Some aspects of the Statistical Distribution of Upper Winds over India

S. RANGARAJAN and R. Y. MOKASHI

Meteorological Office, Poona

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ABSTRACT. For a quantitative evaluation of the probabilities of occurrence of upper wind speed and directions, a number of standard statistical parameters like standard deviations of the zonal and meridional components of the wind and the correlation coefficients between them are required. Utilising all radio-wind observations of the 5-year period, 1959-1963, these statistical parameters have been computed for the standard geometrical heights 1·5, 3·0, 6·0, 9·0, 12·0, 14·1 and 16·2 km a.s.l. for all the twelve months of the year for three representative stations in India, *viz.*, New Delhi, Nagpur and Trivandrum. The brief theory underlying the use of the statistical parameters and the method of constructing the distribution ellipses are outlined. The verification of the procedure has been illustrated by four actual cases of wind distribution. The main features of the distribution of winds in the different seasons have been discussed. In general, there is a tendency for the upper wind distribution to be elliptical rather than circular.

1. Introduction

Statistics concerning the variability of upper winds over India have been hitherto presented in the form of wind roses and in the form of scalar and vector mean winds and the steadiness factor. While these parameters are quite useful in understanding the general upper air climatology, quantitative evaluations of the probability of occurrence of different velocities and directions at the standard levels are possible only, if we have more sophisticated statistical parameters at our disposal. The working out of these is, however, justified only, if the method of routine wind observation does not lead to any biassing of the data in favour of certain preferred situations. Thus, wind data obtained by the pilot balloon method would be unsuitable for the purpose, since the observations tend to represent only cloudless conditions at the levels for which winds are measured. In dealing with radio-wind data, similar biassing does not occur normally and hence the normal laws of statistics can be expected to yield satisfactory results. Radio-wind data for Indian stations have begun to be accumulated only in recent years. In the present paper, the relevant statistical parameters of upper winds for three radio-wind stations in India have been discussed, using the data of a uniform five-year period, 1959 to 1963. The stations chosen are (1) New Delhi, representing the northern parts of the country, (2) Nagpur, representing the central parts and (3) Trivandrum, representing the southern parts. The symbols used in this paper are set out in Table 1.

2. Statistical representation of wind vector distributions

The distribution of vectors, like upper winds, around a mean value can be conveniently represented in the form of a normal bivariate function given by—

$$f(v_x, v_y) = \frac{1}{2\pi\, S_x\, S_y\, (1 - r_{xy}^2)}\, e^{-\frac{1}{2}F(v_x,\, v_y)} \qquad (1)$$

where, $F(v_x, v_y)$ is

$$\left\{\frac{1}{1-r_{xy}^2}\right\} \left\{\frac{(v_x-\overline{X})^2}{S_x^2} - 2\, r_{xy} \times \times \frac{(v_x-\overline{X})\,(v_y-\overline{Y})}{S_x\, S_y} + \frac{(v_y-\overline{Y})^2}{S_y^2}\right\}$$

where v_x and v_y are the components of the winds along orthogonal axes. The parameters v_x and v_y can both be considered as having a normal distribution around their means. However, they are not usually uncorrelated and some correlation usually exists between the components. A special case of distribution arises when $r_{xy} = 0$ and $S_x = S_y$. We have then $S_v = \sqrt{2}\, S_x = \sqrt{2}\, S_y$ and by changing the origin of co-ordinates to the point $\overline{X}$, $\overline{Y}$ (beginning point of the vector representing $|\overline{\mathbf{V}}|$), the equation (1) becomes—

$$f(|\mathbf{v}_i|) = \frac{1}{\pi\, S_v}\, e^{-|\mathbf{v}_i^2|/S_v^2} \qquad (2)$$

This becomes the well known circular distribution. It is possible then to calculate the radii of circles which contain specified proportions of the total number of the beginning points of the vectors of the winds. Table 2 gives these values.

Brooks *et al.* (1946) derived an approximate expression connecting q, $|\overline{\mathbf{V}}|$, S_v and the wind vector $\mathbf{v}_i$ in the form of an integral, assuming a normal circular distribution and constructed tables $S_v/|\overline{\mathbf{V}}|$ in terms of q.

Using this relationship, Krishnan *et al.* (1961) have estimated the standard vector deviations for the Indian region using pilot balloon data. Standard vector deviations for the entire world have been estimated by Tucker (1960) using the wind data of the period 1949-1953. These computations assume the validity of circular normal distribution.

In the actual atmosphere, however, the circular distribution is an exception rather than the rule. This would be evident from the values actually computed and published by Crutcher (1961). Over large areas of the world, some sort of elliptical distribution appears to be the general rule.

The basic theory underlying the statistical treatment of elliptical wind distributions has been discussed by Crutcher (1957), Crutcher and Baer (1962) and Maher and McRae (1964) and will not be discussed here. The important statistical parameters that are needed to represent the elliptical distribution are the standard deviations of the zonal and meridional components of the winds (S_x, S_y) and the correlation coefficient r_{xy} between the individual components.

Two cases of elliptical distribution will be briefly discussed. In the first case, it is assumed that $r_{xy} = 0$. *i.e.*, the two wind components take random values without there being any correlation between themselves.

Referring to equation (1), the maximum value of its distribution function, $f(v_x . v_y)$ becomes equal to $1/(2\pi S_x S_y)$, where $v_x = \bar{X}$ and $v_y = \bar{Y}$, *i.e.*, $F(v_x, v_y) = 0$.

The distribution of v_x and v_y can be visualised as a three dimensional surface of a humped solid figure. Curves formed by the intersection of the solid figure by a horizontal plane are ellipses which can be represented as

$$\left(\frac{v_x - \bar{X}}{S_x}\right)^2 + \left(\frac{v_y - \bar{Y}}{S_y}\right)^2 = C^2 \qquad (3)$$

where C^2 is a constant.

The centre of the ellipse is at the beginning point of the vector, represented by $|\bar{\mathbf{V}}|$ and the axes are parallel to the N-S and E-W directions. The probability that the beginning of any particular wind vector will fall inside or outside the distribution ellipse can be worked out from standard tables.

In the general case where r_{xy} is not zero, it is still possible to construct the distribution ellipse by a transformation of co-ordinates. All that would be necessary is to choose a set of new axes for the distribution ellipse such that the X-axis makes an angle ψ with the west-east direction where,

$$\tan 2\psi = \frac{2 r_{xy} S_x S_y}{(S_x^2 - S_y^2)} \qquad (4)$$

Positive values of ψ are measured anti-clockwise and negative values clockwise.

The theory underlying the transformation may be found in the paper of Maher and McRae (1964).

The probability ellipse is constructed on the new axes with sides measuring $2S_x\chi_P$ and $2S_y\chi_P$ where χ_P is the factor corresponding to probability function of 2 degrees of freedom. These are given in Table 3.

Instead of defining ψ as above and measuring it as clockwise or anti-clockwise according as the value of the angle is negative or positive, we can introduce an alternate convention. In this convention, ψ is always measured anti-clockwise and is defined as the angle between the west-east direction and the major axis of the ellipse (whether $S_x > S_y$ or $S_y > S_x$). ψ can take all values between 0 and 180°. The four cases that arise have been listed below.

If r_{xy} is +ve, and
- if $S_x > S_y$, ψ lies between 0° and 45°
- if $S_y > S_x$, ψ lies between 45° and 90°

If r_{xy} is −ve, and
- if $S_y > S_x$, ψ lies between 90° and 135°
- if $S_x > S_y$, ψ lies between 135° and 180°

The above formulae are strictly applicable for an infinite population; however, as an approximation, means and standard deviations and correlations based on a limited population of about 100 can be used for practical purposes.

3. Data used for the study

The statistics were worked out utilising the 12 GMT rawin data of the 3 stations for the five-year period 1959-63. The method that had been adopted at these stations for computing the winds at the different standard levels remained identical during the period. The rawinsonde balloons used in routine flights had a rate of ascent of approximately 20 km per hour and the trajectories were drawn using drifts of the balloon at one-minute intervals. Thus, each leg to the trajectory covers approximately a height interval of 330 metres. The time interval chosen for measuring wind at any standard level was one-minute or two-minute intervals according whether the standard level fell within about the middle of a leg of the trajectory (0·3 to 0·7 minute) or without. The heights used for the computation were obtained from the

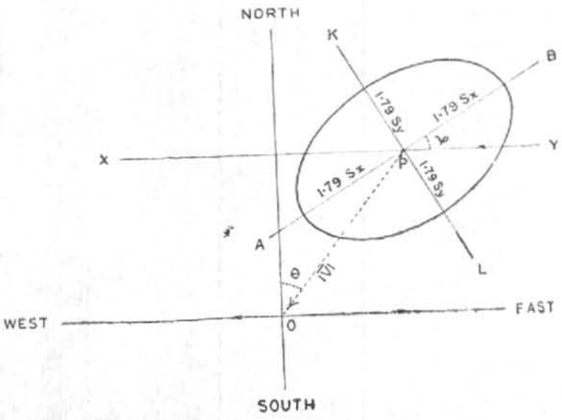

Fig. 1. The construction of the wind distribution ellipse for 80 per cent probability

radiosonde data and smoothened suitably. The winds allocated to any level may thus be considered to be the mean over a height interval of 350—600 metres. The levels chosen for the study were the standard height levels, 1·5, 3·0, 6·0, 9·0, 12·0, 14·1 and 16·2 km above m.s.l. All statistical parameters were worked out separately for each month of the year, with exception of r_{xy} which was worked out for alternate levels only.

The rawin equipment used at all the stations was the METOX Radiotheodolite which, however, fails to give correct readings when the angle of elevation of the balloon decreases below 15°. This happens usually in north India during the winter months, December to February, whenever the westerly jet stream is strong. On such occasions, a truncation of the values occurs; strong winds at levels higher than 9-10 km get suppressed. No allowance for this factor has been made and hence the results in respect of such cases will have to be suitably interpreted.

4. Presentation and discussion of data

Tables 4(a) to 4(c) give the basic statistical parameters in respect of New Delhi, Nagpur and Trivandrum for the standard levels for each of the calendar months. The main features of the upper wind statistics at the three stations are discussed below for the important levels.

New Delhi — During the winter period, December to February, the correlation between the zonal and meridional components is significantly negative at the 1·5 and 3·0 km levels and the ratio S_x / S_y is less than one. At these levels, the meridional fluctuations of the wind outweigh those of the zonal wind and the distribution is elliptical. The negative sign of r_{xy} indicates a preference for the stronger westerly winds to be more associated with a more northerly component. At the 6·0 km level, r_{xy} becomes small $S_x \approx S_y$ and the wind distribution tends to be more or less circular. At 12·0-km level which is near the level of maximum westerly winds, r_{xy} is negative in December but becomes positive in January and February. At this level, during January and February the fluctuations in the zonal components are more than those of the meridional components and the distribution again becomes somewhat elliptical.

In March and April wind distribution at 1·5 km and 3·0 km are similar to winter conditions but at higher levels upto about 15 km nearly circular distribution prevails. In the transition month of June, circular distribution prevails at all levels, except at 1·5 km, where it is elliptical with $S_x >> S_y$ and r_{xy} negative.

During the period of the Asian monsoon, July–September, S_x becomes generally greater than S_y at all levels. At 1·5 and 3·0 km, r_{xy} continues to be significant and negative as during the winter period. This is due to stronger easterly winds being fairly systematically associated with a more southerly component. During the transition month October, wind distribution is markedly elliptical with $S_x >> S_y$ between 9 and 14 km.

Nagpur — Unlike the case of New Delhi, the correlations between the zonal and meridional components do not show any systematic variation with level or with the seasons. They are generally small. Nearly circular distribution prevails in the lower levels upto 6 km in all months except during July to September when S_x becomes significantly larger than S_y .

A very interesting feature of the wind distribution at Nagpur is that S_y is greater than S_x at 12

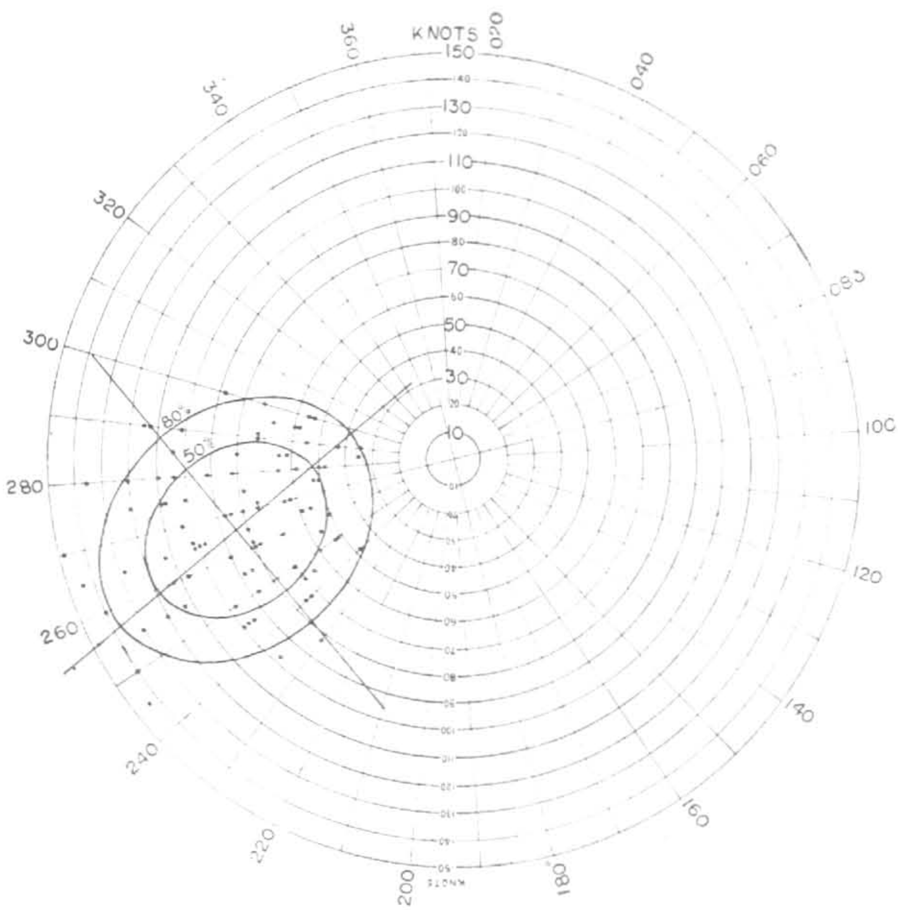

Fig. 2

New Delhi, January, 12·0 km

$|\overline{V}|$ 266°/84·4 kt ψ 26·0°

Total No. of observations 96

No. of points within 50 per cent ellipse : calculated 48, actual 46

No. of points within 80 per cent ellipse : calculated 77, actual 80

km (the level of maximum wind) during the season, November to April. In other words, at 12-km level, the variance of the meridional component outweighs that of the zonal component. This is opposite to what is seen to prevail at New Delhi ($S_x > S_y$).

The physical interpretation of the above appears to be as follows —

At New Delhi which is located near the core of the westerly jet stream, the zonal fluctuations predominate. At Nagpur which is located well to the south of the jet stream, the meridional fluctuations predominate signifying marked activity of the meridional transport of kinetic energy. During May and June, S_x becomes appreciably $> S_y$ at the 12-km and 14-km levels, and the distribution becomes markedly elliptical. As in the case of New Delhi, the maximum values of S_v are associated with the maximum values of $|\overline{V}|$, which occur at the 12-km level. During the transition month of October the standard vector deviation at 16·2 km (21 kt) is over thrice the value of $|\overline{V}|$ (6·3 kt), indicating high variability.

Trivandrum — A conspicuous feature of the upper wind statistics at Trivandrum is that the variances of the zonal components are greater than those of the meridional ones *at all levels* and during all the months. During the period December to April, the

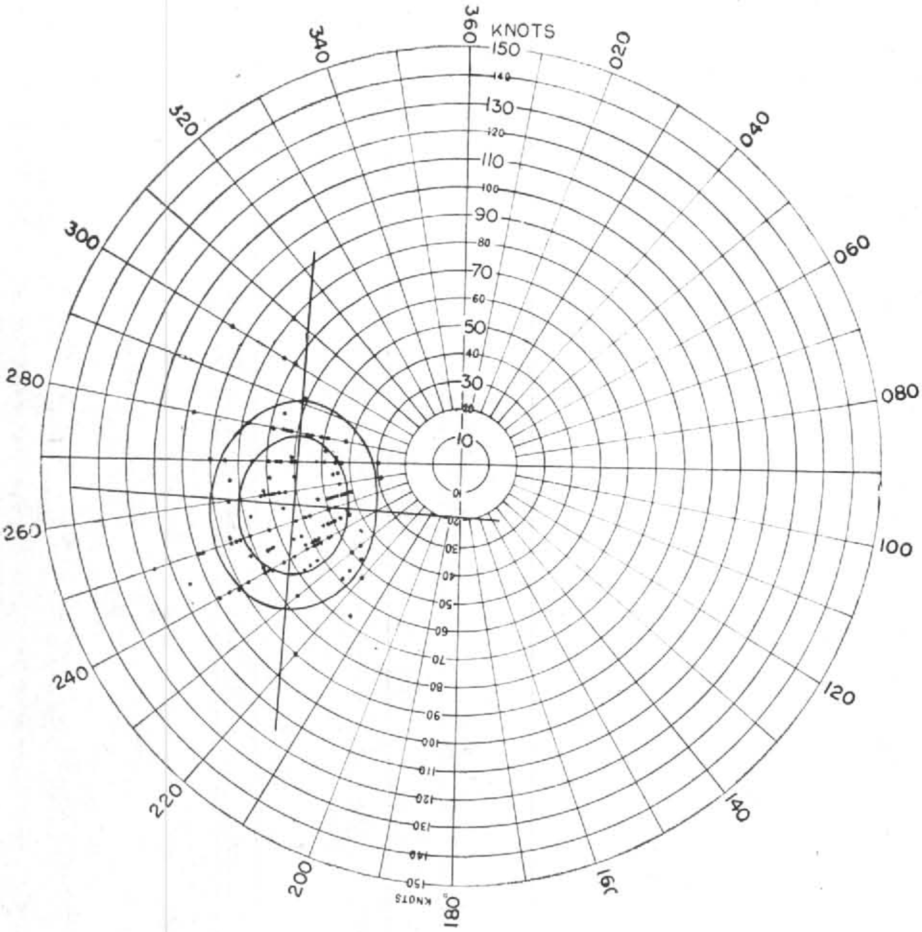

Fig. 3

Nagpur, January, 12·0 km

$|\overline{V}|$ 255°/61·4kt ψ —3·5°

Total No. of observations 122

No. of points within 50 per cent ellipse : calculated 61, actual 65

No. of points within 80 per cent ellipse : calculated 98, actual 102

northeasterly winds in the lower levels are fairly steady and the ellipticity is small. But in the upper troposphere, the variability becomes very pronounced, as also the ellipticity. During the period May to October, the ellipticity becomes pronounced at all levels comprising both the westerlies of the lower troposphere as well as the easterlies of the upper troposphere. In the case of the easterly jet stream which attains a maximum strength at or above 14·1 km, S_x is nearly twice as large as S_y. In comparison, it may be pointed out that in the case of the westerly jet stream of the winter season at New Delhi, the ellipticity at 12 km is much smaller, the ratio S_x / S_y being about 1·1 to 1·3 only.

5. Use of the statistics in estimating wind probabilities

The parameters given in the tables can be directly used to solve a variety of problems involving estimation of the probability with which upper winds having certain ranges in direction or velocity can be encountered. Thus, if the ranges in direction and velocity of winds that would comprise 80 per cent of the occasions are to be calculated, the following steps may be gone through.

First, the vector OP (Fig. 1) representing the $|\overline{V}|$ for the level concerned is drawn in a system of polar co-ordinates. At the beginning of the vector P, draw line XPY parallel to east—west

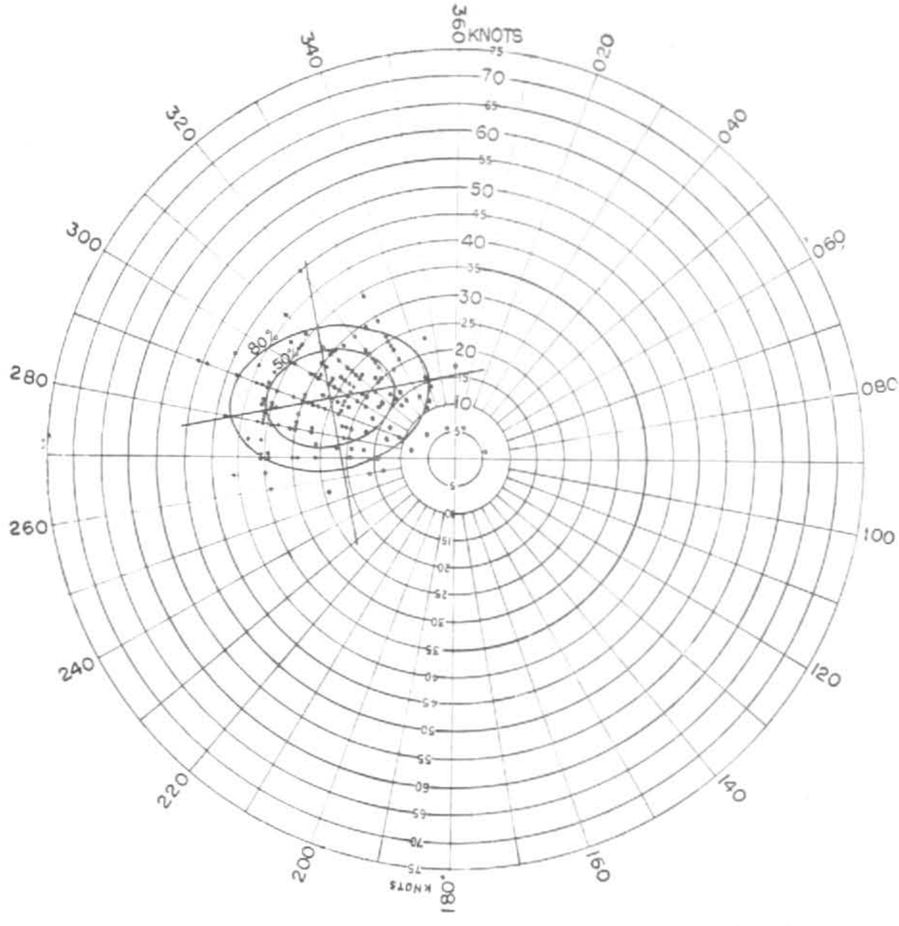

Fig. 4

Trivandrum, July, 1·5 km

$|\bar{V}|$ 295°/25·1 kt ψ 11·3°

Total No. of observations 154

No. of points within 50 per cent ellipse : calculated 77, actual 76

No. of points within 80 per cent ellipse : calculated 123, actual 126

direction. Determine the angle of rotation ψ using the relation.

$$\tan 2\psi = \frac{2\, r_{xy}\, S_x\, S_y}{(S_x^2 - S_y^2)}$$

At P, draw straight line APB making angle ψ with XPY measured anti-clockwise from PY for positive value of ψ. Then the straight line APB represents the axis of the distribution ellipse corresponding to the zonal component of the wind. A straight line KPL perpendicular to APB will then form the other axis of the distribution ellipse. By referring to Table 3 one can find the factor by which the S_x and S_y have to be multiplied to obtain the semi axes of the distribution ellipse. For 80 per cent probability, this factor is 1·79. With P as centre, construct the ellipse with its semi axes 1·79 S_x and 1·79 S_y measured along APB, KPL respectively. The ellipse will now contain the beginning points of 80 per cent of the wind vectors conforming to the particular statistical distribution. The extreme ranges in direction and velocity of this group can easily be found by joining the various points on the outline of the ellipse with O.

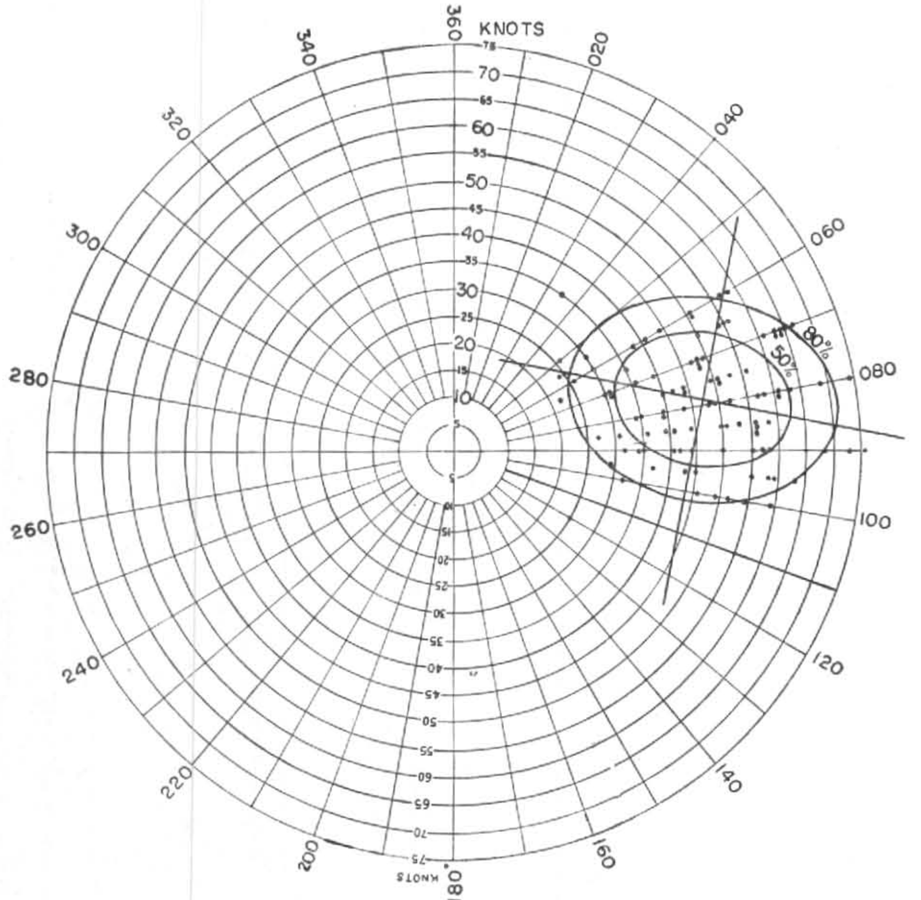

Fig. 5

Trivandrum, July, 12·0 km

|V| 079°/47·0 kt ψ —11·0°

Total No. of observations 104

No. of points within 50 per cent ellipse : calculated 52, actual 48

No. of points within 80 per cent ellipse: calculated 83, actual 86

6. Examples of wind distrbutions

In Figs. 2 to 5 are indicated worked out examples showing 50 and 80 per cent probability ellipses. The actual end points of the individual wind vectors which were utilised in calculating the statistics have also been shown as dots. The calculated and actual number of points falling inside the ellipses have also been indicated.

7. Acknowledgements

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TABLE 1

	Statistical parameters with symbols	Formulae used
$\overline{\lvert \mathbf{V} \rvert}$	Mean vector wind speed	$\left\lvert \frac{\Sigma \mathbf{v}_i}{N} \right\rvert$
θ	Direction of mean vector wind	arc tan $(\overline{X}/\overline{Y})$ measured in degrees clockwise from north
S_v	Standard vector deviation	$\left[\frac{N \Sigma (\lvert \mathbf{v}_i \rvert)^2 - \lvert (\Sigma \mathbf{v}_i) \rvert^2}{N(N-1)}\right]^{\frac{1}{2}} = (S_x^2 + S_y^2)^{\frac{1}{2}}$
S_x	Standard deviation of the zonal component	$\left[\frac{N \Sigma v_x^2 - (\Sigma v_x)^2}{N(N-1)}\right]^{\frac{1}{2}}$
S_y	Standard deviation of the meridional component	$\left[\frac{N \Sigma v_y^2 - (\Sigma v_y)^2}{N(N-1)}\right]^{\frac{1}{2}}$
$\overline{V}_s$	Mean scalar wind	$(\Sigma \lvert \mathbf{v}_i \rvert) / N$
$\overline{X}$	Mean zonal component	$(\Sigma v_x) / N$
$\overline{Y}$	Mean meridional component	$(\Sigma v_y) / N$
q	Steadiness of the wind	$(\lvert \overline{\mathbf{V}} \rvert) / \overline{V}_s$
r_{xy}	Correlation coefficient between the individual zonal and meridional components	$\left[\frac{N \Sigma v_x v_y - \Sigma v_x \Sigma v_y}{N(N-1) S_x S_y}\right]$
ψ	Angle of rotation of axes of distribution ellipse from the east-west axis measured counter-clockwise	$\tan 2\psi = \frac{2 r_{xy} \cdot S_x \cdot S_y}{(S_x^2 - S_y^2)}$
$\mathbf{v}_i$	An individual wind vector	
v_x	East-West component of wind (zonal component)	$\lvert \mathbf{v}_i \rvert \sin \theta_i$, east wind taken as +ve
v_y	North-South component of wind (meridional component)	$\lvert \mathbf{v}_i \rvert \cos \theta_i$, north wind taken as +ve

N = Total number of observations used in each case

θ_i = Direction of an individual vector measured clockwise from north

The convention adopted for representing a wind vector is that the end of the vector should always meet at the origin of a system of polar co-ordinates. Thus, a northeasterly wind is depicted as a vector starting from the northeast quadrant and terminating at the origin.

The unit for wind speed used throughout this paper is knot.

TABLE 2

Radii of circles which contain specified proportions of the beginning points of the vectors

	Percentage											
	10	20	30	40	50	60	63	70	80	90	95	99
Radius/S_v	0·32	0·48	0·59	0·72	0·83	0·96	1·00	1·10	1·27	1·52	1·73	2·15

TABLE 3

Values of χ_P (two degrees of freedom) for probability P

	P (%)										
	10	20	30	40	50	60	70	80	90	95	99
χ_P	0·46	0·67	0·84	1·01	1·18	1·36	1·55	1·79	2·15	2·45	3·03

TABLE 4 (a)

Statistical Parameters of Upper Winds

New Delhi

Level (km)	N	$\overline{X}$	$\overline{Y}$	$\overline{V}_s$	$\lvert\overline{\mathbf{V}}\rvert$	θ	S_x	S_y	S_v	S_x/S_y	r_{xy}
					JANUARY						
1·5	153	— 5·1	+3·3	10·7	6·0	302	6·9	8·4	10·9	0·82	—0·45
3·0	153	—10·5	+1·8	14·9	10·7	280	7·3	10·2	12·5	0·72	
6·0	152	—33·8	+0·5	38·0	33·8	271	16·4	17·5	23·9	0·94	—0·07
9·0	147	—64·1	—2·3	68·4	64·2	268	27·7	21·8	35·2	1·27	
12·0	96	—83·7	—6·1	87·4	84·4	266	30·8	24·5	39·4	1·26	+0·29
14·1	43	—72·5	—2·1	75·5	72·7	268	31·8	20·8	37·9	1·53	
16·2	17	—54·5	+1·5	57·1	54·6	272	21·7	20·2	29·6	1·07	+0·29
					FEBRUARY						
1·5	141	— 8·1	+4·7	12·5	9·4	300	7·1	8·2	10·9	0·87	—0·66
3·0	141	—15·5	+5·4	19·4	16·5	289	8·7	9·9	13·2	0·88	
6·0	135	—36·8	+7·5	40·2	37·8	281	16·9	12·9	21·3	1·31	—0·13
9·0	111	—59·5	+9·3	63·5	60·4	279	24·7	19·2	31·3	1·29	
12·0	71	—82·7	—0·2	86·9	82·7	270	34·2	26·4	43·4	1·30	+0·24
14·1	48	—73·5	—1·0	77·8	73·5	270	25·3	25·6	36·0	0·99	
16·2	35	—46·0	+7·3	48·7	46·7	278	17·8	14·8	23·1	1·20	+0·19
					MARCH						
1·5	153	— 8·8	+4·5	13·9	9·9	297	6·6	9·8	11·8	0·67	—0·56
3·0	154	—15·2	+2·7	17·9	15·4	280	8·3	11·7	14·3	0·71	
6·0	152	—34·8	+3·2	37·5	35·2	275	14·7	14·1	20·4	1·04	+0·02
9·0	136	—55·3	+4·4	59·9	55·9	275	23·8	23·8	33·7	1·00	
12·0	106	—77·7	+2·4	82·2	77·9	272	26·2	27·4	37·9	0·96	+0·02
14·1	85	—69·0	+0·5	72·1	69·0	270	19·8	20·7	28·7	0·96	
16·2	65	—44·2	—1·6	46·0	44·3	268	19·4	12·9	23·2	1·50	+0·14
					APRIL						
1·5	150	— 8·1	+4·6	12·6	9·3	300	7·1	7·9	10·6	0·90	—0·33
3·0	150	—12·9	+2·0	15·9	13·0	279	6·9	9·2	11·5	0·75	
6·0	146	—24·7	+1·8	28·5	24·8	274	13·6	12·1	18·3	1·12	+0·29
9·0	140	—37·3	+0·6	41·9	37·3	271	22·2	17·3	28·1	1·28	
12·0	115	—56·0	—0·4	61·7	56·0	270	26·5	26·6	37·6	1·00	+0·12
14·1	91	—54·2	—2·0	58·4	54·0	269	20·8	18·4	27·8	1·13	
16·2	65	—38·1	—2·6	41·1	38·2	266	22·2	15·1	26·8	1·47	+0·35
					MAY						
1·5	155	— 9·5	+5·0	13·7	10·8	297	8·7	6·8	11·0	1·28	—0·31
3·0	151	—13·8	+3·5	16·9	14·3	284	6·9	8·5	10·9	0·81	
6·0	153	—21·2	+6·7	25·4	22·3	287	9·7	12·2	15·6	0·79	+0·13
9·0	146	—37·4	+5·0	42·1	37·7	277	20·7	16·9	24·8	1·22	
12·0	121	—49·7	+2·6	54·1	50·0	273	23·1	19·4	30·1	1·19	+0·09
14·1	105	—43·3	—0·3	47·6	43·3	270	22·5	18·7	29·3	1·20	
16·2	75	—25·6	—2·6	30·9	25·8	265	19·3	12·9	23·2	1·50	+0·10
					JUNE						
1·5	149	— 7·7	+4·0	13·4	8·7	297	10·0	6·9	12·1	1·45	—0·25
3·0	148	—11·5	+6·1	16·2	13·0	298	8·4	7·8	11·5	1·08	
6·0	147	—10·4	+5·7	17·1	11·8	299	10·3	10·2	14·5	1·01	+0·01
9·0	142	—15·0	+0·5	20·9	15·1	272	14·4	12·3	18·9	1·17	
12·0	129	—13·7	—3·2	19·7	14·1	257	14·0	12·1	18·5	1·16	+0·10
14·1	113	— 9·0	—3·5	18·0	9·7	249	13·8	13·3	19·1	1·04	
16·2	89	+ 2·3	—3·0	30·4	3·8	142	12·0	9·9	15·6	1·21	+0·29

TABLE 4 (a) — *contd*

Level (Km)	N	$\overline{X}$	$\overline{Y}$	$\overline{V}_s$	$\lvert\overline{\mathbf{V}}\rvert$	θ	S_x	S_y	S_v	S_x/S_y	r_{xy}
					JULY						
1·5	153	+ 0·2	—0·9	11·8	1·0	165	11·7	7·1	13·6	1·65	—0·48
3·0	152	— 1·9	+2·6	13·5	3·3	325	11·2	9·4	14·7	1·19	
6·0	147	+ 0·1	+2·1	11·9	2·1	003	10·7	8·3	13·5	1·29	—0·37
9·0	142	+ 0·3	—1·6	12·9	1·6	170	11·2	9·7	14·8	1·15	
12·0	136	+ 3·9	—3·4	14·9	5·1	131	14·1	9·9	17·2	1·42	+0·13
14·1	126	+ 8·9	—3·7	18·4	9·7	112	14·2	12·7	19·1	1·12	
16·2	106	+19·5	—0·8	24·0	19·6	092	13·6	12·0	18·1	1·13	+0·22
					AUGUST						
1·5	154	+ 0·1	+1·4	9·8	1·7	036	9·6	6·0	11·3	1·60	—0·45
3·0	154	+ 0·1	+3·5	11·4	3·5	002	9·6	8·1	12·6	1·19	
6·0	148	+ 0·8	+2·2	10·6	2·4	020	9·5	7·1	11·9	1·34	—0·11
9·0	143	+ 1·7	0·0	12·7	1·7	090	11·1	8·7	14·2	1·28	
12·0	129	+ 5·7	—3·3	14·7	6·7	120	12·3	10·0	15·8	1·23	+0·12
14·1	121	+10·1	—2·1	17·6	10·3	102	12·5	12·1	17·4	1·03	
16·2	103	+19·6	—0·3	23·7	19·6	091	13·0	10·9	16·9	1·19	+0·08
					SEPTEMBER						
1·5	149	— 1·6	+2·1	10·5	2·6	323	9·8	5·8	11·4	1·69	—0·69
3·0	147	— 1·7	+3·4	11·4	3·8	335	9·3	8·4	12·5	1·11	
6·0	146	— 3·1	+1·4	11·0	3·4	294	9·3	8·1	12·3	1·15	—0·08
9·0	144	—10·5	—2·6	17·5	10·8	256	15·1	10·5	18·5	1·44	
12·0	137	—10·5	—3·0	19·8	10·9	255	16·7	12·0	20·6	1·39	—0·09
14·1	130	— 6·0	—1·6	19·6	6·2	255	16·9	13·9	21·9	1·22	
16·2	112	+ 1·6	—2·2	15·3	2·7	144	14·6	9·6	17·4	1·52	+0·29
					OCTOBER						
1·5	155	— 4·5	+5·7	10·3	7·3	322	7·2	5·3	9·0	1·36	—0·51
3·0	155	— 5·4	+7·1	11·8	8·9	323	6·3	7·6	9·9	0·83	
6·0	155	—18·1	+5·3	22·0	18·9	286	11·1	10·1	15·0	1·10	+0·08
9·0	148	—38·5	+1·9	41·8	38·6	272	20·0	14·5	24·7	1·38	
12·0	129	—48·4	—4·8	51·5	48·8	265	25·3	14·4	29·1	1·76	+0·13
14·1	115	—42·9	—6·9	46·5	43·5	261	22·4	15·3	27·2	1·46	
16·2	88	—24·9	—3·6	30·2	25·2	262	19·2	12·9	23·2	1·49	—0·13
					NOVEMBER						
1·5	150	— 6·3	+4·1	10·3	7·6	303	5·5	6·7	8·7	0·82	—0·46
3·0	150	—10·9	+3·8	14·0	11·6	290	6·7	7·9	10·3	0·85	
6·0	150	— 31·1	+3·0	33·5	31·4	275	11·7	10·7	15·8	1·09	—0·05
9·0	139	—58·1	—0·7	60·6	58·1	270	16·2	17·1	23·6	0·95	
12·0	101	—80·5	—1·0	83·7	80·5	269	19·8	22·5	30·0	0·88	—0·12
14·1	60	—71·9	—3·8	75·5	71·9	268	19·9	17·6	26·6	1·13	
16·2	32	—46·0	—2·3	48·8	46·0	270	19·3	16·3	25·3	1·18	+0·02
					DECEMBER						
1·5	155	— 6·3	+4·2	10·5	7·6	304	6·1	6·8	9·2	0·90	—0·49
3·0	155	—12·8	+2·5	17·6	13·0	280	8·2	9·2	12·3	0·89	
6·0	153	—35·8	+1·7	38·0	35·9	272	12·7	13·7	18·7	0·93	—0·20
9·0	149	—66·0	—2·8	69·8	66·1	268	18·9	21·7	28·8	0·87	
12·0	95	—80·4	—7·2	84·8	80·8	265	20·3	26·6	33·5	0·76	—0·32
14·1	53	—76·7	—2·9	79·1	76·7	268	21·7	20·7	29·5	1·05	
16·2	30	—52·5	+0·9	54·5	52·5	270	21·8	14·3	26·1	1·52	+0·44

TABLE 4(b)

Statistical Parameters of Upper Winds

Nagpur

Level (km)	N	$\overline{X}$	$\overline{Y}$	$\overline{V}_s$	$\lvert\overline{\mathbf{V}}\rvert$	θ	S_x	S_y	S_v	S_x/S_y	r_{xy}
					JANUARY						
1·5	155	— 2·7	— 0·1	7·2	2·7	269	4·6	6·3	7·8	0·73	—0·03
3·0	155	—12·8	+ 1·1	17·6	12·9	275	8·5	8·7	12·2	0·98	
6·0	154	—33·9	+ 0·1	36·2	33·9	270	9·6	12·6	15·9	0·75	+0·12
9·0	149	—52·6	— 6·6	56·2	53·0	263	14·7	18·6	23·7	0·79	
12·0	122	—59·1	—16·0	64·3	61·4	255	16·7	20·9	26·7	0·80	+0·03
14·1	97	—51·5	—11·7	55·1	52·8	257	18·5	15·2	24·0	1·22	
16·2	81	—38·6	— 7·1	41·7	39·3	260	22·2	14·5	26·5	1·53	+0·16
					FEBRUARY						
1·5	141	— 3·7	—0·3	7·7	3·7	265	5·9	5·4	8·1	1·07	+0·15
3·0	141	—11·3	+3·9	15·4	12·0	289	9·5	8·5	12·7	1·12	
6·0	139	—30·6	+5·7	33·8	31·1	280	13·9	12·5	18·7	1·11	+0·06
9·0	135	—50·8	+1·5	54·0	51·0	272	17·3	18·4	25·2	0·94	
12·0	113	—56·9	—6·3	60·5	57·3	264	16·1	19·9	25·6	0·81	+0·19
14·1	95	—48·8	—6·5	52·6	49·1	264	16·9	18·8	25·2	0·89	
16·2	76	—35·9	—2·5	37·8	36·0	266	19·2	12·2	22·7	1·57	+0·09
					MARCH						
1·5	155	— 3·6	—0·4	7·2	3·6	264	5·2	5·4	7·6	0·96	+0·23
3·0	155	—11·2	+0·5	13·9	11·2	272	7·6	8·2	10·9	0·93	
6·0	155	—27·2	+3·2	31·3	27·4	276	11·4	12·2	16·7	0·92	+0·17
9·0	151	—46·5	+1·9	50·8	46·6	272	16·5	21·0	26·7	0·79	
12·0	130	—55·5	—2·3	60·6	55·6	267	20·4	25·0	32·2	0·82	+0·14
14·1	109	—48·5	—4·8	52·1	48·7	265	17·8	19·9	26·7	0·89	
16·2	81	—36·7	—1·6	39·4	36·8	266	18·3	12·4	22·2	1·48	+0·23
					APRIL						
1·5	149	— 3·7	—0·1	7·2	3·7	268	5·8	5·1	7·7	1·16	+0·01
3·0	149	— 6·9	+1·2	9·5	7·0	280	5·6	5·7	8·0	0·98	
6·0	149	—15·9	+1·8	20·4	16·0	276	10·8	11·3	15·6	0·96	+0·24
9·0	143	—34·3	—4·2	39·7	34·5	263	15·1	19·2	24·4	0·79	
12·0	132	—50·2	—8·8	55·6	51·1	260	19·7	22·8	30·1	0·86	—0·02
14·1	104	—40·5	—7·1	45·3	41·1	260	17·4	16·9	24·2	1·03	
16·2	85	—24·1	—4·4	27·7	24·5	260	20·1	10·6	22·7	1·88	+0·30
					MAY						
1·5	155	— 4·2	+2·2	8·1	4·7	297	5·7	6·0	8·3	0·95	—0·11
3·0	155	— 5·0	+3·1	8·9	5·8	302	6·0	5·8	8·3	1·03	
6·0	154	— 9·6	+3·5	14·0	10·3	290	7·8	8·9	11·9	0·88	+0·25
9·0	143	—18·3	—1·4	23·7	18·3	266	14·8	13·8	19·0	1·07	
12·0	121	—17·6	—2·0	24·8	16·1	263	21·2	13·1	24·9	1·62	+0·08
14·1	99	—10·4	—2·8	22·5	10·8	255	20·6	13·5	24·6	1·52	
16·2	67	+ 1·8	—0·4	18·6	10·8	102	16·6	12·8	21·0	1·30	—0·08
					JUNE						
1·5	147	— 7·1	+1·8	11·0	7·3	284	7·7	6·0	9·8	1·28	+0·03
3·0	146	— 3·5	+4·3	11·8	5·5	320	9·3	7·2	11·8	1·29	
6·0	141	— 1·1	+3·6	10·3	3·7	344	8·8	6·7	11·1	1·31	—0·14
9·0	129	+ 6·3	+2·4	11·7	6·7	069	9·5	6·7	11·6	1·41	
12·0	103	+17·8	—1·2	21·5	17·9	094	13·5	8·8	16·1	1·53	—0·38
14·1	86	+30·6	—1·5	32·1	30·7	093	14·2	9·8	17·3	1·44	
16·2	71	+38·8	+0·4	39·4	38·8	089	13·4	9·4	16·3	1·43	—0·03

TABLE 4(b) — *contd*

Nagpur

Level (km)	N	$\overline{X}$	$\overline{Y}$	$\overline{V}_s$	$\lvert\overline{\mathbf{V}}\rvert$	θ	S_x	S_y	S_c	S_x/S_y	r_{xy}
					JULY						
1·5	153	—13·7	+2·5	17·5	13·9	281	11·2	6·8	13·0	1·65	—0·04
3·0	143	— 9·6	+3·4	15·0	10·2	289	12·3	6·2	13·8	1·98	
6·0	129	+ 2·5	+2·7	10·9	3·7	043	10·2	7·1	12·4	1·44	—0·07
9·0	106	+16·9	+2·3	19·4	17·1	084	11·5	6·4	13·1	1·79	
12·0	82	+36·6	+4·0	37·3	36·8	084	13·5	10·2	16·9	1·32	—0·10
14·1	72	+51·0	+4·7	51·3	51·3	085	15·6	15·3	21·8	1·02	
16·2	44	+55·3	+8·2	57·1	55·9	083	16·1	12·0	20·1	1·34	+0·23
					AUGUST						
1·5	150	—13·0	+5·5	16·0	14·1	293	8·1	6·2	10·2	1·31	—0·14
3·0	141	— 9·0	+4·2	12·8	9·9	295	8·2	6·6	10·5	1·24	
6·0	132	+ 3·7	+1·6	10·1	4·0	068	8·7	6·9	11·1	1·26	+0·01
9·0	119	+17·8	+0·3	19·5	17·8	088	9·2	7·0	11·6	1·31	
12·0	106	+36·8	+3·2	37·7	36·7	085	13·1	8·3	15·6	1·58	—0·10
14·1	91	+48·2	+8·2	50·7	48·9	080	13·4	12·5	18·3	1·07	
16·2	66	+58·2	+7·2	59·4	58·6	083	13·2	10·2	16·7	1·29	+0·32
					SEPTEMBER						
1·5	147	— 7·1	+5·3	13·4	8·8	307	9·9	6·8	12·0	1·46	+0·40
3·0	148	— 5·1	+4·6	12·3	6·9	312	9·3	7·8	12·2	1·19	
6·0	142	+ 1·0	+1·1	10·4	1·5	041	8·5	9·1	12·5	0·93	+0·03
9·0	129	+ 8·3	+0·8	12·3	8·3	085	8·1	7·4	11·0	1·09	
12·0	107	+18·0	+0·6	21·2	18·0	089	11·3	9·9	15·0	1·14	+0·04
14·1	95	+25·3	+1·0	28·2	25·3	089	12·8	10·8	16·8	1·18	
16·2	75	+36·2	+1·7	38·0	36·3	087	13·9	10·3	17·3	1·35	+0·30
					OCTOBER						
1·5	154	+ 2·1	+ 4·1	8·9	4·6	027	6·1	6·7	9·6	0·91	+0·08
3·0	153	— 1·2	+ 3·4	9·8	3·7	340	7·4	7·8	10·7	0·95	
6·0	145	— 5·2	+ 0·4	12·1	5·6	274	11·2	8·7	14·2	1·29	+0·15
9·0	132	—12·4	— 2·2	17·5	12·6	260	15·6	8·8	17·9	1·77	
12·0	115	—12·6	— 8·5	21·9	15·2	237	17·6	12·7	21·7	1·39	+0·50
14·1	93	— 7·4	—10·4	21·8	12·7	215	18·5	13·3	22·8	1·39	
16·2	71	+ 1·8	— 6·1	18·5	6·3	164	17·8	11·1	21·0	1·60	+0·30
					NOVEMBER						
1·5	149	+ 2·5	+ 3·1	5·9	3·9	039	4·0	3·8	5·5	1·05	+0·06
3·0	150	— 5·3	+ 4·2	9·4	6·7	308	6·5	5·9	8·8	1·10	
6·0	150	—19·5	— 0·4	21·8	19·6	269	11·1	9·4	14·5	1·18	+0·23
9·0	144	—33·6	— 4·8	37·3	33·9	263	12·9	13·3	18·5	0·97	
12·0	126	—40·5	—11·1	46·5	42·0	255	15·8	18·7	24·5	0·84	—0·14
14·1	94	—36·9	—13·0	42·2	39·2	250	15·9	15·0	21·8	1·06	
16·2	73	—24·6	— 6·4	28·8	25·4	255	16·6	11·8	20·3	1·41	—0·14
					DECEMBER						
1·5	155	— 1·1	+ 4·0	8·2	4·1	345	5·7	6·5	8·7	0·88	+0·05
3·0	155	— 9·6	+ 3·0	14·1	10·1	287	8·7	8·4	12·1	1·04	
6·0	155	—26·0	— 1·4	29·4	26·1	267	13·9	12·3	18·5	1·13	—0·22
9·0	146	—44·0	— 7·6	47·3	44·5	260	17·7	17·2	24·7	1·03	
12·0	119	—52·5	—17·2	60·2	55·2	252	21·7	23·4	31·9	0·93	—0·09
14·1	90	—50·2	—11·2	55·6	51·2	257	18·1	20·9	27·7	0·87	
16·2	66	—39·4	—10·1	43·3	40·7	255	20·8	17·4	27·1	1·19	+0·37

TABLE 4(c)

Statistical Parameters of Upper Winds

Trivandrum

Level (km)	N	$\overline{X}$	$\overline{Y}$	$\overline{V}_s$	$\lvert\overline{\mathbf{V}}\rvert$	θ	S_x	S_y	S_v	S_x/S_y	r_{xy}
					JANUARY						
1·5	152	+6·9	+ 5·8	10·0	9·1	050	5·1	4·4	6·7	1·16	+0·13
3·0	151	+4·5	+ 1·3	9·2	4·8	073	8·1	5·5	9·8	1·47	
6·0	149	+6·5	+ 2·1	13·4	6·8	073	12·3	7·2	14·2	1·71	+0·04
9·0	141	+2·6	— 4·4	18·5	5·1	150	15·9	12·1	20·0	1·31	
12·0	122	+4·8	—13·3	24·4	14·2	160	19·2	13·2	23·3	1·46	—0·22
14·1	98	+7·9	—11·7	25·5	14·2	146	20·5	14·7	25·2	1·39	
16·2	66	+5·8	— 0·9	19·6	5·9	100	18·5	12·4	22·3	1·49	—0·22
					FEBRUARY						
1·5	140	+ 9·8	+ 6·9	12·8	12·0	055	5·6	4·3	7·1	1·30	+0·19
3·0	140	+ 8·1	+ 2·5	11·5	8·5	073	8·4	5·3	9·9	1·58	
6·0	140	+11·4	+ 3·1	15·5	11·9	075	10·4	7·4	12·7	1·41	+0·15
9·0	132	+ 6·3	— 0·2	16·0	6·3	092	13·7	9·3	16·6	1·47	
12·0	114	+ 8·5	—11·3	22·2	14·1	143	16·5	13·5	21·3	1·22	—0·16
14·1	93	+ 6·0	— 7·9	25·1	10·0	143	21·5	16·9	27·3	1·28	
16·2	65	+ 6·3	— 3·8	19·0	6·6	120	17·6	11·1	20·8	1·54	+0·03
					MARCH						
1·5	154	+ 8·1	+5·9	11·9	11·0	058	5·6	4·3	7·1	1·30	+0·48
3·0	154	+11·8	+5·7	14·8	13·1	065	9·4	6·7	11·6	1·40	
6·0	152	+10·2	+3·5	14·9	10·8	071	11·1	7·7	13·4	1·44	+0·04
9·0	145	+ 2·2	+1·2	16·0	2·6	061	13·9	11·1	17·8	1·25	
12·0	130	— 2·4	—5·8	20·6	6·2	203	18·7	11·8	22·1	1·59	—0·18
14·1	101	— 2·7	—1·5	20·4	3·1	241	19·6	12·2	23·1	1·62	
16·2	73	— 1·5	—1·5	18·0	2·1	225	17·5	9·6	20·0	1·82	—0·08
					APRIL						
1·5	148	+ 4·7	+3·5	8·2	5·8	054	5·4	4·3	6·9	1·26	+0·04
3·0	148	+10·2	+4·3	13·3	11·1	067	8·3	7·4	11·2	1·12	
6·0	146	+ 4·0	+0·2	11·4	4·0	087	10·2	6·9	12·3	1·48	—0·03
9·0	136	— 3·0	—0·4	14·1	3·1	263	12·9	9·1	15·8	1·42	
12·0	111	— 2·3	—5·1	17·6	5·7	205	17·2	11·2	20·5	1·53	—0·06
14·1	94	+ 0·1	—3·0	18·2	2·9	178	18·3	9·9	20·8	1·85	
16·2	63	+ 5·9	—2·1	17·8	6·3	110	15·7	11·2	19·2	1·40	—0·17
					MAY						
1·5	152	— 8·1	+5·3	14·9	9·7	303	12·3	7·6	14·5	1·62	—0·18
3·0	152	— 4·5	+3·3	16·3	5·6	306	16·7	7·4	18·3	2·25	
6·0	148	— 4·2	—0·1	13·4	4·3	269	12·8	8·0	15·1	1·60	+0·15
9·0	135	+ 1·0	—0·4	10·9	1·1	113	8·9	8·6	12·3	1·03	
12·0	116	+ 9·8	+1·1	17·0	9·9	083	15·2	9·9	18·1	1·54	—0·07
14·1	94	+21·7	+2·3	27·3	21·9	084	20·7	9·0	22·6	2·30	
16·2	67	+32·9	+0·1	36·5	32·9	089	20·7	11·1	23·5	1·86	—0·33
					JUNE						
1·5	147	—19·9	+8·9	23·2	21·9	294	9·9	6·4	11·8	1·55	—0·21
3·0	146	—19·8	+3·6	21·5	20·1	281	11·1	6·9	13·1	1·61	
6·0	145	— 6·6	+0·3	13·2	6·6	272	13·3	7·0	15·0	1·90	—0·16
9·0	133	+10·5	+2·3	15·7	10·8	077	11·0	9·2	14·4	1·20	
12·0	116	+38·5	+6·5	40·9	39·1	080	17·0	10·5	20·0	1·62	—0·07
14·1	93	+64·6	+5·4	66·2	64·7	085	24·7	14·6	28·7	1·69	
16·2	67	+49·1	0·0	50·3	49·1	091	26·2	11·7	28·7	2·24	+0·18

TABLE 4(c) — *con'd*

Trivandrum

Level (km)	N	$\overline{X}$	$\overline{Y}$	$\overline{V}_s$	$\|\overline{\mathbf{V}}\|$	θ	S_x	S_y	S_c	S_x/S_y	r_{xy}
					JULY						
1·5	154	—22·6	+10·9	26·6	25·1	295	10·2	7·3	12·6	1·39	+0·15
3·0	154	—21·4	— 5·3	23·7	22·1	284	12·1	5·9	13·4	2·05	
6·0	151	— 7·9	— 0·8	14·0	7·9	276	13·8	7·2	15·6	1·91	—0·17
9·0	139	+15·1	— 1·2	20·2	15·2	085	11·7	9·7	15·2	1·21	
12·0	104	+46·0	— 8·5	48·0	47·0	079	13·9	10·4	17·3	1·34	—0·12
14·1	90	+64·1	— 9·2	66·4	64·9	077	15·5	12·0	19·6	1·29	
16·2	64	+53·7	+ 1·9	55·4	53·7	088	22·5	13·4	23·2	1·68	+0·10
					AUGUST						
1·5	155	—19·1	+14·1	24·6	23·8	306	8·5	7·0	11·0	1·21	—0·44
3·0	155	—18·6	+ 7·2	21·2	20·0	291	9·6	6·6	11·6	1·45	
6·0	154	— 3·7	+ 0·4	9·5	3·8	277	8·2	6·4	10·4	1·28	—0·16
9·0	143	+14·5	— 0·9	17·7	14·5	094	9·9	8·2	12·8	1·21	
12·0	134	+47·2	— 6·7	49·0	47·7	083	14·7	10·4	18·0	1·41	+0·02
14·1	119	+61·7	— 7·7	64·1	62·2	083	20·6	10·9	23·3	1·89	
16·2	83	+51·2	— 0·8	53·7	51·2	092	21·3	12·1	24·5	1·76	—0·14
					SEPTEMBER						
1·5	150	—15·9	+ 8·5	19·5	18·0	299	8·9	5·8	10·7	1·53	—0·39
3·0	150	—16·1	+ 4·1	18·2	16·7	285	11·3	6·0	12·8	1·88	
6·0	150	— 2·0	+1·9	8·9	2·8	313	8·3	5·1	9·7	1·63	—0·12
9·0	144	+12·5	—1·4	15·4	12·6	096	9·7	7·2	12·1	1·35	
12·0	127	+41·9	+0·6	43·4	41·9	089	15·3	9·9	18·2	1·55	+0·44
14·1	94	+53·5	+0·2	56·7	53·5	089	17·5	12·9	21·7	1·36	
16·2	66	+36·9	+0·2	38·3	36·9	089	18·6	11·0	21·6	1·69	—0·11
					OCTOBER						
1·5	150	— 5·7	+4·7	11·9	7·3	310	10·4	6·3	12·2	1·65	—0·39
3·0	149	— 5·4	+3·1	12·7	6·2	300	12·5	5·9	13·8	2·13	
6·0	145	+ 3·2	—0·5	11·1	3·2	100	10·6	6·9	12·6	1·54	—0·03
9·0	135	+10·2	—1·9	13·2	10·4	100	9·7	7·1	12·1	1·37	
12·0	109	+25·0	—2·6	27·1	25·2	096	13·8	8·9	16·4	1·55	0·0
14·1	85	+38·6	—4·0	41·1	38·8	095	17·2	11·2	20·5	1·54	
16·2	58	+27·0	—2·8	29·5	27·1	096	19·0	8·4	20·8	2·26	—0·14
					NOVEMBER						
1·5	149	+ 6·2	+ 2·5	10·0	6·7	069	7·0	5·5	8·9	1·27	+0·03
3·0	146	+ 6·8	+0·1	10·7	6·8	089	8·1	6·2	10·2	1·31	
6·0	143	+11·2	—0·3	14·3	11·2	091	10·2	6·6	12·1	1·54	+0·12
9·0	130	+13·8	—1·8	16·0	14·0	098	9·9	7·8	12·6	1·27	
12·0	108	+15·7	—6·1	21·8	16·9	111	15·6	10·3	18·7	1·52	—0·18
14·1	85	+13·6	—4·9	19·6	14·5	110	17·5	10·2	20·3	1·72	
16·2	54	+15·8	—3·7	20·0	16·3	104	14·2	10·1	17·4	1·41	—0·21
					DECEMBER						
1·5	154	+6·2	+ 4·4	9·5	7·6	055	5·7	4·9	7·5	1·16	+0·25
3·0	154	+6·2	+ 1·5	11·2	6·4	086	9·4	6·8	11·6	1·38	
6·0	153	+7·8	+ 1·9	12·7	8·1	076	9·2	8·2	12·3	1·12	—0·04
9·0	144	+4·9	— 5·4	15·0	7·3	139	11·6	11·3	19·0	1·03	
12·0	123	+3·1	—11·3	24·2	11·8	165	21·0	12·8	24·6	1·64	—0·05
14·1	110	+2·0	— 9·5	25·7	9·7	168	25·4	12·3	28·3	2·07	
16·2	85	+2·6	— 4·0	17·9	4·8	147	17·7	11·7	21·2	1·51	—0·12