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An analysis of the high tropospheric wind circulation over India in winter

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ABSTRACT. The distribution of winds and temperature at various heights along roughly longitude 80°E has been discussed for two days of approximately westerly flow in winter. The existence of "jet streams" over Northern India in the high troposphere is observed and the thermal and wind structures associated with the streams are discussed. It is observed that on 30 January 1951, the jet stream occurred in association with a break in the tropopause as in middle latitudes while on 2 February 1951, it was found entirely in the tropical troposphere. The former is classified as the polar front type and the latter as the sub-tropical type as postulated by Palmen.

1. Introduction

One of the outstanding features of the general circulation of the atmosphere is the existence of the "jet stream", a narrow band of strong westerlies embedded in relatively stagnant air to the north and south of it, which meanders round the globe in the middle latitudes (University of Chicago 1947). Its properties and characteristics have been extensively studied mainly over the North American and European areas by various workers. For the Asian region, in recent years, Chaudhury (1950) and Yeh (1950) have studied conditions along the 75°E, 115°E and 135°E longitudes respectively, the former with the aid of radiosonde data of the winter of 1946 and the latter with radar winds during the autumn and winter of 1945-46. Chaudhury claimed the existence of three jets, one over Siberia and two over India, one along the Himalayas along 31°N and the other approximately over 15°N. Yeh found evidence for the first two jets over the Chinese area but not for the equatorial maximum. The position of the more southern jet was approximately 27° to 30°N over China. Namias and Clapp (1949) found from a study of the hemispherical constant pressure charts for the 300 mb level, that the jet stream extends from the North African continent over the Indian area roughly along latitude 25°N.

From a study of pilot balloon winds for various levels Indian workers had found evidence for wind maxima in winter roughly along 25°N for quite a long time. Ramanathan and Ramakrishnan (1933) pointed out that the westerly winds of winter in sub-tropical latitudes have their maximum strength at heights about 10-12 km and that as an interesting consequence, there is a rapid variation of the tropopause which will often have a folded structure. In an analysis of normal upper winds in 1937 the same authors (1939) found that the zone of maximum wind strength from pibal winds remains at 25° to 27°N at the 8 km level which they attributed to the distribution of temperature and not due to the obstructive effect of the Himalayas. Venkiteshwaran (1950) examined winds at 10 km and above over India, from available high pilot balloon flights and pointed out that between 10 and 20 km during winter, the maximum wind strength of 40 to 50 mps is reached in the neighbourhood of latitude 25° N. His data obviously could not have included occasions of high winds when high pilot balloon flights were not possible and hence would be useful for determining the latitude of the wind maximum though not the strength of the maximum. From an analysis of normal pressures of Poona and Agra from sounding balloon data, Koteswaram (1951) pointed out that the maximum wind speed in winter between 20° and 30°N occurs between 10 and 15 km.

With a view to study the structure of the zonal westerlies over India in winter in greater detail, a study of constant pressure charts for various standard isobaric levels on a number of days, as well as for mean conditions during winter months, has been undertaken. An analysis of meridional cross-sections for two typical days will be presented in the following paragraphs.

2. Analysis of data

There are at present 11 radiosonde stations functioning in India taking one ascent a day at about 1500 GMT of which New Delhi at Lat. 28° 35′ N is the northernmost. As such, the only cross-section that can be constructed with the maximum north to south extent can be roughly about the longitude of New Delhi.

Depending upon the availability of radiosonde data up to high levels, days were chosen for analysis during the months January and February 1951 when zonal winds were known to be high. In order to avoid corrections due to curvature of the trajectories, days of straight flow as far as practicable were selected but the analysis of the wind by this method could not be extended south of 17°N generally, due to the existence of the sub-tropical anticyclonic cells.

Constant pressure charts were drawn for the 850, 700, 500, 400, 300, 200, 150 and 100 mb levels wherever possible and the patterns of contours and isotherms determined. A smoothed out latitude-height curve was drawn representing the average condition between roughly 70° and 85°E for each standard isobaric surface and a smoothed height profile thus constructed corresponding to approximately 80°E meridian. From these profiles the slopes of the isobaric surfaces were determined at every $2\frac{1}{2}$° interval of latitude between 15° to 30° N and the corresponding geostrophic west wind speeds calculated from the usual formula :

$$u_g = \frac{-g}{2\,\omega \sin\phi} \cdot \frac{dz}{dy}$$

where u_g is the geostrophic west wind and dz/dy is the northward slope of the pressure surface ; the other symbols have the usual significance. The wind speeds thus obtained were used in the final meridional cross-section.

3. Temperature distribution

The average vertical distribution of temperature was determined in the usual way from the average temperature values at intervals of $2\frac{1}{2}$° latitudes for the various standard pressure surfaces. Individual tephigrams were examined for the existence of tropopause or significant discontinuities in lapse rate and these were entered at the appropriate latitudes in the cross-section.

On 30 January 1951 the tropopause over New Delhi was at 192 mb with a temperature of 214°A and potential temperature of 342°A. The ascent extended up to 60 mb and the layer between 192 and 60 mb was isothermal. This was presumably the polar tropopause. Koteswaram (1952) has recently pointed out that generally a deep isothermal layer above the tropopause is characteristic of the polar stratosphere while a deep inversion above the tropopause is typical of the tropical stratosphere. At Jodhpur about $2\frac{1}{2}$ degrees to the south, no such tropopause could be observed but there was a significant discontinuity in the lapse rate at 215 mb from 7°·5C km^{-1} to 3°C km^{-1}. Thus it was clear that the polar tropopause, as such, did not extend southwards much beyond Delhi. At Nagpur further south (21°N), the lapse rate discontinuity occurred at 150 mb and the lapse rate above this leve lwas less than 2°C km^{-1} to the limit of the ascent ; *i.e.*, nearly 110 mb. This may be taken to be an extra-tropical tropopause as suggested by Palmen and Nagler (1948). The temperature at this tropopause was 209°A and the potential temperature 360°A. The tropical tropopause was not reached in any of the ascents and was assumed to be at its normal position of nearly 80 mb over latitudes to the south of Delhi. Fig. 1 gives the temperature distribution at Delhi, Jodhpur, Nagpur on a T - log P diagram.

The situation on 2 February 1951 was different from the above. The jet stream was located to the south of its position on 30 January 1951, roughly about $22\frac{1}{2}$ ° N. There was no well marked tropopause discernible in any of the ascents, but significant lapse

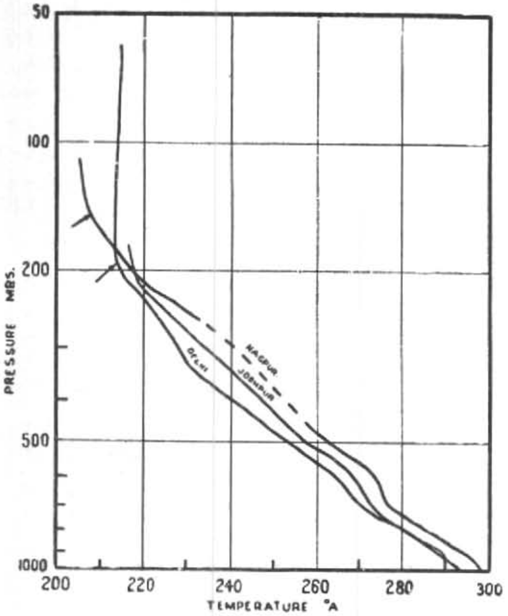

Fig. 1. T—log P diagrams for Delhi, Jodhpur and Nagpur for 30 January 1951, 1500 GMT. Tropopause indicated by arrows

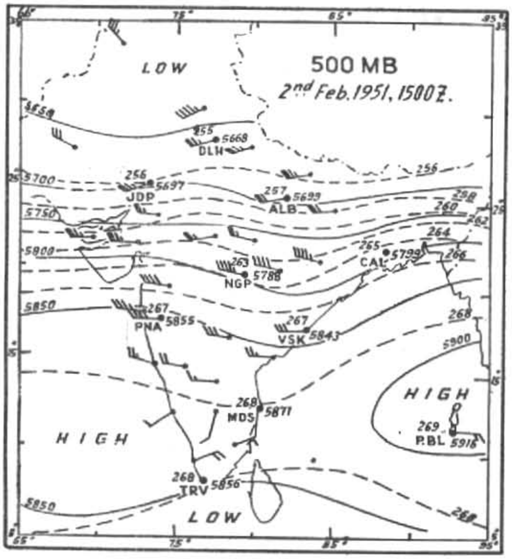

Fig. 2. 500 mb contour chart
Full lines—Contours in geopotential metres
Dashed lines—Isotherms (°A)

rate discontinuities were seen at Delhi nearly at 320 mb from 8°C km^{-1} to nearly 3°C km^{-1} the ascent extending up to 185 mb and over Jodhpur at 275 mb from 8°C km^{-1} to 3°·7C km^{-1}. No such significant changes in lapse rate occurred at Nagpur in a sounding extending to 110 mb.

4. Distribution of winds and horizontal temperature gradients at different heights

Figs. 2 to 4 give the constant pressure charts for 2 February 1951 for the 500, 300 and 200 mb surfaces. The contours have been drawn at intervals of 50 geopotential metres and the isotherms for every 2°C. The concentration of the contour lines and the isotherms can be seen between the latitudes 20° and 25°N on the 500 mb chart. A similar concentration of contours is clear on the 300 and 200 mb charts indicating the location of the jet stream at those levels. A south to north gradient of temperature is seen up to 300 mb but at 200 mb there is a marked change. A band of low temperature of 218°A is seen extending from Jodhpur to Visakhapatnam, temperatures increasing both to the south and north. This is in accordance with the observations by Palmen and Nagler (1948) of a band of low temperature just to the south of the zone of maximum wind at the 200 mb level.

Similar effects have been observed in the charts on 30 January 1951 when the jet stream was well formed only at 300 mb and above. The latitudinal decrease of temperature and its concentration in the jet stream zone are observed up to 200 mb. The reversal of temperature gradient in the jet stream zone occurs at 150 mb the band of lowest temperatures of 208° to 210°A occurring between 20° and 25°N and temperatures increasing to the north. At 110 mb the temperature was 214°A at Delhi and 205°A at Nagpur.

5. Meridional cross-sections

Figs. 5 and 6 give the meridional cross-sections along roughly Long. 80°E for 30 January 1951 and 2 February 1951. The usual characteristics associated with jet streams may be seen in the two cross-sections, *viz.*, the concentration of wind velocities in a narrow jet in the high troposphere with velocities of 80 to 110 mps and the steep downward slope of isentropes below the zone of strongest wind and the upward slope above it.

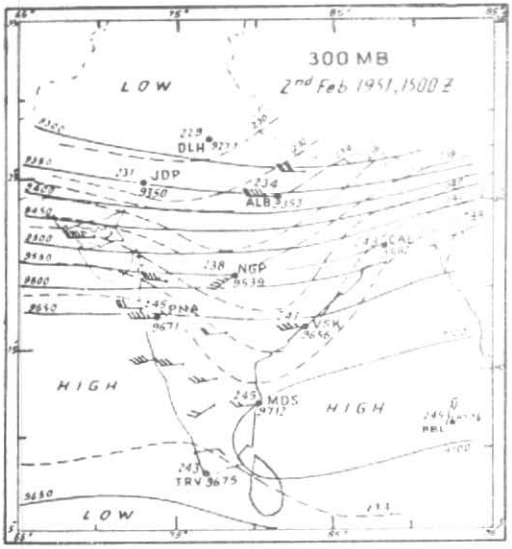

Fig. 3. 300 mb contour chart

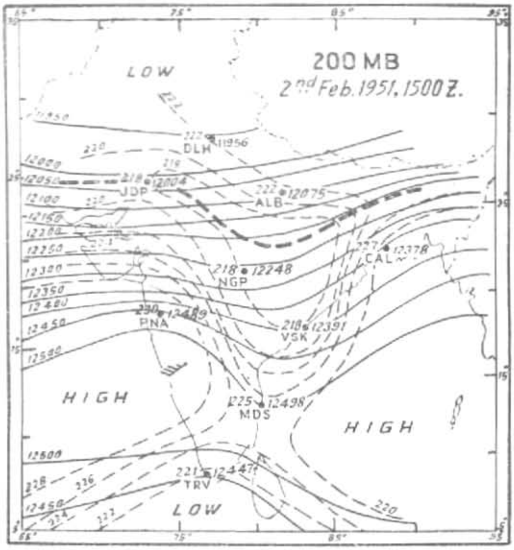

Fig. 4. 200 mb contour chart

Full lines—Contours in geopotential metres

Dashed lines—Isotherms (°A)

Thick dashed line—The zone of lowest temperature

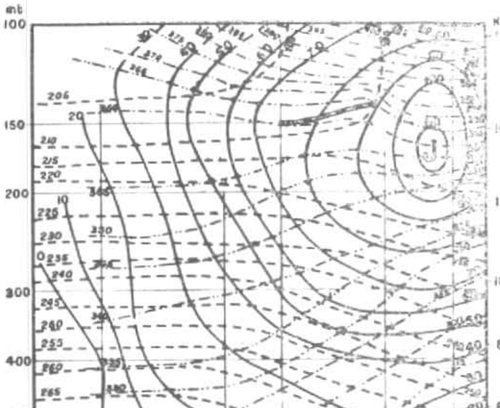

Fig. 5. Mean cross-section at 1500 GMT on 30 January 1951

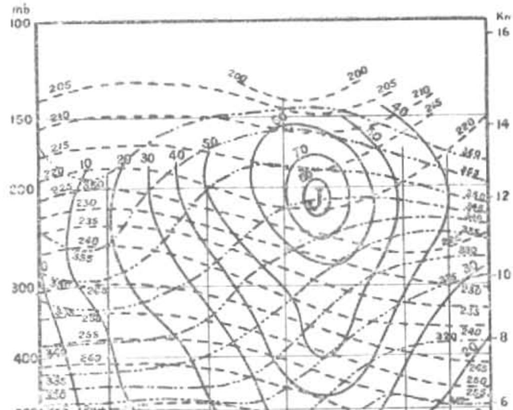

Fig. 6. Mean ~~slight~~ cross-section at 1500 GMT on 2 February 1951

Vertical lines—Heights up to which ascents have reached

Thick continuous lines—West components of wind velocity in mps

Dashed lines—Temperature (°A)

Dash and dot lines—Potential temperature (°A)

Thick dashed lines—Tropopause

While the jet stream of 30 January 1951 is located near $27\frac{1}{2}$°N and at a height of between 200 and 150 mb, the jet on 2 February 1951 is found at a lower latitude, nearly 22°N, and is located between 250 and 200 mb level. In the former case the jet was found between the polar and the tropical tropopause as in middle latitudes and the extra-tropical tropopause also is perceptible. But on 2 February 1951 no distinct tropopause can be seen except the largely reduced lapse rate to the north of the jet stream maximum.

The latitudinal profiles of the geostrophic winds and temperatures for both the days at different levels are illustrated graphically in Fig. 7. The coincidence of the jet stream with strong temperature gradient below the level of the highest jet and the reversal of temperature gradient above it can be seen in the diagrams. Thus, as pointed out by Palmen and Nagler (1948), there seems to exist rings of cold and warm air closely connected by the zones of strongest west wind and migrating with the belts of strong westerlies.

6. Thermal structure near the Jet Stream level

From the simplified zonal thermal wind equation

$$\frac{u_H - u_\circ}{H} = \frac{g\,\bar{\gamma}}{f\,\bar{T}}$$

where, u_H = zonal wind at height H,

$u_\circ$ = zonal wind at sea level,

$\bar{\gamma}$ = mean tropospheric temperature gradient northwards at the latitude below the level of H,

$\bar{T}$ = mean tropospheric temperature at the latitude below the level of H,

and f = coriolis parameter.

The Chicago University group (1947) had shown that when H is the height of the tropopause, a large increase in u_H should lead to a very sharp increase in H or $\bar{\gamma}$ or both ; *i.e.*, there must be an abrupt increase in the height of the tropopause at the jet and a

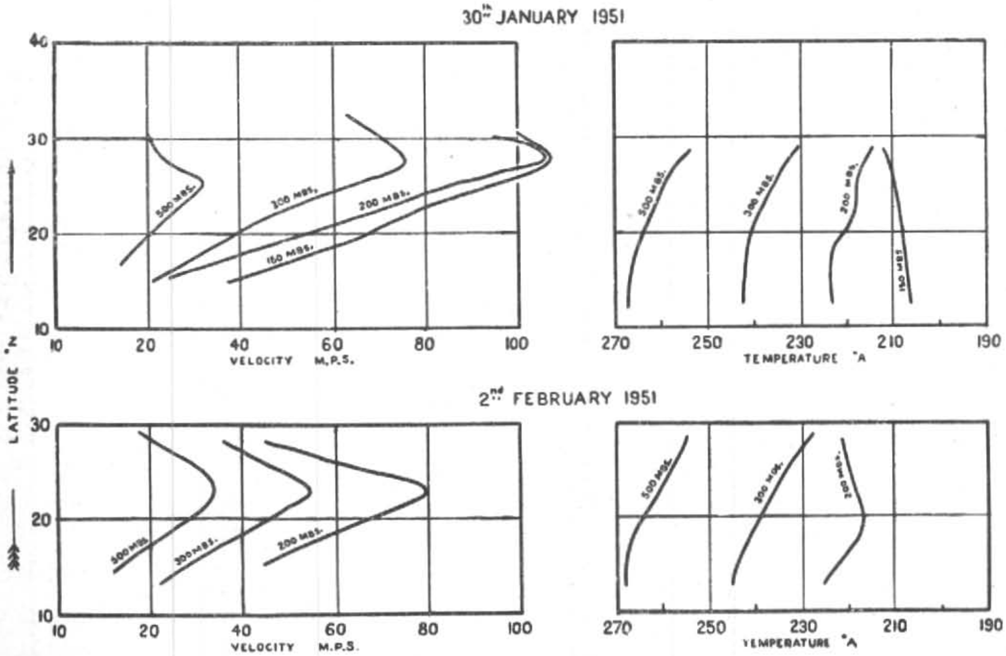

Fig. 7. Velocity and Temperature profiles at different isobaric surfaces

marked increase in the horizontal gradient below the jet—which is in agreement with the observations.

From the above equation it may also be seen that u_H goes on increasing with H as long as $\bar{\gamma}$ remains positive, *i.e.*, as long as the mean northward decrease of temperature below the level H is maintained.

If u_J is the zonal velocity of the jet stream at a height J, the zonal wind u_h at a height h above J will be given by

$$u_h = u_J + h\frac{g\bar{\gamma}}{f\bar{T}}$$

where, $\bar{\gamma}$ and $\bar{T}$ correspond to the layer between J and h. The velocity decreases above the jet stream level, *i.e.*, $u_h < u_J$ if the sign of $\bar{\gamma}$ is reversed above J, *i.e.*, if $\bar{\gamma}$ becomes negative. Thus there should be a reversal of temperature gradient above the level of the maximum wind in the jet stream. This feature has also been pointed out by Magata (1950). It thus appears that a reversal of latitudinal temperature gradient above the level of the wind maximum is a necessary concomitant of the jet stream. Where there is a tropopause break, this reversal is caused by the difference in the temperatures of the polar stratosphere and the equatorial troposphere at the same level. But even if there is no break in the tropopause and a reversal of tropospheric temperatures occurs, concentration of wind will take place into a jet in the troposphere itself, as happened at 22½°N on 2 February 1951.

It may be pointed out that this reversal of temperature gradient in the high troposphere over North India seems to be a normal feature as may be seen from the sounding balloon normal temperatures (Ind. met. Dep. 1939) for Poona (Lat. 18° 32′N Long. 73° 51′ E) and Agra (Lat. 27°10′N Long. 78° 02′E) and radiosonde normals for the period (1944-1951) worked out by the India Meteorological Department (unpublished). Comparative figures are given in Tables 1 and 2.

In both the sets of normals the reversal of temperature gradient is clearly perceptible at 200 mb or above in the troposphere itself. Hence the maximum normal zonal wind also should occur over North India between the latitudes of Nagpur and Delhi in the high troposphere normally at about 12 km or so, which is in accordance with previous evidences cited in Section 1 above.

TABLE 1

Sounding balloon normal temperatures over Poona and Agra for January

Height	Poona		Agra	
gkm	*n*	*T*	*n*	*T*
10	32	234·0	40	228·5
12	31	217·5	41	217·0
14	29	203·0	36	209·5
16	28	195·5	34	202·5
18	21	198·0	30	203·0

TABLE 2

Radiosonde normal temperatures for stations in North India for January

Height	Poona		Nagpur		Allahabad		Delhi	
mb	*n*	*T*	*n*	*T*	*n*	*T*	*n*	*T*
300	180	238·8	94	237·3	145	233·7	176	233·6
200	99	217·4	33	219·7	77	218.2	108	219·6
150	59	203·5	9	208·7	25	210.3	46	211·3
100	14	188·5*			4	203.6	18	207·1

n = number of observations T = Temperature in degrees Absolute

* Appears too low ; the corresponding values for February and December are $n=7$, $T=198·5$ and $n=10$, $T=195·6$

7. The Sub-tropical and the Polar Front Jet Streams

Palmen (1951) has recently postulated the existence of two types of jet streams—one of the sub-tropical and the other of the polar front type—to explain the observations of double jet streams made by a number of workers. He argues that since the latitude of the maximum poleward flux of angular momentum coincides with the latitude of the sub-tropical high pressure belt, this must be the same as the latitude of the maximum zonal wind from the equation

$$\left[M_{\phi} \right]_{p_o}^{o} = \frac{2\pi a^2 \cos^2\phi}{g} \left\{ \int_o^{p_o} \bar{u}\,\bar{v}\; dp + \int_o^{p_o} \bar{u'}\,\bar{v'}\, dp \right\}$$

where, $\bar{u}$ and $\bar{v}$ are the mean zonal and meridional wind components at the pressure surface p at latitude ϕ, $\bar{u'}$, $\bar{v'}$ are the local deviations from the mean values at the latitude circle, a is the radius of the earth and $\left[M_{\phi} \right]_{p_o}^{\circ}$ is the net meridional transfer of angular momentum per unit time through a vertical plane extending from the earth's surface pressure= p_o to the top of the atmosphere. Hence he concludes that if the momentum flux is primarily determined by the drift term (the first term in the above equation), the strongest wind in the upper troposphere must be observed almost vertically above the sub-tropical high pressure belt, *i.e.*, about latitude 30°. He has also described schematically the southward movement of the polar front jet into the tropics till it gets combined with the sub-tropical jet and a new polar front jet is formed.

Of the jet streams on 30 January 1951 and 2 February 1951, the former was associated with a western disturbance with a surface low which became active and gave precipitation during the next two days, while the latter was associated with the normal surface high over West Pakistan and North India. With the synoptic situation on 30 January 1951 the comparatively low tropopause at 192 mb and the deep isothermal layer in the lower stratosphere over New Delhi and the break in the tropopause as shown in Fig. 5, the jet stream on that day has been classified as of the polar front type of Palmen. On 2 February 1951 however, the surface high was well established and its axis at 80°E was nearly 25°N at 2000 ft level. The jet stream on this day has been classified as the sub-tropical type and its location at 22½°N agrees with Palmen's postulate that it should be vertically above the sub-tropical ridge line at the surface.

It may be pointed out in this connection that the individual jet streams studied were found over North India to the north of 20°N and no such jet streams were found over the peninsula near about 15°N, where Chaudhury (1950) found an "Equatorial Jet" from the mean values for 1946. The region to the south of 15°N is generally that of the sub-tropical high at high levels extending to 200 and 100 mb as pointed out by Yeh (1950) in his analysis of Chinese data. The problem of mean jet streams over the Indian sub-continent will be discussed in a subsequent paper.

8. Rainfall associated with the Jet Streams

The University of Chicago workers (1947) had postulated a meridional circulation pattern in the jet stream region with sinking southward motion in the upper troposphere to the south of the west wind belt and ascending northward motion below the west wind belt in the region of maximum concentration of isentropic surfaces. Starret (1949) examined a number of cases of jet streams in the United States and found that allowing for latitudinal variation in the availability of moisture, precipitation tends to be a maximum underneath the jet. Yeh (1950) examined the mean precipitation pattern over China and found that it practically coincides with the centre of the upper jets, decreasing rapidly to the north and south but more rapidly to the south. Chaudhury (1950) found a similar association between the winter rainfall in India and the "Himalayan" jet near 31°N. Fig. 8 gives the rainfall recorded between 1200 GMT of 30 January 1951 and 1200 GMT of 31st and the approximate position of the jet over North India on 30th evening. The rainfall is confined to the jet stream zone and to the north of it. It should be mentioned that

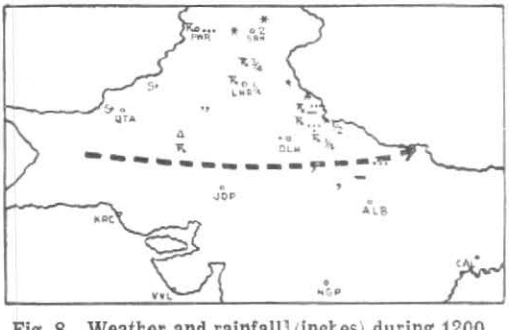

Fig. 8. Weather and rainfall (inches) during 1200 GMT of 30 January to 1200 GMT of 31 January 1951. Jet stream position on 30 January 1951 (1500 GMT) indicated by broken line

the intensity and distribution of rainfall must be largely conditioned by the nature of the disturbance affecting the area under consideration and the mountainous terrain of the Himalayan ranges but what is noteworthy is that the distribution of vertical motion with reference to the polar front jet stream is in accord with the meridional circulation pattern postulated by the Chicago group (1947). On 2 February 1951, however, no rainfall occurred near the jet presumably because the jet was of the sub-tropical type and due to the non-availability of moisture.

9. Geostrophic and actual winds

The maximum wind velocity computed for the centre of the jet stream is about 110 mps on 30 January 1951 and 80 mps on 2 February 1951. In the case of steady state zonal motion, the gradient wind u is related to the geostrophic wind u_g by the equation (Palmen 1948)

$$u = u_g - \frac{u^2}{fR} \tan \phi$$

where, R is the radius of the earth, ϕ the latitude and f the coriolis parameter. Thus the actual wind corresponding to a geostrophic wind of 100 mps works out to be nearly 88 mps between latitudes 20° to 30°N. It may also be pointed out that the cyclostrophic term gives large corrections at low latitudes at high speeds. For cyclonic curvature of even 4000 km radius, the curvature correction for a geostrophic wind of 100 mps is 37 per cent at 20°N and —27 per cent at 30°N as can be worked out from tables given by Pramanik (1948). Hence though we have assumed more or less a straight flow and have averaged the heights of pressure surfaces with available heights at the same latitude, the two factors mentioned above may constitute an error of 20 to 30 per cent at high velocities.

A comparison of the computed winds at 500 mb level made with the average pibal winds at 0900 GMT at different latitudes for both the days gave an agreement which can be said to be satisfactory for low velocities At high velocities, the pilot balloon wind at Gwalior at 0900 GMT on 30 January 1951 at 9 km was 110 knots while the computed geostrophic wind at the same latitude from radiosonde ascents at 1500 GMT at 300 mb (9·4 km) was nearly 70 mps (136 knots). On 2 February 1951, the maximum computed geostrophic wind was 80 mps (156 knots) at 200 mb level while a Rawin observation at Bahrein (Lat. 26° 14′ N Long. 50° 35′ E) at the same level was reported as 125 knots.

10. Jet Streams and the pibal charts

The concentration of winds along the latitudes of the jet streams can be usually seen on the pibal charts at 20, 25 and 30 thousand feet on clear days. The pibal observations in India are taken at 0300, 0900 and 2100 GMT. As such, the afternoon 0900 GMT pilot balloon winds which are followed to great heights cannot always represent the conditions when the radiosonde ascent is made some six hours later. On 30 January 1951 on the 0900 GMT pibal chart, the belt of strongest winds extended from 22° to 29°N at 20,000 ft roughly at longitude 80°E. At higher levels, however, the winds are scanty to make any conclusion. This coincides fairly well with the conditions in the meridional cross-section.

On 2 February 1951 at 0900 GMT, the belt of strongest winds is between 21° and 29°N at 20,000 and 25,000 ft while the meridional cross-section at 1500 GMT shows the maximum at 22½°N. At 0300 GMT of 3 February 1951 the zonal wind maximum had shifted to the belt between 20° and 25°N at 20,000 ft and at 0900 GMT on the same day it existed as a sharp maximum near about 23°N at 20,000 and 25,000 feet. The pibal wind at Bhopal (23½°N) was 55 knots while that at Poona (18½°N) was 35 knots and at Delhi (28½°N) it was 25 knots at 20,000 ft. Apparently the jet attained the position indicated in the meridional cross-section at about 1500 GMT and the 0900 GMT winds were not apparently representative of the condition at 1500 GMT. The rapid variation in the centres of jet streams has been pointed out by Berggren, Bolin and Rossby (1949), who found vertical shifts in isobaric surfaces at Larkhill of the order of 60 metres in 6 hours and in the centre of the jet stream of the order of 1 km in 6 hours. Though it is not possible to specify the magnitude of short period shifts in the heights of the isobaric surfaces from radiosonde ascents taken at 24 hour intervals in India, it may be pointed out that the 24 hour shift of the 200 mb surface over Delhi from 1500 GMT of 2nd to 1500 GMT of 3rd was 164 metres.

11. Wind shear and vorticity

Palmen and Newton (1948) found extremely strong horizontal shears on either side of the jet stream axis, the maximum cyclonic and anticyclonic shears occurring about 200 km to the north and south of the jet and also the existence of absolute vorticity exceeding that of the polar regions ($14 \cdot 6 \times 10^{-5}$ sec $^{-1}$) to the north of the jet and of vorticity very near zero to the south of the jet. Similar results have been obtained by other workers on the subject. Fig 9 gives the distribution of absolute vorticity on either side of the wind maxima at different

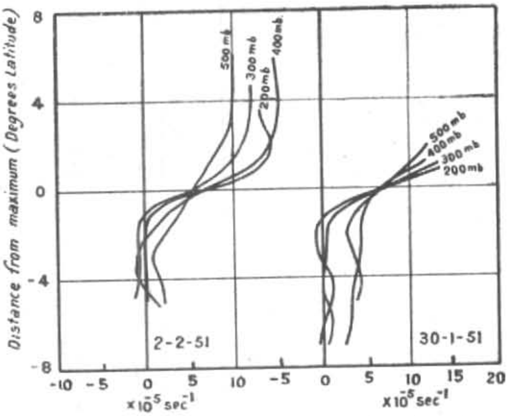

Fig. 9. Absolute Vorticity on either side of the Jet Stream

pressure surfaces on 30 January 1951 and 2 February 1951. The absolute vorticity has been calculated from the equation

$$\zeta_a = \frac{\partial u}{\partial y} + f$$

where $\partial u / \partial y$ is zonal wind shear, positive for cyclonic shear neglecting the curvature of the trajectories. The occurrence of near zero absolute vorticities to the south of the jet stream axis is evident in both the cases as pointed out by a number of workers.

13. Acknowledgement

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