delhi. It also includes the geostrophic wind calculated between these two stations. It can be seen from this table that the maximum core-speed finally accepted is very

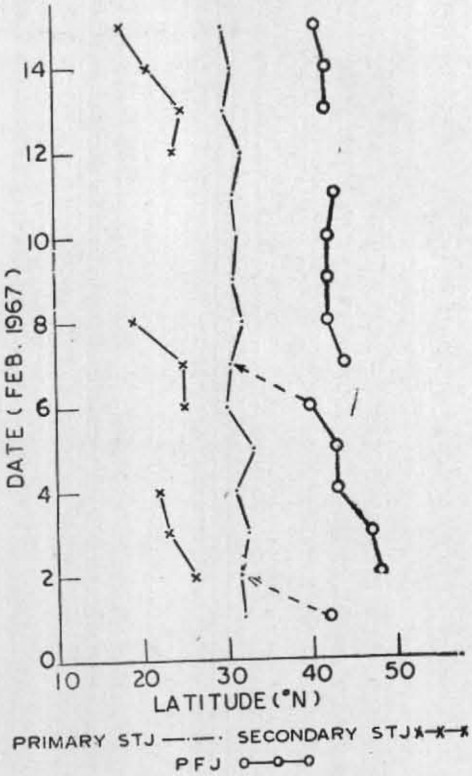

Fig. 1. Location of Jet Stream

near the maximum reported by either of the two stations *i.e.*, Srinagar or Delhi on all days except 2nd, 3rd, 9th and 10th. On the 2nd the PFJ from the north migrated southwards and merged with the STJ. The result was a steep temperature gradient between Delhi and Srinagar. The wind estimated, therefore, is higher than reported. In fact, it appears that on this day winds were yet to adopt to large temperature change brought about by the incursion of cold polar air. On the remaining three days the cores rose very high *i.e.*, 160, 140, 135-mb levels, upto which no winds were reported. But even the geostrophic approximations on these days show very high values, *i.e.*, 250, 176 and 229 kt. Hence the estimated maximum values, *i.e.*, 200, 180 and 180 kt seem to be reasonable though definitely an underestimation. It may be noted that on most of the other days when fairly reliable observations were available the geostrophic winds (Table 1) fell much short of the reported maximum. It may be mentioned that geostrophic winds were calculated between Delhi and Srinagar, a distance of about 5·5° latitude. Therefore, they represent only a rough estimate of the average wind in this broad belt and have to be much lower than the wind at the jet-core. On the 1st and 12th, however, they are very low in comparison to the

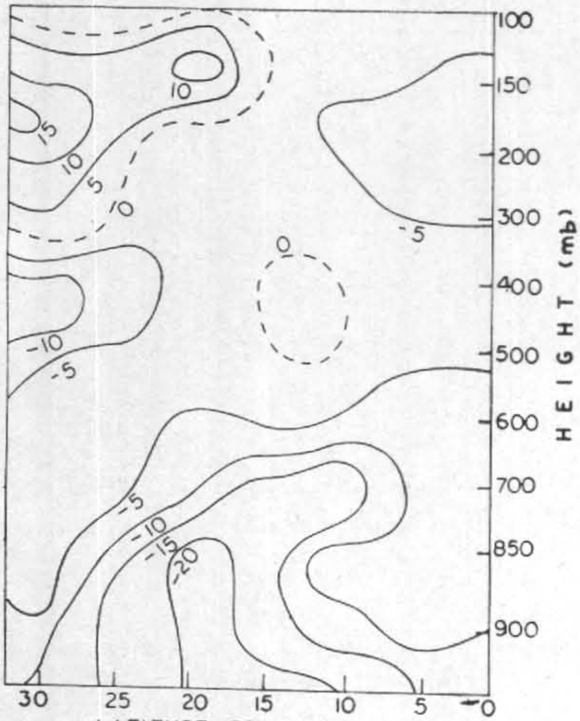

Fig. 2. Total energy change (cal/cm) along 75°E from December 1967 to January 1968

speed at the core, probably due to slight error in the height values of these stations.

The average core speed comes to 150 kt. But of these three days are excluded, *i.e.*, 3rd, 9th and 10th, the average works out to be 140 kt. The average height is about 200 mb and average position is 31·3°N. Thus the main jet stream over India based on this study is situated at about 200-mb level between 31° and 32°N and has an average maximum speed of 140 to 150 kt though occasionally speed may exceed 200 kt. This agrees fairly well with the findings of Koteswaram (1953, 1954) and others except its position. It is really interesting that the jet core remained every day between Srinagar and Delhi inspite of the fact that many developments took place, like the combination with the PFJ and developments to the south during this period. It may be possible that during the development of a very strong western disturbance, it may shift southwards (Koteswaram 1953) or a strong ridge may take it northwards (Singh 1964). But these situations are necessarily very few. In general, the period studied is typical of the winter situations over northern part of the country. It seems reasonable, therefore, to state that the main sub-tropical jet during winter is situated north of Delhi around 31°N. It does not, however, contradict the findings of Koteswaram that the mean jet in February is around 25°N. This jet stream, having a higher horizontal shear to its north than to its south, as will be shown later, will be estimated at a southerly latitude than the actual day-to-day position, on the basis of the geostrophic approximations (Bannon 1954) and that is the basis of Koteswaram's estimation. The mean location will naturally shift further southwards if the secondary jet core which is situated at about 23°N is also included in the averaging process.

The location of this jet-core north of 30°N as well as a secondary core at 23°N is strongly supported by energy considerations. Garde (1970) calculated the total energy content of the winter circulation over India along 75°E and 90°E. He found (Fig. 2) that there is a rapid increase in the total energy north of Lat. 30°N above 300-mb level from December to January at 75°E which is further augmented in February (after which it decreases). The maximum of this energy concentration is at 200-mb level north of Lat. 30°N and another weak maximum above 200 mb between Lats. 20° and 25° N. Thus, the main jet core will be located north of Lat. 30°N at 200 mb and another weaker core above 200 mb between Lats. 20° and 25° N.

It may also be noted (Table 1) that the positions of the wind maxima reported at Srinagar or Delhi are not at the height of the core of the jet but are either above or below. They also vary within wide limits from day-to-day both in strength as well as position. Hence the consideration of either the wind maxima or the wind at any particular level will not give the actual position of the core which has to be determined from the considerations of temperature and wind both at the surrounding stations. This core is situated above the isotherm of —17°C (range ±3°C) at 500-mb and —44°C (range ±4°C) at 300-mb level. The core temperature is —50°C (range±5°C).

3.2. *Jet stream front and the STJ*

It is observed that a jet stream front is associated with the STJ everyday of this study and the core of the jet is situated just above this front on most of the days. It is also noted that the middle tropopause extending from the core of the PFJ decends below the STJ and forms the base of this front. This front, however, greatly varies in extent as well as sharpness. It appears that the extension and the sharpening of the jet stream front is associated with the process of

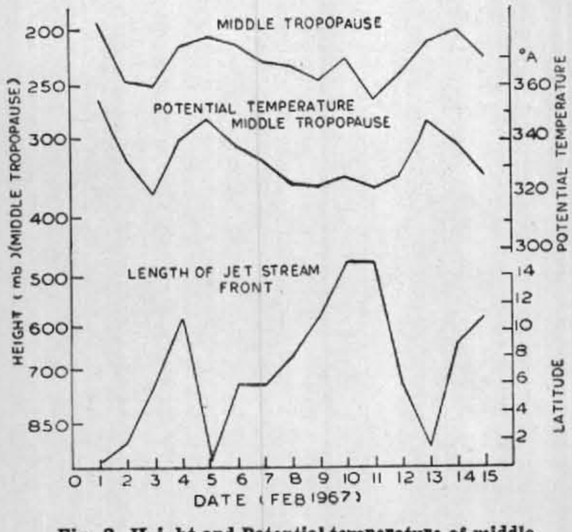

Fig. 3. Height and Potential temperature of middle tropopause and length of Jet front

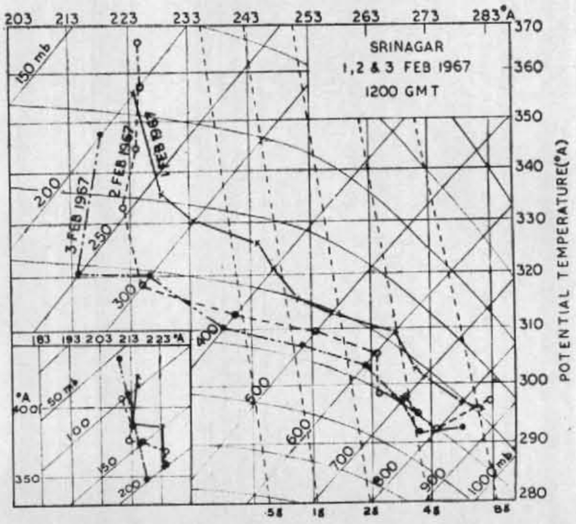

Fig. 4. Temperature of Srinagar on 1, 2 & 3 February 1967 (1200 GMT)

unstable development at the jet, *i.e.,* merging of the PFJ and the STJ or flowing in of cold air from the north or warm air from the south. And it is weak and limited in extent when these activities are absent. One thing, however, is clear that it is always present north of the jet core *i.e.,* over Srinagar in this case, and shows more or less an isothermal structure. It is also apparent that it is quite broad north of the jet and narrows as it extends south and downward.

It was observed that on 1 Frebruary 1967 this front did not extend much beyond Srinagar. But in the next three days it extended progressively to 23°N (Fig. 3). This extension was associated with the progress of migration of the PFJ southwards and its merging with the STJ which caused cold polar air incursion into the country from the north and simultaneous incursion of warm air from the south (Fig. 4). Once this process stopped, it again shrank back, as on the 5th. On the 6th again the extension started as another PFJ approached the STJ from the north and merged on the 7th and subsequent days (Figs. 5 and 6). The associated cold air incursion from the north continued upto 11th. As a result, the jet stream front extended from 34°N on the 5th to 19°N on the 11th (Fig. 3). In the next two days it again shrank back as the cold air incursion stopped. Incursion again started on the 14th, this time from the west, and the front again extended. Thus, there is an intimate relation between the length of the jet stream front and the unstable development at the jet.

Fig. 3, which shows the height and the potential temperature of the middle tropopause and also the length of the jet stream front, brings out this association clearly. The cold air incursion is indicated by the lowering of the middle tropopause and the fall in its potential temperature. It is seen that during these periods the length of the front also increases. The correspondence is very good except on the 5th. It appears that on the 5th cold air incursion had stopped in the upper layers but was still active in the lower layers. This is quite possible in the transition period. Thus, the jet stream front is a manifestation of the unstable conditions in the jet stream region and is strengthened by the cold and warm air incursions during such periods and also by subsidence in the upper layers. When the unstable conditions cease, the normal turbulence destroys it, particularly in the lower layers (Briggs and Roach 1963).

Its thickness is the maximum to the north of jet core, *i.e.,* at Srinagar in this case, about 3 km. The front extends from the middle tropopause which is at 227 mb (11 km), to 150-mb level (14 km). It is more or less isothermal (*i.e.,* average temperature at the base —56·1°C and at the top, —54·3°C) with an average temperature of —55°C. As it extends southwards slantingly its thickness reduces and it becomes narrow. In this study, it extends on an average by 7° latitude and narrows down from 3 km to about 1 km. It slants at an angle of 112° from the vertical.

4. Tropopause

4.1. *Tropical tropopause* — The tropical tropopause was around 100 mb at all the stations south of Delhi. Delhi also showed this tropopause mostly around 100 mb except on 6th and 11th when it lowered to 128 and 135 mb respectively.

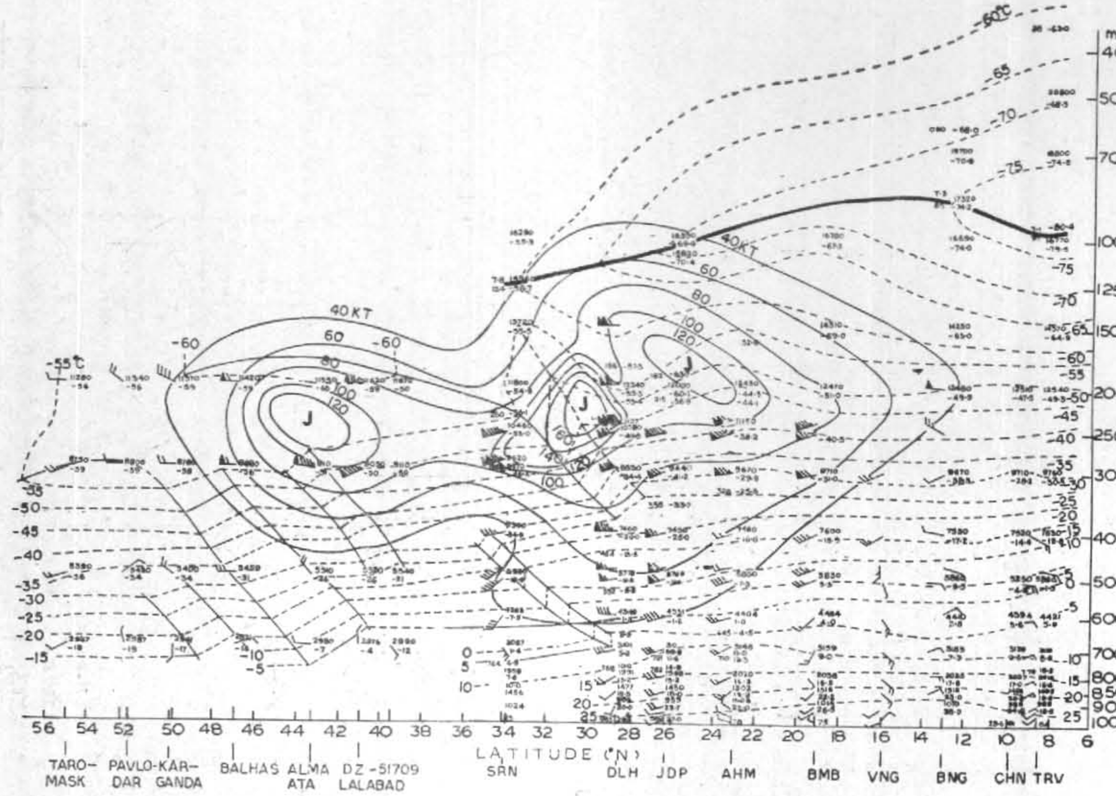

Fig. 5. Vertical cross-section — 7 February 1967 (1200 GMT)

TABLE 2

Characteristics of Tropical tropopause

Date (Feb 1967)	Tropical tropopause over Delhi and other stations to south: Height (mb)	Temp. (°C)	Potential temp. (°A)	Tropical tropopause at Srinagar: Height (mb)	Temp. (°C)	Potential temp. (°A)
1	84	—78·2	396	125	—59·5	388
2	94	—75·4	390	137	—60·9	376
3	97	—75·4	394	—	—	—
4	101	—74·4	375	150	—59·0	368
5	98	—76·2	384	—	—	—
6	112	—73·0	376	150	—60·0	368
7	97	—75·0	385	124	—58·7	390
8	97	—73·3	395	110	—58·5	402
9	105	—73·7	379	—	—	—
10	109	—71·3	382	—	—	—
11	96	—76·6	385	—	—	—
12	94	—72·7	394	110	—57·5	402
13	91	—71·5	401	112	—56·8	402
14	85	—75·8	398	118	—57·9	398
15	91	—75·9	393	—	—	—
Total	1451	—1118·4	5727	1136	—528·8	3494
Average	97	—74·6	382	126	—58·8	388

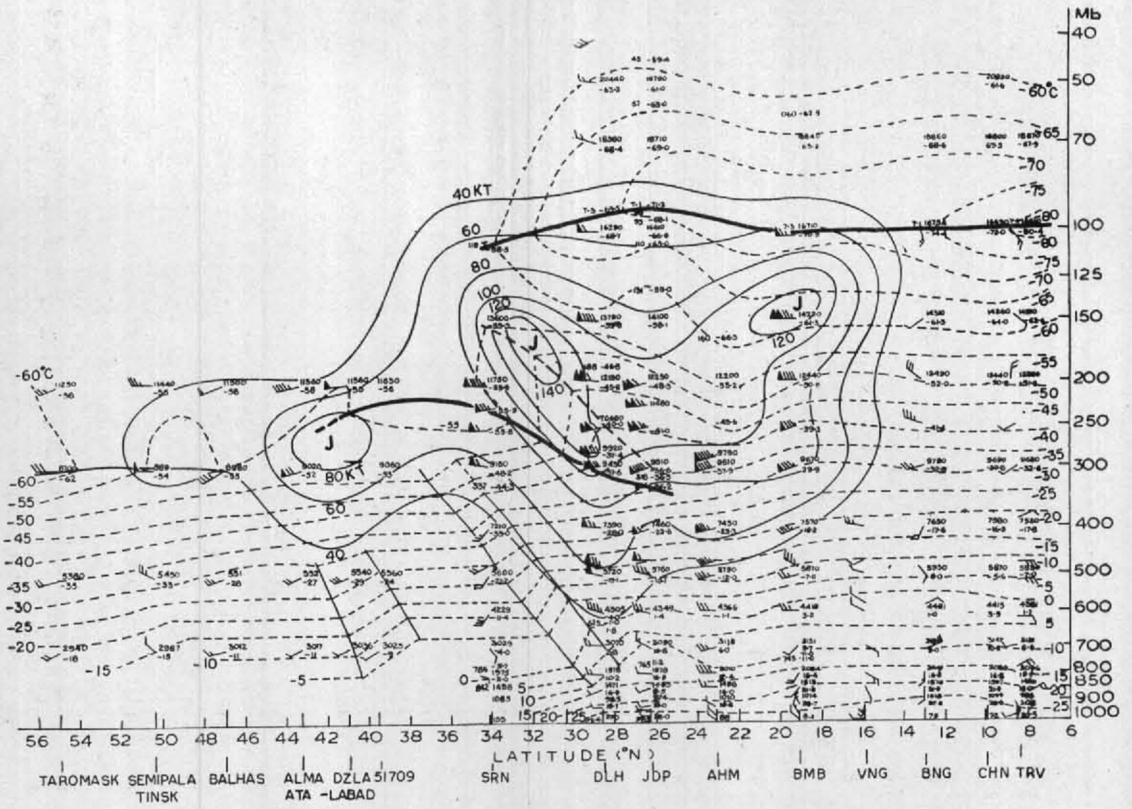

Fig. 6. Vertical cross-section — 8 February 1967 (1200 GMT)

Srinagar, however, whenever reported a high tropopause, it was at a lower level with a higher temperature. Daily tropical tropopause values for Delhi, Jodhpur, Ahmedabad, Bombay, Bangalore and Trivandrum were tabulated and averages worked out. They are given in Table 2 which also includes the high tropopause values reported by Srinagar. It can be seen that over Delhi and southern stations tropical tropopause is on average at 97-mb level with temperature of —74·6°C and potential temperature of 382°A. At Srinagar, however, the higher tropopause is at 126 mb with average temperature of —58·8°C but its potential temperature is 388°A. Thus, the upper tropopause at Srinagar has the same potential temperature as the southern tropical tropopause and hence is a tropical tropopause. Thus, the tropical tropopause in winter is situated at about 16·5 km (97 mb) at a temperature of about —75°C over Delhi and southern stations and lowers to 15 km over Srinagar and warms to —60°C. Its characteristic potential temperature is 380°A to 390°A.

4.2. *Middle tropopause* — Middle tropopause is daily observed at Srinagar where its average position is 227 mb (11 km) and temperature —56°C. Its potential temperature is 334°A in keeping with the findings of other workers (Riehl *et al.* 1954 ; Defant and Taba 1957, 1958). It dips southwards from Srinagar and forms the base of the jet stream front. To the north, it rises to above 200 mb and then dips to about 250 mb over the core of the PFJ. The average northerly position of this tropopause is 43°N, *i.e.*, the average position of the PFJ. The lowest temperatures are attained at its highest point and are between —60° and —65°C. In all aspects it conforms to the findings of other workers.

Thus, at Srinagar where there is a clear break between the middle and the tropical tropopause, the gap is of the order of about 100 mb or 4 km and the core of the jet is about 3 latitudes to the south of this break at about 12 km below the tropical tropopause.

4.3. *Sub-tropical tropopause*—No sub-tropical tropopause was observed on any day in this study.

4.4. *Polar tropopause* — Polar tropopause does reflect in the soundings of Srinagar on many days during the period of this study in association with the incursion of cold polar air from the north. It appears mostly as a level of very weak lapse rate below the middle tropopause, as on 2nd (300 mb), 4th (300 mb) and then again on 9th

TABLE 3

Horizontal shear in the sub-tropical jet stream

Date (Feb 1967)	Core location (°N)	Cyclonic (kt) at latitude 37	36	35	34	33	32	31°N core speed (kt)	Anticyclonic (kt) at latitude 30	29	28	27	26	25	24	23	22	21	20	19	18
1	32	—	—	—	—	16	0	140	0	10	16	12	10	9	12	11	8	6	6	—	—
4	31	—	—	13	19	30	15	160	10	—	—	—	—	—	—	—	—	—	—	—	—
5	33	—	—	16	18	15	7	170	0	5	17	20	14	12	8	8	6	6	7	5	7
6	30	—	12	9	9	6	0	150	2	16	15	10	8	7	6	7	5	5	5	5	6
7	30·5	—	—	—	36	40	14	160	10	—	—	—	—	—	—	—	—	—	—	—	—
8	32	11	13	16	22	25	9	140	0	14	15	9	—	—	—	—	—	—	—	—	—
11	31	—	18	22	26	30	7	140	3	17	5	5	5	5	5	7	8	12	—	—	—
12	32	—	10	11	14	19	1	100	0	7	19	—	—	—	—	—	—	—	—	—	—
13	30	—	8	12	10	2	0	100	12	18	8	—	—	—	—	—	—	—	—	—	—
14	31	—	—	—	32	14	0	140	0	15	15	12	—	—	—	—	—	—	—	—	—
15	30	—	15	18	18	21	6	120	0	10	6	8	7	7	5	4	4	5	5	4	6
Total	342·5	11	76	117	204	218	59	1520	37	112	116	76	44	40	36	37	40	34	23	14	19
Average	31	11	13	15	20	20	5	138 (140)	3	12	13	11	9	8	7	7	8	7	6	5	6
f (Coriolis parameter)				18·2	18	17·6	17		16	15·6	15										

(300 mb) and 10th (300 mb), and sometimes merges with the middle tropopause, as on the 3rd (250 mb), 11th (280 mb), 12th (240 mb) and 15th (225 mb). It is very clearly seen, however, in the regions north of India in association with the PFJ. It is at about 300 mb and extends northwards from below the PFJ.

5. Layers of Maximum Wind (LMW) associated with STJ

The layers of maximum wind associated with the sub-tropical jet are mainly two on the anti-cyclonic side and one on the cyclonic side. The LMWs on the anticyclonic side are well-marked except on the 12th and 13th and also on 3rd. The upper LMW on the anticyclonic side is apparently more prominent in the mean than the lower one though on individual days any one may be more prominent. The upper one rises to about 150 mb from the jet core at 200-mb level and extends to 15°N from 31°N, an expansion of 16 latitudes. The lower one descends to about 430 mb and reaches upto 20°N from the core of the jet. These LMWs disappear when a strong jet appears to the south. But on most of the other occasions, the upper LMW includes a discrete core of 80 to 120 kt strength which sharpens this LMW.

To the north, the LMW is not so elongated as in the south. But the core shows pointedness which may dip downward sometimes. But mostly it points upwards. On the average, it rises from the core (at 200 mb) to about 178 mb at Srinagar. The LMWs tilt at the following angles from the core of the jet on the average :

Anticyclonic side (upper) : 7° above horizontal

Anticyclonic side (lower) : 30° below horizontal

Cyclonic side : 14° above horizontal.

6. Horizontal shear in the STJ

Horizontal wind profiles in the core of the STJ were prepared for all days except 2nd, 3rd, 9th and 10th. These four days were left out because on these days the jet was very strong and at a high level where no direct wind observations were available. In estimating the horizontal shear, only that region was taken into consideration which was under the direct influence of the main STJ and no jet fingers were intruding. Fig. 7 gives the 11 profiles prepared in this way and Table 3 gives the values of horizontal wind shear per degree latitude picked up from these profiles. Included in the table is the value of f (Coriolis parameter) for a few latitudes near the core.

It can be seen from this table that on both sides of the jet the maximum shear occurs in the 2nd or 3rd latitude from the core. On the anticyclonic side the maximum average shear is in the third latitude and is 13 kt/latitude which is about 90 per cent of the value of Coriolis parameter for that latitude. The same has been found by Pisharoty *et al.* (1957) also. In the individual cases, however, the zero or even the negative absolute vorticity has been attained in narrow regions, particularly, in the 2nd and 3rd latitudes from the centre of the core.

On the cyclonic side the shear is of the order of 20 kt/latitude in 2nd and 3rd latitudes from the core which is about 110 per cent of the value of the Coriolis parameter at these latitudes. In individual cases, however, the values are much higher. In one case the horizontal shear is double the value of f. It should, however, be noted that for want of sufficient observations, the placement of isotachs has got an element of subjectivity. Hence, small errors in the estimation cannot be avoided. On the average, the shear on the anti-cyclonic side is about 8 kt per degree latitude and on the cyclonic side, 15 kt per degree latitude. Utilising these values, as calculated in Table 3, an average horizontal wind profile of the STJ is prepared which is also shown in Fig. 7.

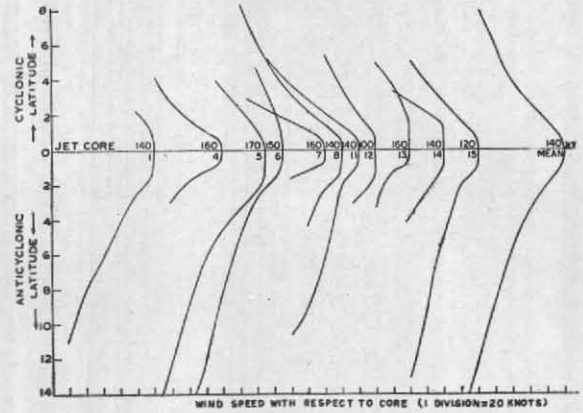

Fig. 7. Horizontal wind profile of STJ (1 to 15 February 1967)

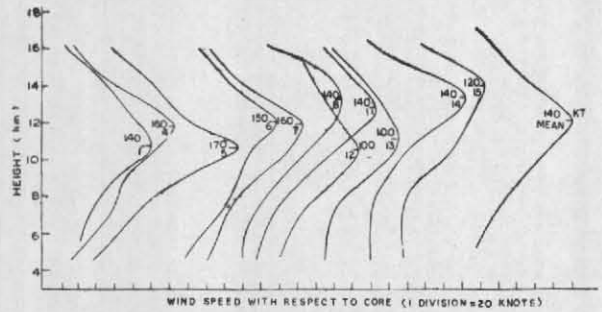

Fig. 8. Vertical wind profile of STJ (1 to 15 February 1967)

7. Vertical wind shear in STJ

For the same 11 days, the vertical wind profiles were also prepared which are shown in Fig. 8. Table 4 gives the values of vertical shear per kilometre above and below the jet core picked up from these profiles. As per this table maximum vertical shear occurs at a distance of about 2 km from the core both above as well as below. The maximum shear above is 29 kt per km and below, 22 kt per km, that is, about 15 mps/km above and 11 mps/km below. On the average, vertical shear is about 22 kt/km above and 15 kt/km below, *i.e.*, 11 mps/km above and 8 mps/km below, a value not much different from other findings. In individual cases, however, values exceed much more than these, particularly in the first 3 kilometres from the jet core. Utilising the average values of the vertical shear (Table 4) thus obtained, an average vertical wind profile was prepared. This also is given in Fig. 8.

8. Model STJ

From the average horizontal and vertical wind profiles of the STJ, given in Figs. 7 and 8, the positions of the 10, 20, 30, 40 and 50 per cent reduction in the core speed were picked up (the average core speed is 140 kt at 200-mb level for these 11 cases). And utilising the average position and the extent of the middle tropopause, tropical tropopause, jet stream front and LMWs on the cyclonic and anticyclonic sides, a model jet stream profile was prepared. It is shown in Fig. 9. This profile gives a reasonable realistic picture of the sub-tropical jet in India during winter. It shows more shear on the cyclonic side than the anti-cyclonic side and more shear above than below. Its LMW to the north rises just above the middle tropopause. In the south there are two LMWs. The upper one is stronger than the lower. And the lower one shows stronger shear in the region of jet stream front than outside, as observed by Endlich and McLean (1957, 1965). The profile has not been extended to more than 50 per cent of the core speed because in doing so it goes beyond Srinagar, where not much data are available. The extension of middle tropopause has been taken upto 43°N where the mean PFJ is situated. The PFJ is shown there schematically. No calculations were made for the PFJ due to the paucity of data. Similarly the polar front and the polar tropopause have been shown schematically. The position of the jet core at 23°N is also indicated.

9. Propagation of the wind maximum of the STJ

Having investigated the structural features and other properties of the STJ at 75°E, it is

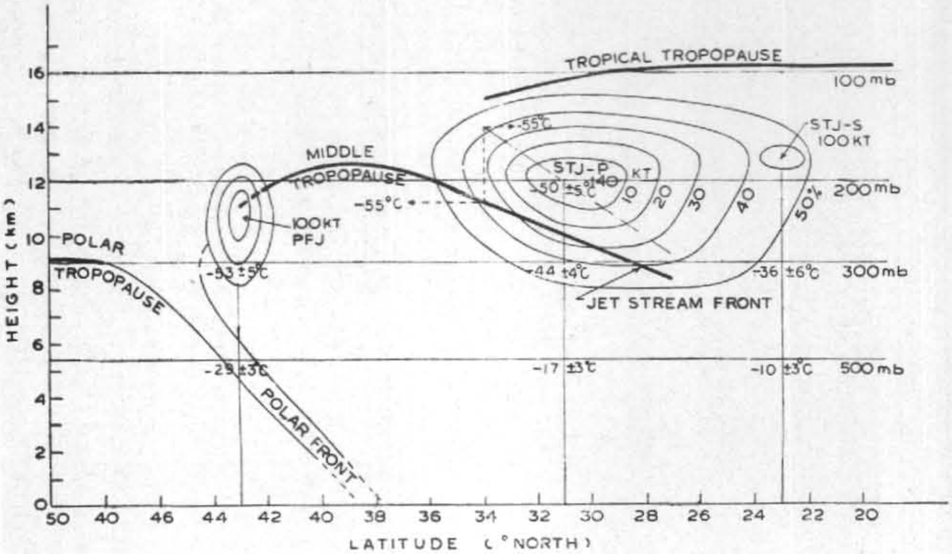

Fig. 9. Model wind profile of jet streams in India and neighbourhood

TABLE 4

Vertical shear in the sub-tropical jet stream

Date (Feb 1967)	Vertical shear (kt) at distance(km) +5	+4	+3	+2	+1	Jet core Height (mb)	Jet core speed (kt)	Vertical shear (kt) at distance (km) —1	—2	—3	—4	—5	—6	—7
1	20	22	16	16	14	240	140	16	19	17	12	9	—	—
2	—	19	30	35	21	210	160	15	23	17	6	12	17	19
5	25	20	18	37	30	250	170	35	38	30	19	20	18	--
6	—	17	21	28	12	210	150	19	14	10	10	14	17	16
7	—	17	25	36	21	210	160	13	20	24	17	10	8	10
8	—	—	40	27	6	175	140	7	17	22	19	17	12	10
11	—	—	20	20	15	180	140	11	26	22	20	21	13	9
12	12	12	13	14	12	250	100	9	21	22	16	10	7	—
13	21	18	15	9	0	250	100	18	26	20	11	8	4	1
14	—	—	29	49	26	170	140	16	30	22	14	14	8	0
15	—	—	—	43	27	150	120	6	11	10	16	25	15	7
Total	78	125	227	314	184	2295	1520	165	245	216	160	160	119	72
Average	19	18	23	29	17	209	140	15	22	20	15	15	12	9
Total average			22								15			

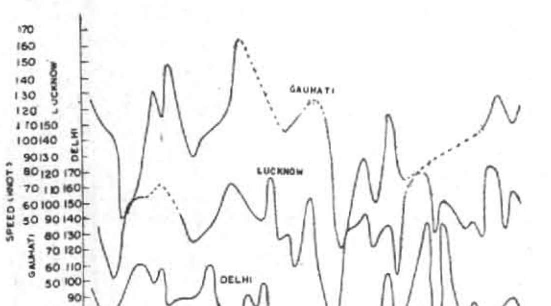

Fig. 10. 9-km winds at Delhi, Lucknow and Gauhati

worthwhile to see how the STJ core at this longitude propagates itself eastwards. For this purpose the daily wind observations at 9 km of Delhi, Lucknow and Gauhati were plotted for each day of February 1967. It is given in Fig. 10. It is unfortunate that on many days wind observations even at this level are not available. Winds are missing more often at Gauhati than at other two stations. However, the examination of this figure brings out a few things clearly. In the figure, the maxima and minima which are apparently the same are given the same number. It can be seen that the jet maxima and minima sometime appear simultaneously at all the three stations. But on other occasions they take as much as 72 hours to travel from Delhi to Gauhati. Maximum time

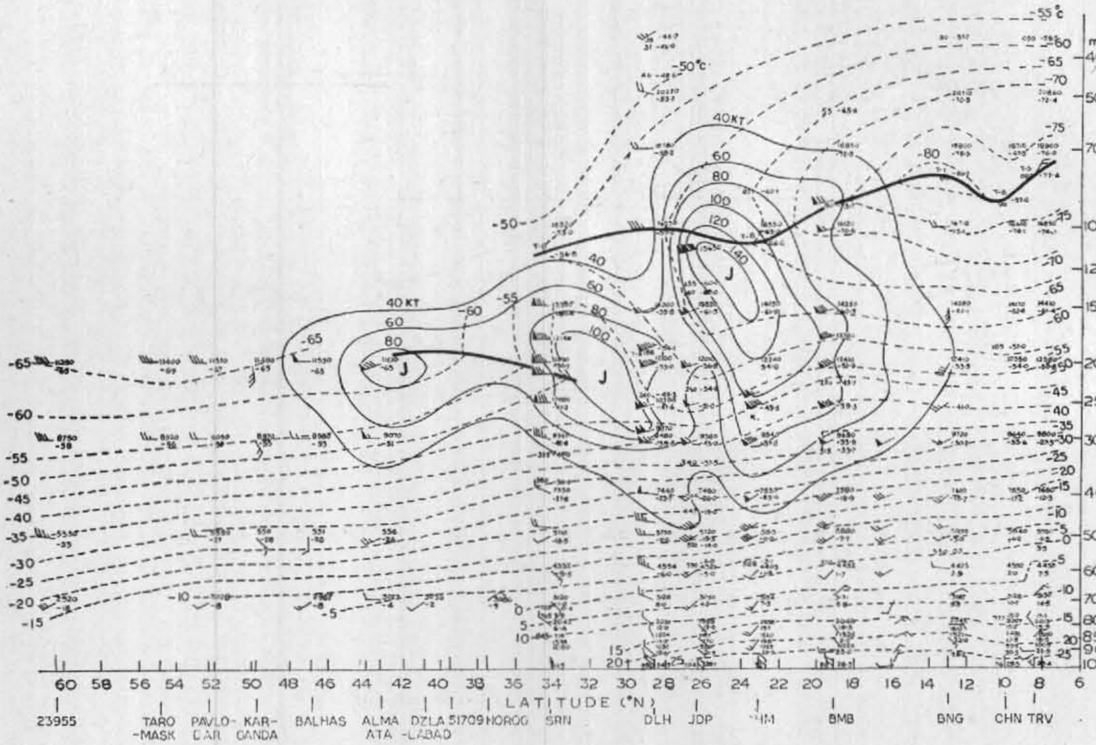

Fig. 11. Vertical cross-section — 13 February 1967 (1200 GMT)

taken for the maxima/minima to propagate from Delhi to Lucknow and from Lucknow to Gauhati is 36 hours. It is, of course, necessary to have a longer period analysis to give the correct average value of the propagation period. But it can safely be said based on this limited analysis, that the jet maximum takes up to three days in reaching from Delhi to Gauhati, a speed of about 5° longitude per day, though it can appear simultaneously on quite a number of occasions on all the three stations.

10. Secondary Sub-tropical Jet

As said earlier, on most of the days there is a discrete jet core to the south of the main STJ which is quite variable both in horizontal as well as vertical, as shown in Fig. 1. It can be seen that on 10 days out of 15 a separate core is present whose mean position is about 23°N, *i.e.*, latitude of Ahmedabad, and height about 178 mb (12·7 km) with an average speed of 100 kt. On most of the days, this core forms part of the upper LMW to the right of the main STJ and can rightly be called a jet finger. Only on certain days it is a distinct jet, for instance, 13th, 14th and 15th, (Figs. 11, 12 and 13) when it is associated with a synoptic development. On these days, a deep trough in the westerlies extending into Arabian peninsula approached the country from the west and the jet approached associated with it (Joseph 1967). The secondary jet is located above 500 mb temperature of —10°C (±3°C) and 300 mb temperature of —36°C (±6°C).

11. Polar Front Jet

It has been found from this study (Table 5) that there is a polar front jet (PFJ) to the north of the country present between 40 and 50° latitudes (Fig. 1). It is, on average, located at 43°N at a height of about 11 km (240 mb) with an average core speed of about 100 kt. It is situated above 500-mb level isotherm of —29°C (±3°C) and 300-mb isotherm of —53°C (±5°C). This is a weaker and more meandering jet than the STJ.

12. Conclusion

The following conclusions can be drawn regarding the westerly jet streams over India and to its north in winter based on this study of fifteen days, 1 to 15 February 1967 between 8° and 60°N along 75°E.

1. There are three jet cores present in this latitude belt on most of the days of this study.

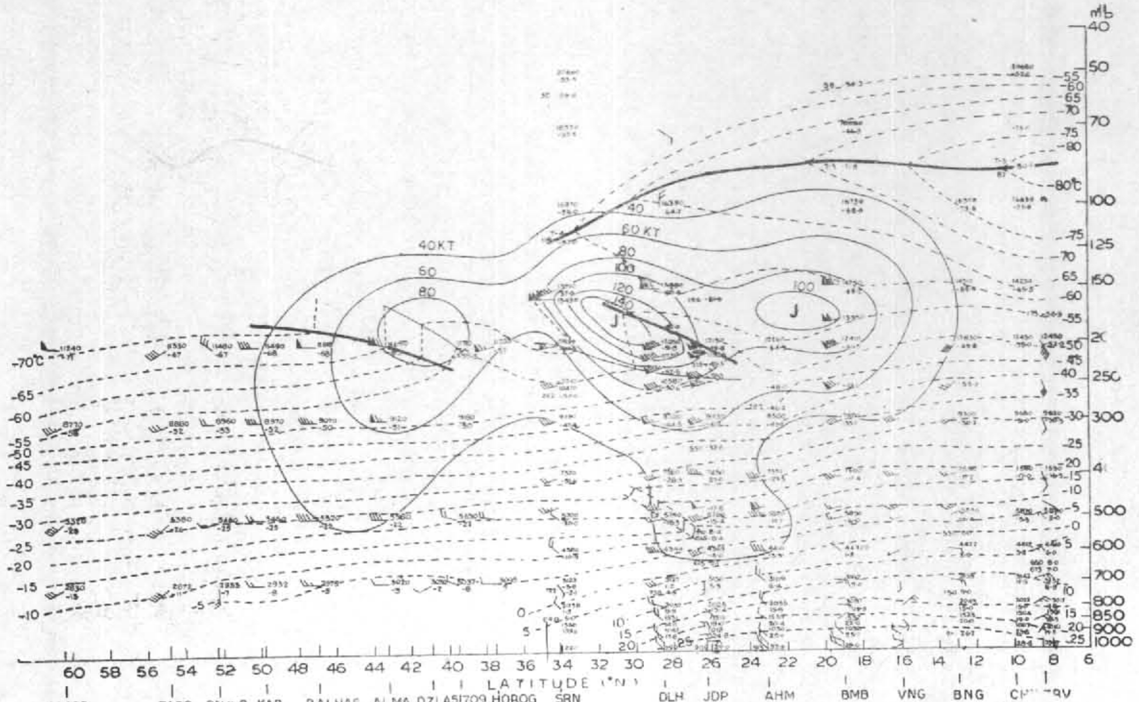

Fig. 12. Vertical cross-section — 14 February 1967 (1200 GMT)

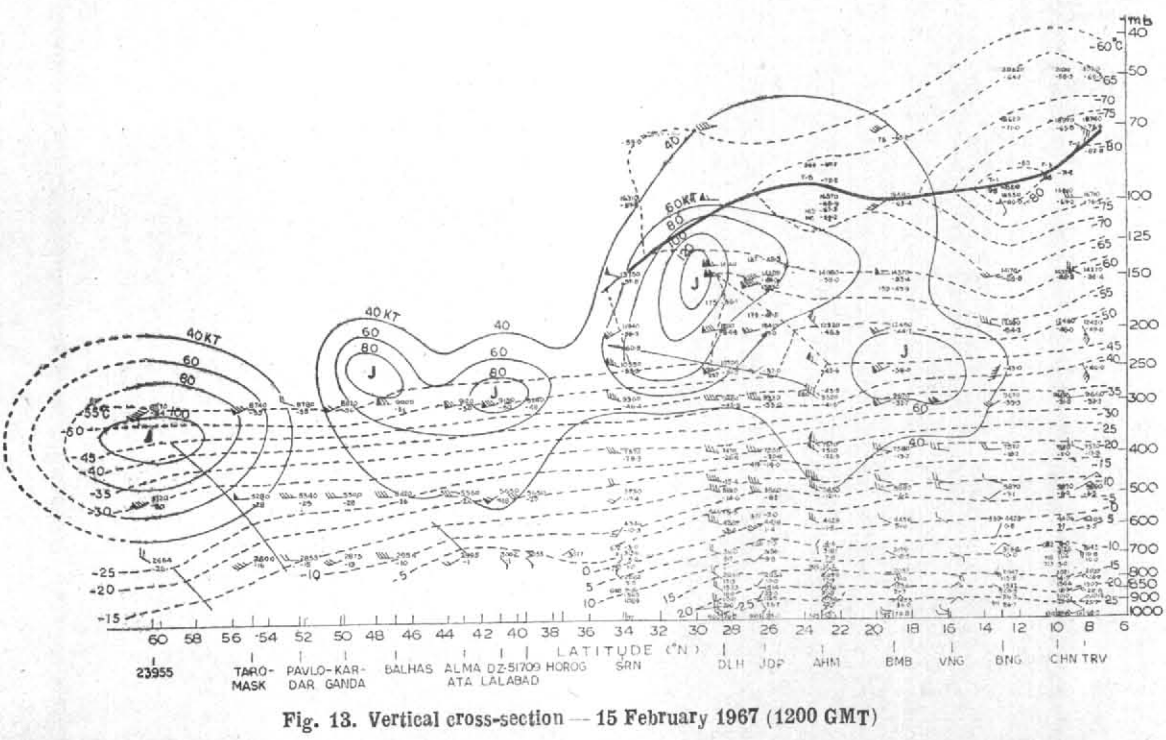

Fig. 13. Vertical cross-section — 15 February 1967 (1200 GMT)

TABLE 5

STJ — Secondary and Polar Front Jet

Date	STJ (Secondary)			Polar Front Jet		
(Feb 1967)	Location (°N)	Height (mb)	Speed (kt)	Location (°N)	Height (mb)	Speed (kt)
1	—	—	—	42	225	120
2	26	160	100	48	265	100
3	23	250	80	47	300	140
4	22	180	100	43	275	120
5	—	—	—	43	200	120
6	25	140	120	—	—	—
7	25	185	120	44	235	120
8	19	140	120	42	265	80
9	—	—	—	42	250	80
10	—	—	—	42	250	60
11	—	—	—	43	250	50
12	24	175	120	—	—	—
13	25	125	140	42	200	80
14	21	175	100	42	180	80
15	18	250	60	41	180	80
Total	228	1780	1060	561	3075	1230
Average	22·8	178 (13 km)	106	43	237 (11 km)	95

2. Primary Sub-tropical Jet stream

(*a*) The most prominent and the least variant of the three is the sub-tropical jet over north India which is situated in the mean, at about 31°N and at the 200-mb level (12 km) with a core speed of 140 to 150 kt, though on individual days speeds may exceed 200 kt and the core may rise to above 14 km.

(*b*) The jet is located above the isotherm of —17°C (±3°C) at 500 mb and that of —44°C (±3°C) at 300 mb with a core temperature of —50°C (±5°C).

3. Layers of Maximum Wind (LMW)

This jet has one LMW on the cyclonic side and two on the anticyclonic side. The one on the cyclonic side rises slightly from the core northwards, *i.e.*, by 14°, from the horizontal along the core. Of the two on the anticyclonic side, the upper one is more prominent than the lower one and includes a discrete core of 80 to 120 kt strength on most of the days. It rises at an angle of about 7° from the horizontal at the core, *i.e.*, from 200 mb (12 km) at the core to 150 mb (14 km) at about 15°N. The lower one is less prominent than the upper one and dips by an angle of 30° from the horizontal at the core and lowers by 5 km at 20°N.

4. Jet stream front

(*a*) There is a jet stream front associated with this jet which extends slantingly from the north of the jet to the south at an angle of 22° from the horizontal. It extends from Srinagar to 27°N and dips from 11 km to about 8·5 km equatorward.

(*b*) The base of this front is the middle tropopause. The front is more or less isothermal to the north of the jet core, *i.e.*, at Srinagar, with a temperature of —55°C and has depth of about 3 km. As it slants south its thickness reduces and is about 1 km at the southern end in the mean.

(*c*) It is always present north of the jet, *i.e.*, at Srinagar. But its southward extension is highly variable. Its extension southwards is associated with the unstable development in the jet stream region, like the incursion of the polar front jet or cold polar air from the north. As long as the incursion lasts, it is extensive. Once the inflow stops, it is wiped out, mostly in the lower layers.

5. Horizontal and vertical shear in the STJ

(*a*) The horizontal shear at the core of this jet is of the order of 15 kt per degree latitude on the cyclonic side and 8 kt per degree latitude on the anticyclonic side. The maximum shears on both sides occur in the 2nd or 3rd latitude from the core. The average anticyclonic shear is 90 per cent of the Coriolis parameter. In individual cases, however, the cyclonic shear may rise to twice the Coriolis parameter whereas on the anticyclonic side it may equal the Coriolis parameter or may become slightly negative in narrow zones, particularly in the 2nd and 3rd latitudes from the core.

(*b*) The vertical shear is of the order of 22 kt per kilometre above and 15 kt per kilometre below on average though the maximum is much higher. The maximum shear occurs in the second kilometre from the core and can be of the order of 30 kt/km above and 22 kt/km below.

6. Movement of STJ

The jet core may take upto 3 days in travelling from Delhi to Gauhati (*i.e.*, a speed of 5° latitude per day) though on quite a few occassions it appears simultaneously both at Lucknow and Gauhati.

7. Secondary Sub-tropical Jet

(*a*) There is a discrete core present south of the main jet which is quite variable in position as well as altitude. On the average, it is at Lat. 23°N at a height of about 12·5 to 13 km with an average speed of 100 kt. It is mostly a jet finger which forms part of the upper LMW of the main jet on the anticyclonic side.

(*b*) On some days, a distinct sub-tropical jet does appear at this latitude which is associated with the approach of deep troughs in the westerlies which move through comparatively lower latitudes. On such occasions also there is no break in the tropopause or any extension of the jet stream front at this core. It is purely in the tropical troposphere and develops due to the temporary incursion of cold air in the wake of such troughs.

8. Polar Front Jet

To the north of the country there is a jet of polar front type located at about latitude 43°N at 11 km (240 mb) with an average speed of 100 kt. It is located over the 500-mb level temperature of —29°C (±3°C) and at the 300 mb temperature of —53°C (±5°C).

9. Tropopause

(*a*) The tropical tropopause extends from Trivandrum to Delhi at about 16·5 km with a characteristic temperature of —75°C and then dips to 15 km at Srinagar and warms to —60°C. The characteristic potential temperature, however, remains between 380° to 390°A.

(*b*) The middle tropopause regularly occurs at Srinagar at an average height of 11 km and temperature —56°C. The characteristic potential temperature is about 335°A. It lowers southwards from Srinagar to form the base of the jet stream front and rises northwards above 200 mb in 39° to 41° latitudes and then dips to 250 mb above the PFJ.

(*c*) The polar tropopause is regularly seen north of the PFJ at about 300-mb level. In India it is reflected in the temperature profiles of Srinagar when polar air incursion takes place into the country.

10. Polar Front

The polar front is also seen in the northern parts of the country, mostly north of Delhi, in the upper air, *i.e.*, 850 mb upwards, when cold polar air incursion takes place from the north.

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