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PROFESSIONAL NOTES NO. 15.

DIURNAL VARIATION

IN

WIND VELOCITY AND DIRECTION AT DIFFERENT HEIGHTS.

BY

J. DURWARD, M.A.

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DIURNAL VARIATION IN WIND VELOCITY AND DIRECTION AT DIFFERENT HEIGHTS.

BY J. DURWARD, M.A.

1. Convection and turbulence in the lower layers of the atmosphere are the chief factors which control the observed diurnal changes of wind velocity and direction. During the day, the effect of the sun's rays heating the earth is to promote convection and turbulence, and the result is a transfer of momentum by which the air near the ground gains at the expense of the faster moving layers above. At night, on the other hand, air near the ground gets cooled and is slowed down by increased friction with the earth : turbulence to a great extent ceases and accordingly the wind in the upper layers tends to increase in velocity. Thus the surface wind shows a maximum velocity by day and a minimum by night, whilst at a certain height the wind ought to be a minimum during the day and a maximum by night. The height at which the change in the nature of the variation takes place depends on the wind velocity, being higher for strong winds than for light winds, and on the time of year, being higher in summer than in winter. The lowest height may be taken as 150 feet—corresponding to light winds in winter.

Results obtained from the top of the Eiffel Tower show that the minimum wind velocity occurs about 9h. in summer and about 13h. in winter; the maximum wind velocity occurs about 21h. and the magnitude of the variation varies from 12 ft./s. in summer to 7 ft./s. in winter.

2. The question of diurnal variation at greater heights in the free atmosphere has been discussed by Reboul.* His results are briefly as follows :—Of a series of 218 ascents performed at a fairly high station 158 show a minimum velocity in the middle of the day at heights between 200m. and 1,000m.; of a series of 212 ascents performed at a valley station 142 show a minimum in the middle of the day. The diminution occurs oftener with Easterly winds (82% of occasions) than with Westerly winds (56% of occasions).

As regards direction : of a series of 193 ascents 132 show a backing in the middle of the day, and of a series of 198 ascents 131 show a veering during the night. In general, therefore, at heights between 200m. and 1,000m., the wind decreases and

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* Comptes Rendus, vol. 166, p. 295, 1918.

backs by day, increases and veers during the night or early morning.

Rouch* gives a table, of which an extract is given below, showing the difference in m/s between the morning wind and afternoon wind at certain stations for certain given heights—a negative sign indicates that the afternoon wind is less than the morning wind. The number of observations on which the results are based is given after each station.

TABLE I.—DIFFERENCES OF VELOCITY IN M/S. BETWEEN THE MORNING AND AFTERNOON WINDS.

Height in m.	Oran.	Bayonne.	Cette.	Rochefort.	Le Havre.
2,000	− 0·2	− 1·1	—	+ 0·8	—
1,500	− 0·4	− 0·4	− 1·7	− 0·8	− 1·0
1,000	− 1·4	− 0·4	− 1·7	− 0·8	− 1·0
800	− 1·7	− 0·9	− 1·5	− 2·1	− 1·0
600	− 0·9	− 2·1	− 1·6	− 3·2	− 2·0
400	+ 0·4	− 2·3	− 2·2	− 3·6	− 1·8
200	+ 2·7	− 0·4	− 0·8	− 4·6	+ 0·5
Hours of Obs. ...	7 & 16	7 & 13	7 & 13	7 & 12	7 & 13
No. of Obs. ...	58	44	69	36	21

3. The following note is an attempt to discuss in somewhat greater detail, the diurnal variation as revealed by the results of Pilot Balloon ascents. The variation considered is therefore confined to those days when pilot ballooning is possible; but if the results are to have any practical value, it is the variations to be expected on such days which ought to be known.

From March, 1917, onwards Pilot Balloon ascents (single theodolite) were made at certain stations on the British Front in France at intervals of approximately four hours. The hours of observation were roughly 1h., 5h., 10h., 13h., 17h. and 21h. G.M.T. or B.S.T. The ascents made at these hours will be denoted by index figures 1—6 respectively in the tables given below.

The observations made at Noyelle-Vion (140m. above M.S.L., 20k. E. of Arras) have been summarized according to the time at which the ascent was made and according to the direction of the wind at 2,000 feet—approximately the gradient wind. Thus a wind is considered West if at 2,000 feet its direction lies between 225° and 315°. The components of velocity along the West-East and the South-North axes have been written down and a record of direction, as well as of velocity, has thus been obtained.

* La variation de la vitesse du vent—Comptes Rendus, Aug 11, 1919.

(30806—12) Wt. 23915—418 750 3/21 H. St. G. 3

Unfortunately, it has not always been possible to measure winds at all these hours: 3 or 4 measurements only may have been made on any particular day. But if a sufficient number of ascents be taken for each hour of observation and no selection of ascents be made, it is probable that the means of such observations will reveal the diurnal variation at the height under consideration.

To test this, all ascents reaching 3,000 feet between March, 1917, and September, 1918, have been summarized. The number of ascents so summarized is 1,736 arranged as follows:—

TABLE II.—CLASSIFICATION OF ASCENTS REACHING 3,000 FEET.

Index Number.	1.	2.	3.	4.	5.	6.	Totals.
W.	133	107	102	120	118	115	695
E.	60	42	61	49	60	69	341
N.	48	44	46	52	82	87	339
S.	54	43	64	70	64	66	361
Totals ...	295	236	273	291	324	317	1,736

The curves obtained by plotting mean values derived from this number of observations are given in Figures 1—4. For reference the curves representing diurnal variation near the ground are also given, and for comparison the curve representing the diurnal variation of all winds at 1,000 feet is shown on the same diagram (Figure 5) as that representing the diurnal variation of wind velocity at the top of the Eiffel Tower. The latter is based on the yearly means given in the Meteorological Glossary, p. 287. It is seen that the curves of variation at 1,000 feet are of the same form as that for the general wind at the top of the Eiffel Tower: a minimum about the middle of the day and a maximum about 21 hours. Southerly and Northerly winds show two maxima, an early morning one and another during the early evening. The magnitude of the variation appears to be greatest with Northerly and Easterly winds and least with Westerly and Southerly: but this is probably due to the relatively small proportion of Westerly winds which exhibit any diurnal variation.

The curves for 2,000 feet and 3,000 feet are somewhat different. Most of the curves tend to show a maximum at 9h. (5h. in the case of a North wind) and a minimum during the afternoon and a maximum about 21h. From midnight till about 9h. the 1,000 feet wind diminishes while the 2,000 feet and 3,000 feet winds begin to increase, and when the 1,000 feet wind increases in the afternoon and evening, the winds at 2,000 feet and 3,000 feet decrease until late afternoon when all three winds increase again towards 21h. The variations of wind velocity and the differences between the curves for the heights considered are probably best seen in the case of a Southerly wind—which case is reproduced in Figure 6.

Figure 1.

Professional Notes No. 15.

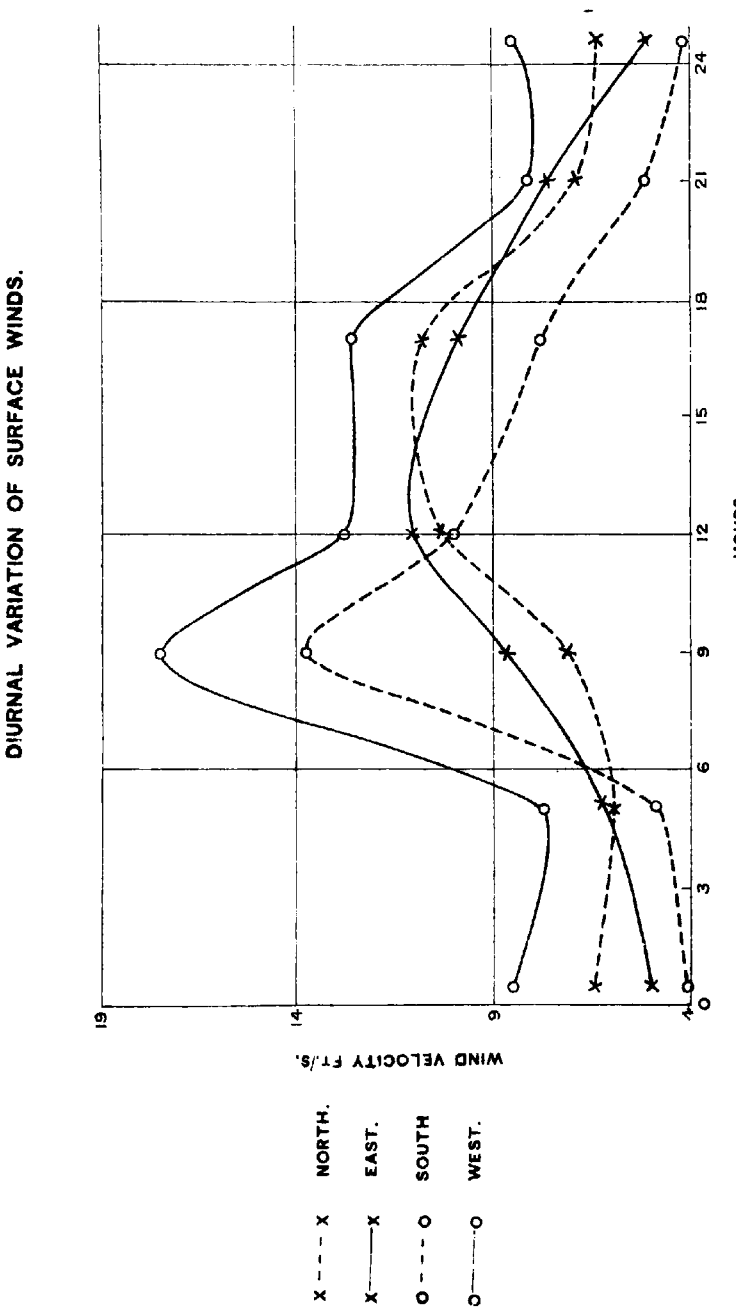


Figure 2.

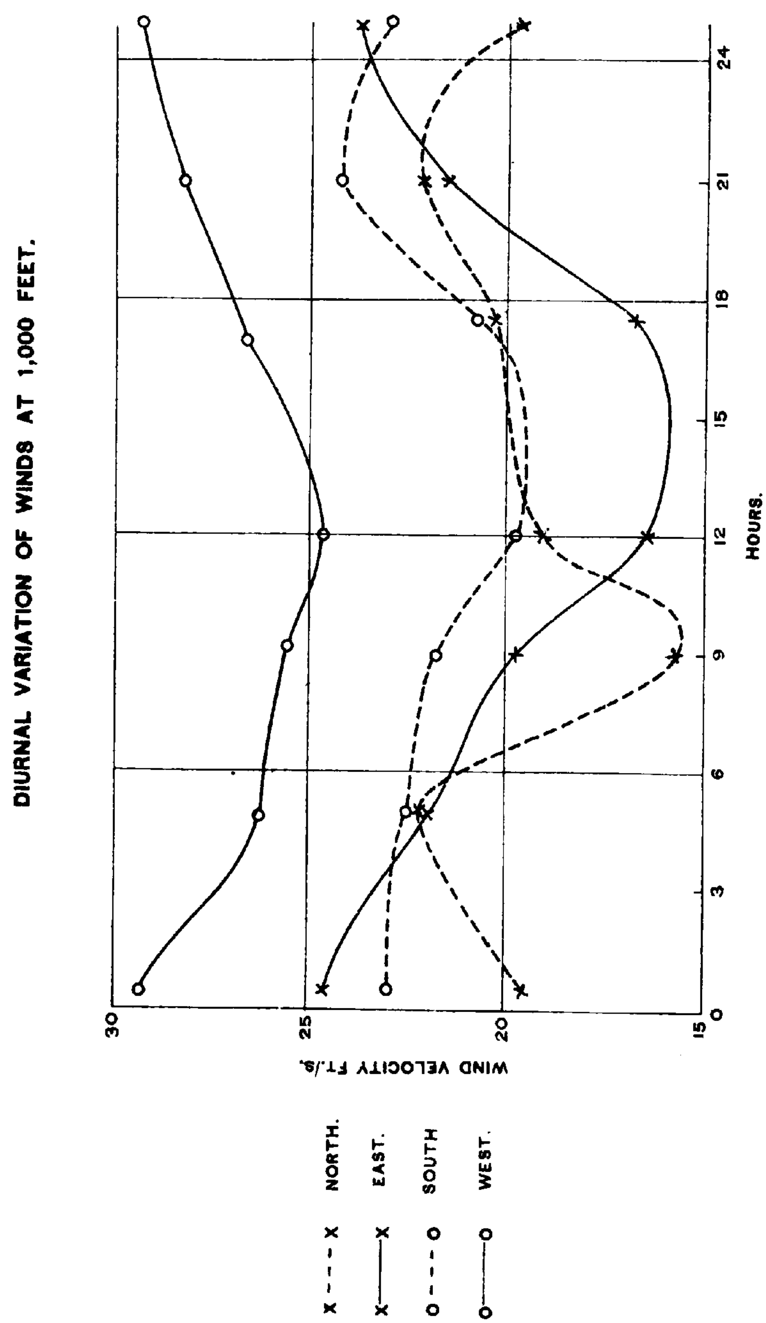

DIURNAL VARIATION OF WINDS AT 1,000 FEET.
HOURS.
0
3
6
9
12
15
18
21
24
WIND VELOCITY FT./S.
15
20
25
30
x - - - x NORTH.
x——x EAST.
o - - - o SOUTH
o——o WEST.

Figure 3.

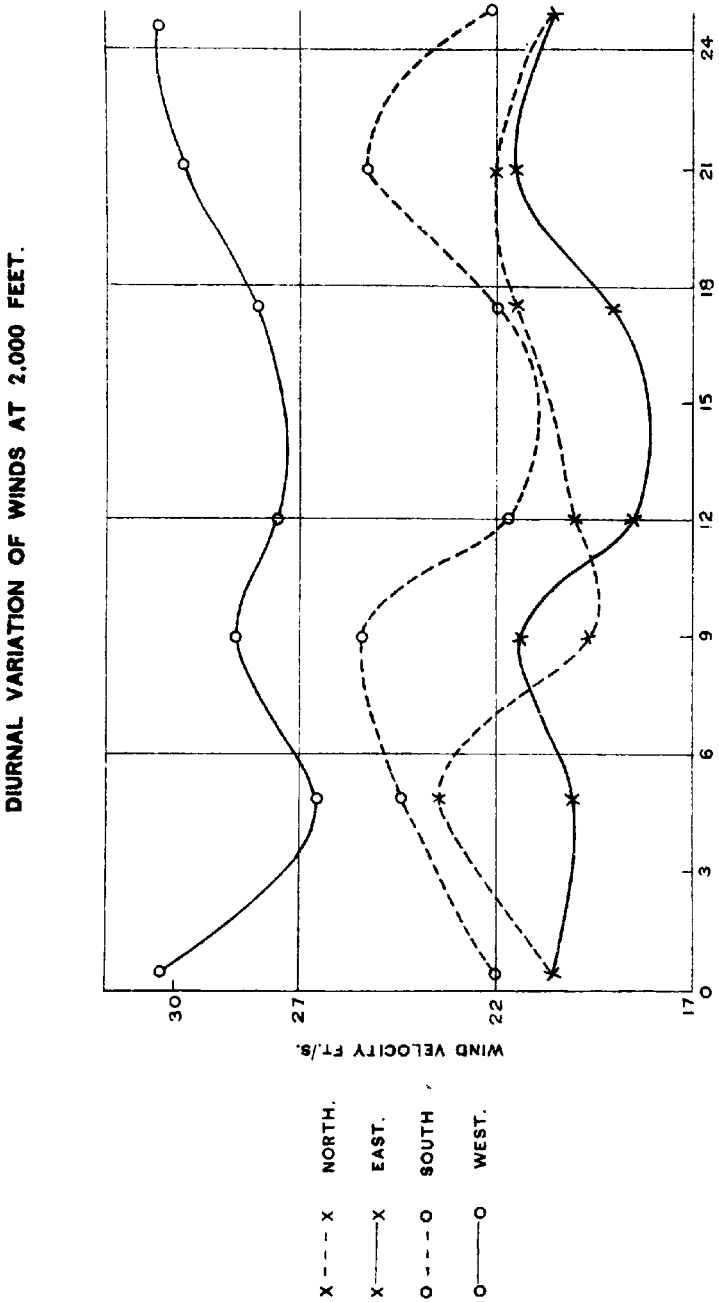

DIURNAL VARIATION OF WINDS AT 2,000 FEET.
HOURS.
0
3
6
9
12
15
18
21
24
WIND VELOCITY FT./S.
17
22
27
30
X - - - X NORTH.
X——X EAST.
O - - - O SOUTH
O——O WEST.

Figure 4.

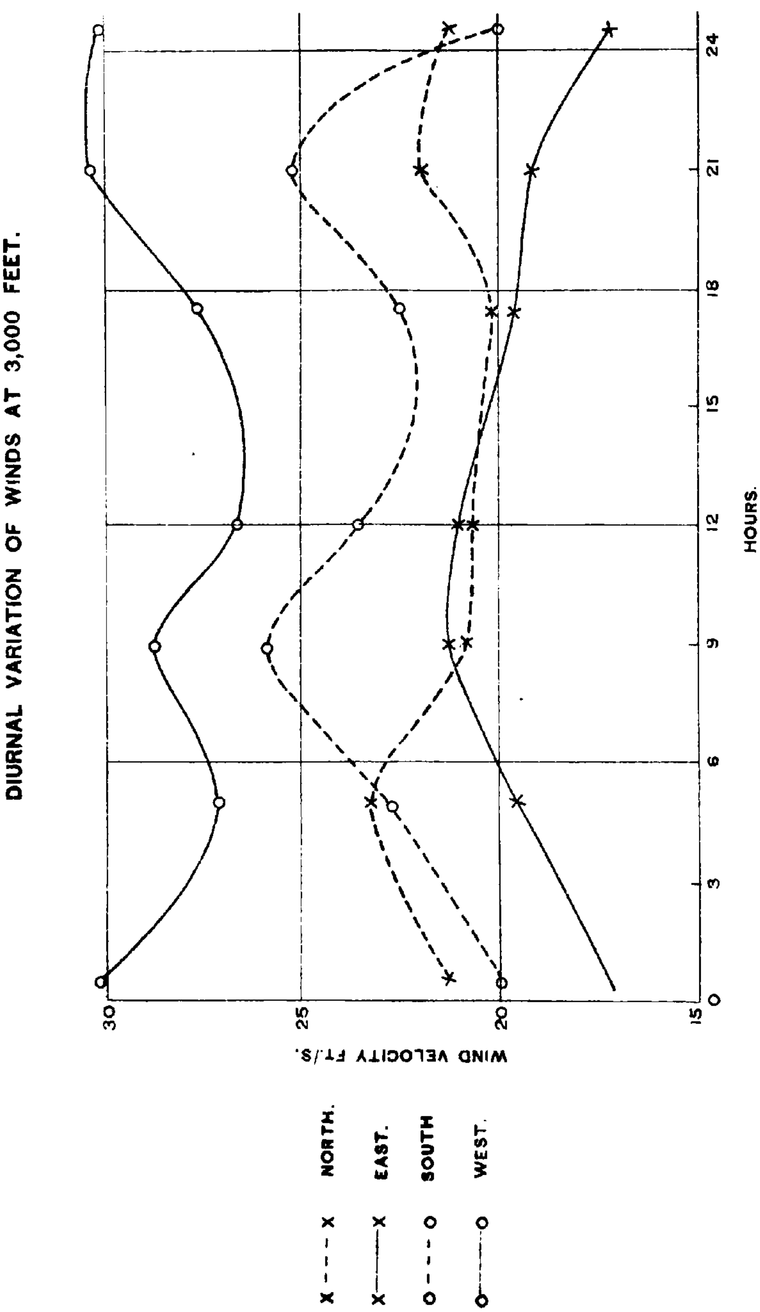
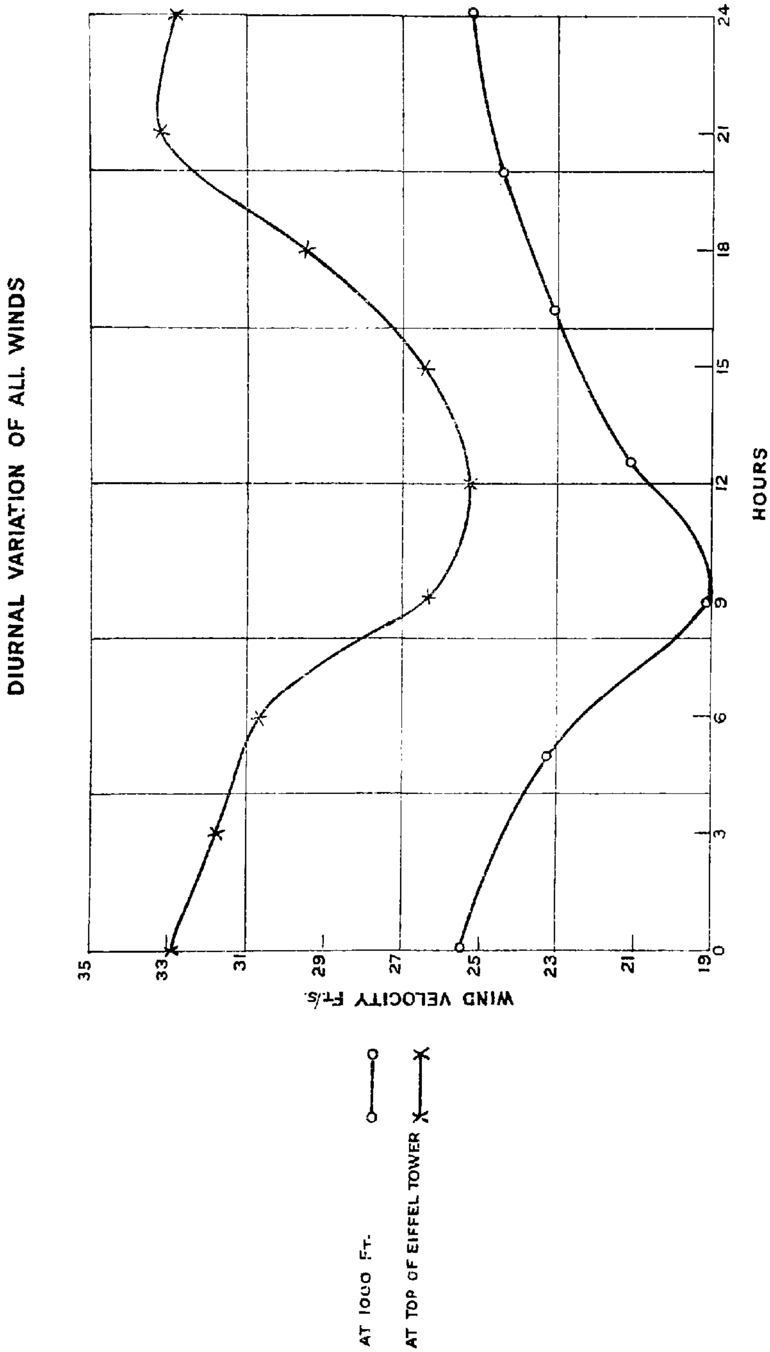
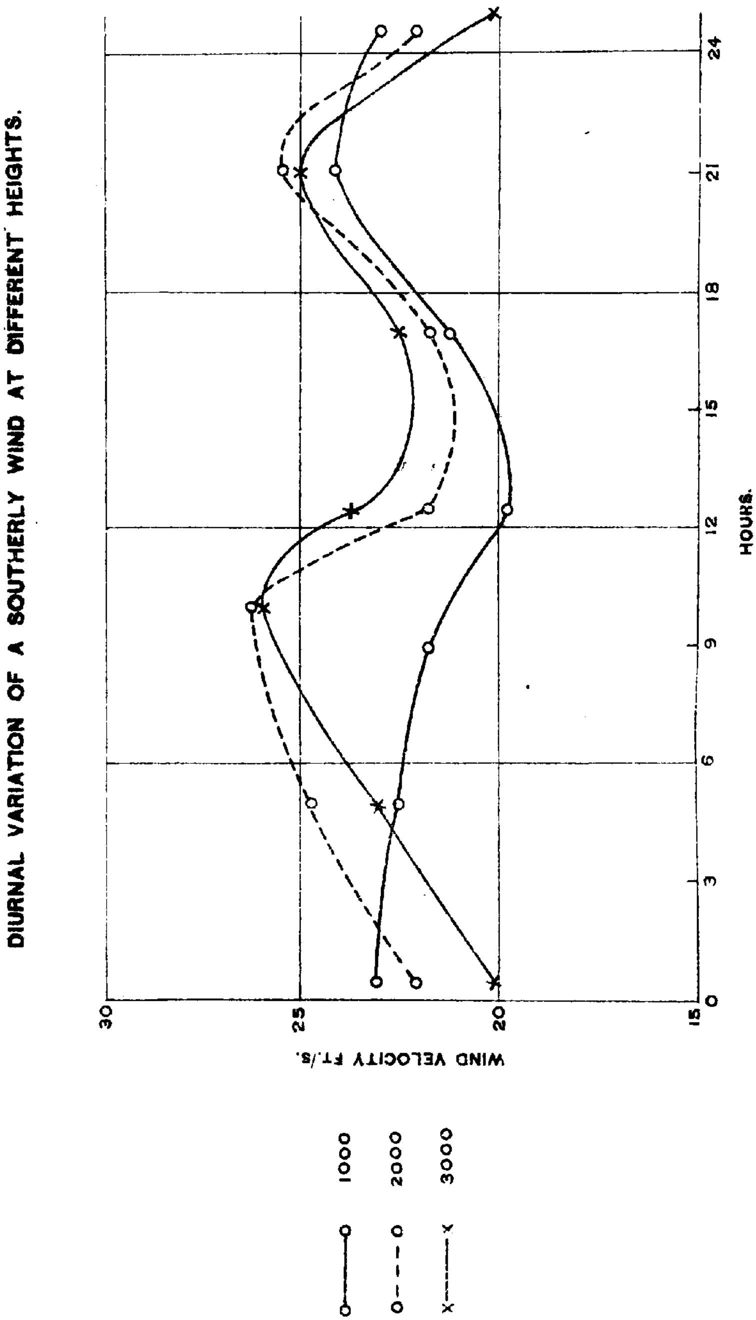

DIURNAL VARIATION OF WINDS AT 3,000 FEET.
WIND VELOCITY FT./S.
HOURS.
0
3
6
9
12
15
18
21
24
15
20
25
30
X - - - X NORTH.
X——X EAST.
O - - - O SOUTH
O——O WEST.

Figure 5.


DIURNAL VARIATION OF ALL WINDS
WIND VELOCITY FT/S.
35
33
31
29
27
25
23
21
19
HOURS
0
3
6
9
12
15
18
21
24
AT 1000 FT.
AT TOP OF EIFFEL TOWER


DIURNAL VARIATION OF A SOUTHERLY WIND AT DIFFERENT HEIGHTS.
HOURS.
0
3
6
9
12
15
18
21
24
WIND VELOCITY FT./S.
15
20
25
30
1000
2000
3000

It is worthy of note that the curve for an East wind at 3,000 feet indicates that the variation at that height is the same as at the ground. This, however, will be discussed later.

The average magnitude of the variation for different winds is as follows :—

TABLE III.—AVERAGE VARIATION FOR DIFFERENT WINDS.

Heights in Feet	W.	E.	N.	S.	Mean.
3,000	4·0	4·3	3·2	6·0	4·4
2,000	3·5	2·6	4·2	4·3	3·7
1,000	4·5	7·2	6·5	4·4	5·7

4. Of the 1,736 ascents already considered, 1,101 have reached 6,000 feet; these are distributed as follows :—

TABLE IV.—DISTRIBUTION OF WINDS AT 6,000 FEET.

Index Number.	1.	2.	3.	4.	5.	6.	Total.
W....	101	56	43	53	66	86	405
E.	48	35	34	37	88	55	247
N.	34	21	20	20	44	47	186
S.	52	32	40	39	51	49	263
Total... ...	235	144	137	149	199	237	1,101

The results in this case up to 3,000 feet agree fairly well with those already found, but the individual curves are much more irregular. At 4,000 feet and 6,000 feet the curve for all winds shows practically no variation at all. A West wind shows a minimum between 9h. and 12h.; a South wind shows a maximum between these hours and a minimum later; an East wind shows the same variation as a surface wind with a maximum about mid-day; while there is nothing characteristic about a North wind except that it appears to be a maximum by night.

Differences between maximum and minimum readings at different heights for different winds are given in the table below. These differences are greater than those given in Table III. above because of the clearer nature of the weather during which the 6,000 feet ascents were made.

TABLE V.—DIFFERENCES BETWEEN MAXIMUM AND MINIMUM READINGS.

Heights in Feet.	W.	E.	N.	S.	Mean.
6,000	5·0	4·7	5·8	7·0	5·6
4,000	5·4	6·8	6·5	7·0	6·4
3,000	6·0	3·4	5·1	7·5	5·6
2,000	6·5	4·0	5·1	7·0	5·7
1,000	7·6	9·3	9·8	10·7	9·3

5. On 104 days, 6 ascents per day were followed to a minimum height of 3,000 feet. The results for these days revealed the fact that the wind decreased from midnight onwards except in the case of Easterly winds. This is doubtless due to the fact that in selecting days of continuous observation one has in many cases to select days on which the wind velocity is likely to be affected by changes of barometric pressure. Thus it is likely that a South or West wind which can be measured six times daily up to moderate heights is decreasing in velocity : the observation of an increasing Southerly or Westerly wind will usually be terminated by clouds or rain. The fact that Easterly winds show the expected variations is because the Easterly winds measured by Pilot Balloons in N.E. France were usually due to steady anticyclonic conditions.

Accordingly it has been necessary to study the synoptic charts for these 104 days and to reject all days on which the diurnal change was likely to be masked by rapid variation of pressure. This leaves 55 days of continuous observation up to 3,000 feet, 17 of Westerly winds, 20 of Easterly, 8 of Southerly and 10 of Northerly winds.

The average velocities in ft./s. for various wind directions, times and heights are given in Table VI.

TABLE VI.—AVERAGE VELOCITIES IN FT/S FOR DIFFERENT WIND DIRECTIONS, TIMES AND HEIGHTS.

Heights in Ft.	W.						E.						N.						S.						Mean.					
	1.	2.	3.	4.	5.	6.	1.	2.	3.	4.	5.	6.	1.	2.	3.	4.	5.	6.	1.	2.	3.	4.	5.	6.	1.	2.	3.	4.	5.	6.
*6,000 ...	22·8	28·0	20·8	—	15·7	15·0	9·3	13·5	—	13·5	11·3	12·8	20·1	20·7	21·3	—	17·0	16·0	5·8	11·8	18·7	—	26·5	25·3	14·8	19·0	—	—	15·8	15·4
*4,000 ...	30·0	28·5	26·7	—	26·2	27·2	15·0	16·9	20·0	18·0	15·7	15.3	17·7	17·7	19·5	—	17.0	19·3	17·7	19·0	22·8	25·0	27·0	26·2	20·5	21·0	22·4	—	20·8	22·6
3,000 ..	27·7	27·0	23·7	23·5	24·3	29·0	20·9	20·7	22·0	18·2	17·0	19·3	19·0	19·5	20·7	19·7	18·8	21·5	21·0	22·7	23·0	22·3	26·7	25·8	22·7	22·7	22·4	20·7	21·0	23·6
2,000 ...	29·2	26·3	23·5	22·3	26·2	26·3	24·2	22·0	23·0	19·2	16·3	22·7	20·9	23·0	19·3	18·3	22·0	22·0	23·2	25·0	22·5	22·2	23·2	23·1	25·0	23·9	22·0	20·4	21·0	23·4
1,000 ...	31·3	26·2	21·0	20·5	25·7	22·5	30·2	23·7	18·3	13·8	14·5	25·7	25·2	23·7	17·0	16·3	20·7	25·0	23·0	22·5	21·3	20·8	22·0	20·7	28·6	24·3	19·3	17·3	20·2	23·9

* The number of days on which the means for these heights are based is Westerly 15, Easterly 18, Southerly 7, Northerly 8.

The figures confirm the results already obtained above; all winds at 1,000 feet show a minimum about noon; and in general this holds for winds at 2,000 feet and 3,000 feet as well. But in the case of the two latter heights there is a tendency for the minimum to occur later, *e.g.*, with an East or a South wind at 3,000 feet the minimum occurs about 17h. The average variation at 1,000 feet is 11·3 ft./s., which is almost exactly the variation found for all winds measured at the top of the Eiffel Tower during the summer months; at 2,000 feet and 3,000 feet the average variations are 4·6 and 2·9 ft./s. respectively.

The number of ascents on which the means for 4,000 and 6,000 feet are based is somewhat small, but the fact is again indicated that winds from different quadrants behave differently. Considering Westerly and Easterly winds of which the examples are most numerous, we see that at 4,000 feet Westerly winds show a maximum about midnight and a minimum during the afternoon, and at 6,000 feet a maximum about 6h. and a minimum about 21h. On the other hand, at 4,000 feet Easterly winds show a maximum about 9h. and then a gradual decrease: and at 6,000 feet practically the same sort of variation.

The diurnal variation of a Westerly wind is therefore not materially different at any height up to 6,000 feet, and the difference in the nature of the variation of West and East winds might be explained on the assumption that convection extends to greater heights in Westerly than in Easterly winds. Also as the atmosphere is most expanded about 16h. and most contracted at 4h. one would expect, in the upper air, an overflow current from the region of maximum expansion to the region of maximum compression. This overflow current would be Westerly by night and Easterly by day and would help to explain the increase of Westerly winds by night and of Easterlies by day.

Diurnal Variation in Direction.

6. It has been noted on Salisbury Plain that with a fairly steady distribution of pressure there is a considerable backing of the wind about 13h. or 14h. up to heights of at least 4,000 feet. It is likely that this backing is associated with the decrease in velocity which generally occurs at that time. The following table shows how far this is true: the backing or veering of the wind between successive observations is expressed in degrees. A positive sign indicates that the wind has veered since the previous observation.

TABLE VII.—VEERING OR BACKING OF WINDS BETWEEN SUCCESSIVE OBSERVATIONS IN DEGREES.

Height in Feet.	W.					E.					N.					S.					Mean.				
	2.	3.	4.	5.	6.	2.	3.	4	5.	6.	2.	3.	4.	5.	6.	2.	3.	4.	5.	6.	2.	3.	4.	5.	6.
4,000 ...	−7	− 6	—	−6	−6	−12	+ 1	+11	+ 6	+12	+32	−12	—	− 1	+12	0	+6	−15	0	+7	−1·3	− 2·6	—	+ 0·2	+ 5·7
3,000 ...	−5	−11	−6	+3	−5	− 7	+ 5	+ 8	−15	+17	+16	− 6	+4	+ 1	− 1	+10	+6	−18	+5	+3	+0·3	− 1·8	−0·8	− 3·7	+ 4·9
2,000 ...	−3	−17	−3	+5	0	+ 9	−18	+ 8	−13	+20	+13	− 4	−3	−11	+26	+ 8	+1	− 9	−2	+3	+5·9	−12·4	+0·1	− 5·5	+12·4
1,000 ...	−6	−19	+1	+3	+3	+ 9	−21	− 6	− 4	+14	+16	−10	+4	− 4	+25	+18	−8	−12	+2	+5	+7·0	−16·5	−2·9	− 1·0	+11·3

Comparison with the table of average velocities shows that any decrease in the wind's velocity is accompanied by a backing and any increase by a veering. Thus at 1,000 feet an East wind backs until about 17h. ; at 3,000 feet it increases and veers up to midday and then backs when the velocity decreases about 17h.

The same result follows if all ascents reaching 3,000 feet are considered. Average results for all winds show a backing about the time of minimum wind velocity.

7. A concise way of representing changes of direction and velocity is by means of a vector diagram. By plotting the components of velocity along the West-East and North-South axes, points are found, the radius vector to which represents the wind velocity in magnitude and direction. Distances between successive points represent in magnitude and direction the wind which is superimposed on one to give the other. Diagrams for four wind directions and for heights of 3,000 feet and 4,000 feet are given. In this diagram the origin is different for the two heights, in order that the figure for one height may not come on the top of that for the other height. The unit of velocity is 100 ft./min., *i.e.*, 10/6 ft./s., and if it is remembered that the velocities represented lie between 900 and 1800 ft./min., it will be clear which point is the appropriate origin for any particular figure.

Summary.

(*a*) Winds up to heights of 3,000 feet have a minimum velocity which occurs about noon.

(*b*) The tendency is for this minimum to occur later, the higher one goes.

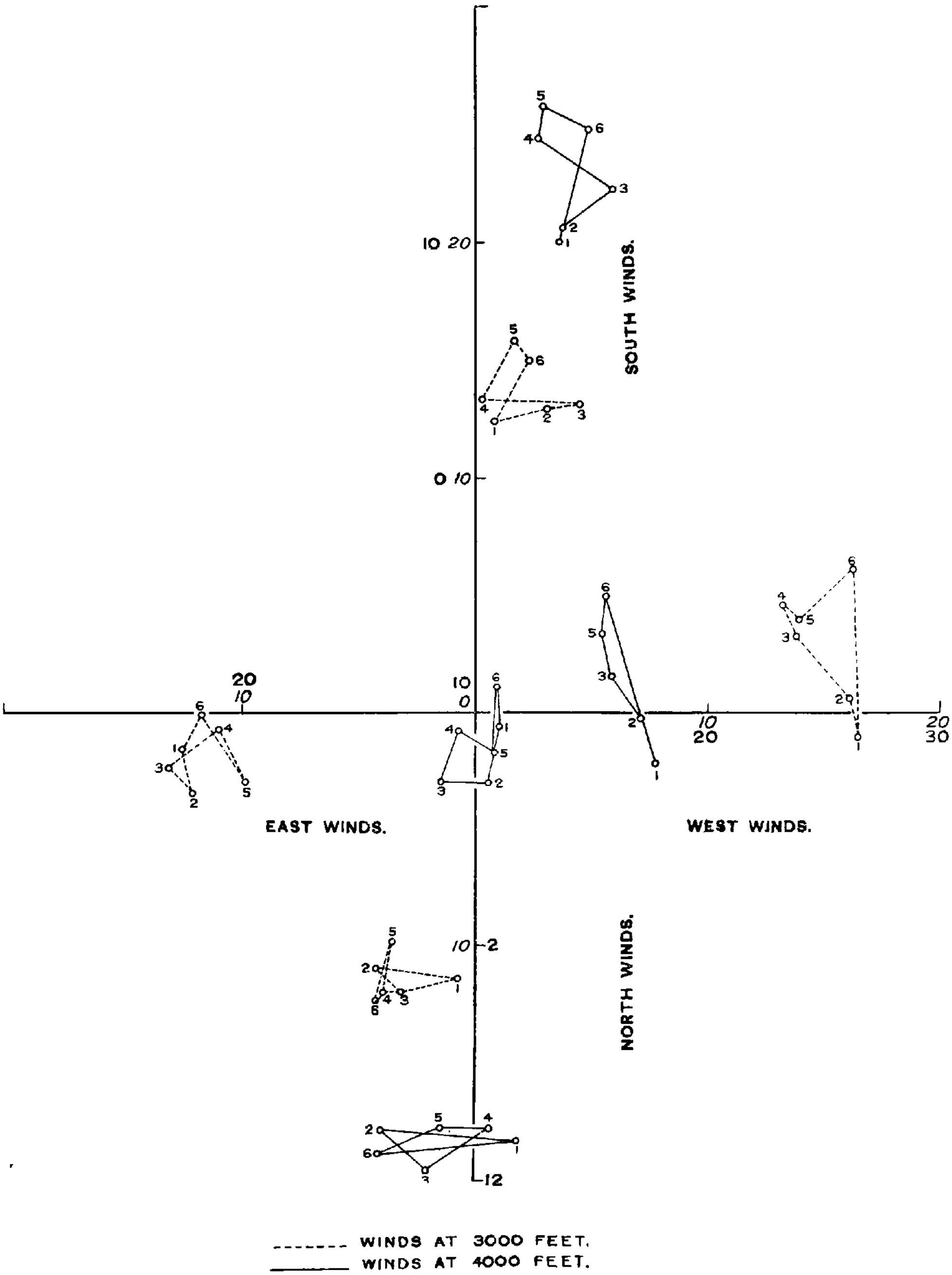
(*c*) At 4,000 feet and 6,000 feet the number of observations is insufficient to indicate exactly what happens; but the behaviour of Easterly and Westerly winds appears to be different. West winds decrease by day and East winds increase. This difference (unless it be purely fortuitous) may be due to (1) Convection and turbulence extending to greater heights with West than with East winds, (2) An overflow current from region of maximum expansion to region of maximum contraction, (3) Diurnal variation of the gradient of temperature to the Northwards.

(*d*) In general a decrease in velocity is accompanied by a backing which may amount to as much as 20°.

A knowledge of the diurnal variation of wind at different heights is important in many ways. A forecaster who has at 18h. to give an estimate of the wind during the night must allow for the possible increase. A long-distance bombing raid may just fail because sufficient account was not taken of this factor. Kite balloons have been lost at night by encountering during their descent an unexpectedly high wind at 2,000 feet. The accuracy of a shoot has been spoiled through neglect of the fact that the wind backs about midday and thereby increases or decreases the head or cross wind along a trajectory. The success of sound-ranging operations at night is due in large measure to the increase of wind velocity at heights of 1,000 and 2,000 feet; the "wind-gradient" is then very favourable and the sound rays are bent downwards to the earth's surface.

Professional Notes No. 15.

VECTOR DIAGRAMS SHOWING DIURNAL VARIATION FOR FOUR WIND DIRECTIONS AT HEIGHTS OF 3,000 AND 4,000 FEET.



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Addendum.

Since the above was written Captain Brunt has drawn the writer's attention to a paper by Mario Tenani* dealing with the same subject.

Tenani discussed 322 pilot balloon ascents made at Vigna di Valle in the summer of 1917—observations made at 1h., 7h., 14h., and 19·22h. (Central European Time). Considering the variations of velocity independent of direction, he found that at the ground (260 metres above M.S.L.) the amplitude of oscillation was about 3 m./s., and maximum occurred about 15h. With increasing height up to 1,000 metres the maximum became steadily later, and at 1,000m. occurred between 18 and 19 hours, and minimum about 9h.

Tenani next considered only those ascents made on days when no large changes of pressure distribution were taking place, retaining only those days when diurnal variation of the barometer was noticeable. The 227 ascents so retained showed the same features as the total of 322 ascents made.

The diurnal variations were next resolved along and perpendicular to the coastline, which runs approximately N. 53° W. It was found that the diurnal variation of the component parallel to the coast was negligible by comparison with that perpendicular to the coast, the latter being of the nature of land and sea breeze blowing from land to sea in the morning, being reversed in the evening and night.

Colonel Gold has also drawn attention to a paper by Van Bemmelen† in which the results of a series of observations by means of pilot balloons in Batavia are utilised to find the diurnal and semi-diurnal oscillation of the air in the free atmosphere; the results are compared with the theoretical values given by the former,‡ and in the lower layers good agreement is found between the observed and theoretical values of the phase and amplitude of the semi-diurnal variation.

If u_2, v_2 represent the semi-diurnal variation of the wind components from West and North respectively, then from Gold's results we find for Lat. 51° and $l=\frac{1}{4}n$ the following values for u_2 and v_2

$$u_2 = 36 \sin(2nt + 2\lambda_2 + 214^\circ)$$
$$v_2 = 36 \sin(2nt + 2\lambda_2 + 119^\circ) \quad \text{(A)}$$

where $2\lambda_2$ is the phase of the semi-diurnal variation of pressure and the amplitude is in cm./sec.

In order to see what agreement exists between the results now obtained and those given by equations (A), the values derived by the method on p. 46 have been treated as follows: The average West component of the westerly winds has been plotted for each

* Atti Reale Accad. Lincei XXIX., p. 272, 1920.
† Proceedings of the K'. Akad. Wet. Amsterdam. Vol. XX. No. 1.
‡ Phil. Mag., January, 1909, pp. 26–49.

hour of observation, and from the resulting curve the diurnal and semi-diurnal terms have been calculated; and similarly for the other wind directions. The results are given below in Table VIII.

TABLE VIII.—PHASES AND AMPLITUDES OF u_2 AND v_2.

Height.	u_2		v_2	
	Phase.	Amplitude.	Phase.	Amplitude.
Ft.	°		°	
3,000	167	16	16	24
2,000	9	15	6	31
1,000	351	9	349	36

The phase of the semi-diurnal pressure variation is approximately 143° (value for Greenwich), and, assuming a diminution of phase of 2° per 1,000 feet, we find from equations (A) that the phase of the West component between 1,000 and 3,000 feet lies between 355° and 351°, and of the North component between 260° and 256°.

The phase of the West component is, therefore, in pretty good agreement with the theoretical values for 1,000 and 2,000 feet; but that of the North component differs by about 90°. It may be remarked, however, that if Southerly winds are neglected and the phase of the North component calculated from Northerly winds only, the observed phases are 330°, 305° and 285°, which agree somewhat better with the theoretical values.

As regards amplitudes, that of u_2 is too small, whilst that of v_2 agrees fairly closely with the theoretical value.

The phase and amplitude of the semi-diurnal variation have also been calculated from the values derived from 55 days of continuous observation. The results are given in Table IX.

TABLE IX.—PHASES AND AMPLITUDES OF u_2 AND v_2.

Height.	u_2		v_2	
	Phase.	Amplitude.	Phase.	Amplitude.
Ft.	°		°	
6,000	357	33	—	—
4,000	3	19	—	—
3,000	329	18	206	8
2,000	349	34	315	8
1,000	354	58	321	20

The agreement in phase is, therefore, very close in the case of the West component, but only very approximate in the case of the North component; also the amplitude of the former agrees fairly well with the theoretical value, but that of the latter is too small.

It must be remembered that the horizontal wind velocities deduced from observations of pilot balloons are incorrect when convection is present, and at the time when convection is most vigorous one would get velocities which are too low. For this reason the agreement between the observed and calculated amplitudes can only be approximate; also, for the same reason, the difference in phase between u_2 and v_2 will be diminished, as has been found.

The diurnal variation of the wind components will be so much affected by convection that no attempt will be made to discuss the results. Van Bemmelen* gives the phases of the diurnal variation of the East component as illustrating the influence of the Espy-Koppen effect, and it may be interesting to compare his values with those now found. The close resemblance between the curve for 1,000 feet and that for Eiffel Tower shows that the effect of convection on the apparent diurnal variation at that height is not very great.

TABLE X.—PHASE OF THE DIURNAL VARIATION OF THE EAST COMPONENT.

Height.	Phase from Van Bemmelen.	Phase found.
6,000	294	305
4,000	12	299
3,000	33	18
2,000	79	55
1,000	84	55

The manner in which the phase changes with height is very similar in the two cases.

* Loc. cit.