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The mean Jet Stream over India and Burma in winter

P. KOTESWARAM, C.R.V. RAMAN and S. PARTHASARATHY

India Meteorological Department

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ABSTRACT. The mean jet stream over the Indian sub-continent and Burma has been computed from all available radiosonde data and is found to exist at about 27°N at an altitude of 12 km. No secondary 'equatorial jet' as postulated by Chaudhury (1950) is found.

A study of the mean distribution of thermal gradients and lapse rates in the troposphere has been made both for the Indian cross section and the Hess'cross section for North America. The thermodynamic properties of the jet stream typified by the two cross sections have been compared. It is found that the gradient of the lapse rate concentrates into a maximum in the vicinity of the jet stream. The occurrence of the two types of jet streams is discussed from thermodynamic considerations.

1. Introduction

In a recent paper, Koteswaram (1953) discussed the high tropospheric circulation over India in winter on two individual situations and found jet streams at 22½°N and 27½°N. He did not find any jet over the peninsula near 15°N. While the one at a northern latitude (27½°N) was associated with a break in the tropopause with a distinctly polar tropopause over Delhi, there was no tropopause in evidence in the second case (22½°N) and the jet was entirely in the troposphere and not associated with any weather. Following a recent schematic presentation by Palmen (1951), Koteswaram designated the two jets as of the polar front and the sub-tropical types. Since there is a reversal of mean temperature gradient in the high troposphere over India in winter, he also pointed out that a jet stream should exist over northern India as a normal feature in this season.

With a view to locate and study the properties of this mean jet stream, a mean cross section has been constructed for the winter season (December-February), from the normal radiosonde and sounding balloon data available from stations in India, Pakistan and Burma. The analysis extends over the area 5° to 35°N and 60° to 100°E and upto a level of 80 mb.

2. Data used in the analysis

Radiosonde mean temperatures were used upto 100 mb. Daily radiosonde data are available for Indian stations from 1944 onwards, for Pakistan stations for 1944-47 and for Burma stations for 1945-46. Table 1 gives the list of the stations and the period covered by the data.

For levels 100 mb and above, the sounding balloon mean temperatures were used. These are available for the stations given in Table 2 for the periods indicated. They are from occasional ascents during the winter months during this period.

A comparison of the mean temperatures from sounding balloons and radiosonde did not exhibit any appreciable differences upto 150 mb at the following stations—

(1) Agra (S.B.) and New Delhi (R.S.)

(2) Peshawar

(3) Poona

At Calcutta where the two sets differed by 3°C, weighted means were worked out and used in the analysis.

3. Analysis of data

Mean temperatures at the standard isobaric surfaces 700, 500, 300, 200, 150 and 100 mb have been worked out by the India Meteorological Department for all the stations (unpublished). In addition, monthly means of heights of standard isobaric surfaces are available from 1947 onwards. Since the 500-mb height is reached on almost all days, the mean height of the 500-mb surface was determined for each station from all available data. At higher levels the number of

TABLE 1

Radiosonde data

INDIA	
1. Allahabad	1945-51
2. Bangalore	1945-46
3. Calcutta	1945-51
4. Chabua (Dibrugarh)	1945-46
5. Cuttack	1946
6. Jodhpur	1947-51
7. Lalmanirhat (Cooch Behar)	1944-46
8. Madras	1947-51
9. Nagpur	1947-51
10. New Delhi	1944-51
11. Poona	1945-51
12. Trivandrum	1948-51
13. Veraval	1945-51
14. Visakhapatnam	1945-51
PAKISTAN	
15. Chittagong	1945-46
16. Karachi	1945-47
17. Multan	1946
18. Peshawar	1944-46
BURMA	
19. Akyab	1945
20. Myitkyina	1945
21. Rangoon	1946
CEYLON	
22. Colombo (Ratmalana)	1945

TABLE 2

Sounding balloon data

Agra	1926-40
Ahmedabad	1938-40
Bangalore	1938-40
Calcutta	1937-40
Poona	1928-40
Peshawar	1940-42
Sambalpur	1938-40

observations decreases rapidly particularly above 300 mb. Hence it was considered desirable to compute the heights of the 300, 200 and 150-mb surfaces from the mean temperature distribution. At 100 mb, the number of radiosonde observations was so small that the temperatures were not representative of mean conditions and so no consistent contour pattern could be computed. Sounding balloon mean values (also of the India Meteorological Department) were, therefore, used for this level and the analysis extended into the tropical stratosphere upto 80 mb. Since the number of high ascents at Madras and Trivandrum was very small, their data were combined with the data of Bangalore and Colombo respectively for the higher levels.

The mean temperatures at various altitudes used in this investigation are given in Table 3.

Figs. 1 to 4 give the mean contour charts for the levels 500, 300, 200, 150 mb. Heights are in geopotential metres (gpm) and isotherms are in degrees absolute.

A mean meridional cross section for the entire sub-continent was constructed according to a method adopted by Palmen and Nagler (1948). Mean height profiles were constructed along three longitudes 75°E, 85°E and 95°E making use of available data in each of the three 10-degree longitudinal strips and the geostrophic west winds computed at each $2\frac{1}{2}°$ latitude from 15° to 35°N. From the wind profiles along the three meridians, a mean wind profile was constructed. As the three profiles were nearly parallel to each other and the wind maxima occurred at about the same latitude at each meridian, they could be combined into a single profile representative of the Indian sub-continent and Burma.

TABLE 3

Mean temperatures at different levels

	Pressure level in millibars													
	700		500		300		200		150		100		80	
	n	$T(a)$	n	$T(a)$	n	$T(a)$	n	$T(a)$	n	$T(a)$	n	$T(b)$	n	$T(c)$
Agra	..	..	..	..	..	..	..	..	..	..	153	203·5	126	203·5
Ahmedabad	..	..	..	..	..	..	..	..	..	..	20	200·0	18	200·0
Akyab	30	279·7	27	264·7	16	240·4	10	219·2	4	204·9	1	199·0	..	..
Allahabad	545	276·3	505	259·5	389	234·7	223	219·2	64	211·9	12	206·7	..	..
Calcutta	569	279·1	543	263·9	389	237·0	215	218·0	136	208·0	60	202·0	34	203·5
Chabua	119	271·9	116	258·6	98	235·8	67	218·9	34	210·0	8	200·3	..	..
Chittagong	170	279·0	159	263·2	123	238·8	103	219·7	72	208·5	23	199·5	..	..
Cuttack	81	280·4	78	264·8	69	236·2	48	216·1	31	203·4	7	193·5	..	..
Jodhpur	404	275·1	396	258·3	325	232·5	166	216·9	69	209·0	15	203·7	..	..
Karachi	242	277·5	217	260·7	172	234·9	122	218·7	52	211·3	8	203·2	..	..
Lalmanirhat	171	275·7	160	260·4	115	236·2	30	219·9	8	208·0	1	208·5	..	..
Madras (Bangalore)	424	282·6	373	266·7	273	240·7	214	218·3*	90	205·5*	53	195·0*	34	196·0
Myitkyina	87	274·3	86	262·0	79	238·5	65	219·5	41	208·9	6	198·5	..	..
Nagpur	420	279·8	398	263·9	277	237·3	102	220·0	37	208·3	12	201·0	..	..
New Delhi	669	274·2	644	256·5	519	232·7	250	219·0	156	211·3	71	206·7	..	..
Peshawar	250	269·3	243	252·1	149	227·3	83	218·0	49	215·1	45	212·0	11	212·5
Poona	627	281·0	611	265·2	503	239·1	275	218·2	141	205·2	108	195·0	68	198·0
Rangoon	84	281·5	75	267·0	70	241·0	66	219·2	51	207·1	21	199·8	..	..
Trivandrum (Colombo)	347	282·6	334	266·7	271	240·9	196	219·0*	113	206·5*	58	196·0*	..	..
Veraval	548	280·5	496	264·2	336	238·1	136	218·5	28	206·3	8	195·9	..	..
Visakhapatnam	514	280·7	446	265·3	328	238·9	190	217·3	111	204·4	30	195·5	..	..

n = No. of observations

T = Temperature in degrees Absolute

* Combined with station in brackets

(*a*) Temperatures derived from radiosonde data

(*b*) Temperatures derived from radiosonde and sounding balloon data combined

(*c*) Temperatures derived from sounding balloon data only

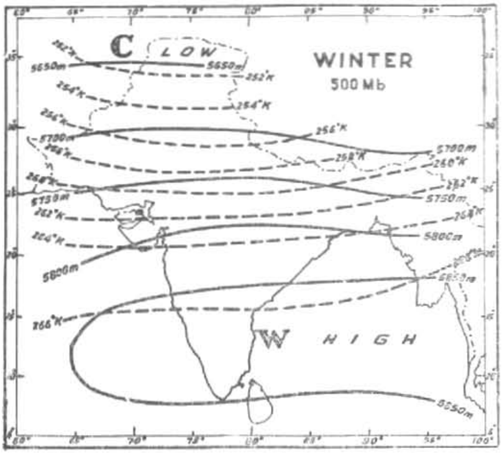

Fig. 1

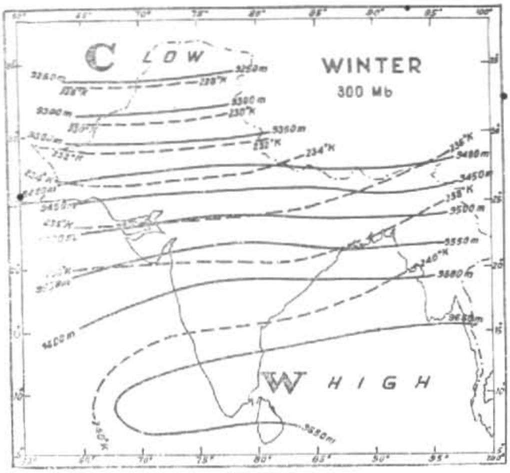

Fig. 2

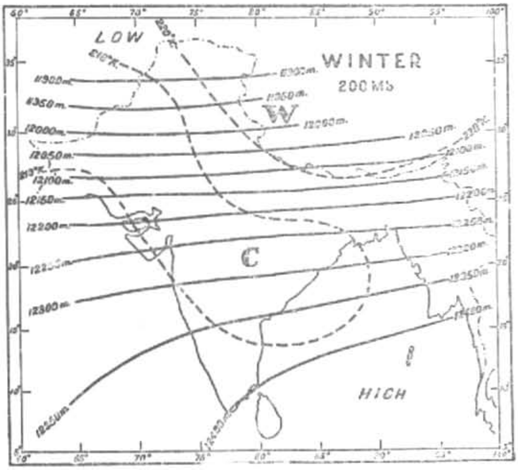

Fig. 3

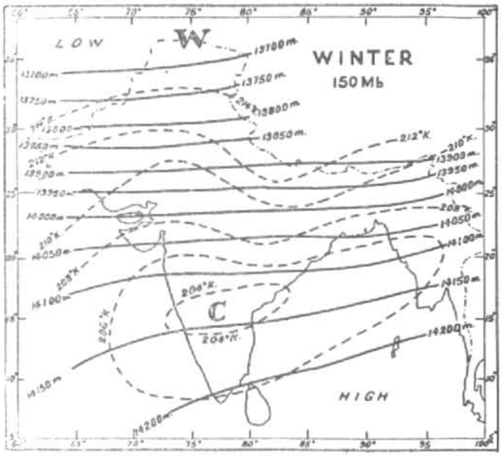

Fig. 4

Figs. 1—4. Mean contours and isotherms of different surfaces in winter over India and neighbourhood
Contours (gpm) :— Solid lines ; Isotherms (°K) :— Dashed lines

The zonal winds were computed from $\cos\phi$—height profiles by the geostrophic wind equation

$$u = -\frac{g}{2a\omega}\cdot\frac{\partial z}{\partial \cos\phi}$$

where ϕ is the latitude, a is the radius of the earth and the other symbols have the usual meanings. The velocities can be obtained directly from the contour slope by multiplying by a constant factor.

The mean temperature profiles were also similarly constructed from the three longitudinal strips. A mean meridional cross section for the Indian sub-continent and Burma was drawn with the aid of the mean temperatures and mean zonal winds (Fig. 5). Computed winds were used for 500 mb and above, and normal pilot-balloon values at lower levels. A comparison of normal computed and normal pilot-balloon winds at the 500 mb is given in Table 4. The pilot-balloon winds have also been averaged over the sub-continent as explained above.

The agreement between the computed and the actual mean winds is quite satisfactory.

4. Location of the Jet

The distribution of wind in the mean cross section follows the same pattern as in similar cross section over other parts of the globe. The maximum wind in the mean cross section occurs at about 27°N at 12 km level and is about 53 mps. The corresponding maximum at 80°W is about 53 mps at 12 km but occurs at about 36°N. It is also clear that there is no secondary maximum to the south as claimed by Chaudhury (1950). Chaudhury's data were limited to one year and for a few stations nearly along 75°E. The equatorial maximum according to him, was located between Bangalore (13°N) and Poona (18½°N). Unfortunately, the temperatures and consequently the height of the pressure surfaces reported by Poona during the winter of 1946 were too low and hence the computed winds were perhaps high between 13°N and 18°N. Table 5 gives the mean heights of 300 and 200-mb surfaces (for the winter season) at Poona and Visakhapatnam which is 8 degrees to the east at nearly the same latitude.

It may be seen that the heights of the pressure surfaces over Poona were too low in 1946 as compared with the heights in other years as well as with the height over Visakhapatnam in the same year.

Chaudhury also claims that the equatorial maximum could be found in the mean climatological charts of pilot balloon winds. No such maximum can be seen in the *Climatological Atlas for Meteorologists and Airmen* (1943) referred to by him. The mean zonal winds for winter in different latitudes at 20,000 ft level as given in the charts under reference as well as the latest normals of the India Meteorological Department (upto 1950) are given in Table 6.

It is clear from this table that there is only a single zonal wind maximum (jet stream) in winter at 25°N over northern India. As pointed out earlier (Koteswaram 1953) the sub-tropical ridge lies over the peninsula at higher levels.

TABLE 4

Comparison of mean zonal winds at 500 mb (Computed and Pilot-balloon)

Latitude °N	Computed (*mps*)	Pilot-balloon (*mps*)
15	3	4
20	14	13
25	22	21
30	16	16
35	8	9

TABLE 5

Mean heights in geopotential metres in winter of 300 and 200-mb levels over Poona and Visakhapatnam in different years

	300 mb		200 mb	
Year	Poona (*gpm*)	Visakhapatnam (*gpm*)	Poona (*gpm*)	Visakhapatnam (*gpm*)
1945	9594	..	12305	..
1946	9569	9603	12221	12297
1947	9625	9584	12329	12312
1948	9630	9612	12381	12330
1949	9637	9640	12393	12296
1950	9634	9666	12412	12302
1951	9642	9658	12454	12408

TABLE 6

Mean zonal winds from pilot balloon ascents (1950 and 1940 normals)

Latitude (°N)	1950 normals (*mps*)	1940 normals (from published charts) (*mps*)
15	4	4
20	13	16
25	21	24
30	16	18
35	9	12

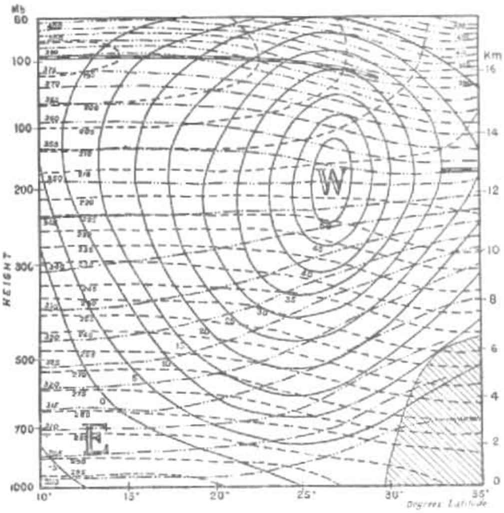

Fig. 5. Mean distribution of zonal components of geostrophic winds in winter over India and neighbourhood
Zonal winds (mps) :—Solid lines ; Temperature (°K) :—Dashed lines ; Potential temperature (°K) :—Dash and dot lines ; Tropopause :—Heavy broken lines and Terrain :—Shaded

5. Distribution of mean absolute vorticity

Fig. 6 gives the meridional cross section of mean absolute vorticity calculated from the usual equation—

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

The mean maximum absolute vorticity is about $11 \cdot 4 \times 10^{-5}$ radian per second to the north of the jet and falls to about 2×10^{-5} radian per second to the south. The concentration of absolute vorticity about two degrees south and north of the jet stream and found in a number of individual cross section (pointed out by Palmen and Newton 1948) is smoothed out in the mean cross section. A similar smoothing is noticed in the vorticity diagram constructed from Hess' cross section also.

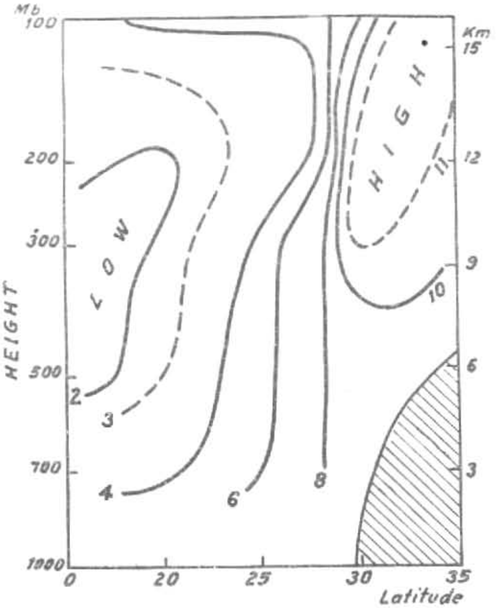

Fig. 6. Mean distribution of absolute vorticity ($11 \cdot 4 \times 10^{-5}$ sec^{-1}) in winter over India and neighbourhood
Terrain : shaded

6. Tropopause and the Jet Stream

The tropical tropopause in the mean cross section (Fig. 5) has been indicated from sounding balloon data, as no reliable radiosonde data are available at that level. Its height is nearly 17 km from 5°N to 27°N (Agra latitude) and is fairly sharp, the lapse changing to an inversion at that level. At New Delhi ($28\frac{1}{2}$°N) where radiosonde data are available upto 16 km, the mean lapse rate decreases up to 16 km but falls to below 2°C km^{-1} between 15 and 16 km. At Peshawar (34°N) the mean lapse rate falls to 2°C km^{-1} slightly above 12 km and reduces to zero at 17 km, with inversion above. This may be due to the statistical effect of the advection of the polar and tropical tropopauses over this station. Hence the tropopause over Peshawar has been taken as 12·5 km. The mean tropical tropopause is, therefore, at 17 km (90 mb) between equator and 25°N bending towards Delhi to 14·5 km (115 mb). The polar tropopause begins at Peshawar at 190 mb and extends northwards. The break in the tropopause pointed out by Hess, probably occurs between the two latitudes.

The mean jet stream at 27°N appears to be located entirely in the tropical troposphere, the break in the tropopause being well to the north of it. On the other hand, the mean jet over North America (Hess 1948) is found at the southern end of the polar tropopause just at the break. Hence the mean Indian jet (80°E) appears to be of the sub-tropical type, while the mean North American jet

(80°W) is of the polar front type. The polar front type of jet stream may occasionally appear over North India in association with western disturbances bringing in polar air and the sub-tropical type occurring during days of normal winter circulation and clear weather as pointed out by Koteswaram (1953).

7. The thermodynamics of the Jet Stream

An analysis was made of the thermal structure of the Indian cross section (Fig. 5) and the American cross section (Hess 1948). The mean meridional cross sections of temperature gradient (β), temperature lapse (γ), as well as the second derivatives like the gradient of lapse rate $\partial\gamma/\partial y, \partial\beta/\partial y$ and $\partial\gamma/\partial z$ were constructed. Figs. 7 to 10 are cross sections of β and γ over India and America. Isopleths of $\partial\beta/\partial z$ and $\partial\gamma/\partial y$ are marked as dashed lines. The position of the core of the jet stream is given by marking the 50 mps velocity isopleth in each section.

7.1. *Distribution of temperature at the Jet Stream*—From the zonal thermal wind equation, the University of Chicago group (1947) have shown that an abrupt change in the height of the tropopause causes an abrupt shear near the jet stream. Koteswaram (1953) has explained the sub-tropical jet stream on the basis of reversed meridional temperature gradient above and below the jet stream level.

The usual thermal wind equation can be written as

$$T\frac{\partial u}{\partial z} - u\gamma = -\frac{g}{f}\beta \quad \ldots\ldots\ldots (i)$$

where f is the coriolis parameter and other symbols have usual meanings.

At the jet stream, $\frac{\partial u}{\partial z} = 0$

Hence, either $\beta_J = \gamma_J = 0 \quad \ldots. \ (ii)$

$$\text{or } u_J = \frac{g}{f}\,\frac{\beta_J}{\gamma_J} \quad \ldots\ldots\ldots (iii)$$

The symbols with suffix $_J$ denote the values at the jet stream level.

In the polar front type the jet is found at the southern end of the polar tropopause where $\gamma_J = 0$. Hence according to (ii) β_J also must be equal to zero. In the sub-tropical jet stream, γ_J is a finite quantity since the jet is found well within the troposphere. Hence β_J also must be a small finite quantity given by equation (iii). At latitude 30°N, for a velocity $u_J = 100$ mps and $\gamma_J = 5°\text{C km}^{-1}$, $\beta_J = 0{\cdot}36°\text{C}$ per 100 km.

Since a reversal of temperature gradient is necessary for the reduction of the velocity above the jet stream level, the zero value for β occurs almost immediately above the jet stream level.

The level of zero temperature gradient ($\beta = 0$) may be seen passing through the jets in both the cases but it is slightly above the centre of the jet in the Indian cross section (Fig. 7) while it passes through the centre and coincides with the polar tropopause in the American cross section (Fig. 9). This is in agreement with the conditions derived in equations (i) and (ii).

It is also interesting to observe that the isopleth $\beta = 0$ reaches its maximum height at about 25°N in both the cross sections with a southern minimum at about 15°N, beyond which it is almost vertical. The maximum perhaps signifies the position of the sub-tropical jet stream and the minimum, the southern limit beyond which a jet cannot exist at that level.

7.2. *Distribution of* β *and* γ. In the cross sections of temperature gradient (β), it may be seen that the maximum temperature gradients occur at about the *latitude* of the jet stream, both below and above it, with a rapid variation near about the jet stream. On the other hand, the cross section of lapse rates (γ) indicates the maximum and the minimum lapse rates occurring at about the *altitude* of the jet stream, with a rapid variation through the jet. Thus the two cross sections locate the latitude as well as the altitude of the jet.

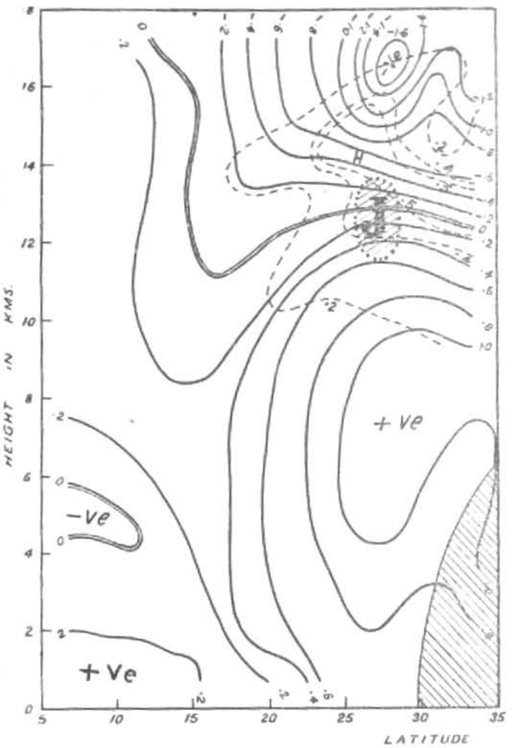

Fig. 7. Mean distribution of temperature gradient in winter over India and neighbourhood

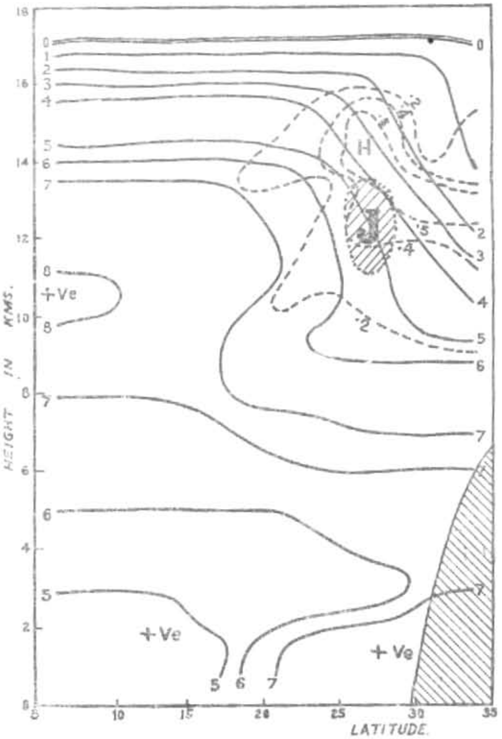

Fig. 8. Mean distribution of temperature lapse in winter over India and neighbourhood

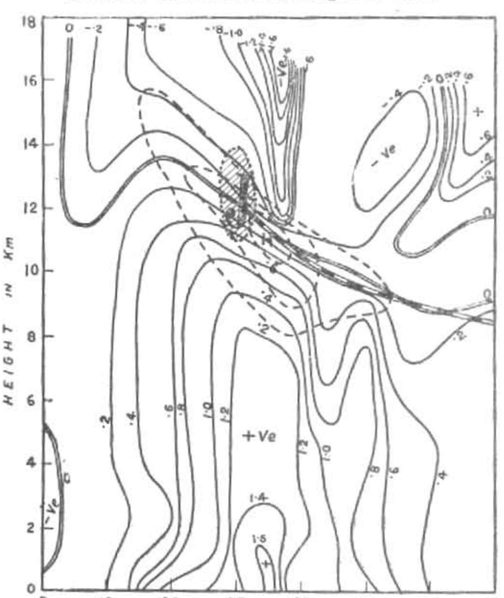

Fig. 9. Mean distribution of temperature gradient in winter over North America (80°W)

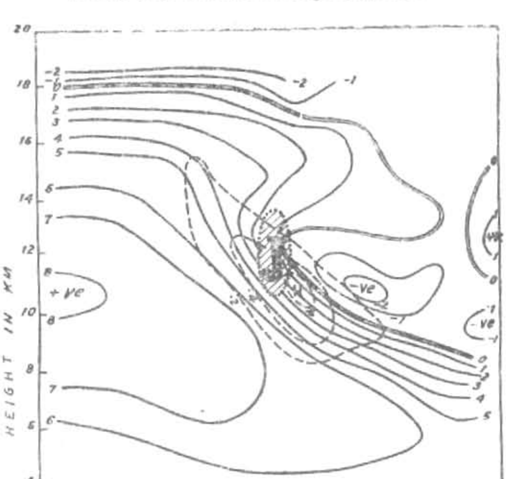

Fig. 10. Mean distribution of temperature lapse over North America (80°W)

β(°K/100 km) in Figs. 7 and 9 and γ (°K/km) in Figs. 8 and 10 :—Solid lines; $\partial\beta/\partial z$ (°K 10^{-3} km) :—Dashed lines ; β or $\gamma=0$:—Double line ; Position of Jet :—J shaded ; Terrain :—Shaded portion in the right hand corner in Figs. 7 and 8 ; Tropopause :—Heavy broken lines in Figs. 9 and 10.

It is also seen that at the jet latitude, β is almost uniform with height upto about 10 km over India and 8 km over America and then diminishes rapidly, the reversal occurring above the jet stream level.

The corresponding vertical distribution of velocity can be studied from the thermal wind equation, by expressing the mean temperature gradient as $\beta_m = \beta_0 + \frac{1}{2}\frac{\partial\beta}{\partial z}z$ where β_0 is the surface gradient and $\partial\beta/\partial z$ is its mean lapse in the layer.

Neglecting the wind at the surface,

$$u = -\frac{g}{f}\,\frac{1}{T_m}\left\{\beta_0\,z + \tfrac{1}{2}\frac{\partial\beta}{\partial z}z^2\right\}\ldots\ldots(iv)$$

The wind at any level may thus be seen to be composed of two terms, one varying directly as the height and the other depending upon the lapse of the temperature gradient and the square of the height. Since in the cross sections in Figs. 7 and 9 $\partial\beta/\partial z$ is nearly zero up to 8 or 10 km, its contribution is negligible. Above this level, since it is opposite in sign to β_0, it contributes to cut down the velocities built up by $\beta_0\,z$ for providing the jet stream profile.

As regards the distribution of γ, the lapse rate is seen to be uniformly high at nearly the jet stream altitude from low latitudes to about 20°N in both the cross sections and falls off rapidly through the jet stream. The jet lies at the southern end (near the high lapse rate region) in the sub-tropical type and at the northern end (near the zero lapse rate region) in the polar type.

7.3. *Horizontal gradient of lapse rate.* The quantity

$$\frac{\partial^2 T}{\partial y \partial z}\ (i.\ e.)\ \frac{\partial\beta}{\partial z}\ \text{or}\ \frac{\partial\gamma}{\partial y}$$

may be seen to attain its maximum above the sub-tropical jet and below the polar front jet. The role of this term in building up of the velocity in equation (*iv*) has already been pointed out as a negative one, *viz.*, of reducing the velocity built up by the first term. In the polar-front type, this term is a consequence of the tropopause break, since γ varies rapidly to zero at the break in the tropopause, and in the sub-tropical type, it is caused by a rapid diminution of the lapse rate without the lapse rate reaching zero values. Hence, though the break in the tropopause is the contributing factor for concentrating velocities into a jet stream, its role is negative rather than positive, in as much as it prevents the velocities from rising further with height.

The significant feature in both the diagrams is that this quantity $\partial\gamma/\partial y$ (gradient of lapse rate) concentrates into a maximum near the jet stream in much the same manner as the zonal wind speed concentrates into a maximum. The concentration is confined to the jet stream vicinity and is not a gradual one all over the troposphere.

The vertical shear in an interval z from the jet stream level at any latitude is given by the equation

$$\triangle u_J = u_J - u =$$

$$-\ \frac{g}{f}\cdot\frac{1}{T_m}\left[\beta_J\,z + \tfrac{1}{2}\frac{\partial\beta}{\partial z}\cdot z^2\right]\ldots\ldots(v)$$

In the polar front type $\beta_J = 0$ (eqn *ii*) and the wind shear $\triangle u_J$, therefore, is directly proportional to $\partial\beta/\partial z$. In the sub-tropical type, though β_J is not equal to zero, it is small and the $\beta = 0$ line passes close to the jet stream centre. Hence, the wind shear in this case also is largely contributed by the $\partial\beta/\partial z$ term. Since $\partial\beta/\partial z$ reaches a maximum near about the jet stream, in both the cases the vertical shear should also be maximum there. Hence the horizontal shear also varies rapidly according to the variation of $\partial\beta/\partial z$.

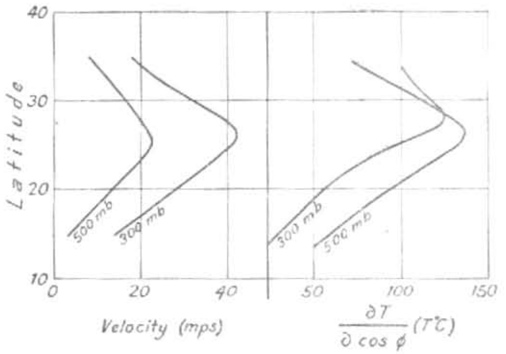

Fig. 11. Mean profiles of velocities and $\partial T/\partial \cos\phi$ at 500 and 300 mb in winter over India and neighbourhood

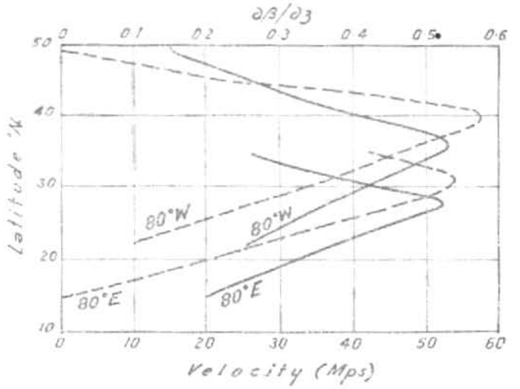

Fig. 12. Mean profiles of velocities and lapse rate of temperature gradient at 200 mb over 80°W and 80°E
Velocity (mps) :—Solid lines ; $\partial\beta/\partial z$ (°K× 10^{-3}km):—Dashed lines

7.4. *Latitudinal variation of zonal wind at different levels.* Upto 8 or 10 km where the second term in equation (*iv*) does not contribute appreciably, the velocity may be seen to be proportional to β_0. Since it is found that the maximum temperature gradient occurs at about the same latitude at all levels upto 8 or 10 km the maximum wind at any level also must occur at about the latitude of maximum temperature gradient at that level as may be seen from Fig. 11 which gives the meridional profiles of u and $\partial T/\partial \cos\phi$ at 500 and 300-mb levels over India.

At the jet stream level, from equation (*v*) it is seen that

$$u_J = -\frac{g}{2f}\frac{1}{T_m}\left(\frac{\partial\beta}{\partial z}\right)_m H^2$$

where the suffix m denotes the mean value from the jet stream level to the surface, neglecting u_0 and β_J. Since $\partial\beta/\partial z$ is almost concentrated within 2 km below the jet stream with its maximum very near the jet stream level, we should expect u_J to be very nearly proportional to $\partial\beta/\partial z$ at the jet stream level.

Fig. 12 gives the profiles of u_J and $\partial\beta/\partial z$ for both the types of jet stream. The agreement between the two curves is satisfactory.

It, therefore, appears that the gradient of the lapse rate in the atmosphere is an important factor in concentrating the winds into a jet. Both the polar front and the sub-tropical jets form at the latitudes where the gradient of the lapse rate attains its highest value. In the sub-tropical type, it attains its maximum near the region of high lapse rate and in the polar front type, its maximum is reached near the polar tropopause (zero lapse rates), *i.e.*, at the break in the tropopause.

Table 7 gives a summary of various thermodynamic properties of the mean jet streams as revealed by the two mean cross sections.

7.5. *The sub-tropical ridge and the jet stream.* It is evident from the two cross sections discussed in this paper that the polar front type is more predominant in the American (80°W) cross section while the sub-tropical type is predominant in the Indian (80°E) cross section. The mean position of both the jets is almost vertically above the surface high as postulated by Palmen (1951). In the higher levels there is a trough along 80°W while there is a ridge along 80°E, the trough being formed further to the east off the coast of Asia (1948). The advection of polar air into the 80°W trough and the advection of equatorial air over the 80°E ridge, may perhaps be responsible for the thermal lapse-rate gradients associated with the two types of jet streams.

TABLE 7

Mean thermal properties of the two jet stream types

	Sub-tropical type	Polar front type
T	Isotherms diverge northwards below and above the jet stream. T is almost constant both to the south and north of the jet at the jet stream level	Isotherms diverge northwards below and above the jet stream. T rises slightly to the north of the jet
θ	Isentropes diverge towards the south above and below the jet stream Nearly constant to the south and north at jet level	Same as sub-tropical Greater to the north than to the south at jet level
β*	About 0·1°C per 100 km at the jet Positive below and negative above the jet	Zero at the jet Positive below and negative above the jet
$\|\beta\|$	Maximum at jet latitude below and above decreasing rapidly vertically through the jet	Same as sub-tropical
γ†	About 5°C km–1 at the jet Positive all round the jet	Zero at the jet Positive to the south and slightly negative to the north. Positive below and above
$\|\gamma\|$	Maximum at nearly the jet level to the south and decreases rapidly to the north. Decreases also vertically upwards	Maximum at the level of the jet to the south. Decreases rapidly to the north to nearly zero values. Decreases upto the jet and increases slightly above
$\frac{\partial\beta}{\partial y}$	Zero at the jet stream height and latitude	Same as sub-tropical
$\frac{\partial\gamma}{\partial z}$	Zero just below the jet and increases upwards through the jet. Almost 0 to the south and rapidly increases to the north	Zero at the jet, positive below and negative above. Positive to the south and negative to the north
$\frac{\partial\beta}{\partial z}$	Positive maximum above the jet stream centre. Decreases to zero at about 8 km. Decreases to the south and increases to the north	Positive maximum below the jet. Decreases to zero at about 8 km. Decreases to the south and north

* Positive when temperature decreases from south to north

† Positive when temperature decreases with height

8. Conclusion

The following conclusions may be drawn.

(*i*) The mean jet stream over the Indian sub-continent in winter lies over latitude 27°N at a height of 12 km. The mean wind speed is 53 mps.

(*ii*) The mean jet lies entirely within the tropical troposphere, about 4 km below the tropical tropopause and is of the sub-tropical type. The mean polar tropopause commences at about latitude 34°N.

(*iii*) There is definitely a single mean jet stream over the country at about 27°N and none over lower latitudes.

(*iv*) An explanation of the concentration of wind into a jet may be obtained from thermodynamical considerations, the main condition being a reversal of the temperature gradient below and above the jet stream. The gradient of lapse rate is found to concentrate near the jet stream level and the maxima being above the jet in the sub-tropical type and below it in the polar front type. The two types appear to occur at the extremeties of the region of maximum gradient of lapse rate. The meridional profile of the zonal winds at the jet stream level also closely follows the meridional profile of the lapse rate gradient.

(*v*) Climatologically the situation of the jet at 80°W over a trough and that at 80°E over a ridge, favour the advection of polar air in the former case and of equatorial air in the latter, thus providing the temperature contrast required for the concentration of the lapse rate gradient.

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