551·557 : 551·508·99 (545) "324"

A study of vertical wind profile of the Westerly Jet stream over Delhi, using radar wind data

R. Y. MOKASHI

Meteorological Office, Poona

(*Received 15 February 1967*)

ABSTRACT. Radar wind obervations for the months December to February (winter season) during three consecutive years (1963-1966) have been utilised to study the vertical wind profile of the sub-tropical westerly jet stream over Delhi and the observed features have been discussed. The main finding is that the stronger the sub-tropical westerly jet stream, the lower is the altitude of maximum wind.

1. Introduction

1.1. Previous studies of jet streams over India were mainly based on upper wind data observed by methods which have their limitations as compared to the more recent radar technique of wind measurement. While the pilot balloon method fails on occasions of cloudy skies and in the region of strong winds, the radio theodolite (METOX type in use at Delhi) is not dependable to give correct readings when the angles of elevation of the balloon is very low. In north India, whenever the westerly jet stream is strong, the problem of low angle of elevation and the consequent suppression of wind speed values at higher levels is serious with the radio theodolite method. The values of wind shears obtained by this method in the region of the jet stream will also not be fully representative. The wind finding radar has an advantage over the radio direction finding method as it is more accurate at low elevation angles. The radar is also not free from errors in the observations of balloon position (Reiter 1963). However, the errors involved are much less as compared to the radio wind finding method.

1.2. A Decca Wind Finding Radar (Type WF 2) has been functioning at New Delhi (Lat. 28°35'N, Long. 77°12'E, Ht. 209 m a.m.s.l.) for about six years and a preliminary study of the vertical structure of the westerly jet stream based on the data from December 1960 to February 1961 has been reported by Seshadri (1966). It was considered advantageous to use the radar wind observations made during the recent past when more frequent observations were available than in earlier years, in order to have a better understanding of the vertical wind profile over Delhi during winter. The wind data collected during the three months, December to February in the years 1963–64, 1964–65 and 1965-66 (both 00 and 12 GMT) have been utilised in the present study.

2. Method of study and presentation of data

2.1. During the period under consideration 240 observations with winds $\geq$60 kt were available. These were grouped into the following three categories depending upon the value of the maximum wind reported in the observation, for facility of handling the data.

Category 1 : No. of ascents with maximum wind speed $\geq$ 150 kt

Category 2 : No. of ascents with maximum wind speed $\geq$ 100 and $<$ 150 kt

Category 3 : No. of ascents with maximum wind speed $<$ 100 kt

Table 1 gives the number of radar ascents under the three categories during each of these years together with mean speed and height of maximum mean wind.

Maximum wind speeds between 100 and 150 knots are more frequent than other speeds over Delhi during winter. The percentage frequencies of the three categories are 17, 49 and 34 per cent respectively.

2.2. Table 2 shows the mean speed of the maximum winds along with their heights reported over Delhi during the three winter seasons (1963–66).

Maximum wind speeds of 115–120 kt occur over Delhi on about 50 per cent of the number of days during the three months December to

TABLE 1

	Category 1	2	3	Total
Dec 1963—Feb 1964				
No of ascents	23	31	19	73
Mean speed (kt)	169	119	88	125
Mean height (km)	10·9	11·7	12·5	11·7
Dec 1964—Feb 1965				
No of ascents	5	23	19	47
Mean speed (kt)	155	128	79	121
Mean height (km)	11·9	12·0	12·7	12·2
Dec 1965—Feb 1966				
No of ascents	14	63	43	120
Mean speed (kt)	155	124	82	120
Mean height (km)	11·1	11·4	12·5	11·7

February. It may be mentioned here that in the 240 ascents over Delhi, the highest value of the maximum wind reported was 204 kt at 9·9 km.

2·3. The mean heights of the level of maximum wind relating to the three categories of flights are suggesting a significant relationship between the maximum wind speeds and the heights of the levels of their occurrence (Tables 1 and 2). For Category 1 with maximum wind speeds exceeding 150 kt the mean height of the level of maximum wind is seen to be 11·1 km while for Categories 2 and 3 with lower wind speeds the mean levels are 11·6 and 12·6 km respectively (Table 2). It would thus appear that the stronger the jet stream, the lower is the altitude of the maximum wind. It is well known that the heights measured by radar are subject to correction due to the curvature of the earth when the wind speeds are strong and the balloons are carried away to considerable distances from the observation station. The correction K is given by $K = l^2/2R$ (Reiter 1963), where l is the horizontal projection of the distance of the balloon from the radar and R is earth's radius of curvature. The correction for the heights due to the earth's curvature have been calculated for the three-year period under study. These are as follows —

Category 1 : + 0·248 km
Category 2 : + 0·176 km
Category 3 : + 0·108 km

TABLE 2

Mean speed and height of the maximum wind over Delhi

Category	Mean speed (kt)	Mean height (km)
1	163	11·1
2	124	11·6
3	82	12·6
Three categories together	116	11·9

The corrected heights become 11·3, 11·8 and 12·7 km for the Categories 1, 2 and 3 respectively, thus lending support to the existance of relationship between the level of the maximum wind and the speed of the maximum wind pointed out earlier.

2·4. Table 3 gives the frequency of occurrence of maximum wind speeds over Delhi in ranges of 10 kt.

The level of maximum wind shown in the speed ranges 60—89, 90—129 and 130—179 kt has frequency maxima near 13, 12 and 11 km respectively, leading to the inference that the stronger the jet stream, the lower is its altitude.

2·5. Further, it was considered helpful in this connection to study the westerly jet stream over a station in the neighbouring countries, which lies nearly in the a same latitude as New Delhi. Bahrain (Lat. 26° 16′ N, Long. 50° 37′ E, Ht. 2 m a. m. s. l.) was chosen and maximum wind data (Radar) of the station for the three months, December to February of 1960-65 have been collected from *The Daily Weather Report, Overseas Supplement* of London Meteorological Office and utilized for the purpose. These were grouped into the three Categories, 1, 2 and 3 mentioned in 2·1.

Table 4 gives the number of rawin ascents under the three categories. The table shows that ascents of Category 2 are more common over Bahrain during winter (as in the case of Delhi) than ascents of Categories 1 and 3. The ascents of Category 1 are comparatively very few. The percentage frequencies of 1, 2 and 3 categories, are 2·6, 65·3 and 32·1 per cent respectively.

Table 5 gives the mean values of the maximum winds and their heights over Bahrain, during the period under study. The mean values of the

TABLE 3

Frequency of occurrence of max. wind speeds over Delhi

Height (km)	Wind speed (kt)														
	60—69	70—79	80—89	90—99	100—109	110—119	120—129	130—139	140—149	150—159	160—169	170—179	180—189	190—199	200—209
17	1														
16	3	1													
15		2	3	1	1										
14	2	4	4	4		1	3		3						
13	4	7	5	4	4	5	2	3		2	3				
12	2	4	4	6	8	11	12	8	5	4	1			1	
11		1	4	3	1	5	6	11	6	15	4	2			
10		2	1	4	5	3	2	6	1	4	1			3	1
9			2	1	1	2	1	1				1			
8			1	1											

TABLE 4

Maximum wind data of Bahrain

Period (Dec-Feb)	No. of Rawin ascents			Total of three categories
	Category 1	Category 2	Category 3	
1960–61	7	89	64	160
1961–62	3	136	39	178
1962–63	2	76	80	158
1963–64	8	126	26	160
1964–65	1	103	52	156
1960–65	21	530	261	812

TABLE 5

Mean values of max. winds and their heights over Bahrain

Category	Mean wind speed (kt)	Mean height (km)
1	156	11·7
2	119	11·9
3	86	12·5
Three categories together	109	12·1

maximum wind over Bahrain exceeds well over 100 kt. The percentage frequency of ascents of Category 2 (65·3 per cent) and the Table 5 show that on 66·6 per cent of the number of days, the wind speeds of about 115–120 kt are observed.

The same relationship exists between the maximum wind speeds and the heights of the levels of their occurrence, as in the case of Delhi. In the case of Category 1 with mean speeds exceeding 150 kt, the mean heights of the level of maximum wind is 11·7 km and for Categories 2 and 3 with lower wind speeds, the mean levels are 11·9 and 12·5 km respectively. Thus, giving support to the finding that the stronger the subtropical westerly jet stream, the lower is the altitude of the maximum wind.

3. Pictorial representation of the vertical wind profiles

3·1. In the initial stages of the study, the data of the seasons December–February 1963–64 and 1964–65 only were available. Figs. 1, 2 and 3 depict the vertical wind profiles of the three categories of ascents over Delhi. The mean profile is also indicated in the diagrams by means of dashed thick lines. The mean profile was drawn by picking out values of wind speeds at 1-km interval from ground for each of the ascents and evaluating their means which were then connected up smoothly. Fig. 4 shows the mean profiles for the three categories, separately for the three winter seasons (1963–66). The values of wind speed in this case for the levels between 10·0 to 14·0 km were picked up at half a km interval. Due to the variance in the levels of maximum

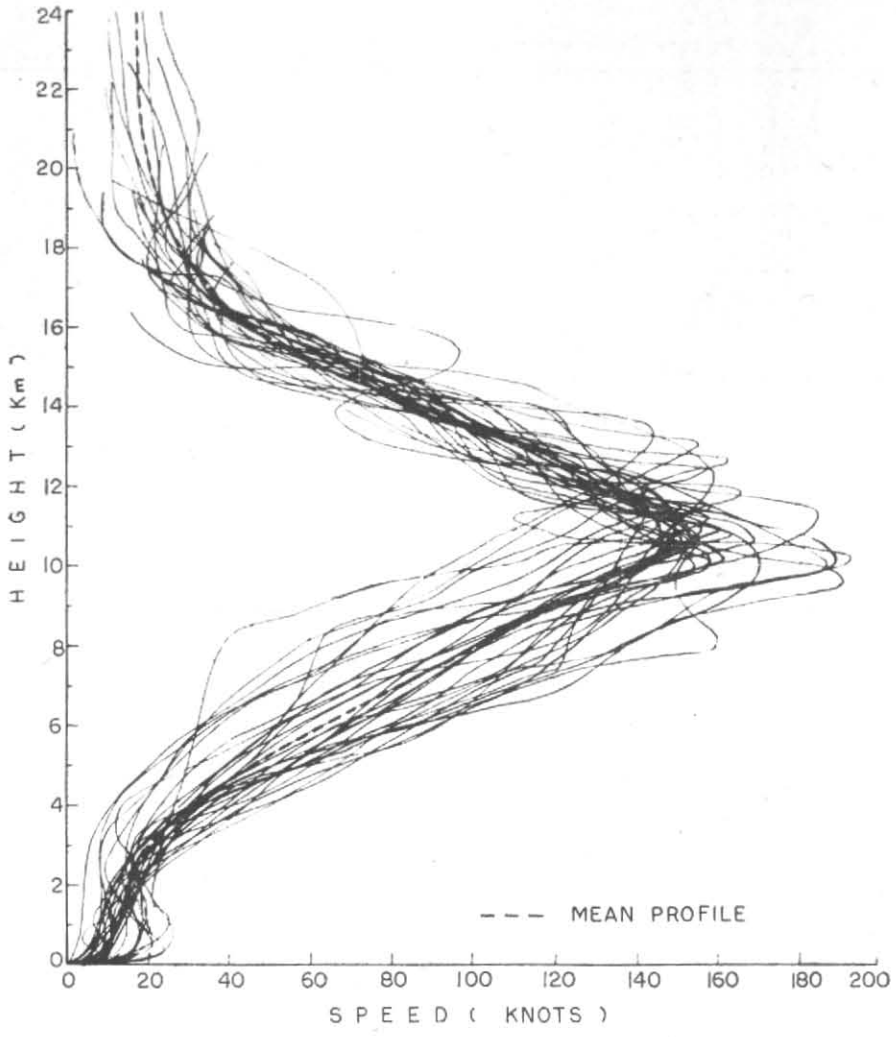

Fig. 1. Two winter seasons (1963-1965)

Maximum wind speed $\geqslant$ 150 kt

wind from flight to flight, this process of obtaining a mean profile has actually resulted in the mean profiles showing peak values which fall short of the mean values given in Table 2. Fig. 4 shows that the wind speed values are nearly the same from the surface to about 3 km above. From 3 km, the mean profiles for the three categories branch out till they rejoin at about 16 km. The heights of the peak values for Categories 1, 2 and 3 ascents again show difference in the same way as discussed above. Another feature noticed in Figs. 1 to 3 is that there is steady increase of wind speed with height in the case of ascents of Categories 1 and 2 while there are fluctuations in the changes of wind speeds with height for Category 3 ascents.

3·2. Fig. 5 depicts percentage frequencies along the vertical of the levels of maximum wind for the 240 ascents taken up for study. It is seen that the highest percentage frequencies of the levels of maximum wind for the three categories of ascents occur at about 11, 12 and 13 km respectively. The curves also indicate that for Category 1, nearly 50 per cent of the ascents have the level of maxiumum wind at about 11 km while for the other two categories, the values of the highest percentage frequencies of the level of maximum wind are about 35 and 20 per cent. The nature of these curves clearly show that faster wind speeds occur at lower altitudes.

3·3. In Fig. 6 the vertical wind shears calculated for levels between 3·0 and 18·0 km, separately for

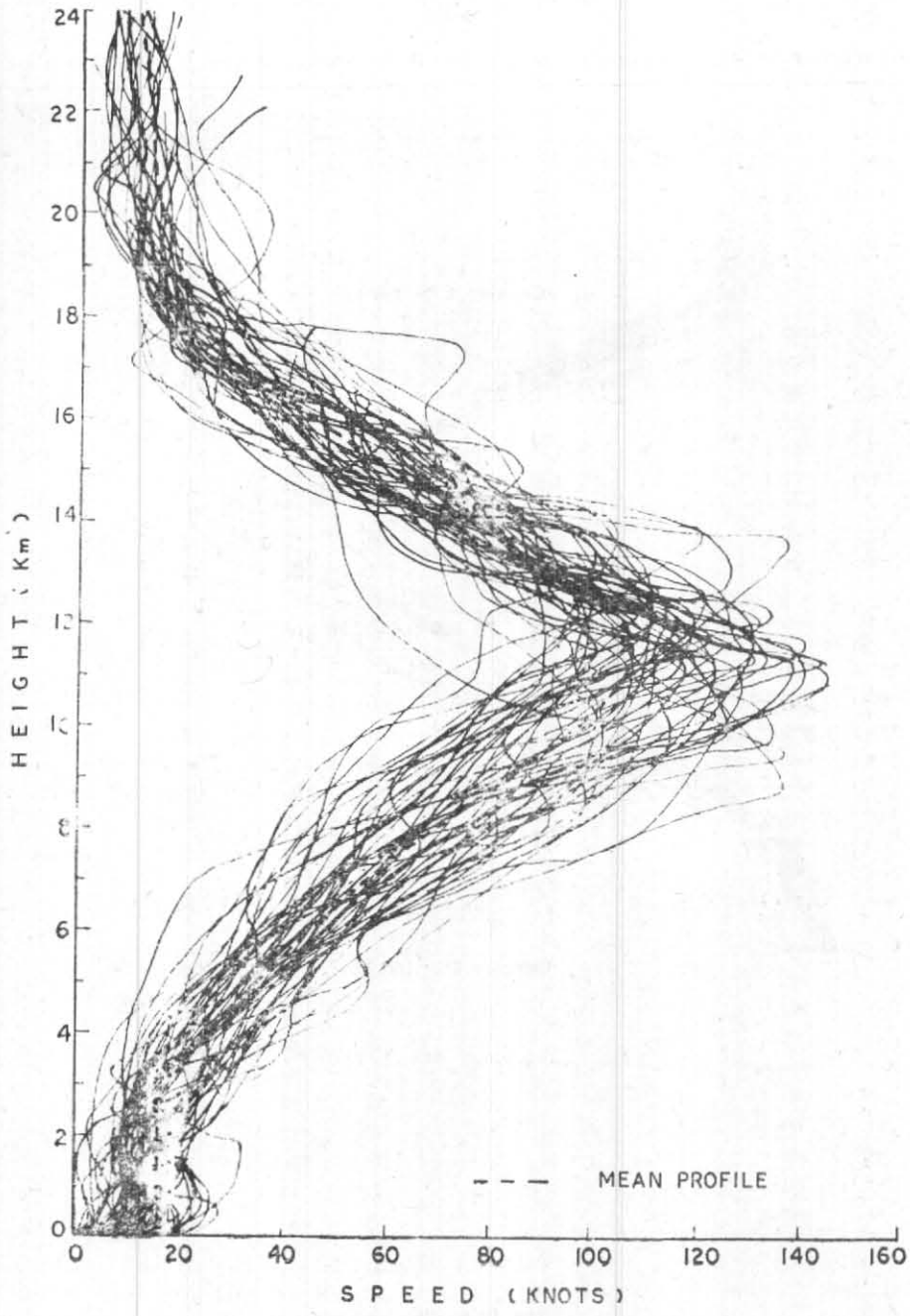

Fig. 2. Two winter seasons (1963-1965)
Maximum wind speed $\geq$100 and $<$ 150 kt

the three categories are shown. The wind shear is lowest at about 10.5, 11·5 and 12·5-km levels for the Categories 1, 2 and 3 respectively. Thus showing that the stronger the jet maximum, the lower is its level of occurrence. It may be seen from Fig. 6 that the highest and lowest values of wind shear are in the Catagories 1 and 3 respectively.

4. Statistical parameters of upper winds and discussion

For the levels 10·0 to 14·0 km a. m. s. l., at intervals of half a km, statistical parameters of upper winds have been computed. Table 6 gives the various parameters for the three categories of ascents separately and for the three categories together.

TABLE 6

Various parameters of the three categories of ascents over Delhi separately and for the three categories together

Level (km)	No. of observations	Mean zonal comp.	Mean meridional comp.	Mean scalar wind	Mean vector wind	Direction of mean vector wind (°)	Standard deviation of the zonal comp. (Sx)	Standard deviation of the meridional comp. (Sy)	Standard vector deviation	Sx/Sy	Steadiness factor (per cent)
Category 1 ⩾ 150 kt											
10·0	42	—132·3	2·3	137·7	132·3	271	27·0	37·9	46·5	0·71	96
10·5	42	—137·1	0·6	143·9	137·1	271	21·8	42·5	47·8	0·51	95
11·0	42	—136·0	3·2	143·4	136·0	272	20·3	44·6	49·0	0·46	95
11·5	42	—129·6	2·3	136·7	129·6	271	21·1	42·8	47·7	0·49	95
12·0	39	—122·0	4·3	128·4	122·2	272	24·9	37·3	44·8	0·67	95
12·5	38	—123·2	7·2	127·4	123·7	274	24·2	30·3	38·7	0·80	97
13·0	38	—102·6	9·5	106·5	102·8	275	23·4	25·6	34·7	0·91	97
13·5	37	—96·5	10·3	99·9	97·1	276	16·6	23·7	28·9	0·70	97
14·0	38	—80·4	1·9	83·3	80·4	271	20·3	20·3	28·7	1·00	97
Category 2 ⩾ 100 and < 150 kt											
10·0	117	—94·6	0·1	99·1	94·6	271	18·5	29·6	34·9	0·63	95
10·5	117	—97·9	—0·8	102·9	98·0	269	17·7	31·4	36·1	0·56	95
11·0	116	—101·6	0·2	106·3	101·8	271	18·0	30·7	35·7	0·59	96
11·5	114	—102·4	—0·8	106·5	102·6	269	17·1	29·1	33·8	0·59	96
12·0	113	—101·6	—0·2	105·7	101·8	268	16·5	28·7	33·2	0·58	96
12·5	112	—98·5	—0·2	101·8	98·5	269	14·8	25·9	29·8	0·57	97
13·0	107	—89·5	0·8	93·1	89·7	271	15·2	25·2	29·4	0·60	96
13·5	105	—86·8	—0·2	89·5	86·8	269	16·1	22·1	27·4	0·73	97
14·0	101	—75·9	—2·5	79·3	76·0	268	15·9	22·4	27·5	0·71	96
Category 3 < 100 kt											
10·0	81	—55·9	5·1	60·2	56·1	275	18·3	21·3	28·1	0·86	93
10·5	81	—57·5	5·0	61·8	57·7	275	16·9	21·5	27·4	0·78	93
11·0	81	—61·6	4·0	64·5	61·8	274	14·5	18·4	23·4	0·79	96
11·5	80	—63·1	4·0	65·9	63·3	274	13·6	18·2	22·7	0·75	96
12·0	81	—66·1	2·9	69·0	66·2	273	12·9	19·4	23·3	0·66	96
12·5	81	—66·6	1·0	68·6	66·8	271	12·5	15·4	19·9	0·81	97
13·0	81	—65·5	0·7	67·8	65·7	271	13·4	16·6	21·3	0·81	97
13·5	81	—64·9	0·9	66·8	65·1	271	13·5	15·4	20·5	0·87	97
14·0	81	—60·8	—3·5	62·9	61·0	267	14·6	15·1	21·0	0·96	97
Three Categories together											
10·0	240	—88·0	2·1	92·9	88·2	272	33·4	28·8	44·1	1·16	95
10·5	240	—91·1	1·4	96·2	91·1	271	33·3	30·8	45·4	1·08	95
11·0	239	—94·2	2·1	98·7	94·2	272	31·5	30·3	43·7	1·04	95
11·5	236	—93·8	1·4	98·1	94·0	271	29·4	29·0	41·3	1·01	96
12·0	233	—92·7	0·9	96·7	92·9	271	26·9	27·6	38·5	0·97	96
12·5	231	—91·3	1·4	94·2	91·5	271	25·7	23·7	34·9	1·09	97
13·0	226	—83·1	2·3	86·3	83·3	271	21·4	22·7	31·2	0·94	97
13·5	223	—80·4	1·9	83·1	80·6	271	19·5	20·5	28·3	0·95	97
14·0	220	—71·1	—2·1	74·0	71·3	272	18·1	19·7	26·7	0·92	96

Note — Sign convention for wind components: Wind components from east and north are designated as *positive* while wind components from west and south are designated as *negative*. The unit for wind speed is knot

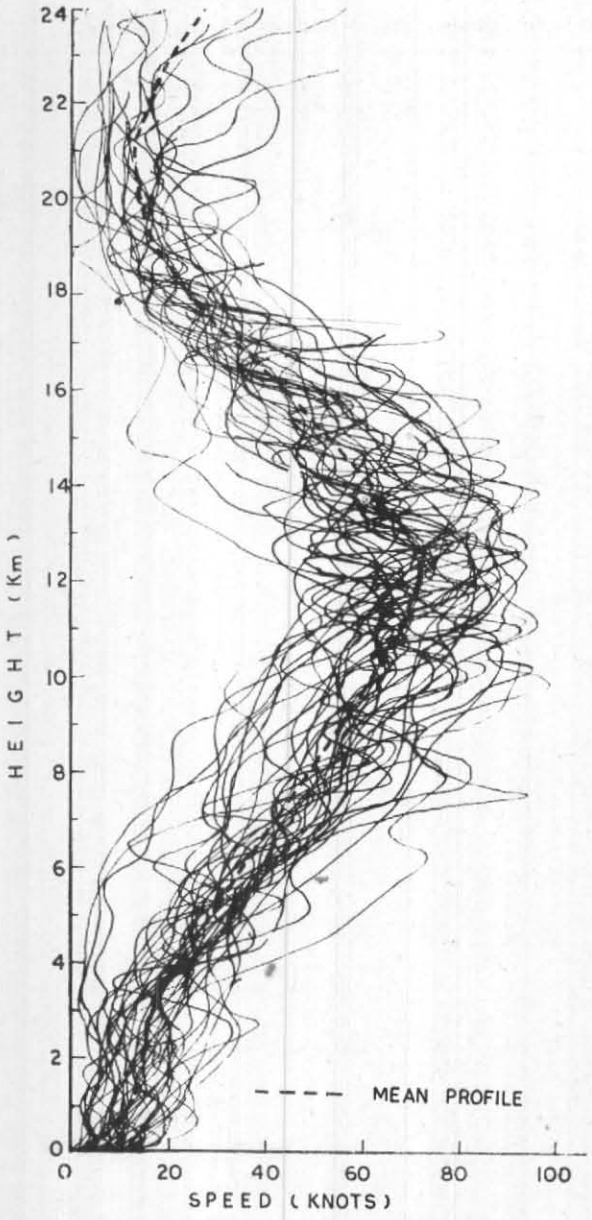

Fig. 3. Two winter seasons (1963-1965)
Maximum wind speeds <100 kt

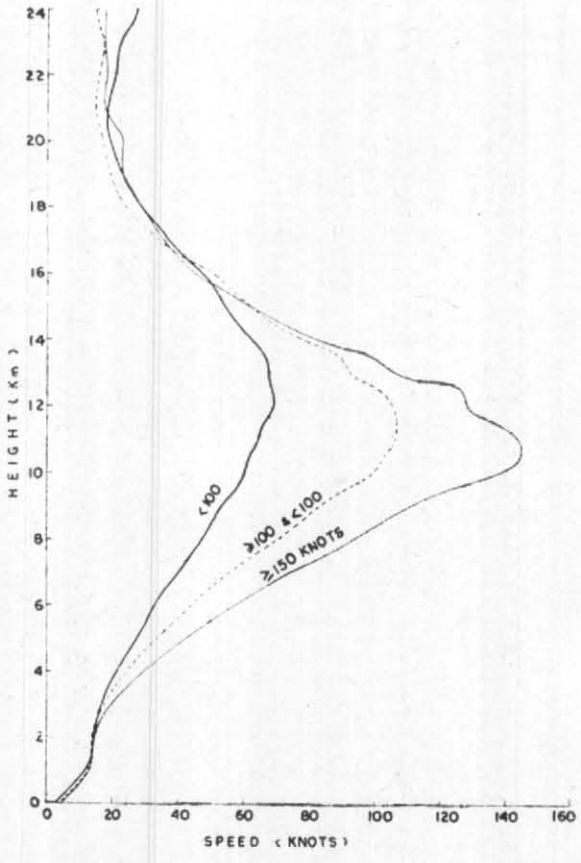

Fig. 4
Three winter seasons (1963-1966)
Mean profiles

4.1. The highest values of mean zonal component and mean vector wind are at 10·5, 11·5 and 12·5 km and those of mean scalar wind at 10·5, 11·5 and 12·0 km, for the Categories 1, 2 and 3 respectively. The results confirm that the stronger the sub-tropical westerly jet stream, the lower is the altitude of maximum wind.

The westerly jet stream is very steady. The steadiness factor is of the order of 95 per cent. Its speed, however, seems to vary from day-to-day with a standard vector deviation of the order of about 33 per cent of the mean vector wind and the ratio of the standard deviation of the zonal component to that of the meridional component is of the order of 0.6.

4.2. The sub-tropical westerly jet stream is present over northern India in winter at about 12 km. When polar air associated with lower tropopause comes down to the lower latitudes in winter, the jet-level lowers down to about 10 km and the maximum wind increases to higher values at lower heights.

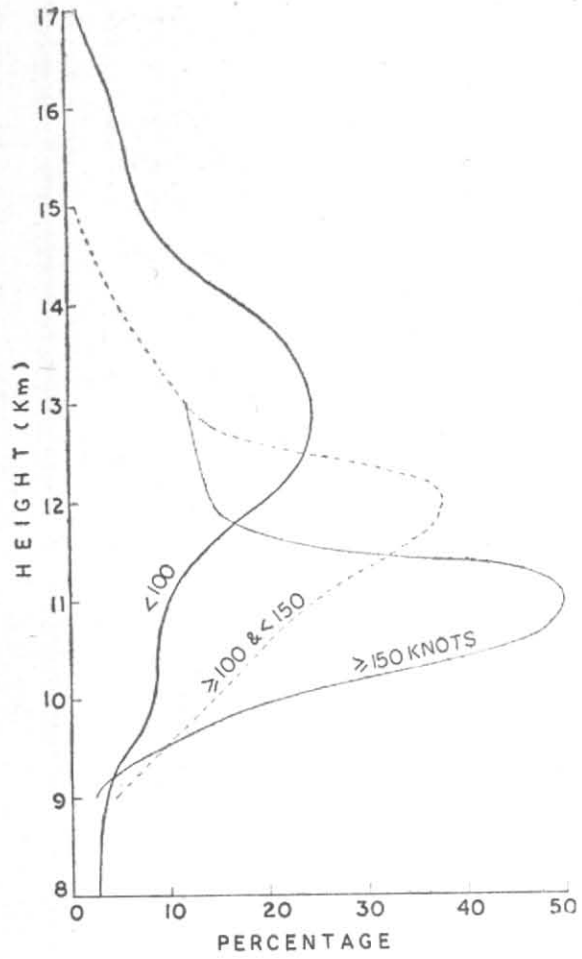

Fig. 5. Three winter seasons (1963-1966) Percentage frequencies of levels of wind maxima

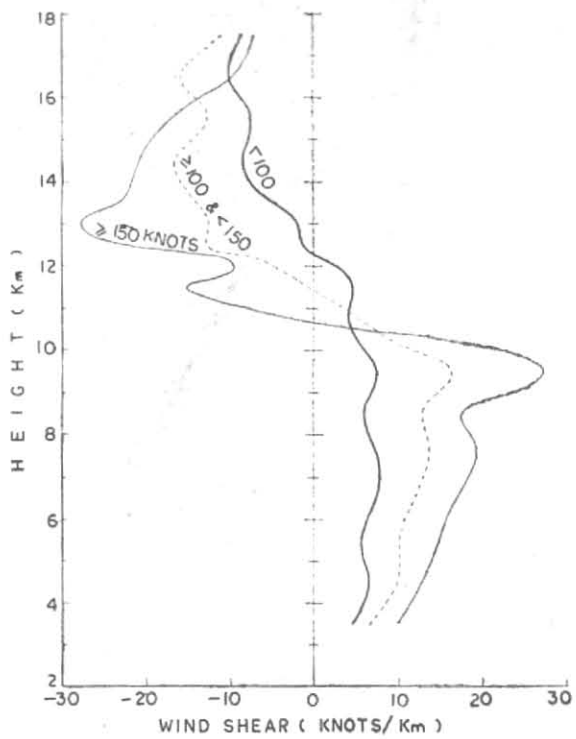

Fig. 6. Three winter seasons (1963-1966) Vertical wind shears (kt/km)

5. Acknowledgement

The author wishes to express his thanks to members of staff of the Upper Air Section, Poona who have helped in the computations of the various statistical parameters and in the preparation of the diagrams.

REFERENCES

Reiter E. R. 1963 *Jet Stream Meteorology*, The University of Chicago Press, Chicago and London.

Seshadri, N. 1966 *Indian J. Met. Geophys.*, **17**, p. 225.