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The study of jet streams over India and to its north in winter: Part II

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ABSTRACT. Characteristics of the jet streams over India and to its north in winter were studied with the help of the vertical cross-sections (1200 GMT) along Long. 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 in this belt on most of the days, two inside the country and one outside. The study of the two jet cores inside the country formed the earlier part of this paper (Singh 1971). This part deals with the third jet core. It was found that there is a polar front jet to the north of the country situated in the mean at 43°N at about 240-mb level (11 km) with an average wind maximum of 100 kt. It forms generally at a northern latitude and migrates southward. The confluence of this jet with the STJ over the country causes the STJ to rise, intensify and expand in a very deep layer in the troposphere. The migration of the PFJ takes place along the isentropic surface on which it was located before the start of this process, *i.e.*, 340°A in the mean.

1. Introduction

Murray (1953) studied the lateral movement of jet streams over western Europe and found that weakening jets generally rise as they move southward. Riehl *et al.* (1954) noted that the jet streams generally form in a northerly latitude and migrate southward and they do so with a rising tendency. McIntyre and Lee (1953), however, noted that where jet streams suffered considerable displacement to the south they showed a tendency to move downward. They further noted that the observed motion of the cores, at least in the troposphere, followed approximately the mean position of the isentropic surface. Mohri (1958) studied the cases of very strong jets over Japan and its vicinity and noted that the strongest jets were the result of the confluence of the two jets, *i.e.*, PFJ and the STJ, over the region. He argued that in the explanation of the strong mean jet over the Far East, "we have to study not only the confluence pattern but also the mechanism which is responsible for the horizontal convergence in the cyclonic region and the indirect circulation above the jet axis". In other words, for the confluence process to cause the strengthening of the jet, there should be subsidence on the cyclonic side at the jet-core level and rising motion on the anticyclonic side, as is the case in the entrance region of the jet stream. He also showed that such is the case over southwest Japan during winter when the jet is extremely strong.

Koteswaram (1953) studied a case of the migration of polar front jet over India in association with a strong western disturbance. But nothing more is known about this migration and its subsequent behaviour. In this paper, the characteristics of the polar front jet to the north of the country and its migration into the country will be discussed.

2. Data

For the study of the characteristics of the westerly jet streams over India and to its north in winter, daily vertical cross-sections for 1200 GMT along 75° E for the period 1 to 15 February 1967 were prepared for the latitude belt 8°N to 60°N. The extra-Indian data utilised in this study 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
Eranakulam	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
Srinagar	34° 05′N	74° 51′E

Extra-Indian stations used are the following —

Horog	37° 31′N	71° 30′E
51709	39° 30′N	76° 00′E
Dzlalabad	40° 30′N	73° 00′E
Alma Ata	43° 14′N	76° 56′E
Balhas	46° 54′N	75° 00′E
Karganda	49° 48′N	73° 08′E
Pavlodar	52° 17′N	76° 57′E
Taromask	54° 56′N	73° 24′E
Aleksan Drovkoe	60° 26′N	77° 52′E

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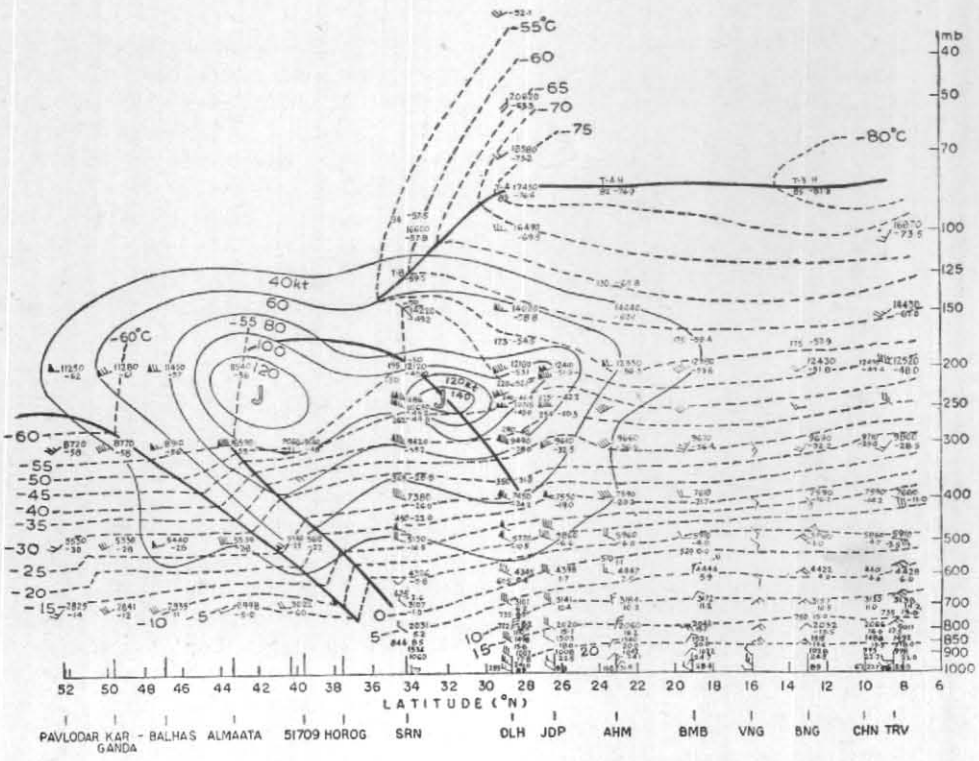

Fig. 1. Vertical cross-section, 1 Feb 1967 (1200 GMT)

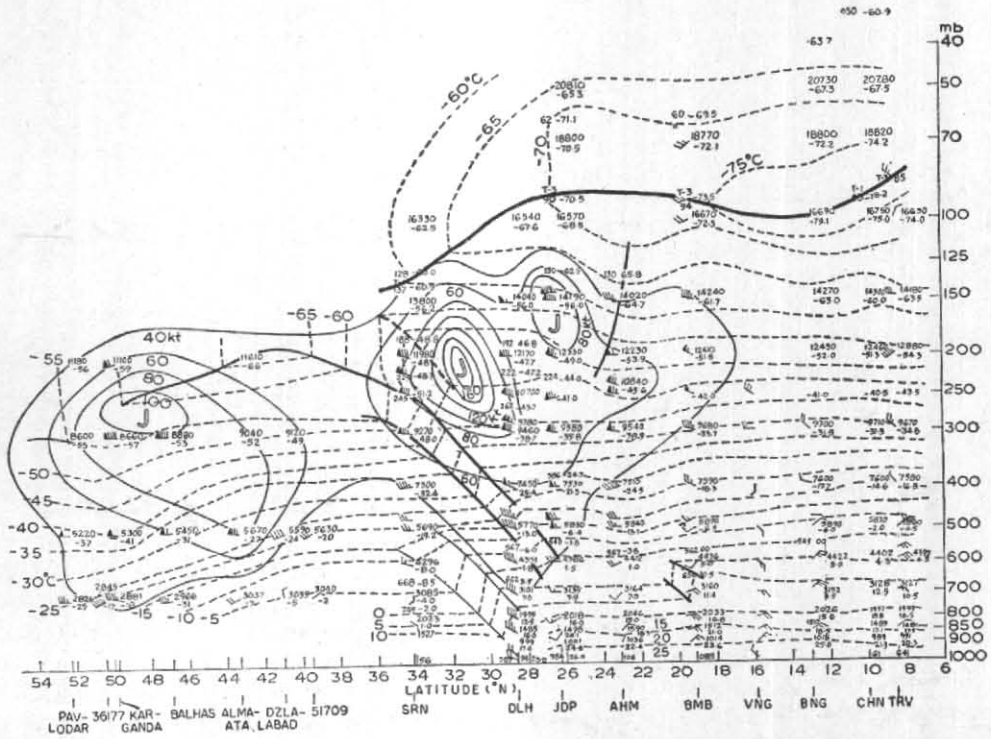

Fig. 2. Vertical cross-section, 2 Feb 1967 (1200 GMT)

TABLE 1

Characteristics of PFJ

Date (Feb 1967)	Location (Lat °N)	Height (mb)	Speed (kt)	Temperature (°C) below core at 500 mb	Temperature (°C) below core at 300 mb
1	42	215	120	—27	—53
2	48	265	100	—36	—55
3	47	300	140	—32	—52
4	43	275	120	—30	—53
5	43	200	120	—26	—50
6	—	—	—	—	—
7	44	235	120	—27	—51
8	42	265	80	—28	—52
9	42	250	80	—29	—55
10	42	250	60	—35	—55
11	43	250	50	—31	—57
12	—	—	—	—	—
13	42	200	80	—26	—51
14	42	180	80	—22	—50
15	41	180	80	—21	—50
Total	561	3065	1230	—370	—684
Average	43	236 (11 km)	95	—29	—53

Besides, pibal data of Indian stations along this longitude (75°E) were utilised. Morning (00 GMT) data were used whenever the 1200 GMT observations were absent. Due to low reliability of the high level wind and temperature observations, the jet-core analysis was carried out with great care utilising all the available data of wind and temperature, keeping in view the consistency of the result.

3. Discussion

From the study of these cross-sections it was found that on most of the days there were three separate jet cores in this latitudinal belt, two inside the country and one to its north. The one to the north of the country was undoubtedly of the polar front type and was located generally between 40° and 50° N (Fig. 7). Of the two inside the country, one was invariably located between Srinagar and Delhi with minor latitudinal variations from day-to-day and the other was further south, around 23°N. The characteristics of these two were discussed in Part I of this paper (Singh 1971). We shall now study the PFJ to the north of the country.

3.1. *Wind and temperature characteristics—PFJ*

Table 1 gives the location, height, core-speed and temperatures at 500 and 300-mb levels below the core of this jet stream. It can be seen that this jet is mainly located between 40° and 50°N at altitudes varying from 300 mb to 180 mb. The average location is 43°N and the average altitude 11 km (240 mb). The average core-speed is 100 kt, though this may be an underestimation as the maximum wind reports were not included in the data of Russian stations. It is located above the —29°C (Range —29°±3°C) isotherm at 500 mb and —53°C (Range —53°±5°C) isotherm at 300-mb level. It is situated in the break between the middle and the polar tropopauses as at other longitudes. The middle tropopause extends from south to above the core of this jet and the polar tropopause extends northwards from below the core of this jet.

A polar front or a deep zone of baroclinity is invariably associated with this jet at lower levels. This jet mostly appears at higher latitudes and gradually shifts southwards. This movement stops when it reaches in the belt of 42° to 44° N (Table 1). There is a slight tendency to rise as it moves southwards as can be seen on 3rd, 4th and 5th and also on 13th, 14th and 15th (Table 1). But it will need more data for confirmations. On the 3rd, it sank as it intensified, and afterwards it rose as weakened. The vertical and horizontal shears and other characteristics of the jet could not be determined for want of data.

3.2. *Migration of PFJ into India*

In this period of 15 days, the PFJ migrated into the country twice, firstly on the 2nd and then again on the 7th. And on both these occasions significant changes took place in the upper air flow over the country. On both these occasions western disturbances affected the northern parts of the country but the weather was not very extensive. It appears that the PFJ migrated into the country in association with the upper air troughs in the westerlies, which affected the northern parts of India.

Case I — On 1 February1967 (Fig.1) the upper tropospheric flow pattern at this longitude (75°E) was quite simple. A strong subtropical jet (STJ) with a core-speed of about 140 kt was located at about 240-mb level at latitude 32°N. The polar front jet was at 42°N at 215-mb level. There was a well marked polar front associated with it extending from ground to 300-mb level.

On the 2nd (Fig. 2) significant changes took place. The PFJ at 42° N moved southwards and apparently merged wth the STJ at 32°N. Due to this migration the polar air incursion started into the country and Srinagar showed a very significant temperature fall (Fig. 8) right from low levels to 200 mb. Delhi also showed a moderate temperature fall in low levels. Jodhpur, on the other hand, warmed up between 600 and 250-mb levels. It is apparent from this that the polar air incursion affected Srinagar and reached upto Delhi, whereas

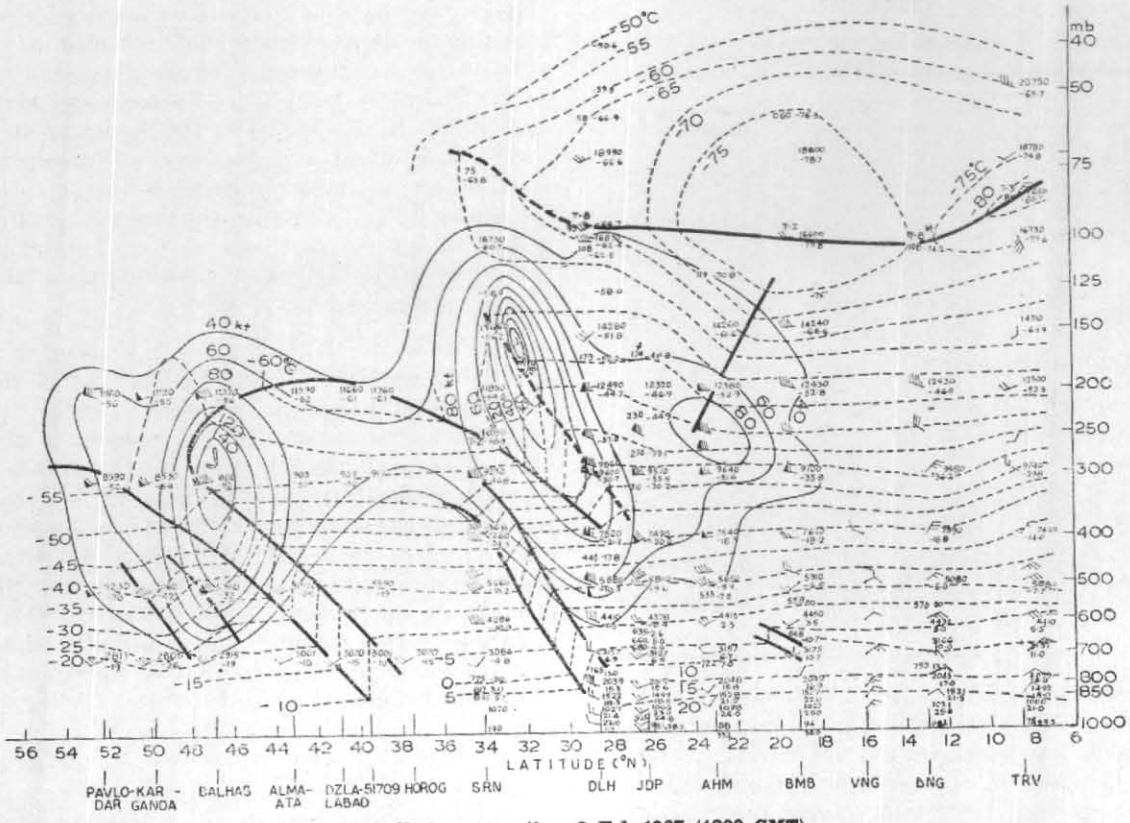

Fig. 3. Vertical cross-section, 3 Feb 1967 (1200 GMT)

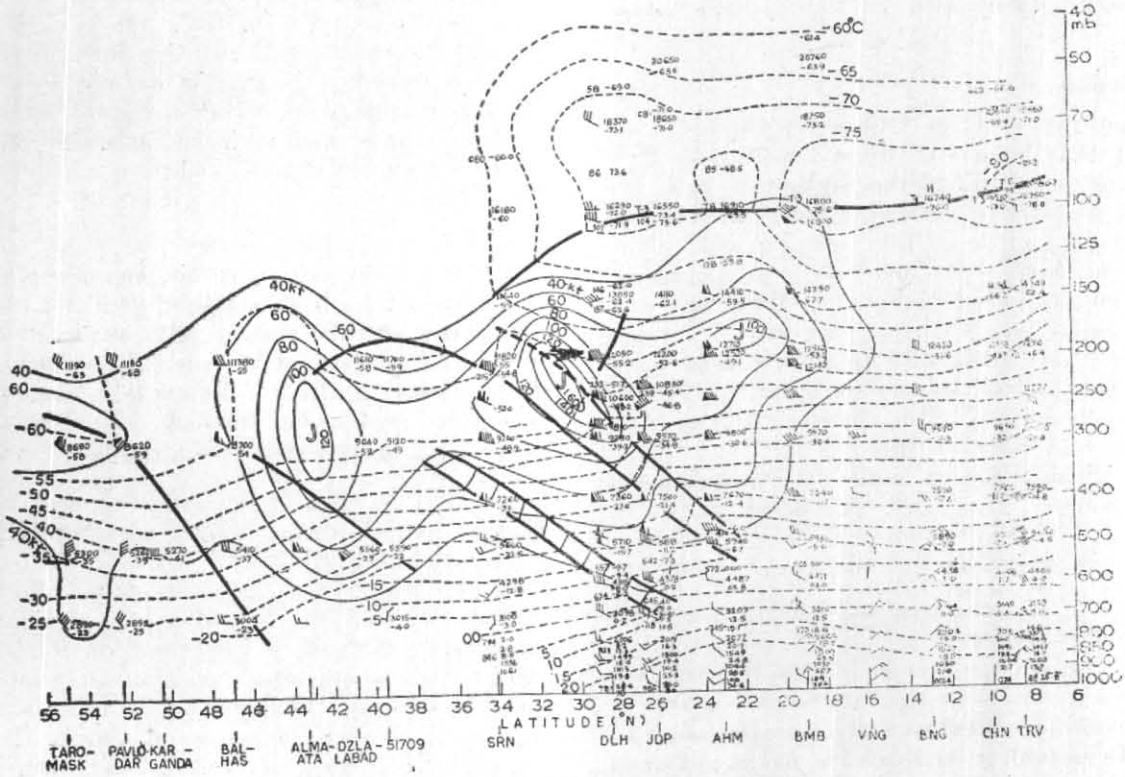

Fig. 4. Vertical cross-section, 4 Feb 1967 (1200 GMT)

TABLE 2

Movement of Polar Front Jet (PFJ) from 1-11 Feb 1967

Date (Feb 1967)	PFJ Core			Remarks
	Height (mb)	Location (°N)	Potential temp. (°A)	
	Migration of First PFJ			
1	215	42	340	Core height determined only approximately for want of data
2	225	34	342	
3	290	28	343	
	Migration of Second PFJ			
5	200	43	342	Seen as a separate core
6	200	Between 43 & 34	342	It formed part of the LMW of the STJ on cyclonic side
	275	34 (near Srinagar)	330	Srinagar reported maximum wind at this level (124 kt)—Position a little uncertain for want of data
8	275	28·5 (near Delhi)	340	Wind at Delhi at this level rose from 85 to 128 kt and it was its maximum
9	300	26 (near Jodhpur)	339	Jodhpur reported max. wind at this level, *i.e.* 136 kt which showed a rise of 44 kt from the previous day
10	300	23 (near Ahmedabad)	342	Wind at Ahmedabad at this level rose from 74 to 103 kt and that was its maximum
11	350	24 (near Ahmedabad)	336	Wind at Jodhpur at 400 mb rose from 60 to 90 kt and that at Ahmedabad from 65 to 100 kt
Total			3396	
Average			340	

Jodhpur warmed up due to simultaneous incursion of warm air from the south. The result was a strong temperature gradient between Srinagar and Delhi and a moderate one between Delhi and Jodhpur. Hence the STJ between Delhi and Srinagar intensified to 160 kt and rose to a higher level (210 mb).

Another jet core appeared between Jodhpur and Delhi with a core speed of 100 kt at 160-mb level.

The core of the STJ remained at the same latitude (32°N) on this day, but showed a kink (Fig. 2) on the cyclonic side in the isotach pattern at about 225-mb level. It was suspected, therefore, that the kink was caused by the approach of the PFJ from the north. Comparison of the potential temperature at the PFJ core the previous day with the potential temperature at this point showed that this was the case (Table 2). Actual position of the PFJ on the 2nd was between 42°N and Srinagar at about 225-mb level. The associated polar front was now inside the country extending from Srinagar to Jodhpur between 250 and 600-mb levels and was quite well marked. Another polar front also appeared between these two stations between 500 and 850-mb levels (Fig. 2).

On 3 February (Fig. 3) the incursion of cold polar air was limited to Srinagar at high levels. Delhi warmed up significantly and showed temperatures similar to Jodhpur. The resulting temperature gradient between Delhi and Srinagar was even greater than the previous day. Hence the STJ on the 3rd intensified to above 200 kt and rose to 160-mb level. Its core was also very elongated, *i.e.*, from 600 to 100-mb level, a span of about 12 km, a result of the merging of the two jets (Spiegler 1968). It was also observed that though the STJ core was at 160-mb level, Delhi reported a wind maximum of 146 kt at 290-mb level which gave the isotach pattern a kinkishness at this level. It was suspected that this kinkishness was due to the migration of the PFJ at this level over Delhi on the 3rd. The same was confirmed from the potential temperature considerations (Table 2). Potential temperature at Delhi at 290 mb (—32°C) was 342°A, about the same as was at the jet core on the 1st. On 4 February (Fig. 4) though the process of cold air incursion stopped completely and the STJ attained the normal pattern, the kinkishness at Delhi showed further descent becoming an extended layer of high winds upto very low levels at Delhi. It was apparent that the PFJ sank further on this day. The polar front was now less intense though more elongated extending from Jodhpur to Srinagar above 700-mb level. Even on the 5th (Fig. 5) when the main STJ was not affecting the lower layers at all, the descending motion of the remnants of the PFJ continued. It could easily be seen over Delhi upto 850-mb level as a distinct bulge in the isotach pattern (Fig. 5). The polar front was now completely obliterated. This bulge disappeared the next day. Thus the PFJ on the 1st at 42°N and 215-mb level discended to about 300 mb at 28°N on the 3rd following the isentrope at its core on the 1st, *i.e.*, 340°A, in the mean. Afterwards, it simply sank to lower levels at the same latitude for the next two days and then disappeared.

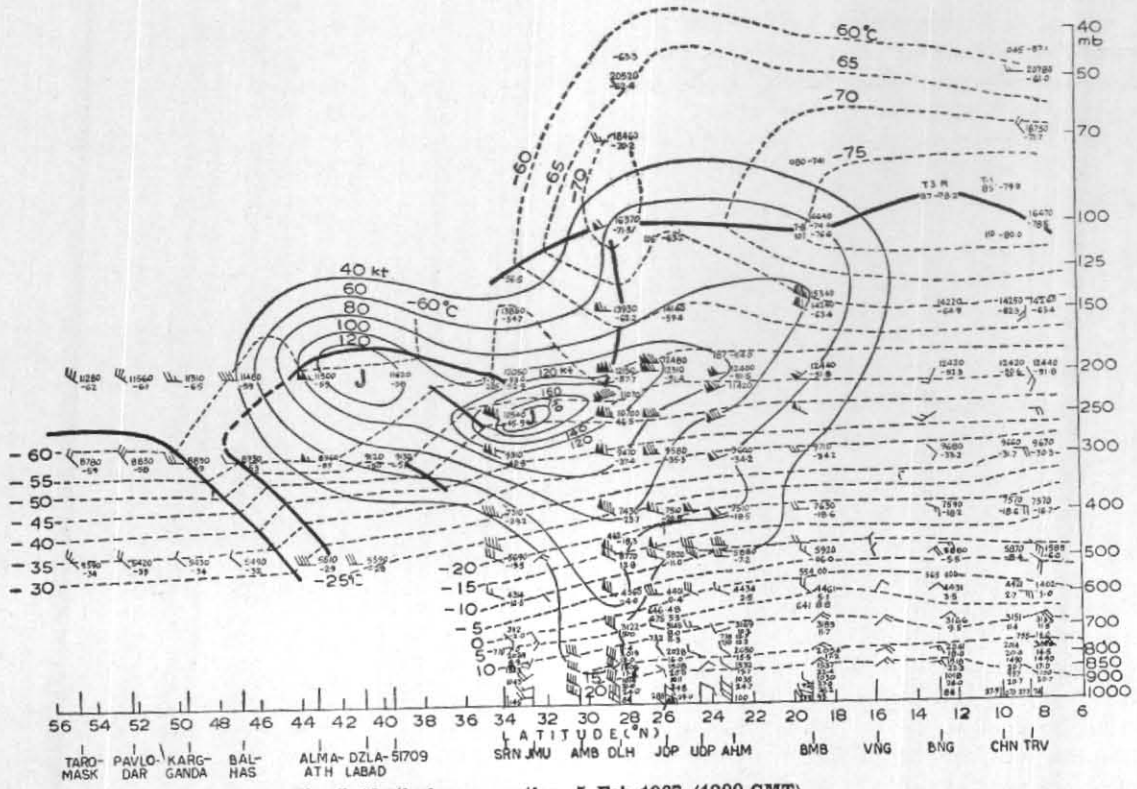

Fig. 5. Vertical cross-section, 5 Feb 1967 (1200 GMT)

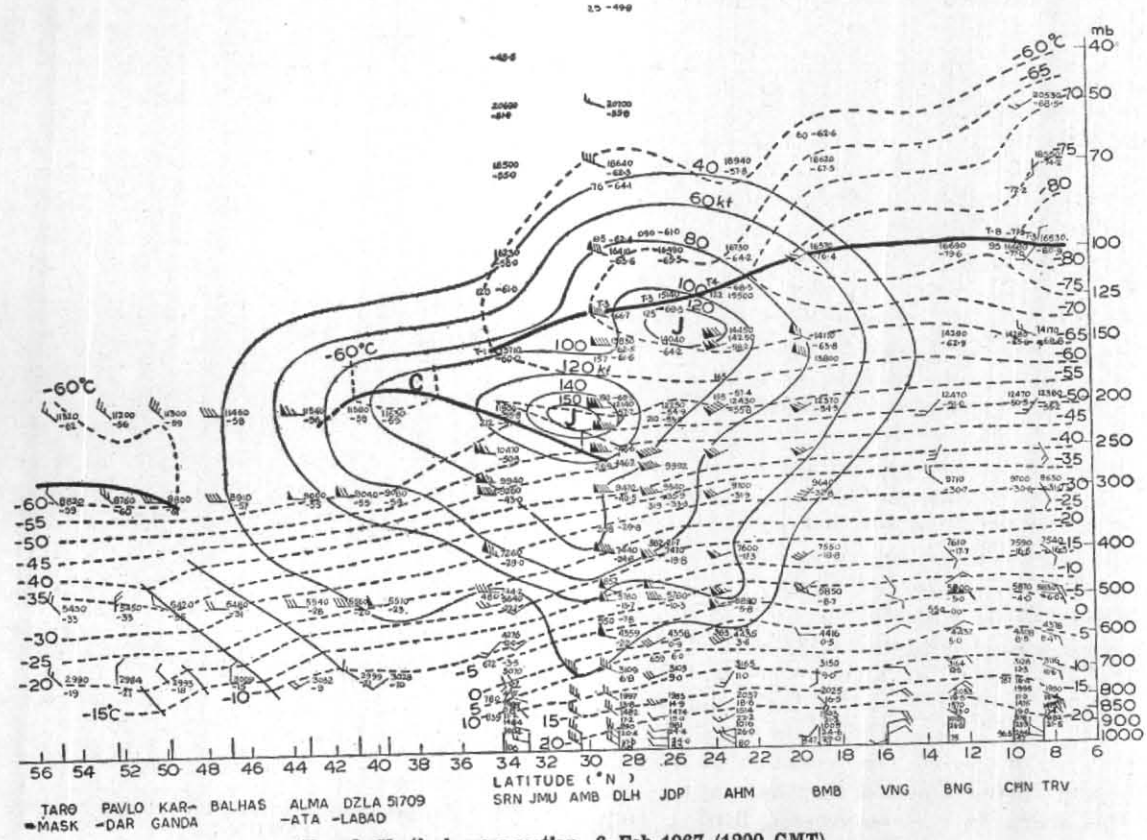

Fig. 6. Vertical cross-section, 6 Feb 1967 (1200 GMT)

The weather associated with this migration was very mild. On the 2nd a feeble western disturbance was located over Afghanistan and adjoining West Pakistan and Jammu & Kashmir, causing isolated rain/snow in the valley. On the 3rd it caused scattered precipitation over Jammu & Kashmir and on the 4th moved eastwards to hills.

Case 2 — The same type of migration took place from 7 to 11 February also. On the 5th (Fig. 5) the STJ was at about 33°N at 250-mb level with a wind maximum of 170 kt. The PFJ was at 43°N at 200-mb level with a core speed of 120 kt. The following day (Fig. 6) the PFJ became a part of the LMW of the STJ, which showed an unusual elongation on the cyclonic side. On the 7th the STJ core became more or less vertical and the LMW to the north disappeared. A kink in the isotach pattern of the STJ, however, was visible at Srinagar at 275-mb level indicating that the PFJ was approaching at about this level. But it was still away from Srinagar as the STJ itself was not affected. On the 8th the kink shifted to Delhi at the same level (275 mb) where Delhi reported its wind maximum. The core of the STJ at the same time rose to 175 mb. It was suspected, therefore, that the effect of the PFJ was felt up to Delhi at this level and the same was confirmed from the potential temperature considerations (Table 2).

On the 9th (Fig. 9) the STJ core rose to 140 mb and intensified to 180 kt due to the merging of the approaching PFJ with the STJ. At the same time, the kink in the isotach pattern which took the shape of a LMW now, extended upto Ahmedabad. The migrating PFJ which was causing this extension was apparently at Jodhpur at 300-mb level where this station reported its wind maximum. The same was confirmed by the potential temperature values (Table 2). On the 10th (Fig. 10) this LMW extended upto Bombay with the PFJ core at Ahmedabad just above 300-mb level which was again confirmed by the potential temperature considerations (Table 2). On the 11th (Fig. 11) the migrating PFJ got detached from the STJ and sank to about 400-mb level between Jodhpur and Ahmedabad. As it sank, it brought in a pool of warm sinking air which caused a double jet stream front, a rare thing in these latitudes. This sinking jet was wiped out the next day. Table 2 and Fig. 13 show the migration of the PFJ into the country. It can be seen that the PFJ migrated from 200 mb at 43°N on the 5th to about 350 mb at 24°N on the 11th. The potential temperature at its core remained more or less the same throughout this migration, *i.e.*, on average, 340° A. Only

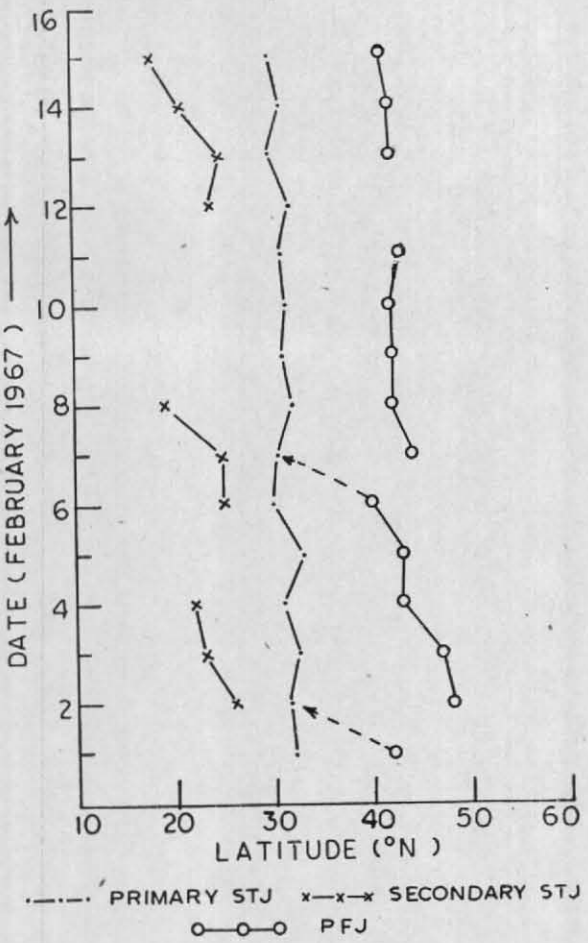

Fig. 7. Location of jet streams

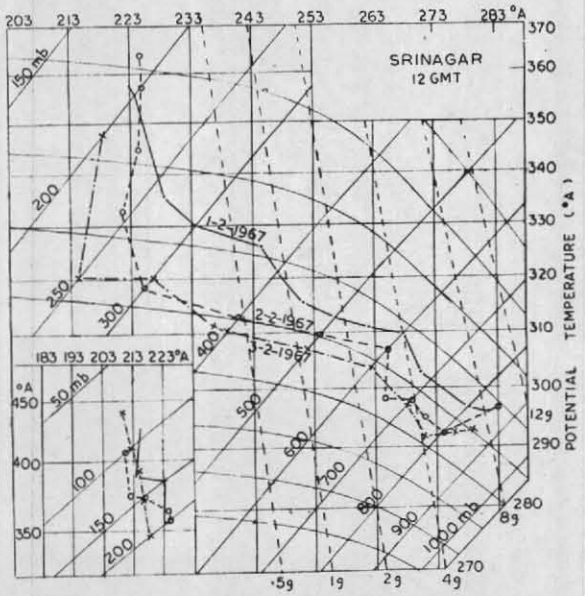

Fig. 8. Temperatures of Srinagar on 1, 2 & 3 Feb 1967 (1200 G M T)

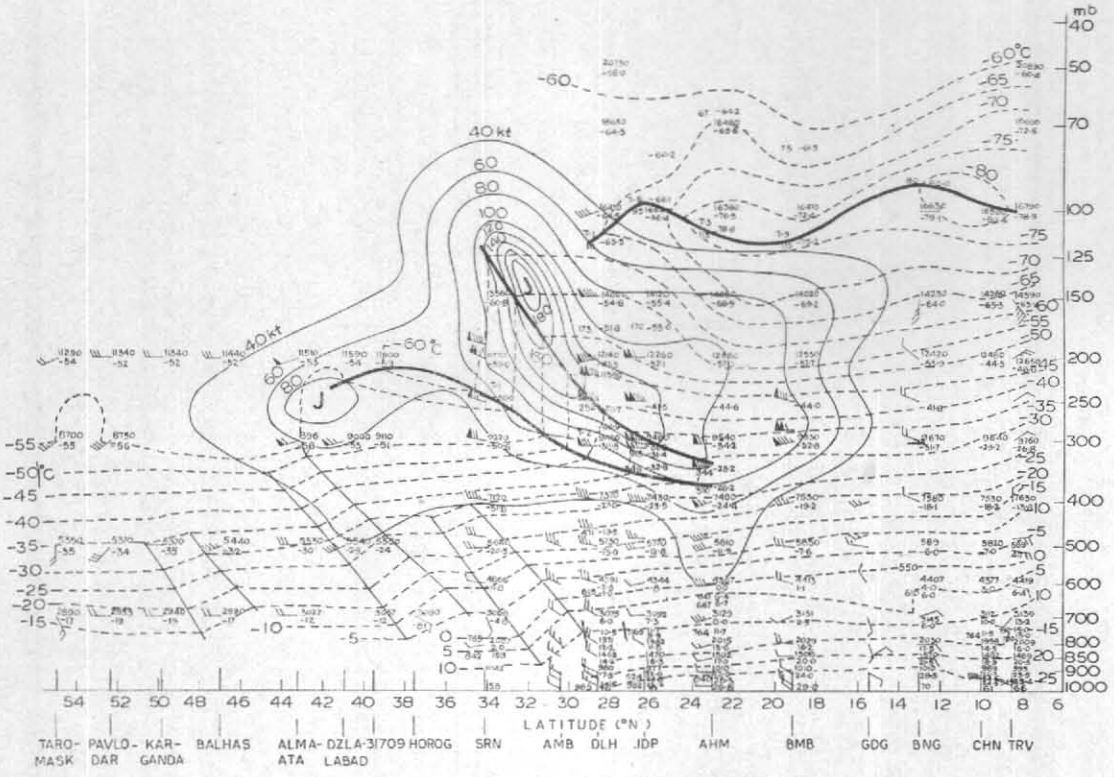

Fig. 9. Vertical cross-section, 9 Feb 1967 (1200 GMT)

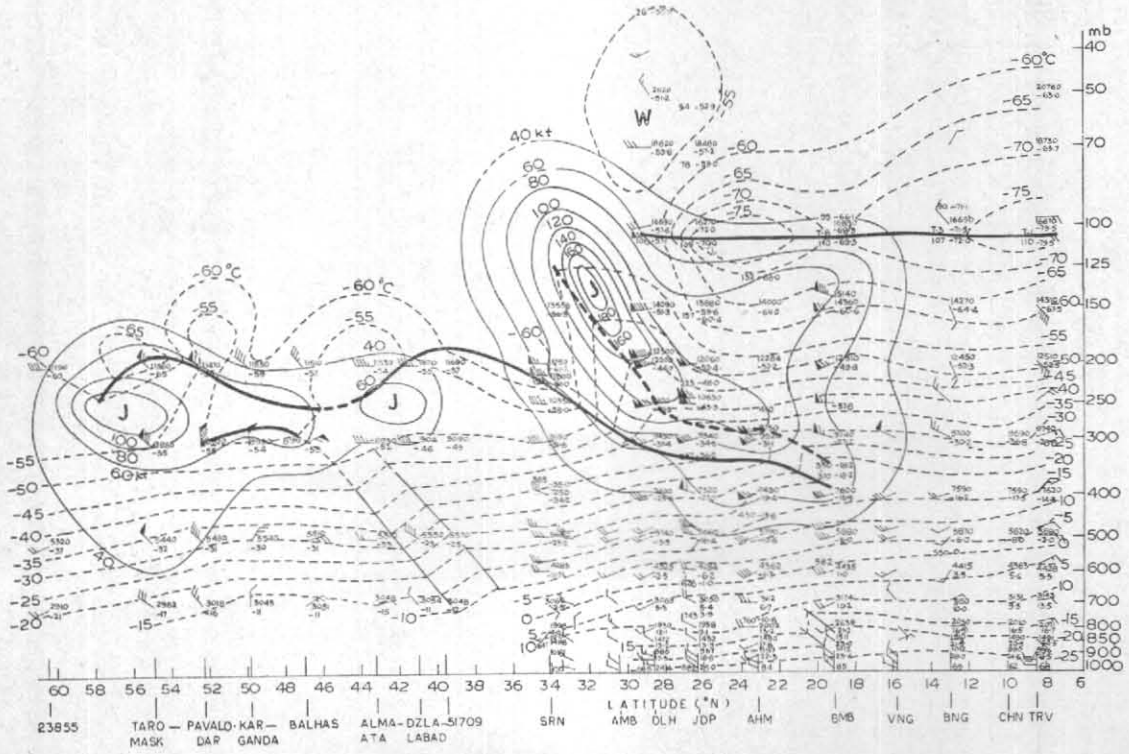

Fig. 10. Vertical cross-section, 10 Feb 1967 (1200 GMT)

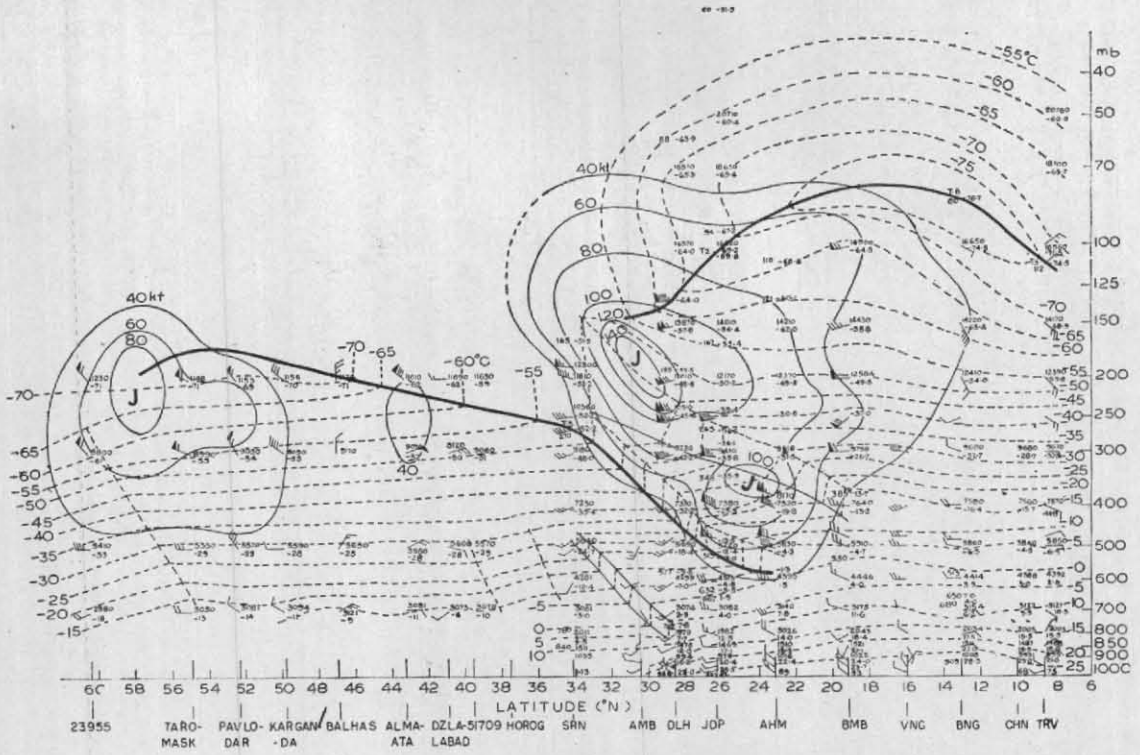

Fig. 11. Vertical cross-section, 11 Feb 1967 (1200 GMT)

on the 7th it was rather low because the core could not be fixed accurately for want of data. This migrating PFJ caused the intensification of the STJ as well as the rise of its core when it was in the same latitude. At the same time, the combined core covered a very deep tropospheric layer.

This migration was very clear from the cold air incursion accompanying it. It started on the 6th and continued on the 7th and 8th. The migration was also apparent from the intrusion of the polar fronts into the country as well as from the elongation and intensification of the jet stream fronts. It also brought about significant changes in the characteristics of the middle tropopause.

3.3. *Incursion of polar front*

The polar fronts associated with the migration of the PFJ on the 2nd and 3rd disappeared on the 5th. On 7 February 1967, however, a polar front appeared between Delhi and Srinagar in association with the second migration. The following day it became an extensive and well marked front extending from 850 mb at Delhi to 300 mb north of Srinagar. It became weak on the 9th but could be seen as a temperature discontinuity upto 11th.

3.4. *Jet stream front*

The same was the case with the jet stream front. It extended from Srinagar to Ahmedabad in association with the migration of the PFJ on 2nd and 3rd. It was longest on the 4th, but was obliterated on the 5th. On 6 February 1967, it again started extending southwards from Srinagar in association with the migration of the second PFJ. It extended upto Delhi on the 6th but was still weak. On the 7th it was well marked upto Delhi. On the 8th it extended upto Jodhpur, on the 9th upto Ahmedabad, and on the 10th upto Bombay. It was the longest and the strongest on the 11th. On the 12th (Fig. 12), however, it was completely wiped out except near Srinagar. Fig. 14 gives its extension throughout this period.

3.5. *Middle Tropopause*

The middle tropopause also lowered (Fig. 14). But there was a greater lowering of its potential temperature. Actually, it showed characteristics of a modified polar tropopause on these days with the characteristic potential temperature of about 320° to 325° A.

3.6. *Subsidence and Ozone*

It has been shown by various workers (Newell 1963) that there is descent of stratospheric air into the tropospheric regions through the break between the tropopauses which are located north of the jet streams. It has also been shown (Craig 1965) that the variation of ozone at any station reflects the movement in the lower stratospheric air at that station. It means, if there is a general

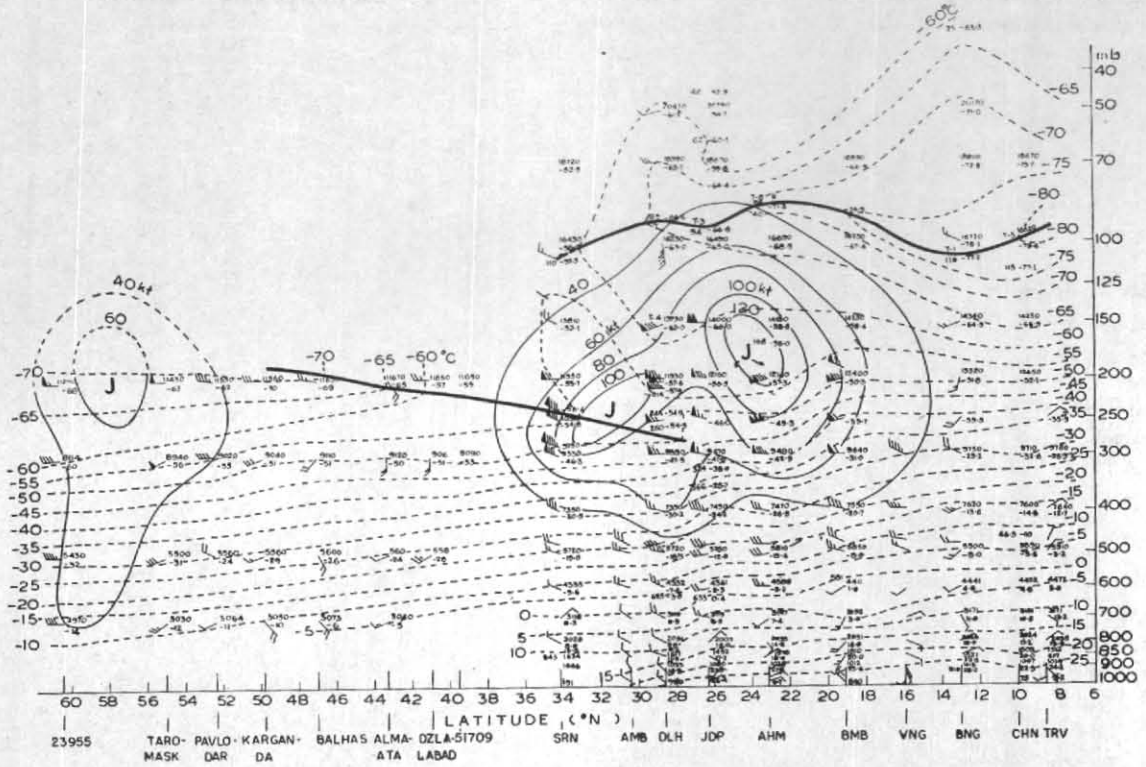

Fig. 12. Vertical cross-section, 12 Feb 1967 (1200 GMT)

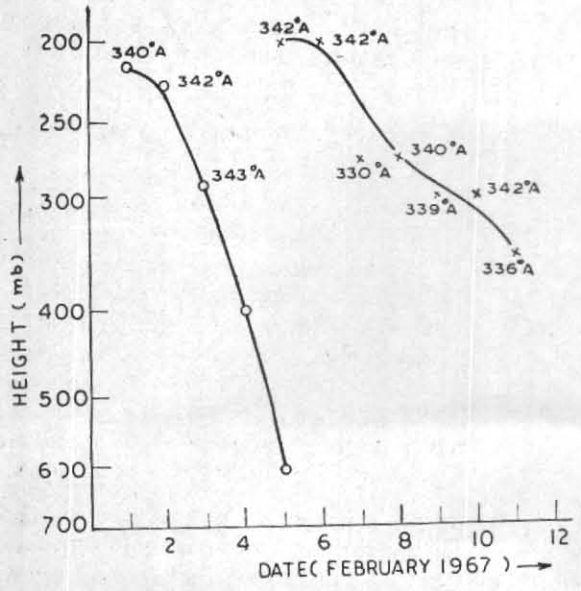

Fig. 13. Movement of PFJ into India. Position and potential temperature

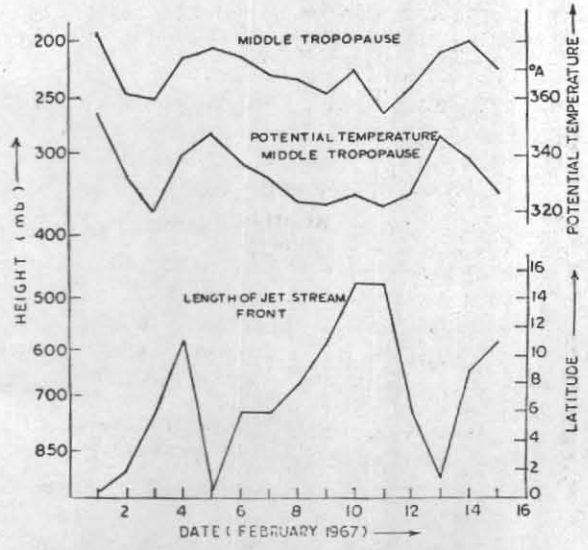

Fig. 14. Height and potential temperature of middle tropopause and length o jet front

descent of ozone rich stratospheric air at any station, it will be reflected in the increase in the total ozone amount at that station. Table 3 gives the daily observation of total ozone over Srinagar, Delhi and Ahmedabad during this period. It can be seen that there was a significant increase in the amount of ozone at Srinagar from 3rd to 12th with a possible break on the 9th, and at Delhi from 5th to 12th. Even Ahmedabad showed an increase on 6th and 7th and again after 10th. It is obvious, therefore, that there was a significant subsidence to the north of the STJ during the period of these migrations of the polar front jet. The increase in ozone at Ahmedabad on the 13th, 14th and 15th was associated with the approach of a deep trough in the upper tropospheric westerlies from the west on the 12th and subsequent days.

TABLE 3

Daily Ozone Data (Total amount)

Date (Feb 1967)	Srinagar		Delhi		Ahmedabad	
	GG	ΩΩΩ	GG	ΩΩΩ	GG	ΩΩΩ
1	07	277	07	256	11	233
2	07	273	07	257	11	233
3	07	274	07	252	11	232
4	05	283	07	250	04	228
5	07	295	05	250	—	—
6	06	316	07	254	11	230
7	07	330	07	268	11	236
8	—	—	09	274	04	232
9	08	301	06	276	11	229
10	10	316	07	276	11	231
11	07	323	07	280	04	234
12	08	331	07	289	—	—
13	05	317	07	280	11	244
14	—	—	06	274	11	240
15	09	311	08	259	11	243

3.7. *Weather*

Weather associated with the second migration was not severe though quite active. A western disturbance appeared over Afghanistan and extended upto Jammu & Kashmir on the 6th. It intensified as a distinct low pressure area on the 7th causing scattered rain/snow in the valley. On the 8th it was still active and associated upper air trough extended upto 10 km. It caused fairly widespread precipitation in Jammu & Kashmir. On the 9th it moved away eastwards.

4. Conclusion

The following conclusions can be drawn from this study regarding the characteristics of the PFJ north of the country along 75° E longitude, and its association with the upper air circulation over the country in winter :

1. There is a polar front jet north of the country between 40° and 50° N with a mean position of 43° N. It occurs in the mean at 11 km (240-mb level) with a wind maximum of about 100 kt. It is located above 500-mb level temperature of —29° C (±3° C) and 300-mb level temperature of —53° C (±5° C). It is located in the break between the middle and the polar tropopauses, as at other longitudes.

2. *Movement of the PFJ* — It is quite variable both in position and height. Sometimes it appears at a northerly latitude and gradually shifts southwards and stabilises between 42° and 44° N latitudes.

3. Occasionally PFJ crosses into the country and merges with the STJ which is normally located at about 31° N. When it does so it moves with a downward tendency and goes quite far to the south. It appears as an abnormal extension of the lower LMW of the STJ on the anticyclonic side.

4. PFJ migrates along an isentropic surface which is the same at which it was located before the start of migration (McIntyre and Lee 1953). The average isentrope along which it migrates is 340° A.

5. With its migration into the country the cold polar air is brought in which intensifies the temperature gradient and builds up the main STJ. The STJ intensifies and rises to a much higher level. And the combination of the two jet-cores gives it a very elongated structure, sometimes covering the whole troposphere. In fact, this elongation is due to the rise of the STJ and the sinking of PFJ at the same latitude.

6. When its migration southwards stops it normally sinks to a lower level and then disappears.

7. *Polar Front* — Associated with the migration of the PFJ, the polar front also appears over the country, particularly in the upper air. It can come down to 850 mb and is sometimes quite well-marked and sharp. Due to this, the weather also becomes active. In this study, the polar front extended up to Jodhpur on some days in the upper air. But the weather was limited to Jammu & Kashmir.

8. *Middle tropopause and jet stream front*— The lowering of the potential temperature of the middle tropopause and the

extension of the jet stream front take place in the wake of this migration and give a good indication of the unstable development at the core of the STJ.

9. *Subsidence and Ozone* — The subsidence at jet stream level is associated with the migration of the PFJ into the country. It is shown by the increase in total ozone amount at affected stations, *i.e.*, Srinagar Delhi and Ahmedabad.

10. *Confluence* — The confluence of the PFJ and the STJ with sinking air on the cyclonic side is what brings about the intensification of the STJ as envisaged by Mohri (1958).

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