Reports

Satellite Observations of the Earth's Radiation Budget

Abstract. *Meteorological satellites have provided the first complete data on energy exchange between earth and space. The planetary albedo is 29 percent for the mean annual case, and the entire earth-atmosphere system is in near radiative equilibrium. More energy is absorbed in tropical regions than previously believed, and major energy source and sink regions exist within latitude belts.*

The earth's radiation budget, on a global or local scale, is defined as the difference between solar energy absorbed in the atmosphere or at the surface and infrared energy emitted by the earth and its atmosphere. Thus, the net energy exchange across the "top of the atmosphere" can be measured from orbiting earth satellites and is termed the net radiation RN. Where

$$RN = I_0\,(1.0 - A) - RL$$

and I_0 is the direct incoming solar radiation (derived from knowledge of the solar constant), A is the planetary albedo (fraction of I_0 which is reflected and scattered back to space by the atmosphere, clouds, and surface features), and RL is the infrared energy loss to space.

For many years scientists have tried to estimate the magnitude and variations of this energy exchange because its variation with latitude, from equatorial to polar regions, is the ultimate driving force for large-scale atmospheric and oceanic circulations. Most of the earlier work in this area has been reviewed (*1*). These earlier studies were faced with two major problems: (i) the difficulty of computing the transfer of radiation in a cloudy atmosphere and (ii) the lack of global observations of temperature, moisture, and cloudiness.

The first complete set of satellite measurements during all seasons was recently used (*2*) to study the earth's radiation budget. Vonder Haar evaluated more than 30 months of observations (1962 to 1965) from low-resolution sensors flown on Tiros-type satellites. Other scientists (*3*) had discussed the radiation budget for shorter periods, and Winston (*4*) had computed satellite measurements to weather patterns. This latter application points out the usefulness of the results of studies of the radiation budget as applied to local areas. In addition to providing a measure of the energy exchange between the local area and space, the magnitude and variation of the satellite observations yield inferences regarding atmospheric conditions, especially cloudiness, over areas of the world where conventional meteorological observations may be very sparse or nonexistent.

For the mean annual case, the measured global planetary albedo is 29 percent and the entire earth-plus-atmosphere system is in near radiative equilibrium since the infrared emission averages 0.33 cal cm^{-2} min^{-1}. No significant differences between the total radiation budgets of the Northern and Southern hemispheres are noted on a mean annual scale. This points out the overriding influence of cloudiness on the energy exchange between earth and space, since the surface features of the hemispheres are quite different.

Instrumental accuracies and the present-day uncertainty in the absolute magnitude of the solar constant (or its variation) contribute almost equally to uncertainties in the total global radiation balance derived from the satellite measurements. In order to provide more information about this problem, the solar load on the satellite radiation sensors at each terminator crossing was combined with data on prelaunch sensor absorptivity to measure the solar constant from the orbiting satellite. A value of 1.99 ± 0.03 cal cm^{-2} min^{-1} was obtained (*5*). When a value of 2.00 cal cm^{-2} min^{-1} is used for the solar constant with the albedo and infrared measurements, an average global radiation gain of $+0.01$ cal cm^{-2} min^{-1} yields a small net warming of the entire system during the period of observation. If a solar constant of 1.92 cal cm^{-2} min^{-1} were chosen, global balance within the limits of instrumental accuracy is attained.

Averaged values for the radiation budget in latitudinal zones present a mean meridional profile for the annual case (Fig. 1). The longwave radiation observations from satellites have a north-south variation similar to that estimated by London (*6*) and others. These measurements of infrared energy have magnitudes generally higher than, but within 5 percent of, those computed in earlier studies. Measured values of planetary albedo, however, are much lower in the tropical regions than was earlier assumed. A probable reason for the difference was the overestimate, in earlier work, of the amount of opaque

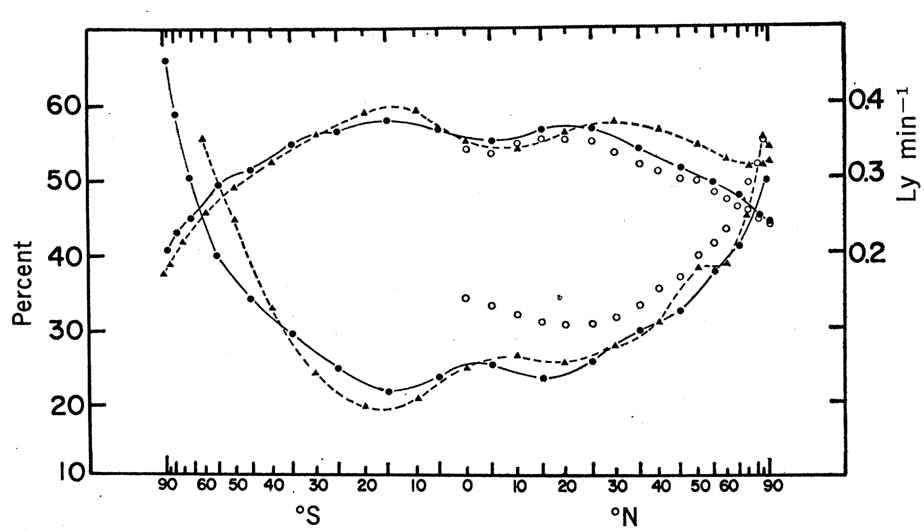

Fig. 1. Mean meridional profiles of outgoing infrared radiation (*Ly min*$^{-1}$, upper portion) and planetary albedo (*Percent*) from our study and other sources (1 langley min^{-1} = 1 cal cm^{-2} min^{-1} = 698 watt m^{-2}). Dashes joined by solid circles mean 1963–1965 (*2*); dashes joined by solid triangles, July 1966 (*7*); open circles mean annual (*6*).

cloud cover. This result is confirmed by the first measurements returned from our second-generation (Nimbus) meteorological satellites. Data for July 1966 (7) differ from the mean annual results of this study only in a manner to be expected due to seasonal effects.

As a result of the "darker" tropics, the satellite data show that as much as 30 percent more energy is absorbed by the earth-atmosphere system in these latitudes. This causes a stronger poleward gradient of net energy exchange across the upper atmospheric boundary and requires increased transport by the atmosphere and ocean to offset the equator-to-pole imbalances. In the tropics the prime mechanisms involved may be more convective energy transport to the upper troposphere, higher values of direct absorption of solar energy in the atmosphere or increased energy transport by ocean currents. If a major amount of the extra solar energy is directly absorbed in the atmosphere, it is immediately available for use as an energy source for atmospheric motions. By contrast, if it is absorbed primarily in the oceans then the acknowledged importance of air-sea energy transfer is further emphasized. A study (8) based on satellite data and surface observations of solar radiation indicates that the ocean receives most of the additional energy at two Pacific locations.

For the mean annual case, these first satellite measurements of the radiation budget of the polar regions show that the effective radiating temperatures of the Arctic and Antarctic are 232° and 225°K, respectively. Albedo measurements exceeding 50 percent in the north and 70 percent near the South Pole are naturally heavily weighted by the summertime conditions. The subtropical zone of the Southern Hemisphere has the highest mean annual value of outgoing infrared radiation and the lowest planetary albedo.

Maps of the geographical distribution of outgoing longwave radiation and albedo (Fig. 2) point out areas of prime departure from the zonal mean values. These maps provide a wealth of information about the energy exchange across the top of selected earth-atmosphere columns and also yield inferences about the surface and atmospheric conditions that regulated this exchange. Even over periods as long as a year, pronounced east-west variations in the radiation budget parameters can be noted within the region 30°N to 30°S. When considered as a whole this region is a net source of energy for the earth-atmosphere system. The radiation maps point out the major source areas which can be further observed and studied with more recent satellite observations and conventional data. They also show relative minima of net radiation (high values of A and RL) over the continental and oceanic deserts of the subtropics and over a region of the eastern Pacific that has been noted to have special weather activity from the photographs of the National Aeronautics and Space Administration's Applications Technology Satellite (9).

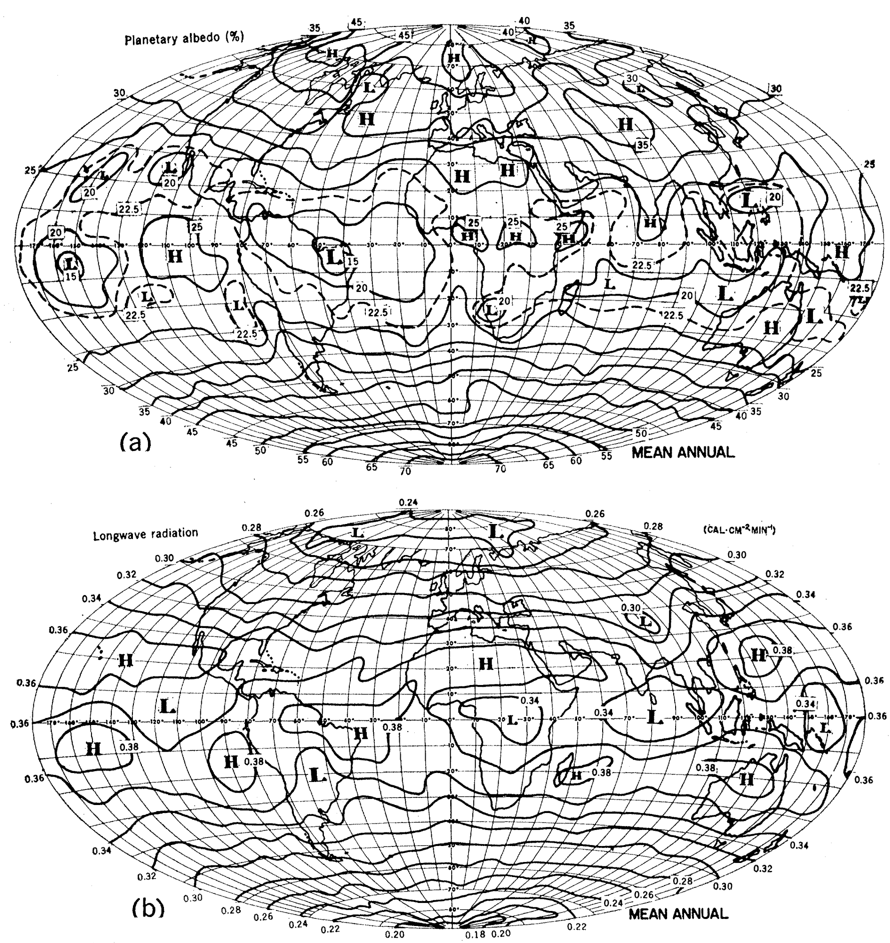

Fig. 2. (a) Geographic distribution of planetary albedo. (b) Geographic distribution of outgoing infrared radiation. Data obtained from satellite observations; H, high; L, low.

In contrast to the lower latitudes, the areas poleward of 30° have albedo and infrared patterns that are rather zonal, a result of the influence of migratory weather systems (that is, alternating clear and cloudy periods) at these latitudes. However, the maps do show meridional patterns extending north and south from the "maritime continent" region east of New Guinea. These patterns may mark a preferred region for poleward energy exchange. In addition, the influence of surface reflection (that is, snow and ice cover) on the albedo measurements over the continents of the Northern Hemisphere is apparent. Both the albedo and longwave radiation maps emphasize the dissimilarity of the radiation budgets of the two polar regions. Over a year, the Antarctic is a greater energy sink region.

Since the net radiation budget, as measured from satellites, is the prime forcing function that drives our atmospheric and oceanic circulations, it is important that these first results be extended by additional measurements. Particular attention must be given to improved accuracy and areal resolution of the radiometers. Furthermore, a more precise determination of the absolute magnitude (or variation) of the solar constant is required (10). When these new data are combined with results of the present study we shall have just begun to adequately explore the energy exchange between earth and space.

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Water on the Moon and a New Nondimensional Number

Abstract. *A nondimensional number called the Jeffreys number, which represents the ratio of the Reynolds number to the Froude number, is useful in geophysical problems related to the motion of viscous masses under gravity. The Jeffreys number is used to show that it is impossible for the lunar maria to be underlain by a layer of material 1 kilometer thick having the plastic properties of ice.*

Urey (*1*) proposed that the lunar surface has been shaped by flowing water in some places, especially in the so-called sinuous rills. These are meandering channels, generally thought to be the work of some fluid, often regarded as the channels of flows of lava (*2*) or ash (*3*). Urey's main point is that, with a couple of minor exceptions, there are no signs of deltas at the lower ends of these channels. Since the amount of material which has been eroded away in forming the channel may be hundreds of cubic kilometers, the lack of evidence of deposition is certainly significant and is not due to any problem associated with observing the deposits, unless they are widely dispersed.

Urey agrees with suggestions by Gold that the maria are underlain with permafrost having the properties of "plastic ice" (*4*). In this case, the melting, evaporation, and eventual escape of the water would explain the lack of delta deposits.

This paper demonstrates that the dynamic behavior of ice is inconsistent with what is known about the maria. In particular, the viscosity of ice is so low that the maria, if composed of ice, should show no craters over a kilometer in diameter. Larger craters should have smoothed out as a result of gravitational action.

In problems which involve both gravitational and inertial forces, it is customary to consider the ratio of the Reynolds number to the Froude number. The Reynolds number is

$$\mathrm{Re} = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{\rho v L}{\mu} \quad (1)$$

where ρ is the fluid density, v is the velocity of the fluid, L is a characteristic length, and μ is the fluid viscosity.

The Froude number is

$$\mathrm{Fr} = \frac{\text{inertial forces}}{\text{gravitational forces}} = \frac{v^2}{gL} \quad (2)$$

where g is the gravitational acceleration. The ratio of the Reynolds number to the Froude number occurs so frequently in geophysical problems that it should perhaps be given a separate designation, such as the Jeffreys number

$$\mathrm{Je} = \frac{\text{gravitational forces}}{\text{viscous forces}} = \frac{\rho g L^2}{\mu v} \quad (3)$$

or if we introduce a characteristic time $t = L/v$

$$\mathrm{Je} = \rho g L t/\mu \quad (4)$$

For example, the equation of Jeffreys (*5*) for the flow of a viscous liquid of thickness L down an incline of angle A can be written

$$\mathrm{Je} = 3/\sin A \quad (5)$$

The equation of Heiskanen and Vening Meinesz (*6*) for the rate of recovery of a continental area after the disappearance of a glacial ice sheet may be written

$$\mathrm{Je} = 2\pi S \quad (6)$$

where S is a nondimensional shape factor, namely, the ratio of the width of the area to the depth of deformation. Even the application of the Stokes equation to the rise of a bubble of radius L, consisting of gas of negligible density, through a liquid of density ρ may be written

$$v = (-2/9)(L^2\rho g/\eta) \quad (7a)$$

where v is the terminal velocity of the sphere and η is the coefficient of viscosity. Thus

$$\mathrm{Je} = -9/2 \quad (7b)$$

In general, the Jeffreys number is of the order of the ratio of width to height in the collapsing structure.

Glacier ice behaves like a fluid of viscosity 10^{14} poise (*7*). Since the temperature of the moon's interior does not fall below $-33°C$, properties of ice in the interior of the moon would resemble those of glacial ice. For a crater 1 km in radius, with a depth-to-radius factor of ½, if $\mathrm{Je} = 2$ and $g = 162$ cm sec^{-2}, t is approximately 10^7 seconds. We would therefore expect a lifetime of the order of a few months, whether we regard it as the limiting case of a large bubble or as a problem in continental uplift, if we consider the rate at which the walls of the crater will slump inward. Since the maria do contain numerous craters of this size, it is not likely that they have a substantial layer of ice.

The Jeffreys number can be used directly to study the analogy (*4*) between terrestrial pingos (craterlets a few tens of meters in diameter formed by the diapiric motion of ice) and certain lunar craters with large central peaks, such as Alpetragius, which are about three orders of magnitude larger. Pingos occur in regions that were once glaciated; hence, their lifetimes are under 10^4 years. Alpetragius, which is a rather sharp feature of the moon, may be only 10^8 years old. If these two structures are fundamentally analogous, they should have the same Jeffreys number. Using the second form of the Jeffreys number (Eq. 4), we find that the material in Alpetragius, which is analogous to the ice of the pingos, cannot be ice; it must have a viscosity of the order of 10^{20} poise or more, like the material of the upper mantle of the earth.

These principles can be applied to the problem raised by Urey. If a sinuous rill, such as Schröter's Valley, about 5 km wide and 1 km deep, were to be cut in ice, the Jeffreys number would probably be about 5. The corresponding value of t is about 10^7 seconds; it appears that Schröter's Valley would disappear within a year, even if the ice were protected from melting by an overburden of soil. These rates of movement are quite consistent with the observed movements of thick glaciers, which advance at rates up to 10 m per day.