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Effect of cloud and sun positions upon the horizontal distribution of solar radiation incident on the earth's surface*1

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When clouds form shadows on the earth's surface, the shadowed areas receive far less solar energy than do shadowless areas. This results in non-uniform distribution of solar energy over the earth's surface. Shadow positions formed on the earth's surface are governed not only by cloud distribution but also by the sun's position. In order to investigate the effect of the sun's position, the diurnal variation in shadow position of a simple cloud model was calculated each month in the southern North Pacific. The results show that the diurnal loci of shadow position vary largely with the season, and that in general they are formed away from the cloud position projected on the surface. It is also shown that shadows formed at about noon may occupy nearly the same position for a long time. This suggests the development of a characteristic "cool part", or an area receiving a small amount of solar energy. In order to make a more quantitative study, horizontal distribution of daily cumulative solar irradiance was calculated when stationary and moving clouds were present. The variation of energy with location is discussed in the case of stationary and moving clouds.

1 Introduction

The clouds present over the earth's surface reflect, scatter and absorb a large amount of direct solar radiation, and form shadows on the surface. Since shadowed areas receive much less direct sun radiation than do shadowless areas, the horizontal distribution of the amount of solar irradiance absorbed and transformed into heat by materials such as sands and sea water is dependent on cloud distribution. Thus, cloud distribution holds the key to better understanding of the earth's heat budget.

Recently, satellites have made it possible to observe the distribution of clouds over a vast area. On the basis of satellite data, the downward irradiances at the earth's surface have been estimated by, for example, Gautier et al.[1], Meoeser and Raschke[2], Dedieu[3] and Darnell et al.[4]. In computing the solar energy incident on the earth's surface, after determining the location of shadowed areas from satellite data, these researchers seem to have assumed that such shadows are formed on the surface directly below the clouds. This assumption is acceptable when dealing with large-scale phenomena such as climate changes. For application to local variations in radiation, however, we should pay much more attention to temporal variations in shadow position as a function of the positions of both cloud and sun.

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In this paper, diurnal variations in shadow position and horizontal distribution of total amount of daily solar irradiance incident on the earth's surface are computed using a simple optical model. In addition, the effect of cloud movement upon daily solar irradiance is taken into consideration.

2 Computational schema

Let us consider a cloud at a height h above the earth's surface, where the coordinates of its projection on the surface are (a,b). When the cloud is irradiated by the sun in the direction (θ , ϕ), where θ represents altitude and ϕ azimuth (clockwise from the east), the coordinates of the shadow generated on the sea surface (a',b') are expressed by,

$$
\begin{aligned}
a' &= a - h \cdot \cot\theta \cdot \cos\phi \\
b' &= b + h \cdot \cot\theta \cdot \sin\phi
\end{aligned}
\qquad (1)
$$

The sun direction, (θ , ϕ) in Eq. (1), is a function of local time and obtainable with equations based on those presented by Escobal[5].

Meanwhile, shadow position is affected by cloud thickness. In order to take this into consideration, the cloud is divided into thin layers 10m in thickness, and the shadow position due to each thin layer is computed by Eq. (1).

In addition to calculation of the shadow position as described above, the sun irradiance which reaches the earth's surface after passing through the cloud may be calculated if absorption and reflection of the clouds, as well as atmospheric transmittance, are given. In actual calculations, absorption and reflection of solar radiation by clouds are taken from those reported by Liou 6). The atmospheric transmittance of one air-mass and total solar irradiance outside the atmosphere were taken as 0.7 and 1376W/m^2, respectively.

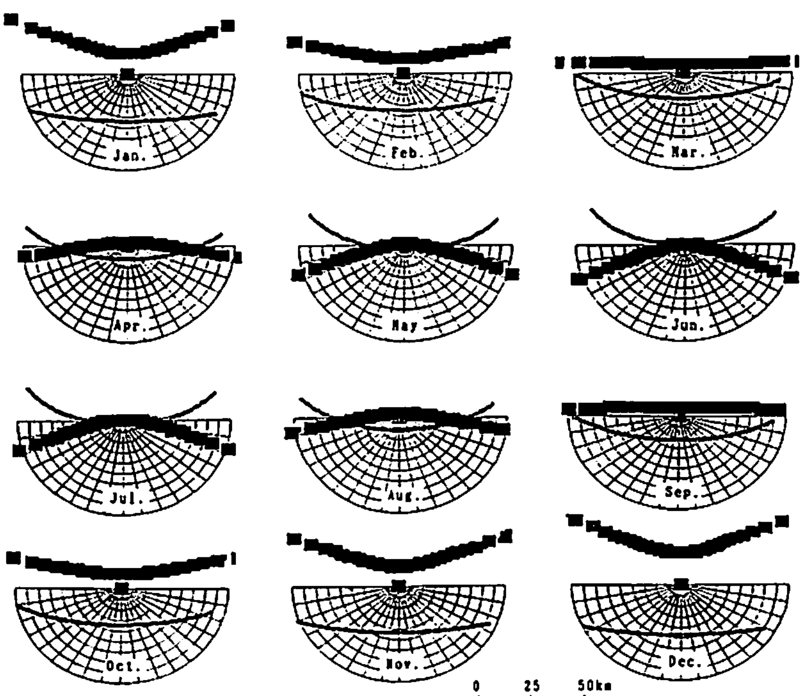

Fig. 1. Computed shadow position (squares) on the 19th of each month, assuming a cloud fixed at 10 km over the surface at 23°N and 135°E, which is shown by square in the center of polar coordinate of the figure.

3 Computational results

3.1 Variation of shadow position with time

First, it is assumed that a cloud 10m in thickness with an area of 3 km x 3 km is fixed at 10 km over the surface at a latitude of 23° N and longitude of 135°E. Shadow position is computed using Eq. (1) at 10-minute intervals from sunrise to sunset on the 19th of each month.

Shadow positions on a 1 km grid along with the sun direction (projected on the sea surface on the polar coordinate) are plotted in Fig.1. The loci of the shadow are nearly symmetrical around the North-South axis. In January and February, the cloud is irradiated by the sun which declines southward. This results in the shadow positions' being located always to the north of the cloud. As the sun altitude becomes higher in spring, the shadow locations become closer to the cloud position on the surface. In both morning and evening, from May to July, the shadows becomes located to the south of the cloud, whereas around noon they are formed directly below the cloud. In August, the shadows return to the north of the cloud throughout most of the day. From September to March, the shadows are located to the north of the cloud during the daytime. It is noteworthy that in December the shadows are located far from the cloud position projected on the surface; the nearest distance is about 16 km to the north of the cloud, observed at about noon.

Thus, diurnal and seasonal variation in shadow position is great. Similar variation seems to occur in other regions; the higher the latitude, the more northward shifts the shadow position. Accordingly, the assumption of a constant cloud position directly below the cloud is not acceptable in dealing with small-scale phenomenon. It should be noted here that the shadow position of mid-level and low-level clouds may appear nearer to the cloud position projected on the surface, since the cloud height of 10 km assumed in this calculation is applicable only to high-level clouds.

3.2 Horizontal distribution of sun irradiance

If the horizontal variation in the shadow position of clouds is great, as described above, it seems that the effect of shadows on horizontal distribution of irradiance falling on the surface would then be slight. However, we can anticipate that the effect of shadow upon direct sun irradiance is very slight in both the morning and evening, when shadows move very quickly. On the other hand, shadow movement around noon is very slow, and shadows may occupy the same surface position for a long time during this period. The result is that there is a characteristic region "cool part" receiving considerably less solar irradiance than do other regions. At the same time, a large amount of solar irradiance falls on shadowless regions at around noon, when altitude of the sun is great. Accordingly, differences in the solar irradiance distributed to the shadowed and shadowless regions might become very large, provided that clouds were thick enough to absorb and scatter most of the energy from the sun. This might result then in further development of cool part. It should be noted that a cooler part is always present when a constant shadow position is assumed. When, however, shadow movement is also taken into consideration, the cool part is formed away from the area directly below the cloud, except when the sun is at its zenith.

In order to investigate quantitatively clouds' effect upon surface irradiance, the horizontal distribution of total daily sun irradiance incident on the earth's surface is calculated at 13°N and 148°E to the southeast of the previous position. In this case, cloud area is 3 km x 3 km, and base height and thickness of the cloud are set at 4.2 km and 0.6 km, respectively, which are taken from those for middle-level clouds appearing in the table prepared by Liou[6]. It is also assumed that transmittance of the cloud and atmosphere are 0.995217 /0.01km and 0.7/air-mass, respectively.

The results for Apr. 19, Aug. 19 and Dec. 19, in terms of the ratio of irradiance at each grid to maximal irradiance, are shown on the 100 m grid in Fig. 2. The ratio between maximal and minimal irradiances are 0.68, 0.66 and 0.68 in April, August and December, respectively, showing no remarkable difference among seasons. As we expected, the shadow effect on total incident irradiance is concentrated in a small area located directly below the cloud (in both April and August) and below the cloud, to the north (in December). In this case, daily integrals of irradiance calculated in the shadowless regions, which show maximal irradiance, are 6437 Wh/m^2, 6459 Wh/m^2 and 4275 Wh/m^2 in April, August and December, respectively. The areas receiving irradiance of less than 80% of the maximal are about 16.7 km^2, 17.7 km^2 and 21.4km^2 in April, August and December, respectively. The same shadow distance as the length of the cloud is maintained in a north-south direction, but shadow distance becomes larger in an east-west direction.

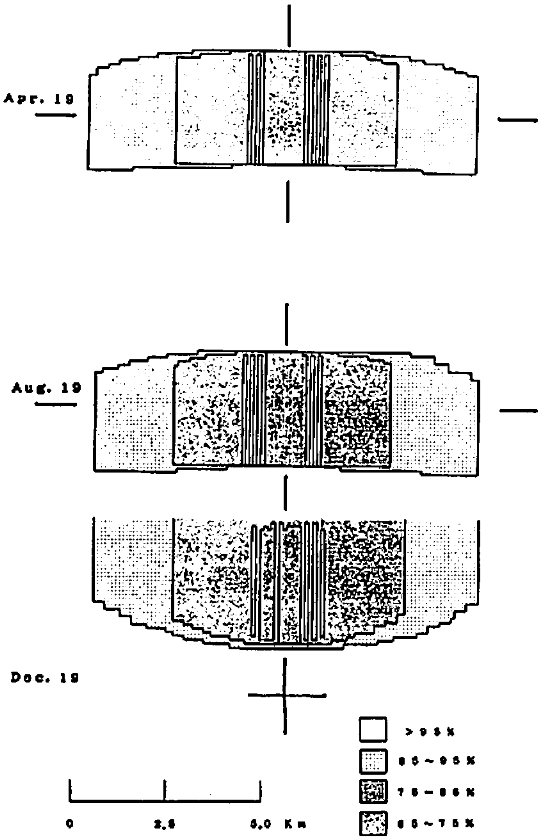

Fig. 2. Relative daily integral of solar irradiance falling around 13°N and 148°E in terms of percentage of maxial irradiance (found at shadowless area) when a motionless cloud with an area of 3 km x 3 km and a thickness of 0.6 km is fixed at 4.2 km over the surface. Solid lines represent latitude and longitude of cloud position.

In order to make the effect of shadow movement upon the surface irradiance clearer, daily cumulative irradiance is computed on the assumption that the shadow is formed directly below the cloud all day long; all other assumptions are left unchangeable. When shadow position is kept constant, the daily cumulative irradiance in the shadowed and shadowless regions on Aug.19 are 956 Wh/cm^2 and 6459 Wh/cm^2, respectively; the ratio between them is about 0.15, which is very small compared with the 0.66 obtained when shadow movement is taken into consideration. Thus, if shadow movement is taken into consideration, the shadow effect extends over the larger region, but a smaller difference is obtained in terms of the irradiance of the shadowed and shadowless regions. Even in this case, however, a cool part where irradiance less than 70% of maximum falls is formed.

3.3 Effect of cloud movement

To this point, a constant cloud position was assumed in calculations. But in fact, it is natural to consider that the cloud itself also moves. In order to investigate the effect of cloud movement on surface irradiance distribution, the irradiance falling on the surface is calculated

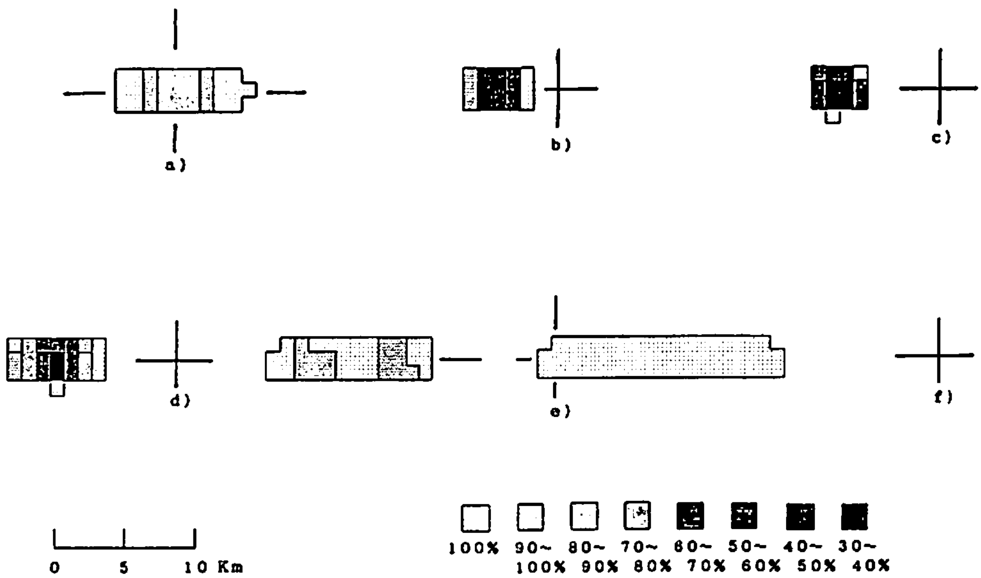

Fig. 3. Relative daily integral of solar irradiance around 13°N and 148°E on Aug.19 in terms of percentage of that at shadowless areas when a cloud with areas of 3 km x 3 km and a thickness of 0.6 km moves westward at various velocities: 0 km/h (a), 1 km/h (b), 1.5 km/h (c), 2 km/h (d), 3 km/h (e) and 4 km/h (f). Cloud height is kept constant at 4.2 km. Solid lines represent latitude and longitude of original cloud position.

for varying cloud velocities. In these calculations, the same values of input parameters concerning cloud and atmosphere as those described in the previous section are used.

Fig.3 shows the horizontal distribution of the daily integrals of solar irradiance reaching the surface on Aug.19 for various cloud velocities. When a cloud moves to the west at a speed of 1 km/h, the ratio between minimal and maximal irradiance is about 0.30, which is about half and twice that obtained in the case of the stationary cloud and constant shadow position, respectively. In addition, the area receiving irradiance less than 90% of that of the shadowless area ($S_{<90}$) decreases to 15 km^2, from 29 km^2, for the motionless cloud. It should be noted that the shadow center shifts to 5 km to the west of the original cloud position projected on the surface. When cloud speed is 1.5 km/h, the ratio and $S_{<90}$ attain the minimums of 0.26 and 13 km^2, respectively. The center of $S_{<90}$ is located 7.5 km to the west of the original cloud position. With further increases to cloud speed, the ratio and $S_{<90}$ increase again; 0.29 and 21 km^2 for 2 km/h, and 0.73 and 35 km^2 for 3 km/h wind speed suggest a lesser effect on the development of uneven irradiance distribution.

When the cloud moves toward the north, east or west at a speed of 2 km/h, the horizontal irradiance distribution is as shown in Fig. 4. The ratios between maximal and minimal irradiances are 0.82, 0.88 and 0.81, respectively, and $S_{<90}$ increases, showing the slight effect upon the development of cool part.

Thus, maximal concentration of the shadowed areas on the smaller regions are found when the cloud moves toward the west at a speed of about 1.5 km/h, in the case of mid-level clouds. Thus, clouds of a certain velocity cause a larger horizontal difference in solar irradiance than do stationary clouds, but the difference cannot equal that obtained on the assumption that shadows are formed directly below clouds.

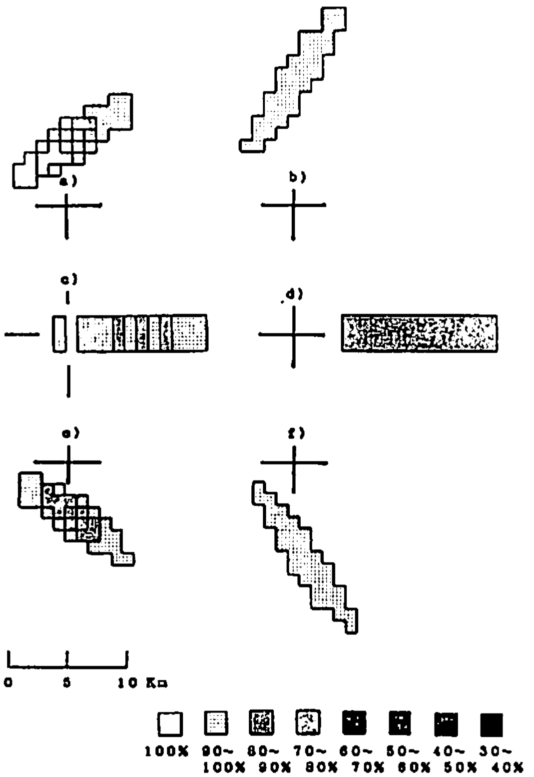

Fig. 4. Relative daily integral of solar irradiance around 13°N and 148°E on Aug.19 in terms of percentage of that at shadowless areas when a cloud with an area of 3 km x 3 km and a thickness of 0.6 km moves northward at 1 km/h (a) and 2 km/h (b) velocities, eastward at 1 km/h (c) and 2 km/h (d) velocities, and southward at 1 km/h (e) and 2 km/h (f) velocities. Cloud height is kept constant at 4.2 km. Solid lines represent latitude and longitude of original cloud position.

4 Discussion

When a cloud at a height of 1.2 km moves westward at a speed of about 1.5 km/h, the presence of a "cool part" where solar energy is very little as compared with that of the surrounding areas, is stressed above on the basis of the simple cloud model. Judging from the cloud imagery obtained from satellites such as GMS, cloud speeds of 1.0 to 2.0 km/h toward the west are often observed around this region. Hence, the results obtained here are very interesting and significant for many different fields of study. Since sun irradiance is unevenly distributed to the surface, it is natural to suppose that the temperature of materials present on the surface will also vary with geographical location. As a result, an ascending air stream, generated by the heated air near the surface, would develop actively in shadowless regions while it might remain very weak in the cool part. Accordingly, the shadow is, more or less, able to affect the circulation and mixing of air.

In general, most solar energy penetrating into the sea water is absorbed by the water in an upper layer of the sea. Since most of the absorbed energy is converted to heat, a total amount of heat distributed to the sea water, if there is cloud, varies not only with vertical direction but also with horizontal direction. Resultant differences in the density of sea water are likely to induce small-scale water movement.

On the other hand, when the velocity of a cloud becomes great, almost equal amounts of solar energy are distributed to each region, including that directly below the cloud. Moreover, cloud movement in any direction other than to the west results in a decrease in the development of uneven irradiance distribution.

In the present study, no vertical cloud movement was taken into consideration. But shadow position and energy distribution are affected by vertical cloud movement, which frequently occurs in actual situations. Therefore, this effect must be taken into consideration in future studies although this factor makes the computational procedures slightly more complicated.

Concerning the actual ocean, sea water movement should also be taken into consideration. If sea water moves towards, for example, the east, at a speed of 1 km/h to 2 km/h while a cloud is kept steady, results similar to those obtained for the cloud moving to the west at the same speed would occur, and a cool part might also develop because a similar geometry is supposed, which would mean that an uneven distribution of solar irradiance to the geographical location might also occur. Strictly speaking, however, variations in local time which determine the sun's position must also be taken into consideration as the sea water moves.

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地上に入射する太陽エネルギーの水平分布に影響を与える雲

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太陽が雲に遮られたとき，地球上にできる影の部分の入射エネルギーは非常に少ない。影の位置は，雲の位置ばかりでなく太陽の位置にも依存する。この太陽の位置の影響を明らかにするため，模式的な雲からの影の位置の日変化を各月において計算した。その結果，雲の影の位置は季節によって大きく変動することを示した。また正午前後に影の位置は長時間にわたって同じ場所を占め，周囲よりも非常に「冷たい」場所が形成されることを指摘した。

定量的に取扱うため，日射積算量の水平分布を計算した。4.8kmの高度に静止した雲があると仮定すると，最大積算日射量と最低積算日射量の比は，0.67であった。雲が西に移動を始めると，この比は減少して，1.5kmの雲の早さで0.26と最低値をとる。さらに雲の早さが増大すると，この比は増大して，日射量が等配分される傾向となる。