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RADIATION MEASUREMENTS AT LEWIS GLACIER, MOUNT KENYA, KENYA

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ABSTRACT. Short- and long-wave radiation on variously oriented vertical surfaces, direct solar radiation, global radiation, and long-wave radiation on a horizontal surface were measured on Lewis Glacier, Mount Kenya, at 4 800 m. For the orientation of vertical surfaces, the following azimuths were selected: 45°, facing the steep slope of the upper glacier; 135°, facing a rock ridge and some glacier surface in the foreground; 225°, facing down-glacier towards the Teleki valley with open sky occupying much of the view; and 315°, directed towards the steep south-east face of the Nelion peak.

The horizontal components of diffuse short-wave radiation reach a magnitude comparable to those of direct radiation. As a result of contrastingly different albedos of natural surfaces, the horizontal component of diffuse short-wave radiation is particularly large from the direction of the upper glacier, with values around 330–500 W m^{-2}, and smallest from the direction of the rock face of Nelion peak, where values are around 150–330 W m^{-2}. Long-wave radiation seems enhanced from the direction of the Nelion face, and reduced from the azimuth of the upper glacier, thus apparently reflecting differences in emissivity and temperature.

RÉSUMÉ. *Mesures de la radiation au Lewis Glacier au Mount Kenya, Kenya.* On a mesuré sur le Lewis Glacier au Mount Kenya à 4 800 m les rayonnements de courte et de grande longueur d'onde sur des surfaces verticales d'orientation variée, ainsi que le rayonnement solaire direct, le rayonnement global et le rayonnement de grande longueur d'onde sur une surface horizontale. Pour l'orientation des surfaces verticales, on a chois les azimuths suivants: 45° face à la pente forte du glacier supérieur, 135° face à une paroi rocheuse et un peu de surface en glace au premier plan, 225° face à l'aval du glacier vers la vallée de Teleki, avec le ciel libre occupant la plus grande part du champ de vision, et 315° en direction de la face sud-est très raide du Pic Nelion.

Les composantes horizontales de la radiation diffuse de courte longueur d'onde atteignent un ordre de grandeur comparable à ceux de la radiation directe. En raison des différences très marquées d'albédos des surfaces naturelles, la composante horizontale de la radiation diffuse de courte longueur d'onde est particulièrement forte en provenance de la direction du glacier supérieur avec des valeurs d'environ 330 à 500 W m^{-2} et est minimum en provenance de la paroi rocheuse face au Pic Nelion où les valeurs sont de l'ordre de 150 à 330 W m^{-2}. Les radiations de grande longueur d'onde semblent presque nulles en provenance de la direction de la face du Nelion et réduites en provenance de l'azimuth du glacier supérieur, ces phénomènes étant apparemment dus à des différences d'émissivité et de température.

ZUSAMMENFASSUNG. *Messung der Strahlung am Lewis Glacier, Mount Kenya, Kenya.* Auf dem Lewis-Glacier am Mount Kenya wurden in 4 800 m Höhe kurz- und langwellige Strahlung auf vertikalen Flächen unterschiedlicher Orientierung, direkte Sonnenstrahlung, Globalstrahlung und langwellige Strahlung auf eine horizontale Fläche gemessen. Für die Orientierung der Vertikalflächen wurden die folgenden Azimute ausgewählt: 45°, auf den Steilhang des oberen Gletschers zu; 135°, mit Blick auf einen Felsrücken und etwas Eisfläche im Vordergrund; 225°, gletscherabwärts auf des Teleki-Tal zu, wo das Blickfeld vornehmlich freien Himmel einschliesst; 315°, mit Blick auf die steile Felswand des Nelion-Gipfels.

Die horizontalen Komponenten der diffusen kurzwelligen Strahlung erreichen eine ähnliche Grösse wie die der direkten Strahlung. Infolge der unterschiedlichen Albedo natürlicher Flächen ist die Horizontalkomponente der diffusen kurzwelligen Strahlung aus der Richtung des oberen Gletschers, mit Werten um 330–500 W m^{-2} besonders gross; dagegen ergeben sich die geringsten Werte aus der Richtung der Nelion-Felswand, wo sie nur 150–330 W m^{-2} betragen. Die langwellige Strahlung ist vergleichsweise gross aus Richtung der Nelion-Felswand, und wesentlich geringer im Azimut des oberen Gletschers, offenbar infolge unterschiedlicher Emissivität und Temperatur.

1. INTRODUCTION

As part of a multi-annual field project on Lewis Glacier, Mount Kenya (Hastenrath, 1975; Caukwell and Hastenrath, 1977) studies related to the mass and heat budget were conducted during the 1977–78 field season. A variety of radiation measurements were made. The limited radiation equipment proved versatile enough for measurements on the anisotropy of radiative fluxes. Earlier studies (Untersteiner, 1957; Hastenrath, 1978) have demonstrated the importance of the reflectivity of large ice masses for the diffuse radiation on a horizontal surface, although the diffuse component contributes only a small fraction to global radiation in locations at high elevations and in free exposure outside the glacier. Angular variations in the long-wave part of the spectrum have long been used in the remote sensing of the temperature of various natural surfaces (Dronia, 1978). The 1977–78 Lewis Glacier Expedition provided a useful opportunity for measuring various radiative flux components from different azimuths with contrasting surface properties in a high-mountain glacier environment.

2. Instrumentation and observation program

In the experiment reported here a "UPYR" multi-purpose radiation kit of Firma Rosenhagen (Georgi, 1956) was used, while a variety of other radiation instruments were available for the overall project. The "UPYR" instrument permits the measurement of total short-wave and short- plus long-wave radiation on a horizontal and variously-oriented vertical surfaces. The direct short-wave radiation on a surface perpendicular to the solar rays can also be measured by use of a collimator tube. Independently, the direct and diffuse components of the total flux can be separated by means of a small disc used to blot out the direct solar radiation.

A site on the middle glacier near the equilibrium line was chosen for a variety of measurements related to the mass and heat budget and for the present experiments (Fig. 1). The measurement set-up is illustrated in Figure 2. A pole was inserted vertically in the ice at this location. A horizontal bar of 70 cm was strapped to the vertical pole by means of a right-angled metal piece in such a way that the horizontal bar could be rotated freely through all azimuths.

The radiation sensor, a Moll–Gorczynski thermopile, was installed at the free end of the horizontal bar. The output from the thermopile is read on a sensitive galvanometer. A strictly horizontal or vertical orientation of the sensor surface could be ensured by a rotation

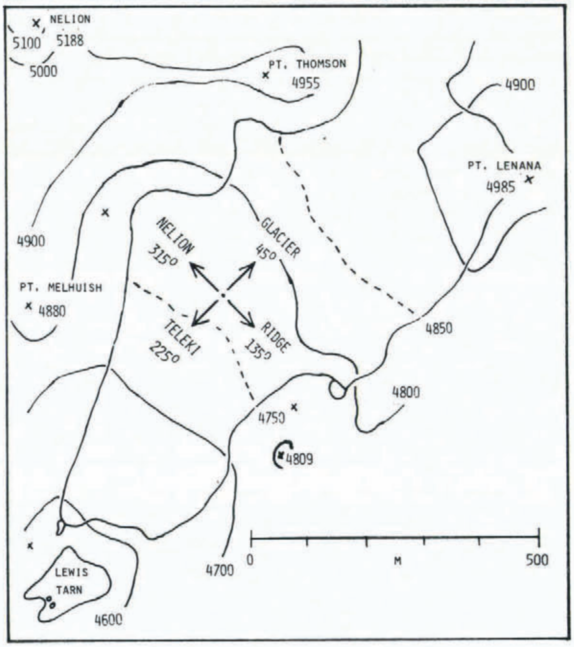

Fig. 1. Orientation map of Lewis Glacier. Contours in meters. Dot indicates observation site, and arrows denote the four azimuths of measurements depicted in Figure 2: 45° glacier, 135° ridge, 225° Teleki, 315° Nelion.

Fig. 2. Installation for measurement of radiation on a vertical surface.

device around a horizontal axis and levelling bubbles. Interchangeable glass and plastic (lupolén) cupolas yield measurements in the spectral regions of 0.3–4.0 µm and 0.3–30.0 µm respectively. Radiation in the long-wave region 4–30 µm is obtained by difference. A small thermometer inserted in the thermopile head permits an estimate of the temperature of the sensing surface and hence the calculation of the black-body radiation emitted from the sensor surface according to the Stefan–Boltzmann law. Thus the long-wave radiation impinging on the sensor surface can be determined. The thermopile is fitted with a white collar to eliminate short-wave reflection from the opposite hemisphere.

Measurements with a vertically-oriented sensor surface and both glass and lupolén cupolas were made in the four directions at right angles to each other as shown in Figure 1. The four directions were chosen to represent contrastingly different natural surfaces. At 45° (Glacier) the instrument faces a steep ice slope, at 135° (Ridge) the view consists of a rock ridge and some glacier surface in the foreground, 225° (Teleki) faces down glacier and sky occupies much of the view, at 315° (Nelion) the view is dominated by the close and high south-east face of Nelion.

Measurements of radiation incident on a horizontal surface were made with both the glass and lupolén cupolas, both with and without the use of the small disc for blotting out direct solar radiation. Furthermore, the direct solar radiation on a surface perpendicular to the solar rays was measured, as well as the instrument temperature.

It was considered important to complete an observation series in a short time interval and under essentially unchanged atmospheric conditions, so that all measurements of a series could be regarded as synchronous. The sequence within a series was as follows: temperature of the thermopile; direct radiation on a surface perpendicular to solar rays using the collimator tube; radiation on a vertical surface using the glass cupola at azimuths 45°, 135°, 225°, 315°, and repeating 45°; radiation on a vertical surface using the lupolén cupola, at azimuths 45°, 135°, 225°, 315°, and repeating 45°; radiation on a horizontal surface, glass cupola with disc, then without disc; radiation on a horizontal surface, lupolén cupola without disc, then with disc; direct radiation on a surface perpendicular to solar rays; temperature of the thermopile.

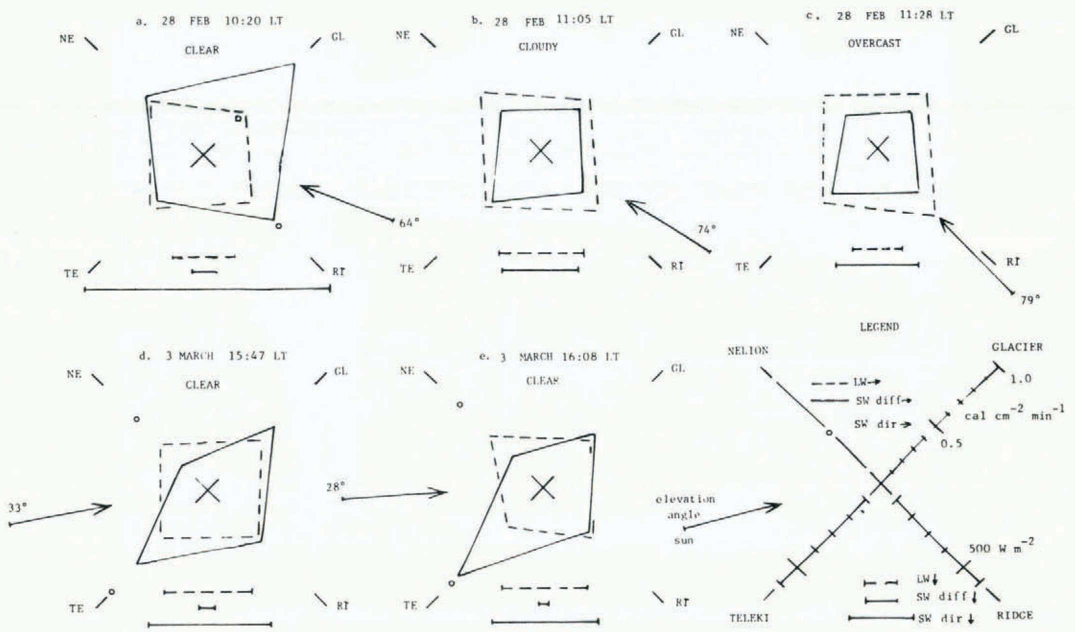

Fig. 3. Azimuth dependence of radiation. a. 28 February 1978, 10.20 h L.T., clear; b. 28 February, 11.05 h L.T., cloudy; c. 28 February, 11.28 h L.T., overcast; d. 3 March, 15.47 h L.T., clear; e. 3 March, 16.08 h L.T., clear. Plots in the four azimuths denote diffuse short-wave (solid lines), direct short-wave (dots), and long-wave (broken lines) radiation perpendicular to orthogonally oriented vertical surfaces. For comparison with the fluxes across vertical surfaces, the long-wave (broken lines) and direct and diffuse short-wave (solid lines) radiative fluxes measured on a horizontal surface are represented in the lower portion of each diagram. See key in lower right-hand diagram. Arrow denotes azimuth of sun, and number at its tail solar elevation angle.

After some practice and with a team of two it proved possible to complete a series in about 5 min. Series are ascribed to the middle of this time span. Series within which the repeated measurements did not agree within 0.1 cal cm^{-2} min^{-1} (71 W m^{-2}) were rejected. Only the remaining five series are discussed here (Fig. 3).

Solar azimuth and elevation angle are a function of latitude, declination, and hour angle. Accordingly, the direct radiative flux components on the four aforementioned vertical surfaces can be calculated from the measurements of direct radiation on a surface perpendicular to the solar rays. These figures of direct solar radiation on vertical surfaces were subtracted from the measured values of direct plus diffuse short-wave radiation so as to yield the diffuse short-wave radiation on vertical surfaces. The direct and diffuse components of solar radiation on vertical surfaces of the four aforementioned azimuths are plotted in Figure 3. Accounting for the black-body radiation of the sensor itself, the horizontal components of long-wave radiation from the four azimuths are also plotted in Figure 3.

3. Short-wave radiation

A characteristic feature related to the reduced air density in the high-mountain environment is the extremely small contribution of the diffuse component to the total solar radiation received on a horizontal surface (global radiation). Figure 3 a, d, e, for three clear-sky situations bear out the subordinate role of the diffuse component of global radiation even with the rather high albedo conditions at Lewis Glacier. In fact, around the measuring site and in late February to early March 1978, surface albedo was of the order of 70–80%. Diffuse radiation on a horizontal surface is enhanced under the cloudy to overcast sky conditions represented in Figure 3 b and c. In the latter two cases direct solar radiation was blotted out completely. Considering the conventional horizontally-oriented reference surface, Figure 3 shows radiation conditions similar to those found in the high-mountain environment outside the glacier.

More remarkable is the azimuth distribution of short-wave radiation fluxes on vertically oriented surfaces shown in Figure 3. For the cloudy and overcast conditions depicted in Figure 3 b and c, the diffuse short-wave radiation through vertical surfaces is similar for the various azimuths and of a magnitude comparable to the diffuse radiation with reference to a horizontal surface. By contrast, the clear-sky series, Figure 3 a, d, and e, exhibit a marked azimuth asymmetry of diffuse short-wave radiation. Also, the horizontal components of the diffuse short-wave radiation are relatively important in that they reach a magnitude comparable to the horizontal and vertical components of direct short-wave radiation.

An enhancement of diffuse short-wave radiation is to be expected in portions of the sky near the sun. Some indication of this effect is apparent in Figure 3a, where the values for the azimuth nearest the sun, Ridge, is larger than that for Teleki and Nelion, although it is smaller than that for Glacier. Likewise in Figure 3d, the azimuth nearest to the sun, Teleki, has the largest value, although that for Glacier is exceeded only slightly. A similar state of affairs is apparent in Figure 3e, where the largest value is again found for Teleki, the azimuth nearest to the sun. Asymmetry is less pronounced under an overcast sky, Figure 3c, although the value is largest for Ridge, which differs little from the solar azimuth.

An essential objective of the experiment was a quantitative estimate of the azimuth dependence of diffuse short-wave radiation resulting from contrastingly different albedos of natural surfaces. The clear-sky series, Figure 3 a, d, and e, indeed shows a marked enhancement of diffuse short-wave radiation from the azimuth with a bright glacier surface, as opposed to the quadrants with predominantly dark rock surfaces. Thus in Figure 3a, Glacier has the largest value, although Ridge is closest to the solar azimuth. In Figure 3d, Glacier has values much larger than Ridge and Nelion, and only little smaller than Teleki, the azimuth largely made up of open sky. A similar state of affairs is indicated in Figure 3e.

Very small values of diffuse short-wave radiation are borne out for Nelion, especially when this is near the solar azimuth, such as in Figure 3d and e. In Figure 3a, the south-east face of Nelion is approximately opposite to the solar rays, and reflection from the high rock face appears comparatively large.

4. Long-wave radiation

The azimuth dependence of long-wave radiation is rather less pronounced than that of diffuse short-wave radiation. Figure 3 a, b, c, and e, but not d, show larger values for Nelion as compared to Glacier. This may in part reflect the different temperature and emissivity of a rock face as compared to an ice surface. The rather large range of values in the Teleki quadrant is probably related to the varying cloudiness at low elevation angles. It should be recalled that sky makes up large part of the view at this azimuth.

5. Concluding remarks

For purposes of the terrestrial heat budget, radiative fluxes are conventionally referred to a horizontal surface. In the thin air of the high mountain environment, the diffuse component of short-wave radiation tends to become vanishingly small compared to the direct component. Long-wave and diffuse short-wave fluxes on vertical surfaces are not commonly measured.

The recent Lewis Glacier Expedition provided the opportunity for a small experiment to document the typical magnitude of horizontal flux components from directions with contrasting terrain properties. The diffuse short-wave radiation contributed by reflection from extensive ice masses of high albedo is substantial, both in comparison with the horizontal components of direct radiation and global radiation. By contrast, azimuths with extensive rock faces are associated with only a small horizontal component of diffuse short-wave radiation. Long-wave radiation appears smaller from directions with glacier surfaces than from azimuths with rock faces. While azimuth asymmetries of long-wave and diffuse short-wave radiation are likely to be small in locations of free exposure at high altitudes, they are found to reach important proportions in the complicated terrain conditions of a valley glacier.

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