551·553·21 : 551·524·4(54)

Zonal wind circulation and vertical temperature distribution along the Indian longitudes during the monsoon and winter seasons

D. A. MOOLEY

Regional Meteorological Centre, New Delhi

(*Received 28 June 1954*)

ABSTRACT. The study is based on all the available wind and temperature data for 1944-49. Sections of geostrophic zonal wind and temperature and of observed zonal winds have been prepared. Frequencies of strong winds (speed 70 knots or more) along the section have been worked out for the different latitudes. The chief features of the monsoon sections are—(*i*) Generally small latitudinal temperature variation upto 300-mb level and an appreciable variation at 200-mb and 150-mb levels in Madras-Nagpur and Nagpur-Jodhpur sectors (*ii*) Strong easterly winds south of 15°N at 14 km and above. The chief features of the winter sections are—(*i*) An appreciable latitudinal temperature gradient between Poona and Peshawar upto 400-mb level and reversal of gradient above 200-mb level as observed by others, (*ii*) Strongest zonal (west) wind near 23°N and a secondary wind maximum apparently near 30°N and (*iii*) A fairly high frequency of strong winds between 21° and 31°N. From a consideration of the frequency of high winds, a well-marked jet south of 20°N seems unlikely. A comparative study of the various mean sections indicates that during winter, jets in the northern hemisphere are found over a much wider latitudinal belt than in the southern hemisphere and during summer, the westerly jets in northern hemisphere are much weaker than those in the southern hemisphere.

1. Introduction

The vertical cross-sections of the atmosphere prepared by Venkiteshwaran (1950) for longitude 78°E across India for winter and monsoon seasons on the basis of data for a large number of years indicated a maximum westerly wind of 40 mps near latitude 28°N at about 13 km during winter and a maximum easterly wind of the same speed near 10°N at 16 km during summer. Chaudhury's (1950) cross-section for Indo-Pakistan, representing mean winter conditions for 1946 along longitude 76°E, showed a double maximum of geostrophic zonal wind —one with westerly 70 mps near 31°N at 200-mb level and the other (designated by him as 'Equatorial Jet') with westerly 40 mps between latitudes 13° and 18½°N at nearly the same height. The mean winter cross-section representing conditions over India, Pakistan and Burma prepared by Koteswaram, Raman and Parthasarathy (1953) shows the existence of geostrophic zonal wind maximum of 53 mps near 27°N at 200-mb level. In connection with the Equatorial Jet of Chaudhury, Koteswaram and co-workers have pointed out that Poona temperatures and consequently the heights of the constant pressure surfaces, during the winter of 1946 were too low and hence geostrophic winds between 13° and 18½°N were high and they have concluded that there is definitely a single mean jet stream over the country at about 27°N and none over lower latitudes.

Gibbs (1952) has shown the existence of double maximum of geostrophic zonal wind across 150°E during winter—one at 29°S and the other at 20°S, both having the same speed and the same height.

To study conditions during the monsoon, cross-sections Colombo to Peshawar giving temperatures and calculated (geostrophic) and actual zonal winds based on the data of stations lying between 71½° and 80½°E and between latitudes 7° and 35°N were prepared for the monsoon months, July and August. Similar cross-sections have also been prepared for the winter months (mean of January and February).

Observational data

2·1. *Temperature*—Temperature data for all radiosonde stations for January, February, July and August for the years 1944-49 in respect of evening ascents only have been considered as indicated in Table 1.

All the stations lie within the longitudinal range 71½° to 80½°E. The time of ascents varied from 1300 to 1700 GMT and the data may be considered as those relating to 1500 GMT, the mean time of ascents. During July and August 1948, radiosonde ascents were made in the morning at 0300 GMT and these data have not been considered.

2·2. *Wind*—The available upper wind data for January, February, July and August for the years 1944-49 for 0900 GMT only for all the pilot balloon stations lying within the same longitudinal range, *viz.*, 71½° to 80½°E, have been considered. The stations are shown in the map of India (Fig. 1). Data for the following stations were available for a shorter period—

Drosh	1944-47
Suratgarh	1944-46
Bikaner	1947-49
Rajsamand	1944-47
Udaipur	1948-49
Anantapur	1947-49

3. Tabulation and analysis of data

3·1. *Temperature and humidity*—The data were extracted from the Indian Daily Weather Reports for the years 1944-49. In a few cases, data were not available in I.D.W.R. and they were obtained from the records of plotted T-φ grams. As the main purpose is to study the distribution of temperature and wind above 6 km only those days on which ascents reached 500-mb level or higher were considered. Daily values of temperature for each station were tabulated for the surface level and pressure levels 1000, 900, 850, 800, 700, 600, 500, 400, 300, 250, 200, 150, 100, 80 and 60 mb. Relative humidity was tabulated upto 500-mb level since on account of

TABLE 1

Serial No.	Station	Lat. (N)	Long. (E)	Height (metres)	Years for which data have been used	
					Winter	Monsoon
1	Peshawar	34° 01′	71° 35′	335	1944-47	1944-46 (Also a week's data for July 1947)
2	Multan	30 12	71 31	126	1946 and Feb 1945	1945
3	New Delhi	28 35	77 12	217	1944-49	1944-47 and 1949
4	Jodhpur	26 18	73 01	224	1947-49	1946-47 and 1949
5	Nagpur	21 09	79 07	312	1947-49	1947 and 1949
6	Poona	18 32	73 51	559	1945-49	1944-47 and 1949
7	Madras	13 04	80 15	16	1947-49	1946-47 and 1949
8	Trivandrum	08 29	76 57	61	1948-49	1947 and 1949
9	Ratmalana (Colombo)	06 54	79 52	7	1945-46	1945

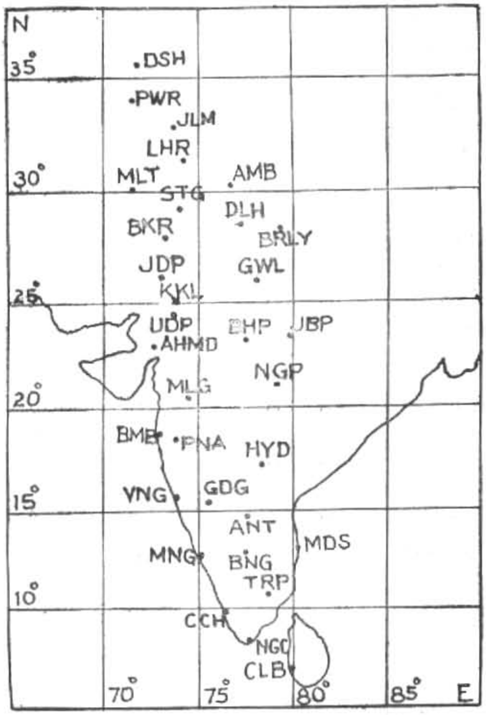

Fig. 1

low moisture content of air above this level virtual temperature corrections are negligible. For stations where marked ground inversion of temperature is a rule during winter, daily mean temperature between ground and 900-mb level was also tabulated and the average of these daily mean temperatures for ground—900 mb layer was used in the calculation of the mean height of 900-mb surface instead of the average of mean temperatures at surface and 900 mb. Mean virtual temperatures upto 500-mb level were obtained for each of the radiosonde stations. Mean values of temperature and humidity for each of the stations for the various pressure levels are given under Tables 2 and 3 for the monsoon and winter respectively. Number (n) of temperature values available at each of these levels is also given in these tables.

Annual seasonal means for monsoon and winter as well as the range of the annual means for each of the levels from 900 to 100 mb for New Delhi and Poona were calculated. The values are given under Tables 4 and 5 for monsoon and winter respectively. The number of observations available for each level is given within brackets. New Delhi was considered as representative of the northern radiosonde stations and Poona, representative of southern radiosonde stations. A study of Tables 3 and 4 shows that there are considerable variations from year to year.

3·2. *Calculation of zonal geostrophic winds*—Geostrophic winds were calculated for latitudes north of 13°N from the slope of the isobaric surfaces for levels upto 100 mb. From the mean virtual temperature distribution, heights above mean sea level of the various constant pressure surfaces were obtained for Peshawar, New Delhi, Jodhpur, Nagpur, Poona and Madras. Longitudinal separation between two successive stations from Delhi to Madras in the order of decreasing latitude would be more than the latitudinal separation; in some cases it may be almost double, *e.g.*, between New Delhi and Jodhpur, Nagpur and Poona. This factor is likely to influence the geostrophic wind if slopes (given by height differences) of the constant pressure surfaces between two successive stations in the order of decreasing latitude are considered. Theoretically, there should be no objection to considering successive stations provided the wind is entirely zonal, the distribution of data in respect of space and time are identical and instrumental errors in the temperature data are absent. Wind is predominantly zonal above 6 km and for latitudes north of 15°N: but the distribution of data is not symmetrical and instrumental errors are not absent. The geostrophic wind was, therefore, calculated for the two sections—one along Peshawar, Jodhpur, Poona and Trivandrum and the other along New Delhi, Nagpur and Madras. The stations along these two sections differ very little in longitude. Winds along one section were superposed over those of the other section. Thus a section of the zonal geostrophic wind extending

TABLE 2

Mean temperature and humidity during monsoon

Station	1000 H	1000 T	900 H	900 T	850 H	850 T	800 H	800 T	700 H	700 T	600 H	600 T	500 H	500 T
	Pressure (mb)													
Peshawar	..	..	50	302·1 (153)	55	298·4 (153)	60	294·4 (153)	55	287·6 (153)	35	279·6 (153)	40	269·9 (152)
Multan	..	..	55	301·5 (53)	60	297·0 (53)	65	292·8 (53)	65	284·9 (53)	50	276·4 (53)	40	267·0 (53)
Delhi	..	..	70	299·2 (278)	75	296·0 (278)	80	292·0 (278)	75	285·3 (278)	70	278·1 (278)	65	270·1 (278)
Jodhpur	..	..	65	299·1 (153)	75	295·2 (153)	70	291·9 (153)	60	285·8 (151)	70	277·9 (153)	65	270·0 (152)
Nagpur	..	..	75	297·0 (97)	75	294·3 (96)	75	290·8 (96)	70	284·7 (96)	70	278·1 (96)	70	270·4 (96)
Poona	..	..	80	294·5 (286)	85	291·6 (286)	85	289·0 (286)	65	284·4 (286)	65	277·5 (285)	65	269·6 (286)
Madras	70	301·8 (161)	70	296·6 (161)	75	293·1 (161)	80	289·3 (161)	75	282·3 (160)	70	275·0 (159)	70	266·9 (158)
Trivandrum	85	298·5 (106)	80	293·0 (106)	80	290·5 (106)	75	288·0 (105)	65	283·0 (104)	60	275·5 (104)	..	266·5 (104)
Ratmalana	80	299·5 (40)	80	292·0 (40)	75	290·0 (40)	75	287·0 (40)	60	281·5 (40)	55	274·5 (40)	60	266·5 (40)

Station	400 T	300 T	250 T	200 T	150 T	100 T	80 T	60 T
	Pressure (mb)							
Peshawar	261·5 (147)	246·1 (139)	236·4 (131)	225·3 (121)	212·7 (59)	202·5 (15)	201·0 (3)	..
Multan	257·8 (53)	243·8 (42)	235·2 (30)	222·3 (24)	210·2 (13)	202·3 (3)	200·0 (2)	..
Delhi	259·7 (262)	245·7 (237)	235·7 (199)	224·3 (166)	211·4 (89)	202·9 (30)	200·5 (12)	196·7 (4)
Jodhpur	259·8 (122)	245·8 (106)	234·1 (85)	222·3 (68)	208·3 (25)	207·0 (3)	..	..
Nagpur	260·7 (81)	246·6 (67)	238·1 (42)	227·4 (20)	213·4 (7)	204·0 (1)	..	..
Poona	259·9 (261)	246·0 (192)	236·5 (140)	224·6 (87)	210·2 (30)	196·8 (5)	..	..
Madras	256·5 (141)	241·1 (109)	231·5 (81)	218·9 (50)	203·0 (15)	..	..	..
Trivandrum	256·0 (99)	241·5 (90)	231·5 (47)	220·5 (27)	208·0 (2)	..	..	..
Ratmalana	256·0 (40)	241·5 (38)	230·5 (33)	218·5 (28)	205·5 (11)	196·5 (2)	193·0 (1)	..

H indicates mean relative humidity, *T* the mean temperature (°A)

The number of temperature values available is given within brackets

TABLE 3

Mean temperature and humidity during winter

Station	Pressure (mb) 1000 H	1000 T	900 H	900 T	850 H	850 T	800 H	800 T	700 H	700 T	600 H	600 T	500 H	500 T
Peshawar	..	..	40	283·7 (197)	40	280·2 (199)	45	276·7 (198)	50	269·2 (199)	45	261·1 (199)	45	252·3 (198)
Multan	..	..	30	287·1 (71)	35	283·3 (71)	35	280·0 (71)	40	272·5 (71)	35	264·7 (71)	..	256·1 (71)
Delhi	..	..	45	287·2 (317)	40	283·9 (318)	55	280·6 (317)	40	273·7 (318)	40	265·7 (319)	35	256·7 (321)
Jodhpur	..	..	35	290·0 (150)	45	285·5 (150)	50	281·6 (149)	45	275·0 (150)	45	267·4 (149)	..	258·3 (152)
Nagpur	..	..	45	293·5 (151)	45	289·8 (151)	55	285·6 (151)	45	278·2 (150)	30	271·5 (150)	35	262·9 (148)
Poona	..	..	35	296·2 (286)	35	292·5 (286)	40	288·4 (286)	35	280·8 (284)	25	274·0 (284)	..	264·8 (284)
Madras	75	298·0 (156)	60	292·3 (155)	50	289·7 (153)	45	286·9 (150)	30	282·2 (151)	25	275·3 (150)	..	266·4 (142)
Trivandrum	70	299·5 (112)	70	293·1 (111)	70	290·0 (110)	55	287·4 (110)	35	282·4 (111)	25	275·0 (112)	30	266·4 (112)
Ratmalana	80	298·3 (53)	75	291·4 (52)	75	288·7 (53)	65	285·2 (53)	35	281·4 (53)	30	274·2 (53)	35	265·8 (53)

Station	Pressure (mb) 400 T	300 T	250 T	200 T	150 T	100 T	80 T	60 T
Peshawar	240·7 (180)	228·7 (141)	222·1 (112)	218·8 (69)	215·5 (34)	211·2 (26)	210·0 (16)	210·3 (7)
Multan	245·5 (64)	234·3 (46)	227·5 (36)	222·0 (29)	214·3 (13)	210·0 (2)	207·5 (2)	..
Delhi	245·3 (305)	232·9 (229)	225·9 (186)	219·8 (131)	212·1 (76)	206·8 (25)	206·8 (10)	206·5 (2)
Jodhpur	247·0 (143)	232·8 (126)	224·8 (92)	217·2 (59)	208·8 (22)	199·6 (5)	195·5 (2)	..
Nagpur	251·3 (134)	236·5 (95)	228·2 (76)	218·7 (32)	209·4 (12)	205·0 (1)	203·0 (1)	..
Poona	253·4 (278)	238·4 (256)	228·8 (231)	217·7 (161)	204·3 (77)	193·2 (20)	190·0 (6)	..
Madras*	255·0 (138)	239·6 (98)	229·1 (76)	218·6 (65)	206·8 (39)	197·4 (11)	..	..
Trivandrum	255·4 (105)	239·6 (80)	229·5 (65)	219·6 (19)	..	..	..	..
Ratmalana	254·9 (45)	238·7 (27)	228·0 (23)	216·3 (23)	204·7 (9)	200·5 (4)	..	..

*Temperature values for 150 and 100-mb levels are for Bangalore only, while those for 200-mb level are for Madras and Bangalore

H indicates mean relative humidity, *T* the mean temperature (°A)

The number of temperature values available is given within brackets

TABLE 4

Mean annual temperature during monsoon at New Delhi and Poona

Year	Pressure (mb) 900	850	800	700	600	500	400	300	250	200	150	100
						NEW DELHI						
1944	298·9	295·5	291·9	285·6	277·7	269·9	259·3	245·3	235·7	224·0	210·2	200·0
	(62)	(62)	(62)	(62)	(62)	(62)	(60)	(50)	(48)	(41)	(23)	(9)
1945	299·1	295·6	291·9	284·9	277·7	269·7	259·7	246·1	236·5	225·7	213·9	204·4
	(59)	(59)	(59)	(59)	(59)	(59)	(57)	(55)	(49)	(43)	(22)	(8)
1946	298·9	295·6	291·8	285·2	277·9	270·4	258·8	245·0	234·9	223·7	210·6	—
	(40)	(40)	(40)	(40)	(40)	(40)	(33)	(29)	(20)	(12)	(5)	
1947	300·0	296·7	292·5	285·5	278·7	271·1	260·8	247·2	237·7	227·0	212·8	204·0
	(57)	(57)	(57)	(57)	(57)	(57)	(52)	(47)	(29)	(21)	(5)	(2)
1949	299·1	296·2	291·8	285·1	277·9	269·7	259·3	244·7	234·0	222·3	210·6	204·0
	(60)	(60)	(60)	(60)	(60)	(60)	(60)	(56)	(53)	(49)	(34)	(11)
Mean	299·2	295·9	292·0	285·3	278·0	270·2	259·6	245·7	235·8	224·5	211·6	203·1
Range	1·1	1·2	0·7	0·7	1·0	1·4	2·0	2·5	3·7	4·7	3·7	4·4
						POONA						
1944	293·9	290·6	288·5	284·3	277·7	270·0	260·0	245·8	236·5	226·8	212·5	—
	(57)	(57)	(57)	(57)	(57)	(57)	(51)	(41)	(33)	(18)	(2)	
1945	294·2	290·9	288·1	283·0	276·3	268·2	258·5	244·9	235·0	222·3	208·4	198·7
	(59)	(59)	(59)	(59)	(59)	(59)	(56)	(44)	(36)	(25)	(14)	(3)
1946	294·5	291·7	289·1	284·5	278·3	270·2	260·6	246·2	236·4	224·1	210·4	194·0
	(55)	(55)	(55)	(55)	(55)	(55)	(47)	(37)	(31)	(22)	(12)	(2)
1947	295·5	292·7	290·4	285·3	278·1	270·1	261·1	248·0	239·5	229·0	218·5	—
	(57)	(57)	(57)	(57)	(57)	(57)	(55)	(39)	(26)	(12)	(2)	
1949	294·5	291·8	289·2	284·8	277·6	269·6	259·3	245·2	234·9	222·0	—	—
	(58)	(58)	(58)	(58)	(57)	(58)	(52)	(31)	(14)	(10)		
Maan	294·5	291·5	289·1	284·4	277·6	269·6	259·9	246·0	236·5	224·8	212·5	—
Range	1·6	2·1	1·9	2·3	2·0	2·0	2·6	3·1	4·6	7·0	10·1	—

Note: Figures within brackets indicate the number of temperature values

TABLE 5

Mean annual temperature during winter at New Delhi and Poona

Year	Pressure (mb) 900	850	800	700	600	500	400	300	250	200	150	100
						NEW DELHI						
1944	285·8	282·2	279·4	272·7	265·6	257·0	245·5					
	(45)	(45)	(45)	(45)	(45)	(45)	(36)					
1945	286·1	282·5	279·0	271·5	263·6	254·2	243·5	232·2	226·0	217·5	209·2	205·5
	(53)	(53)	(53)	(53)	(53)	(53)	(51)	(39)	(28)	(20)	(10)	(2)
1946	288·8	285·8	282·8	276·0	267·8	258·6	247·0	234·5	227·6	222·6	213·0	209·0
	(56)	(56)	(56)	(56)	(56)	(56)	(55)	(45)	(39)	(21)	(7)	(3)
1947	286·8	283·5	280·7	274·7	266·5	258·3	246·8	234·3	229·1	225·3	219·5	215·5
	(53)	(53)	(53)	(54)	(55)	(55)	(52)	(45)	(39)	(31)	(19)	(4)
1948	286·3	283·1	279·9	273·3	265·4	256·1	244·3	232·7	224·0	219·0	213·0	—
	(57)	(57)	(56)	(55)	(55)	(57)	(56)	(48)	(29)	(11)	(3)	
1949	289·1	285·7	281·8	273·9	265·0	256·0	244·7	231·0	223·3	216·1	208·9	204·3
	(53)	(54)	(54)	(55)	(55)	(55)	(55)	(52)	(51)	(48)	(37)	(16)
Mean	287·2	283·8	280·6	273·7	265·7	256·7	245·3	232·9	226·0	220·1	212·7	208·6
Range	3·3	4·3	3·8	4·5	4·2	4·4	3·5	3·5	5·8	9·2	10·6	11·2
						POONA						
1945	295·2	291·0	287·5	280·3	273·9	265·3	254·3	238·9	228·3	216·1	203·0	191·4
	(58)	(58)	(58)	(57)	(57)	(57)	(55)	(52)	(48)	(36)	(25)	(9)
1946	297·8	293·5	288·6	280·5	273·2	263·2	251·8	236·2	226·6	215·7	204·6	193·5
	(58)	(58)	(58)	(58)	(58)	(58)	(57)	(57)	(55)	(51)	(28)	(7)
1947	295·5	292·0	288·3	280·3	274·1	265·1	252·9	239·3	229·8	218·6	205·2	196·7
	(59)	(59)	(59)	(59)	(59)	(59)	(55)	(51)	(45)	(34)	(24)	(4)
1948	295·5	292·4	288·4	281·1	274·4	265·3	254·0	238·9	230·3	221·3	—	—
	(54)	(54)	(54)	(53)	(53)	(54)	(54)	(44)	(39)	(17)		
1949	296·9	293·3	289·1	281·7	274·5	265·1	254·3	238·8	229·8	220·5	—	—
	(55)	(55)	(55)	(55)	(55)	(55)	(55)	(50)	(43)	(23)		
Mean	296·2	292·5	288·4	280·8	274·0	264·8	253·4	238·4	229·0	218·4	204·3	193·9
Range	2·6	2·5	1·6	1·4	1·3	2·1	2·5	3·1	3·7	5·6	2·2	5·3

Note : Figures within brackets indicate the number of temperature values

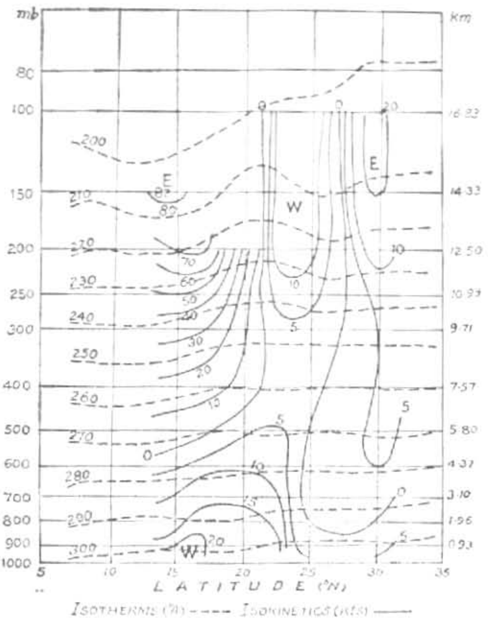

Fig. 2. Mean distribution of virtual temperature and zonal geostrophic wind at 1500 GMT during monsoon

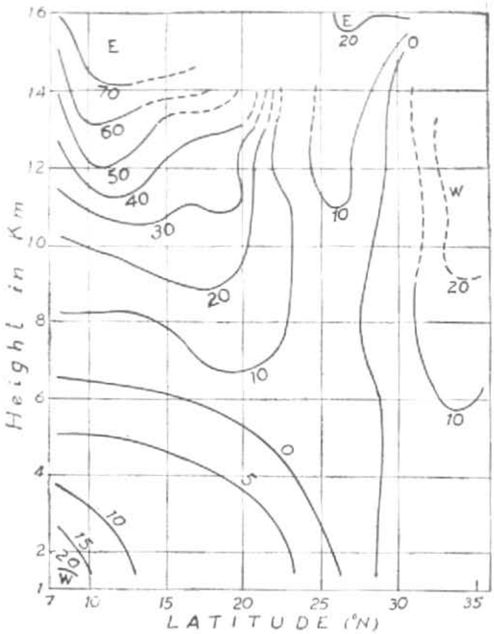

Fig. 3. Mean zonal wind distribution at 0900 GMT during monsoon (1944-49)

Speed in knots indicated on isokinetics
E — Easterly, W — Westerly

from 13° to 30°N was obtained. This was slightly extended northwards by taking into account geostrophic winds between Peshawar and New Delhi. South of latitude 13°N, the geostrophic winds were not found to be consistent.

3·3. *Wind data from pilot balloon observations*—Here also only those ascents were considered which reached 6 km or more. Mean zonal components for each of the stations were obtained for levels, 1·5, 3, 4·5, 6, 7·5, 9 and for each kilometre between 10 and 20 km. For Indian stations data were obtained from the relevant upper air registers. For Pakistan stations, data upto 9 km were collected from I. D. W. Rs. and above 9 km these could be obtained for only 1947 winter from the Monthly Weather Reports. Data for Colombo also were obtained from I.D.W.Rs. Stations very near to each other were grouped together and mean zonal winds for the mean latitude were obtained. The way how stations have been grouped can be seen from Table 6 (p. 123).

4. Distribution of temperature and wind along the section

4·1. *During monsoon*—Fig. 2 shows the distribution of virtual temperature. Upto 300-mb level, the latitudinal temperature variation is generally small except at levels between 500 and 300 mb where temperature decreases from Poona (19°N) to Madras (13°N). At 250-mb level, the temperature decreases from Nagpur(21°N) to Madras and also from Nagpur to Jodhpur (26°N), while at 200 and 150-mb levels, the temperature decrease in these sectors is appreciable. The distribution of geostrophic zonal wind is also shown in Fig. 2. A strong easterly wind of 82 knots is seen near 13°N at 150-mb level, *i.e.*, near $14\frac{1}{2}$ km. The zonal wind between 25° and 30°N and below 10 km is light, being 5 knots or less.

The observed zonal wind distribution is shown in Fig. 3. The prominent feature of this distribution is the strong easterly wind in low latitudes above 14 km. The easterly maximum as pointed out by Krishna Rao (1953) is found over Nagercoil (8°N) at 18 km. The maximum speed is 91 knots. The mean winds at Nagercoil at 17, 19, 20 and 21 km are 78, 78, 62 and 54 knots respectively. Unfortunately, Colombo upper wind data do not extend beyond 4·5 km, Trichinopoly (11°N) data are available upto 16 km only and data for stations between 13° and 25°N are available upto 13 km only. Under these circumstances it is not possible to fix the latitude of easterly jet, if any. This distribution also shows that between 25° and 30°N the zonal wind is generally less than 5 knots below 10 km. This, in general, is the region where air masses from the two hemispheres meet the lower levels.

Strong easterly winds (direction almost exclusively within the range 070-100°) are found above 12 km at latitudes 13°N and south. Winds with speeds of 100 knots or more are observed on a few occasions at 18 km and above over Nagercoil. The number of occasions of strong winds (⩾70 knots) and the number of wind observations (in brackets) are given below—

	13	14	15	16	17	18	19 km
Lat. 13 °N	2(4)	1(2)	..	..	..	..	..
10½°N	1(5)	2(4)	1(3)	2(3)	..	..	..
8 °N	0(22)	1(16)	2(10)	5(6)	3(6)	4(4)	2(3)

4·2. *During winter* — The temperature distribution is shown in Fig. 4. North of 19°N, the latitudinal temperature decrease is appreciable upto 400-mb level. In general, there is a slight variation at 200-mb level and a reversal of temperature gradient above this level. It may be mentioned that almost at each of the levels 850 to 250 mb, the temperature decrease from Poona (19°N) to Jodhpur (26°N) is greater than that from Jodhpur to Peshawar (34°N), the difference in the rates of decrease being rather appreciable at 850, 800, 300 and 250-mb levels. Jodhpur is exactly mid-way between Poona and Peshawar.

The mean tropopause has been shown in Fig. 4 by a double line. Mean tropopause

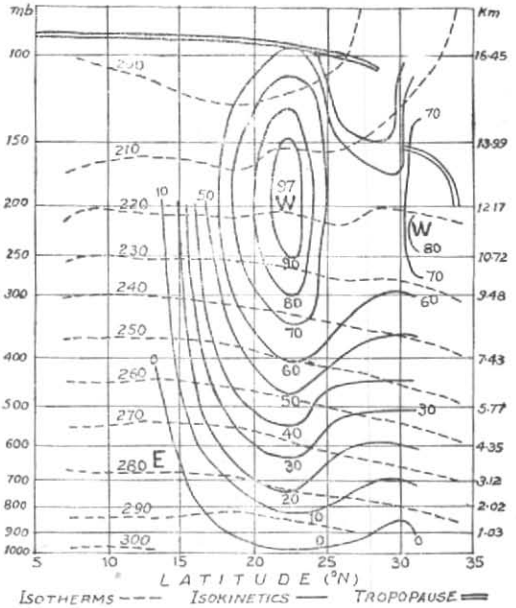

Fig. 4. Mean distribution of virtual temperature and zonal geostrophic wind at 1500 GMT during winter

heights for Delhi (29°N), Multan (30°N) and Peshawar were obtained from the mean temperature distribution as the base of the layer at least 1 km deep with a lapse-rate of 2°C km^{-1} or less. South of Delhi, the mean tropopause shown has been the one based on sounding balloon data, since the radiosonde data were insufficient for the purpose.

Fig. 4 also shows the distribution of geostrophic zonal wind. The strongest wind of 97 knots is found at 22½°N. A secondary maximum of 80 knots appears to be near 31°N.

The distribution of observed zonal wind is shown in Fig. 5. The strongest wind of 110 knots is found at 23°N. A secondary maximum of 84 knots is observed near 30°N.

Tables 6 and 7 give frequencies of winds ⩾70 and ⩾100 knots respectively at heights 6 km and above for the various latitudes. From a consideration of the frequency of high winds, a well-marked maximum south of 20°N appears unlikely (Fig. 6). The

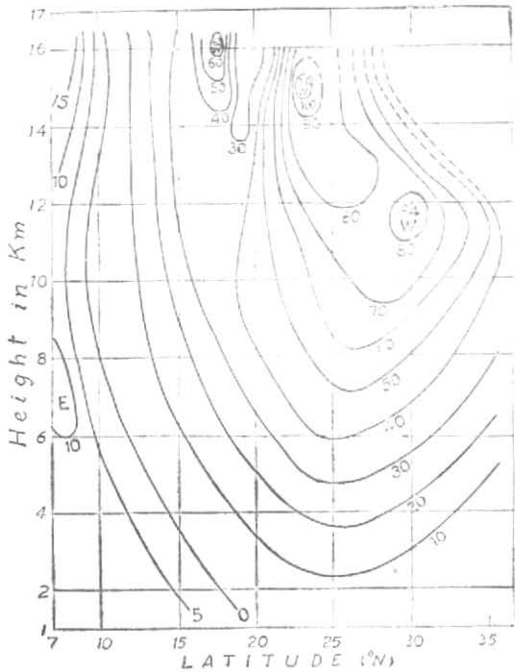

Fig. 5. Mean zonal wind distribution at 0900 GMT during winter (1944-49)

Speed in knots indicated on isokinetics
E — Easterly, W — Westerly

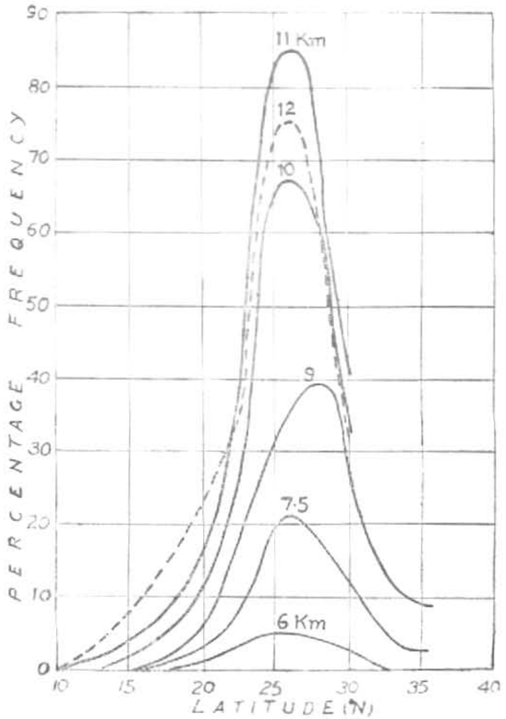

Fig. 6. Percentage frequency distribution of strong winds (speed ⩾ 70 knots) at levels from 6 to 12 km during winter (1944-49)

temperature distribution south of 20°N would support this view.

4·2·1. *Comparison of the results with upper wind normals*—Table 8 gives upper wind normals (based on data upto 1950) for January and February for 11 and 12 km for Ambala, New Delhi, Agra, Gwalior, Jabalpur, Ahmedabad, Nagpur and Malegaon: there are no normals for Rajsamand and Udaipur. The computed zonal components (z in knots) for winter are given below—

Gwalior and Delhi have only January normals, hence figures for these two places have not been given.

The available normal upper winds would indicate the highest zonal wind near 23°N and a secondary maximum north of 30°N. At 12 km, normal zonal component for Agra (Latitude 27°N) is comparatively weaker than that for 23°N and this holds for each of the individual months January and February.

	11 km		12 km		13 km	
	n	z	n	z	n	z
Ambala	22	72	10*	80		
Agra (27°N)	52	64	27	65	13†	73
Latitude (23°N)	68	64	20	82	9‡	84
Latitude (21°N)	89	48	40	47		

*5 observations for January and 5 for February, †9 for January and 4 for February, ‡3 for January and 6 for February

TABLE 6

Frequency of winds (70 knots or more) at heights from 6 to 12 km during winter

Stations	Mean latitude (°N)	Height (km)					
		6·0	7·5	9·0	10·0	11·0	12·0
Drosh	35½	1(*1*)	1(*3*)	0	0	0	0
Peshawar	34	0	2(*3*)	2(*10*)	0	1	—
Jhelum	33	0	3(*4*)	2(*12*)	—	—	—
Lahore	31½	1(*1*)	2(*9*)	3(*43*)	—	—	—
Ambala, Multan, Suratgarh	30½	11(*3*)	32(*14*)	23(*25*)	9(*33*)	5(*42*)	2(*33*)
Delhi, Bareily, Bikaner	28½	13(*3*)	31(*14*)	31(*39*)	19(*56*)	10(*63*)	5(*56*)
Gwalior, Jodhpur	26	16(*5*)	24(*21*)	15(*35*)	14(*67*)	11(*85*)	6(*75*)
Udaipur, Rajsamand	25	12(*5*)	17(*16*)	8(*29*)	1(*11*)	1(*100*)	
Bhopal, Jabalpur, Ahmedabad	23	23(*4*)	35(*14*)	22(*23*)	15(*32*)	9(*47*)	2(*40*)
Nagpur, Malegaon	21	6(*2*)	6(*3*)	5(*5*)	5(*9*)	6(*21*)	6(*32*)
Bombay, Poona	19	3(*½*)	6(*2*)	9(*5*)	9(*9*)	4(*9*)	2(*8*)
Begumpet	17½	0	1(*½*)	2(*1*)	3(*4*)	0	0
Gadag, Vengurla, Anantpur	15½	0	0	0	5(*4*)	5(*8*)	5(*12*)
Bangalore, Mangalore, Madras	13	0	0	0	0	2(*2*)	2(*4*)

Note: Figures within brackets are the percentages of frequencies to the total number of observations

TABLE 6 (*contd*)

Frequency of winds (70 knots or more) at heights from 13 to 17 km during winter

Latitude (°N)	Height (*km*)				
	13	14	15	16	17
30	1	1	1	1	
28½	5	1	0		
26	4	2			
23	4	3	2	1	
21	3	3	0	0	
19	1	0	0	0	0
17½	0	1	0	0	0
15½	2	1	1	1	1
13	1	0	1	1	1
10½	0	0	0	0	0
8	0	0	0	0	0

TABLE 7

Frequency of winds (100 knots or more) at heights from 6 to 12 km during winter

Latitude (°N)	Height (*km*)					
	6·0	7·5	9·0	10·0	11·0	12·0
30½	1	5(*2*)	5(*5*)	3(*11*)	1(*8*)	2(*33*)
28½	0	4(*2*)	10(*13*)	8(*24*)	4(*25*)	2(*22*)
26	0	0	1(*2*)	1(*5*)	3(*23*)	3(*37*)
25	2(*1*)	1(*1*)	1(*4*)	1(*11*)		
23	1	0	3(*3*)	2(*4*)	1(*5*)	1(*20*)
21	1	0	0	0	0	1(*5*)

Note: Figures within brackets are the percentages of frequencies to the total number of observations

TABLE 8

Upper wind normals (Based on data upto 1950)

Station	January						February					
	11 km			12 km			11 km			12 km		
	n	*v*	*D*	*n*	*v*	*D*	*n*	*v*	*D*	*n*	*v*	*D*
Ambala	11	74	270				11	70	271			
New Delhi	30	67	265	16	69	269	No normals					
Agra	31	68	273	17	70	285	21	59	278	10	65	286
Gwalior	35	72	271	23	81	265	No normals					
Jabalpur	15	71	270				15	52	275			
Ahmedabad	17	75	270	10	87	267	21	62	279	10	81	280
Nagpur	19	66	263				25	40	261	13	49	266
Malegaon	23	48	276	14	59	279	22	40	270	13	45	275

n denotes the number of observations, *v* vector wind in knots and *D* the direction in degrees

5. Comparative study of other longitudinal cross-section

Only the mean seasonal cross-sections extending over the tropical and subtropical latitudes, including the section from Colombo to Peshawar by the author, have been considered. The study is mainly from the viewpoint of wind maxima (jet streams). The relevant information for each of the cross-sections excepting the one by the author has been given under Tables 9 and 10, for summer and winter respectively. Wind speeds and heights of wind maxima have been reduced to the same units, *viz*, knots and kilometres respectively to facilitate comparison.

5·1. *Summer* — Majority of the sections give geostrophic winds.

In the northern hemisphere the westerly jet streams are located at and north of 40°N and the associated wind speeds are less than half the speeds during winter. In the southern hemisphere, the westerly jets are mainly confined to 30°–40°S and the associated wind speeds are generally more than half the speeds during winter.

The prominent feature is the easterly wind maximum at 16 km and above in low latitudes in the northern hemisphere. To find out whether easterly maxima exist in southern hemisphere also vertical sections giving observed winds in that hemisphere have to be awaited. The wind speed associated with the easterly maximum is generally more than 70 knots. The strongest mean wind observed is 91 knots at 8 °N (over Nagercoil) at 18 km.

From his section covering 40°N to 20°S over the Atlantic for August-September roughly along 25°W, Vuorela (1948) gives an easterly wind of 87 knots at 13 km at 8°N. The section is based on only 29 pilot balloon ascents made during the Atlantic expedition of August-September 1939. No strong easterly winds were observed for the corresponding latitude in the southern hemisphere, but it may be mentioned that wind data south of the equator may be for September. Vuorela has associated these strong easterlies with the regeneration of the sub-tropical high and consequent strengthening of the zonal index.

The easterly maxima in the low latitudes as yet have not been studied sufficiently. The inherent difficulties are—(*i*) generally higher cloudiness over low latitudes which makes only very few pilot balloon ascents available for study; this is particularly so over India and other countries of southeast Asia, swept by the southwest monsoon and (*ii*) the high altitude (15–20 km) of the easterly maximum requires the balloons to be of a very high quality so that they may not burst before they reach these heights. Extensive rawin data reaching upto very high levels thus become a necessity for a thorough study of the easterly jets.

In the northern hemisphere, continents are dominated by low pressure systems, the high pressure belt over ocean being near 35°N; pressure is relatively high over the continents near equator. The high pressure belt in the southern hemisphere lies at 30–35°S. The westerly jets of the northern hemisphere are not located above regions of high surface pressure but those of the southern hemisphere are located very nearly above the high pressure belt.

As a result of the intense heating which occurs over the huge land mass of the northern hemisphere a well-marked low pressure area is developed over southwest Asia and north Africa during July. The mean chart for July shows lowest pressure over West Pakistan. Strong monsoonal flow from south of the equator takes place over South Asia and the neighbouring parts of Africa in the lower troposphere and this is probably compensated by a marked counter-flow in the

TABLE 9

Summer sections

Author		Wind maximum				Latitudinal range of section	Longitudinal range of section	Longitude representative of section	Wind, whether observed or geostrophic	Month	Period
		Dir.	Speed (knots)	Latitude	Height (km)						
Willett (1944)	(*i*)	W	39	49°N	12	17° to 72°N	80-87°W	83°W	Geostrophic	Jul & Aug	Two years' sounding balloon data
	(*ii*)	E	104	near 17°N	above 18						
Hess (1950)	(*i*)	W	49	55°N	12	2°S to 73°N	78-84°W	80°W	Geostrophic	Jul & Aug	1942-1945
	(*ii*)	E	50	21°N	17						
Venkiteshwaran (1950)		E	78	10°N	above 16	Equator to 35°N	..	78°E	Observed	Jul & Aug	Data used for a large number of years
Loewe & Radok (1950)		W	43	40°S	10	15° to 54°S	131-153°E (For portion between 15° and 38°S)	150°E	Geostrophic	Dec, Jan & Feb	..
Hutchings (1950)	(*i*)	W	59	46°S	11	10° to 70°S	155-175°E	170°E	Geostrophic	Mainly Feb	1944-1948
	(*ii*)	W	49	31°S	12						
Frost (1952)	(*i*)	W	35	40°N	12	1°S to 35°N	33-50°E	40°E	Observed (radar-wind)	Jul	1948-1950
	(*ii*)	E	70	15°N	16						
Gibbs (1952)		W	60	33°S	12	15° to 46°S	..	130°E	Geostrophic	Jan	One to five years
	(*i*)	W	50	34°S	12	,,	..	150°E	,,	,,	,,
	(*ii*)	W	50	20°S	12						

TABLE 10

Winter sections

Author		Wind maximum Dir.	Speed (knots)	Latitude	Height (km)	Latitudinal range of section	Longitudinal range of section	Longitude representative of section	Wind whether observed or geostrophic	Month	Period
Willett (1944)		W	96	30°N	12	17° to 72°N	80-87°W (For portion 17-36°N)	83°W	Geostrophic	Jan & Feb	Two years sounding balloon data
Hess (1948)	(*i*)	W	103	36°N	12	2°S to 73°N	78-84°W	80°W	,,	Jan & Feb'	1942-1945
	(*ii*)	W	53	55°N	14						
Venkiteshwaran (1950)		W	78	28°N	13	Equator to 35°N	..	78°E	Observed	Dec, Jan & Feb	Data used for a large number of years
Loewe & Radok (1950)		W	101	25°S	12	15° to 54°S	131-153°E (For portion between 15°S and 38°S)	150°E	Geostrophic	Jun, Jul & Aug	..
Chaudhury (1950)	(*i*)	W	136	31°N	12	13° to 55°N	71-82°E (For portion upto Lat. 34°N)	76°E	,,	Jan & Feb	1946
	(*ii*)	W	78	Between 15° and 20°N	12						
Hutchings (1950)		W	97	30°S	12	6° to 46°S	155-175°E	170°E	,,	Jun, Jul & Aug	1943-1948
Tu-Cheng Yeh (1950)	(*i*)	W	104	30°N	12	11° to 40°N	113-128°E	120°E	Observed (radar-wind)	Dec 1945 & Jan 1946	..
	(*ii*)	W	96	40°N	12						
James (1951)		W	68	40°N	10	15° to 60°N	Mainly 1°E-8°W	0°	Geostrophic	Feb	1951
Frost (1952)		W	100	26°N	12	1°S to 35°N	33-50°E	40°E	Observed (radar-wind)	Jan	1948-1950
Gibbs (1952)		W	100	27°S	12	10° to 46°S	..	130°E	Geostrophic	Jul	One to five years
	(*i*)	W	80	29°S	12	10° to 46°S	..	150°E	,,	Jul	,,
	(*ii*)	W	80	20°S	12						
Koteswaram, Raman & Parthasarathy (1953)		W	103	27°N	12	10° to 35°N	67°-97°E	..	,,	Dec, Jan & Feb	1944-1951

upper troposphere and lower stratosphere. The cause of easterly jets appears to be connected with the peculiar distribution of land and sea in the northern hemisphere.

5·2. *Winter.* Here also majority of cross-sections give geostrophic winds.

The mean height of the jet streams is fairly constant, being about 12 km in most of the sections. Maximum wind speeds associated with major jets lie generally within the range 80–110 knots. In the southern hemisphere, jets seem to be confined to the belt 20–30°S, while in the northern hemisphere they are confined to a broader belt, 23–40°N. This difference may be due to the markedly different distributions of land and sea in the two hemispheres but to some extent it can be due to the fact that fewer cross-sections are available for the southern hemisphere and that they are confined to the small longitudinal range 130° to 170°E, *i.e.*, Australasia.

Jet streams are located above the portions of the atmosphere having rather marked latitudinal temperature gradients and there is a reversal of the latitudinal temperature gradient above the level of jet stream. The concentration of isotherms over a rather narrow latitudinal belt may be associated with the polar front as mentioned by Palmen and Newton (1948) or with the advection of cold air from higher latitudes or advection of warm air from lower latitudes or both as stated by Namias and Clapp (1949). Over Indo-Pakistan, the concentration of isotherms must be due to the confluence of colder air from north and warmer air from south.

According to Palmen (1951), the strongest west wind in the upper troposphere must be observed almost vertically above the sub-tropical high pressure belt, provided momentum flux is primarily determined by the meridional flow or 'drift' of air at different pressure surfaces. During northern winter, the high pressure belt is mainly confined to 30°N over the water surface, but is shifted to the belt 40–50°N over the land masses, being particularly at 50°N over Central Asia, while during southern winter, high pressure belt is confined to 25–30°S. It can be seen that southern hemispheric jet streams are either located above the sub-tropical high pressure belts or their vicinity, but only a few of the northern hemispheric mean jets lie over or near the mean high pressure belts.

6. Acknowledgements

The author wishes to express his thanks to Mr. K. P. Ramakrishnan for making available upper wind data and to Mr. P. R. Krishna Rao and Dr. P. K. Sen Gupta for going through the manuscript and giving suggestions.

REFERENCES

Chaudhury, A. M. 1950 *Tellus*, **2**, 1, p. 56.
Frost, R. 1953 *Professional notes*, Meteorological Office, London, 107.
Gibbs, W. J. 1952 *J. Met.*, **9**, 4.
Hess, Seymour L. 1948 *ibid.*, **5**, 6, p. 293.
Hutchings, J. W. 1950 *ibid.*, **7**, 2, p. 94.
James, R. W. 1951 *Met. Mag.*, **80**, 954, p. 341.
Koteswaram, P., Raman, C. R. V. and Parthasarathy, S. 1953 *Indian J. Met. Geophys.*, **4**, 2, p. 111.
Krishna Rao, P. R. and Ganesan, V. 1953 *ibid.*, **4**, 3, p. 193.
Loewe, F. and Radok, U. 1950 *J. Met.*, **7**, 1, p. 58.
Namias, J. and Clapp, P. F. 1949 *ibid.*, **6**, 5, p. 330.
Palmen, E. 1951 *Quart. J. R. met. Soc.*, **77**, p. 339.
Palmen, E. and Newton, C. W. 1948 *J. Met.*, **5**, 5, p. 220.
Tu-cheng Yeh 1950 *Tellus*, **2**, 3, p. 173.
Venkiteshwaran, S. P. 1950 *Mem. India met. Dep.*, **28**, Pt. II.
Vuorela, L. A. 1948 *J. Met.*, **5**, 3, p. 115.
Willet, H. C. 1944 *Descriptive Meteorology*, New York, pp. 131-135.