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On Winds at Poona

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ABSTRACT. The diurnal and seasonal characteristics of wind at a height of 130 ft above ground at Poona have been studied on the basis of anemographic data collected during the period 1949 to 1958.

It is seen that a considerable part of the variation in the mean wind at any time is ascribable to variation due to the seasons and next in order comes the diurnal variation.

The periodic variation of the mean wind speed, the range of gust and the gustiness during the course of the day could to a fair degree of accuracy be represented by the first two harmonics, the first of period of 24 solar hours and the second 12 solar hours. The seasonal variation of the means, the amplitudes and phase angles of the diurnal and semi-diurnal waves have been studied.

To get an insight into the structure of the diurnal wind variation the 24-hour and 12-hour component oscillations have been separated out. The features of the hodograph ellipse during the different seasons have been discussed.

1. Introduction

A Munrow Dines Pressure Tube anemograph has been functioning on the top of the tower at the Meteorological Office, Poona, since 1929. The head of the anemograph is 130 ft* above ground and about 18 ft above the flat top of the tower which measures 16′ 10″ × 16′ 6″ with a parapet wall 4′ high on all four sides. The instrument enjoys an excellent exposure on all directions.

In this paper the diurnal and seasonal variation of wind characteristics, *viz.*, speed, direction and gustiness at the level of the instrument have been discussed.

In accordance with the practice in the India Meteorological Department, the terms 'mean wind speed' etc have the following definitions—

Mean wind speed V at any specified hour is the mean speed during a period of 10—15 minutes immediately preceding the hour (IST) obtained from the speed ribbon on the anemographic chart. The speed is estimated correct to 1 mph.*

Mean range of gust R_g is the average width of the speed ribbon, ignoring solitary gusts or lulls during the 10-minute interval immediately preceding the hour.

Gustiness of wind G is the quotient, R_g/V

Mean direction of wind D is the mean direction during the 10-minute interval immediately preceding the hour. The direction is estimated to the nearest sixteen points of the compass.

The anemograph data collected during the 10 years from January 1949 to December 1958 have been utilized for the study here.

2. Variation of wind

The wind characteristics at a particular level in a locality recorded on different occasions differ between themselves due to a variety of causes.

Behind the transient features exhibited in the anemographic records, there is a systematic variation with period of the order of a day and another of the order of a year. The analysis of variance (Table 1) shows how the variation in the mean

*Since 1957 the units have been changed to metric system but for the purpose of the study here, the British system of units has been retained

TABLE 1

Analysis of variance of mean wind speed

Source of variation	Degrees of freedom	Sums of squares	Mean squares	F
Seasonal (between months)	11	1974·02	179·45	142·5
Diurnal (between hours)	23	1174·07	51·04	40·6
Residual	253	319·70	1·26	
Total	287	3467·79		

hourly values of wind speed are accounted for by these two causes.

It is seen from col. 3 of Table 1 that a considerable part of the variation is ascribable to variation between the months, *i.e.*, the seasonal variation. The variation between hour-to-hour is also high while the residual or error variance is considerably smaller. The variation in the mean wind speeds is thus to a large extent accounted for by the seasonal and diurnal variations. The residual variation may be due to variation between the different years, those due to observational errors and other random causes.

Table 2 shows the standard deviation of the hourly values of wind speed. This represents the day-to-day variation during the 10 years in the wind speed at the specified hours. The variations are large in the afternoons of February, March and April and least in the mornings of November, December and January. Variations are generally high practically during the whole day of the monsoon months.

3.1. Mean hourly wind speed V

Table 3·1 shows the mean hourly wind speed in mph in the different months. Winds are weak, 4–6 mph during October to March and strongest during the monsoon months June, July and August. In the morning about 1–2 hours after sunrise winds are weakest but strengthen later attaining a maximum in the afternoon or evening. The maximum is attained sometime between 3 and 4 P.M. during the monsoon and between 6 and 7 P.M. during January to May.

3.2. Mean hourly range of gust R_g

The range of gusts (*see* Table 3·2) are largest during the monsoon months of June and July and smallest during November and December. Winds are most gusty in the afternoon and least gusty at about the time of sunrise. The range is of the order of 10 mph between 4 and 7 P.M. during April and May and between 1 to 5 P.M. during June to September.

3.3. Mean hourly gustiness G

It will be seen from Table 3·3 that the gustiness is largest between 11 and 16 hours and least during the late night and early morning hours. Winds are most gusty during April, May and June. There is a secondary maximum in December and January; February is the least gusty month.

3.4. Vector mean winds

The hourly winds on the different days have been combined vectorially and the resultant value has been given hour by hour for each of the months in Table 3·4. The winds are strong and blow steadily from W/NW during May to September, and weak variable during October and January. During November and December throughout the nights and practically till about 9 A.M. winds are S to SW and become E during the day. During January to March the winds are WNW in the afternoons till about 9 P.M. and SW-W later till about 9 A.M.

4. Graduation of periodic variation

For graduation of a time series whose variations are almost periodic, it is most convenient to represent the value of the variable as a fourier function of time. If V_1, V_2..................V_n are the measured values of the variate at 1, 2.......n units of time, a function can be put in the form

$$V = \bar{V} + \sum_r a_r \sin (A_r + r\theta) \qquad (1)$$

in which a_r and A_r are the amplitude and phase angle of the r^{th} harmonic and $\theta = 2\pi/n$.

In an almost periodic series a few of the harmonics may be sufficient to represent the variation adequately. If p harmonics $(p < |\frac{1}{2}n|)$ have been used in the graduation, the standard residue, *i.e.*, the standard deviation of the difference between the actual and the calculated values is

$$\sigma' = \left[\frac{\Sigma (V - V')^2}{n - 2p - 1}\right]^{\frac{1}{2}} \qquad (2)$$

Due to the orthogonal property of the different harmonics, it has been found that if σ is the standard deviation of the series $V_1, V_2 \ldots\ldots\ldots V_n$

$$\sigma'^2 = \sigma^2 - \tfrac{1}{2} \sum_r a_r^{\,2}$$

If σ'^2 is very small when compared to σ^2, then the p harmonics have accounted for a significant proportion of the variation. A comparison of the values of a amongst themselves will also indicate the relative importance of the several harmonics.

If a_r is the amplitude of the r^{th} harmonic, the probability that $a_r^{\,2}$ exceeds 3 times expectancy is about 5 per cent and that it exceeds 4·5 times expectancy is about 1 per cent (Conrad and Pollak 1950).

The values of the constants $\bar{V}$, a_r, A_r entering in equation (1) have been calculated for $r = 1$ and 2, and the characteristics of the diurnal variation are discussed with reference to these constants.

4.1. Wind speed — Diurnal and semi-diurnal oscillations

The values of the mean daily wind speed and the amplitudes and phase angles of the diurnal and semi-diurnal variations are given in Table 4.1.

In the last column of the table are given the residual variance as percentage. It is seen that the harmonics have generally accounted for about 90 per cent of the variation, practically in all the months. In the case of January and February the 3rd and 4th harmonics were also fitted. However, it was found that they accounted for only 2·8 and 3·4 per cent of the variance respectively in the case of January and 3·6 and 2·8 per cent in the case of February. It is thus seen that the variation from hour to hour are mainly governed by the first and second harmonics. Thus for example in the month of January the wind speed at any time t reckoned from 0 hrs IST can be represented as a function of time as follows—

$$V_t = 4{\cdot}75 + 1{\cdot}89 \sin\left(197^\circ\, 13' + \frac{\pi}{12} t\right) + $$
$$+\, 0{\cdot}86 \sin\left(350^\circ\, 19' + \frac{\pi}{6} t\right) + \epsilon''_t \qquad (3)$$

where ϵ''_t is the error involved in this estimation with the 2 harmonics. The probable value of this error in the case of January is 0·3 mph.

The times at which the wind speeds attain maxima in the individual oscillations are readily given by

For diurnal wave

$$\sin\left(A_1 + \frac{\pi}{12} t_{\text{max. 1}}\right) = 1 \text{ or}$$

$$t_{\text{max. 1}} = \left\{(4s + 1)\ \frac{\pi}{2} - A_1\right\} \frac{12}{\pi} \qquad (4)$$

For semi-diurnal wave

$$\sin\left(A_2 + \frac{\pi}{6}\ t_{\text{max. 2}}\right) = 1 \text{ or}$$

$$t_{\text{max. 2}} = \left\{(4s + 1)\ \frac{\pi}{2} - A_2\right\} \frac{6}{\pi} \qquad (5)$$

Considering the two waves together the times at which the wind speed attains a maximum and minimum can be calculated by solving $dV/dt=0$. As a quadratic in $\tan t\ \pi/24$, the equation yields four solutions, two relating to the maximum and two to the minimum. The maxima and the minima speeds and the times at which they occur are calculated from the harmonics fitted. The secondary maxima and minima are not pronounced except in the months November to February when a slight oscillation is perceptible with a minima

TABLE 2

Variation of wind speed hour by hour—Poona (Standard deviation)

Hr	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	2·94	3·35	3·08	3·47	3·81	3·51	3·43	3·36	3·22	2·93	2·97	2·35
1	2·95	3·21	3·01	3·67	3·95	3·61	3·70	3·91	3·33	2·66	3·04	2·76
2	2·96	3·03	3·12	3·58	3·41	3·53	3·66	3·80	3·36	2·69	2·85	2·83
3	2·93	3·28	3·17	3·67	3·76	3·90	3·72	4·06	3·58	2·75	2·70	2·71
4	2·84	3·01	3·04	3·35	3·91	3·81	3·64	4·04	3·49	2·59	2·73	2·58
5	2·97	2·96	3·08	3·47	3·77	4·09	3·95	4·14	3·54	2·55	2·82	2·68
6	2·88	3·05	3·21	3·63	3·73	3·86	4·01	4·23	3·63	2·50	2·55	2·72
7	2·81	2·91	3·05	3·38	3·91	4·06	4·15	4·18	2·92	2·72	2·66	2·59
8	2·47	2·72	2·48	3·11	4·57	4·12	3·93	4·18	4·08	2·44	2·01	1·91
9	1·94	2·52	2·55	3·26	4·57	4·41	4·07	4·42	4·39	3·09	2·53	2·03
10	3·02	3·16	3·21	3·38	4·32	4·67	4·10	4·10	4·55	3·35	2·62	2·76
11	3·10	3·42	3·37	3·71	4·13	5·04	3·99	4·28	4·76	3·49	3·12	3·22
12	3·26	3·58	3·47	3·90	4·33	5·12	4·15	4·11	4·66	3·67	3·05	3·31
13	3·10	3·61	3·33	3·85	4·47	4·88	4·04	4·08	4·84	3·61	3·14	3·21
14	3·14	3·47	3·76	4·43	4·49	4·57	3·74	3·81	4·73	3·64	3·17	2·90
15	3·43	3·80	4·26	5·34	4·15	4·17	3·50	3·43	4·34	3·69	3·23	2·90
16	3·62	4·58	4·43	5·43	3·71	4·01	3·90	3·15	3·91	3·70	3·00	2·86
17	3·93	4·73	5·05	5·28	4·25	3·51	3·00	3·17	3·52	3·92	3·15	3·13
18	4·05	5·13	5·38	4·89	3·49	3·46	2·80	3·15	3·27	3·65	3·21	3·11
19	2·66	4·44	4·28	4·46	3·54	3·48	2·94	2·93	2·97	3·12	3·05	2·96
20	3·41	3·67	3·17	3·94	3·35	3·59	3·12	3·13	2·92	2·89	2·87	2·68
21	3·04	3·16	3·21	4·07	3·53	3·62	3·20	3·40	2·95	2·62	2·92	2·57
22	3·06	3·21	3·39	3·53	3·66	3·59	3·32	3·48	2·91	2·91	2·92	2·87
23	3·03	3·19	3·10	3·49	3·56	3·54	3·55	3·56	3·24	2·68	2·93	2·86

TABLE 3·1

Mean hourly wind speed (mph)—Poona

Hr	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	3·95	4·61	4·83	5·62	7·08	8·39	10·27	8·18	6·31	3·59	3·63	3·79
2	3·94	4·95	4·73	5·31	6·77	8·13	9·27	8·04	6·31	3·56	3·53	3·63
3	3·68	4·85	4·76	4·67	6·66	7·92	9·04	7·89	5·85	3·39	3·26	3·67
4	3·81	4·85	4·56	4·63	6·21	7·64	8·87	7·80	5·80	3·15	3·23	2·96
5	3·84	4·75	4·14	4·10	6·24	7·42	8·62	7·80	5·52	2·98	3·28	2·89
6	3·49	4·30	4·16	3·74	6·07	7·38	8·92	7·80	5·56	3·13	3·13	2·88
7	3·38	4·15	4·10	3·63	5·86	7·17	8·78	7·69	5·33	2·96	2·91	2·58
8	2·31	2·91	2·15	2·69	6·76	9·48	9·26	8·25	5·87	2·24	1·28	1·38
9	1·35	1·47	1·53	2·91	7·58	10·61	11·42	10·19	7·64	3·00	2·01	1·24
10	3·30	2·97	3·33	5·01	8·35	11·56	12·51	11·66	9·01	4·47	4·44	3·35
11	5·31	5·50	5·57	5·92	9·00	12·16	13·32	12·74	9·76	5·89	6·68	5·31
12	6·13	5·80	6·28	6·60	9·62	13·15	14·29	13·60	10·07	6·45	7·28	6·40
13	6·33	6·50	6·34	6·91	10·03	13·56	14·79	14·19	10·59	6·36	6·59	6·40
14	6·62	7·10	7·15	7·57	11·01	14·40	15·12	14·32	11·69	6·67	6·90	6·20
15	6·78	7·98	7·90	8·54	12·11	14·96	15·42	14·76	12·28	7·15	6·16	6·17
16	6·91	8·17	8·74	9·86	13·49	15·52	14·99	14·29	12·68	7·71	5·79	5·67
17	6·81	8·51	9·43	11·19	13·89	15·33	14·61	13·67	12·40	8·05	5·31	5·36
18	6·72	8·80	11·02	12·69	14·26	14·77	13·84	13·00	13·38	7·37	4·63	5·14
19	6·87	8·95	10·80	12·57	13·30	13·39	12·22	11·15	9·67	6·09	4·52	5·12
20	5·97	7·51	9·60	10·75	11·99	11·88	11·09	9·90	8·38	5·06	4·10	3·98
21	4·69	5·89	7·41	7·94	9·96	10·64	10·12	9·23	7·51	4·58	3·75	3·50
22	4·07	4·69	5·92	7·08	9·10	9·72	9·70	8·72	7·00	4·24	4·11	3·61
23	3·77	4·53	5·00	5·99	8·21	9·09	9·58	8·56	6·92	4·03	3·87	3·80
24	4·03	4·60	4·85	5·57	7·52	8·84	9·31	8·43	6·51	3·95	3·83	3·68
Mean	4·75	5·60	6·01	6·64	9·21	11·00	11·47	10·49	8·33	4·84	4·34	4·10

TABLE 3·2

Mean hourly range of gust (mph)—Poona

Hr	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1·19	1·28	1·74	3·07	4·31	5·09	5·35	4·79	4·02	1·95	1·18	1·26
2	1·22	1·31	1·64	2·52	4·03	5·24	5·32	4·72	3·97	1·50	1·22	1·34
3	1·19	1·42	1·66	2·51	4·04	4·98	5·04	4·34	3·67	1·73	1·06	1·13
4	1·10	1·37	1·39	2·25	3·80	4·75	5·00	4·29	3·44	1·57	0·92	0·97
5	1·05	1·36	1·18	1·97	3·66	4·51	4·99	4·31	3·32	1·67	0·95	0·86
6	1·12	1·25	1·11	1·72	3·37	4·60	5·06	4·37	3·18	1·58	0·93	0·74
7	1·01	1·13	1·20	1·91	3·68	4·96	5·23	4·39	3·46	1·69	0·39	0·75
8	1·21	1·44	1·40	2·15	4·80	6·30	5·62	5·09	4·49	2·14	1·07	0·86
9	1·14	1·64	1·23	2·83	5·38	7·93	7·26	6·45	6·31	2·93	1·60	1·07
10	2·35	2·13	2·74	4·44	6·89	9·07	8·28	7·88	7·53	4·06	3·50	2·91
11	4·28	4·14	4·89	5·95	7·94	9·73	9·35	9·07	8·49	5·80	5·19	4·86
12	5·68	4·80	5·22	6·71	7·57	10·91	10·30	9·87	9·25	6·29	5·98	6·05
13	6·21	5·10	5·72	6·51	8·72	11·07	10·81	10·30	9·43	6·51	5·70	6·35
14	6·27	5·27	6·00	7·36	9·27	11·40	10·84	10·23	10·34	6·54	5·28	6·08
15	6·24	5·69	6·01	7·57	9·90	11·23	10·71	10·20	10·67	6·69	4·80	5·60
16	6·16	5·63	5·96	8·62	10·57	11·53	10·35	9·94	10·67	6·76	3·98	4·85
17	5·34	5·59	6·71	8·86	10·52	11·32	9·91	9·39	10·18	6·76	3·25	4·09
18	4·64	5·78	7·39	10·43	10·87	10·82	9·17	8·45	9·15	5·86	2·39	2·86
19	4·28	5·54	7·06	10·01	9·81	9·47	7·70	7·03	7·28	4·85	2·38	2·66
20	4·04	9·72	5·92	3·19	7·99	8·08	6·93	5·91	6·08	4·00	2·02	2·21
21	2·76	3·27	4·60	6·42	6·58	7·14	6·13	5·43	5·19	3·06	1·53	1·53
22	2·04	2·14	3·28	4·85	5·72	6·50	5·77	4·86	4·69	2·65	1·54	1·49
23	1·56	1·69	2·36	3·53	5·11	5·99	5·45	4·80	4·64	2·33	1·59	1·42
24	1·35	1·48	1·91	3·14	4·70	5·62	5·26	4·58	4·18	2·32	1·31	1·43
Mean	3·06	3·13	3·68	5·14	6·63	7·82	7·33	6·79	6·40	3·80	2·51	2·64

TABLE 3·3

Mean hourly gustiness of wind—Poona

Hr	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0·256	0·237	0·336	0·477	0·498	0·605	0·549	0·545	0·518	0·430	0·272	0·284
2	0·305	0·219	0·311	0·379	0·489	0·631	0·544	0·549	0·528	0·477	0·284	0·276
3	0·298	0·244	0·312	0·473	0·528	0·592	0·516	0·520	0·501	0·407	0·266	0·335
4	0·235	0·243	0·266	0·421	0·546	0·576	0·529	0·503	0·463	0·360	0·211	0·273
5	0·247	0·245	0·252	0·393	0·536	0·584	0·544	0·504	0·452	0·349	0·215	0·264
6	0·275	0·237	0·247	0·325	0·498	0·561	0·479	0·505	0·464	0·387	0·238	0·204
7	0·267	0·187	0·269	0·416	0·592	0·644	0·568	0·537	0·522	0·391	0·220	0·236
8	0·355	0·349	0·415	0·502	0·696	0·721	0·572	0·626	0·641	0·629	0·343	0·350
9	0·419	0·304	0·400	0·631	0·794	0·775	0·639	0·626	0·702	0·722	0·460	0·430
10	0·680	0·507	0·681	0·911	0·850	0·767	0·667	0·704	0·745	0·910	0·769	0·704
11	0·957	0·715	0·866	0·979	0·894	0·819	0·706	0·734	0·829	0·950	0·858	0·953
12	0·967	0·776	0·869	1·010	0·897	0·807	0·708	0·739	0·850	1·026	0·913	1·015
13	1·007	0·807	0·946	0·978	0·878	0·823	0·725	0·741	0·830	0·972	0·839	1·037
14	0·971	0·776	0·894	0·997	0·876	0·807	0·712	0·736	0·770	0·913	0·886	1·052
15	0·902	0·755	0·814	0·926	0·787	0·757	0·705	0·708	0·768	0·882	0·850	0·955
16	0·886	0·661	0·747	0·868	0·793	0·750	0·699	0·710	0·754	0·808	0·703	0·838
17	0·733	0·760	0·708	0·797	0·758	0·730	0·681	0·696	0·728	0·757	0·627	0·725
18	0·556	0·594	0·650	0·792	0·749	0·721	0·667	0·666	0·730	0·687	0·418	0·417
19	0·571	0·545	0·598	0·774	0·744	0·705	0·640	0·655	0·669	0·687	0·436	0·480
20	0·602	0·559	0·614	0·751	0·670	0·667	0·626	0·600	0·667	0·681	0·442	0·525
21	0·547	0·532	0·632	0·700	0·663	0·659	0·608	0·597	0·633	0·596	0·342	0·428
22	0·452	0·387	0·568	0·681	0·632	0·654	0·572	0·556	0·591	0·553	0·347	0·378
23	0·367	0·322	0·454	0·606	0·612	0·643	0·579	0·545	0·578	0·481	0·417	0·412
24	0·312	0·270	0·374	0·561	0·607	0·619	0·569	0·557	0·449	0·484	0·323	0·332
Mean	0·549	0·464	0·551	0·681	0·661	0·692	0·617	0·619	0·641	0·647	0·486	0·538

TABLE 3·4

Vector mean winds hour by hour—Poona (Direction *D* in degrees from north and Speed *S* in mph)

Hr	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1 *D*	240	260	259	267	280	279	277	280	279	257	230	225
S	2·3	3·3	3·5	4·3	5·9	7·0	8·8	7·2	5·5	1·9	2·3	2·1
2 *D*	241	251	249	263	279	278	278	280	279	255	237	228
S	2·5	3·7	3·5	3·6	6 3	7·2	8·7	6·8	5·6	1·7	2·6	2·1
3 *D*	242	244	247	268	283	278	277	278	279	251	236	233
S	2·6	3·5	3·1	3·6	5·4	6·9	8·0	6·8	5·1	1·8	2·4	1·8
4 *D*	244	250	246	267	272	279	277	279	275	254	232	236
S	2·2	3·1	3·4	3·1	4·8	6·3	8·1	6·6	8·7	1·4	2·1	1·6
5 *D*	245	249	250	265	280	278	278	281	278	246	229	237
S	2·4	3·5	3·2	3·0	5·3	6·4	8·2	6·8	5·1	1·3	2·3	1·7
6 *D*	240	246	250	258	279	277	277	281	278	249	231	236
S	2·2	3·3	3·3	2·9	3·9	6·3	9·0	11·2	4·8	1·3	1·7	1·5
7 *D*	242	250	244	258	275	277	277	280	277	248	228	236
S	1·9	3·0	3·1	2·6	4·9	6·3	8·0	6·7	4·5	1·3	1·5	1·3
8 *D*	235	245	246	260	284	285	284	282	279	246	197	237
S	1·4	2·2	1·9	1·8	5·8	4·8	8·6	7·2	5·2	1·1	0·6	0·7
9 *D*	217	258	224	295	296	282	281	286	283	242	087	073
S	1·0	0·8	3·2	1·9	6·2	9·1	10·5	9·4	6·1	0·3	1·6	1·0
10 *D*	078	063	043	338	320	281	282	285	291	084	088	082
S	2·1	1·1	1·1	2·5	4·4	9·8	11·5	10·1	7·6	1·6	3·5	0·9
11 *D*	090	086	057	039	313	283	283	286	299	090	100	097
S	3·3	2·4	2·1	1·9	6·2	9·9	11·3	11·2	8·4	3·2	5·8	4·5
12 *D*	101	125	069	023	321	284	282	285	305	081	103	107
S	3·5	2·4	2·6	2·2	6·6	10·8	13·0	12·3	8·3	3·7	6·3	4·5
13 *D*	109	122	024	354	287	280	283	285	295	062	100	127
S	2·8	1·4	1·2	1·9	7·7	10·8	12·4	12·6	8·7	3·2	5·6	1·5
14 *D*	143	330	023	347	323	283	282	287	294	065	113	128
S	2·0	0·4	1·8	2·7	7·8	12·1	13·7	13·1	10·0	2·4	2·1	0·9
15 *D*	157	277	358	317	311	282	283	286	288	041	095	104
S	0·2	0·8	2·5	4·8	8·7	12·6	14·3	13·6	9·2	1·8	4·0	2·8
16 *D*	287	307	340	304	316	280	283	286	294	013	093	088
S	0·5	3·2	2·9	5·7	7·7	12·7	13·8	13·4	11·1	1·8	3·5	2·8
17 *D*	318	309	311	307	302	282	282	286	291	335	091	083
S	1·9	4·3	5·9	8·0	10·8	13·1	11·9	12·9	11·1	2·5	2·8	2·2
18 *D*	329	315	308	305	300	293	281	283	289	316	083	120
S	2·1	5·4	8·2	10·0	11·5	12·8	13·6	12·5	10·4	3·1	1·6	0·6
19 *D*	321	312	319	304	297	277	279	283	287	306	044	046
S	2·9	6·1	5·6	10·0	11·4	12·1	11·7	10·6	8·6	3·1	0·6	0·8
20 *D*	305	306	293	305	287	275	278	283	285	298	249	260
S	3·0	5·5	7·8	8·9	13·5	11·7	10·6	9·3	7·5	2·5	0·8	0·4
21 *D*	299	287	289	293	283	276	278	280	283	277	247	229
S	2·5	4·1	5·7	7·6	9·1	9·8	9·8	8·2	6·7	2·5	1·6	1·3
22 *D*	263	274	280	284	281	280	278	280	281	264	222	228
S	2·0	3·3	4·3	5·4	8·4	9·1	9·2	7·8	6·3	2·6	1·7	1·6
23 *D*	240	267	272	274	277	277	275	279	279	261	226	225
S	1·8	3·6	2·3	4·6	7·4	7·9	8·5	7·9	6·1	2·3	2·1	1·9
24 *D*	245	260	236	269	274	277	277	280	274	251	226	231
S	2·2	3·4	1·1	4·4	6·4	7·6	8·4	7·6	5·8	1·9	2·3	1·9

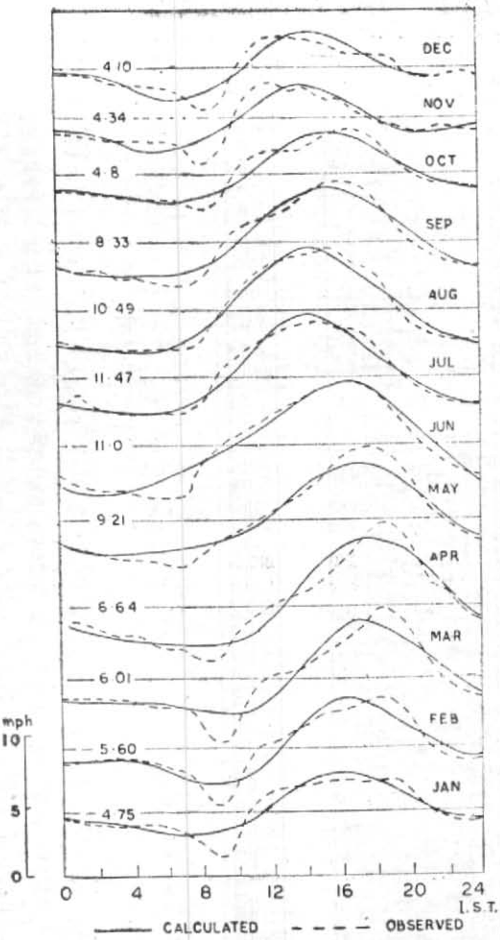


Fig. 1·1. Diurnal variation of wind speed

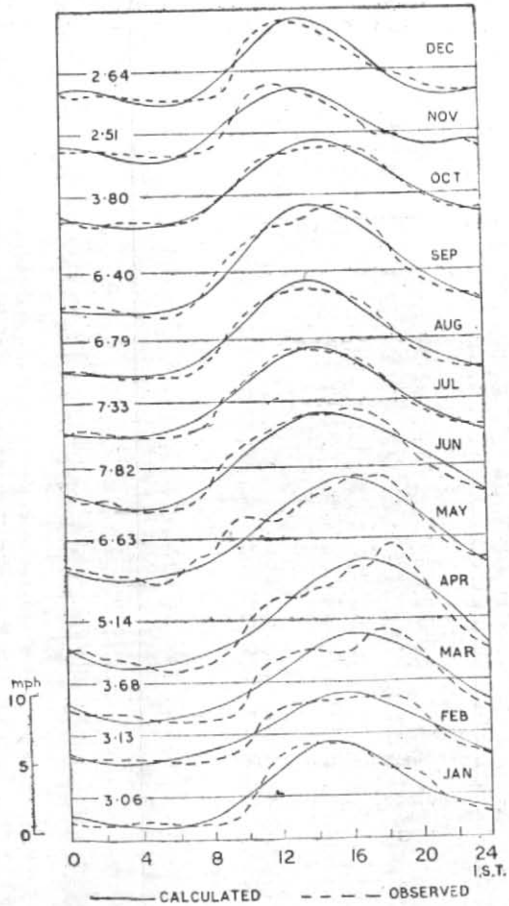


Fig. 1·2. Diurnal variation of average range of gusts

about 3 hours before midnight and maxima 1—3 hours after midnight, the range being of the order of half to one mile per hour. The maxima and minima and the times at which they occur are given below.

The calculated values of wind speeds have been indicated by continuous curves and observed values by broken curves in Fig. 1.1. The chief features of the diurnal variation are summarised in the following paragraphs.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	7·3	8·5	10·0	11·4	13·1	15·3	15·7	15·0	12·3	7·8	6·9	6·7
Time	1535	1645	1725	1740	1700	1600	1425	1420	1500	1525	1425	1425
Minimum	2·9	3·0	3·0	3·6	6·0	7·8	8·7	7·6	5·6	2·8	1·7	1·2
Time	0740	0900	0925	0835	0250	0230	0370	0500	0555	0630	0650	0700

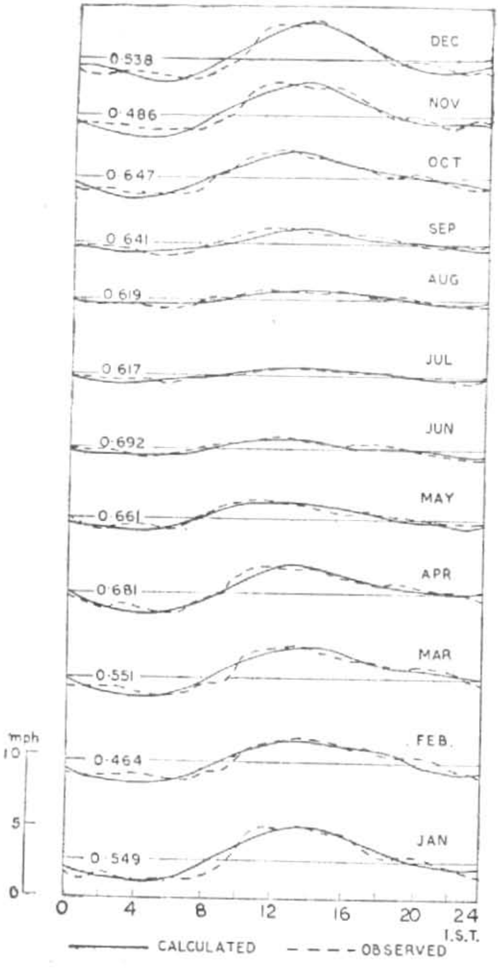


Fig. 1·3. Diurnal variation of mean gustiness at Poona

(i) Daily Maxima and Minima

The daily maximum wind speed goes on increasing steadily from a value of 6·7 mph in December to 15·3 mph in June. It remains between 15-16 mph during June, July and August and rapidly falls off to 12·3 mph in September and to 7·8 mph in October. The maximum wind is experienced at about 1425 in November and December and gets delayed with the advance of the hot weather season to 1740 IST in April. Subsequently in May and June the maximum wind occurs earlier and it occurs as early as 1425 and 1420 IST during the height of the monsoon in July and August. As the monsoon weakens, the insolation delays the maximum to about 1500 hours in September and 1525 hours in October.

The minimum in the wind speed is smallest being 1·2 mph which occurs at about 7 IST in the month of December. During January to April the minima are of the order of 3 mph which are delayed upto 9 hrs in February and 9-25 hrs in March. In May and June minimum speeds of 6·0 and 7·8 mph respectively occur earlier than 3 A.M. In July a minimum speed of 8·7 mph is experienced as early as 3–30 A.M. In August the minimum gets delayed upto 5 A.M. and gradually gets further delayed with the advance of the season.

(ii) Seasonal variation

The mean speeds are strong during June to August being over 10 mph and become less than 5 mph during October to January. To represent the seasonal variation of mean daily wind speeds the following equation has been fitted—

$$V_t = 7{\cdot}23 + 4{\cdot}00 \sin\left(282°06' + \frac{\pi}{6}t\right) + 1{\cdot}06 \sin\left(72°26' + \frac{\pi}{3}t\right) \qquad (6)$$

where V_t is the mean daily wind speed on the day represented by t reckoned from 16 January. The first term on the right hand side represents the mean wind speed for the year as a whole. The second term is

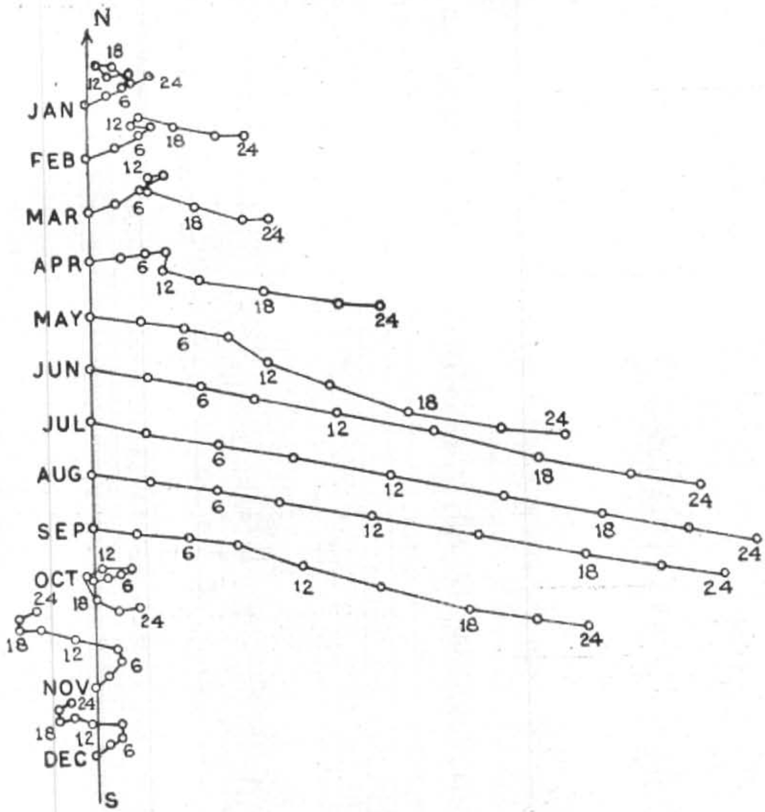
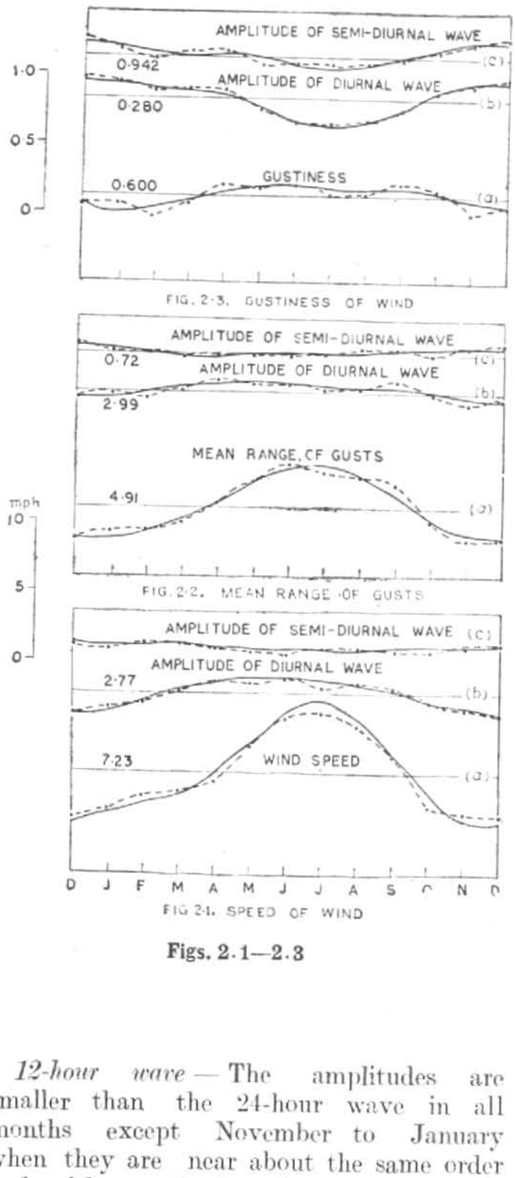


Fig. 1.4. Mean trajectories of winds at Poona at 130 ft above ground level

the annual oscillation, the amplitude of which is 4·00 mph the maximum in the oscillation occurring on 5 July. The third term is the semi-annual oscillation the amplitude of which is only a quarter of that of the annual oscillation. The maximum in the oscillation occurs on 23 January and 25 July. Fig. 2.1 (a) shows the seasonal variation of mean wind speed.

Fig. 3·1 shows the harmonic dials of the 24-hour and 12-hour waves separately. The vortices of the polygon represent the vectors corresponding to the different months, the distance from the origin being the amplitude and the angle measured from the positive x-direction in anticlockwise direction the phase angle. The times of maximum in the wave are marked out on the rim of the dial.

24-hour wave—The amplitudes are small during October to February, being smallest in December. The maximum is attained during 15 and 16 hrs during October to December and 16 and 18 hrs during January, February. From February to April the amplitude increases steadily, the time of maximum remaining at about 18 hrs. During April to June the amplitude remains practically constant while the maximum in the oscillation tends to occur earlier with the advance of the season. During the monsoon months, there is a slight reduction in the amplitude, the maximum occurring at about 1430 hrs during the height of the monsoon during July-August and at about 1530 hrs during the weaker part of the season, *viz.*, June and September,



Figs. 2·1—2·3

12-hour wave — The amplitudes are smaller than the 24-hour wave in all months except November to January when they are near about the same order and with amplitudes about 1 mph. The maximum in the oscillation occurs during 2 to 3 A.M. and 2 to 3 P.M. during July to January getting delayed to 4 A.M. and 4 P.M. in February and to about 5 A.M. and 5 P.M. during March to June. Due to the fact that the amplitudes of the diurnal wave during the winter months are of the same order as that of the semi-diurnal wave the secondary maxima are perceptible during these months.

The seasonal variation of the two amplitudes are represented by the following equations—

Amplitude of the diurnal wave

$$a_{1\cdot t} = 2\cdot77 + 1\cdot12 \sin\left(302° \; 22' + \frac{\pi}{6}t\right) + $$
$$+ 0\cdot29 \sin\left(320° \; 22' + \frac{\pi}{3}t\right) \quad (7)$$

Amplitude of the semi-diurnal wave

$$a_{2\cdot t} = 0\cdot97 + 0\cdot20 \sin\left(80° \; 46' + \frac{\pi}{6}t\right) + $$
$$+ 0\cdot06 \sin\left(15° \; 32' + \frac{\pi}{3}t\right) \quad (8)$$

The calculated and actual values are shown in Figs. 2·1 (b) and 2·1 (c).

The diurnal wave has a mean amplitude of 2·77 mph with an annual oscillation of amplitude 1·12 mph, the maximum occurring on 14 June and a half-yearly oscillation of amplitude 0·29 mph, only a fourth of the annual oscillation, the maxima occurring on 23 March and 22 September.

The semi-diurnal wave has a mean amplitude of 0·97 mph with an annual oscillation of amplitude 0·20 mph, maxima occurring on 25 January and a half-yearly oscillation of amplitude 0·06 mph, the maxima occurring on 23 February and 25 August.

4·2. Mean range of gusts—Diurnal and semi-diurnal oscillations

The values of mean R_g in the different months and the amplitudes and phase angles of the diurnal and semi-diurnal variations are given in Table 4.2. The calculated and actual values are shown in Fig. 1·2.

(*i*) *Daily Maxima and Minima*—The maxima in the range of gusts are smallest during November to February and largest during May to September. The time at which the maximum is attained is earliest

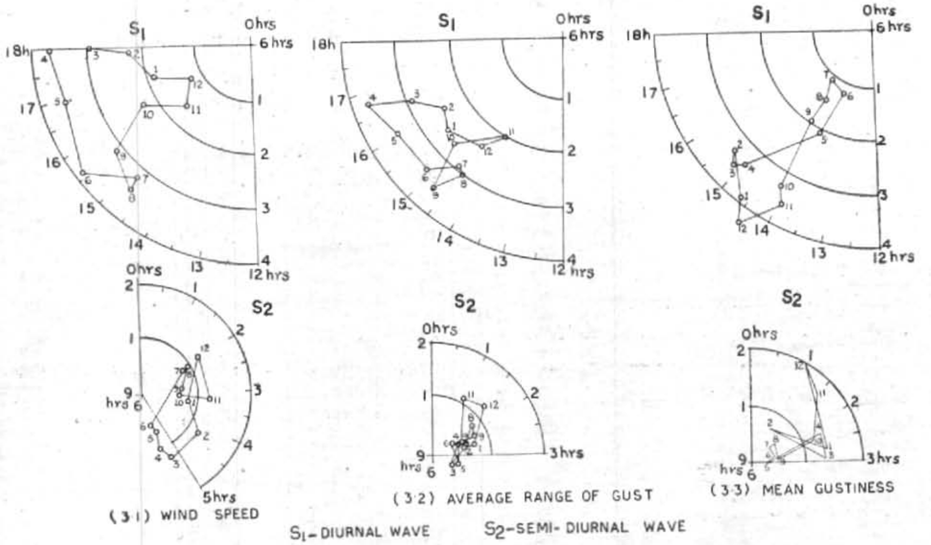


Fig. 3. Harmonic dial vectors of wind characteristics at Poona

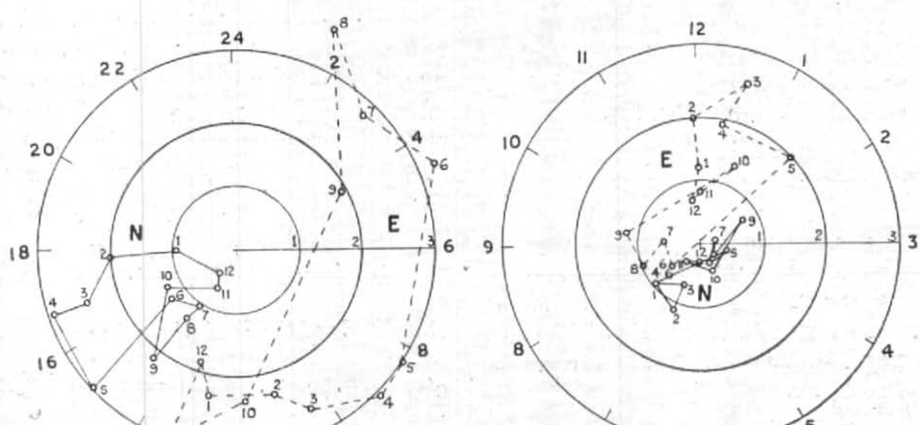


Fig. 4. N and E components of wind

in November and gradually gets delayed with the advance of the season to 1715 hrs in April after which it rapidly advances with the maxima in the range of gusts occurring as early as 1415 hrs during the height of the monsoon. As the monsoon weakens there is again a recession in time of maxima upto 1500 hrs in October.

The minima in the ranges of gusts are again smaller during November to March, but increase to about 5 mph during the monsoon months June-July. The minima occur between 5 and 6 A.M. during October to January and between 3 and 4 A.M. during the rest of the year.

(*ii*) *Seasonal variation* — The following equation represents the seasonal variation of the average range of gusts

$$R_{g.t} = 4\cdot 91 + 2\cdot 61 \sin\left(283°12' + \frac{\pi}{6}t\right) + $$
$$+ 0\cdot 34 \sin\left(80°12' + \frac{\pi}{3}t\right) \quad (9)$$

where $R_{g.t}$ is the average range of gusts on any day represented by t reckoned from 16 January. The mean of the average range of gusts over the year is 4·91 mph. The amplitude of the annual oscillation is 2·61 mph, the maxima in the oscillation occurring on 4 July, practically about the same time as for the amplitude of the annual oscillation of the mean wind speed. The 6-monthly oscillation has the amplitude of 0·34 mph, about an eighth of the amplitude of the annual wave; the maxima occur on 21 January and 23 July again at about the same time as the amplitude of the 6-monthly oscillation of the wind speed. Fig. 2·2 (a) shows the seasonal variation of the average range of gusts.

Fig. 3·2 shows the harmonic dials of the 24-hour and 12-hour waves separately.

24-hour wave

The amplitudes are smallest in November, the maxima in the oscillation occurring at 1400 hrs. With the advance of the season, the amplitude increases and the time of maxima gets delayed rapidly from 1424 hrs in December to 1600 hrs in February and thence gradually to 1648 in April. During April to June the amplitude remains fairly constant but the time of occurrence of maximum advances rapidly to 16 hrs in May and 1506 in June. With the advance of the monsoon the amplitudes decrease and are lowest for the season in July and August. The maxima during the monsoon months occur between 1430 and 1500 hrs. After the monsoon has withdrawn the amplitudes decrease attaining a value of 2·76 mph in October.

12-hour wave

The amplitudes are small and considerably smaller than the 24-hour wave. The amplitudes are largest during November-December being 1·05 to 1·31 mph and the maxima occurring between 1 and 1-30 A.M. and again at corresponding times in the afternoon. Later the amplitudes get decreased and the time of maxima delayed. They are smallest in March being 0·37 mph, the maxima occurring at 3-54 A.M. and 3-54 P.M. During April to June the amplitudes remain at about ½ mph. There is some increase during the months July to September, the maxima occurring at about 2 A.M. and 2 P.M.

The seasonal variations of the two amplitudes are represented by the following equations—

Amplitude of the diurnal wave

$$a'_{1.t} = 2\cdot 99 + 0\cdot 55 \sin\left(304°33' + \frac{\pi}{6}t\right) +$$
$$+ 0\cdot 22 \sin\left(300°00' + \frac{\pi}{3}t\right) \quad (10)$$

Amplitude of the semi-diurnal wave

$$a'_{2.t} = 0\cdot 72 + 0\cdot 26 \sin\left(155°32' + \frac{\pi}{6}t\right) +$$
$$+ 0\cdot 10 \sin\left(133°03' + \frac{\pi}{3}t\right) \quad (11)$$

The calculated and actual values are shown in Figs. 2·2(b) and 2·2(c).

The diurnal wave of average range of gust has a mean amplitude of 2·99 mph. The amplitude of the annual oscillation is 0·55 mph, the maxima in the oscillation occurring on 12 June. The half yearly oscillation has an amplitude of 0·22 mph, the maxima occurring on 2 April and 2 October.

The semi-diurnal wave has a mean amplitude of 0·72 mph with an annual oscillation of amplitude 0·26 mph, the maxima in the oscillation occurring on 12 November. The six-monthly wave has an amplitude of 0·10, the maxima occurring on 26 June and 26 December.

4.3. Gustiness of wind—Diurnal and semi-diurnal oscillations

The values of mean gustiness in the different months, the amplitudes and phase angles of the diurnal and semi-diurnal waves are given in Table 4.3. The calculated and actual values are shown in Fig. 1.3.

(i) Daily Maxima and Minima

The maximum gustiness has a small seasonal variation. In the months of July and August, the maximum gustiness are lowest being 0·72 and 0·76 while during October to January and March to May they are of the order of 0·9 to 1·0. The times of maxima are between 1300 and 1330 hrs except during May-June when they occur earlier by another half an hour and August to September when they get delayed upto 1400 hrs.

The minimum gustiness is of the order of 0·2 during November to March and about 0·5 during May to September; April and October lying in between. The minima occur between 4 and 5 A. M. throughout except during August and September when they occur at 3-30 and 3 A.M. respectively.

(ii) Seasonal variation

The following equation represents the seasonal variation—

$$G_t = 0\cdot600 + 0\cdot497 \sin\left(277^\circ\,24' + \frac{\pi}{6}\,t\right) + 0\cdot205 \sin\left(257^\circ 18' + \frac{\pi}{3}\,t\right) \qquad (12)$$

where G_t is the mean gustiness on the t^{th} day reckoned from 16 January. The mean gustiness for the year as a whole is 0·600. The amplitude of the annual oscillation is 0·497, the maximum in the oscillation occurring on 10 July. The half-yearly oscillation has an amplitude of 0·205, the maxima occurring on 23 April and 23 October. Fig. 2.3(a) shows the seasonal variation of mean gustiness.

Fig. 3·3 shows the harmonic dials for the 24-hour and 12-hour waves separately.

24-hour wave

The amplitudes are smallest in July having a value of 1·16 and increase to 4·32 in December and thence decrease. The time of maxima in the oscillation remains about 14 to 15 hrs.

12-hour wave

The amplitudes are smaller than those of diurnal wave. They are smallest during May to September when they are about 0·5 or less. During October to December the amplitude increases from 1·2 to 2·0 and decreases afterwards to 1·25 in April. The time of maximum oscillation between 1 and 3 A. M. and P. M. in the course of the year remain between 2 and 3 A. M. and P. M. during May to October.

The seasonal variation of the two amplitudes are represented by the following equations—

Amplitude of the diurnal wave

$$a''_{1\cdot t} = 0\cdot280 + 0\cdot873 \sin\left(93^\circ 00' + \frac{\pi}{6}\,t\right) + 0\cdot228 \sin\left(246^\circ 30' + \frac{\pi}{3}\,t\right) \qquad (13)$$

Amplitude of the semi-diurnal wave

$$a''_{2\cdot t} = 0\cdot094 + 0\cdot411 \sin\left(108^\circ\,00' + \frac{\pi}{6}\,t\right) + 0\cdot162 \sin\left(212^\circ 18' + \frac{\pi}{3}\,t\right) \qquad (14)$$

The calculated and actual values are shown in Figs. 2·3(b) and 2·3(c).

TABLE 4·1

Components of diurnal and semi-diurnal wave—wind speed—Poona

Month	Mean A_0 (mph)	First harmonic: Amplitude a_1 (mph)	Phase angle A_1	Time of maximum (h m)	Second harmonic: Amplitude a_2 (mph)	Phase angle A_2	Time of maximum† (h m)	Residual (%)
Jan	4·75	1·89	197°13′	16 48	0·86	350°19′	03 18	10·80*
Feb	5·60	2·24	182°22′	17 50	1·26	323°37′	04 12	9·41*
Mar	6·01	2·97	179°50′	18 00	1·27	294°03′	05 12	10·40
Apr	6·64	3·70	180°24′	18 00	1·04	287°42′	05 24	12·90
May	9·21	3·56	195°38′	16 57	0·74	291°35′	05 18	8·09
Jun	11·00	3·87	215°56′	15 36	0·61	284°52′	05 30	6·55
Jul	11·47	3·22	227°23′	14 48	0·94	27°54′	02 04	7·34
Aug	10·49	3·47	228°53′	14 45	0·96	27°55′	02 04	6·68
Sep	8·33	3·16	216°43′	15 36	0·75	5°48′	02 48	11·23
Oct	4·84	2·26	208°01′	16 06	0·69	0°15′	03 00	10·16
Nov	4·34	1·63	222°18′	15 12	1·26	354°18′	03 12	13·22
Dec	4·10	1·26	208°30′	16 06	1·22	32°10′	01 54	8·33

*In these two cases the 3rd and 4th harmonics were fitted. The 3rd and 4th harmonics accounted for 2·8 and 3·4 per cent in the case of January and 3·6 and 2·8 per cent in the case of February

†The second maximum is exactly 12 hrs later

The diurnal wave of gustiness has a mean amplitude of ·280. The amplitude of the annual oscillation is ·873. The maxima in the oscillation occurs on 13 January. The half-yearly oscillation has an amplitude of ·228. The maxima in the oscillation occur on 29 April and 29 October.

The semi-diurnal wave has a mean amplitude of 0·094 with an annual oscillation of amplitude of 4·115. The maximum in the annual oscillation occurs on 26 December. The six-monthly wave has an amplitude of ·162, the maxima occurring on 15 May and 14 November.

4.4. Diurnal and semi-diurnal circulations

The mean trajectories of wind during the course of the day, month by month, are shown in Fig. 1·4. These represent the path of a balloon floating in air at a height of 130 ft over Poona.

To get an insight into the mechanism of the diurnal variation, it would be necessary to dissect and separate out the component movements. The daily variations of the north and east components separately have been analysed harmonically into their diurnal and semi-diurnal oscillations. The components of the harmonic vectors and other

TABLE 4·2

Components of diurnal and semi-diurnal waves of average range of gusts—Poona

Month	Mean (mph)	First harmonic: Amplitude a_1 (mph)	Phase angle A_1	Time of maximum	Second harmonic: Amplitude a_2 (mph)	Phase angle A_2	Time of maximum	Residual (%)
				h m			h m	
Jan	3·06	2·69	218°36′	15 24	0·80	13°48′	02 30	9·38
Feb	3·13	2·49	210°00′	16 00	0·59	12°24′	02 36	7·51
Mar	3·68	3·00	201°54′	16 30	0·37	331°36′	03 54	10·25
Apr	5·14	3·75	198°06′	16 48	0·54	21°24′	02 18	9·82
May	6·63	3·48	209°42′	16 00	0·49	343°00′	03 24	6·67
Jun	7·82	3·45	223°55′	15 06	0·45	28°20′	02 06	12·27
Jul	7·33	3·02	230°54′	14 36	0·66	18°54′	02 24	7·15
Aug	6·79	3·10	233°32′	14 24	0·90	34°36′	01 50	5·49
Sep	6·40	3·63	228°54′	14 42	0·84	23°42′	02 12	5·82
Oct	3·80	2·76	223°38′	15 06	0·59	22°24′	02 42	6·24
Nov	2·51	2·09	240°01′	14 00	1·05	59°00′	01 00	7·07
Dec	2·64	2·48	233°44′	14 24	1·31	42°42′	01 36	6·43

TABLE 4·3

Components of diurnal and semi-diurnal waves of mean gustiness of wind at Poona

Month	Mean (mph)	First harmonic: Amplitude a_1 (mph)	Phase angle A_1	Time of maximum	Second harmonic: Amplitude a_2 (mph)	Phase angle A_2	Time of maximum	Residual (%)
				h m			h m	
Jan	0·549	·400	230°31′	14 36	·139	8°54′	2 42	17·3
Feb	0·464	·339	220°26′	15 18	·072	58°36′	1 03	8·7
Mar	0·551	·354	223°46′	15 05	·122	3°19′	3 36	8·4
Apr	0·681	·340	225°06′	15 00	·125	22°54′	2 15	8·0
May	0·661	·213	242°00′	13 54	·021	357°12′	3 06	10·5
Jun	0·692	·127	244°54′	13 42	·044	9°00′	2 42	14·2
Jul	0·617	·116	230°44′	14 36	·028	33°36′	1 54	2·0
Aug	0·619	·136	236°20′	14 15	·033	34°00′	1 54	4·3
Sep	0·691	·204	235°49′	14 18	·054	6°37′	2 48	11·7
Oct	0·647	·333	238°59′	14 04	·121	19°11′	2 21	7·2
Nov	0·486	·364	241°18′	13 54	·171	46°24′	1 27	8·2
Dec	0·538	·432	234°12′	14 24	·203	60°00′	1 00	5·9

associated details are given in Table 4·4 and the harmonic dials represented in Fig. 4.

The movement of air particles due to the diurnal and semi-diurnal oscillations can be visualized as compounded vectorially of the north and east components of the constituent oscillations. If the velocity vector associated with the k^{th} harmonic oscillation is—

$$\dot{\mathbf{R}} = \mathbf{I}\, a_k \sin\left(\frac{2kt\pi}{T} + A_k\right) + \mathbf{J} a'_k \sin\left(\frac{2kt\pi}{T} + A'_k\right) \qquad (15)$$

where **I** and **J** are unit vectors in the east and north directions and $k=1, 2$, other symbols have the usual meaning.

Integrating we have

$$\mathbf{R} = \mathbf{C} - \frac{T}{2k\pi}\left[\mathbf{I} a_k \cos\left(\frac{2kt\pi}{T} + A_k\right) + \mathbf{J} a'_k \cos\left(\frac{2kt\pi}{T} + A'_k\right)\right]$$

$$= \mathbf{C} + \frac{T}{2k\pi}\left[\mathbf{I} a_k \sin\left(\frac{2kt\pi}{T} + \overline{A_k - \frac{\pi}{2}}\right) + \mathbf{J} a'_k \sin\left(\frac{2kt\pi}{T} + \overline{A'_k - \frac{\pi}{2}}\right)\right] \qquad (16)$$

where **C** is a vector constant of integration.

Thus a particle of air moving in the wind field of the k^{th} harmonic oscillation will trace a path, of which the position vector at any time t is given by (16) above. It can be readily seen that the hodograph traced by the velocity vector $\dot{\mathbf{R}}$ in (15) is similar to the path traced by the air particle given by (16) except for the fact that the phase angles $A_k - \pi/2$ and $A'_k - \pi/2$ are replaced by A_k and A'_k respectively and the amplitude scales are reduced in the ratio $(T/2k\pi) : 1$.

For simplicity we shall work with equation (15). If we eliminate t, the equation of the curve in cartisian co-ordinates can be written as

$$a'^2_k X^2 + a^2_k Y^2 - 2a_k a'_k \cos(A_k - A'_k) \times X Y - a^2_k a'^2_k \sin^2(A_k - A'_k) = 0 \qquad (17)$$

X and Y are the co-ordinates in the east and north directions. Turning the axes through an angle θ given by

$$\theta = \tfrac{1}{2} \tan^{-1} \frac{-2a_k a'_k \cos(A_k - A'_k)}{a^2_k - a'^2_k}$$

Eq. (1) transforms to

$$\alpha X'^2 + \beta Y'^2 = \Psi^2 \qquad (18)$$

where $\Psi^2 = a^2_k a'^2_k \sin^2(A_k - A'_k)$ and X′ and Y′ are co-ordinates with reference to the transformed axes.

From the theory of invariants we get

$$\left.\begin{aligned} \alpha + \beta &= a'^2_k + a^2_k \\ \alpha\beta &= a'^2_k a^2_k - a'^2_k a^2_k \cos^2(A_k - A'_k) \\ &= a'^2_k a^2_k \sin^2(A_k - A'_k) \\ &= \Psi^2 \end{aligned}\right\} \qquad (19)$$

This is positive and hence (18) is an ellipse.

The semi-major and minor axes are $\Psi/\sqrt{\alpha}$ and $\Psi/\sqrt{\beta}$; these can be got by solving (19) for α and β or which is the same as solving the quadratic

$$\alpha^2 - \alpha\,(a^2_k + a'^2_k) + \Psi^2 = 0 \qquad (20)$$

The solutions are—

$$\alpha = \tfrac{1}{2}\left\{(a'^2_k + a^2_k) \pm \pm\sqrt{(a'^2_k + a^2_k) - 4\,\Psi^2}\right\} \qquad (21)$$

The inclination of the axis of the ellipse from the x-axis is

$$\theta = \tfrac{1}{2} \tan^{-1} \frac{-2a'_k a_k \cos(A_k - A'_k)}{a^2_k - a'^2_k}$$

The actual winds at the station are obtained by the super-position of the diurnal and semi-diurnal wind fields on the general wind field.

The constants of the ellipses in respect of the diurnal and semi diurnal oscillations during the different months are given in Table 4·5 and the hodograph ellipses shown in Fig. 5. These represent also the paths of the air particles when the speed scale is changed into the length scale enlarged $T/2k\pi$ times and the time marks are advanced by 6 hours in the case of the diurnal circulation and 3 hours in the case of the semi-diurnal one. T denotes the length of the solar day in hours.

In the same Table 4·5 are given the ellipticity, and area of hodograph ellipses, indicated positive if the circulation is in the anti-clockwise direction and negative if in the clockwise direction. These show characteristic variation from month to month.

(1) *Diurnal and semi-diurnal winds*

The hodograph ellipses in Fig. 5 show the following features—

Diurnal component—In November—December the diurnal component introduces a fairly steady wind mainly from WSW from about 8–9 P.M. to 7–8 A.M. The speed steadily increases till about midnight and remains at the maximum speed of 2–3 mph till about 2 or 3 A.M. after which it steadily decreases. In October and January the winds from the SW quadrant start much later in the night and cease by about dawn. During these two months winds from the NW quadrant, but of slightly lesser speed, blow during the early part of the night. The current reverses during the day.

During February to May, it introduces a wind from the northwesterly quadrant during the early hours of the night with a maximum of about 3 mph from WNW in February–March and NW in April–May. The time at which the maximum occurs, however, advances with the season from about 22 hrs in February to about 18 hrs in May. During the later part of the night, winds back to SW quadrant but are lighter.

During June to August it introduces a steady WNW'ly wind and during September a NW'ly wind mainly during the day time and attains a maximum at about 3 to 4 P.M. while during the corresponding hours of the night the wind component is reversed.

Semi-diurnal component—The semi-diurnal component introduces a wind from WNW in the morning and evening with a maximum at about 6 A.M. to 6 P.M. during October to March. The winds reverse direction during the intervening 6-hourly periods. In April and May the maximum westerly wind occurs 1–2 hours later than in the other months. During June to September the semi-diurnal effect is least but still there is a significant oscillation from NW to SE with a maximum speed of 1—1½ mph at about 3 A.M. to 3 P.M. from NW and the return current at 9 A.M. to 9 P.M. from SE.

Humphreys (1940) notes what may be called a *heliotropic variation*, whereby the wind veers gradually during the day from east to west following the Sun. He remarks further that "the entire phenomenon is only a diurnal surge, a flux and reflux of the atmosphere due to the diurnal heating and cooling." This simple heliotropic model is complicated by the nocturnal development of katabatic mountain breeze (Atmanathan 1931) and the day time valley breeze and the sea and land breezes (Ramanathan 1931). Further it is interesting to compare the winds introduced by the diurnal and semi-diurnal components with the pressure fields associated with the S_1 and S_2 pressure variations (Jagannathan and Alvi 1961). Thus it is clear that the diurnal inequalities of wind are controlled both by the diurnal inequalities of temperature as well as pressure. These aspects will be discussed separately.

(2) *Diurnal and semi-diurnal circulation of air**

The furthest deviation of any air particle from its mean position due to a component circulation is when it is at the tip of the major axis of the ellipse.

For the diurnal circulation the deviation from the mean position is largest in the month of August being about 15 miles S 71°10′E at about 9 P.M.* and at the same distance N 71°10′W at about 9 A.M. It is smallest in the month of December S 77°5′E at about 7 P.M. and the same distance N 77°5′W at about 7 A.M.

In the semi-diurnal circulation the deviation from the mean position is largest in the month of March being about 5 miles

*Note that the paths of air particles discussed in this section are similar to the hodograph ellipses in Fig. 5 with the time marks advanced by 6 hours in the case of diurnal and 3 hrs in the case of semi-diurnal circulation.

TABLE 4·4

Harmonic constants of north and east components of wind at Poona

Month	Diurnal wave				Semi-diurnal wave			
	Amplitude		Phase angle		Amplitude		Phase angle	
	N-Comp. a_1'	E-Comp. a_1	N-Comp. A_1'	E-Comp. A_1	N-Comp. a_2'	E-Comp. a_2	N-Comp. A_2'	E-Comp. A_2
Jan	0·92	2·26	178°08′	258°15′	0·93	1·17	222°47′	89°13′
Feb	1·95	2·28	181°02′	283°30′	1·10	1·94	246°42′	91°32′
Mar	2·42	2·69	197°51′	294°28′	0·69	2·56	246°55′	72°09′
Apr	2·92	3·15	197°52′	313°27′	0·94	1·86	221°23′	77°40′
May	3·03	3·07	221°57′	324°39′	0·41	1·93	354°33′	42°13′
Jun	1·23	3·33	214°16′	21°56′	0·31	0·54	302°18′	207°07′
Jul	1·04	2·83	235°20′	44°36′	0·23	0·57	14°36′	174°40′
Aug	1·27	3·70	232°14′	64°41′	0·27	0·94	339°20′	199°39′
Sep	2·08	1·89	230°57′	27°81′	0·73	1·15	28°16′	170°49′
Oct	1·18	2·31	206°02′	272°35′	0·47	1·31	292°44′	64°56′
Nov	0·60	3·07	245°02′	248°59′	0·54	0·83	218°40′	88°21′
Dec	0·43	1·80	234°21′	251°32′	0·40	0·67	240°36′	97°41′

TABLE 4·5

Constants of the ellipse of diurnal and semi-diurnal circulation of air at Poona

Month	Diurnal circulation					Semi-diurnal circulation				
	Semi major axis	Semi minor axis	Inclination of axis	Area of the ellipse	Eccentricity	Semi major axis	Semi minor axis	Inclination of axis	Area of the ellipse	Eccentricity
Jan	2·28	0·87	+ 4°45′	+ 6·23	·9254	1·38	0·57	—35°42′	—2·47	·9130
Feb	2·37	1·82	—26°58′	+13·54	·6414	2·19	0·41	—28°17′	—2·82	·9817
Mar	2·77	2·33	—23°13′	+20·27	·5415	2·55	0·61	—15°02′	—4·88	·9725
Apr	3·66	2·25	—40°00′	+25·86	·7896	2·02	0·51	—23°47′	—3·23	·9653
May	3·38	2·68	—43°17′	+28·44	·6095	2·00	0·22	+ 8°19′	+1·38	·9950
Jun	3·53	0·25	—19°56′	+ 2·77	·9972	0·55	0·29	— 4°21′	—0·50	·8545
Jul	3·03	0·18	—19°56′	+ 1·71	·9967	0·63	0·07	—21°03′	+0·14	1·0000
Aug	3·87	0·26	—18°50′	— 3·16	·9974	0·95	0·17	—12°46′	—0·51	·9789
Sep	2·59	0·58	—42°00′	+ 4·72	·9730	1·30	0·39	—29°38′	+1·59	·9538
Oct	2·37	1·05	+14°24′	+ 7·81	·8987	1·35	0·34	—14°30′	+1·44	·9704
Nov	2·91	0·04	+11°02′	+ ·37	1·0000	0·92	0·37	—28°22′	—1·07	·9130
Dec	1·82	0·12	+12°55′	+ ·69	·9945	0·76	0·22	—27°34′	—0·53	·9605

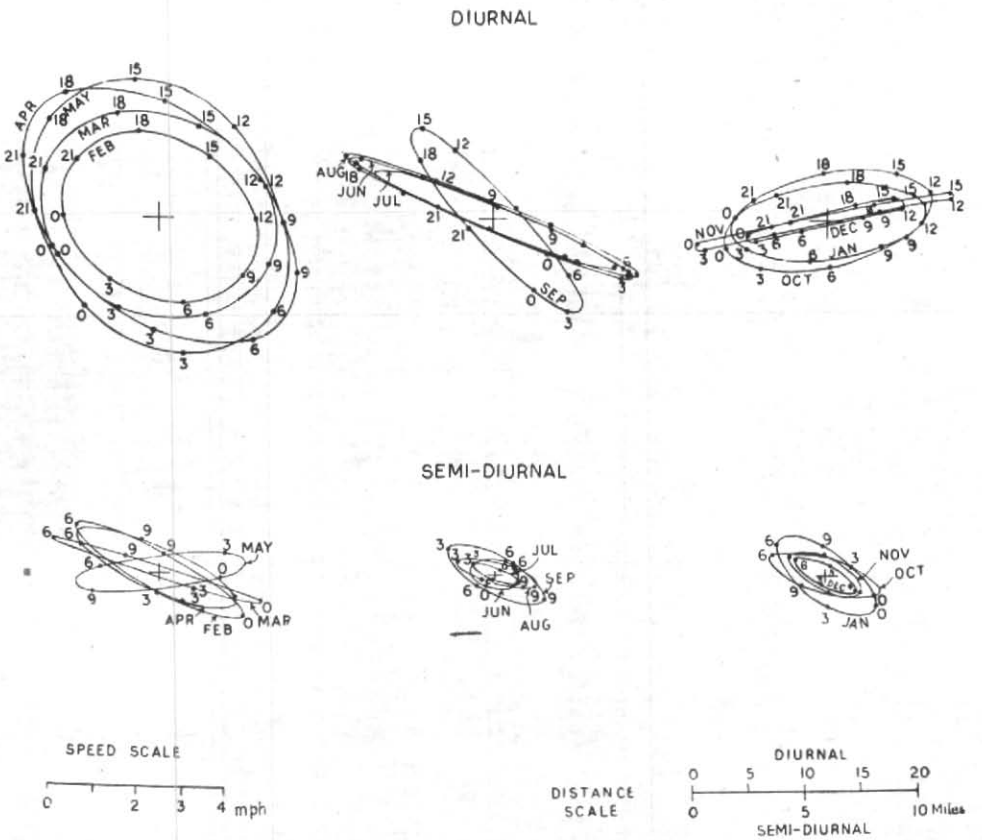


Fig. 5. Circulation of air at Poona

S 74°58′E at about 9 P.M. and 9 A.M. and at the same distance N 74° 58′W 6 hrs later. It is smallest in the month of June being about a mile S 85°39′E about 5 A.M. and 5 P.M. and the same distance N 85° 39′W 6 hours later.

The diurnal paths are nearly circular in the months of February to May with a slight elongation in SE to NW direction. During June to September, the paths are actually elliptical changing from a southeasterly direction at about 9—1030 P.M. to a northwesterly direction 12 hours later. October to January witness a slightly different pattern with elongation NE/E at about 6–7 A.M. veering to SW/W by about 6–7 P.M. In November-December the orbits are acutely elliptical, while in October–January they are less so.

The semi-diurnal paths are elongated mainly in an ESE to WNW direction except in May and June when they are mainly E–W. The semi-diurnal circulations are pronounced during January to April with the air particle making excursions to the ESE of the mean position about 9 A.M. and 9 P.M. and to WNW 6 hours later. They are least pronounced in June, July and December.

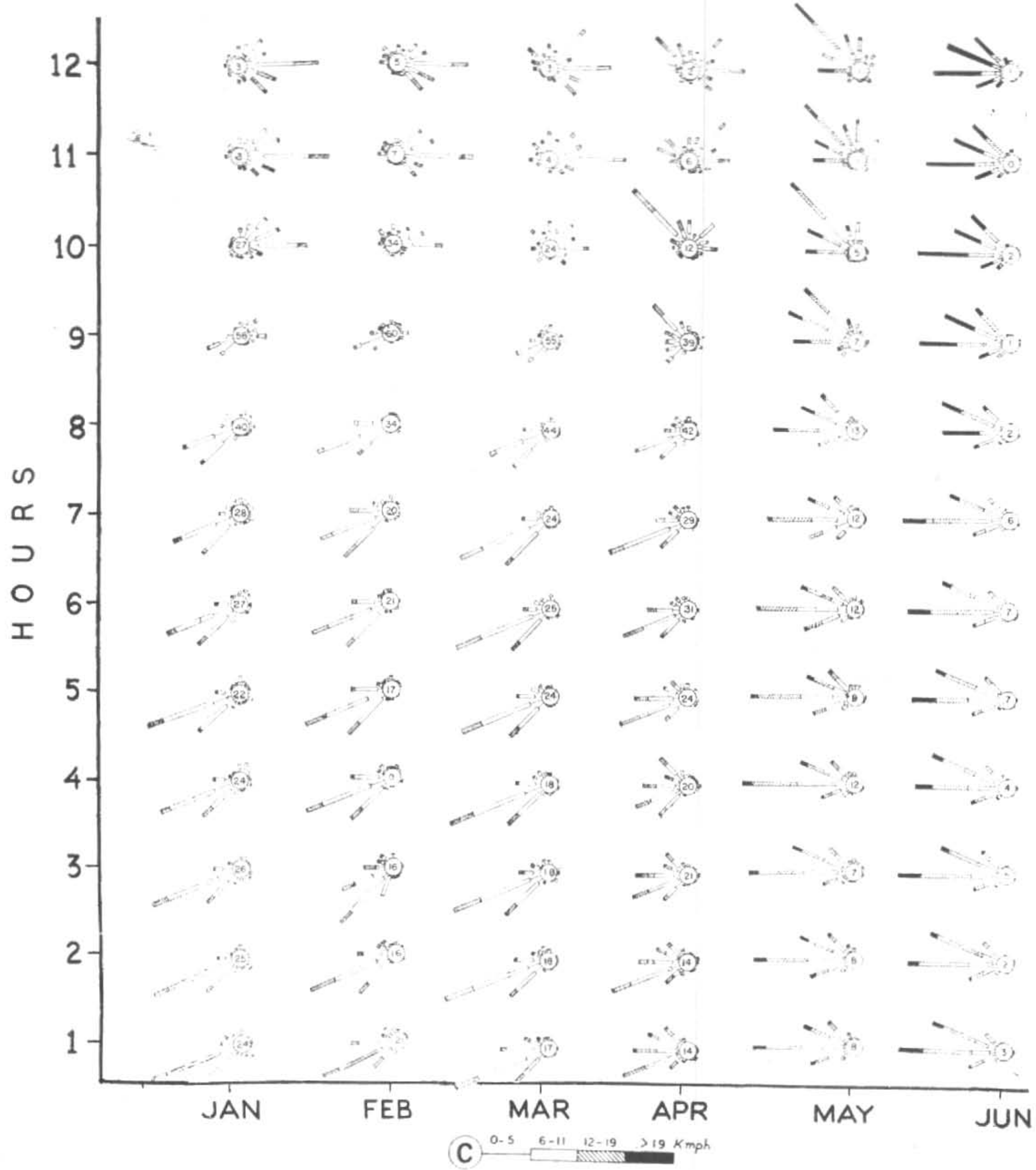


Fig. 6. Hourly Wind Roses of Poona

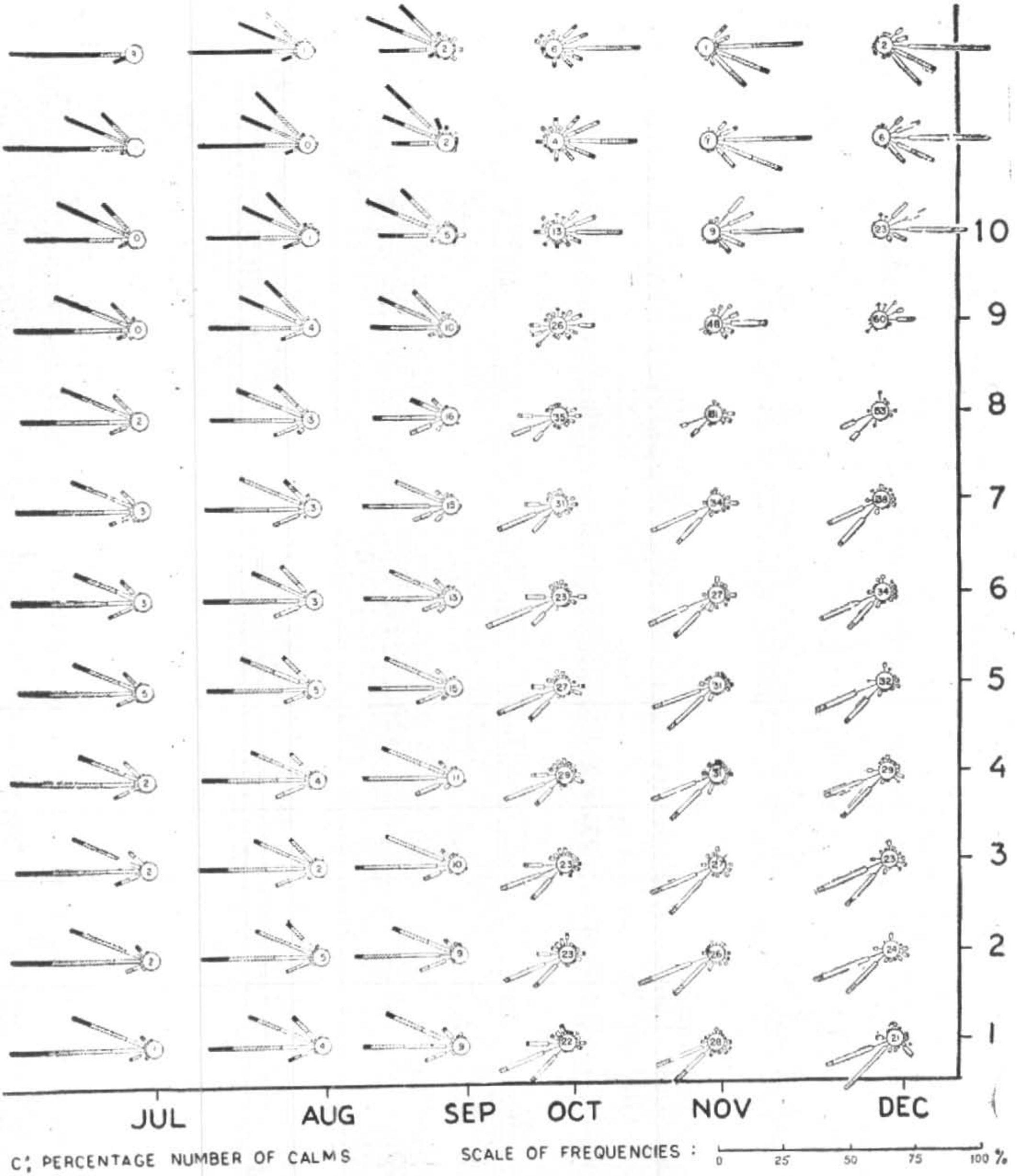


Fig. 6. Hourly Wind Roses of Poona

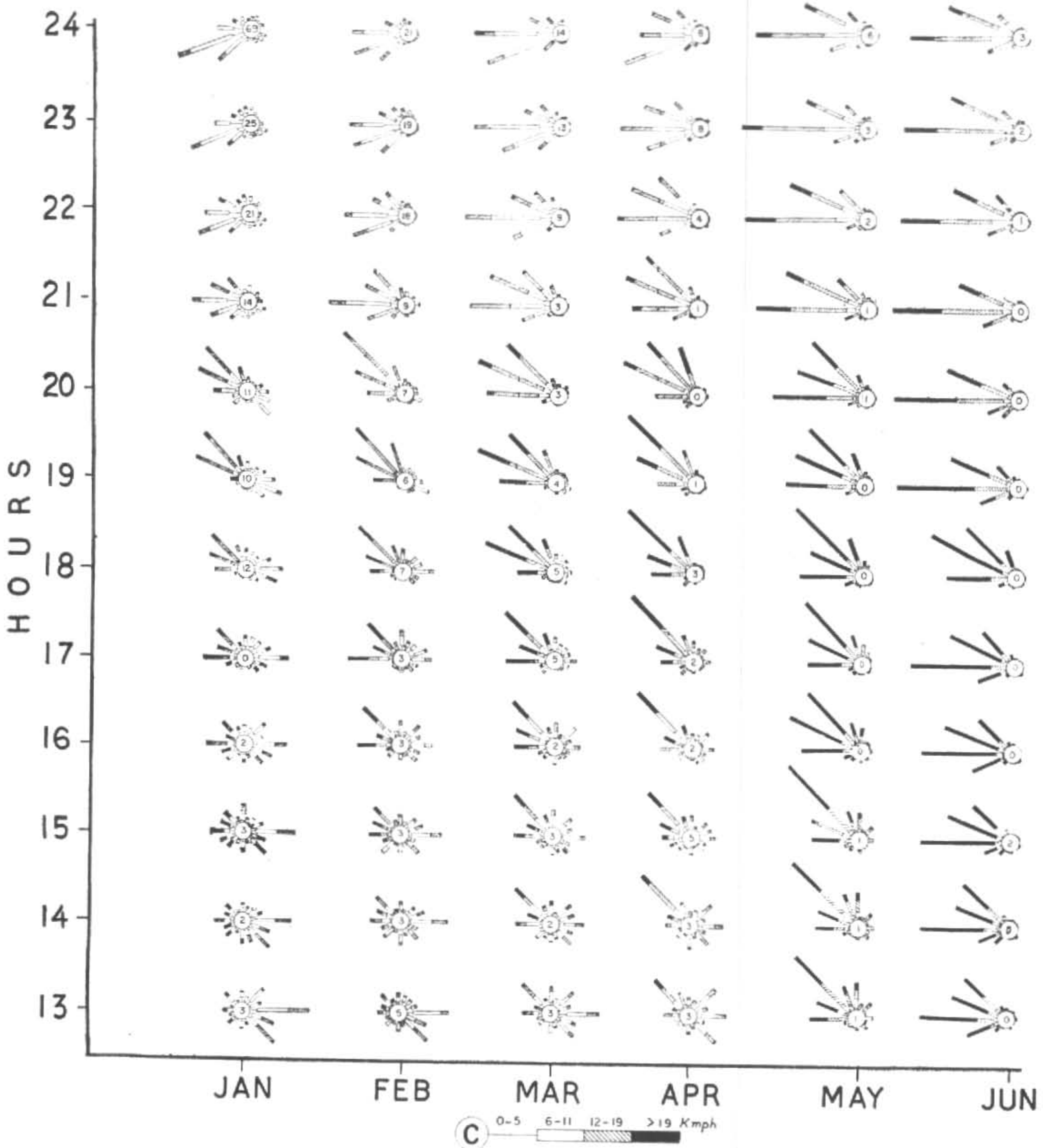


Fig. 6. Hourly Wind Roses of Poona

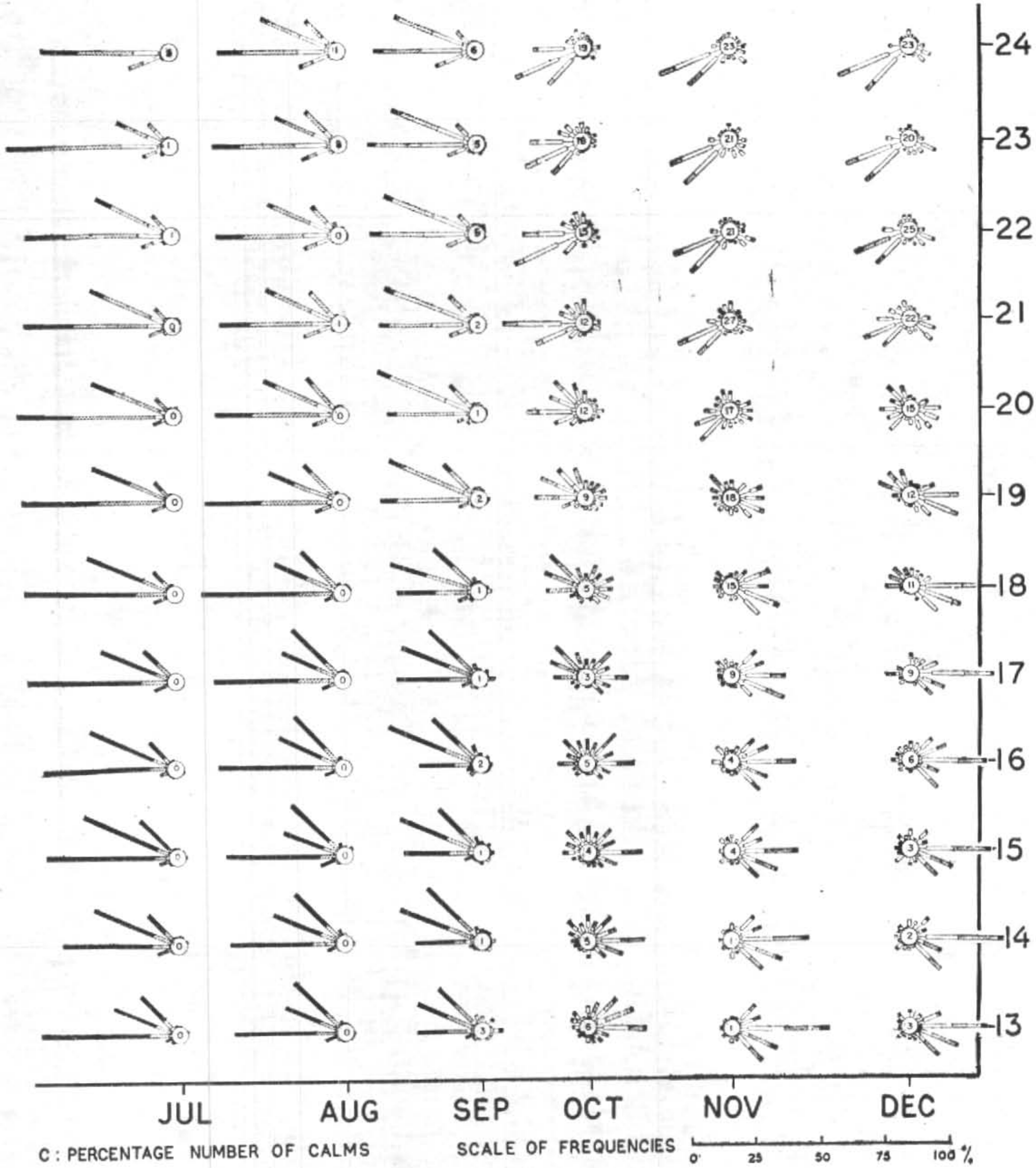


Fig. 6. Hourly Wind Roses of Poona

The circulation of the air particles in the anti-clockwise direction builds up energy while the circulation in the clockwise direction depletes energy; in each case the energy being proportional to the area enclosed. It will be seen that the areas of the diurnal circulation ellipses are largest during the months of March to May; with February coming next with half that amount and October and January almost a quarter of that during May. During August a slight tendency for anihilation of energy by diurnal circulation is noticed.

In the semi-diurnal circulation, the circulation of the air particle takes place twice in the day. As the distance scale of the semi-diurnal ellipse is twice as big as the diurnal ellipse, the energy contributed by the circulation is represented by only half of the area of the ellipse indicated in column 9 of Table 4·5. The mean daily energy contributed during the different months by the diurnal and semi-diurnal circulations are proportionate to the figures given in the last column.

These aspects will be discussed in greater detail in the subsequent communication.

5. Hourly Wind Roses

Wind roses representing percentage frequency of wind in the 16 points of compass are shown in Fig. 6 (pp. 22—25). The percentage frequencies of winds of different speeds are indicated by proportionate lengths of hatchings.

The features revealed by the figure are in brief—

June to September—Winds are mainly westerly. The most predominant directions practically throughout the day is W; WNW or NW coming next. WSW or SW winds are more frequent in the early morning and forenoon and less so in the afternoons.

Winds are stronger in the afternoons than in the night and earlier part of the day.

The number of calms are least during this season.

October to January—The percentage of calms are the largest. From about 21 hrs in the night to about 8 hrs in the morning, WSW is the most predominant direction; with SW coming next. After about 10 A.M. till 6 P.M. winds are predominantly easterly, the frequency decreasing considerably in January.

During February to April winds are predominantly WNW during afternoons and early part of the night and SW-W during the early hours of the morning and forenoons.

In May westerly winds are more frequent with tendency for more NW'ly winds during the day time upto about 8 P.M.

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REFERENCES

Atmanathan, S. 1931 *India met. Dep. Sci. Notes*, 40, p. 109.

Conrad, V. and Pollak, L. W. 1950 *Methods in Climatology*, 2nd Ed., Cambridge, Mass. Harvard University Press, p. 390.

Humphreys, W. J. 1940 *Physics of the Air*, 3rd Ed., McGraw Hill Book Co., Inc., New York/London.

Jagannathan, P. and Alvi, S. M. A. 1961 Diurnal Variation of Atmospheric Pressure in India—Seminar on Aeronautical Sciences, N.A.L., Bangalore (under publication).

Ramanathan, K. R. 1931 *India met. Dep. Sci. Notes*, 30, p.131.