551·510·52:551·558(54)

The mean Jet Stream over India in the pre-monsoon and post monsoon seasons and vertical motions associated with sub-tropical Jet Streams

P. KOTESWARAM and S. PARTHASARATHY

India Meteorological Department

(*Received 7 September 1953*)

ABSTRACT. On lines similar to the authors' work on the jet stream in winter (1953b) the mean jet stream over the Indian sub-continent has been computed for the post monsoon and pre-monsoon seasons. It is found that the westerly jet stream persists in these two seasons also, but with diminished velocity. The monthly variation of the position of the jet in the dry season has been studied and the thermodynamic features of the mean jet discussed.

From pibal means, the vertical motion over the country in the dry seasons has been evaluated. An attempt has been made to picture the circulation patterns near the jet stream as well as over the sub-tropical anti-cyclone. The convergence and vertical motion patterns in the vicinity of the jet over India give support to the confluence mechanism for its formation.

Reports of clear air turbulence over India have been examined in relation to the vertical motion pattern and it is pointed out that the region to the south of the sub-tropical jet is favourable for such turbulence.

1. Introduction

The characteristics of the mean westerly jet stream over northern India in the winter season were studied by the authors and Raman recently (1953 b). The study was extended to the other months of the dry season (Oct—May) when strong westerlies persist over northern India and a preliminary statement about the existence of the jet during the pre-monsoon and post monsoon seasons was made in a recent note (1953 c). Ramage (1952) also pointed out the intensification of the zonal westerlies over northern India in autumn and the dissolution of the jet in summer. He attempted to get a picture of horizontal divergence over India at the jet stream level in winter from rather meagre pilot balloon wind data at 12-km level.

Details of the authors' study of the post monsoon and pre-monsoon jet streams are given in this paper. Since pilot-balloon data are available upto fairly high levels in these seasons, an attempt has been made to study mean horizontal divergence and vertical motion in the troposphere over the country with particular reference to the circulation in the vicinity of the jet streams. This was also extended to the winter season upto the levels for which data were available.

2. Thermal structure of the Upper Troposphere in the post monsoon and pre-monsoon periods

Monthly normal temperatures for different standard pressure levels in the upper air at a number of radiosonde stations in India, Pakistan, Burma and Ceylon, have been worked out by the India Meteorological Department (unpublished). The extent of available data has been indicated in a previous paper (1953 b). These normals have been extended, wherever possible, by the authors to cover the period 1944—1951 and the seasonal means worked out for the post monsoon and pre-monsoon seasons. Since the radiosonde data above 200 mb are scanty, sounding balloon values have been utilised wherever available, for these levels. October-November and April-May have been taken as representative months of these two seasons.

Tables 1 and 2 give the seasonal mean temperatures used in this investigation.

It will be seen from these tables, as also from the charts in Figs. 1-10, that as in the winter season, there is a reversal of temperature gradient over North India above the 200-mb level. That this reversal of temperature is a feature of jet stream has already been pointed out (1953 a). Applying the same criterion, one should expect the jet stream to persist even in the post monsoon and pre-monsoon seasons also at about 200 mb.

TABLE 1

Mean Upper Air Temperatures for the post monsoon season (October-November) at different stations

	700 mb		500 mb		300 mb		200 mb		150 mb		100 mb	
Station	n	T(a)	n	T(a)	n	T(a)	n	T(a)	n	T(b)	n	T(b)
Akyab	58	280·7	52	265·3	49	239·7	47	217·8	25	207·0	5	196·0
Allahabad	417	280·0	383	263·9	328	239·0	213	219·0	83	209·2	20	200·6
Calcutta	419	281·3	388	265·8	280	239·5	164	218·0	98	207·5	49	199·2
Chabua	99	275·8	93	262·8	82	237·9	61	219·9	18	207·8	—	—
Chittagong	109	280·6	101	264·7	95	238·8	80	217·0	48	206·7	27	196·8
Cuttack	62	281·7	52	266·0	46	238·6	30	217·8	12	205·0	5	194·1
Jiwani	58	281·7	53	265·4	32	238·2	23	218·4	11	208·0	—	—
Jodhpur	329	279·0	316	263·0	263	237·3	178	217·7	70	207·6	19	201·5
Karachi	155	280·0	125	264·5	103	241·7	46	216·6	8	208·0	—	—
Lalmanirhat	103	278·8	98	264·3	87	237·8	28	219·5	16	207·0	1	190·2
Madras (Bangalore)	355	282·5	314	267·6	234	242·3	102	220·8*	69	207·2*	39	194·7*
Myitkyina	75	280·5	64	266·0	53	241·0	45	219·5	5	208·5	—	—
Nagpur	338	280·7	294	266·4	204	241·1	63	219·8	19	205·7	3	201·0
New Delhi	489	278·6	472	261·6	414	236·7	286	220·1	141	210·1	44	202·5
Peshawar	123	278·2	119	259·0	106	232·6	62	218·0	26	211·1	4	206·6
Poona	494	281·6	441	267·3	322	241·0	166	220·0	139	206·2	74	194·4
Port Blair	102	283·5	90	264·9	75	243·2	37	222·1	13	209·4	1	199·0
Rangoon	74	282·0	68	267·5	62	242·1	57	219·3	36	207·8	9	198·0
Trivandrum (Colombo)	281	282·5	254	267·0	204	241·8	151	221·6*	73	207·7*	43	197·2*
Veraval	349	281·4	344	266·3	231	239·7	86	218·0	47	206·0	23	195·0
Visakhapatnam	371	282·5	336	267·3	237	241·8	117	221·0	48	209·0	15	198·5

n—Number of observations

T (a)—Temperature (°K) derived from radiosonde data

T (b)—Temperature (°K) derived from radiosonde and sounding balloon data combined

* Combined value with that of station in brackets

TABLE 2

Mean Upper Air Temperatures for the pre-monsoon season (April-May) at different stations

Station	700 *mb*		500 *mb*		300 *mb*		200 *mb*		150 *mb*		100 *mb*	
	n	*T*(*a*)	*n*	*T*(*a*)	*n*	*T*(*a*)	*n*	*T*(*a*)	*n*	*T*(*b*)	*n*	*T*(*b*)
Akyab	39	281·1	38	266·5	36	241·5	32	217·8	31	205·3	7	196·6
Allahabad	366	283·0	345	262·5	265	237·9	155	220·0	41	210·7	3	201·0
Calcutta	583	282·8	539	265·0	426	240·8	236	222·0	162	211·7	96	201·9
Chabua	169	279·8	159	264·0	136	239·4	118	221·9	86	211·8	46	202·8
Chittagong	111	281·9	105	265·7	93	241·9	71	221·9	49	210·5	14	200·8
Cuttack	111	282·9	101	264·5	87	239·2	63	218·2	30	207·7	3	201·5
Jiwani	56	286·4	55	265·9	46	238·7	41	221·4	11	210·0	—	—
Jodhpur	322	282·6	312	262·3	240	236·8	130	219·6	43	211·0	5	204·5
Karachi	223	286·0	192	266·8	148	241·2	108	222·7	54	213·9	14	212·0
Lalmanirhat	133	281·3	117	264·9	89	239·4	55	221·3	27	213·5	10	205·3
Madras (Bangalore)	284	284·8	256	268·0	197	243·0	199	221·3*	78	208·4*	23	195·9*
Myitkyina	58	281·5	54	265·1	52	241·4	45	221·8	34	209·5	5	197·8
Nagpur	271	285·4	256	264·7	192	240·3	94	222·0	31	211·8	3	200·0
New Delhi	559	283·2	543	262·3	466	236·3	356	219·6	136	211·7	21	206·6
Peshawar	176	280·3	174	259·9	156	233·0	82	220·5	62	214·7	54	208·2
Poona	482	285·1	448	266·5	413	241·0	265	221·0	156	207·5	39	195·8
Port Blair	117	284·1	113	267·1	84	245·0	57	224·6	26	211·8	6	201·7
Rangoon	49	284·8	46	270·2	41	246·0	38	226·0	31	212·3	10	201·2
Trivandrum (Colombo)	234	284·0	217	268·6	194	243·8	177	221·6*	34	211·5*	15	201·5*
Veraval	368	285·0	335	266·2	246	240·5	132	222·5	43	210·0	8	204·0
Visakhapatnam	325	284·5	305	266·7	227	242·3	110	222·0	50	209·5	12	203·7

n—Number of observations

T(*a*)—Temperature (°K) derived from radiosonde data

T(*b*) Temperature (°K) derived from radiosonde and sounding balloon data combined

* Combined value with that of station in brackets

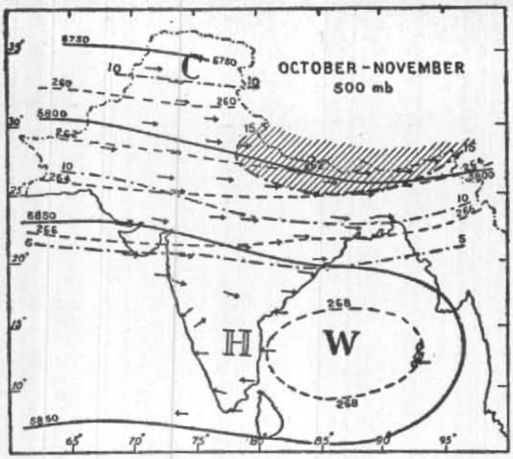


Fig. 1

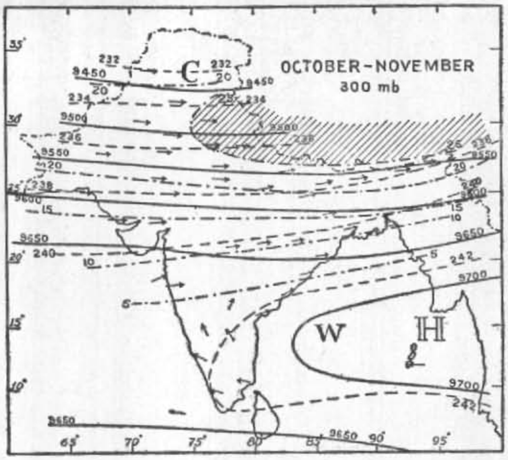


Fig. 2

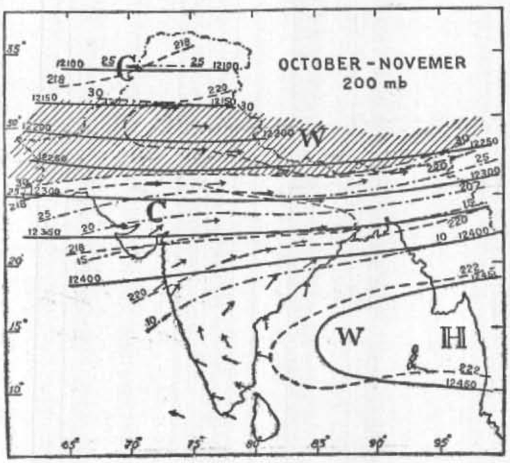


Fig. 3

Fig. 4

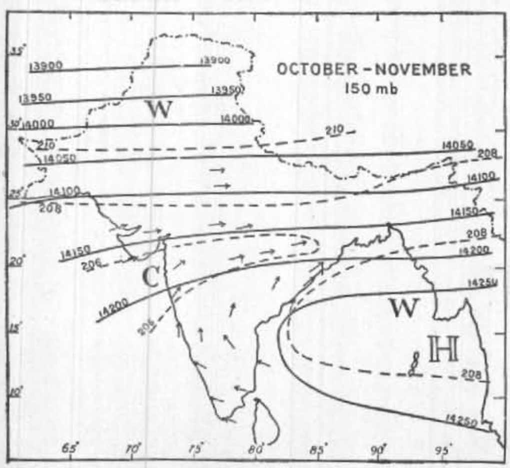
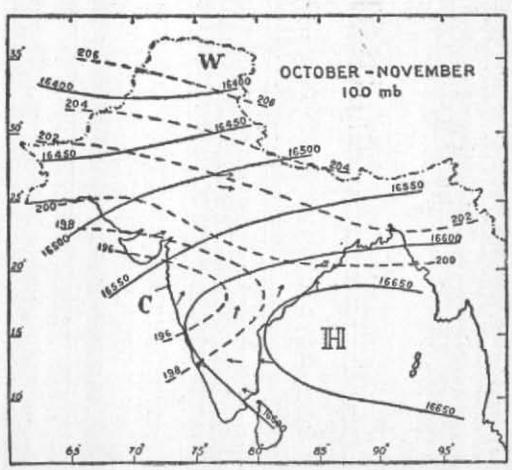


Fig. 5



Figs. 1—5. Mean constant pressure charts over India and neighbourhood during October-November
Contours (gpm) :—Solid lines ; Isotherms (°K) :—Dashed lines ; Isotachs of resultant mean winds (mps) ;—Dash and dot lines ; Arrows :—Direction of pibal winds ; Shaded area :—Pibal maxima

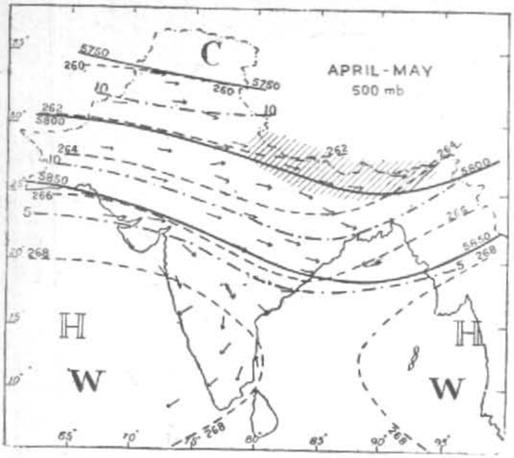


Fig. 6

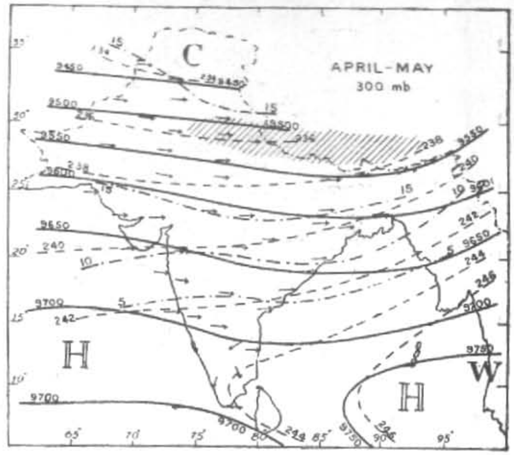


Fig. 7

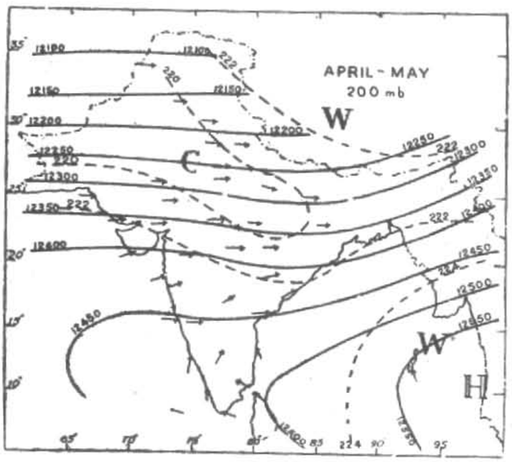


Fig. 8

Fig. 9

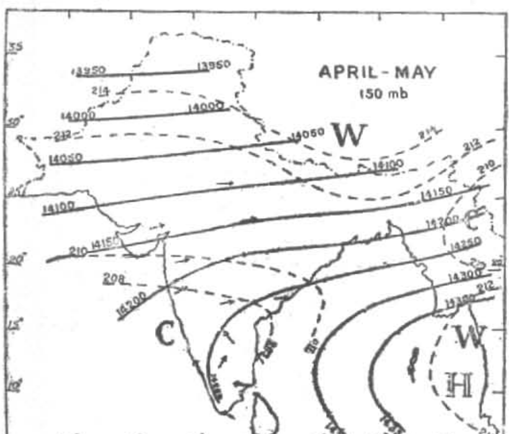
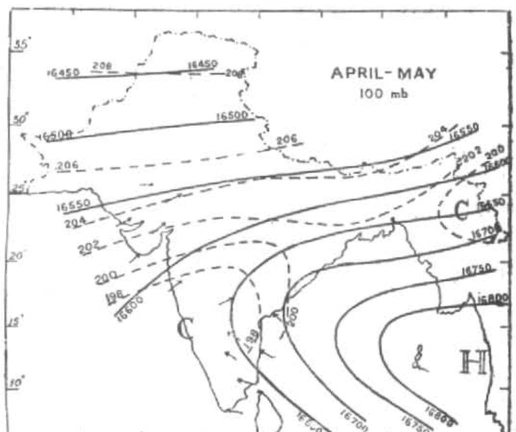


Fig. 10



Figs. 6—10. Mean constant pressure charts over India and neighbourhood during April-May

Contours (gpm) :—Solid lines ; Isotherms °(K) :—Dashed lines ; Isotachs of resultant mean winds (mps) :—Dash and dot lines ; Arrows :—Direction of pibal winds ; Shaded area :—Pibal maxima

3. Mean contour topography at various Standard Pressure Levels

3·1. Construction of mean contour charts—In order to determine the existence of and study the nature of the jet stream in these seasons, mean contour charts were prepared for the standard pressure levels 700, 500, 300, 200, 150 and 100 mb using the same technique as for the winter season (1953b). Figs. 1 to 10 give the mean charts for 500, 300, 200, 150 and 100 mb for both the seasons. Isotachs based on I.Met.D. normals of pilot-balloon winds (upto 1951) are indicated in these figures, wherever consistent isotach patterns could be drawn.

3·2. Features of the post monsoon season—The main feature of the constant pressure charts in this season (Figs. 1 to 5) is the concentration of contour lines north of 25°N at all levels above 500 mb, the maximum concentrations occurring between 25°N and 30°N at 200 mb, and north of 30°N at 150 mb. The pibal wind maxima occur between 26°N and 32°N at 500,300 and 200 mb. Temperatures decrease towards north at all levels upto 300 mb. At 200 mb a cold pool exists between 20°N and 25°N. Another cold region also seems to exist near Peshawar, the mean temperatures at Nagpur, Jodhpur, New Delhi and Peshawar being 220, 218, 220 and 218°K respectively. In order to ensure that the lower temperature at Peshawar as compared to Delhi is not a spurious effect, caused by comparison of the means for different years, the monthly mean temperatures of these stations were compared during the period when simultaneous ascents were available for both and it was found that the Peshawar temperatures were consistently lower than those of Delhi at these levels.

3·3. Features of the pre-monsoon season—In the pre-monsoon season also, the constant pressure contour charts as well as pilot-balloon isotachs (Figs. 6—10) indicate maximum winds between 26 and 32°N at levels above 500 mb. Due to cloudiness over northeast India, the number of pilot-balloon observations in this season at higher levels is small and hence pibal means for this region are not reliable. Mean temperatures in the upper air diminish northwards upto 300 mb. At 200 mb there is a cold pool extending from West Pakistan to Central India ; at higher levels it shifts southwards.

4. Mean Meridional Cross-sections

Using the same technique as for the winter analysis (1953 b), *viz.*, computing the velocity profiles for three longitudinal strips and combining them, the mean meridional cross-section of the distribution of the geostrophic west winds over India have been constructed. Since the sub-tropical high pressure cells extend to more northerly latitudes in the upper levels, the computation of winds at and above 200 mb was confined to the north of 20°N only. To the south of this latitude reliable pilot-balloon means were available for India, the winds being weak in this region, and have been used.

It is also seen that the sub-tropical cell is rather intense at the higher levels (150 and 100 mb) and consequently there is a considerable concentration of contour lines over Burma even at these levels. The high contour topography at these two levels over the Andaman Sea is supported by the observations of both Port Blair and Rangoon, though they belong to two different periods of time, the mean geopotential (in gpm) for these levels for Port Blair and Rangoon being as shown below.

	Port Blair	Rangoon
150 mb	14392 (*26*)	14351 (*31*)
100 mb	16840 (*6*)	16802 (*10*)

The figures in brackets give the number of observations. Due to the small number of these observations and the absence of reliable values for other stations in Burma, no conclusions are drawn.

Figs. 11 and 12 give the mean meridional cross-sections for the post monsoon and the pre-monsoon seasons. The cross-sections generally indicate the features explained in the above paragraphs. In both the seasons a westerly jet stream exists at 200 mb at about $27\frac{1}{2}$°N. In addition, another jet seems to exist at 150 mb to the north of 34°N in the post monsoon season. The existence of this

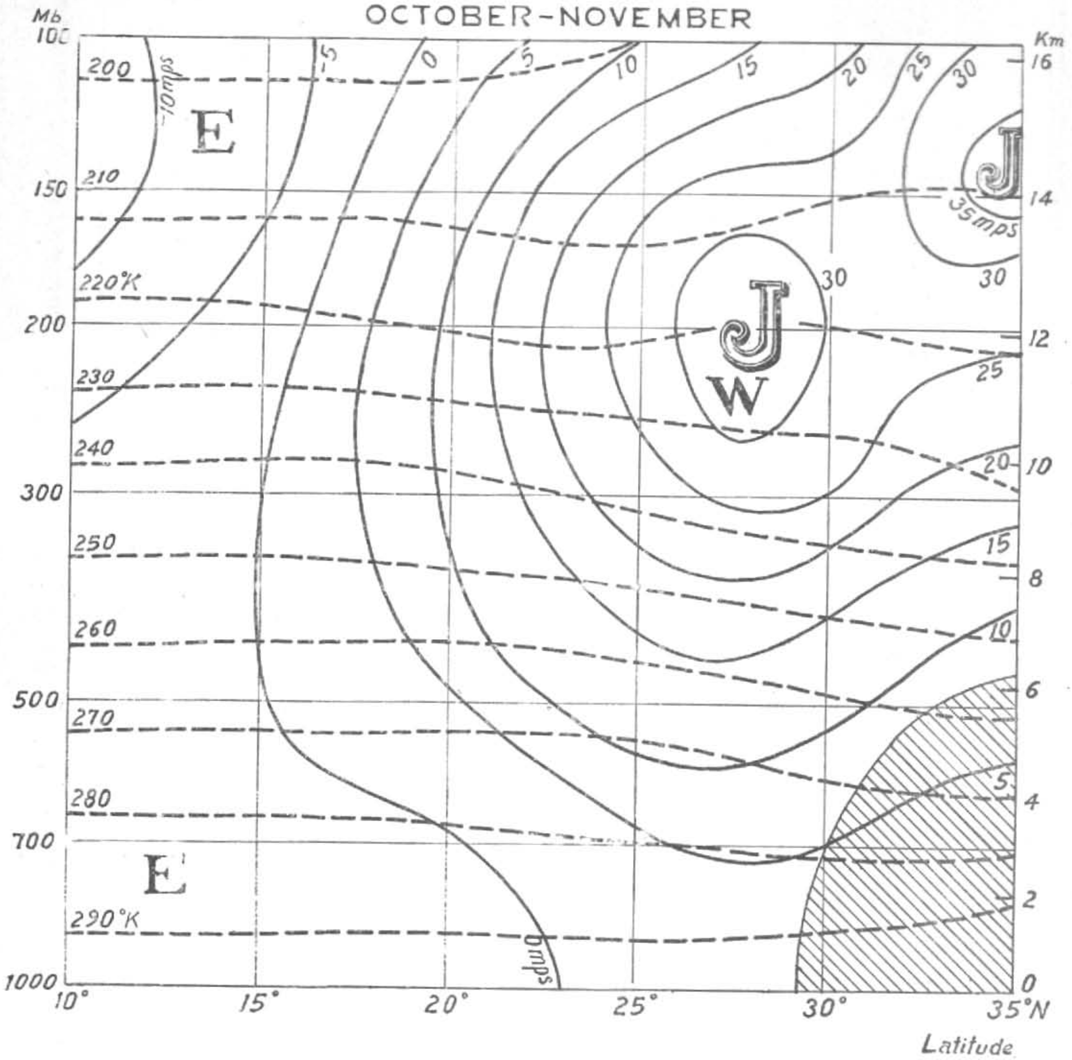


Fig. 11. Mean distribution of zonal components of geostrophic winds in October-November over India and neighbourhood

Zonal winds (mps) :—Solid lines ; Temperature (°K) :—Dashed lines ; Terrain :—Shaded

maximum is also supported from the pilot-balloon means. The mean winds at 9, 12 and 14 km at Agra and Peshawar are given in Table 3. While the maximum over Agra occurs at 12 km (200 mb) that over Peshawar is at 14 km (150 mb) or above.

TABLE 3

Altitude (*km*)	9		12		14		16	
Station	*n*	*v*	*n*	*v*	*n*	*v*	*n*	*v*
Agra	917	25	207	32	71	27	38	21
Peshawar	524	18	143	25	38	34	—	—

n : No. of observations *v* : Mean velocity in mps

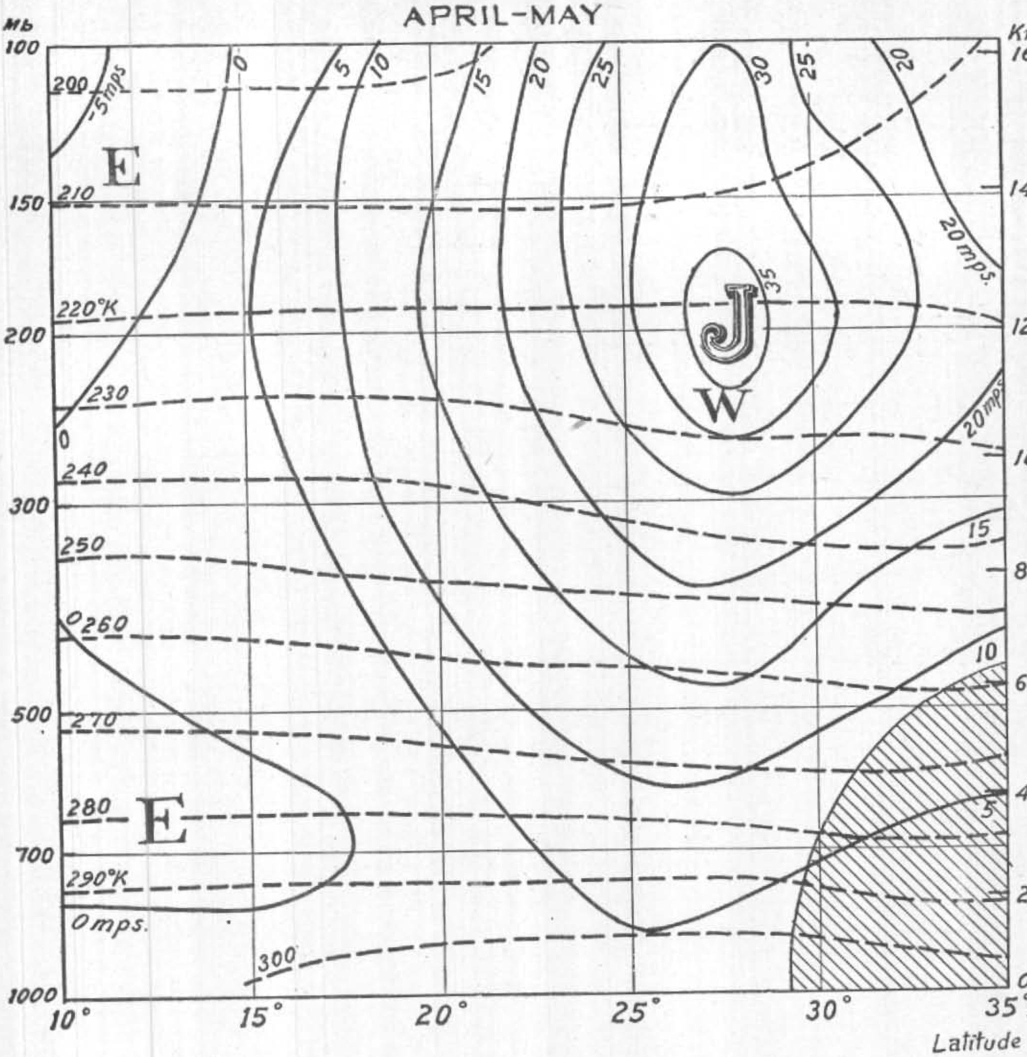


Fig. 12. Mean distribution of zonal components of geostrophic winds in April-May over India and neighbourhood

Zonal winds (mps) :—Solid lines ; Temperature (°K) :—Dashed lines ; Terrain :—Shaded

The mean position of the jet stream is the same in all the dry months of the year though its speed varies from 30 mps in October-November to 50 mps in December—February and 35 mps in April-May.

5. Monthly variation of the Jet Stream

Since the jet stream persists over the country for about eight months of the year (October—May), an attempt has been made to examine its mean monthly variation. It is seen in the mean charts as well as in the daily charts, that the latitude where the jet stream is located generally coincides with the position of the wind maximum at 500 mb. A study of the mean monthly wind profiles at 500 mb along any meridian would, therefore, enable an appreciation of the monthly variations of the position of the jet stream itself.

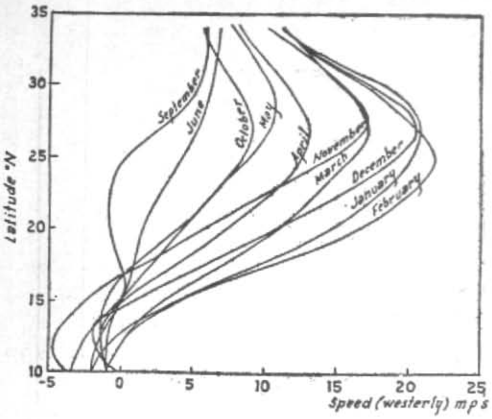


Fig. 13. Monthly mean meridional profiles of pibal winds at 6 km along 75°E during September to June

Fig. 13 indicates the variation of the mean pilot-balloon wind speeds at 6 km at stations along or near longitude 75°E in various months. It will be seen from the figure that the characteristic jet stream profile with a distinct maximum appears in October. The maximum generally increases and shifts southward in February but decreases and shifts northward during the pre-monsoon season. Table 4 gives the position and intensity of the maximum in various months. The lowest latitude (25°N) is reached in February. It shifts to 29°N in May and moves further north, out of the country, later.

6. The Tropopause and the Jet Stream

It may be seen from the meridional cross-sections that the mean tropopause does not occur below 100 mb. During these months, it is generally situated at 16·5 km (95 mb), and its lowering is occasional. The jet streams form in the upper troposphere well below the tropopause and hence are of the sub-tropical type as in winter (1953 b). The upper jet at 150 mb in the post monsoon season, however, may be a part of the polar front jet probably occurring to the north of 35°N.

TABLE 4

Position and strength of maximum mean westerly winds along 75°E at 6 km

Month	Position (°N)	Strength (*mps*)
October	27	9
November	27	17
December	27	20
January	27	21
February	25	22
March	26	17
April	26	13
May	29	13

7. Thermodynamical aspects of the Jet Stream

In the analysis of the sub-tropical jet stream in winter, the authors (1953 b) made a detailed study of the thermal structure of the jet stream and the distribution of the temperature lapse rates and gradients in its vicinity. The occurrence of the jets at the transitions between the low latitude zones of high lapse rate and the high latitude zones of low or zero lapse rate, was also pointed out. The distribution of lapse rate in the post monsoon and pre-monsoon seasons is given in Figs. 14 and 15. The persistence of high lapse rates in the layer between 8 and 14 km to the south of the jet stream and the rapid fall of lapse rates to the north of it is a feature of these cross-sections in common with the winter cross-section (1953 b—Fig. 8). During the pre-monsoon season, high lapse rates at the surface which are so well known in North India extend upto 8 km, and lapse rates rapidly diminish aloft. Over the peninsula, low lapse rates occur at lower levels (4—6 km) and high lapse rates at higher levels in both the seasons. The concentration of the lapse rate gradient in the vicinity of the jet stream, which was pointed out in the winter cross-section, may be noticed in these cross-sections also. In the post monsoon season, the gradient does not persist to the north of the sub-tropical jet as in the pre-monsoon season. A strong gradient may exist to the north of the more northerly (Polar-front) jet.

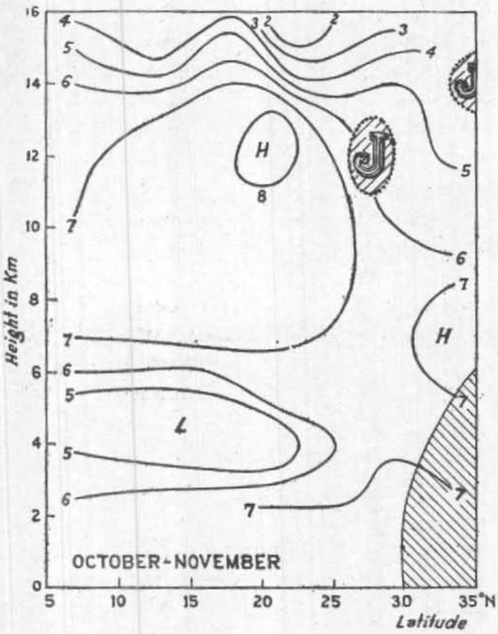


Fig. 14

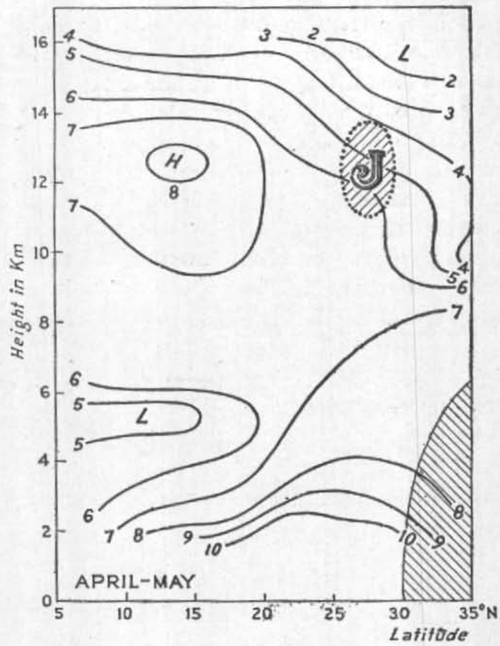


Fig. 15

Mean distribution of temperature lapse over India and neighbourhood during post monsoon and pre-monsoons seasons

γ (°K/km) :—Solid lines ; Position of jet :—J shaded ;

Terrain :—Shaded portion in the right hand corner

8. Vertical motion in the vicinity of Jet Streams—(General concepts)

In their classical paper on jet streams, the Chicago group of workers (1947) pictured 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. Palmen and Newton (1948) observed that the potential temperature fields suggested rising motion to the south of the jet (where isentropic surfaces are far apart) and sinking motion to the north, (where isentropic surfaces are closer) which they felt, was not in conformity with the absolute vorticity field. Namias and Clapp (1949) while postulating a confluence mechanism for the jet stream pictured an ascending motion to the south of the jet stream and descending motion to the north of it. Nyberg (1949) estimated downward motion in the cold air north of the jet stream and upward motion in the warm air to the south. Clapp and Winston (1951) in a case study of confluence in a jet stream found a maximum of downward motion to the north of the jet and a maximum of upward motion to the south, at the 10,000-ft level. Riehl and Teweles (1953) find that the vertical circulation postulated by the Chicago group (1947) is supported by the data in the vicinity of the mean maxima of the jets studied by them. Murray and Daniels (1953) find evidence for a transverse flow across the jet stream, with components to the left in the entrance region and to the right in the exit region, looking downstream. They postulate the existence of 'direct' thermal circulation at the entrance of jet streams and 'indirect' circulation at the exit. They have, however, no direct evidence for the vertical branches of the circulations.

9. Horizontal divergence over India

From normal zonal and meridional components (for morning and afternoon ascents) available with the I.Met.D. for all the pilot-balloon stations, mean horizontal divergence

$$\text{div}_2\, \mathbf{V} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$$

has been computed for the following levels for each of the three seasons, post monsoon, winter and pre-monsoon:

0·5, 1·5, 3, 6, 9, 12, 14 and 16 km.

The data are poor over North India above 9 km in winter and pre-monsoon and above 12 km in post monsoon seasons. Figs. 16—22 give charts of mean horizontal divergence at 6 and 9 km for the three seasons, and at 12 km for the post monsoon season. The following are the main features of distribution of horizontal divergence.

9·1. Post monsoon Season—At ·5-km level, the country to the north of 22°N is a divergent area, and the rest convergent. Convergence is well marked along the coastal belts of the south peninsula south of latitude 18°N. At 1·5 km there is general divergence all over the country. At 3 km a region of convergence appears along latitude 25°N over lower Sind and southwest Rajputana. This zone extends eastwards and southwards with height. At 12 km (Fig. 18) it is just to the south of the jet stream extending from nearly 27°N to 16°N and has two distinct maxima, one over Saurashtra and Gujarat and the other over Orissa. The maximum cannot be located definitely further eastwards due to absence of data.

9·2. Winter Season—During this season there is general divergence all over the country upto 3 km, except along Malabar coast where convergence exists upto 0·5 km. At 3 km a region of convergence develops over the central parts of the country and this zone spreads laterally at higher levels. At 9 km (Fig. 20) the convergence zone lies between 15°N and 25°N with two maxima one over Saurashtra and the other over Orissa. The computation could not be extended to higher levels due to lack of data. The regions of convergence follow almost the same pattern as in the post monsoon period.

9·3. Pre-monsoon Season—It is well known that this is a period of intense surface heating over the country. At ·5 km there is convergence all over the country, the maximum being over northeast India and along the Malabar coast. At 1·5 km the region of convergence is confined to the central parts of the country and the interior of the peninsula, the maximum being near Chota Nagpur. At 3 km there is general divergence all over the country. At 6 km (Fig. 21) convergence develops over northeast India and Uttar Pradesh and also along a narrow belt along 20°N. At 9 km (Fig. 22) a well marked zone of convergence extends from the west coast to northeast India with two maxima at either ends of this zone. Available data indicate that the zone of convergence persists at 12 km also but with its western maxima slightly shifted eastwards.

10. Vertical motion over India (Kinematic method)

From the mean horizontal divergence charts, the mean vertical motion at each level can be worked out with the help of the equation of continuity from the formula

$$w = -\frac{1}{\rho}\int \rho\, \text{div}_2\, \mathbf{V}\, dz \qquad .. \text{(1)}$$

where w is the vertical velocity at a height of z above the surface of the earth and the other symbols have their usual significance. Horizontal variations in ρ have been neglected

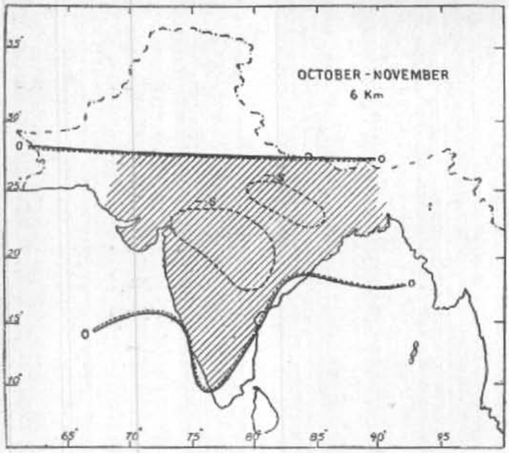


Fig. 16

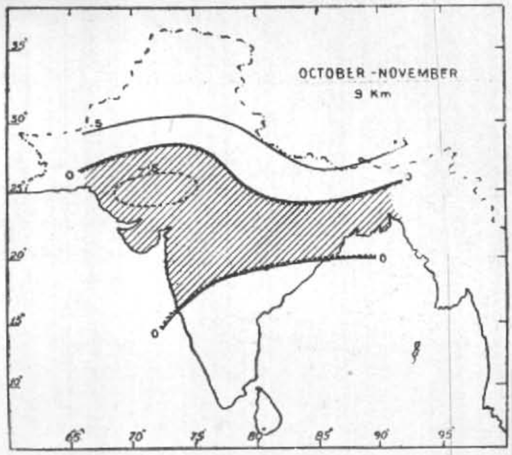


Fig. 17

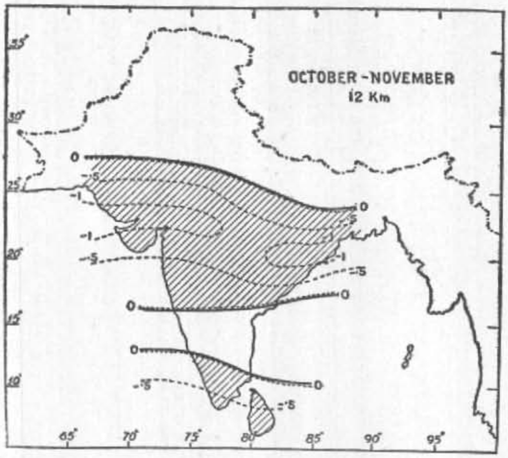


Fig. 18

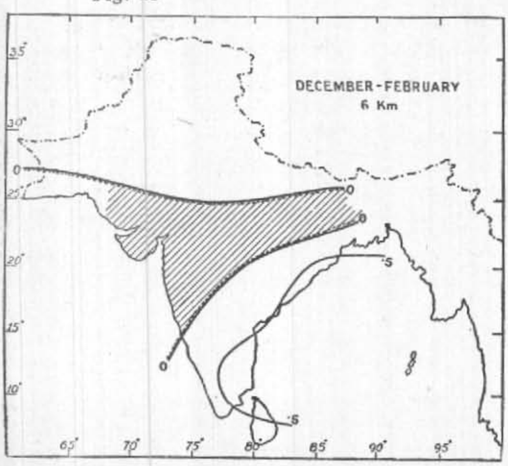


Fig. 19

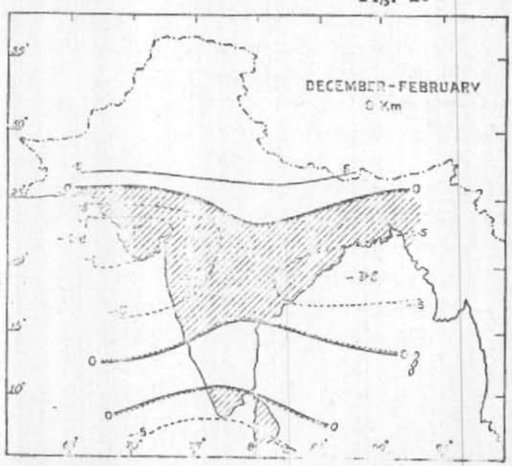


Fig. 20

Figs. 16—20. Charts of mean horizontal divergence over India and neighbourhood during October-November and December—February

Isopleths of divergence (units of 10^{-5}) :—Solid lines ; Isopleths of convergence :—Dashed lines ; Convergent area :—Shaded

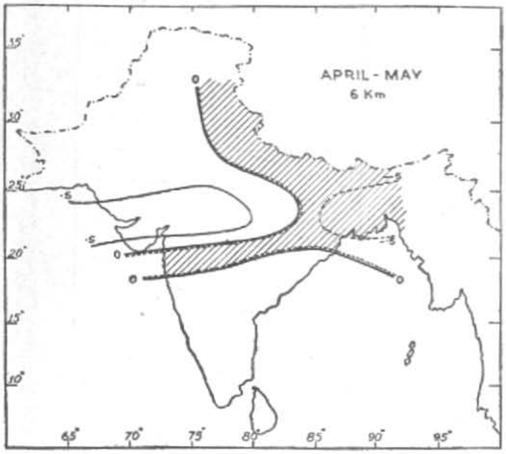


Fig. 21

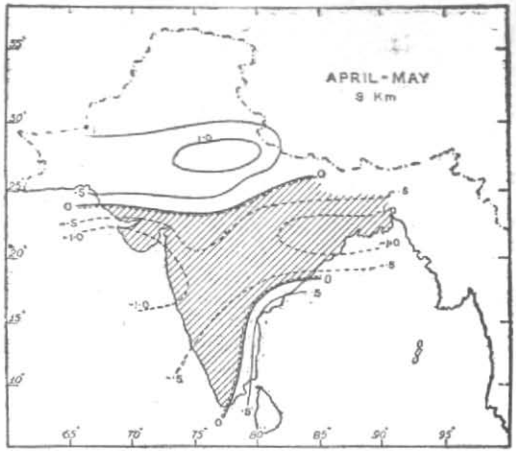


Fig. 22

Charts of mean horizontal divergence over India and neighbourhood during April-May

Isopleths of divergence (units of 10^{-5}) :—Solid lines ; Isopleths of convergence :—Dashed lines ; Convergent area :—Shaded

To get a composite picture for the whole country, the horizontal divergence was averaged for each latitudinal strip and the average taken to represent the divergence for the latitude concerned. The profiles of ρ $\text{div}_2 \mathbf{V}$ with altitude were constructed for each $2\frac{1}{2}°$ latitude and the vertical velocity at each standard level computed, from equation 1. Vertical velocities for levels above 9 km, are based upon decreasing number of observations and were computed only when consistant values of horizontal divergence at these levels were available. Figs. 23–25 give the meridional cross-sections of vertical velocities for each of the three seasons. The mean meridional (horizontal) components of winds at each level have also been indicated in the cross-sections. The vertical components being in cm sec^{-1} and the meridional components in m sec^{-1}, the relative scales of the arrows have to be borne in mind when examining these cross-sections. The salient features of the vertical currents in the vicinity of the jet stream in each season, as seen in these cross-sections, is the rising motion to the south of the jet and sinking motion to the north of it. The jet stream region itself appears to be one of subsidence. Another feature that is noticeable in the charts for the post monsoon season, where data are available above the jet stream level also, is the existence of a circulation pattern postulated by Namias and Clapp (1949). There is a southward transport of air below the jet and a northward transport above it. Similar circulation patterns may be inferred in the cross-sections for the other seasons. In the pre-monsoon season, the northerly components persist to a lower latitude at and above the jet stream level than in the post monsoon season, though the vertical motion pattern remains nearly the same. It may also be observed that the level at which vertical ascent of air to the south of the mean jet stream begins varies with the seasons. It is lowest in winter (4·5 km) and highest in the pre-monsoon season (10 km).

11. Vertical motion over India (Adiabatic method)

11·1. General—An idea of the vertical motion in the atmosphere may be obtained from the temperature and wind distribution by the application of what is known as the adiabatic method (Panofsky 1946). The

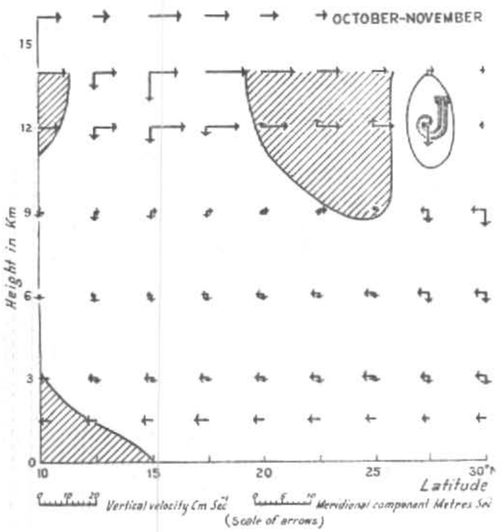


Fig. 23

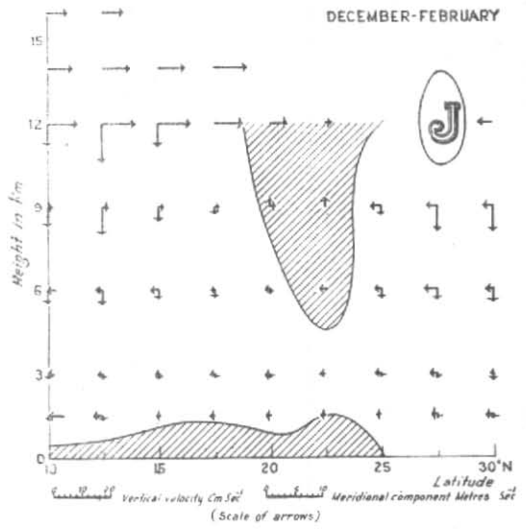


Fig. 24

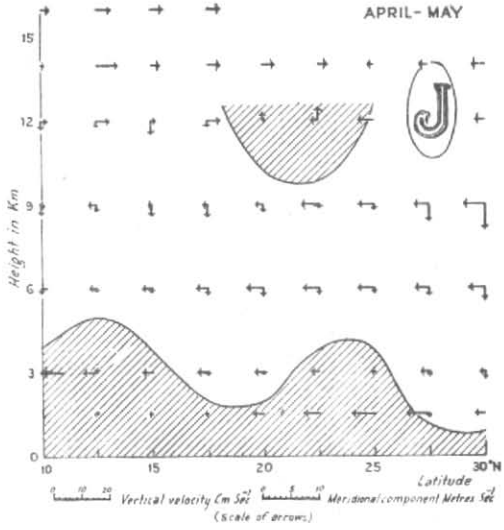


Fig. 25

Figs. 23-25. Mean distribution of vertical and meridional components derived from pibal winds during dry seasons

Vertical and meridional components :—Arrows ; Areas of upward motion :—Shaded : Position of jet :— J magnitude of the computed motions in this method would be somewhat large due to the neglect of non-adiabatic processes, but one can estimate the signs of the vertical motion correctly.

From the equation

$$\frac{\partial T}{\partial t} + \mathbf{V}.\nabla T + w(\gamma_{ad} - \gamma) = 0 \quad \ldots (2)$$

Since $\frac{\partial T}{\partial t} = 0$ for mean values

$$w = -\frac{\mathbf{V}.\nabla T}{(\gamma_{ad} - \gamma)}$$

For mean meridional cross-sections,

$$\mathbf{V}.\nabla T \approx v\frac{\partial T}{\partial y}$$

$$\therefore w = \frac{v\beta}{(\gamma_{ad} - \gamma)} \quad \ldots \ldots (3)$$

where v is the mean southerly component of velocity and β is the temperature gradient (positive when temperature decreases northward). Since $(\gamma_{ad} - \gamma)$ is always positive, the sign of w should be same as $v\beta$. Below the jet stream level, β is mostly positive and hence w and v are of the same sign, indicating ascent in southerly streams and descent in northerly streams, which is generally supported by the results of the kinematic method.

11·2. Vertical motion near the jet—Above the jet stream level, the reversal of temperature (β negative) does not take place right upto the equator as may be seen from Figs. 7 and 9 of the authors' paper on winter jet streams (1953 b), there being still a region of positive gradient over very low latitudes. This is caused by the existence of a ring or pool of cold air to the south of the jet streams at the level of the jet maximum which spreads southwards with height. The transport of air at these levels is generally from south to north round the sub-tropical high pressure cells, as can be seen from the 150 and 100 mb charts. As such, to the north of the jet and above it, since β is negative, w becomes negative and there is sinking motion in the southerly currents. Any advection of northerly air in this region would give rise to ascending motion.

Just to the south of the jet, at the jet stream level, however, there is a region of almost constant temperature and hence equation (3) does not indicate any vertical motion. It may be pointed out that equation (3) neglects the ∇p factor as mentioned in the foot note to Panofsky's paper (1946). Taking ∇p into account, equation (2) may be written as

$$\frac{\partial T}{\partial t} + \mathbf{V}.\nabla T + \frac{A\mathbf{V}.\nabla p}{\rho c_p} + w(\gamma_{ad} - \gamma) = 0 \quad (4)$$

where $A = \frac{1}{J}$

Since $\frac{1}{\rho}\nabla p$ on a constant level surface is equivalent to $g\nabla z$ on a constant pressure surface, neglecting $\partial T/\partial t$ and approximating for meridional cross-section, the equation may be written as

$$w = \frac{v}{\gamma_{ad} - \gamma}\left(\beta - \frac{\partial z}{\partial y} \cdot \frac{g.A}{c_p}\right) \quad \ldots \quad \ldots (5)$$

The second term in the equation (5) assumes importance in the vicinity of the jet maximum where $\beta = 0$, due to the large values of $\partial z/\partial y$ (contour gradient). Hence though β may be zero or slightly negative, in the region just south of the jet and above it, the second term gives positive values which leads to upward motion. Thus it may be seen that in the cold pool region to the south of the jet, the upward moving air from the lower levels continues its course even above the jet level. As however, β assumes increasingly negative values with height, the upward motion is retarded and probably ceases near about the tropopause.

A dynamical necessity for the existence of the cold pool to the south of the jet, may be inferred by an examination of the upward currents in Figs. 23-25, which were derived from mean pilot-balloon values. The upward currents to the south of the jet increase with height upto the jet altitude without showing any tendency to decrease. Since, as per continuity consideration, upward currents should extend even above the jet, and the air motion in this region is generally southerly, β has to be positive (temperature decreasing northwards) to give rise to upward velocities. Hence there must be a region to the south of the jet stream and above it, where the temperature still decreases northwards and, therefore, is the necessity for the cold pool.

Thus adiabatic considerations indicate a circulation pattern of southerly tropical air rising to the south of the jet, spreading northwards over it and sinking through and to the north of the jet similar to that derived by the kinematic method.

11·3. Vertical motions in the sub-tropical anticyclonic cells— In the above paragraphs, the study of vertical motion was cofined mainly to the vicinity of the jet stream. Since the jets form at the northern edges of the sub-tropical high pressure cells, an estimation of the vertical motion in the sub-tropical cells will be of interest for getting a picture of the general circulation in the tropical regions. It may be seen from the mean contour charts in this paper and in the earlier paper on Winter Jet (1953 a), as well as from the departmental upper wind charts (1943) that the sub-tropical ridge is a very prominent feature above the 2-km level. Its axis is generally located between 10°N and 15°N above the 500-mb level. During the dry season, it reaches its southern limit in winter and northern limit in post monsoon. In the monsoon season, it shifts further north, a feature which will be discussed elsewhere.

The sub-tropical ridge breaks up into cells and the western extremity of the eastern cell is located at the higher levels over the Bay of Bengal and Peninsular India. This feature helps in producing confluence over northern India leading to the vertical motion pointed out in the previous paragraphs. The sub-tropical cells being warm anti-cyclones, the temperature decreases north and south of the axes of the cells. The reversal of temperature gradient at and above the jet stream level first occurs to the north of the cells resulting in a cold pool of upward moving air between the jet stream and the axis of the sub-tropical ridge and the cold pool spreads southwards at higher levels as pointed above. With this spreading, the anti-cyclone extends northwards with height.

We may now apply adiabatic considerations as per equation 3, to the air motion in these cells. Below the jet stream level, since β is positive to the north of the axis of the cell and negative to the south, northerly currents in this region indicate subsidence in the northern half of the cells and ascent in the southern half, whereas southerly currents denote ascent in the northern half and descent in the southern half. Even above the jet level, due to the formation of the cold pool mentioned above, β still remains positive in the northern half of the cell and hence the vertical motion of the southerly air in this region is ascent. With the spreading of the cold pool southwards at high levels, the southward decrease of temperature at low latitudes (β negative) ceases, and β tends to become positive which would indicate rising motion in the prevailing southerly currents. Thus the rising currents in the northern half of the sub-tropical ridge, seem to extend to the southern half also, above the jet stream level. This ascending motion over the sub-tropical ridge at high levels, may perhaps give a clue to the existence of the high tropopause over the tropics.

11·4. Vertical motion and lapse rate—The picture of downward motion below the jet stream level and upward motion above it in the sub-tropical anti-cyclones would result in a vertical stretching of the air at the jet altitude and hence large lapse rates, which is in accord with observations. Above the jet level, the ascending motion below the tropopause and the descending motion above should produce a compression and low lapse rates and since the transition from large lapse rates to zero takes place rather rapidly, the tropopause discontinuity should be sharp. On the other hand at the higher latitudes where lapse rates in the upper troposphere are not large, the transition to zero takes place gradually or in stages. In the latter case, a number of tropopause discontinuities may occur. Sinking motions in air of low lapse rates produce isothermal layers in these regions which are sometimes interpreted as extra-tropical tropopauses.

The existence of low lapse rates to the north of the jet stream cannot be explained only by the downward motion of the southerly air spreading to the north of the jet. It is found that higher lapse rates occur at lower levels in this sinking air. Moreover, there is evidence for a northerly air stream also in this region at higher latitudes, and this according to adiabatic considerations, should undergo a rising motion, which is in accord with the observation of high tropopause extending considerably north of the sub-tropical jet. The cause of these diminished lapse rates may have to be found from other factors, *e.g.*, stratospheric advection. If the northerlies mentioned above have their origin from the polar stratosphere, they are warmer and hence contribute to the diminution of lapse rates in the tropical troposphere just to the north of the jet stream. The break in the tropopause would facilitate such an advection. A plausible method of detecting such advection would be from ozone measurements and it is significant that Karandikar and Ramanathan (1949) report an increase in ozone amount with the advection of northerly air over north India and decrease in southerly air. They find such increases, though small, occurring during winter and early hot season in the layer 9-18 km. These observations lend support to the conjecture of stratospheric advection as mentioned above and the consequent decrease in lapse rates of the high troposphere over the tropics.

12. Mechanism of Jet Streams

The studies of divergence and vertical motion both from actual pibal wind charts by the kinematic method and from temperature advection by the adiabatic method, indicate the existence of confluence over northern India during the dry season, the two confluent currents being the equatorial southwesterlies round the sub-tropical anticyclonic cell over the Bay of Bengal and the south peninsula and the continental westerlies or northwesterlies from high latitudes. The possibility of such a confluence was pointed out by Namias and Clapp (1949). It may, however, be pointed out that Namias and Clapp postulated the confluence theory for the jet stream occurring at the tropopause (polar front type). They picture the tropopause piercing through the jet and undergoing such a deformation due to the upward current to the south of the jet and downward motion to the north of it. Though such currents exist in the sub-tropical jet over India, it is found that the tropopause is well above the jet and sensibly horizontal above it. A plausible explanation for this non-deformation of the tropopause over the sub-tropical jet has already been suggested as due to the existence of upward currents in the high troposphere just below the tropopause even to the north of the jet latitude. Thus, except for this little difference, it appears that the sub-tropical jet stream over India is of the confluent type.

Due to this confluence over northern India, the jet stream is in the process of acceleration and the mean jet stream over India should, therefore, be considered as representative of the ' entrance ' to the jet, *i.e.*, the part of the jet where air is accelerating downstream. The northward transport of air through the jet and above it over India is thus in accord with the observation of Murray and Daniels (1953) that at the entrance to the jet, the transport of air is to the left, looking downstream. Murray and Daniels postulate a double circulation of opposite directions below and above the jet, for which there is, however, no evidence from the Indian data. As regards the condition at the ' exit ' or decelerating portion of the jet, it is evident that this portion will be located at the eastward end of the sub-tropical anticyclonic cell. Since the air motions in the eastern end is the reverse of that in the westward end, adiabatic consideration should lead to the conclusion of a reverse circulation pattern through this portion of the jet as was found by Murray and Daniels.

It may, however, be mentioned that most of the jets studied by Murray and Daniels must have been of the polar front type, considering the high latitudes of their occurrence. Hence the existence of reverse circulations in the polar front type of jet also may give a possible explanation for the conflicting conclusions about vertical motion made by various authors as mentioned in Section 8. The existence of double jets should still further complicate the circulation patterns depending upon whether either of them is in the developing or dissipating stage.

The inference that could be drawn from the available data at this stage, however, seems to be that, looking downstream, the circulation in a jet stream is cyclonic at its accelerating end and anti-cyclonic at its decelerating end.

13. Clear air turbulence near the sub-tropical jet

The occurrence of clear air turbulence at high altitudes above 20,000 ft is fairly well known. In most aircraft reports this turbulence is described as slight or moderate but there are cases when bumpiness can be severe. One of the obvious causes for such bump is the existence of adjacent ascending and descending currents in the atmosphere as in the case of convective clouds. The vertical motion cross-sections in Figs. 23–25 may, therefore, be of help in giving an idea of the probable areas where high altitude turbulence can exist. From an examination of these cross-sections, it will be seen that at the southern edge of the jet stream there is a sharp transition from the descending currents to ascending currents. This zone could be a region of turbulence in the mean, and hence day to day occurrences of turbulence may be expected mainly in this region. No such transition occurs to the north of the sub-tropical jet stream, though there must be a relative shear in the downward currents. As such, though there may be turbulence in this area, it is not likely to be severe.

An attempt has been made to verify the above conclusion about the existence of a clear disturbance zone to the south of the jet stream, from the reported regions of incidence of clear air turbulence by BOAC Comet aircraft on the main International air routes over India, *viz.*, Rangoon-Calcutta-Delhi-Karachi and Karachi-Bombay-Colombo in the dry season October to April. Out of 187 aircraft reports available, only 17 reported clear air turbulence, 3 being severe, 6 moderate and 8 slight. The latitudes of occurrence were between 16° and 26°N and the altitudes mainly between 9 and 12 km. Fig. 27 indicates the distribution of air turbulence reports. The 3 reports of severe turbulence occur between 23° and 25°N, *i.e.*, just south of the mean jet stream. Inspite of the meagre data, the locations of these reports is significant and is in accordance with the conclusion mentioned above.

It would be interesting to note in this connection that Bannon (1952) who investigated the incidence of high altitude turbulence with reference to the jet stream over the U.K., found that in most cases the region of incidence was at the tropopause discontinuity to the north of the jet. Associating the zones of incidence with wind shear, he found that in most cases observations of severe turbulence near a jet stream were probably associated with large vertical shear but that it seems likely that in a few cases they were associated with large horizontal shears also. Since the jet stream over U.K. is of the polar front type, if we assume that the vertical motion associated with it are of the type postulated by the Chicago group (1947), the transition from ascending to descending currents should occur to the north of the polar front jet stream at the polar tropopause, the zone gradually sloping upwards in the tropical troposphere.

14. Conclusions

The following are the main conclusions of this investigation :

1. A sub-tropical westerly jet stream exists over northern India during all the months of the dry season (Oct-May) at about 27½°N. Mean speed fluctuates from 30 mps in post monsoon and pre-monsoon seasons to 50 mps in winter.

2. The jet stream sets in soon after the withdrawal of the southwest monsoon and withdraws before the setting of the monsoon in northern India. It reaches its southern-most position (25°N) in February and northern-most position (29°N) in May and shifts out of the country later. It is strongest in February and weakest in May.

3. As in the winter season, high lapse rates exist to the south of the jet stream at higher levels and low lapse rates to the north of it. The zone of maximum lapse rate gradient lies near the jet.

4. A zone of convergence exists in the higher levels to the south of the jet. The formation of the jet to the north of this convergence zone gives strong support to the confluence mechanism for its formation, the confluent currents being the southwesterlies round the sub-tropical high pressure cell and the west to northwesterlies from the higher latitudes.

5. The vertical motion in the vicinity of the jet, as derived both by an analysis of the pibal winds by the kinematic method and also of the temperature fields by the adiabatic method, indicates ascending motion to the south of the jet and descending motion to the north of it, with a southward transport of air below it and northward transport above it. Thus there is evidence for a circulation pattern of the type postulated by the confluence theory. This pattern should be considered as applicable to the ' entrance' or accelerating portion of the jet.

6. The pattern for vertical motion above gives an indication about the lapse rate pattern in the troposphere, high lapse rate occurring in zones with marked distention and low lapse rates in zones of compression.

Ascending currents are found just below the tropical tropopause above the sub-tropical anti-cyclone, thus giving a possible explanation for the high tropopause over the sub-tropical cells which consist of mainly descending air.

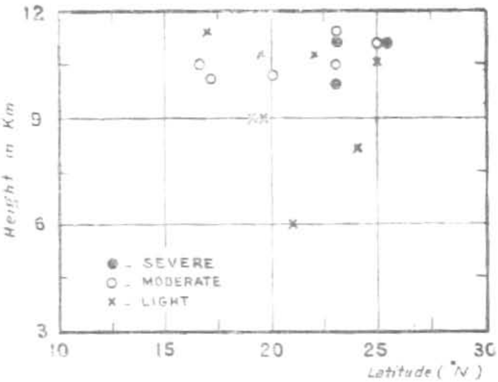


Fig. 26. Distribution of clear air turbulence reports over India (October—May)

7. The low lapse rates to the north of jet stream over northern India at high levels, which cannot be explained solely by dynamical processes are attributed to the advection of polar stratospheric air into the tropical troposphere, which is supported by evidence from ozone measurements.

8. The existence of adjacent strong upward and downward currents indicates a region of clear air turbulence to the south of the jet. Available reports of clear air turbulence from high level aircraft lend support to the same.

REFERENCES

Bannon, J. K. (1952). *Met. Mag.*, **81**, 958, p. 97.

Clapp, P.F. and Winston, T. S. (1951). *J. Met.*, **8**, 4, p. 231.

Ind. met. Dep. Climatological charts of India and neighbourhood for meteorologists and airmen (1943).

Karandikar, R. V. and Ramanathan, K. R. (1949). *Proc. Ind. Acad. Sci.*, **29A**, 5, p. 330.

Koteswaram, P. (1953a). *Ind. J. Met. Geophys.*, **4**, 1, p. 13.

Koteswaram, P., Raman, C. R. V. and Parthasarathy, S. (1953b). *Ind. J. Met. Geophys.*, **4**, 2, p. 111.

Koteswaram, P. and Parthasarathy, S. (1953c). *Ind. J. Met. Geophys.*, **4**, 2, p. 187.

Murray, R. and Daniels, S. M. (1953). *Quart. J. R. met. Soc.*, **79**, 340, p. 236.

Namias, J. and Clapp, P. F. (1949). *J. Met.*, **6**, 5, p. 330.

Nyberg, A. (1949). *Tellus*, **1**, 1, p. 44.

Panofsky, H. A. (1946). *J. Met.*, **3**, 2, p. 45.

Palmen, E. and Newton, C. W. (1948). *J. Met.*, **5**, 5, p. 220.

Ramage, C. S. (1952). *J. Met.*, **9**, 6, p. 403.

Riehl, H. and Teweles, Jr., S. (1953). *Tellus*, **5**, 1, p. 66.

Univ. Chicago (1947). *Bull. Amer. met. Soc.*, **28**, 6, p. 255.