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# Vertical variation of the Constancy of Upper Winds over India

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ABSTRACT. The paper discusses with the aid of diagrams the variability of the upper winds at 12 rawin stations in India based on monthly normals computed from daily observational data. The monsoon and winter circulations are characterised by distinct patterns of upper wind variability with characteristic transitional patterns in May/June and September/October.

## 1. Introduction

The variability of upper winds over India based on the results of pibal observations has been discussed by Krishnan, Pant and Ananthakrishnan (1961) for the four typical months January, April, July and October, for the levels of 1·5, 3·0, 5·0, and 9·0 km a.s.l. It is well known that on cloudy days pibal observations can give wind information only upto the base of the cloud layer and as such, pibal winds are definitely biassed in favour of occasions of clear skies especially for higher levels in the atmosphere. Rawin observations do not suffer from this limitation. Hence it was considered to be of interest to examine the variability of upper winds at the rawin stations in India. Data of twelve rawin stations, the monthly mean upper winds for which have been recently computed by the Upper Air Section of the Meteorological office, Poona have been utilised in the present study.

## 2. Analysis of Data

The names of the twelve rawin stations, their geographical co-ordinates, and the period covered by the wind data utilised in each case are given in Table 1. Based on 1200 Z rawin ascents the monthly mean values of vector wind speed $V_r$, scalar wind speed $V_s$ and the direction of the resultant wind in degrees from north $D$ were computed for the following levels— Surface, 0·3, 0·6, 0·9, 1·5, 2·1, 3·0, 3·6, 4·5, 5·4, 6·0, 7·2, 9·0, 10·5, 12·0, 14·1, 16·2 and 18·0 km above sea level. Above 9 km there was a rapid decline in the total number of observations. The number of observations at the level of 16·2 km was only about 10 per cent of the number for the lower tropospheric levels in some cases.

From the values of $V_r$ and $V_s$ the constancy of the wind $q=100(V_r/V_s)$ was calculated for all levels. The results are presented diagrammatically in Figs. 1 to 12 for the twelve rawin stations. In these figures the variations of $q$, $V_s$ and $D$ with elevation are shown for the individual months of the year. $(100-q)$ may be taken as a measure of the variability of the winds.

## 3. Results

The variability of upper winds at the different stations as brought out by Figs. 1 to 12 is closely linked with the seasonal changes in the upper air circulation over India. Broadly speaking the summer monsoon circulation conditions prevail during the four months June to September and the winter monsoon circulation conditions during the six months November to April. May and October are transitional months. Against this general background the features shown by the individual stations in the order of increasing latitude have been examined.

### (1) *Trivandrum*

Inspection of Fig. 1 shows the great similarity in the variation of $V_s$, $D$ and $q$ with height for the months June to September. The scalar mean wind speed shows two maxima, a lower maximum of the order

TABLE 1

| Station | Latitude | | Longitude | | Period of data |
|---|---|---|---|---|---|
| Trivandrum | 08 | 30′N | 76 | 59′E | 1956—1960 |
| Port Blair | 11 | 40 | 92 | 43 | 1956—1960 |
| Madras | 13 | 00 | 80 | 11 | 1951—1960 |
| Bombay | 19 | 04 | 72 | 06 | 1954—1960 |
| Veraval | 20 | 55 | 70 | 22 | 1957—1960 |
| Nagpur | 21 | 09 | 79 | 07 | 1953—1960 |
| Calcutta | 22 | 39 | 88 | 27 | 1952—1960 |
| Allahabad | 25 | 27 | 81 | 44 | 1953—1960 |
| Gauhati | 26 | 05 | 91 | 43 | 1955—1960 |
| Jodhpur | 26 | 16 | 73 | 03 | 1956—1960 |
| New Delhi | 28 | 35 | 77 | 12 | 1951—1960 |
| Amritsar | 31 | 38 | 74 | 52 | 1957—1960 |

of 25 knots between 1·5 and 2·0 km and the upper maximum of the order of 60 to 65 knots at 14 km. The values are somewhat less for September as compared with the other three months. The minimum speed of about 12 knots occurs at a height of 7 km in June and July: in August and September the minimum speed of about 8 knots occurs at 6 km. The resultant vector wind is from WNW/W upto 6 km and easterly above 7·2 km. Below 3 km and above 10 km the constancy of the wind is 90 per cent or more. The constancy falls off rapidly above 4 km and reaches a minimum at 7·2 km in June and July and at 6 km in August and September. Thus in the southwest monsoon months, the mid-tropospheric layers between the westerlies below and the easterlies aloft are characterised by very unsteady winds. The vector mean wind speed in this transition layer is of the order of 2 to 5 knots while the scalar mean speeds are two to three times higher.

Conditions in October are similar to those for September. However, there is a decrease of wind speed at all levels. The level of most unsteady wind is somewhat lower as compared with the previous months. The lower maximum in the curve of mean scalar wind speed is hardly noticeable; the upper maximum at 14 km is still present. While the scalar mean speeds vary very little upto 7·2 km, the constancy of wind decreases rapidly from about 90 per cent close to the surface to 5 per cent at 5·4 km.

In November there is a steady increase of mean scalar wind speed with height from about 5 knots near the surface to about 25 knots at 12 km. Very close to the surface, winds are westerly. At 0·9 km the resultant wind is from NNE. With increasing elevation the winds gradually veer and blow from ESE in the upper troposphere. The constancy of the wind decreases from the surface to a minimum of 25 per cent at 0·9 km. At all levels in the troposphere the constancy is less than 75 per cent. The steadiness appears to increase in the lower stratosphere.

The main change from November to December is an increase in the steadiness of the winds in the lower troposphere and a decrease in steadiness in the upper troposphere. The direction of the vector mean wind is from NE E in the lower troposphere and southerly aloft. In January winds are extremely unsteady between 7 to 9 km although the scalar mean wind speed rises continuously from the surface up to 12 km. The mean scalar speed at 9 km is 18 knots while the speed of the resultant vector wind is less than 3 knots. The variations for February are generally similar to those for January except for the fact that the steadiness of the upper tropospheric winds which are from ESE/ENE is greater. The variation with height in the months of March and April shows very similar features. The ENE winds between 2 and 3 km blow with great steadiness (exceeding 80 per cent) in both these months, the mean speeds being of the order of 10 to 15 knots. The upper tropospheric winds between 9 to 16 km are very unsteady. The 9-km level continues to be subject to the largest fluctuations of wind direction in March and April.

The changes from April to May are substantial and significant. The westerlies in the lower troposphere and the easterlies in the upper troposphere characteristic of the southwest monsoon months have appeared in May. Wind speeds have increased in the upper troposphere. The constancy shows a flat minimum between 4 and 7 km with a steady increase with elevation in the upper troposphere. While the value of $q$ is less than 20 per cent at the 16-km level in April, it is as high as 90 per cent in May.

The observed features of the vertical variation of steadiness of upper winds over Trivandrum discussed above are intimately linked with the location, orientation and intensity of the sub-tropical high pressure ridge in the middle and upper troposphere. In the months November to April the subtropical ridge lies to the south of 15°N. The axis of the anticyclonic cell which generally lies over the south peninsula and the adjoining sea areas has a southward tilt with elevation. During the southwest monsoon months the ridge is displaced northwards and lies over the Tibetan plateau.

(2) *Port Blair*

The vertical variation of the parameters $V_s$, $D$ and $q$ for Port Blair (Fig. 2) shows nearly the same features as in the case of Trivandrum. The lower maximum of $V_s$ in the monsoon months June to September occurs at about 1 km. The upper maximum is not reached up to 14 km above which there are no observations for the months July, August and September. In October the winds below 3 km which have a resultant S/SSE direction are unsteady. In November the steadiness is practically 75 per cent at all levels in the troposphere. In December, the layer at 9 km which separates the easterlies below and the southerlies above is characterised by unsteady winds. In January and March winds are least steady in the middle troposphere; in February the steadiness is less than 50 per cent at all levels above 3 km. The progressive backing of the wind from north through west to south between 4 and 14 km in February is noteworthy. The large changes from April to May are similar to those which occur at Trivandrum.

(3) *Madras*

The features for the monsoon months June to September (Fig. 3) are similar to those for Trivandrum and Port Blair. The gradual veering of the winds with height from southerly near the surface to westerly at 1 km is a noteworthy feature over Madras in all these months. The lower maximum of windspeed of 20/25 knots occurs at 3 km. The maximum strength of the easterlies in the upper troposphere appears to be attained at or slightly above 16 km. The mean maximum scalar speed is 60/65 knots in June and September and about 75 knots in July and August. The level of most unsteady winds continues to be at 7·2 km from June to August. This level lowers to 6 km in September and to 4·5 km in October. During the months December to April the transitional layer between the easterlies of the lower troposphere and the westerlies of the upper troposphere is characterised by very unsteady winds. Below this layer the subtropical ridge lies to the north of Madras and above the layer to the south of Madras.

(4) *Bombay*

Fig. 4 shows that in the monsoon months June to September the curves for Bombay are similar to those for Trivandrum and Madras. The level of least steady wind is at 4·5 km in June and at 6 km in July, August and September. There is a gradual change in direction of the lower tropospheric winds from WSW to W from June to September. In the upper troposphere the easterlies increase in speed steadily from 9 km to 18 km in June. In July and August the mean scalar speed of the easterlies attains the value of 65/70 knots at 16 km and remains practically at the same value up to 18 km. In September the easterlies have weakened to 45 knots. The changes in the wind parameters from September to October are very conspicuous. There is a fall of steadiness at all levels. The layer from 3 to 8 km is characterised by extremely unsteady winds in October. The westerlies in the lower troposphere in September have given place to N/E winds below 3 km in October.

The easterlies veer with height to become westerlies at 6 km above which there is a continuous backing of the wind direction with height through SW, S and SE. From November to January the level of least steady wind descends progressively from 4·5 km to 0·9 km. The westerlies in the middle and upper troposphere are extremely steady in all the months November to April. The maximum scalar speed of the upper tropospheric westerlies occurs at 12 km in all these months. The maximum speed increases from 40 knots in November to 65 knots in January and decreases again to 20 knots in May. There is indication of a secondary maximum of wind speed at 12-km level in the month of March. The changes from April to May are very important. The wind speeds have decreased to less than 25 knots at all levels in May and the steadiness of the wind is less than 50 per cent at all levels in the troposphere except in the first 1·5 km. The winds are most unsteady in the layer from 3 to 6 km where the mean direction is from S/SE. At these levels the sub-tropical anticyclone lies on the mean over the centre of the peninsula to the east of Bombay.

(5) *Veraval*

The general features (Fig. 5) are similar to those for Bombay. The main difference is that the transition from winter to summer monsoon conditions is shown by the curves for June in the case of Veraval as against May for Bombay. The upper tropospheric westerlies continue throughout May although there is an appreciable decrease in speed. The level of maximum strength of westerlies continues to be at 12 km in May as in the previous month. The level of least steadiness in the monsoon months is 4·5 km.

(6) *Nagpur*

The curves for the monsoon months from June to October (Fig. 6) are very similar to those for Veraval. The upper easterlies continue to increase in speed with elevation reaching a strength of 60 knots at 18 km. The steady increase in the speed of the westerlies from 3 to 12 km is a common feature for all the months October to May. The mean scalar wind speed at 12-km level increases steadily from about 25 knots in October to nearly 70 knots in January and falls off again to 25 knots in May. There appears to be a secondary maximum of 60 knots in March. The level of minimum steadiness is at 1 km above the ground in the months December and January and is practically at the ground level in the months February, March and April.

(7) *Calcutta*

In July and August (Fig. 7) southerlies prevail up to 3 km gradually backing to easterlies at 6 to 7 km and aloft. Winds are least steady in this transitional layer. The upper tropospheric easterlies which increase in strength above 9 km up to 18 km are very steady in these months. The maximum speed of the easterlies is 50/60 knots. Features are nearly similar in September. However the easterlies of the upper troposphere have weakened considerably. In October the low level winds below 2 km are extremely unsteady. Aloft, the westerlies blow with a steadiness of 50 to 75 per cent. From November to April the westerlies above 3 km blow with a steadiness of 90 per cent or more. The maximum speed of the westerlies occurs at 12 km in all these months. The mean scalar maximum speed of the upper westerlies has the highest value of little over 75 knots in January. In December, February and March the corresponding speed is nearly 70 knots. In April the speed decreases to 50 knots and in May to 25 knots. The changes from May to June which mark the transition from winter to summer monsoon circulation conditions are very striking. In June the winds are extremely variable from 3 to 12 km. In this layer the wind direction backs from WNW through west, south and southeast to east above 12 km. The easterlies increase in speed and steadiness from 12 to 18 km.

(8) *Allahabad*

The typical monsoon months are July and August (Fig. 8). In these months the winds are very unsteady up to 3 km. Above this level the winds gradually increase in steadiness to a value of over 75 per cent above 8 km. The easterlies increase in speed with elevation from 6 to 16 km. In September the winds are extremely unsteady throughout the troposphere. The mean scalar speed is of the order of 10/15 knots. The winter circulation prevails from October to May with steady westerlies above 3 km. The maximum mean scalar speed of the westerlies is attained at 14 km in October, and at or near 12 km in the months November to May. The transition from May to June is striking. The wind speeds have decreased considerably at all levels. The steadiness curve shows a maximum at about 3 km above which the steadiness gradually declines with height to a minimum value of about 25 per cent at 10·5 km.

(9) *Gauhati*

Except for the months July to October wind data are available only up to 14 km for this station (Fig. 9). July and August show nearly the same type of wind structure. The mean scalar speeds are about 10/15 knots up to 10 km and increase to about 25 knots at 16 km. The direction of the resultant wind backs steadily from WSW/W in the lowest levels through south to ENE above 9 km. The winds are least steady between 4 and 6 km. From the surface to about 8 km the steadiness is less than 50 per cent. Above 12 km the easterlies increase in speed and steadiness attaining a speed of 30/35 knots at 16 km. In September the wind speed is less than 15 knots throughout the troposphere and the steadiness is less than 50 per cent at all levels, being as low as 5 to 10 per cent between 6 and 8 km. This is the transitional month from the summer to the winter monsoon circulation conditions. From October to May the westerlies blow with great steadiness above 3 km. The maximum speed of the westerlies of 35/40 knots occurs at 14 km in October. The speed increases rapidly to about 100 knots at 12-km level in January/February. Thereafter the maximum decreases gradually to about 75 knots by April and rapidly to 30/35 knots by May and 10/20 knots by June. In June the steadiness has begun to decline with height above 6 km showing the transitional nature of this month.

(10) *Jodhpur*

In July and August (Fig. 10) the winds are southwesterly upto 1·5 km. At 3 km the winds are NNE and steadily veer with height to easterlies at 12 km. At the transitional level of 2 km the steadiness is as low as 20 per cent. Above this the steadiness increases with height and attains a value of 75 per cent or more at and above 12 km. The scalar mean wind speed is 10/15 knots up to 9 km and increases to 30/35 knots at 16 km. In September mean wind speeds are less than 15 knots and the steadiness less than 50 per cent at all levels in the troposphere. This is the transitional month. In October westerlies associated with the winter circulation have established themselves above 6 km with extreme steadiness. Below this level the N/NW winds are more variable. The level of steady westerlies comes down to 3 km in November and December, to 2 km in January and February and practically up to the surface in March, April and May. The upper tropospheric westerlies attain their maximum speed at about 12 km in all the months October to June. The maximum speed increases from 40 knots in October to nearly 100 knots in January and thereafter decreases slowly to 45 knots in May. From May to June the speed decreases rapidly to 20 knots which is also the mean speed of the easterlies at this level in July and August.

(11) *New Delhi*

The months of July and August are characterised by very unsteady winds over Delhi (Fig. 11) throughout the troposphere. The steadiness is less than 50 per cent at all levels from the surface to 14 km with two minima of 10 per cent or less at about 1 to 1·5 km and 7 to 8 km. There is a feeble maximum at about 3 to 4 km. Above 14 km the steadiness increases rapidly with height to a value of nearly 90 per cent at 18 km. Below 1 km the winds are SE veering to northerly at 3 km and remaining so up to about 6 km. Between 9 and 11 km the winds are southeasterly backing to easterly aloft. Mean scalar speeds are of the order of 10/15 knots below 14 km. The easterlies continue to increase in speed with height in the lower stratosphere, the mean scalar speed reaching the value of 20/25 knots at 18 km and 30/35 knots at 21 km. The changes from August to September are most striking. The winter westerlies have already got established in the upper troposphere. Although the mean scalar wind speeds are less than 20 knots throughout the troposphere, the large increase in the steadiness of the winds between 6 and 12 km is very conspicuous. From October to June the westerlies prevail with great steadiness at all levels above 3 km. The steadiness in all these months increases rapidly from the surface to 3 km. The maximum speed of the westerlies occurs at 12 km in all the months. The rapid increase in speed at this level from 20 knots in September to 60 knots in October is noteworthy. The speed increases to 80 knots in November and December and to 85 knots in January and February. Thereafter, it decreases to 50/55 knots by May and rapidly to 20 knots in June. It is noteworthy that despite the large decrease in speed, the steadiness of the upper tropospheric westerly winds continues to be as high as 75 per cent in June. There is, however, a decrease in steadiness, and backing of the winds with height towards south and southeast above 12-km level. The sudden change in the nature of the steadiness curve from June to July is very striking and significant.

(12) *Amritsar*

The rawin station at Amritsar was started at the beginning of the IGY in July 1957 and functioned till January 1960. The period covered by the wind observations is, therefore, much less than in the case of the other stations. Nevertheless, the monthly mean upper winds of this station have also been included in the present study because of some interesting features associated with it.

Fig. 12 shows the vertical variation of $V_s$, $D$ and $q$ for Amritsar, which is the northernmost of the 12 rawin stations. Although the station is only 3° to the north of Delhi and 2° to its west, the vertical variation of wind over Amritsar in the months of July and August is quite different from that at Delhi. While the resultant upper tropospheric winds above 9 km are from E/ESE at Delhi in these months the winds at the corresponding levels over Amritsar are from W/WSW. Indeed in the middle and upper troposphere westerly winds continue to prevail at Amritsar in all the months of the year. The scalar mean wind speeds are lowest in July. In this month the mean speed increases gradually from about 5 knots near the surface to about 25 knots at 12 km and remains nearly constant above that level up to 18 km. The constancy of the wind is greater than 75 per cent between 7 and 12 km and decreases to 50 per cent above that level. In August the scalar mean wind speed shows a maximum of about 30 knots at 14 km. The steadiness is practically 75 per cent or more at all levels from 7 to 16 km. Near the surface, the resultant wind direction is from E/ESE. There is a continuous veering of the wind to NW at 3 km above which the wind gradually backs becoming westerly at 7 km. Winds are least steady in the lowest levels below 2 km above which the steadiness increases to 50 per cent or more. The changes from August to September are not very striking unlike in the case of Delhi. The noteworthy feature is the increase in the steadiness of the upper tropospheric westerlies which attain a mean maximum scalar speed of 35 knots at 12 km. The rapid increase in speed of the zonal westerlies beginning from September is very conspicuous. The level of minimum speed continues to be at or near 12 km although in the months March to May there is some indication that the maximum speed of the westerlies is attained at the level of 14 km. However on account of the limited period of the data this is not conclusive. During the months December to March winds are least steady below 3 km while in the upper troposphere the steadiness of the westerlies exceeds 90 per cent. Throughout the year the westerlies in the upper troposphere attain their maximum speed at the levels of 12 to 14 km. The maximum is flat and feeble in the months July and August but sharp and conspicuous in the winter months.

## 4. Discussion

The most conspicuous feature of the wind circulation over India and neighbourhood is the seasonal variation associated with the summer and winter monsoons of South Asia. Comparing the winter (January) and summer (July) mean positions of the axis of the equatorial trough of low pressure round the world (Riehl 1954), it is seen that the maximum northward displacement of the trough in the summer months occurs along the meridian of about 80° E passing across India. Along this meridian the axis of the trough lies at about 5°S in winter and at about 25°N in summer. (The corresponding position along the meridian of 80° W running across the American Continent are 5°S and 5°N). Associated with this large northward swing of the equatorial trough in summer over the Indian area there is a corresponding movement of the subtropical anticyclonic ridge along the northern periphery of the equatorial trough. In the upper troposphere above 300 mb the subtropical anticyclone lies over the Tibetan plateau with its ridge line approximately along the parallel of 30°N. In the winter months the corresponding position of the subtropical anticyclonic ridge is at about 10°N.

The study of the pattern of variability of winds with height at the 12 rawin stations brings out the following features.

(*i*) The change from the winter type of circulation to the summer or southwest monsoon type of circulation occurs in the month of May at stations to the south of latitude 20°N and in June at stations to the north of this latitude.

(*ii*) The reverse change occurs in September at stations to the north of latitude 25°N, and in October at stations to the south of 25°N.

(*iii*) The middle troposphere is a region of very unsteady winds throughout the country in the summer monsoon months of July and August.

(*iv*) The upper tropospheric zonal easterlies of the summer monsoon months are characterised by great steadiness, south of latitude 25° N, their northernmost limit being about 30°N.

(*v*) The zonal westerlies of the non-monsoon months blow with great steadiness north of latitude 15°N, their southernmost limit being about 10°N.

(*vi*) The transitional layer separating regions of different wind regimes is always one of very unsteady winds.

In order to bring out the characteristics of the wind circulation in the upper troposphere during the winter and summer seasons, the resultant wind speeds $V_r$, the resultant wind direction in degrees from north $D$, the constancy $q$ and the number of observations $n$ for the standard levels of 6·0, 7·2, 9·0, 10·5, 12.0, 14·1, 16·2 and 18·0 km for the months of January and July have been listed in Tables 2 and 3 for the 12 rawin stations. (The geometric levels correspond approximately to the pressure levels of 500, 400, 300, 250, 200, 150, 100 and 75 mb).

In January the highest wind speeds at almost all the rawin stations north of Madras occurs at 12 km. (In the case of Allahabad and Gauhati the highest speed occurs at 10·5 km level but the wind speed at 12 km is nearly the same as at the lower level). We also notice that the speeds at 10·5 and 14·2 km levels are not appreciably lower than the maximum at 12-km level indicating that the level of maximum wind speed can oscillate

TABLE 2—(January)

| | | Level (km) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 6·0 | 7·2 | 9·0 | 10·5 | 12·0 | 14·1 | 16·2 | 18·0 |
| TRIVANDRUM | *Vr* (kts) | 5·3 | 3·0 | 2·9 | 10·0 | 8·9 | 4·3 | 3·2 | 8.1 |
| | *D* (deg) | (062) | (032) | (228) | (184) | (194) | (203) | (050) | (114) |
| | *q* (%) | 44 | 21 | 17 | 45 | 38 | 20 | 15 | 61 |
| | *n* | 114 | 113 | 106 | 94 | 83 | 54 | 27 | 10 |
| PORT BLAIR | *Vr* | 2·1 | 2·9 | 8·1 | 14·5 | 17·7 | 24·0 | 17·7 | 40·7 |
| | *D* | (166) | (241) | (266) | (248) | (241) | (233) | (255) | (251) |
| | *q* | 15 | 19 | 40 | 61 | 67 | 66 | 55 | 67 |
| | *n* | 116 | 114 | 96 | 74 | 54 | 31 | 15 | 5 |
| MADRAS | *Vr* | 3·7 | 7·3 | 16·1 | 19·6 | 21·2 | 19·2 | 10·1 | 9·3 |
| | *D* | (287) | (284) | (268) | (252) | (258) | (255) | (259) | (260) |
| | *q* | 25 | 37 | 63 | 68 | 66 | 67 | 48 | 57 |
| | *n* | 210 | 201 | 172 | 158 | 123 | 93 | 49 | 18 |
| BOMBAY | *Vr* | 29·0 | 38·0 | 51·6 | 59·0 | 60·0 | 56·7 | 40·0 | |
| | *D* | (267) | (269) | (265) | (263) | (267) | (265) | (270) | |
| | *q* | 93 | 85 | 92 | 94 | 96 | 94 | 94 | |
| | *n* | 173 | 172 | 143 | 124 | 99 | 53 | 11 | |
| VERAVAL | *Vr* | 33·0 | 43·0 | 58·6 | 63·5 | 69·3 | 59·7 | 36·4 | 18·2 |
| | *D* | (270) | (268) | (268) | (265) | (267) | (270) | (269) | (288) |
| | *q* | 92 | 93 | 94 | 94 | 94 | 97 | 87 | 70 |
| | *n* | 92 | 91 | 82 | 66 | 45 | 30 | 15 | 11 |
| NAGPUR | *Vr* | 34·1 | 43·0 | 55·0 | 63·5 | 63·3 | 59·0 | 53·0 | 34·0 |
| | *D* | (270) | (269) | (266) | (267) | (267) | (268) | (265) | (274) |
| | *q* | 92 | 92 | 92 | 93 | 93 | 96 | 97 | 81 |
| | *n* | 210 | 184 | 150 | 115 | 79 | 39 | 24 | 16 |
| CALCUTTA | *Vr* | 42·5 | 51·3 | 64·0 | 70·8 | 72·5) | 70·7 | 69·0 | |
| | *D* | (270) | (266) | (266) | (263) | (260) | (263) | (259) | |
| | *q* | 96 | 96 | 94 | 93 | 95 | 97 | 93 | |
| | *n* | 244 | 236 | 204 | 163 | 140 | 72 | 21 | |
| ALLAHABAD | *Vr* | 42·4 | 51·5 | 67·5 | 78·1 | 77·5 | 76·0 | | |
| | *D* | (270) | (269) | (266) | (265) | (267) | (268) | | |
| | *q* | 95 | 95 | 92 | 92 | 95 | 97 | | |
| | *n* | 146 | 134 | 115 | 86 | 48 | 17 | | |
| GAUHATI | *Vr* | 52·0 | 61·0 | 80·0 | 93·0 | 91·0 | 91·0 | | |
| | *D* | (272) | (272) | (273) | (270) | (270) | (267) | | |
| | *q* | 96 | 95 | 94 | 93 | 93 | 98 | | |
| | *n* | 147 | 146 | 92 | 50 | 23 | 6 | | |
| JODHPUR | *Vr* | 42·0 | 51·5 | 70·3 | 88·1 | 94·4 | 86·0 | | |
| | *D* | (270) | (273) | (270) | (269) | (272) | (267) | | |
| | *q* | 93 | 93 | 96 | 95 | 96 | 90 | | |
| | *n* | 114 | 105 | 84 | 59 | 36 | 11 | | |
| NEW DELHI | *Vr* | 34·4 | 45·7 | 65·0 | 76·0 | 81·0 | 78·5 | 73·6 | |
| | *D* | (271) | (269) | (268) | (270) | (269) | (270) | (272) | |
| | *q* | 91 | 93 | 94 | 95 | 95 | 96 | 98 | |
| | *n* | 271 | 244 | 206 | 160 | 93 | 59 | 10 | |
| AMRITSAR | *Vr* | 23·9 | 30·9 | 46·8 | 63·7 | 70·0 | 61·5 | 57·0 | |
| | *D* | (267) | (272) | (270) | (272) | (266) | (270) | (270) | |
| | *q* | 76 | 78 | 87 | 92 | 93 | 94 | 100 | |
| | *n* | 80 | 77 | 68 | 55 | 38 | 9 | 1 | |

**TABLE 3—(July)**

| | | Level (km) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 6·0 | 7·2 | 9·0 | 10·5 | 12·0 | 14·1 | 16·2 | 18·0 |
| TRIVANDRUM | *Vr* (kts) | 5·4 | 2·6 | 16·5 | 29·6 | 51·0 | 64·5 | 53·5 | 54·3 |
| | *D* (deg) | (268) | (106) | (091) | (085) | (080) | (078) | (089) | (093) |
| | *q* (%) | 41 | 20 | 80 | 93 | 98 | 97 | 97 | 98 |
| | *n* | 112 | 111 | 104 | 87 | 72 | 56 | 31 | 10 |
| PORT BLAIR | *Vr* | 5·1 | 2·9 | 14·5 | 25·6 | 34·2 | 47·0 | | |
| | *D* | (230) | (164) | (084) | (074) | (068) | (073) | | |
| | *q* | 36 | 22 | 80 | 91 | 93 | 97 | | |
| | *n* | 99 | 98 | 78 | 67 | 49 | 22 | | |
| MADRAS | *Vr* | 8·6 | 1·4 | 10·5 | 23·8 | 39·6 | 60·0 | 79·1 | 58·0 |
| | *D* | (276) | (268) | (091) | (085) | (084) | (085) | (086) | (079 |
| | *q* | 57 | 11 | 62 | 87 | 96 | 97 | 98 | 96 |
| | *n* | 217 | 196 | 164 | 139 | 110 | 79 | 32 | 14 |
| BOMBAY | *Vr* | 2·6 | 4·9 | 15·3 | 24·1 | 37·5 | 55·0 | 70·0 | 70·2 |
| | *D* | (267) | (080) | (089) | (082) | (084) | (089) | (086) | (085) |
| | *q* | 22 | 39 | 86 | 93 | 97 | 98 | 97 | 95 |
| | *n* | 164 | 161 | 135 | 113 | 93 | 63 | 29 | 15 |
| VERAVAL | *Vr* | 4·2 | 9·1 | 18·3 | 28·0 | 39·9 | 54·0 | 56·5 | 61·5 |
| | *D* | (099) | (092) | (090) | (088) | (094) | (090) | (090) | (094) |
| | *q* | 34 | 60 | 87 | 92 | 92 | 91 | 97 | 99 |
| | *n* | 106 | 104 | 89 | 84 | 70 | 62 | 47 | 22 |
| NAGPUR | *Vr* | 3·5 | 7·6 | 16·7 | 26·4 | 36·4 | 48·0 | 59·5 | 56·8 |
| | *D* | (028) | (078) | (086) | (087) | (084) | (082) | (080) | (090) |
| | *q* | 30 | 60 | 87 | 96 | 97 | 96 | 98 | 99 |
| | *n* | 176 | 169 | 122 | 89 | 67 | 54 | 26 | 10 |
| CALCUTTA | *Vr* | 6·3 | 9·1 | 15·7 | 22·2 | 28·4 | 36·7 | 48·5 | 58·0 |
| | *D* | (112) | (091) | (091) | (087) | (081) | (078) | (082) | (088) |
| | *q* | 54 | 72 | 88 | 93 | 95 | 92 | 95 | 95 |
| | *n* | 231 | 223 | 203 | 177 | 160 | 98 | 30 | 9 |
| ALLAHABAD | *Vr* | 6·7 | 9·9 | 12·8 | 17·7 | 20·6 | 25·4 | 33·0 | 45·4 |
| | *D* | (089) | (085) | (088) | (086) | (086) | (087) | (075) | (084) |
| | *q* | 54 | 73 | 82 | 89 | 92 | 87 | 91 | 97 |
| | *n* | 167 | 163 | 136 | 112 | 77 | 35 | 9 | 6 |
| GAUHATI | *Vr* | 2·8 | 3·9 | 8·0 | 13·2 | 13·4 | 20·6 | 36·0 | |
| | *D* | (139) | (091) | (065) | (063) | (061) | (062) | (072) | |
| | *q* | 24 | 34 | 63 | 76 | 65 | 79 | 97 | |
| | *n* | 148 | 147 | 123 | 99 | 80 | 36 | 12 | |
| JODHPUR | *Vr* | 5·4 | 6·7 | 10·4 | 13·2 | 17·2 | 32·8 | 35·9 | |
| | *D* | (056) | (073) | (080) | (089) | (089) | (091) | (096) | |
| | *q* | 42 | 51 | 70 | 79 | 79 | 96 | 94 | |
| | *n* | 126 | 116 | 98 | 79 | 61 | 31 | 9 | |
| NEW DELHI | *Vr* | 2·2 | 1·2 | 1·8 | 3·4 | 5·5 | 10·3 | 20·6 | 26·2 |
| | *D* | (004) | (046) | (093) | (121) | (114) | (106) | (085) | (095) |
| | *q* | 19 | 9 | 14 | 25 | 36 | 54 | 83 | 87 |
| | *n* | 295 | 284 | 270 | 245 | 209 | 159 | 95 | 65 |
| AMRITSAR | *Vr* | 7·9 | 12·6 | 14·9 | 15·7 | 17·0 | 12·9 | 10·0 | 13·9 |
| | *D* | (278) | (265) | (260) | (248) | (243) | (240) | (300) | (282) |
| | *q* | 61 | 73 | 81 | 79 | 75 | 53 | 45 | 55 |
| | *n* | 76 | 76 | 64 | 50 | 40 | 32 | 14 | 4 |

between these limits on individual occasions. Comparing the speeds at the 12-km level it is seen that the maximum occurs at Jodhpur whose latitude is 26° 15′N. The maximum wind speed at Gauhati which lies almost along the same latitude is also nearly the same as at Jodhpur. Thus we may take the parallel of 26°N as the mean position of the subtropical westerly jet stream over India in this month. The mean maximum wind speed along the axis of the jet stream is about 95 knots.

In July the maximum speed of the zonal easterlies over India is reached at 14·1 km over Trivandrum and at 16·2 km over Madras. At stations to the north of Madras, with the exception of Nagpur, the easterlies do not reach a maximum speed at 16·2 km but continue to increase in speed at least up to 18 km (limit of observations). The highest maximum speed of the zonal easterlies is observed at the 16·2 km over Madras. The mean position of the axis of the easterly jet stream of the summer monsoon season may, therefore, be taken to be at or slightly to the north of the latitude of Madras. However, along a meridional section, the axis of the core of strongest wind shifts northward from about 8°N (latitude of Trivandrum) to 19°N (latitude of Bombay) as we move upwards from 14 to 18 km. Such a feature is not noticed in the case of the sub-tropical jet stream of the winter months. In this case the zonal westerlies continue to be strongest along 26°N (latitude of Jodhpur/Gauhati) at all levels from 9 to 14 km. This difference in behaviour between the sub-tropical westerly jet stream of the winter season and the tropical easterly jet stream of the summer monsoon season is apparently connected with the thermal structure of the atmosphere over India in these two seasons and needs further investigation.

5. Acknowledgement

We are indebted to the Upper Air Section of the Office of the Deputy Director General of Observatories (Climatology and Geophysics) for the wind data used in this study.

*REFERENCES*

| | | |
|---|---|---|
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| Riehl, H. | 1954 | *Tropical Meteorology*, p. 13. |

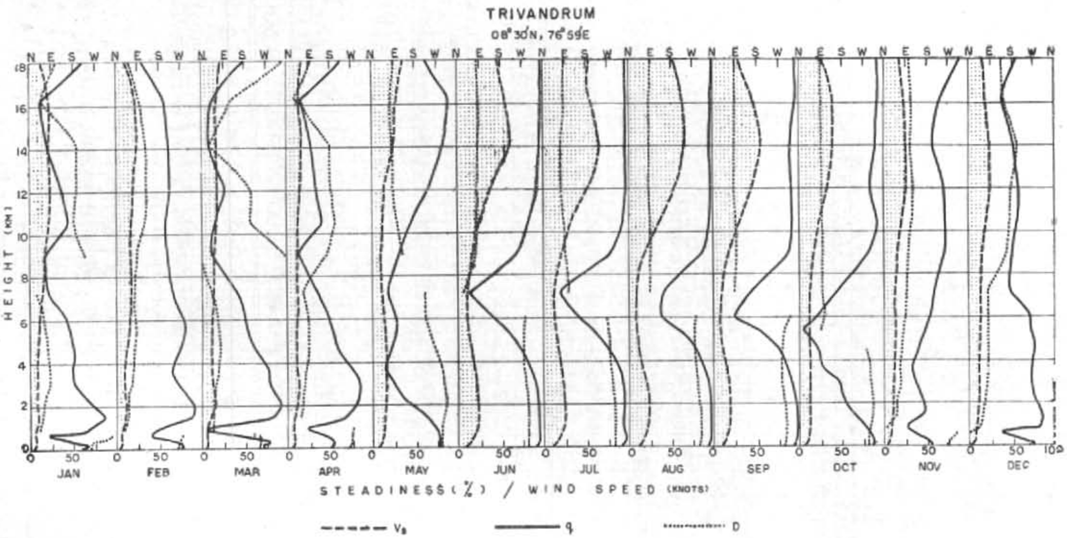
TRIVANDRUM
08°30'N, 76°59'E
N E S W N
HEIGHT (KM)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
STEADINESS (%) / WIND SPEED (KNOTS)
$V_s$
q
D

Fig. 1

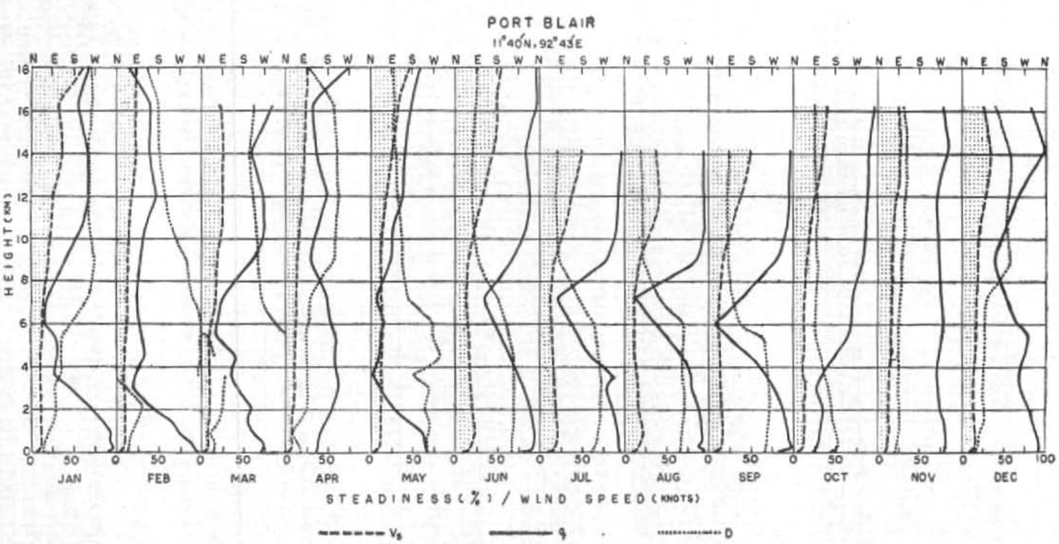
PORT BLAIR
11°40'N, 92°43'E
N E S W N
HEIGHT (KM)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
STEADINESS (%) / WIND SPEED (KNOTS)
$V_s$
q
D

Fig. 2

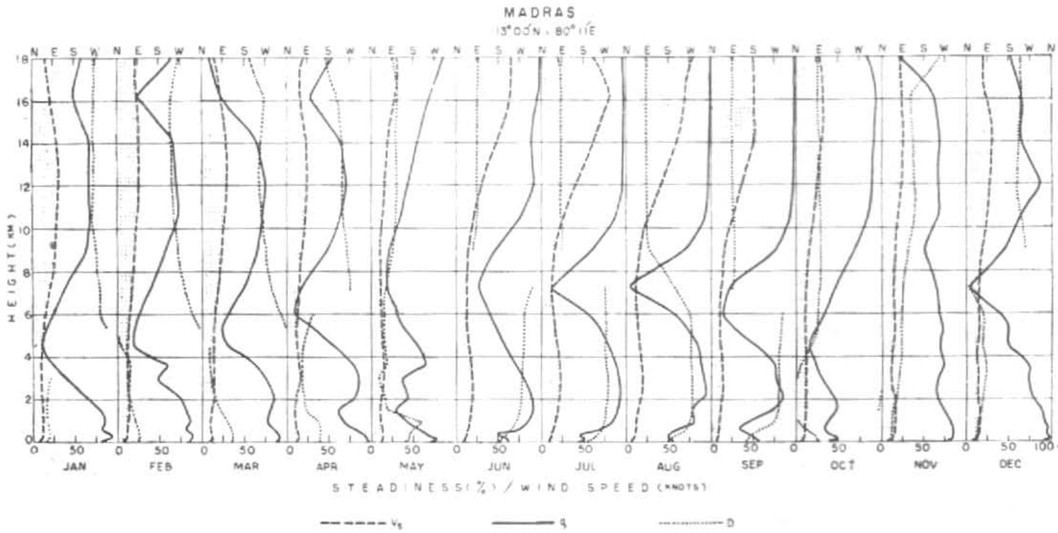
MADRAS
13° 00'N, 80° 11'E
HEIGHT (KM)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
STEADINESS (%) / WIND SPEED (KNOTS)
Vs
q
D

Fig. 3

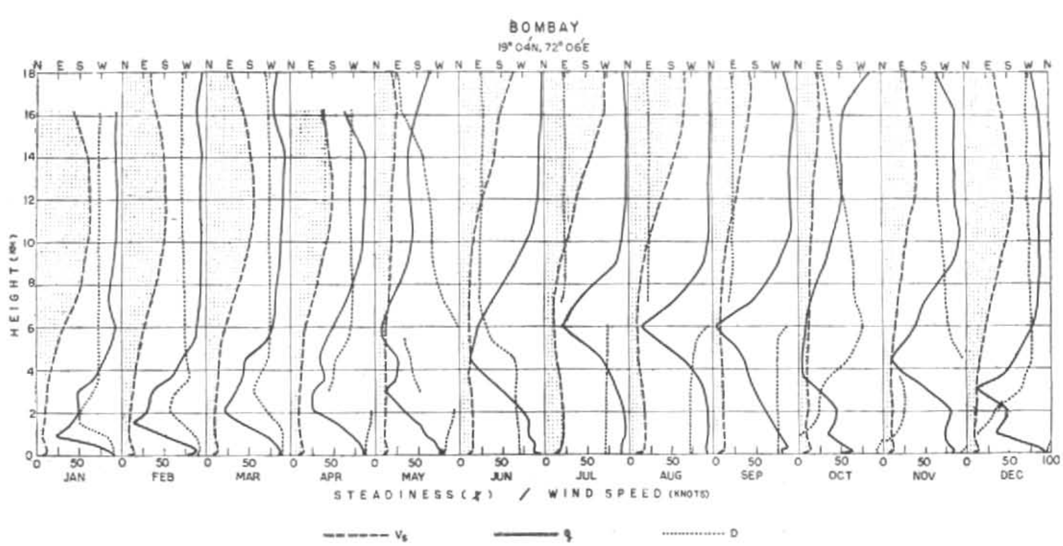
BOMBAY
19° 04'N, 72° 06'E
HEIGHT (KM)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
STEADINESS (%) / WIND SPEED (KNOTS)
Vs
q
D

Fig. 4

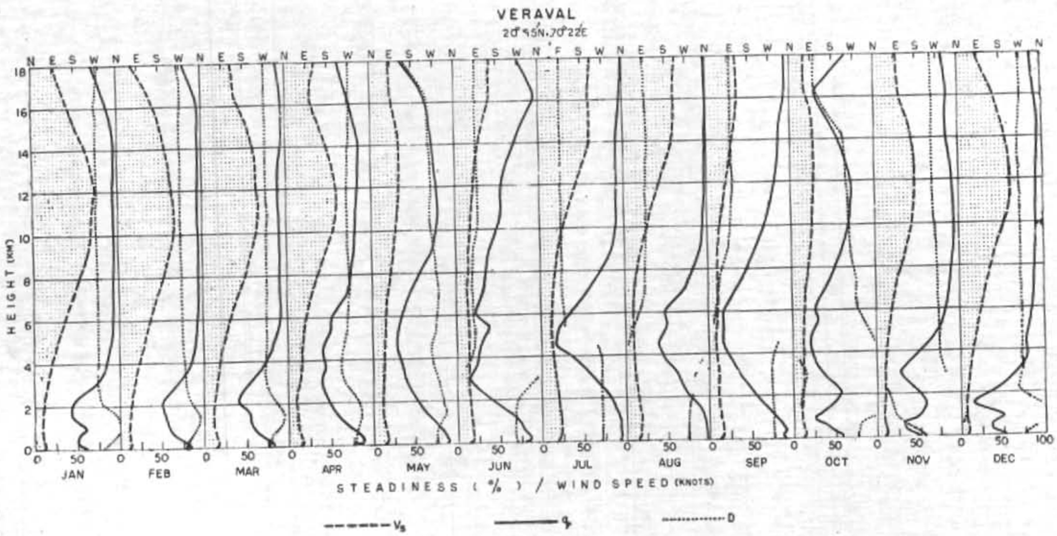
VERAVAL
HEIGHT (KM)
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
STEADINESS (%) / WIND SPEED (KNOTS)

Fig. 5

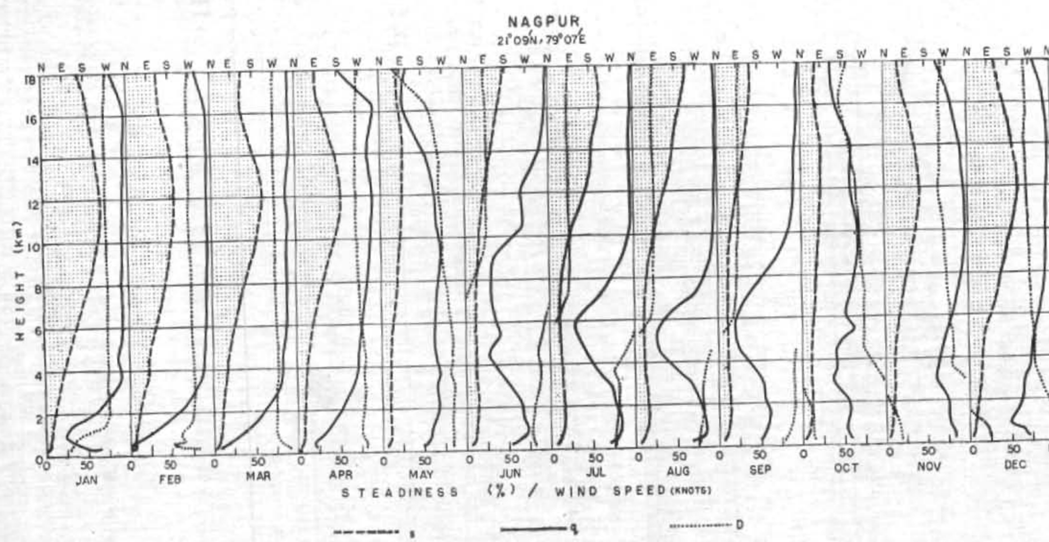
NAGPUR
HEIGHT (Km)
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
STEADINESS (%) / WIND SPEED (KNOTS)

Fig. 6

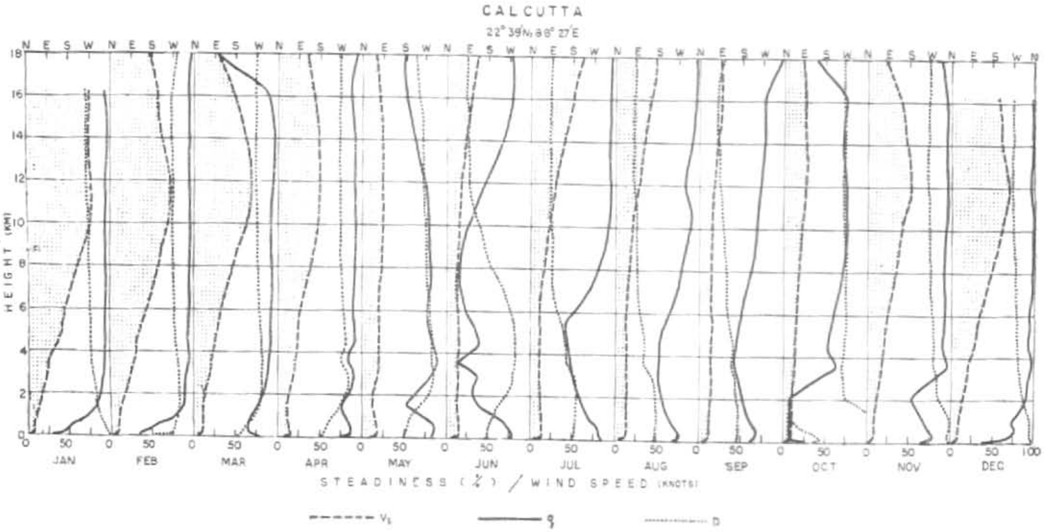
CALCUTTA
22° 39'N, 88° 27'E
HEIGHT (KM)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
STEADINESS (%) / WIND SPEED (KNOTS)
Vs
q
D

Fig. 7

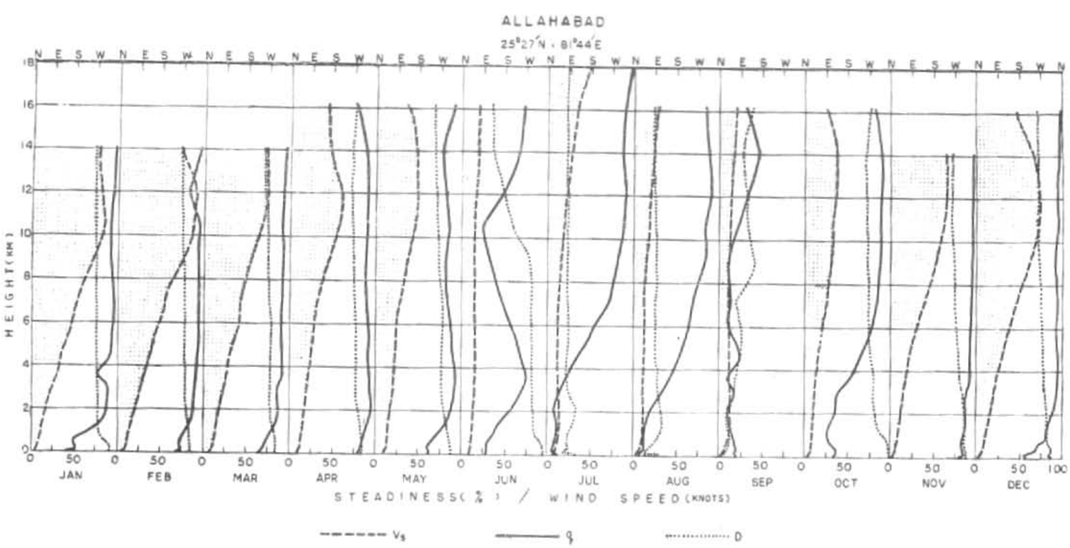
ALLAHABAD
25°27'N · 81°44'E
HEIGHT (KM)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
STEADINESS (%) / WIND SPEED (KNOTS)
Vs
q
D

Fig. 8

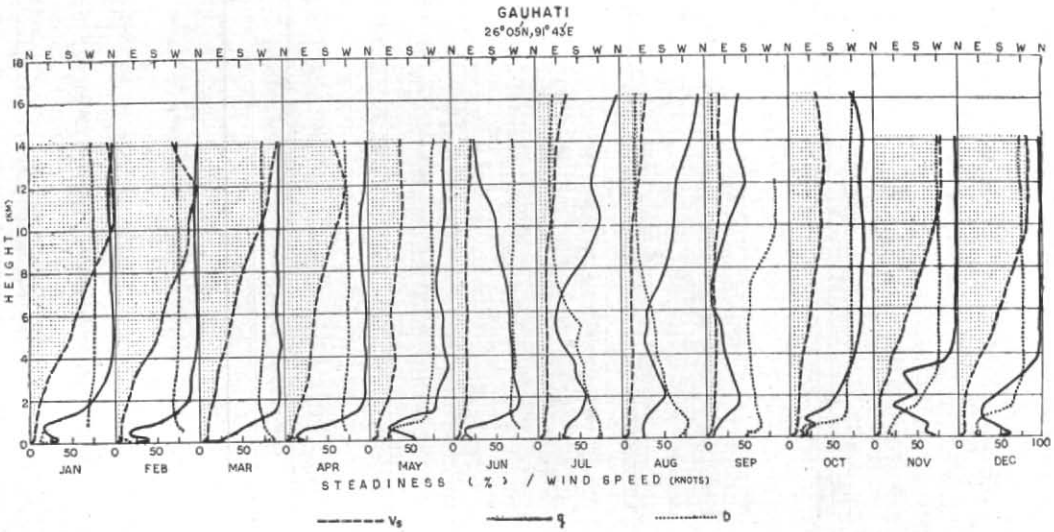
GAUHATI
26°05'N, 91°43'E
HEIGHT (KM)
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
STEADINESS (%) / WIND SPEED (KNOTS)
$V_s$
q
D

Fig. 9

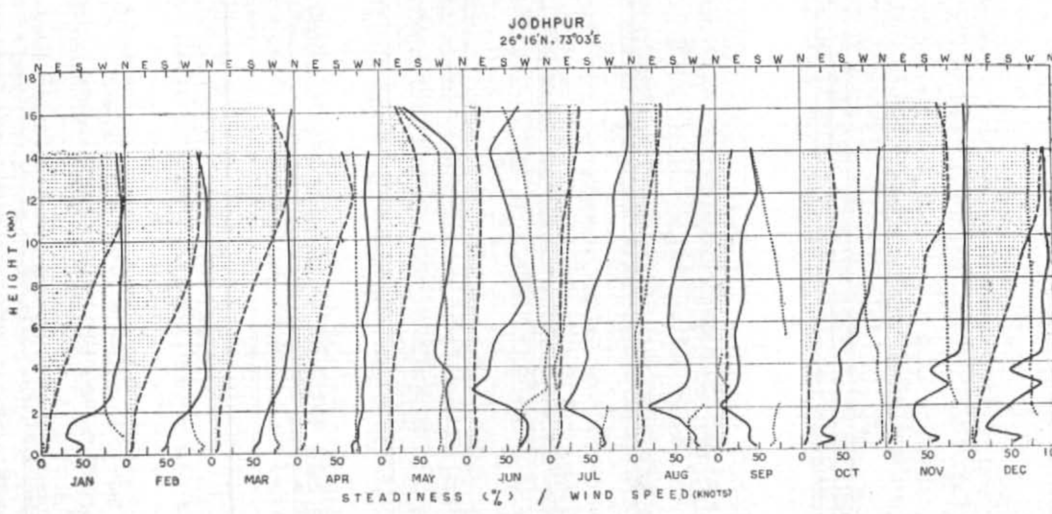
JODHPUR
26°16'N, 73°03'E
HEIGHT (KM)
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
STEADINESS (%) / WIND SPEED (KNOTS)
$V_s$
q
D

Fig. 10

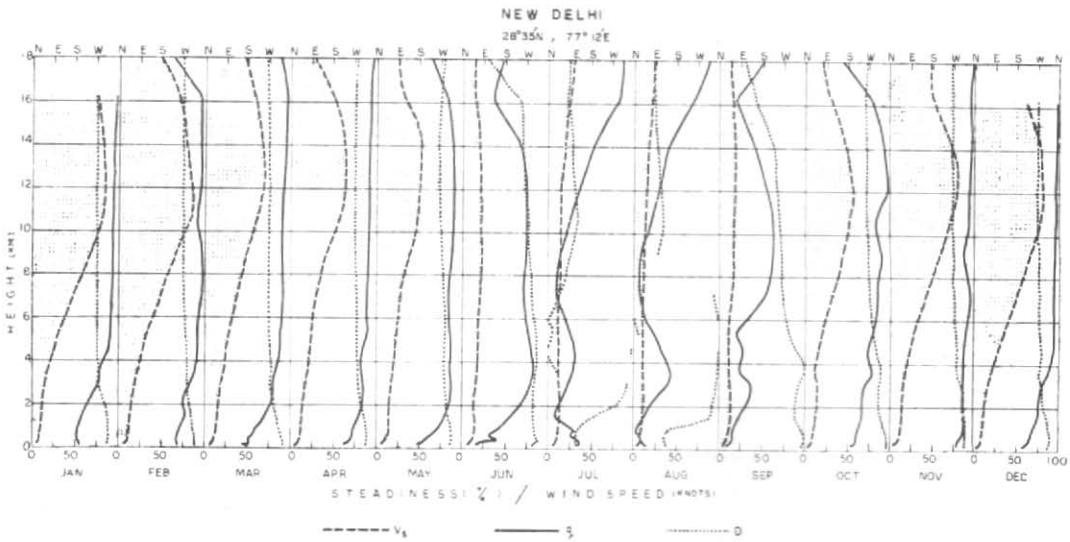
NEW DELHI
28°35'N , 77° 12'E
HEIGHT (KM)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
STEADINESS (%) / WIND SPEED (KNOTS)
V_s
q
D

Fig. 11

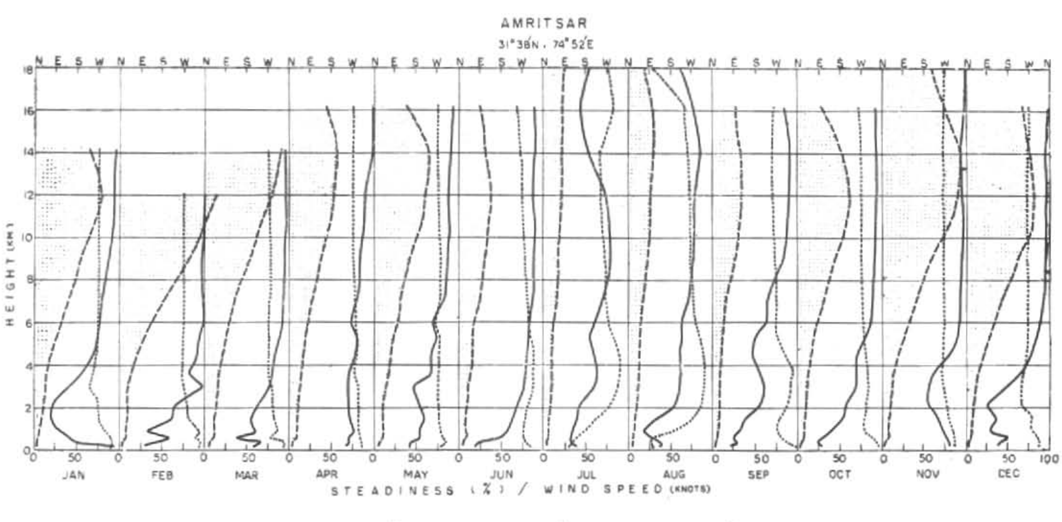
AMRITSAR
31°38'N , 74°52'E
HEIGHT (KM)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
STEADINESS (%) / WIND SPEED (KNOTS)
V_s
q
D

Fig. 12