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DIURNAL VARIATION OF TEMPERATURE

AS AFFECTED BY

WIND VELOCITY AND CLOUDINESS

A DISCUSSION OF OBSERVATIONS ON THE EIFFEL TOWER

BY

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DIURNAL VARIATION OF TEMPERATURE AS AFFECTED BY WIND VELOCITY AND CLOUDINESS

A Discussion of Observations on the Eiffel Tower.

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Captain J. Durward.

In order to get an idea of the numerical magnitude of the rise or fall of temperature at different levels under different conditions, the temperatures as recorded[1] at Parc St. Maur and on the top of the Eiffel Tower for the five months May–September and for the five years 1905–09 have been extracted and classified as indicated below.

The heights above M.S.L. of the thermometers at the two stations are 50·3 metres and 335·3 metres respectively; Parc St. Maur is situated 11·5 km. to the east-south-east of the centre of Paris.

(*a*) *As regards Wind Velocity.*—The temperatures have been classified according as the mean wind velocity on the Eiffel Tower for the period under consideration lay between the following limits: 0–2 m/s, 2–5 m/s, 5–10 m/s, 10–15 m/s and > 15 m/s. The wind at the higher level is taken as the basis of classification because the diurnal range is smaller and less complicated than that at the surface. Under certain conditions, however, it will be seen that this wind is not a suitable basis of classification for examining the temperature variations at ground level.

(*b*) *As regards Time of Day.*—Day and night have been considered separately—day being regarded as extending from 6h. to 18h. and night from 18h. to 6h., except in May and September, when the mean day wind has been taken as the mean of the 9h., 12h. and 15h. winds.

(*c*) *As regards State of the Sky.*—Two subdivision have been made according as the mean cloud amount was less or greater than 6. Skies less than $\frac{6}{10}$ covered will be referred to as fair, greater than $\frac{6}{10}$ covered as cloudy.

Fair Nights.—The case of the fair night is probably the most interesting and a knowledge of the temperature distribu-

[1] Paris: *Annales du Bureau Central Météorologique*, Part II.

tion with height on such occasions is important from various points of view. When the sky is clear at night and radiation is unimpeded, the layer of air in contact with the ground gets cooled more quickly than the layers immediately above, and having been cooled it tends to remain near the earth's surface. Thus, sooner or later we get an inversion in the lower layers of the atmosphere and the magnitude of this inversion will depend on the wind velocity, for turbulence due to wind is an important agent by which the layers not in immediate contact with the ground are cooled. We should, therefore, expect to find that, with a light wind, the fall of temperature on the Eiffel Tower is much less than it is with a strong wind and the reverse should hold for surface temperatures. The figures in Table I. illustrate this very well as regards the fall of temperature at the higher level; for the lower level the figures are inconclusive because, unfortunately, on fair nights there is no simple relation between the winds at the different levels. It seems as likely to be calm at the surface when the Eiffel Tower wind is 5–10 m/s, as it is when the latter is 0–2 m/s. At the same time, the very large fall at the ground for strong winds is remarkable.

TABLE I.—TEMPERATURES ON FAIR NIGHTS.

Wind on Eiffel Tower m/s.	Eiffel Tower.					Fall from 21 h. to 3 h.	Parc. St. Maur.					Fall from 21 h. to 3 h.	No. of Occasions.
	18 h.	21 h.	24 h.	3 h.	6 h.		18 h.	21 h.	24 h.	3 h.	6 h.		
0–2	18·5	17·2	16·4	15·5	16·3	1·7	18·7	13·8	11·6	10·5	10·4	3·3	12
2–5	18·2	16·7	15·4	14·6	14·7	2·1	19·2	14·8	12·8	11·4	12·3	3·4	85
5–10	17·7	16·0	14·5	13·6	13·4	2·4	19·1	15·0	12·9	11·4	12·1	3·6	222
10–15	17·4	15·4	13·8	12·3	11·7	3·1	18·1	15·0	12·9	11·4	11·7	3·6	120
> 15	16·3	14·0	12·3	10·9	10·4	3·1	17·8	13·7	11·6	10·0	10·7	3·7	16

Figure I. shows the temperature variation at the top of the Eiffel Tower for the different ranges of wind velocity. The slope of each curve between 21h. and 3h. increases until a wind of 10–15 m/s is reached. The curve representing the average temperatures for a wind greater than 15 m/s is almost exactly parallel to that representing the temperatures for a wind of 10–15 m/s, so that nothing is gained by further subdivision. It is also to be noted that in absolute magnitude the average temperatures are lower the stronger the wind, and that the time of minimum temperature is probably earlier for a light wind than for a strong wind, though the shape of the curves is doubtful between 3h. and 6h. These effects are not due to seasonal variation, as the winds in each class are nearly uniformly distributed throughout the five months considered.

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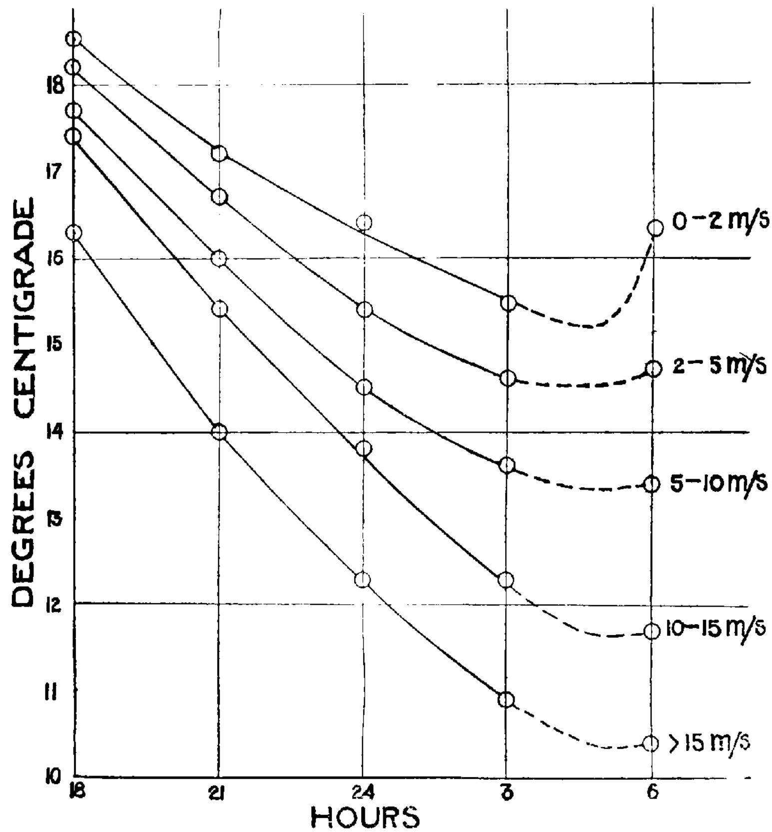

FIG. 1.—NOCTURNAL VARIATION OF TEMPERATURE AT THE SUMMIT OF THE EIFFEL TOWER WITH WINDS OF VARIOUS STRENGTHS. FAIR NIGHTS.

Curves showing the temperatures at Parc St. Maur and Eiffel Tower for a wind velocity of 5–10 m/s are given in Fig. 2. It will be seen that these curves intersect at a point whose abscissa represents 19h. 30m., so that at this time equality is established between the temperatures at the two levels. In general, this equality is established before 21h., the approximate average times being as follows :—

Wind Velocity on the Eiffel Tower.	Time at which the temperatures at the two levels are equal.
0–2 m/s	18h. 15m.
2–5 m/s	18h. 40m.
5–10 m/s	19h. 30m.
10–15 m/s	19h. 30m.
> 15 m/s	20h. 30m.

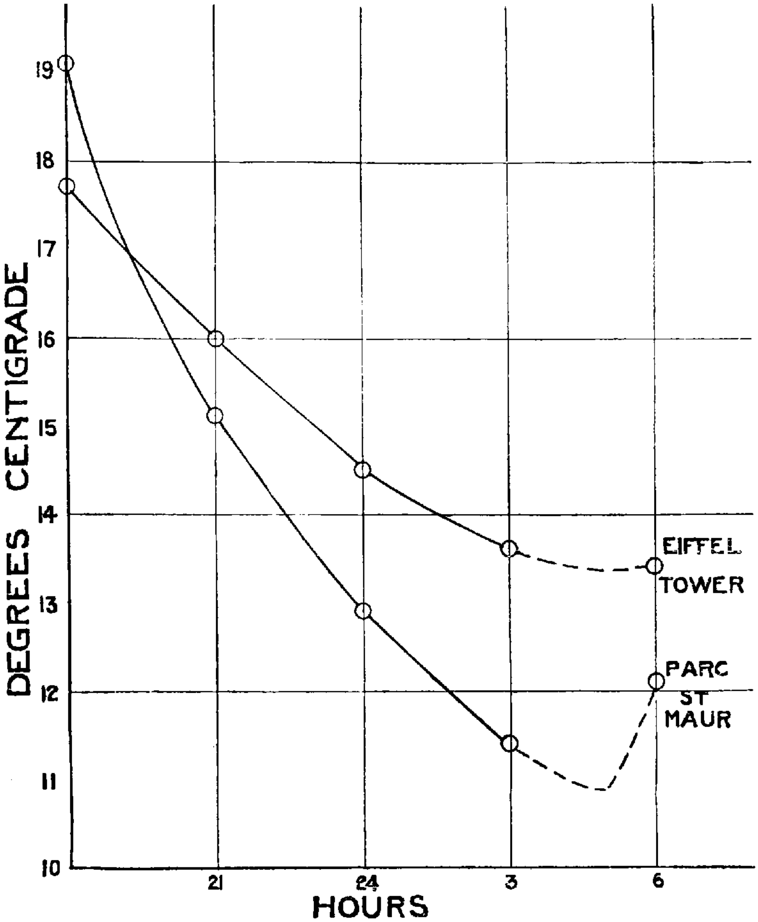

FIG. 2.—NOCTURNAL VARIATION OF TEMPERATURE AT PARC ST. MAUR AND AT THE SUMMIT OF THE EIFFEL TOWER. WIND AT THE SUMMIT BETWEEN 5 AND 10 METRES PER SECOND. FAIR NIGHTS.

Cloudy Nights.—The average temperatures from 18h. onwards are given in Table II.

TABLE II.—TEMPERATURES ON CLOUDY NIGHTS.

Wind on Eiffel Tower m/s.	Eiffel Tower.					Fall from 21 h. to 3 h.	Parc St. Maur.					Fall from 21 h. to 3 h.	No. of Occasions.
	18 h.	21 h.	24 h.	3 h.	6 h.		18 h.	21 h	24 h.	3 h.	6 h.		
0–2	16·0	14·9	14·2	13·3	12·6	1·6	16·8	14·0	12·8	12·0	13·2	2·0	6
2–5	14·8	13·9	12·9	12·3	11·9	1·6	16·3	13·9	12·7	12·0	12·3	1·9	42
5–10	15·7	14·3	13·4	12·5	12·0	1·8	17·5	14·9	13·6	12·9	13·2	2·0	127
10–15	15·8	14·6	13·6	12·4	11·9	2·2	17·8	15·4	14·8	13·4	13·7	2·0	90
> 15	12·9	11·8	10·7	10·2	10·1	1·6	14·8	13·2	12·2	11·5	11·8	1·7	18

The fall of temperature during the night hours at the surface is practically independent of the wind velocity on the Eiffel Tower, though the least fall does occur with the strongest wind. On the Eiffel Tower the fall increases with the wind velocity up to 15 m/s. For winds below 5 m/s a slight inversion occurs, but for winds greater than 5 m/s, the surface temperature does not fall below that at the top of the tower.

If we take wind velocities of 2–5 m/s on the Eiffel Tower, corresponding with the case of little or no turbulence, and consider the average falls of temperature from 21 h. to 3 h. on fair and cloudy nights respectively the following ratios are obtained :—

$$\left.\frac{\text{Fall on a cloudy night}}{\text{Fall on a fair night}}\right\} = \cdot 76 \text{ (Eiffel Tower).}$$

$$\text{,,} \qquad = \cdot 60 \text{ (Parc St. Maur).}$$

These ratios give some idea of the warming effect of clouds at night, due to the combined effect of the radiation emitted by the clouds and the terrestrial radiation reflected by them.

If we compare the fair and the cloudy nights when the wind velocity on the Eiffel Tower did not exceed 5 m/s, that is, when the bottom layer of the atmosphere was not much disturbed, and solve graphically the cooling equation[1] :

$$\frac{dT}{dt} = -\alpha(T - T_0)$$

where T is the temperature of the air, and T_0 is the temperature to which the air is tending asymptotically, we find the following values of T_0 and α, the unit of time being the hour.

	Parc St. Maur.	Eiffel Tower.
Fair Night - -	$T_0 = 10 \cdot 7,\ \alpha = \cdot 24.$	$T_0 = 12 \cdot 7,\ \alpha = \cdot 125.$
Cloudy night -	$T_0 = 11 \cdot 5,\ \alpha = \cdot 25.$	$T_0 = 11 \cdot 9,\ \alpha = \cdot 20.$

The values of α obtained by Gold for clear nights during the summer months, from a consideration of the Potsdam observations are ·108 for 40 metres and ·170 for 2 metres. The value obtained above for Parc St. Maur (·24) is considerably higher than that for Potsdam (·170); on cloudy nights the values of α at Parc St. Maur and the Eiffel Tower are approximately equal.

Fair Days.—The average temperatures from 6h. onwards are given in Table III.

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[1] Gold, *Q.J. Roy. Met. Soc.* Vol. xxxix., p. 255.

TABLE III.—TEMPERATURES ON FAIR DAYS.

Wind on Eiffel Tower m/s.	Eiffel Tower.					Rise from 9 h. to 15 h.	Parc St. Maur.					Rise from 9 h. to 15 h.	No. of Occasions.
	6 h.	9 h.	12 h.	15 h.	18 h.		6 h.	9 h.	12 h.	15 h.	18 h.		
0–2	13·7	16·7	18·2	20·0	19·3	3·3	10·9	17·6	21·4	21·9	19·2	4·3	14
2–5	14·8	16·5	19·2	21·1	20·6	4·6	12·0	19·1	22·7	23·5	20·8	4·4	121
5–10	13·8	15·3	18·2	19·7	18·9	4·4	12·5	18·7	21·9	22·6	20·4	3·9	165
10–15	9·4	10·7	13·9	15·3	14·8	4·6	9·4	14·8	18·0	18·6	16·2	3·8	31
> 15	5·3	6·9	10·8	12·0	11·3	5·1	4·6	10·1	14·4	15·2	12·0	5·1	1

It will be seen that, for very light winds, the rise of temperature from 9h. to 15h. on the Eiffel Tower is less than at the surface. For the three groups of wind velocities 2–5, 5–10, 10–15 m/s, the rise of temperature at the top of the tower is constant and somewhat greater than the rise at the surface. This is rather surprising, for if the rise of temperature is transmitted upwards from the surface by turbulence and convection, one would expect the rise to be greater at the surface. This point, however, will be discussed later.

The average differences of temperature between Parc St. Maur and the top of the Eiffel Tower at 9h., 12h. and 15h. for winds between 5 and 15 m/s are 3·4° C., 3·8° C., 2·9° C. respectively. With dry adiabatic lapse rate the difference in temperature corresponding with a difference in level of 285 metres would be about 2·9° C. If, then, the observations of temperature at the two levels are comparable, the lapse rate during the day is greater than the adiabatic until 15h. is reached, when it becomes the same. Diurnal instability therefore ceases on the average about 15h.

The rise of temperature at surface level from 9h. to 15h. on a fair day for winds between 5 and 15 m/s approximates very closely to the fall from 21h. to 3h. on a fair night for the same wind velocities.

Cloudy Days.—The average temperatures from 6h. onwards are given in Table IV.

TABLE IV.—TEMPERATURES ON CLOUDY DAYS.

Wind on Eiffel Tower m/s.	Eiffel Tower.					Rise from 9 h to 15 h.	Parc St. Maur.					Rise from 9 h. to 15 h.	No. of Occasions.
	6 h.	9 h.	12 h.	15 h.	18 h.		6 h.	9 h.	12 h.	15 h.	18 h.		
0–2	12·6	15·1	16·5	17·1	16·1	2·0	12·5	16·6	19·5	20·1	17·5	3·5	9
2–5	11·7	13·0	15·0	16·0	15·3	3·0	12·3	15·6	18·0	18·8	16·9	3·2	100
5–10	11·7	12·7	14·5	15·5	15·0	2·8	12·9	16·0	17·9	18·4	17·0	2·4	232
10–15	11·0	12·3	13·8	14·6	13·8	2·3	12·4	15·4	17·3	17·6	16·1	2·2	79
> 15	10·7	11·6	13·0	13·2	12·1	1·6	12·2	14·2	15·4	15·9	14·4	1·7	11

As in the case of fair days, the rise of temperature from 9h. to 15h. is considerably less on the Eiffel Tower than at the surface for very light winds : for other wind velocities the rise at both heights decreases as the wind increases, and for winds between 5 and 15 m/s the rise at the higher level is slightly greater than that at the surface. If we take the mean lapse rate between 9h. and 15h. to be the mean of the lapse rates at 9h., 12h. and 15h., the following table shows the relation between lapse rate and rise of temperature.

TABLE V.—THE RELATION BETWEEN THE LAPSE RATE AND THE RISE OF TEMPERATURE.

Wind Velocity.	Lapse Rate per 100 m.	Rise of Temperature. Fair Days 9–15 h.		Lapse Rate per 100 m.	Rise of Temperature. Cloudy Days 9–15 h.	
		Surface.	Eiffel Tower.		Surface.	Eiffel Tower.
m/s.	°C.	°C.	°C.	°C.	°C.	°C.
0–2	0·70	4·3	3·3	0·88	3·5	2·0
2–5	0·98	4·4	4·6	0·98	3·2	3·0
5–10	1·16	3·9	4·4	1·12	2·4	2·8
10–15	1·33	3·8	4·6	1·12	2·2	2·3
> 15	1·16	5·1	5·1	0·91	1·7	1·6

In most cases it appears that the rise in temperature at the higher level is greater than the rise at the surface when the lapse rate exceeds the adiabatic for dry air. It may be, however, that the temperature readings are not strictly comparable; that the readings on the Eiffel Tower are too high during the day due to the artificially heated atmosphere over Paris, so that the super-adiabatic lapse rate found above does not really exist.

The mean differences of temperature at the two levels on cloudy days at 9h., 12h. and 15h. for wind velocities between 5 and 15 m/s are 3·0°, 3·3° and 2·9° C. respectively. These values are not much different from those found for fair days, the reason probably being that on a large number of days regarded as cloudy, the sky was almost covered with convection clouds such as ordinarily develop on a summer's day.

The rise of temperature from 9h. to 15h. on cloudy days is considerably less at both heights than on fair days. For wind velocities between 2 and 15 m/s the ratio—

$$\frac{\text{Rise of Temperature on Cloudy Days}}{\text{Rise of Temperature on Fair Days}} = \cdot 58 \text{ (Eiffel Tower).}$$

$$\text{,,} \qquad = \cdot 64 \text{ (Parc St. Maur).}$$

If the difference in the rises of temperature be due mainly to the difference in cloud amount, it would appear from the above that clouds reflect about 40 per cent. of the sun's insolation.

Values of the Coefficient of Eddy Diffusivity.—Approximate values of the eddy diffusivity k may be got for fair and cloudy weather and for different wind velocities by combining the figures for fair nights and fair days, cloudy nights and cloudy days, and comparing the diurnal ranges of temperature at the two levels in accordance with Taylor's formula.[1]

$$b = \frac{\log_e R_1 - \log_e R_2}{h}.$$

In this formula $b^2 = \frac{\pi}{Tk}$,

R_1 and R_2 are the diurnal ranges of temperature, and h is the difference in level.

If this be done, the following approximate values of k are found :—

Wind Velocity.	Fair Weather.	Cloudy Weather.
2–5 m/s.	$7 \cdot 7 \times 10^4$	$12 \cdot 8 \times 10^4$
10–15 m/s.	$15 \cdot 7 \times 10^4$	$21 \cdot 0 \times 10^4$

These values are to be compared with those found by Taylor[1] and Akerblom.[2] The former found from a consideration of the daily range of temperature at the top and bottom of the Eiffel Tower, that the approximate value of k for the summer months was 15×10^4; and the latter from a consideration of the wind at the top and bottom of the tower found that the mean value of $k\rho$ for the summer months was 115 C.G.S. units, and taking ρ (density) $= \cdot 00125$ this makes the mean value of k, $9 \cdot 2 \times 10$.[4]

It is also to be noted that the average value of k for strong winds is double that for light winds; this was found by Taylor[3] in deriving values of k from the pilot balloon observations of Dobson[4] at Upavon in 1913.

[1] *Phenomena connected with Turbulence in the Lower Atmosphere,* London: Proc. R. Soc. 94 (Ser. A.) 1918.

[2] Akerblom, Filip, *Recherches sur les Courants les plus bas de l'Atmosphère au dessus de Paris.* Upsala, Soc. Scient. Acta. 2 (ser. iv), 1908 No. 2.

[3] *Eddy Motion in the Atmosphere.* Phil. Trans. R. Soc. 215 (Ser. A.), 1915.

[4] *Q.J. Roy. Met. Soc.* Vol. xl., p. 123, 1914.

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