SOIL TEMPERATURES IN RELATION TO OTHER FACTORS CONTROLLING THE DISPOSAL OF SOLAR RADIATION AT THE EARTH'S SURFACE.

By L. A. RAMDAS, *Agricultural Meteorologist and* R. K. DRAVID, *Research Student, Meteorological Office, Poona.*

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I. INTRODUCTION.

The temperatures attained by the surface layers of the soil depend upon a number of factors which control the disposal of solar radiation at the earth's surface. These factors are enumerated below :—

(i) The duration and intensity of the total radiation from the sun and the sun-lit sky received by unit area of a horizontal surface.

(ii) The colour of the soil surface which determines what fraction of the incident energy is absorbed by the surface.

(iii) The thermal conductivity of the soil which depends upon the chemical composition, the water content and the pore space (or apparent density).

(iv) The heat transfer from the heated soil surface by convective processes in the air layers near the ground.

(v) The radiative exchange in the long wavelength (or infra-red) region of the spectrum between the soil surface and the atmosphere.

To determine the heat balance at the earth's surface it is necessary to make systematic measurements of each of the above factors. The Central Agricultural Meteorological Observatory at Poona, which was founded in 1933 under the auspices of the Imperial Council of Agricultural Research, has been provided with the equipment necessary for a complete scheme of observations. The special investigations on radiation and convective heat transfer have been conducted with the assistance of Mr. P. K. Raman and those on soil temperatures with the help of the junior author of this paper.

In the present note we shall briefly mention some of the interesting results on the thermal balance at the surface of the ground obtained by Mr. Raman and then summarise the main results of the soil temperature experiments conducted during the last two years. We shall confine our attention to the clear season at Poona (November–May) when the climate is of the simple continental type, with clear skies and light winds. Mr. M. S. Katti [1,2,3,4,5] working at the observatory at Poona has shown that, during this season, the soil surface loses moisture by evaporation during the day time but re-absorbs moisture during the night from the air layers near the ground so that the net loss by evaporation is negligible. We may therefore leave out phenomena like precipitation and evaporation from the present discussion.

2. Thermal Balance.

(i) The total radiation from the sun and sun-lit sky received by unit area of a horizontal surface during each day can be computed from the records of a self-registering Kipp and Zonen solarigraph. The energy so received varies roughly from 900 gramme calories in summer to 200 gramme calories during the monsoon season.

(ii) Of the above radiation only 86% is absorbed by the black cotton soil, 40% by alluvial soil from the Indo-gangetic plains, 60% by a grass covered soil, and as much as 94% by a surface covered with charcoal powder. At Poona during the summer on clear afternoons, the surface temperature in the black cotton soil often goes up to 75° C.

(iii) The heat carried away by convection during the course of a single day from the surface of Poona soil has been determined experimentally by a new method by Raman[6]. He estimates that the convective heat loss varies between 175 and 340 gramme calories during the clear season.

(iv) The ground surface radiates more or less like a black body in the far infra-red region of the spectrum in which bodies at ordinary temperatures radiate. The energy so radiated is merely a function of the surface temperature ; from the record of a thermograph recording the surface temperature of the soil one can easily estimate the heat radiated to the atmosphere by the ground surface during the course of a single day.

If the atmosphere were quite dry all the energy radiated would be lost to space ; fortunately, owing to the presence of water vapour, an appreciable portion of the heat radiation is absorbed and re-radiated by the different layers of the atmosphere. The total heat radiation received by unit area of a horizontal surface from the night sky has been measured during the last few years at Poona. A discussion of these data will be found in a series of papers published recently[7,8,9,10].

(v) We are left now with (i) the thermal current flowing downwards into the soil during the day hours when the soil surface is warmer than the layers below, and (ii) the thermal current flowing upwards towards the soil surface at night soon after the latter becomes cooler than the soil layers below as a result of radiative cooling. The total amount of heat leaving the surface during the day and returning to the surface from the soil during the night due to conduction may be computed from a knowledge of the variation of the soil temperature with depth and with time during each day.

An account of the gain and loss of thermal energy at the surface of the ground due to the various processes enumerated above is given in the table below (Table 1) for a typical day in March, 1934 at Poona.

TABLE 1.

The Thermal Balance Sheet—March, 1934.

Profit.		Loss.	
Item.	Gramme calories per sq. cm.	Item.	Gramme calories per sq. cm.
Light radiation from the sun and sun-lit sky actually absorbed by the black cotton soil surface.	740	Heat radiated by the soil surface during the day time.	680
Heat radiation from the sky during the day and at night.	654	Heat radiated by the soil surface during the night.	480
Heat conducted to the surface at night from the soil layers below.	222	Heat removed from the soil surface by the atmosphere by convective processes.	210
		Heat conducted from the surface to the lower layers of the soil during the day time.	240
Total Gain ..	1616	Total Loss ..	1610

3. Soil Temperature Experiments.

In a recent note[11] we outlined a simple scheme for conducting experiments on soil temperatures. As mentioned in the previous section the temperatures attained by different layers of a soil, when its surface is exposed to solar radiation and to the other contemporary meteorological phenomena, will depend to a large extent upon the colour and cover of the surface and the chemical and physical composition of the different layers below the surface. For a preliminary and a comparative study of the behaviour of different typical soils with respect to soil temperatures, the variation due to climatic differences from place to place was eliminated by bringing sufficiently large amounts of the selected soils to one place of observation, viz. the observatory at Poona. The experiments were made in distinct stages as follows :—

I. The physical and chemical properties of the soil were kept identical by working with plots of the undisturbed local soil; the plots measured 6½ ft. by 3½ ft. each and similar sets of thermometers were installed at the different depths. The site of the soil temperature plots and their arrangement will be clear from the photograph reproduced here (Fig. 1).

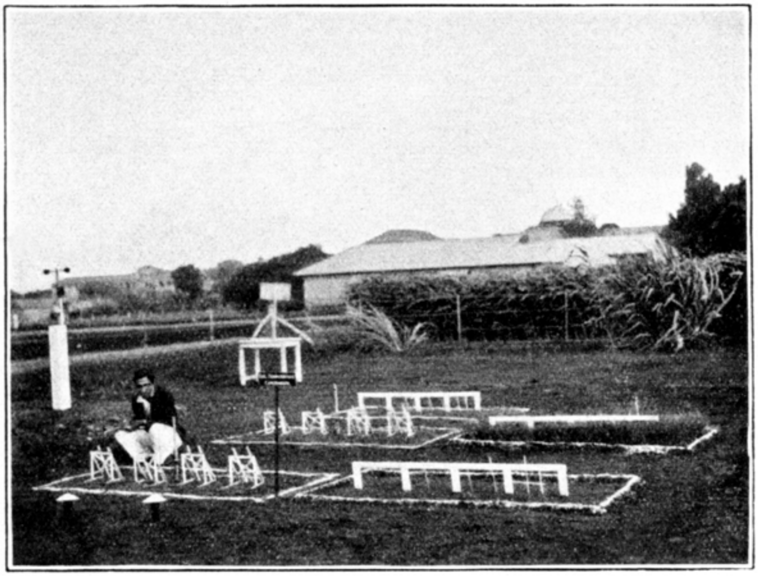

FIG. 1. Soil Temperature Plots.

The type of thermometer used (manufactured by R. Fuess) is shown in Fig. 2. It is sensitive and the bend near the bulb makes it easy to fix the bulb at a definite depth ; it is also convenient to take the temperature readings from the stem. Comparative observations were taken to verify that the temperatures at similar depths were similar. One of the plots was kept as a permanent ' control ' plot and each of the remaining plots covered with thin layers of the different typical soils and of substances like chalk and charcoal powder. The simultaneous observations were then continued in order to record the influence of the ' cover ' on the temperatures of the soil layers below.

Along with these experiments it was also arranged to measure the effects of wetting just the surface of the soil and of growing a short crop on the soil temperatures.

II. Having ascertained the effect of the ' cover ', the effect of varying both the physical and chemical composition of the soil was studied by using blocks of different soils of sufficient depth. The soil blocks were kept with their natural surfaces exposed in the first part of the experiment and, after comparative observations had proceeded for a sufficiently long time, all except the local ' control ' plot were covered with a thin layer of the local black cotton soil so as to eliminate the influence of the surface colour and retain only the variations due to the interior of the blocks of different soils.

Although the several series of comparative observations have been recorded at several fixed hours daily we shall take up only the data recorded

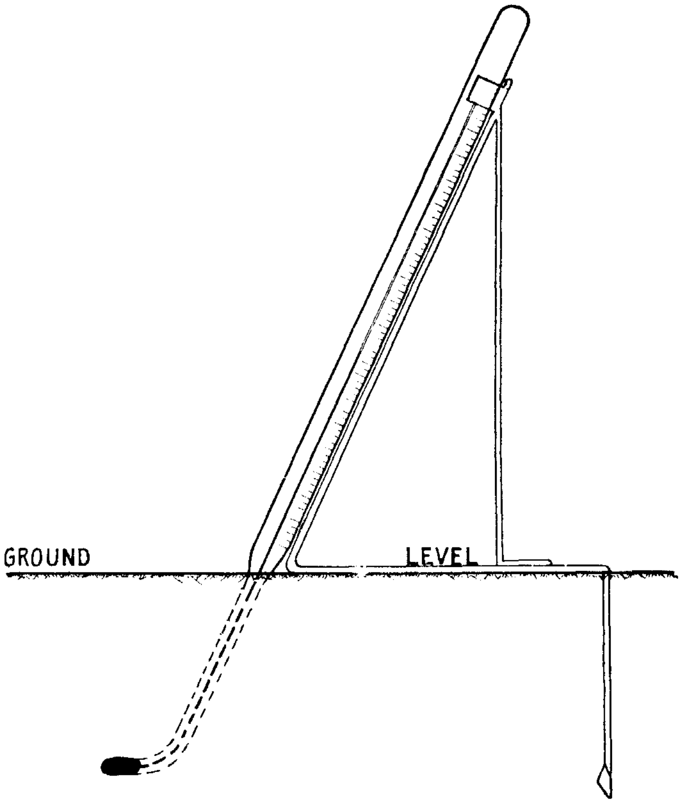

FIG. 2. Fuess Soil Thermometer.

at 6 A.M. and 2 P.M. which represent the extreme conditions of the day and select the more interesting cases for discussion in the present paper.

I. *Experiments on the effect of soil cover.*

(*a*) The effect of covering the local black cotton soil with very thin layers of the following substances was studied.

1.	Chalk or boric powder ..	(white)
2.	Trivandrum sea sand ..	(white)
3.	Soil from Sakrand in Sind ..	(ash coloured)
4.	Soil from Lyallpur	(light brown)
5.	Soil from Pusa	(ash coloured)
6.	Soil from Mekran	(Yellowish brown)
7.	Soil from Bangalore	(red)
8.	Soil from Sholapur	(black)
9.	Charcoal powder	(black)

TABLE 2.

Mean soil temperatures at different depths during the week 30th April to 6th May, 1935.

Depth in centimetres.	Morning 0600 Hours. Soil Temperatures °C.					Afternoon 1400 Hours. Soil Temperatures °C.				
	Control.	Boric Powder.	Pusa soil.	Lyallpur soil.	Sholapur soil.	Control.	Boric Powder.	Pusa soil.	Lyallpur soil.	Sholapur soil.
0	19·3	19·1	19·2	19·7	20·3	62·5	48·3	58·0	58·6	64·6
2	24·6	23·3	25·1	23·8	25·4	49·9	41·3	47·3	48·6	50·4
5	26·8	26·1	26·8	26·9	27·9	45·0	38·2	42·9	43·2	45·3
10	31·0	29·5	30·8	30·7	31·6	37·7	34·5	36·7	36·9	38·1
20	33·3	31·4	33·0	32·4	33·4	33·0	31·2	32·6	32·6	33·2

TABLE 3.

Mean soil temperatures at different depths during the week 24th to 28th January, 1935.

Depth in centimetres.	Morning 0600 Hours. Soil Temperatures °C.					Afternoon 1400 Hours. Soil Temperatures °C.				
	Control.	Trivandrum white sand.	Mekran soil.	Sakrand soil.	Bangalore soil.	Control.	Trivandrum white sand.	Mekran soil.	Sakrand soil.	Bangalore soil.
0	13·6	14·2	13·6	13·2	13·7	50·8	39·4	45·6	45·7	47·3
2	17·4	16·4	16·7	16·7	17·0	41·0	35·2	38·8	38·4	39·2
5	19·9	19·2	19·5	19·8	19·8	34·5	29·5	32·4	32·2	32·9
10	22·9	21·8	22·0	22·2	22·3	27·0	24·7	26·0	25·9	26·0
15	24·3	23·3	23·5	23·4	23·6	24·7	23·4	23·8	23·8	24·0
20	24·5	23·8	24·1	23·9	24·1	24·0	23·3	23·6	23·7	23·8

Table 2 gives the mean soil temperatures at 0, 2, 5, 10, 15, and 20 cm. depths for the week beginning with the 30th April, 1935 on the morning of which date covers* of boric powder, Pusa soil, Lyallpur soil and Sholapur soil were applied to the respective plots. The mean weekly temperatures are given both for 6 A.M. and 2 P.M.

During the weeks prior to 30th April, when the soil plots were all similar, the temperatures of all the plots agreed at all depths, both in the morning as well as in the afternoon. After the application of the different covers, however, the temperatures begin to deviate from those of the control plot, in proportion to the albedo of the respective substances used. These differences are relatively small in the morning but in the afternoon they show up very conspicuously. Thus the effect of boric powder is *to lower the temperature* at 2 P.M. by 14·2° C, 8·6° C, 6·8° C, 3·2° C and 1·8° C at depths of 0, 2, 5, 10 and 20 cm. respectively. The Sholapur soil which is slightly darker than the Poona soil has, on the other hand, caused a slight rise in temperature of the order of 2·1° C, 0·5° C, 0·3° C, 0·4° C and 0·2° C at depths of 0, 2, 5, 10 and 20 cm. respectively.

Table 3 gives the mean temperatures during the week beginning with the 24th January on the morning of which date covers of Trivandrum sand and soils from Mekran, Sakrand and Bangalore respectively were applied to the experimental plots. The effect of all these substances is to depress the soil temperatures in the afternoon by varying extents. Trivandrum white sand has the maximum cooling effect of 11·4° C, 5·8° C, 5·0° C, 2·3° C, 1·3° C and 0·7° C at depths of 0, 2, 5, 10 15 and 20 cm. respectively. The soils from Mekran and Sakrand also produce a similar but less conspicuous cooling in the afternoon, whereas the red soil from Bangalore has the least cooling effect, i.e. only 3·5° C, 1·8° C, 1·6° C, 1·0° C, 0·7° C and 0·2° C at depths of 0, 2, 5, 10, 15 and 20 cm.

Table 4 gives the mean weekly soil temperatures in two plots *A* and *B*, where *A* is the usual standard control plot. The experiment was begun on 25th December, 1933, and lasted upto 1st February, 1934. The different periods designated 1, 2, 3, 4, 5 and 6 in the table were as follows :—

Week No.	*Dates.*
1	25-12-33 to 31-12-33
2	1-1-34 to 7-1-34
3	8-1-34 to 14-1-34
4	15-1-34 to 21-1-34
5	22-1-34 to 28-1-34
6	29-1-34 to 1-2-34

During the first week when the plots were kept similar the soil temperatures at different depths were also similar both in the morning as well as in the afternoon.

* The covers were just thick enough to hide the surface of the local soil (about 2 mm.).

TABLE 4.

Mean weekly soil temperatures in the morning and afternoon at different depths during the period 25-12-33 to 1-2-34 showing the effect of covering the plot B with a thin layer of chalk powder on the morning of 1-1-34 (beginning of week No. 2) and of removing this cover on 21-1-34 (end of week No. 4).

Morning 6 A.M.

Week No.	1		2		3		4		5		6	
Depth cm.	A	B	A	B	A	B	A	B	A	B	A	B
0	11·0	11·1	14·7	14·3	12·1	10·9	9·6	8·4	11·9	11·6	12·7	12·6
5	17·2	17·1	19·5	18·1	18·9	16·4	17·1	14·7	17·6	17·3	19·2	18·7
10	20·5	20·3	21·7	20·1	21·8	19·3	20·5	17·5	20·8	20·1	22·2	21·9
15	22·6	22·5	23·2	21·7	23·6	21·0	22·4	19·6	22·4	21·9	23·9	23·7
20	23·6	23·4	23·7	22·4	24·3	22·0	23·4	20·6	23·2	22·6	24·5	24·5
30	24·4	24·4	24·3	23·2	24·8	22·9	24·1	21·8	23·7	23·2	25·0	25·0
50	24·9	24·8	24·6	24·2	25·0	24·1	24·5	23·3	24·0	23·4	24·7	24·6

Afternoon 2 P.M.

Week No.	1		2		3		4		5		6	
Depth cm.	A	B	A	B	A	B	A	B	A	B	A	B
0	44·9	44·9	42·1	31·3	50·1	31·9	50·7	36·7	49·6	48·8	46·1	45·2
5	30·1	30·3	28·7	24·0	31·3	24·1	31·1	23·6	31·8	31·3	31·6	32·0
10	24·9	24·9	24·8	21·8	26·1	21·4	24·8	20·1	25·0	24·6	26·6	26·7
15	23·0	22·9	23·3	21·5	24·0	20·9	22·7	19·5	23·0	22·3	24·8	24·8
20	22·8	22·9	23·1	21·9	23·7	21·4	22·5	20·0	22·6	22·0	24·3	24·4
30	24·1	23·9	24·1	23·1	24·7	22·8	23·7	21·6	23·4	22·7	24·8	24·7
50	25·2	25·1	24·8	24·3	25·3	24·3	24·7	23·6	24·2	23·7	25·0	24·9

TABLE 5.

Soil temperatures in two plots A (control) and B (experimental) during the period 3rd to 6th May, 1934, showing the effect of wetting the surface of the plot B on the morning of 3-5-34.

Morning 6 A.M.

Dates.	3-5-34		4-5-34		5-5-34		6-5-34	
Depth cm.	A	B	A	B	A	B	A	B
0	22·8	23·8	21·3	20·2	19·2	18·5	16·6	17·1
0·5	24·0	24·7	22·4	20·6	20·5	19·6	18·5	18·0
2	27·0	27·0	25·2	23·0	24·0	23·0	22·0	21·5
5	29·1	29·4	28·0	25·9	27·3	26·0	25·8	25·2
10	31·6	32·0	30·4	28·7	30·6	29·8	29·6	29·5
15	33·2	33·2	32·7	30·2	32·5	31·3	32·1	31·0
20	33·6	33·8	33·6	32·0	33·4	32·0	33·1	32·1
30	33·8	33·8	33·9	32·9	33·8	32·8	33·6	32·6

Afternoon 2 P.M.

Dates.	3-5-34		4-5-34		5-5-34		6-5-34	
Depth cm.	A	B	A	B	A	B	A	B
0	66·4	55·3	63·3	59·8	62·1	60·0	64·5	63·5
0·5	61·0	46·2	57·8	53·4	56·5	54·1	59·8	57·8
2	50·8	40·1	48·0	42·1	46·4	43·3	49·2	46·5
5	41·6	37·2	39·8	36·1	37·8	37·5	39·8	39·6
10	36·9	33·8	36·0	33·3	35·3	33·2	35·6	33·6
15	34·4	32·4	33·8	31·7	33·5	31·6	33·0	31·5
20	33·3	32·9	33·2	32·0	33·0	32·2	32·4	31·9
30	33·5	33·3	33·6	32·6	33·4	32·5	33·1	32·4

At the beginning of the 2nd week, i.e. on the morning of 1st January, 1934, the plot *B* was covered with a thin layer of chalk. During the second week the temperatures in the plot *B* began falling and by the 3rd week the differences became quite marked in the afternoon, being as much as 18·2° C, 7·2° C, 4·7° C, 3·1° C, 2·3° C, 1·9° C and 1·0° C at depths of 0, 5, 10, 15, 20, 30 and 50 cm. respectively. During the 4th week these differences still persisted. At the end of this week the chalk cover was removed from the plot *B*. The effect of this was to enable the plot *B* rapidly to warm up during the fifth week and ultimately to assume temperatures similar to those in the control plot. From the daily observations during this period it is clear that the effect of a change of cover takes some time to become fully established.

(b) *Effect of wetting just the surface of the soil.*

After the soil temperatures in the two plots *A* (control) and *B* (experimental) had become more or less similar for a number of days the surface of the plot *B* was wetted uniformly with water equivalent to 0·5 ″ of rain. From Table 5 it will be seen that the effect of wetting plot *B* on the morning of the 3rd May has been to depress the afternoon soil temperatures in that plot by

TABLE 6.

Morning and afternoon soil temperatures on 17-11-35 *in three plots at different depths showing the effect of a plant cover.*

Depth in centimetres	Morning 0600 Hours. Soil Temperatures °C. Control. A	Morning 0600 Hours. Soil Temperatures °C. Plot with plant cover.* B	Morning 0600 Hours. Soil Temperatures °C. Bare plot watered to the same extent as the one with plant cover. C	Afternoon 1400 Hours. Soil Temperatures °C. Control. A	Afternoon 1400 Hours. Soil Temperatures °C. Plot with plant cover.* B	Afternoon 1400 Hours. Soil Temperatures °C. Bare plot watered to the same extent as the one with plant cover. C
0	8·4	10·5	9·2	53·4	26·6	39·7
2	16·2	15·0	11·8	37·0	26·5	31·5
5	16·7	16·8	13·7	31·2	25·2	26·9
10	21·0	20·5	18·2	25·5	22·0	21·6
15	21·5	21·9	20·9	23·7	21·6	21·2
20	24·5	22·3	22·5	23·9	21·7	21·8

* 'Aleev' growth 20 cm. high.

11·1° C, 14·8° C, 10·7° C, 4·4° C, 3·1° C, 2·0° C, 0·4° C and 0·2° C at depths of 0, 0·5, 2, 5, 10, 15, 20 and 30 cm. respectively. The recovery from the effect of wetting is perceptible even on the next day but it is only after the 6th May that the temperatures in the two plots become more or less equal.

(c) *Effect of Plant Cover.*

The soil temperatures at 6 A.M. and 2 P.M. on the 17th November, 1935, in the following three plots, are given in Table 6.

(A) Bare and dry control plot.
(B) Plot covered with a crop of ' Aleev ' 20 cm. high.
(C) Bare plot receiving the same amount of water as the ' Aleev ' plot during its growing period.

The morning soil temperatures in plot *B* in the layers near the surface are warmer than in plots *A* or *C*. Immediately below the surface the plot *C* is cooler than both *A* and *B*.

In the afternoon, however, plot *B* is cooler than the control plot *A* by as much as 26·8° C, 10·5° C, 6·0° C, 3·5° C, 2·1° C, and 2·2° C at depths of 0, 2, 5, 10, 15 and 20 cm. respectively. The plot *C* is warmer than plot *B* but cooler than the control plot.

The effect of a covering of vegetation in keeping down the afternoon temperatures in the upper layers of the soil is well illustrated by these data.

II. *Experiments with soil blocks.*

These experiments were started with soils from Trivandrum (sand), Sakrand and Bangalore. Pits 6½ ft. by 3½ ft. and 1 ft. or 30 cm. deep were dug, keeping the bottom of the pits quite horizontal. The vertical sides of the pits were supported with a lining of brick and cemented up. The lining of cement helps also to prevent the seepage of water from the sides during rainy weather. These pits were carefully packed with the soils referred to above, the top surfaces of the different soil blocks so obtained being kept horizontal and at the same level as that of the ground in the neighbourhood. The standard sets of soil thermometers were then installed in these soil blocks and compared with those in the permanent control plot.

The natural surfaces of the respective soil blocks were kept undisturbed during the first part of the experiment. Table 7 gives the mean soil temperatures during the week ending with the 10th May, 1936. The temperatures in the upper layers of the white Trivandrum sand are lower than those in the control both in the morning and in the afternoon. The surface temperature in the Sakrand soil is lower than those in the control but higher than in the Trivandrum sand both in the morning and in the afternoon ; but below 15 cm. the temperatures are slightly warmer than in the other two soils.

From Table 8 it will be seen that when the surface colours were equalised on the morning of the 11th May by covering the Trivandrum sand and the

TABLE 7.

Mean soil temperatures during the week ending 10th May, 1936, in Poona soil (control) and in Trivandrum sand and Sakrand soil, each being exposed with its natural colour undisturbed.

Depth in centimetres.	Morning 0600 Hours. Soil Temperature °C. Control.	Morning Trivandrum sand.	Morning Sakrand soil.	Afternoon 1400 Hours. Soil Temperature °C. Control.	Afternoon Trivandrum sand.	Afternoon Sakrand soil.
0	21·2	18·1	20·3	69·2	58·4	64·3
2	27·6	24·3	24·7	53·3	53·0	55·4
5	28·0	26·7	27·5	48·1	45·7	48·5
10	31·9	29·5	31·5	38·0	39·6	40·1
15	33·6	31·9	..	34·3	35·1	..
20	33·6	33·5	34·7	33·2	33·2	34·1
30	33·6	33·2	34·2	33·5	33·1	34·1

TABLE 8.

Mean soil temperatures during the week ending 17th May, 1936, in Poona soil and in Trivandrum sand and Sakrand soil, the last two soils being covered with a thin layer of Poona soil so as to equalise the colours of the surfaces.

Depth in centimetres.	Morning 0600 Hours. Soil Temperatures °C. Control.	Morning Trivandrum sand.	Morning Sakrand soil.	Afternoon 1400 Hours. Soil Temperatures °C. Control.	Afternoon Trivandrum sand.	Afternoon Sakrand soil.
0	22·5	19·7	22·6	70·0	69·1	67·1
2	28·3	25·8	26·7	53·0	60·9	57·5
5	28·8	28·7	29·4	47·4	51·8	50·8
10	32·8	31·7	32·7	38·2	44·0	42·2
15	34·2	34·2	..	34·7	38·4	..
20	34·0	35·4	36·0	33·6	35·3	35·4
30	34·0	34·5	35·2	33·7	34·2	34·9

Sakrand soil with a thin (2 mm.) layer of Poona soil the temperatures in the sand and Sakrand soil began to increase rapidly and approach those in the control. Sand being a poor conductor of heat, the afternoon temperature just below the surface is higher in it than in either the control or the Sakrand soil ; for the same reason the morning temperature in the upper-most layers of the sand are lower than those in the other two cases in spite of the colours having been equalised.

4. Conclusion.

The experiments outlined above suggest the possibility of controlling soil temperatures by suitable surface treatment.

The junior author of this note is discussing these results in a fuller report under preparation. The exact rôle played by thermal conductivity and the interrelations between the amplitudes and phases of the diurnal waves of temperature at different depths will be fully explained there. Further experiments on the above lines are being continued.

The influence of different cultural treatments on the temperature of the soil below will also be investigated during the next clear season.

Our best thanks are due to the Imperial Council of Agricultural Research which, by inaugurating work in India on the subject of Agricultural Meteorology, has made the present investigations possible.

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