Land-Sea Contrast in the Earth Radiation Budget

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Abstract

In order to make clear the difference between the earth's radiation budget over land and over sea, three components of the budget measured by the wide field of view sensors aboard NIMBUS 7 were analyzed for the period during November 1978 to October 1979.

In each of the absorbed solar radiation and the emitted terrestrial radiation, it is confirmed that the zonal average over sea is about 40 W/m^2 larger than over land covering the latitudinal range of 40 degrees around the solar declination. It is interpreted because the clear sky albedo over sea is about half of that over land and also the cloud amount over sea is about 13% less than that over land in the equatorial zone.

In the absorbed solar radiation, it is found that in summer the zonal average over sea is about 15 W/m^2 smaller than that over land covering the latitudinal range of 30 degrees centered 60N or 60S. It is estimated because in the latitude of summer the cloud amount over sea is so larger than over land as to cancel the clear sky albedo effect though clear sky albedo over sea is about half of that over land.

In the emitted terrestrial radiation, it is also found that the minimum zone of it associated with ITCZ is lower over land than over sea, and the maximum zones of it associated with the subtropical high pressure zones are larger over land than over sea. This strangely means that the direct circulation over land looks like more active than over sea in the equatorial zone.

1. Introduction

The earth radiation budget (ERB) consists of three components; absorbed solar radiative flux $S\downarrow$, emitted terrestrial radiative flux $T\uparrow$ and net, total radiative flux $N\downarrow$. And they have a relationship

$$N\downarrow = S\downarrow - T\uparrow \quad (1)$$

where an arrow in the superscript indicates positive direction of the component. $S\downarrow$ is shortwave energy input to the earth and $T\uparrow$ is longwave energy output from the earth. $N\downarrow$ is the heat source or sink which warms or cools the earth and also drives general circulation of the atmosphere and the ocean. Therefore to analyze ERB is basically important in order to investigate the mechanism of climatic change in the planetary scale, for example, generation of the ice age, effect of volcanic eruption to climate, effect of change in solar constant to climate,

warming with increasing of CO_2 and effect of cloud to climate.

The global ERB observation has been performed by polar orbiting, meteorological satellites. Raschke and Vonder Haar (1973), Gruber (1977), Gruber and Winston (1978) and Jacobowitz, Smith, Howell and Nagle (1979) analyzed global distributions in the annual mean and seasonal variations in the zonal mean of ERB. Stephens, Campbell and Vonder Haar (1981) analyzed seasonal variations of the global distribution of ERB. Warren and Thompson (1983) discussed generation of climatological minimum in the tropical outgoing infrared radiation. The latitudinal variation of ERB components are much predominant than the longitudinal variation. Therefore the researches on ERB has been focused in the latitudinal variation than the longitudinal variation.

Examining distributions of ERB components

makes us find that the longitudinal variation appears to be primarily determined by land-sea distribution (Kubota and Imai (1986)). Campbell and Vonder Haar (1980a, b) investigated the difference between $N\downarrow$ over land and $N\downarrow$ over sea, for the first time. The theme of present paper is to extend their researches. Their researches are based on data supplied by polar orbiting satellites; NIMBUS 6 and the predecessors. They compared the net total radiation $N\downarrow$ averaged over land with that averaged over sea each in the zones of 20N–20S, 60N–20N and 20S–60S. Campbell and Vonder Haar (1980a) showed that in the tropical zone between 20N and 20S $N\downarrow$ is about 33 W/m² greater over sea than over land in the annual mean.

Many researchers have debated on the role of cloud to ERB (Manabe, 1983). Particularly the fevered discussions carried out by Cess (1976), Ohring and Clapp (1980) and Hartman and Short (1982) are attractive. According to them, cloud has a shield (or albedo) effect to the solar radiative flux $S\downarrow$ and a cloud top (or greenhouse) effect to the terrestrial radiative flux $T\uparrow$, where the cloud top effect works to decrease $T\uparrow$ because the radiative surface changes from the earth's surface to the cloud top if any cloud exist. They insist that the effect of cloud to $N\downarrow$ is small because the shield effect to $S\downarrow$ offsets the cloud top effect to $T\uparrow$. Ohring and Gruber (1983) and Henderson-Sellers (1984) explain these theory and facts. But the results of the present analysis do not mention any cloud top effect to the $T\uparrow$.

2. Data used for ERB analysis

i. Data source

Analyzed data are monthly ERB data measured by wide field of view (WFOV) radiometer 12 and 13 channel (#12 and #13) aboard NIMBUS 7 for the period from November 1978 to October 1979. These data are included in so-called ERB.MATRIX data set. These sensors of #12 and #13 are coil type thermopile, #12 observes total wave radiative flux from 0.2 to 50 μm in the wavelength without any filter and #13 observes reflected shortwave radiative flux from 0.2 to 3.8 μm filtering longwave radiation by a double hemispheric-shaped filter supraisil

W fused silica. #13 is a kind of precision pyranometer. In order to estimate absorbed solar radiation by the earth, the solar irradiance I at the earth is calculated from

$$I = I_0 (r_0/r)^2 \cos z \quad (2)$$

where I_0 denotes solar constant, r distance between the sun and the earth, r_0 annual average of the distance and z zenith angle of the sun.

NIMBUS 7 has a sun-synchronous polar orbit inclined at 99.3° to the earth's equator and at an altitude of 955 km. The equatorial crossings are at 1200 local time (LT) in the ascending node and at midnight in the descending node. The revolving period is 104.16 min. and the earth rotates 26.1° in longitude in the period (Madrid (1978)). The channels have an unencumbered FOV of 121°, which is equivalent to 59° in the latitudinal range of the earth. The unencumbered FOV enables to receive radiative flux (in W/m²) from full disk of the earth. NIMBUS 7 has other channels for narrow field of view (NFOV) to observe radiance (in W m⁻² str⁻¹). ERB.MATRIX data set has ERB fluxes (in W/m²) data obtained by integrating the radiance of NFOV for all solid angle in full disk of the earth. But in the present study we selected WFOV data.

The radiative flux at the satellite altitude (distance from the earth's center is R_{sat}) and at the top of the atmosphere (the earth's radius $R_e + 15$ km) are different. The radiative flux defined here is the latter, and the former $\times ((R_e + 15)/R_{sat})^2$ makes the latter, where R_e value depends on the latitude (Jacobowitz *et al.*, 1984a).

Output of the channel is a 16 sec integral of the instantaneous readings, but all outputs are not necessarily used to control the quality, and is stopped for one day every four days to save power (Tighe and Shen, 1983).

ii. Quality control of ERB data

ERB data of NIMBUS 7 are made by the ERB experimental team and archived by NESDIS in NOAA. Analyzed data set here consists of monthly net radiation and long wave radiation by WFOV put into the world grid (500 km $\times$ 500 km) of approximately equal area during November 1978 to October 1979.

The quality control of ERB.MATRIX is ex-

plained by Tighe and Shen (1983) and Jacobowitz *et al.* (1984a). Measurements by WFOV and these by NFOV are compared and examined by Jacobowitz *et al.* (1984b).

3. Latitude-time variations of the zonal averages in $S\downarrow$, $N\downarrow$ and $T\uparrow$ each over sea and over land

In the world grid of approximately equal area, if a grid area is occupied over 50% by land (sea), the grid is defined as a land (sea) grid. $S\downarrow$, $T\uparrow$ and $N\downarrow$ are zonally averaged for land and for sea area of the grid. Hereafter the zonal average in whole latitudinal zone is expressed by $\bar{}$, that

in sea area by $\bar{}^s$ and that in land area by $\bar{}^l$.

Latitude-time variations of $\bar{S\downarrow}^l$ and $\bar{S\downarrow}^s$ are shown in Fig. 1. The maximum of $\bar{S\downarrow}^s$ occurs near the solar declination. In the seasons including vernal equinox or autumn equinox when the solar declination passes the equator, the maximum of $\bar{S\downarrow}^l$ does not necessarily locate near the equator, because the active convection increases the planetary albedo particularly over land.

In the latitudes where $\bar{S\downarrow}$ is large (for example, where $\bar{S\downarrow}^s > \text{about } 300 \text{ W/m}^2$), $\bar{S\downarrow}^s$ surpasses $\bar{S\downarrow}^l$ covering the latitudinal range of about 70° . The latitudinal range where $\bar{S\downarrow}^s$ is larger than $\bar{S\downarrow}^l$ by 40 W/m^2 is about 40° .

In the vicinity of 60°N or 60°S , in the summer hemisphere, $\bar{S\downarrow}^l$ surpasses $\bar{S\downarrow}^s$ by 15 W/m^2 covering the latitudinal range of about 30° .

Fig. 2 shows latitude-time variation of $\bar{N\downarrow}^l$ and $\bar{N\downarrow}^s$. The figure shows that as far as the difference between $\bar{N\downarrow}^l$ and $\bar{N\downarrow}^s$ the feature is almost the same as the difference between $\bar{S\downarrow}^l$ and $\bar{S\downarrow}^s$.

In the vicinity of 60°N or 60°S $\bar{N\downarrow}^l$ is larger than $\bar{N\downarrow}^s$ all the year round, since in summer $\bar{S\downarrow}^l$ is larger than $\bar{S\downarrow}^s$ and in other seasons $\bar{T\uparrow}^l$ is weaker than $\bar{T\uparrow}^s$.

Fig. 3 shows latitude-time variation of $\bar{T\uparrow}^l$ and $\bar{T\uparrow}^s$. A common feature of $\bar{T\uparrow}^l$ and $\bar{T\uparrow}^s$ is that there is one minimum near the equator and two maximums at the subtropical zones of each hemisphere.

These maximums of $\bar{T\uparrow}$ may be associated with the sinking motion and the minimum of $\bar{T\uparrow}$ the rising motion of the direct circulation. Or the maximums represent the subtropical high pressure zones and the minimum the inter-tropical convergence zone (ITCZ). Fig. 4 shows climatological distribution of total cloud amount for January and July presented by Berlyand and Strokina (1980). Fig. 5 shows latitude-time variation of climatological total cloud amount averaged over sea and over land ($\bar{C}^s$, $\bar{C}^l$) presented by Berlyand, Strokina and Greshnikova (1980). These figures and other climatological total cloud distributions presented by Hughes (1984) confirm the above view.

The minimum of $\bar{T\uparrow}^l$ tends to be lower than the minimum of $\bar{T\uparrow}^s$ and the both maximums

Fig. 1. Annual variation of latitudinal distributions in absorbed solar radiative flux $S\downarrow$. The ordinate is marked with 400, 300, 000, 100 and 0 W/m^2 only for $S\downarrow$ of November 1978, and with only 0 W/m^2 for $S\downarrow$ of other months. Solid curves are for zonal average over land and broken curves for zonal average over sea. Zonal averages over land in the arctic area northern than 81°N and in the vicinity to 60°S between 54.0°S and 67.5°S are broken off because there is no land. An area, where the average over land is greater than the average over sea, is shaded.

Fig. 2. As Fig. 1 except for net, total radiative flux $N\downarrow$. The ordinate is marked with 200, 100, 0, -100 and -200 W/m^2 only for $N\downarrow$ of November 1978, and with only -200 W/m^2 for $N\downarrow$ of other months.

of $\overline{T\uparrow}^1$ tend to be larger than $\overline{T\uparrow}^s$. The amplitude of $\overline{T\uparrow}^1$ between the maximum and the minimum tends to be larger than that of $\overline{T\uparrow}^s$. These facts strangely mean that the direct circulation over land looks like more active than over sea in the equatorial zone.

The latitude where $\overline{S\downarrow}$ or $\overline{N\downarrow}$ has the maximum nearly agrees with the solar declination, which is ranged in the tropics between 23N and 23S. But the latitude where $\overline{T\uparrow}$ has the minimum varies annually only in the equatorial zone between about 10N and 10S.

4. Causes of land-sea contrast of $S\downarrow$

$S\downarrow$ is represented as follows

$$S\downarrow = I(1 - \alpha) \quad (3)$$

where I is the extra terrestrial solar irradiance in W/m^2 and α is the planetary albedo. α is expressed as follows

$$\alpha = \alpha_c A_c + \alpha_s (1 - A_c) \quad (4)$$

Fig. 3. As Fig. 1 except for emitted terrestrial radiative flux $T\uparrow$. The ordinate is marked with 300 and 200 W/m^2 only for $T\uparrow$ of November 1978, and with only 200 W/m^2 for $T\uparrow$ of other months.

which was proposed by Cess (1976). Here A_c denotes cloud amount, α_c cloud albedo and α_s clear-sky albedo.

The excess of $\overline{S\downarrow}^s$ to $\overline{S\downarrow}^1$ may be attributed to the excess of $\overline{\alpha_s}^1$ to $\overline{\alpha_s}^s$ and the difference between $\overline{A_c}^1$ and $\overline{A_c}^s$. Eliminating α from (3) and (4), and differentiating the result derives

$$\Delta S\downarrow = -I[(\alpha_c - \alpha_s)\Delta A_c + (1 - A_c)\Delta \alpha_s] \quad (5)$$

where Δx denotes the deviation of x over sea from over land, and $\Delta \alpha_c$ is supposed to be zero. Also (5) leads following equation for ΔA_c

$$\Delta A_c = -[\Delta S\downarrow / I + (1 - A_c)\Delta \alpha_s] / (\alpha_c - \alpha_s) \quad (6)$$

- i. Causes of 40 W/m^2 excess of $\overline{S\downarrow}^s$ to $\overline{S\downarrow}^1$ in the vicinity of the solar declination

In the vicinity of the solar declination, referring Fig. 6

$$I \sim 450 \text{ W/m}^2 \quad (7)$$

Fig. 4. Global distributions of total cloud amount for January and July compiled by Berlyand and Strokina (1980). Unit indicates 10%.

Representative cloud amount is, referring Fig. 5,

$$A_c \sim \bar{A}_c \sim 0.6 \quad (8)$$

Concerning α_c and α_s , referring Fig. 7, since $\cos z \sim 0.66$ (z denotes solar zenith angle and $\cos z = \frac{1}{2\tau} \int_{-\tau}^{\tau} \cos z \, dt = \frac{I}{I_0} \frac{\pi}{(I_0/r)\tau} \sim I \times 2/I_0 = (450 \text{ W/m}^2) \times 2/(1370 \text{ W/m}^2) = 0.66$, where τ denotes half length of a day), we get

$$\alpha_c \sim \bar{\alpha}_c \sim 0.55 \quad (9)$$

$$\left. \begin{aligned} \bar{\alpha}_s^1 &\sim 0.22 \\ \bar{\alpha}_s^2 &\sim 0.12 \\ \alpha_s \sim \bar{\alpha}_s &\sim (\bar{\alpha}_s^1 + \bar{\alpha}_s^2)/2 = 0.17 \\ \Delta\alpha_s &= \bar{\alpha}_s^2 - \bar{\alpha}_s^1 = -0.10 \end{aligned} \right\} \quad (10)$$

Supposing $\Delta A_c \sim 0$, and substituting (7), (8), (9) and (10) into (5), we get

$$\Delta S \downarrow \sim 18 \text{ W/m}^2 \quad (11)$$

This means that the excess of $\bar{\alpha}_s^1$ to $\bar{\alpha}_s^2$ contributes to only half of the excess of $S \downarrow$ to $S \downarrow^1$

Substituting (7), (8), (9), (10) and

Fig. 5. Latitude-time variation of zonally averaged cloud amount over land and sea compiled by Berlyand, Strokina and Greshnikova (1980).

$$\Delta S\downarrow \sim 40 \text{ W/m}^2 \quad (12)$$

into (6), we get

$$\Delta A_c \sim -0.13 \quad (13)$$

This means that the excess of $\overline{S\downarrow}^s$ to $\overline{S\downarrow}^1$ around the solar declination is attributed to that $\bar{\alpha}_s^s$ is twice as large as $\bar{\alpha}_s^1$ and $\bar{A}_c^1$ is 13% larger than $\bar{A}_c^s$. According to the climatological cloud distributions shown in Fig. 4 and 5, it is certain that the cloud amount over the ITCZ is larger over land than over sea in the equatorial zone. But it is not true for the subtropical high pressure zone in the summer hemisphere, that is, the 20–30N zone in the northern hemispheric summer and the 20–30S zone in the southern hemispheric summer.

Main deserts distribute in the subtropical high pressure zones. The clear-sky albedo over the desert is larger than that over the entirely averaged land. According Ohring and Gruber (1983), the clear-sky albedo over the desert is 25 to 35%. If we suppose $\bar{\alpha}_s^1 \sim 0.30$ in (10), we get $\Delta A_c \sim 0.06$. This means that in the sub-

Fig. 6. Latitude-time variation of extra terrestrial solar radiative flux I . Unit of numerals is 100 W/m^2 . I is about 450 W/m^2 in the vicinity of the solar declination. I is also about 450 W/m^2 in the vicinity of 60N or 60S in summer.

tropical high pressure zones, the cause of the excess of $\overline{S\downarrow}^s$ to $\overline{S\downarrow}^1$ may be attributed to only the excess of $\bar{\alpha}_s^s$ to $\bar{\alpha}_s^1$.

ii. Causes of 15 W/m^2 excess of $\overline{S\downarrow}^1$ to $\overline{S\downarrow}^s$ near 60N or 60S in the summer hemisphere

As $\cos z \sim 0.66$ referring Fig. 6,

$$A_c \sim \bar{A}_c \sim 0.7 \quad (\text{after Fig. 5}) \quad (14),$$

$$I \sim 450 \text{ W/m}^2 \quad (\text{after Fig. 6}) \quad (15),$$

$$\Delta S\downarrow \sim -15 \text{ W/m}^2 \quad (\text{after Fig. 1}) \quad (16),$$

$$\alpha_c \sim \bar{\alpha}_c \sim 0.55 \quad (\text{after Fig. 7}) \quad (17),$$

$$\bar{\alpha}_s^1 \sim 0.22 \quad (\text{after Fig. 7})$$

$$\bar{\alpha}_s^s \sim 0.12 \quad (\text{after Fig. 7})$$

$$\alpha_s \sim \bar{\alpha}_s \sim (\bar{\alpha}_s^s + \bar{\alpha}_s^1)/2 = 0.17 \quad (18),$$

$$\Delta \alpha_s = \bar{\alpha}_s^s - \bar{\alpha}_s^1 = -0.10$$

Substituting (14), (15), (16), (17) and (18) into (6), we get

$$\Delta A_c \sim 0.17$$

This means that the excess of $\overline{S\downarrow}^1$ to $\overline{S\downarrow}^s$ around 60N or 60S in the summer hemisphere is attributed to about 17% excess of $\bar{C}^s$ to $\bar{C}^1$ in spite of the double of $\bar{\alpha}_s^s$ to $\bar{\alpha}_s^1$. Fig. 4 and 5 support this result.

5. Conclusion and an interesting theme

i. Conclusion

a. Both absorbed solar radiation ($S\downarrow$) and net, total radiation ($N\downarrow$) are about 40 W/m^2 greater

Fig. 7. Relations between cosine (solar zenith angle) and clear-sky albedo α_s (a), or cloud albedo α_c (b) (Ohring and Gruber (1983)).

over sea than over land around the solar declination. An estimation showed that this excess of $S\downarrow$ or $N\downarrow$ over sea to $S\downarrow$ or $N\downarrow$ over land is attributed not only to about double clear-sky albedo over land to over sea but to 13% larger cloud amount over land than over sea in the equatorial zone.

b. Both absorbed solar radiation ($S\downarrow$) and net, total radiation ($N\downarrow$) are about 15 W/m^2 greater over land than over sea around 60°N or 60°S in the summer hemisphere. It was estimated that this excess of $S\downarrow$ or $N\downarrow$ over land to $S\downarrow$ or $N\downarrow$ over sea is attributed to 17% larger cloud amount over sea than that over land, in spite of about double clear-sky albedo over land to over sea.

c. The minimum zone of emitted terrestrial radiation ($T\uparrow$) associated with ITCZ tends to have the smaller value over land than over sea. And each maximum zone of emitted terrestrial

radiation ($T\uparrow$) associated with the subtropical high pressure tends to have the larger value over land than over sea. These facts show that the direct circulation over land looks like more active than that over sea.

The seasonal variation of the latitude of the minimum zone is much smaller than that of the solar declination.

ii. An interesting guess

If it is confirmed that $\overline{N\downarrow}^s$ is about 40 W/m^2 larger than $\overline{N\downarrow}^1$ covering the 40° latitudinal range around the solar declination, it makes us following interesting guess.

In the present age the apogee of the sun is in summer and the perigee is in winter. Difference between I at the apogee and perigee is 7% of I.

The period of the precession of the equinoxes is about 26,000 years. About 13,000 years ago the apogee of the sun was in winter and the perigee was in summer. The land area is 2.5 times larger in the northern hemisphere than that in the southern hemisphere. Therefore about 13,000 years ago the energy input must be smaller than that in the present age. And the energy output must be smaller than that in the present age to balance the energy input. Lower temperature of the earth's surface omits smaller energy output.

To estimate the energy input in about 13,000 years ago and to investigate the effect to the energy output and the temperature of the earth's surface is the interesting next theme.

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地球放射収支の海陸差

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要 約

地球放射収支が海陸によっていかなる差異があるか明確にするため、NIMBUS 7 によって観測された地球放射収支の月平均全球分布を FGGE 期間 (1978. 11—1979. 10) について解析した。その結果次のことが分った。

(1) 正味の太陽放射束、正味の全放射束ともに東西平均をとると、太陽の赤緯を中心とする約 70° 緯度中にわたって陸上より海上で大きく、その差は約 40° 緯度中にわたって 40 W/m^2 を越える。海と陸の晴天アルベド差によって説明できる差はこの量の約半分で、残りの半分は海上と陸上での雲量の差に待たなければならない。正味の太陽放射束、雲量および青天アルベド間の関係式から見積ると、この差を生じるには陸上の雲量が海上より 13% 多くなければならない。量近の気候的な雲量分布図によるとこの見積りは赤道域に限り妥当である。

(2) 一方 60°N 又は 60°S を中心とする高緯度では正味の太陽放射束は逆に海上より陸上で 30° 緯度中にわたって約 15 W/m^2 大きい。海と陸の晴天アルベド差は、上と同じ程度の逆の差を生じるはずなので、陸上より多い海上の雲量が、アルベド差による効果を陵駕していなければならない。これを説明するためには海上の雲量が陸上より 17% 多くなければならない。最近の気候的な雲量分布図はこの見積りが妥当であることを示している。

(3) 正味の地球放射の緯度変化をみると、赤道付近に ITCZ に対応する極小、亜熱帯に高圧帯あるいは下降域に対応する二つの極大がある。この極大、極小、極大といった緯度変化は海上より陸上で大きい。つまり直接循環は海上より陸上で活発のように見える。