The Measurement of the Surface Temperature of the Earth

By
William E. Marlatt

Under Sponsorship of
National Aeronautics and Space Administration
Contract NASr-147

Technical Paper No. 64
Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

January 1965

Colorado State University

Department of Atmospheric Science

Paper No. 64

THE MEASUREMENT OF THE SURFACE TEMPERATURE OF THE EARTH

by
William E. Marlatt

Under Sponsorship of
National Aeronautics and Space Administration
Contract NASr-147

Technical Paper No. 64

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

January 1965

INTRODUCTION

Until recently, requirements for information on the temperature of the surface of the earth have come almost exclusively from meteorologist and other researchers studing problems of agriculture and from biologists whose interests were primarily those involving studies of the relationship of environmental conditions to organisms. For these studies no important degree of accuracy is required (Wang, 1963). Within the past few years, however, a need has emerged for accurate measurements of earth "skin" temperatures for use in studies of atmospheric energy balance and in studies of the physics of radiation transfer. Insufficient knowledge of the true surface temperature and of the emitting, transmitting and reflecting properties of earth surface has also limited the accuracy of evaluation of satellite radiation measurements.

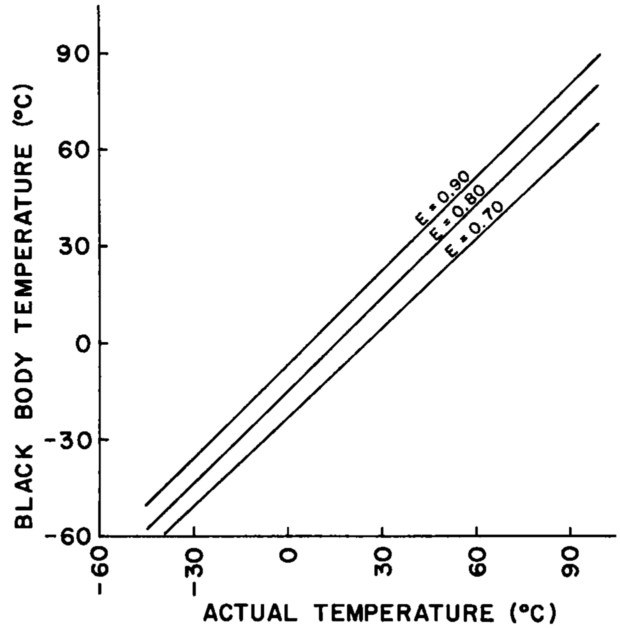
The problem of measurement of the temperature of the earth surface is one of the most difficult and controversial of all micrometeorological observations. Any sensor placed on the surface of the soil has a different heat conduction, heat capacity and moisture content from that of the soil on which it rests and also shields the soil being measured. Vegetation on the soil has a further effect of producing wide variations in temperature within extremely small horizontal and vertical distances. Ideally, a perfect sensor would be one which is infinitely thin, with the same physical and thermal properties as the soil or vegetation, and which could be placed over a broad area of the surface in a manner which would insure a good thermal contact at all locations.

METHODS OF MEASUREMENTS

Nearly all measurements made to date of the earth surface temperature can be separated according to techniques used in measurements. Either the temperature <u>on</u> the surface was measured where the instrument was exposed to the combined influences of radiation, air temperatures and soil temperatures or the sensor was buried <u>in</u> the soil to some depth ranging from 1 mm to 4 inches (Penman, 1943; Cook, 1955; Shaw, 1955; Carter, 1928; Hide, 1942; Jacobs, 1940; Smith, 1939). A third technique was used in which the gradient of temperature in the ground or in the air close to the surface was observed and then extrapolated to the temperature of the surface itself (Nyberg, 1938).

Fig. 1 Relationship between actual and black body temperature for emissivity values of 0.90, 0.80, and 0.70 from the equation

$$T_{bb} = \sqrt[4]{\Sigma T_a}$$



Recently measurements of surface temperatures have been made using remote sensing radiometers.[1,2,3] While this method has the advantage of not being affected by the heat conductivity and capacity problems mentioned earlier in this paper, it is limited by the lack of knowledge the true emissivity of the surface and by absorption of the radiation in the atmosphere between the target and the sensor. While the effect of the emissivity can be calculated (Fig. 1) the true emissivity of complex surfaces such as vegetation and soils with their many variations in color, texture, temperature and moisture content is almost never known. The effect of a 10% error in emissivity may lead to an error of as much as 6-10C in the range of temperature within the limits of most earth surface (-50C to +80C) conditions. Inaccuracies resulting from absorption by the atmosphere between the surface being measured and the sensor can in general be overcome by optimum choice of waveband and by making the path length between target and sensor as short as physically practical.

---

[1] Davis, Paul A., 1964: Satellite radiation measurements and atmospheric heat balance. SRI, Final Report, Contract NAS 5-2919, 85 pp.

[2] Marlatt, W. E., 1964: Investigations of the temperature and spectral emissivity characteristics of cloud tops and of the earth's surface. Colorado State University, Dept. of Atmos. Sci., Technical Paper #51, Contr. NASr-147, 60 pp.

[3] Weiss, M., 1963: Earth and sea surface temperatures measurement using infrared. Proc. Second Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, 343-358.

PAWNEE NATIONAL GRASSLAND FIELD STUDY

During the past two years a field program has been underway to measure the "true surface temperature" of the earth for comparison with measurements from channel 2, (8-13 micron waveband) radiation from TIROS VII. Measurements were made in the Pawnee National Grassland of Northern Colorado, which is a region of low rolling hills and flat plateau covered with a short bunch grass. This paper will compare the use of the thermistors and infrared radiometers for surface temperatures measurements of a sod covered soil.

The presence of grass or other vegetation requires that a large number of observations be made in order to mask the differences in temperature across small horizontal distances. Fig. 2 shows the gradient of temperatures in and around a clump of buffalo grass at different times of the day. Horizontal gradients of as much as 7.6C per inch were noted in Fig. 2 during periods of low sun angles in winter. At other times of the year even larger horizontal gradients were observed. In the field study, 40 thermistors were placed randomly over the surface -- inside the clumps of buffalo grass, on the bare soil between the grass clumps, etc. The size of the thermistors used in relation to the size of a common pin is shown in Fig. 3. The thermistors were not shielded from solar insulation rather each thermistor was sprayed with a flat paint the same color as the soil surface (light gray) and coated with one layer of dust while the paint was still wet. The bead thermistors were installed flush with the soil surface. Positioning of the sensors was checked prior to each measurement.

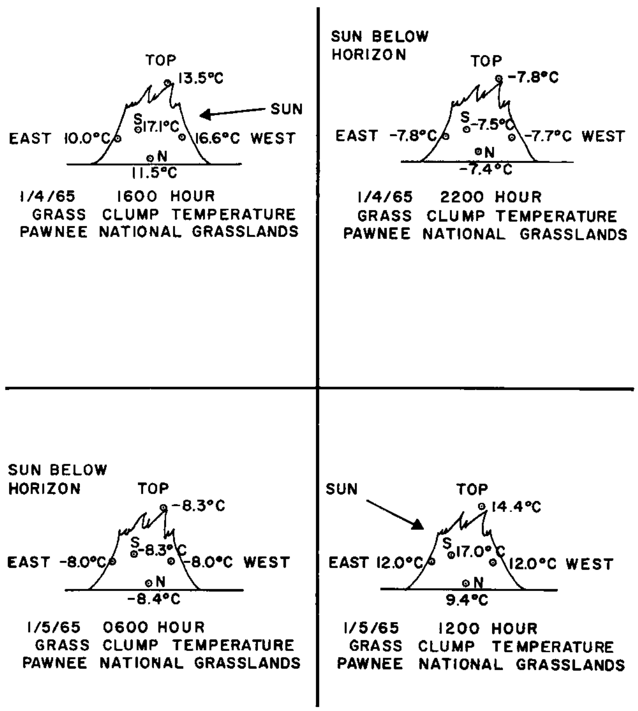
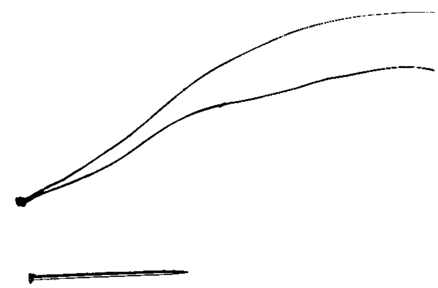


Fig. 2 Surface temperatures in and around a small clump of buffalo grass at different times of day and night, January 4-5, 1965.

Fig. 3 Relative size of thermistors used in surface temperature measurements as compared to size of common pin.



Measurements were made at approximately two-hour intervals for a period of twenty-four hours on days with clear skies. Six sets of measurements were made between February and November, 1964. Recording the surface temperature measurements from the network of thermistor sensors required approximately five minutes. Two sets of measurements were averaged for each observation. Simultaneous measurements of black body temperature of the surface at each thermistor location were made using a 3° view, 8-13 micron waveband radiometer (Barnes Engineering Co., Model IT-2) which was held by hand approximately 12 inches above the earth surface.

Changes in earth surface temperatures within the recording period are always much smaller than the differences between measurement points. Table 1 shows a sample of average surface temperatures with their standard deviations for different times of day and night. This table also allows a comparison of average temperatures measured by the thermistor units to average black body temperatures measured by the radiometer.

Figs. 4 through 9 show the individual comparison of thermistor to black body surface temperatures of the grassland at different times of day and night for different times of the year. Average differences between methods are summarized by hours in Fig. 10. It may be seen from these figures that while the temperatures measured by the radiometer (not corrected for emissivity) are slightly below those measured by thermistors at midday, they tend in most cases to be slightly higher than the thermistor measured temperatures during the nighttime hours. It is believed that the reason for the thermistors measuring nighttime temperatures lower than those measured by the radiometer may be the result of lack of good thermal contact with the soil surface. Under clear, calm weather conditions the temperature of the first millimeter of air above the soil surface may be several degrees lower during the late night and early

TABLE 1. Thermistor and Black Body Temperatures. Pawnee National Grassland, February 10 and 11, 1964.

		Thermistor		Radiation	
Date	MST Time	Surface Temp. °C	Standard Deviation °C	Black Body Temp. °C	Standard Deviation °C
2/10/64	1100	17.2	3.5	17.0	3.2
	1300	23.4	3.2	21.4	3.2
	1500	18.6	3.8	17.1	3.4
	1935	-4.6	1.5	-2.6	1.6
	2130	-3.9	1.1	-3.2	1.3
	2330	-7.5	1.3	-5.8	0.9
2/11/64	0130	-7.1	1.0	-5.3	2.5
	0330	-7.5	0.8	-5.1	0.6
	0540	-4.4	0.7	-3.8	1.0
	0735	-2.4	1.0	-3.2	0.7
	0945	8.4	1.7	7.2	1.7
	1150	12.0	1.3	11.9	0.8

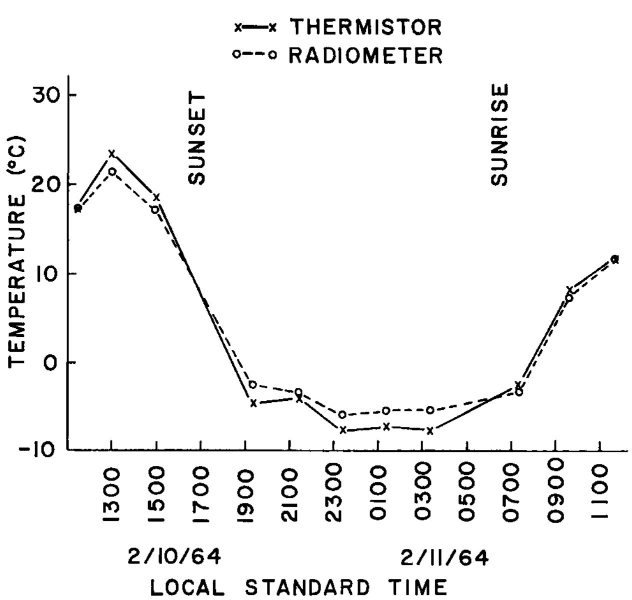


Fig. 4 Comparison of thermistor and 8-13 micron radiometer measurements of earth surface temperature. Pawnee National Grassland, February, 1964. Each point is average of 40 observations.

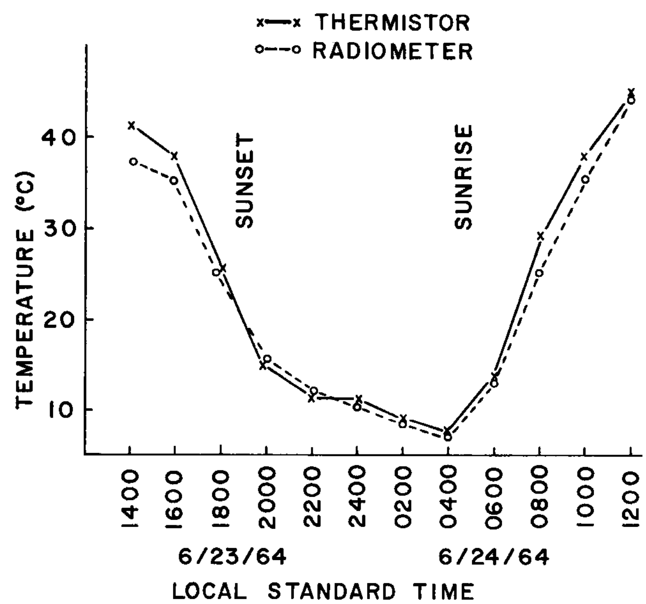


Fig. 5 Comparison of thermistor and 8-13 micron radiometer measurements of earth surface temperature. Pawnee National Grassland, June, 1964. Each point is average of 40 observations.

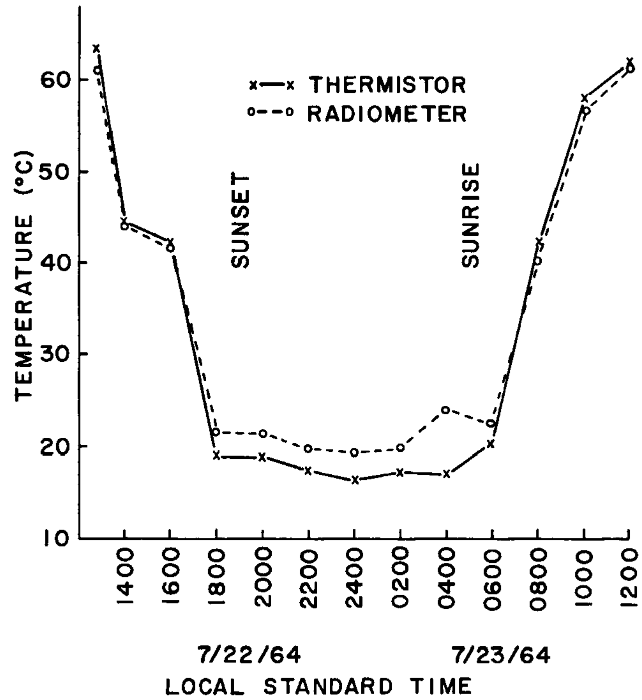


Fig. 6 Comparison of thermistor and 8-13 micron radiometer measurements of earth surface temperature. Pawnee National Grassland, July, 1964. Each point is average of 40 observations.

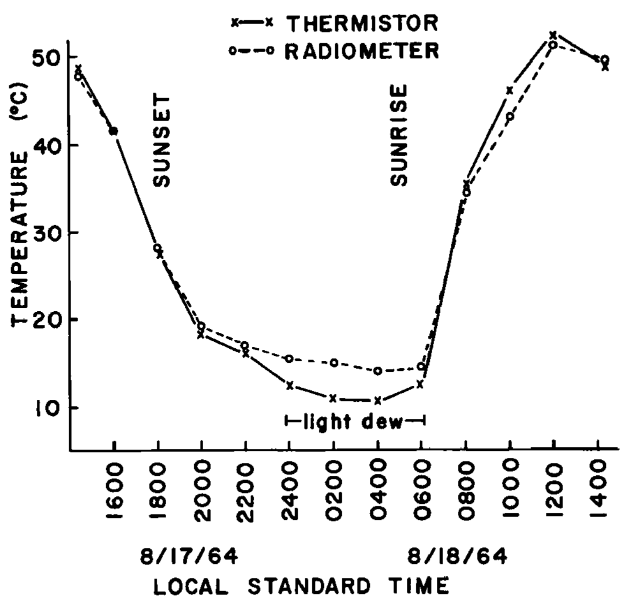


Fig. 7 Comparison of thermistor and 8-13 micron radiometer measurements of earth surface temperature. Pawnee National Grassland, August, 1964. Each point is average of 40 observations.

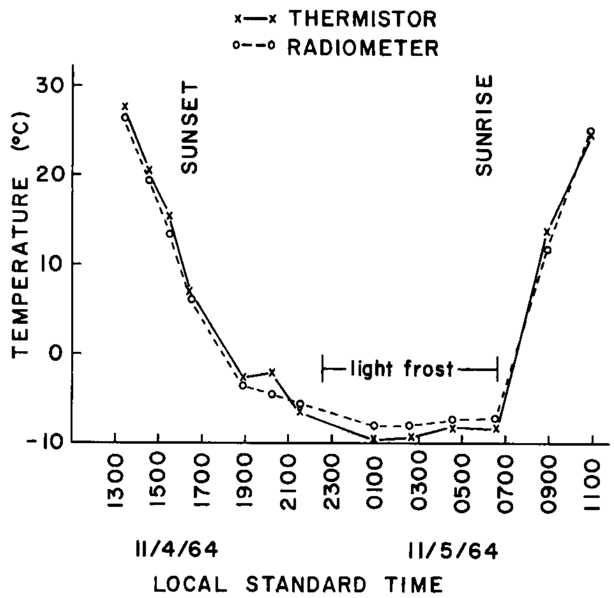


Fig. 8 Comparison of thermistor and 8-13 micron radiometer measurements of earth surface temperature. Pawnee National Grassland, November, 1964. Each point is average of 40 observations.

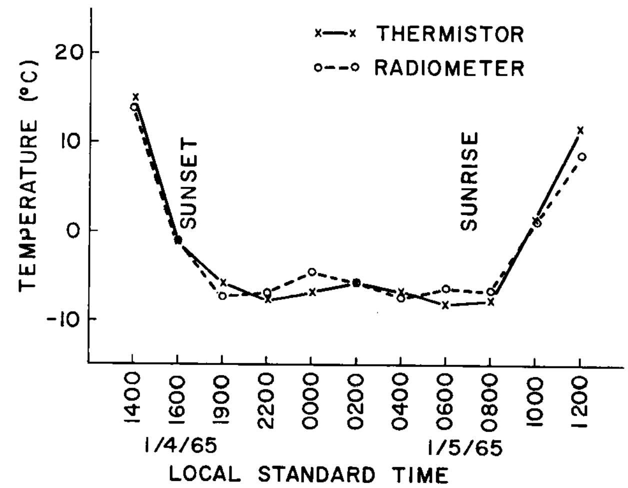


Fig. 9 Comparison of thermistor and 8-13 micron radiometer measurements of earth surface temperature. Pawnee National Grassland, January, 1965. Each point is average of 40 observations.

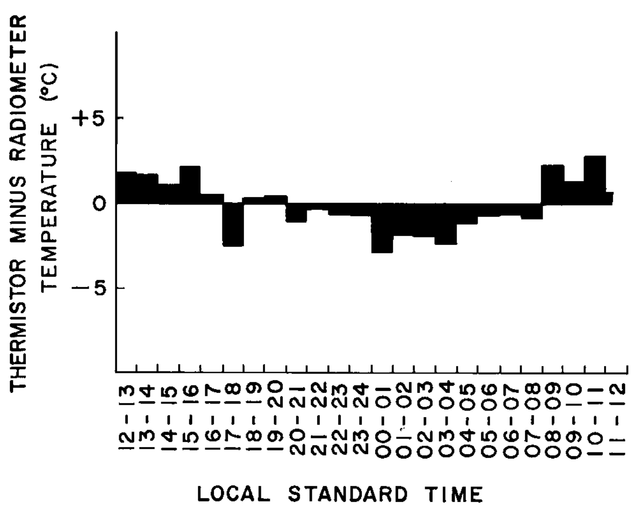


Fig. 10 Average differences between earth surface temperatures measured by thermistors and by 8-13 micron radiometer held 12 inches above surface.

morning hours than that of the soil surface itself; therefore, if the sensor does not stay firmly pressed against the soil surface, its response may be more to that of the temperature of the air than to the soil temperature.

Air temperatures at Weather Bureau stations have been used as estimates of the earth surface temperature (Fritz and Winston, 1962; Wark, Yamamoto, and Lienesch, 1962). From Fig. 11 it may be seen that [redacted] the nighttime surface temperature as measured by thermistors generally fall within $\pm$ 3C of air temperatures measured at shelter height. Daytime differences, however, are often as large as 15-20C. If, as discussed above, it is agreed that nighttime temperatures of the earth surface measured by radiometers are as accurate as those measured by thermistors, then the differences between equivalent black body surface temperatures and shelter height air temperature are slightly increased (Fig. 12).

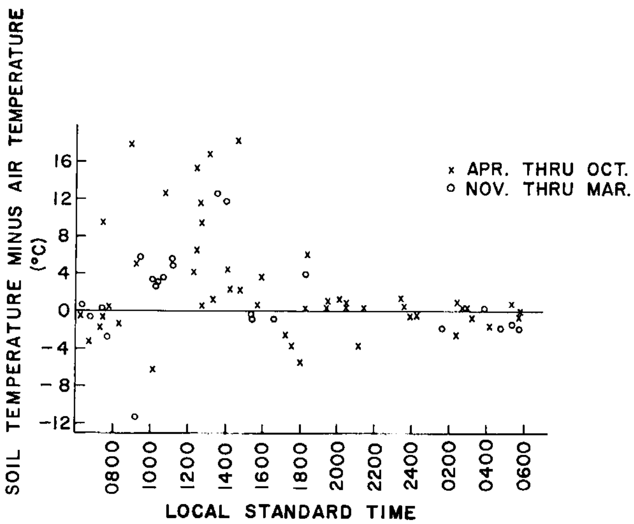


Fig. 11 Comparison of earth surface temperature (measured by thermistors) and air temperature at 6 ft.

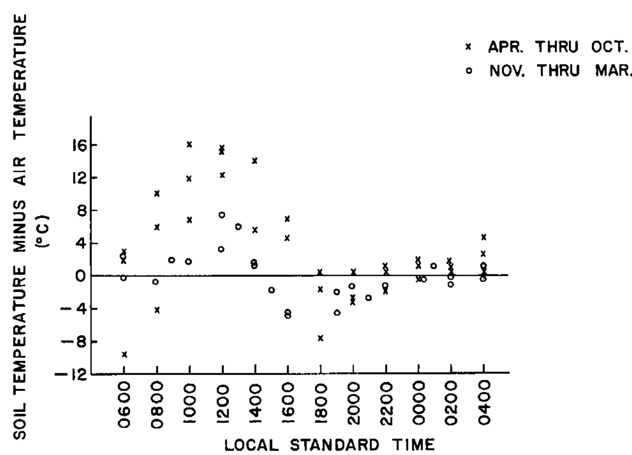


Fig. 12 Comparison of earth surface temperature (measured by radiometer) and air temperature at 6 ft.

In addition to the temperature measurements recorded by the thermistor installed flush with the earth surface and with the radiometer held approximately 12 inches above the thermistors, surface temperatures were also obtained from a radiometer mounted on the underside of a small airplane and flown over the ground site at 100 foot and 1000 foot altitude. The view angle of the airborne radiometer is 30°, thus at 1000 feet, the surface area viewed is a circle of approximately 35 foot diameter. Table 2 gives a comparison of the temperature measured by the three instruments.

A certain amount of attenuation is to be expected as radiation passes through the atmosphere between the target and the sensor due to absorption by carbon dioxide and water vapor. Little or no effect of the atmospheric path length was evidenced

TABLE 2. Comparison of Surface and Airborne Sensors.
January 4-5, 1965

Time MST	Ground Radiometer °C	Thermistor °C	1-2 °C	8-13μ, 100' Aircraft Radiometer °C	1-3 °C	8-13μ, 1000' Aircraft Radiometer °C	1-4 °C	6' Air Temp. °C	100' Air Temp. °C	1000' Air Temp. °C
1400	13.8	15.0	-1.2	13.5	0.3	12.0	1.8	11.8	13.0	10.0
1600	-1.1	-1.2	-0.1	-1.0	0.1	-1.5	-0.4	5.0	11.0	10.0
1900	-7.2	-5.8	-1.4	----	----	----	----	-1.7	----	----
2200	-7.0	-7.8	-0.8	-4.5	-2.5	-5.5	-1.5	-5.4	-2.1	8.6
0000	-4.5	-6.7	2.2	----	----	----	----	-3.9	----	----
0200	-5.6	-5.7	-0.1	-6.0	0.4	-5.0	-0.6	-4.2	0.2	10.0
0400	-6.6	-7.2	0.6	-5.5	-1.1	-5.5	-1.1	-6.1	-2.0	10.4
0600	-6.3	-8.0	1.7	-4.9	-1.4	-6.8	0.5	-6.1	-3.0	10.5
0800	-6.5	-7.6	1.1	-4.6	-1.9	-4.0	-2.5	-5.6	7.5	11.0
1000	1.4	1.6	-0.2	3.0	-1.6	1.0	0.4	-0.8	6.0	11.5
1200	8.9	11.6	-2.7	10.0	-1.1	8.5	0.4	4.8	7.5	11.3
Average			-0.08		-0.09		-0.03			
Absolute Average			1.1		1.2		1.0			

for the flights summarized in Table 2. When the path length was increased significantly, however, (Figs. 13 and 14) the effect of atmospheric attenuation, particularly attentuation due to atmospheric haze was frequently observed. Average path length between the surface and the airborne radiometer for the flights summarized in figures 13 and 14 was 12,000 feet.

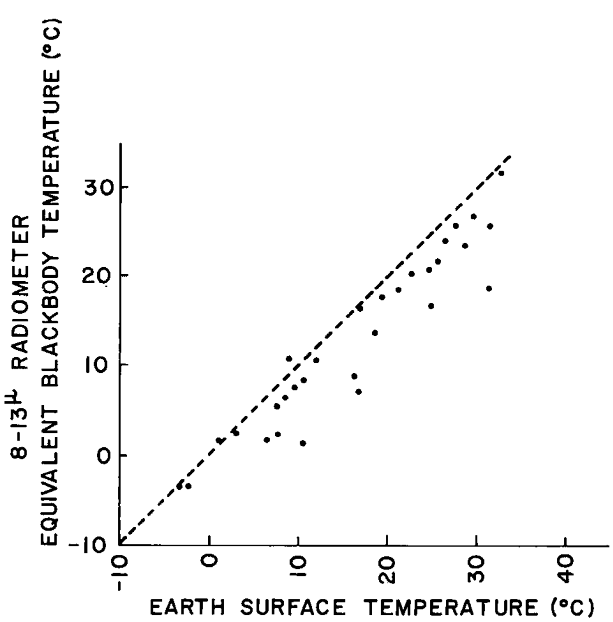


Fig. 13 Effect of atmospheric attenuation on outgoing radiation in the 8-13 micron waveband. Daytime observations.

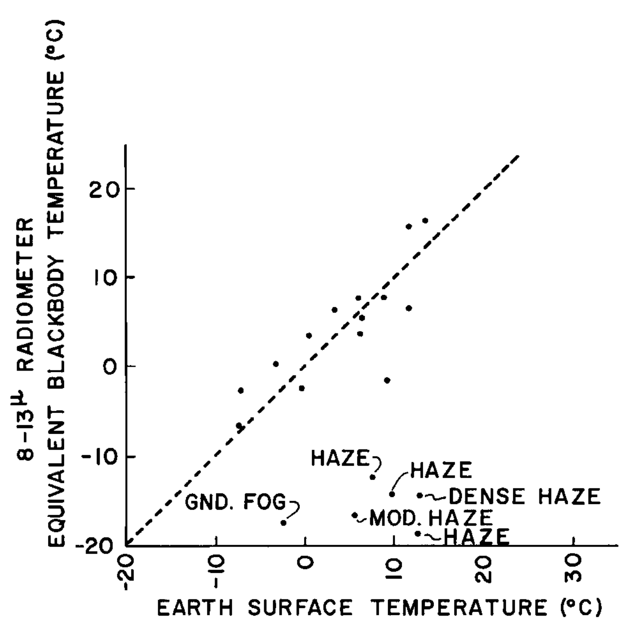
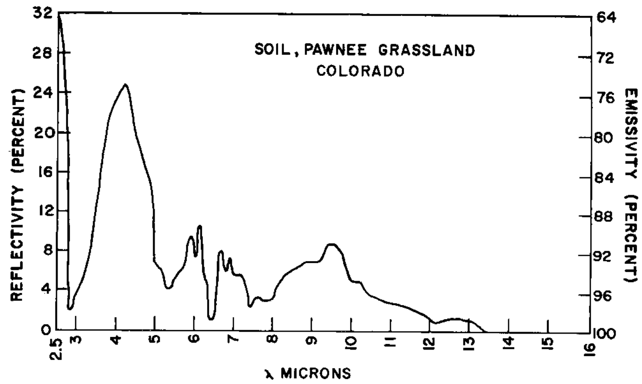


Fig. 14 Effect of atmospheric attenuation on outgoing radiation in the 8-13 micron waveband. Nighttime observations.

Fig. 15 The effect of wavelength on emissivity and reflectivity of the surface soil, Pawnee National Grassland.



To obtain the greatest accuracy of surface temperature only the radiation from the "cleanest" portion of the atmospheric windows should be used. In addition, the emissivity of the surface in the region must be known. Fig. 15 shows the emissivity of the surface soil from the Pawnee National Grassland. From this figure, it is seen that, in the 8-13 micron region, the emissivity averages 0.96. Since this value is for the soil alone, the presence of grass and other organic matter would increase the average emissivity of the earth surface in this region to perhaps approximately 0.98.

DISCUSSION

Instrumentation for measuring the outgoing radiation in the 8-13 micron window region was included on TIROS II, III, V, and VII, for obtaining worldwide measurements of earth surface temperatures. Ozone absorption, however, which occurs between 9 and 10 microns and the wings of water vapor and carbon dioxide bands which extend into the 8-13 micron window region plus atmospheric haze in the lowest troposphere have resulted in the window being "dirty". This "dirtiness" has been a discouraging factor in the usefulness of the TIROS radiation observations (Wark, et al., op. cit.). To avoid the atmospheric attenuation problem, the channel 2 radiometer aboard NIMBUS I was filtered to measure radiation in the 3.8 - 4.2 micron atmospheric window. While the attenuation of outgoing radiation in this window is quite low, i.e. the window is "clean", a limited number of observations indicate that the emissivity of at least certain mineral soils is much lower in the 4 micron region of the spectrum than in the 8-13 micron region (Fig. 15). It is most important, therefore, that radiation measurements in this waveband be corrected for surface emissivity if they are to be used to estimate effective earth surface temperatures.

To minimize the atmospheric influence and yet stay in the region of low soil emissivities, one of the airborne IT-2 radiometers was fitted with a 10-11 micron filter. Measurements using this system have been, however, less accurate than from the 8-13 micron unit. The reason for this loss of accuracy has not been established at the time this paper was written.

CONCLUSIONS

Results from this study indicate that the surface temperature of a grass covered earth can be measured as accurately with infrared radiometers as with miniature thermistors placed on the surface. By proper choice of waveband filter to minimize both atmospheric attenuation and emissivity variations, it has been shown that it should be possible to conduct very accurate satellite and aerial mapping of earth surface temperatures.

REFERENCES

Carter, H. G., 1928: A comparison of air and soil temperatures. Mon. Wea. Review, 56 (4), 138-139.

Cook, F. A., 1955: Near surface soil temperature measurements at Resolute Bay, N.W. territories. Arctic, 8 (4), 237-249.

Dutton, J. H., 1962: Space and time response of airborne radiation sensors for the measurement of ground variables. J. of Geophysical Res., 67 (1), 195-205.

Fritz, S., and J. S. Winston, 1962: Synoptic use of radiation measurements from satellite TIROS II. Mon. Wea. Review, 90 (1), 1-9.

Hide, J. C., 1943: A graphic presentation of temperatures in the surface foot of soil in comparison with air temperatures. Soil Science Soc. of America, Proc., 7, 31-35.

Jacobs, W. C., 1940: A comparison of upper soil temperatures and shelter temperatures. Bull. Amer. Meteor. Society, 21 (5), 181-183.

Nyberg, A., 1938: Temperature measurement in the air layers very close to a snow surface. Geograf. Ann., 20, 234-275.

Penman, H. B., 1943: Daily and seasonal changes in the surface temperatures of fallow soil at Rothamsted. Quart. J. Roy. Meteor. Soc., 69, 1-16.

Shaw, R. H., 1955: The measurement of soil temperature. Iowa State College J. of Science, 30 (2), 255-261.

Smith, A., 1939: Value of mean and average soil and air temperatures. Soil Science Soc. of America, Proc., 4, 41-50.

Wang, J. Y., 1963: Agricultural Meteorology. Pacemaker Press, Milwaukee, Wisc., 693 pp.

Wark, D. Q., G. Yamamoto, and J. H. Lienesch, 1962: Methods of estimating infrared flux and surface temperature from meteorological satellite. J. of Atmospheric Science, 19 (5), 369-384.

ACKNOWLEDGMENTS

This research was conducted under NASA Contract NASr-147. The author wishes to thank W. Hovis, of the Goddard Space Flight Center for the analysis of the soil reflectivity measurements (Fig. 15) and also W. Nordberg, W. Bandeen, and I. Strange, of the Goddard Space Flight Center for advice and assistance in many facets of this study.