

## Baroclinity over India in winter and its relation to western disturbances and jet streams - Part I

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**ABSTRACT.** The existence of baroclinic zones over India in winter has been investigated with the help of histograms of temperatures at selected stations. It has been found that there are two baroclinic zones in winter—one roughly along 25°N over western and central India and the other along 33°N over northwest India. Both are comparable in intensity and weaker than those observed over North America or Western Pacific. The airmasses responsible for their formation and their relation with the western disturbances have been discussed.

### 1. Introduction

The concept of baroclinic zones, the narrow regions where two different airmasses meet, is as old as the concept of airmasses itself. In these zones are found the greatest temperature gradients and hence the greater part of the potential energy of the atmosphere. As the extra-tropical cyclones draw most part of their kinetic energy from the potential energy of these baroclinic zones, the two are intimately connected. In fact migratory cyclones in the extra-tropical latitudes achieve great intensities only in close association with the baroclinic zones and not elsewhere (Palmen and Newton 1969). The concentration of thermal gradients in these zones also causes rapid increase in wind with height which result in jet streams in the upper troposphere. Thus jet streams too are closely associated with the baroclinic zones. Numerous attempts have, therefore, been made to study the characteristics of these zones in the atmosphere and relate them to frontal cyclones and jet streams.

McIntyre (1950) proposed an objective method of delineating the baroclinic fields in the atmosphere with the help of histograms of temperatures at selected stations and used it to locate the main baroclinic zones over North America. He prepared histograms of temperatures at 700, 500 and 300-mb levels to bring out the thermal characteristics of these zones. His main argument in using these histograms is that stations which are consistently under the influence of a single airmass will show a single frequency maximum for the temperature characteristic of that airmass. On the other hand, stations under the strong influence of a baroclinic zone will exhibit on the histograms two distinct

frequency maximum corresponding to the characteristic temperatures of the two airmasses involved, with a lower frequency in between. He preferred these characteristic temperature values obtained from histograms to delineate the airmasses in comparison to normals which by their averaging process give greater weightage to extreme values.

Berggren (1953) utilised this technique to confirm the existence of polar fronts upto stratosphere. Serebreny *et al.* (1957) studied the complex of jet streams over the western and central Pacific with the help of this method and found that in the Pacific the cores of jet streams occur mainly in the three temperature groupings at 500-mb level.

- (i)  $-27^{\circ}\text{C}$  to  $-37^{\circ}\text{C}$  in the northerly latitudes in the western Pacific.
- (ii)  $-16^{\circ}\text{C}$  to  $-27^{\circ}\text{C}$  in the mid-latitudes of the Pacific with a tendency for a subdivision into the ranges  $-16^{\circ}\text{C}$  to  $-23^{\circ}\text{C}$  and  $-24^{\circ}\text{C}$  to  $-27^{\circ}\text{C}$ .
- (iii)  $-9^{\circ}\text{C}$  to  $-16^{\circ}\text{C}$  in the latitudes close to  $30^{\circ}\text{N}$ .

These values correspond quite closely to those given by McIntyre and Lee (1954) for North America at 500 mb. They are (a)  $-28^{\circ}\text{C}$  to  $-36^{\circ}\text{C}$ ; (b)  $-20^{\circ}\text{C}$  to  $-28^{\circ}\text{C}$ ; (c)  $-6^{\circ}\text{C}$  to  $-15^{\circ}\text{C}$ . Attempt has been made in the following to utilise this technique to find if there is any baroclinic zone in India and if it is, whether it can be related to the western disturbances and the subtropical jet stream which affect the country in winter.

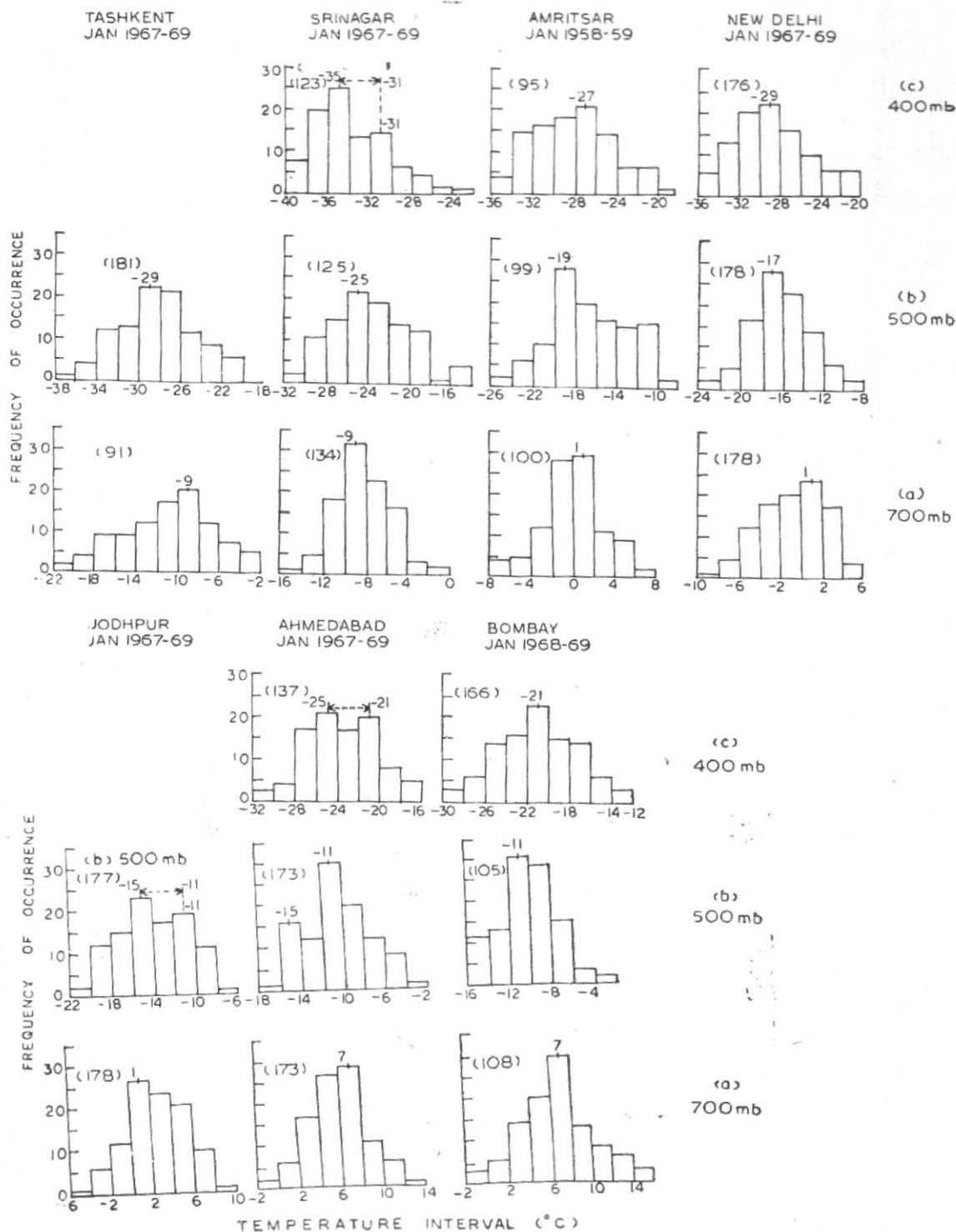


Fig. 1. Histograms of temperatures (percentage frequency of occurrences as ordinate and temp. interval in °C as abscissa) for January (a) 700 mb, (b) 500 mb and (c) 400 mb (Figures in brackets are numbers of observations used)

## 2. Data

As the existence of any baroclinic zone(s) in India, if at all, can be expected only in winter, the study was confined to the month of January. The first attempt was to see if there is any clue to the existence of baroclinic zone(s) along 75°E. For this purpose we used radiosonde data of January for the years 1967, 1968 and 1969 for Srinagar, Delhi, Jodhpur and Ahmedabad and of 1958 and 1959 for Amritsar (the only data available). It may be mentioned that all these stations were using only C-type radiosonde for their observations. Hence their temperatures are comparable. Later we extended our search to Bombay in the south and Tashkent in the north mostly for confirmation purposes. When we found the existence of baroclinic zones along 75°E, we extended the study eastward and used three years' data for Allahabad, Lucknow, Calcutta and Gauhati. Histograms were prepared at two-degree intervals for 700, 500, 400, 300 and 200-mb levels and also at additional levels wherever required.

No histograms were prepared below 700-mb level because ground effects and diurnal variations were to be avoided. As the baroclinic zones are seen prominently only in the middle troposphere, we will consider histograms upto 400 mb for their study. Above this level the effect of subtropical jet stream becomes prominent. Hence the histograms of 300 mb and above will be studied in connection with the subtropical jet stream in Part II of this paper.

## 3. Analysis of histograms

Before we take up the study of these histograms it will be appropriate to describe how a vertically sloping baroclinic zone will be indicated by them. As is well known, on a frontal surface, the warm air rises over the cold air. Hence the cold air will be seen more in lower levels and warm air in higher levels. The histograms representing the baroclinic zones, therefore, will show the increasing dominance of warm air over cold air with height.

Fig. 1(a) gives the histograms of 700 mb for Tashkent, Srinagar, Amritsar, New Delhi, Jodhpur, Ahmedabad and Bombay. Even a cursory glance at this figure will show how strikingly the difference in airmasses is brought out with the help of the characteristic temperature represented by the frequency maximum at each station. Here it shows that :

- (i) The dominant airmass at Bombay and Ahmedabad is the same and has a characteristic temperature of 7°C.

- (ii) A different airmass is prevailing at Jodhpur, Delhi and Amritsar with the characteristic temperature of 1°C.
- (iii) The airmass at Srinagar is different from both of these and extends north upto Tashkent. Its characteristic temperature is -9°C.

Thus there are three airmasses prevailing between Bombay and Tashkent which are quite different from each other though quite homogeneous in themselves. The narrow regions where these airmasses meet will, therefore, show the characteristics of baroclinic zones. It is apparent, therefore, that :

- (i) there is a baroclinic zone between Ahmedabad and Jodhpur at 700 mb and
- (ii) there is another baroclinic zone between Amritsar and Srinagar at this level.

Fig. 1(b) represents the histograms of these stations at 500-mb level. Here we can mark that :

- (1) Bombay and Ahmedabad are under a single dominant airmass with characteristic temperature of -11°C.
- (2) Delhi and Amritsar too show that they are under a single airmass whose characteristic temperature is about  $-17^{\circ}\text{C} \pm 2^{\circ}\text{C}$ .
- (3) Srinagar is again showing the airmass property different from the above two with a characteristic temperature of -25°C.
- (4) Jodhpur, on the other hand, shows the characteristic features of a baroclinic zone with two frequency maxima and the low frequencies in between. Its one frequency maximum is at -11°C which represents the warmer airmass to the south, and the other at -15°C which represents colder airmass to the north. Thus Jodhpur is in the baroclinic zone between these two airmasses.

It may be noted that the colder airmass from Jodhpur to Amritsar shows greater variation of temperature (*i.e.*, from -15°C to -19°C) than the warmer one to the south (-11°C). It is as observed elsewhere also (McIntyre 1950). In fact the warmer airmass originating in the tropics, when moves north over colder surface, gains stability and maintains its original property in the upper air. On the other hand, the colder airmass from the



north moving south over warmer surface gains instability and undergoes rapid changes in its thermodynamic properties. Thus it shows greater temperature variation and upto high levels (Palmen and Newton 1969).

As for the other baroclinic zone (between Srinagar and Amritsar), it is still prominent as the temperature contrast between these two stations (*i.e.*, from  $-19^{\circ}\text{C}$  to  $-25^{\circ}\text{C}$ ) show. But it is not visible over either of these stations. It lies in between the two. The colder airmass prevailing from Srinagar to Tashkent now shows greater temperature variation, *i.e.*, from  $-25^{\circ}\text{C}$  to  $-29^{\circ}\text{C}$ , as expected in this airmass.

Let us now consider Fig. 1(c) showing histograms at 400 mb for all these stations except Bombay and Tashkent. It can be seen that Jodhpur again shows the baroclinic zone between the warmer airmass to the south represented by the characteristic temperature of  $-21^{\circ}\text{C}$  and the colder one to the north with the characteristic temperature of  $-25^{\circ}\text{C}$ . The colder airmass represented by the temperatures at the frequency maxima at Delhi ( $-29^{\circ}\text{C}$ ), Amritsar ( $-27^{\circ}\text{C}$ ) and Jodhpur ( $-25^{\circ}\text{C}$ ) again shows variations. Here the value of Amritsar seems doubtful as the data are limited. Delhi's values were, therefore, checked for five years and were found to be the same, *i.e.*,  $-29^{\circ}\text{C}$ . Hence  $-29^{\circ}\text{C}$  represents the characteristic temperature of the colder airmass away from the baroclinic zone. In the baroclinic zone itself, *i.e.*, at Jodhpur, it shows  $-25^{\circ}\text{C}$  because of the warming due to subsidence in this cyclonically active region.

Summing up, it can be said that the baroclinic zone which was located between Ahmedabad and Jodhpur at 700 mb extended upward to 400 mb at Jodhpur. It showed northward tilt in the vertical as can be seen by the gain of warm air over cold air with height (Table 1).

Even at 300 mb (not shown) this gain of the warm airmass could be seen. Here warm airmass was 20 per cent as against cold airmass which was only 8 per cent. It can also be noted that this baroclinic zone is more prominent at 700 mb with a temperature difference of  $6^{\circ}\text{C}$  than at higher levels where the difference is only  $4^{\circ}\text{C}$ .

The other baroclinic zone, *i.e.*, between Amritsar and Srinagar, also extends upto 400 mb. In fact, here it actually appears over Srinagar where warm air is represented by the frequency maximum at  $-31^{\circ}\text{C}$ , and the cold air by that at  $-35^{\circ}\text{C}$ . This shows that there is a northward sloping baroclinic zone between Amritsar and Srinagar, also, extending up to 400 mb. The temperature contrasts

TABLE 1  
Station : Jodhpur

Level (mb)	Warm airmass		Cold airmass	
	Charac- teristic tempera- ture ( $^{\circ}\text{C}$ )	Percen- tage fre- quency	Charac- teristic tempera- ture ( $^{\circ}\text{C}$ )	Percen- tage fre- quency
700	7	10	1	27
500	-11	19	-15	23
400	-21	20	-25	21

TABLE 2  
Characteristics of baroclinic zone—Amritsar-Srinagar

Level (mb)	Warm airmass ( $^{\circ}\text{C}$ )	Cold airmass ( $^{\circ}\text{C}$ )	Difference ( $^{\circ}\text{C}$ )
700	1	-9	10
500	-19	-25	6
400	-31	-35	4

here are comparable, if not greater, than the one to the south (Table 2).

Seeing the characteristics of airmasses at 700 mb (Fig. 1 a) it can be said that in this baroclinic zone the temperature difference at 700 mb will actually be  $10^{\circ}\text{C}$  though it will be less than  $6^{\circ}\text{C}$  at 500 mb. Hence we can say that this baroclinic zone is stronger than the one to the south at 700 mb though comparable at 500 and 400-mb levels.

Let us now consider the extension of these zones eastward. Of course, the northern one cannot be studied. But for the southern one, we may consider Figs. 2(a), (b) and (c) representing histograms of Allahabad and Lucknow at 700, 500 and 400 mb levels respectively. Here we can see that at Allahabad a baroclinic zone appears at 700 mb and at Lucknow at 400 mb. At 500 mb, Allahabad is under the influence of the warmer airmass and Lucknow under the colder one. Hence at this level the baroclinic zone is between these two stations. Thus there is a baroclinic zone between Allahabad and Lucknow sloping northward with height, *i.e.*, from Allahabad at 700 mb to Lucknow at 400 mb. The characteristic temperatures (Table 3) too show that the airmasses are the same as at Jodhpur (Table 1). Hence it can be said that the baroclinic zone between Ahmedabad and Jodhpur at 700 mb extends to Allahabad at this level sloping northward with height, as expected. Here too it extends upto 400 mb. Further east, Gauhati and Calcutta, do not show any clear cut baroclinic

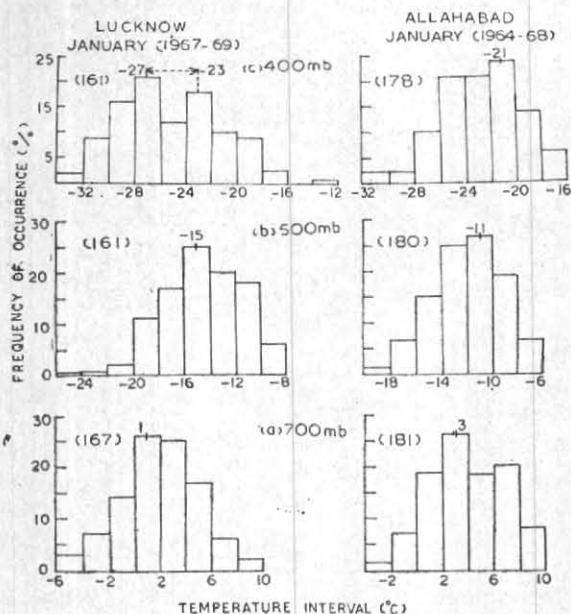


Fig. 2. Histograms of temperatures (a) 700 mb, (b) 500 mb, (c) 400 mb (Legend as in Fig. 1)

zone. Both stations show single frequency maximum at each level and the characteristic temperatures are shown in Table 4.

It appears, therefore, that over northeast India this baroclinic zone becomes diffuse. It has, however, been observed that there is significant rainfall in winter in the northeastern Himalayas. It is suspected, therefore, that there may be a baroclinic zone along the northeastern foothills also, say, between Gauhati and Lhasa, an extension of the one between Amritsar and Srinagar. But in the absence of data from Lhasa it is difficult to confirm it at present.

4. Discussion

Having established that there are two baroclinic zones over the country in January, one running roughly along 25°N over west and central India, and the other between Amritsar and Srinagar over northwest India, it will be interesting to find how they affect the weather over these regions and what are the airmasses involved.

(a) Weather and baroclinic zones

Fig. 3 gives the axes of maxima of low pressure centres in January on the surface chart over Eurasia. It has been adopted from the chart prepared by Rao and Srinivasan (1969). The northern axis is of the well known polar front which is normally along 45° N in winter (in this connection Riehl's

TABLE 3

Characteristic temperatures of baroclinic zone : Allahabad-Lucknow

Level (mb)	Warm airmass (°C)	Cold airmass (°C)
700	7	2±1
500	-11	-15
400	-22±1	-27

TABLE 4

Characteristic temperatures of Calcutta-Gauhati

Level (mb)	Calcutta (°C)	Gauhati (°C)
700	5	3
500	-11	-13
400	-23	-23

diagram reproduced by Palmen and Newton, 1969, in Chapter 3 can be seen). The southern one coincides with the mean track of western disturbances over India in January as shown in *Climatological Atlas For Airmen* (India met. Dep. 1943). Since the baroclinic zone along 25° N runs closely along this southern axis, it is obvious that this baroclinic zone provides a favourable field for formation, intensification and movement of western disturbances over western and central India. In fact, the existence of this baroclinic zone explains why the western disturbances form and move, as they do, over this part of the country during winter. That the baroclinic zone becomes diffuse over northeastern India, explains further why western disturbances become weak in this part. It may also be noted that this baroclinic zone is not very strong. Hence the systems associated with it are also not likely to gain much intensity, as is our experience. This zone is seen to be more marked at 700 mb than at higher or lower levels. It may rather explain why western disturbances too in general, are seen more prominently at 700-mb level in comparison to other levels above or below.

The baroclinic zone between Srinagar and Amritsar in the same way seems to be responsible for the formation and intensification of western disturbances in the extreme north of the country, known earlier as primary western disturbances (Rao and Srinivasan 1969). Though in this part of the country the tracing of western disturbances

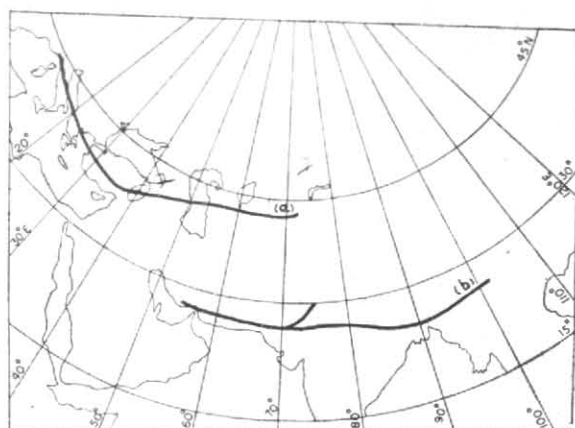


Fig. 3

- (a) Axis of low pressure centres in winter  
 (b) Axis of western disturbances in January

except the very strong ones, becomes difficult because of the hilly terrain, it is well-known that western disturbances affect much more frequently Jammu & Kashmir and the northern Himalayas than to the south. In fact, the tracks of western disturbances in India are only two—one moving through Jammu & Kashmir and the other through western and central India, most probably in close association with the two baroclinic zones.

(b) *Airmasses associated with these baroclinic zones*

As per the latest classification, there are mainly three airmasses corresponding to the three tropopauses and two global jet streams observed (Defant and Taba 1957). These airmasses are more homogeneous in the middle and upper troposphere than at the surface. They are :

(1) Polar Airmass (PA), (2) Middle Latitude Airmass (MLA) and (3) Tropical Airmass (TA).

The regions of their meeting are the polar frontal zone (between PA and MLA) and the northern boundary of the subtropical anticyclonic belt (between TA and MLA) as discussed by Palmen and Newton (1969). Now as the latter is at the periphery of the anticyclonic belt it cannot be seen in the lower levels except in the northwestern part of a cell of this belt. As is common knowledge, warm air from the south is injected northward through the western side of an anticyclonic cell and here it has a chance of meeting the cold air from the north and form a clear baroclinic zone. In the northeastern sector of the cell, however, this becomes weak or diffuse as subsidence prevails there. Hence the convergence between the TA and the MLA can form active baroclinic zones in lower levels only in the northwestern periphery of a subtropical anticyclonic cell. In higher levels, of course, it is seen as the subtropical front, generally above 400 mb.

As in winter, there is an anticyclonic cell (part of the subtropical belt) over central India along about  $20^{\circ}\text{N}$  (centred roughly at  $20^{\circ}\text{N}$ ,  $80^{\circ}\text{E}$  at 0.9 km) with its western periphery along the west coast it may be expected that a baroclinic zone will form along  $25^{\circ}\text{N}$  over western India and extend upto central India becoming diffuse over eastern parts. Hence the existence of a baroclinic zone between the TA and MLA from Jodhpur to Allahabad is as expected, its strength depending on the temperature contrast between the two airmasses involved. The meeting zone of the PA and the MLA, of course, is the polar frontal zone at about  $45^{\circ}\text{N}$  (Fig. 3). Thus over the country mainly two airmasses prevail in winter, *i.e.*, the TA and the MLA with the dividing line roughly along  $25^{\circ}\text{N}$ .

Question arises how two baroclinic zones appear over India when there are only two airmasses prevailing. It appears, the terrain over which the MLA moves (Fig. 3) from the Mediterranean to India is responsible for this. The chain of high hills, *i.e.*, Elburz and Hindukush divide this belt into two. The one to the south (say, MLA I) flows through the central Iran, south Afghanistan, Baluchistan and Sind to the western part of India meeting the TA at  $25^{\circ}\text{N}$  and generating a baroclinic zone as discussed above. The other (say, MLA II) flows through the central Russian plains north of these mountains. A part of this MLA II when blocked by the Pamirs, north of Kashmir, flows south, possibly through Kabul valley, and meets the MLA I which is definitely much warmer because of its long southerly sojourn over deserts. Thus the second baroclinic zone is created possibly south of Kashmir valley along the western and southern hills (roughly along  $33^{\circ}\text{N}$ ) between MLA I and MLA II. The stations Jodhpur, Delhi and



TABLE 5

Airmasses and their characteristics over India in winter

Levels (mb)	Tropical airmass (TA)	Middle latitude airmass (MLA)	
	South of 25°N	MLA I Between 25°N & 33°N	MLA II North of 33°N
700	7°C	1°C	9°C
500	-11°C	-17°C ± 2°C	-27°C ± 2°C
400	-21°C	-28°C ± 3°C	-35°C approx.

Amritsar are under MLA I and Srinagar and Tashkent, under MLA II, so clearly shown by the characteristic temperatures at 700 mb (Fig. 1 a).

It is interesting that the baroclinic zone between these two branches of the same airmass is stronger at 700 mb than that between the TA and the MLA I. This is as has been observed elsewhere also.

The characteristic temperatures of these airmasses over India in winter are given in Table 5 and those of the baroclinic zones in Table 6.

The corresponding values over North America and Western Pacific are as follows (see Introduction):

	500 mb	500 mb
North America	-9° to -16°C	-16° to -27°C
West Pacific	-6° to -15°C	-20° to -28°C

Comparing the temperature contrast in the baroclinic zones over North America and the Western Pacific with those over India, it can be seen that in general the contrast in airmasses is much smaller in the baroclinic zones over India than over North America or Western Pacific. In other words, baroclinic zones over India are in general weaker than over those regions.

5. Conclusion

With the help of histograms of temperatures at 700, 500 and 400-mb levels at selected stations in India and to its north for the month of January, it has been established that:

(1) There are two baroclinic zones over India in winter—one running roughly along 25°N over

TABLE 6

Location and characteristics of baroclinic zones over India

(Location with temperature contrasts)

Levels (mb)	Baroclinic zone I (Along 25°N over west and central India)	Baroclinic zone II (Along 33°N over northwest India)
700	7°C to 1°C	1°C to -9°C
500	-11°C to -15°C	-19°C to -25°C approx.
400	-21°C to -25°C	-31°C to -35°C

western and central India and the other approximately along 33°N over northwest India. Both are more or less of the same strength along 75°E and much weaker in comparison to the baroclinic zones observed over North America or Western Pacific. The characteristics of these zones are given in Table 6.

(2) The baroclinic zone along 25°N represents the meeting zone between the Tropical Airmass (TA) and the Middle Latitude Airmass (MLA). The baroclinic zone along 33°N forms between the two branches of the MLA whose trajectories are quite different because of the terrain over which they move.

(3) The southern branch of the MLA (MLA I) is represented by the temperatures of Jodhpur, Delhi and Amritsar, and the northern branch (MLA II) by those of Srinagar and Tashkent. Their characteristic temperatures are given in Table 5.

(4) These airmasses show remarkably uniform characteristic temperatures at 700-mb level. Higher up they show less homogeneity, particularly the MLA. In fact, 700 mb is a very good level for the delineation of airmasses.

(5) These baroclinic zones coincide with the axes of maxima of western disturbances over India in winter indicating their close association with the formation, intensification and movement of extra-tropical systems, as has been emphasised by almost all the workers in this field.

(6) In fact, the establishment of these baroclinic zones provides a dynamic explanation as to why the formation and intensification of western disturbances is more over Jammu & Kashmir and western Rajasthan than over other parts of north India. That these baroclinic zones are quite weak

explains why the intensification of western disturbances too over India is very minor in general.

(7) Finally it may be stated that this technique of determining the baroclinic zones is quite appropriate.

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