Winter Thermal Radiation Studies in Yellowstone Park

Infrared reveals surface phenomena of hot springs and temperatures of vegetation and Old Faithful geyser.

David M. Gates

An expedition into Yellowstone National Park, 14 through 23 February 1961 (*1*), afforded an unusual opportunity to measure the thermal radiation characteristics of the natural environment. Yellowstone Park offers great extremes in environmental conditions within concentrated areas, a situation which is particularly unusual during winter months. An object or organism on the earth's surface may be subjected to several or all of the following factors affecting the energy exchange between it and its surroundings: direct sunlight, skylight, thermal radiation, heat conduction, heat convection, evaporation and condensation of moisture, and chemical energy from physiological processes. For objects or organisms on or above the surface of the earth, the one factor which is continuously present day or night, winter or summer, is the flux of thermal radiation exchanged by all exposed surfaces. The thermal-radiation component may be the dominant factor during the night or even during the winter day for controlling the temperature of the object or organism. At other times and during other conditions it may represent only a part of the total energy exchange, perhaps being exceeded only by the direct-sunlight component. In areas where there are thermal hot springs, such as those found in Yellowstone Park, the terrestrial heat may dominate the microenvironment of the surface. For objects at the temperature of most natural surfaces—surfaces such as snow, soil, water, and vegetation—the thermal radiation emitted consists entirely of infrared radiation of wavelengths usually more than 5.0 microns, with the peak of the energy distribution centered at wavelengths of about 10 or 12 microns. In order to detect this energy one must use an infrared-sensitive detector such as a thermocouple, bolometer, or photoconductor. There has been such a distinct paucity of environmental measurements at infrared wavelengths that it was decided to carry out a series of such observations in Yellowstone Park on this occasion. In addition, the infrared detection technique afforded the opportunity to determine the temperature of the clouds formed from the geysers and of other geophysical features.

Various types of infrared-radiation instruments have been designed for meteorological purposes. However, most of these are unsuitable for detailed ecological and geophysical measurements of the type performed here. The instrument selected for this work was the Stoll-Hardy (*2*) radiometer with infrared filter. The instrument was originally intended for physiological applications but can be used to measure the surface temperature of various objects or the "radiant" temperature of environments (*3*). The sensitive element consists of two thermistor flakes located at the apex of a polished cone having a 20° field of view. Two more thermistor flakes, located within the radiometer head and shielded from the incident radiation, form the other arms of a Wheatstone bridge and act as temperature compensators. A microammeter is provided, with three scales (0°–10°, 0°–30°, and 0°–100°C), for making readings of temperatures that depart from ambient temperatures.

The thermistor head is normally placed in a cavity in an aluminum block which acts as the reference temperature unit and to which all other temperatures are compared. The instrument is calibrated by means of a Leslie cube of unit emissivity. Several modifications of the instrument were made to facilitate its use in the field. The ambient aluminum block supplied with the instrument was replaced by a much larger aluminum block in order to give greater thermal stability through increased heat capacity. The detector head was embedded in Styrofoam for further insulation in order that thermal gradients from the hand would not disturb the readings. These two modifications proved very satisfactory in the field. In addition, the instrument was provided with a connector to which an auxiliary battery supply could be clipped, the batteries being kept warm by being worn inside the coat of the investigator. The radiometer is relatively simple and easy to use, but, being a direct-current device, requires special care.

The temperature of a surface is obtained from the well-known radiation law

$$E = \epsilon \sigma T^4$$

where E is the energy radiated in calories per square centimeter per minute, ϵ is the emissivity of the surface, σ is the Stefan-Boltzmann constant in calories per square centimeter per minute per degree Kelvin to the fourth power, and T is the surface temperature in degrees Kelvin. For many surfaces such as soil, rock, or snow the emissivity is unity, and for most vegetation it is 0.95 or better (*4*) in the infrared. If the response of the radiometer (the microammeter reading) is plotted against the energy given off by the Leslie-cube black body, a precise straight line results. Therefore, the instrument measures directly the energy received by the conical head, and this can then be converted to temperature if the emissivity of the surface is known. If the emissivity is less than unity but is assumed to be unity, then the temperature obtained is the "radiant" temperature of the surface. By "radiant temperature" is meant the temperature of a black body radiating the same amount of energy as that received by the detector. The "radiant" environmental temperature of the sky is a somewhat fictitious quantity, since it does not represent the actual true temperature of any part of the atmosphere, but is only a means of expressing the amount of energy received from the

The author is assistant chief of the Upper Atmosphere and Space Physics Division of the Central Radio Propagation Laboratory, U.S. National Bureau of Standards, Boulder Laboratories, Boulder, Colo.

sky or, effectively, the strength of the sky as a "sink" for infrared radiation. The Stoll-Hardy radiometer has a distinct advantage over other radiation instruments for field use in that its receiving area is small enough and its field of view is sufficiently narrow that it can pick up detailed features of the thermal environment, particularly when it is used close to the emitting surfaces.

Surface Temperature of Hot Springs

The "radiant" temperature of the surface of some hot-spring pools was investigated. The radiometer "head" was held as close to the surface as possible, usually about 3 millimeters away, and a reading was taken immediately. It was necessary to hold the head close to the surface in order that the moisture in the air would not seriously affect the response through absorption and reradiation. The radiation emitted by the surface of the water originates within the uppermost 20 to 30 microns of the liquid. This can be shown by computation from the absorption coefficients for liquid water given by Dorsey (5) for the wavelength region 6.0 to 18.0 microns. The reflectivity of liquid water is 1.5 percent at 8 microns, and hence the emissivity is 98.5 percent. This correction must be applied to the instrument reading in order to obtain the true surface temperature of the water.

When exploring the surface temperature of the hot springs with the radiometer we noticed at certain places that large temperaure differences may exist within a very short horizontal displacement. At first this was thought to be an error, but it was soon discovered that it was a fundamental property of a very interesting phenomenon involving the surface layer.

Most of the hot-spring pools had a thin film on the surface which extended out a distance from the edge determined by the convection currents within the pool and the action of wind stress on the surface. These films were seen to be very thin and were judged to be monomolecular, in view of the interference fringes they displayed. In the case of the Blue Star spring, this film covered the water in the bay or "thumb," to be seen at lower left in Fig. 1, and the approximate point at which the edge of the film crossed the bay is indicated by the arrow. The film also occurred in other parts of the pool, particularly in some of the other bays.

Fig. 1. Blue Star hot spring, where infrared measurements of the surface temperature were made. The diameter of the spring is approximately 15 feet. (×) Point of inflow of hot water; (arrow) the edge between the monomolecular surface film and the free water surface.

The source of hot water flowing into the pool at a constant rate was at the bottom directly beneath the point marked × in Fig. 1. The hot water flowed up and outward toward the edge. Most of the edge of the pool consisted of a thin shelf of rock which was undercut to a distance of about two feet. The water appeared to be circulating to some distance underneath this ledge. The forced convection within the pool was rather strong, and the temperature throughout the pool at a depth of about 30 centimeters, as well as under the surface film in the bay, was 83.8°C. The temperature at a depth of 5 centimeters under the surface film, as measured with a mercury thermometer, was 83.4°C, and at the same depth just beyond the film the tempera-

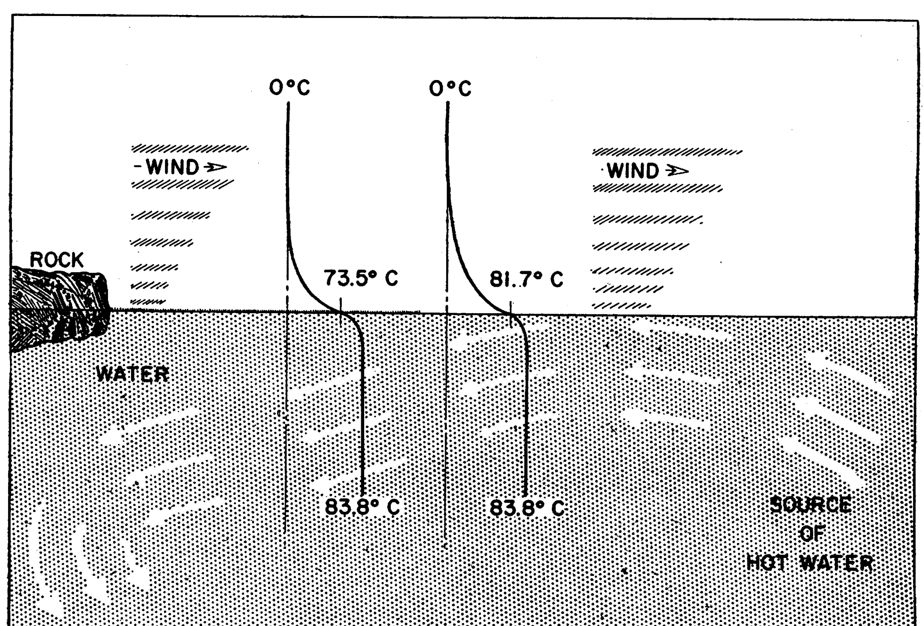

Fig. 2. Schematic drawing illustrating the temperature profile at the water surface and at the water-film surface of the Blue Star hot spring.

ture was 83.5°C. A few millimeters beneath the surface, at a depth just sufficient for immersing the thermometer bulb, the temperature was 82.0°C beneath the film and 82.4°C under the free water surface. The radiometer, when held within 3 millimeters of the surface, indicated a surface temperature of 81.7°C for the free water surface and of 73.5°C where the monomolecular film covered the surface.

This measurement was repeated several times, and the distinction in surface temperature was clearly defined. The results are illustrated in Fig. 2. As the surface film meandered into the bay or farther out, according to the strength of the wind, the surface-temperature boundary shifted with the film. Measurements on other days gave surface temperatures of 79.8° and 70.5°C, 78.2° and 72.0°C, and 80.2° and 69.5°C, respectively, for the free water surface and the monomolecular film. The temperature gradient was measured across the surface-film boundary on another bay at the opposite edge of the pool. The temperatures here were found to be 82.2° and 68.0°C and 76.1° and 69.0°C, respectively, for the free water surface and the monomolecular film. Across this film edge a horizontal difference in temperature as great as 14°C was observed.

It is conjectured that these striking temperature gradients are caused by the differential flow of heat to the surface by internal convection. The surface loses heat through radiation and evaporation. The monomolecular film defines a region where the surface is less disturbed by the wind, due to the protection offered by the rim of rock around the edge, which projects about two inches above the water surface. Warm water is constantly fed to the surface of the pool by forced convection, and this flow mixes the surface layer; however, the stream of warm water slides under the monomolecular film, which is maintained by the surface tension, and leaves at the surface, under the film, a thin layer of water which cools by radiation. These effects are illustrated in Fig. 2.

Another possible cause of the temperature difference may be that the monomolecular film changes the emissivity of the surface. This hypothesis was tested in the laboratory by placing various films, such as oils and turpentine, on a water surface and measuring the surface temperature before and after. No distinction could be detected. One would not expect a difference, on basic

Fig. 3. View of the vegetated thermal area studied, showing the bare soil, the moss, and the grass. The infrared radiometer is at upper right.

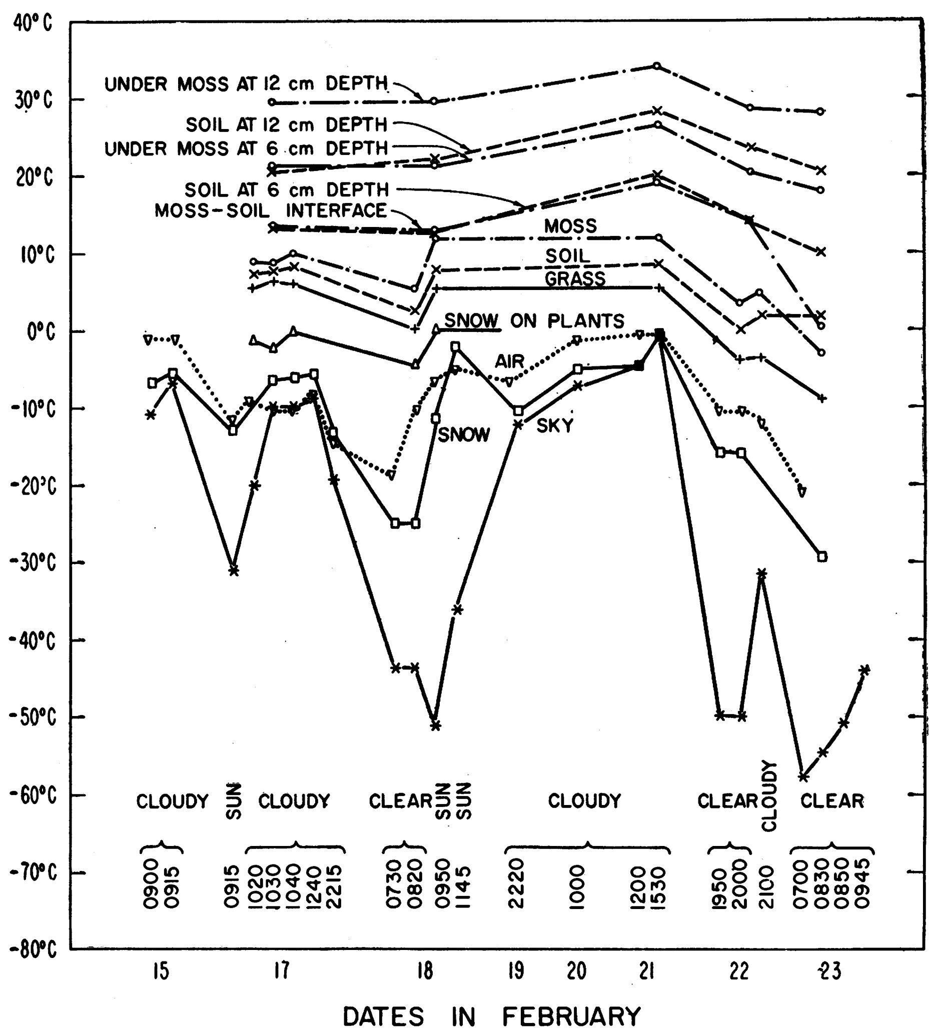

Fig. 4. The surface temperatures of the vegetation, soil, and snow in Yellowstone Park and the "radiant" temperature of the sky during part of February. The temperatures beneath the bare soil and beneath the moss-covered soil are also shown.

principles, but nevertheless the hypothesis required testing. Since the phenomenon seemed to be related to the convection stresses on the surface, we wondered if the monomolecular film might have changed the evaporation rate significantly. This effect was not considered to be important. However, a reduced evaporation rate at the monomolecular film surface would tend to increase the surface temperature rather than decrease it, as observed. A reasonable explanation is the transfer of warm water to the surface by internal forced convection beyond the film boundary and a lack of transport of water immediately beneath the film. Ewing and McAlister (*6*) have also reported an interesting surface-layer characteristic occurring on the ocean, detected by means of an infrared radiometer.

Thermal Environment of Vegetation

Two thermal areas were selected for a detailed investigation of the radiative characteristics of the surface features. The particular area reported upon here is shown in Fig. 3 and consists of an exposed soil surface, an area of moss (*Rhacomitrium canescens* Brid.), and an adjacent area of grass (*Panicum thermale* Bolander). The surface temperatures of these features were measured on several occasions with the radiometer. In addition, the surface temperature of the snow, where the snow was a foot or more deep, was measured. The radiometer was turned to the zenith in order to determine the "radiant" temperature of the sky. A mercury thermometer was used for measuring the temperature in the soil beneath the moss and beneath the exposed soil surface at several depths.

The results of these measurements are shown in Fig. 4 (it was not possible to make all the measurements every day because of other activities). It is clear that the supply of heat in the ground maintained the surface features at a reasonably constant temperature, but that the changes in temperature which did occur essentially reflected the cooling power of the sky. Part of the time the snow was nearly in radiation balance with the sky, as on 15, 19, 20, and 21 February, when there was a heavy stratus-cloud cover. Trees or animals in the area would have been receiving approximately 0.408 calorie of radiant energy per square centimeter per minute from the snow and sky at −5°C, a value which is nearly half the average energy received from the sun on a summer day. The effect of clouds is clearly seen on 22 February, when the sky temperature changed from −50° to −31.5°C (with a corresponding downward flux of radiation of 0.195 to 0.267 calorie per square centimeter per minute). The surface temperatures of the plants, soil, and snow responded to this increased warmth from the sky. The coldest recorded "radiant" temperature for the sky was −58°C, representing a downward flux of 0.169 calorie per square centimeter per minute. The moss surface was at about −3°C and emitted an upward flux of radiation equal to 0.420 calorie per square centimeter per minute, with a net loss of heat through radiation of 0.251 calorie per square centimeter per minute. Since there was no wind, this figure represents much of the total loss of energy by the moss, the transpiration rate probably being very small. The effect of sunlight warming the plant, snow, and soil surfaces is evident at 0950 on 18 February, even though the sky temperature dropped at this time. It should be emphasized that the energy environment of the Old Faithful area of Yellowstone Park in the winter is predominately a thermal-radiation environment, with the sunlight contributing a relatively small amount of energy to the total energy exchange, and the sun is often masked by heavy cloud cover. Of course, at night the energy environment is completely thermal in character, all the radiation exchange being at infrared wavelengths with a relatively weak convective exchange of energy at the surface, or with none at all.

The other vegetated thermal area studied was measured less frequently. It contained a grass (*Poa annua* Rinnaeus) at a surface temperature between 15° and 16°C on 20 February and between 10° and 11°C on 23 February, and a moss association of *Bryum turbinatum* (Hedwig) Schwager and *Ceratodon purpureus* (Hedwig) Brid. at 19° and 15°C, respectively. The bare rock adjacent to the vegetation was at 19°C on each of the two days.

Radiant Temperature of Water-Vapor Clouds

Measurements were made, from a distance of about 1 meter, of the "radiant" temperature of the water ejected from Old Faithful geyser during an eruption. A value of 73.5°C was obtained. This would appear to be correct in view of the fact that a great deal of cooler water is expelled with the steam and superheated water from deeper down and that the whole plume of water is pretty well mixed. Although much of the water plume fell back to the ground, the cloud which formed just downwind of the plume had a temperature of about 10°C, and some 20 meters downwind the cloud temperature was −4.5°C, with variations from 4° to −9°C. It is evident that the cooling rate in these clouds is very rapid; however, it is also apparent that a great deal of cooling takes place in the process of cloud formation during the dispersal of water droplets and the mixing with air. The water which fell back on the ground from the plume was at a temperature of 50°C or higher.

Similar measurements were made of the vapor cloud from Castle geyser. The temperature of the vapor cloud just downwind from the water plume was 26°C. At this point the cloud probably contained a great deal of warm water, which was raining out. Less than 15 meters downwind the temperature had fallen to the range −8° to −13°C, approaching the temperature of the ambient air.

The thermal-radiation measurements reported here show the value and feasibility of using an infrared radiometer in the field for measuring surface temperatures of vegetation and terrain, for measuring cloud temperatures, and for studying the surface temperatures of bodies of water. A good infrared radiometer for field work is needed in order that further systematic measurements of this type can be made readily and accurately.

References and Notes

1. The expedition was sponsored by a National Science Foundation grant to the College of Education (at Albany), State University of New York. I wish to thank Dr. John Marr (director, Institute of Arctic and Alpine Research, University of Colorado) for the loan of the radiometer, which was obtained with a grant from the National Science Foundation. I also wish to thank Dr. William A. Weber (University of Colorado) for identifying the plants; Dr. Claes Rooth (Woods Hole Oceanographic Institution) for his cooperation in making the measurements and for helpful discussions; Dr. Vincent Schaefer, leader and organizer of the expedition, for the opportunity to participate; and the superintendent and personnel of Yellowstone National Park for their excellent cooperation.
2. A. M. Stoll and J. D. Hardy, *Rev. Sci. Instr.* **25**, 184 (1954). The radiometer was manufactured by the Williamson Development Company, West Concord, Mass.
3. ———, *J. Appl. Physiol.* **5**, 117 (1952).
4. D. M. Gates and W. Tantraporn, *Science* **115**, 613 (1952).
5. N. E. Dorsey, *Properties of Ordinary Water-Substance* (Reinhold, New York, 1940), p. 327.
6. G. Ewing and E. D. McAlister, *Science* **131**, 1374 (1960).