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BY

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INFLUENCE DES CONDITIONS SUPERFICIELLES SUR LA TEMPERATURE DU SOL

SOMMAIRE

L'auteur a mesuré les températures du sol de deux parcs de stationnement dont l'un avait été débarrassé de sa neige en hiver, et a établi par extrapolation des moyennes mensuelles et annuelles des températures superficielles. Il les a comparées aux moyennes mensuelles et annuelles des températures superficielles et des températures de l'air à un terrain herbeux voisin. L'auteur a observé que la différence entre les moyennes mensuelles des températures superficielles et des températures de l'air au-dessus de la neige dépend des pertes par convection. Il a établi la relation qui existe entre la moyenne mensuelle des totaux quotidiens du rayonnement solaire et la différence entre la moyenne mensuelle de la température de l'air et la moyenne des températures superficielles des parcs de stationnement. Il démontre qu'il se produit une modification dans la moyenne annuelle des températures du sol d'un parc de stationnement en raison du changement intervenu dans les conditions physiques superficielles. L'auteur étudie ces données en relation avec la formation sporadique de pergélisol.

INFLUENCE OF SURFACE CONDITIONS ON GROUND TEMPERATURE

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Ground temperatures were measured under two parking lots, one of which was cleared of snow in winter, and monthly and annual average surface temperatures were estimated by extrapolation. The surface temperatures were compared with monthly and annual surface and air temperatures measured at a nearby grassed site. A dependence of the difference between the monthly average surface and air temperatures on snow cover and convective loss was observed. A correlation was found to exist between the monthly average of the daily global solar radiation and the difference between monthly average air temperature and monthly average parking lot surface temperature. It was demonstrated that, because of a change in surface conditions, there was a change in annual average ground temperature beneath a parking lot. The observations are discussed with reference to the formation of sporadic permafrost.

The annual average ground temperature and the dependence of ground temperature on depth and time are of interest to scientists and engineers because of their importance in numerous problems. These characteristics of the thermal regime of the ground are established by the thermal properties of the ground and the exchange of heat and moisture between the atmosphere and the surface. As this exchange couples the ground thermally with the air, it would be expected that annual average air temperature and the amplitude of temperature changes in the air would be related to corresponding temperatures at the ground surface and, therefore, could be used to estimate these temperatures. From a knowledge of the thermal properties of the soil, it would then be possible to predict at a given location the dependence of ground temperature on both depth and time.

The components of the heat and moisture transfer at the surface must be in continuous equilibrium. A difference between the surface temperature and the air temperature at a given height is usually required to establish this balance, the size of the difference depending on such variable factors as the characteristics of the surface, the amount of radiation absorbed, the availability of water for evaporation, and the amount of heat to be dissipated by convection. In winter the ground may be snow covered, and this insulating layer will also contribute to the difference. Therefore, to estimate ground temperatures from meteorological observations, it is necessary to know the dependence of the difference between average air temperatures and corresponding average ground surface temperatures, for given periods of time, on snow cover and size of the components of the exchange process.

Observations were made at Ottawa on ground temperatures under a grassed surface and two nearby parking lots, one snow covered in winter and the other cleared. The temperature of the surface of the parking lots was not measured, but it was possible to estimate monthly average values of this temperature by extrapolation of the temperatures measured beneath the surface. Although the surface temperatures obtained in this way are estimates, these estimates and the measurements made beneath the surface demonstrate the significant influence that surface characteristics can have on the underlying ground thermal regime. It was considered, therefore, that a record and discussion of these observations would be useful as background information for future investigations. The results of the study indicate that it may be possible to estimate, with useful accuracy, the difference between monthly average air and corresponding ground surface temperatures by empirical methods requiring only standard meteorological observations.

FIELD INSTALLATION

In 1957, ground temperature probes were installed at a grassed site in association with a study of the influence of snow cover on heat flow from the ground. In 1960, a parking lot about 30 m from the grassed site was abandoned and a new one was built nearby. Temperature probes were installed at the center of each to determine the change in the annual average ground temperature brought about by the modification in surface conditions. The old parking lot measured approximately 38 by 46 m, and the new one approximately 24 by 46 m.

The probes used for measuring temperature consisted of thermocouples placed in a 2.5-cm^2 groove cut in a 7.5- by 7.5-cm pine pole about 7.6 m long. The thermocouples were brought to the surface of the probe at appropriate locations, the groove was filled with plastic and capped with a piece of 2.5- by 7.5-cm pine. At each thermocouple location a groove was cut circumferentially about the pole, and the thermocouple was wound into it and sealed in place. The probes were then painted with a preservative. Temperatures were measured at 0.43, 1.34, 2.86, 5.00, and 7.74 m below the surface of the old parking lot, at 0.61, 1.52, 3.05, 5.18, and 7.92 m below the surface of the new parking lot, and at 0, 0.10, 0.40, 0.90, 2.13, 3.66, and 6.10 m below the surface at the grassed site.

The observation sites were in Leda clay overlying limestone that comes to the surface about 150 m to the south of the parking lots. A heated building is about 60 m to the south of the installations. During construction of the parking lots, the original surface soil was removed and a 30-cm pad of about 25% of 1.9-cm crushed stone and 75% of sand was placed on the old one and a 30-cm pad of coarse crushed stone overlain by a 5-cm layer of fine crushed stone was placed on the new one. The surface of the old lot was about 1.37 m higher than that of the grassed site, the surface of the new lot was about 0.91 m higher.

OBSERVATIONS

Temperatures were recorded in a storage building between the two parking lots. Daily average temperatures were obtained from the charts for each thermocouple location for the period April 1, 1961, to December 31, 1964, for the parking lots, and April 1, 1961, to March 31, 1964, for the grassed site.

Monthly average temperatures were calculated from the daily average values and were plotted against depth.

The thermal conductivity of the crushed-rock surface material was determined for the dry state with a guarded hot plate apparatus, and was found to be 9.1×10^{-4} cal cm^{-1} s^{-1} °C^{-1} for the old parking lot and 7.8×10^{-4} cal cm^{-1} s^{-1} °C^{-1} for the new. In a study by Pearce and Gold (1959) the thermal conductivity of Leda clay in the same location was found to be 2.35×10^{-3} cal cm^{-1} s^{-1} °C^{-1}. These values for thermal conductivity were used in the following way to estimate the monthly average surface temperature. The monthly average temperature at the interface of the crushed rock and clay was obtained by extrapolation of the measured ground temperatures. It was then assumed that the monthly average temperature gradient through the crushed rock was constant and equal to the gradient in the clay just beneath the rock multiplied by the ratio of the two conductivities. The values of monthly average surface temperature obtained in this way for the 2-year period, April 1, 1961, to March 31, 1963, are shown in Fig. 1. Also shown is the monthly average air

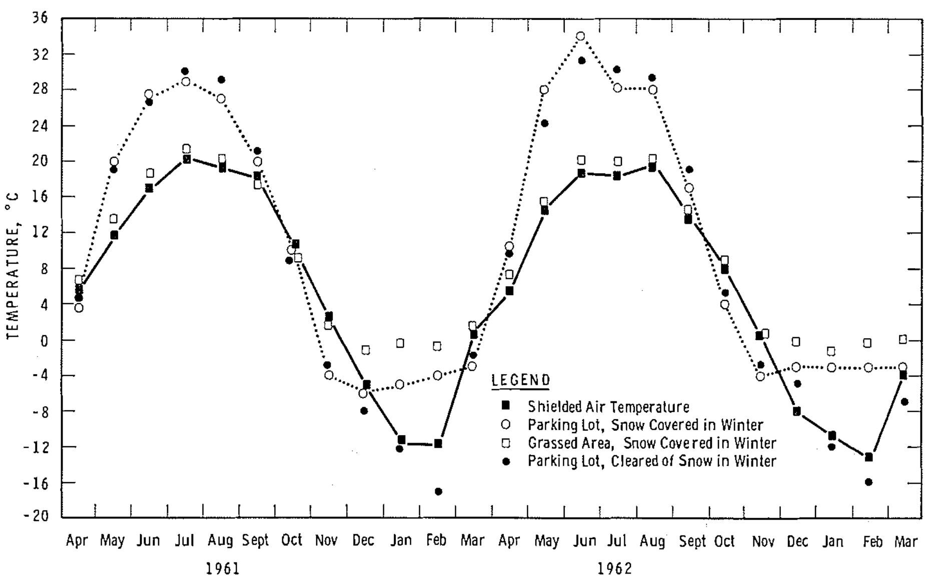

FIG. 1. Monthly average shielded air temperature and monthly average surface temperature for parking lots and grassed area.

temperature 1.2 m above the ground, measured in a Stevenson screen about 46 m northeast of the grassed site.

At the grassed site the monthly average surface temperature in summer was a little warmer than the average air temperature, but was always within 1.7 C degrees of it (Fig. 1). The estimated average surface temperature of the parking lots, on the other hand, was up to 15 C degrees warmer. In winter the estimated average surface temperature of both the snow-covered parking lot and the grassed site were relatively constant; that of the grassed site was about 10 C degrees warmer than the lowest monthly average air temperature, and that of the snow-covered parking lot was about 8 C degrees warmer. The maximum snow depths for the period were about 50 cm in the winter of 1961–62 and 45 cm in that of 1962–63. The lower average surface temperature at the snow-covered parking lot compared with that at the grassed site would be expected because of the lower thermal conductivity of the crushed rock relative to that of the clay immediately beneath the grass.

The estimated monthly average surface temperatures were used to calculate the annual average surface temperature at intervals of 1 month. These temperatures are plotted in Fig. 2. A change in average annual temperature from one

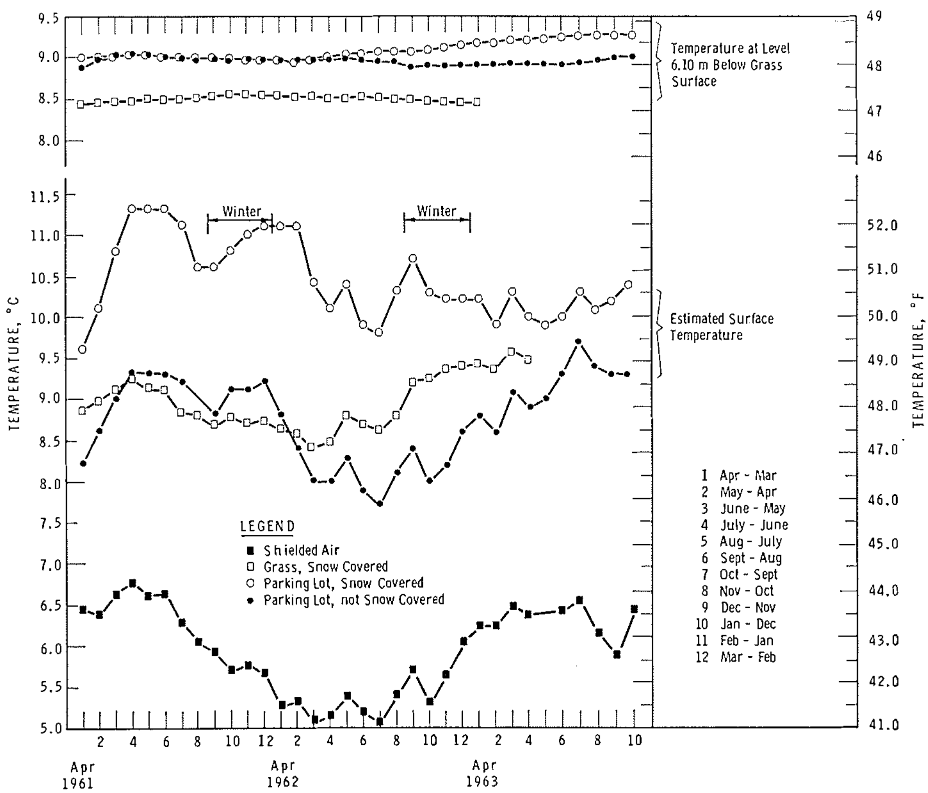

FIG. 2. Change in average annual air temperature with time.

1-year averaging period to the next indicates a difference between the monthly average temperature of the new month that has been added and that of the same month 1 year earlier, and so reflects changes in average weather from 1 year to the next.

It was observed that the annual average temperature at a depth of 7.46 m below the surface of the old parking lot was equal to that 7.00 m below the surface of the new one. These depths correspond to the level 6.10 m below the surface of the grassed site. The annual average temperature at these depths was calculated at intervals of 1 month and is plotted in Fig. 2. Plotted as well is the annual average air temperature.

It may be seen in Fig. 2 that the annual average surface temperature at the grassed site was about equal to the annual average surface temperature at the cleared parking lot, which indicates that the average increase in surface temperature of the parking lot over that of the grassed surface in summer was about equal to the amount by which it was lower in winter. Both annual average surface temperatures were between 2.5 and 3.6 C degrees warmer than the annual average air temperature. Snow cover on the second parking lot caused its average annual surface temperature to be about 1.5 C degrees warmer than the average at the other two sites. Changes in annual average surface temperature with time, particularly those at the parking lot cleared of snow, closely follow corresponding changes in the annual average air temperature, which indicates that the same factor or combination of factors controls both. It was observed that, in general, when the monthly average air temperature increased or decreased, the monthly average surface temperature increased or decreased as well, as is shown in Fig. 3.

The new parking lot was cleared of grass in 1960 and was kept snow free for

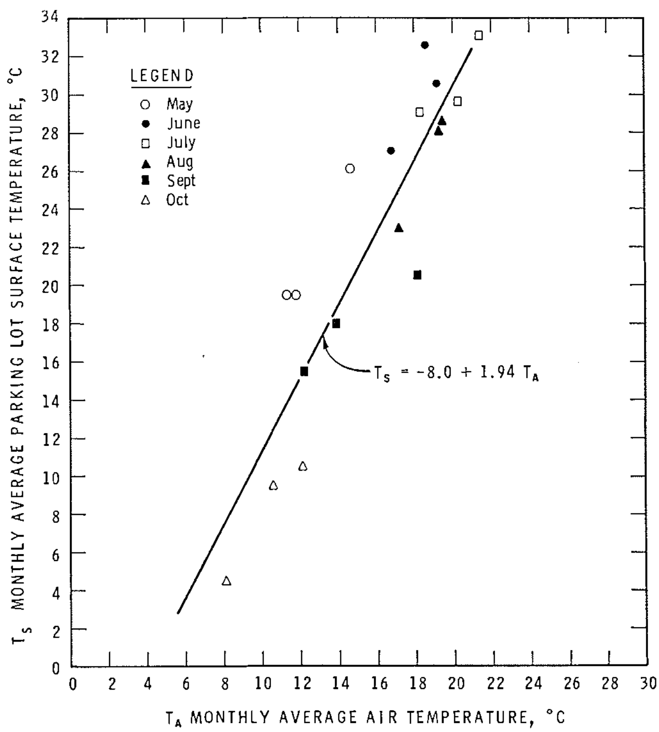

FIG. 3. Monthly average air temperature and corresponding estimated parking lot surface temperature.

the first time during the winter of 1960–61. For the 12 consecutive 1-year intervals, corresponding to the period November 1960 to November 1961, when surface conditions were the same, the average annual ground temperature at about the 7-m depth was the same under both parking lots. Snow was first allowed to remain on the old parking lot during the winter of 1961–62. Warming of the ground because of this snow cover was observed to influence the average annual temperature at the 7.46-m depth in the 1-year interval July 1, 1962, to June 30, 1963. Thereafter the temperature continued to increase, as can be seen in Fig. 2, and by the end of the observation period it had attained a value about 0.3 C degree greater than the corresponding annual average temperature under the new parking lot.

The reflectivity of the surfaces of the parking lots with respect to solar radiation was about the same as that for the grassed surface (about 90% of the incoming solar radiation was absorbed). As the parking lots did not have a cover of vegetation and were reasonably well drained, no heat was dissipated by transpiration and that lost by evaporation was probably nil or very small, except immediately after periods of rain. Therefore the heat dissipated by convection must have increased, and, as a result, the average surface temperature of the parking lots was greater than that of the grassed surface. Because of this the heat dissipated by long-wave radiation must have increased as well.

If the ratio between the convective and evaporative loss for the parking lots remained constant throughout the summer, and if the convective loss was approximately proportional to the difference between the monthly average surface temperature and monthly average air temperature, then that difference should be proportional to the incoming solar radiation. The observed temperature differences for the 3-year observation period are plotted against global solar radiation in Fig. 4, where it can be seen that a good correlation exists.

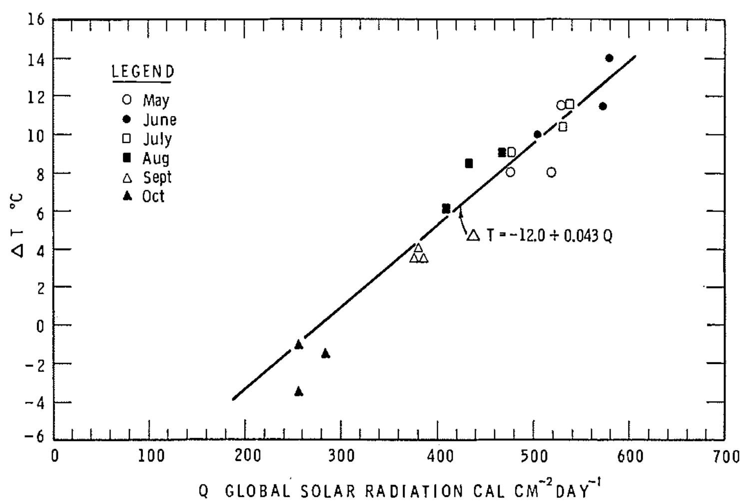

FIG. 4. Dependence of difference between monthly average surface temperature (parking lot) and monthly average air temperature on global solar radiation.

If one assumes that there is no error in the measurement of global solar radiation, a least squares fit to the observations gives

$$T_A - T_S = \Delta T = -12.0 + 0.043Q,$$

where T_A is monthly average air temperature in °C,

T_S is monthly average surface temperature in °C,

Q is monthly average daily incoming global solar radiation in cal cm^2 day^{-1}.

The monthly average surface temperature was obtained by averaging the values determined for the two parking lots.

A good correlation was observed also between the monthly average of the daily net radiation and the difference between the monthly average surface temperature and monthly average air temperature. Observations of net radiation are not as generally available, however, as observations of global solar radiation.

DISCUSSION

The observations at the Ottawa site indicate that significant factors which cause a difference between the average air temperature for a given period of time and the corresponding average ground surface temperature are snow cover and the amount of the average net radiation that must be lost by convection. A comparison of the monthly average surface temperatures in summer at the grassed site and the two parking lots demonstrated the importance of evaporation and transpiration in the dissipation of solar heat and, thus, in the reduction of the convective loss. From these observations it has been possible to estimate the size of the convective component at the grassed and parking lot sites, and these are given in the following paragraph.

An earlier study (Gold and Boyd 1965) at the grassed site indicated that during a period April 1 to September 30 about 48% of the net solar radiation was dissipated by evapotranspiration, about 42% by long-wave radiation, and about 7% by convection, and that about 3% was conducted into the ground. The evapotranspiration loss is equivalent to about 57 cm of water, a little greater than the measured rainfall for the period. The difference between the monthly average surface and air temperatures at the grassed site at the time of maximum monthly average daily net solar radiation was about 1.5 C degrees. The corresponding difference between the monthly average surface temperature of the parking lots and the monthly average air temperature was about 11 C degrees. If it is assumed that the convective loss is proportional to the difference between the monthly average surface and air temperatures, then the observations indicate that this loss in the summer is about seven times greater at the parking lots than at the grassed site. The convective loss at the parking lots would thus be about 50% of the net solar radiation. It was estimated that, because of the increase in surface temperature, the long-wave radiation loss also would be about 50% of the net solar radiation. These rough calculations indicate that the evaporation loss was negligible, as would be expected because of the nature of the surface.

If it is assumed that (1) the global radiation was 540 cal cm^{-2} day^{-1} when the difference between monthly average daily air and surface temperatures was 11 C degrees, (2) the absorptivity of the surface was 0.90, and (3) the convective loss was 50% of the net solar radiation, then a value for the daily average diffusion coefficient can be obtained from the results of Scott (1957). The value obtained with these assumptions was 1 000 cm^2 s^{-1}, which is in reasonable agreement with values presented by Scott, particularly when the approximate nature of the present observations and of the analyses of Scott are taken into consideration. The results shown in Fig. 4 indicate that consideration would have to be given to the hour-to-hour change in the stability of the air if a more accurate value for the diffusion coefficient is desired, particularly during periods when the daily average global radiation is not close to its maximum value.

The good correlation obtained between global radiation and the difference between the monthly average surface temperature and monthly average air temperature suggests that this might provide a practical empirical method of obtaining the ground surface thermal boundary conditions required for some problems. The measurements required to establish the correlation for a given surface type would be average surface temperature, average air temperature, average net or global solar radiation, and perhaps rainfall. These measurements can be made easily under field conditions.

Observations at the Ottawa site by Gold (1963) indicated that the average thermal conductivity of a snow cover can be assumed equal to that associated with a density equal to the average density of the snow cover. If it is possible to estimate the heat flow from the ground during winter, then the average ground surface temperature under a snow cover can be estimated from a knowledge of the monthly average air temperature, snow depth, and density. The maximum average daily heat flow from the ground observed at the grassed site was about 20 cal cm^{-2} day^{-1} in mid-December and had an annual variation that was approximately sinusoidal. Information on the average density of snow covers in Canada and the dependence of thermal conductivity on density was given by Williams and Gold (1958).

Figure 2 shows that the annual average ground temperature at about the 7-m level under the parking lots is about 0.5 C degree warmer than that at the same level at the grassed site. It is considered that this difference may be due to higher temperatures at the same level in the rock adjacent to the parking lots because of heat flow from the nearby buildings constructed on the rock.

One factor that could have an influence on the present observations and their correlation with other measurements should be noted. The air is coupled thermally with the ground surface; if the ground surface area is great enough, the average air temperature will attain an equilibrium value characteristic of the surface type over which the measurement is made. The grassed site was open to the west, the direction of the prevailing wind, but there were buildings about 60 m to the north, south, and east. It is considered, however, that these buildings were sufficiently far away for the air temperature observed to have been in equilibrium with the grassed surface. Therefore, the temperature differences given in Fig. 4 are those between the parking lot surface temperature and the air temperature in equilibrium with a grassed field.

The fact that air temperature at a site is in equilibrium with the surrounding surface conditions should be kept in mind, because air temperatures reported by the Meteorological Service are not necessarily measured over a standard surface of extent great enough to ensure that the temperature is in equilibrium with it. Differences between annual average air and ground temperatures reported, for example, by Brown (1963) may not, therefore, be the true difference that exists at a location where ground temperature only was observed.

Changes in average air temperature that are due to a change in the characteristics of the cover can occur within relatively short distances. For example, observations by Williams (1965) of ground and air temperatures at a bog within 5 mi of the grassed and parking lot sites showed that, because of the low conductivity of the surface material, surface and air temperatures were considerably lower at night than they were for the grassed site under equivalent radiation conditions. The temperatures during the daytime, however, were more nearly the same. It appears that, because of surface characteristics, the bog may have annual average ground and air temperatures lower than those at the grassed site.

The variations in average ground temperature that can occur because of variations in the characteristics of the surface may not be of great significance for many areas of Canada. They are of particular importance, however, in those regions where the annual average ground temperature is close to 0 °C. Variations in annual average ground temperature in such areas, which are due to changes from one location to another in annual average snow depth, availability of water for evaporation and transpiration, character of the surface, etc., can result in islands of permafrost. It is of interest that Brown (1964) found first signs of permafrost in the sporadic permafrost zone under surface cover similar to that of the bog located near Ottawa.

Long-period changes in the thermal regime of the ground, such as those associated with the formation and degradation of sporadic and continuous permafrost, can result from changes with time in the properties of the surface, or from fluctuations in climate. Such changes in the thermal regime of particular types of soil can be troublesome to the scientist and engineer. Although man may have little influence on weather and climate, he can readily change the thermal properties of the ground surface. It is necessary that he should have at least a qualitative understanding of the factors controlling the exchange of heat and moisture between the air and the ground to be able to interpret observed field conditions and to ensure that any changes in those conditions will be beneficial, or at least will not introduce serious problems. The present paper demonstrates the effect on the ground thermal regime of snow cover and surface characteristics that control the relative size of the convective and evaporative components of the heat and moisture balance.

CONCLUSIONS

Observations at a site in Ottawa on ground temperature under a grassed surface and two parking lots, one cleared of snow in winter the other snow covered, showed the following characteristics.

(1) Snow cover maintained the average surface temperature about 10 C degrees warmer than the lowest value of the monthly average air temperature.

(2) The lack of heat loss by evapotranspiration from the parking lots caused their maximum monthly average surface temperature to be about 11 C degrees warmer than the highest value of the monthly average air temperature.

(3) A correlation exists between the monthly average daily global radiation and the difference between the monthly average surface and air temperatures.

(4) A change in the annual exchange of heat between the atmosphere and the ground surface, resulting from a modification of surface characteristics, can have a significant effect on the ground thermal regime.

ACKNOWLEDGMENT

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