The Annual Cycle of Earth Radiation Budget from Clouds and the Earth’s Radiant Energy System (CERES) Data

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(Manuscript received 25 February 2011, in final form 15 July 2011)

ABSTRACT

The seasonal cycle of the Earth radiation budget is investigated by use of data from the Clouds and the Earth’s Radiant Energy System (CERES). Monthly mean maps of reflected solar flux and Earth-emitted flux on a 1° equal-angle grid are used for the study. The seasonal cycles of absorbed solar radiation (ASR), outgoing longwave radiation (OLR), and net radiation are described by use of principal components for the time variations, for which the corresponding geographic variations are the empirical orthogonal functions. Earth’s surface is partitioned into land and ocean for the analysis. The first principal component describes more than 95% of the variance in the seasonal cycle of ASR and the net radiation fluxes and nearly 90% of the variance of OLR over land. Because one term can express so much of the variance, principal component analysis is very useful to describe these seasonal cycles. The annual cycles of ASR are about 100 W m$^{-2}$ over land and ocean, but the amplitudes of OLR are about 27 W m$^{-2}$ over land and 15 W m$^{-2}$ over ocean. The magnitude of OLR and its time lag relative to that of ASR are important descriptors of the climate system and are computed for the first principal components. OLR lags ASR by about 26 days over land and 42 days over ocean. The principal components are useful for comparing the observed radiation budget with that computed by a model.

1. Introduction

Solar radiation that is absorbed by Earth and its distribution over the planet provide the energy that governs our weather and climate. The seasonal cycles of other parameters of climate are driven by the annual cycle of absorbed solar radiation (ASR). The annual cycle of ASR is due to the eccentricity of Earth’s orbit, which results in the cycle of global insolation, and to the annual cycle of solar declination, which creates the annual cycle of the geographical distribution of insolation. ASR depends on the albedo, which is a dynamic quantity that depends largely on the movement of major cloud systems as they interact with the solar heating and other parts of the climate system. Snow and ice cover also affect the albedo to provide a forcing of the absorbed flux of energy. The temperatures of the land, atmosphere, and ocean vary in response to the cyclic heating by ASR and together with the clouds cause the outgoing longwave radiation (OLR) at the top of the atmosphere to vary. The geographical distribution of fluxes and their time variations are fundamental aspects of climate, because these radiation fluxes create the temperature distributions that drive the atmospheric and oceanic circulations that transport energy from low to high latitudes. The purpose of this paper is to examine the seasonal cycles of energy to and from Earth so as to provide information for understanding the dynamics of the system.

Kiehl and Trenberth (1997) and Trenberth et al. (2009) reviewed Earth’s global energy budget. Their focus was on the global-mean energy budget without regard to the geographical distribution of radiation in or out of the Earth system. Fasullo and Trenberth (2008) considered the annual cycle of zonally averaged meridional transport of energy in conjunction with the energetics of the atmosphere. Loeb et al. (2009) also discussed the annual cycle of the global net radiation. Trenberth and Stepaniak (2004) examined the flow of energy in the atmosphere.
and ocean and discussed maps of various parameters for the annual mean and for the annual cycles as described by averages over December–February and over June–August. These parameters include top-of-atmosphere ASR, OLR, and net radiation based on Earth radiation budget data. Earlier studies of the seasonal cycle of Earth-emitted radiation (Bess et al. 1992) and ASR (Smith et al. 1990) used wide-field-of-view data from the Earth Radiation Budget instrument aboard the Nimbus-6 and Nimbus-7 spacecraft (Smith et al. 1977; Jacobowitz et al. 1984). The resolution, even after being enhanced (Smith and Green 1981; Smith and Rutan 1990), was 15° in latitude and, at the equator, 15° in longitude. As a consequence, the intertropical convergence zone (ITCZ) and its movements could hardly be detected. Also, none of these papers considered the annual cycle of net radiation flux, which will be treated in this paper.

The primary objective of this paper is to express quantitatively the annual cycle in the time and space domains. The CERES program has provided an excellent database for studying the seasonal cycles of the radiation budget. This dataset, spanning 10 years, has a resolution of 1° latitude × 1° longitude so that it can describe fine features. Monthly mean maps of reflected solar flux and Earth-emitted flux on a 1° grid are used for the study. The first step is to examine the annual-mean flux maps, after which the seasonal cycles of fluxes about these mean maps are treated. Because the Earth–atmosphere system is a dynamic system, the seasonal cycle of energy into and out of the system should be characterized in the time domain as well as geographically. It is highly desirable to extract from the 12 monthly maps the seasonal cycles over the globe. The seasonal cycles of ASR, OLR, and net radiation fluxes are described in this paper by use of principal components (PCs) for the time variations. Principal component analysis uses the data to define the time variations and their phases globally, rather than imposing a specific form such as sine waves, as in Fourier analysis. The PCs give an understanding of the time variations that cannot be gleaned from looking at monthly mean and seasonal-mean maps. The corresponding geographic variations are the empirical orthogonal functions, which provide the magnitude and sign of the variation for each region. The principal components provide the most concise quantitative description of the data and may be used as a set of basis functions for quantitative comparisons of observed fluxes with those computed by models. The immense heat capacity of the ocean causes it to have a slow response to the seasonal cycle of heating relative to land, and the atmosphere is closely coupled with the surface, and therefore Earth’s surface is partitioned into land and ocean for the analysis. The relations between the input ASR and the output OLR are also investigated. Detailed explanations of the temporal and spatial variations of radiation fluxes that are found in this paper must come from future investigations.

2. Data and analysis method

The CERES Energy Balanced and Filled (EBAF) edition-2.5A data product (available online at http://ceres.larc.nasa.gov) was used for this study (Loeb et al. 2009). The dataset is based on measurements from the CERES Flight Model-1 and -2 (FM-1 and FM-2) instruments aboard the Terra spacecraft and covers 10 years from March 2000 through February 2010. This dataset was formed by adjusting the measurements within their ranges of uncertainty of the monthly mean fluxes to achieve balance of global-mean radiation with the estimated heat storage in the Earth–atmosphere system. This EBAF edition-2.5A dataset is an improvement over the earlier edition-1A dataset because it uses edition-3 instrument calibrations. This dataset covers Earth with 64 800 1° × 1° equal-angle regions, with monthly mean values of the top-of-the-atmosphere (TOA) reflected shortwave radiation and OLR.

The EBAF edition-2.5A product differs from the Synoptic Radiative Fluxes and Clouds (SYN) dataset primarily in that the reflected shortwave radiation of SYN is multiplied by 1.0173 and the OLR of SYN is multiplied by 1.0029. Also, the solar constant has been revised to use the Solar Radiation and Climate Experiment (SORCE) Total Irradiance Monitor (TIM; Kopp et al. 2005) results on a daily basis. The average value for TIM is 1361 W m⁻² rather than the earlier value of 1365 W m⁻².

ASR is calculated as insolation minus the reflected shortwave radiation, and net radiation is ASR minus OLR. The climatological monthly means for each calendar month are computed for the 10-yr period. The climatological annual mean over the period is then formed from the climatological monthly means. Let \( y(x, m) \) denote the average of ASR or OLR for region \( x \) and month \( m \). Then, the annual mean for region \( x \) is

\[
\bar{y}(x) = \frac{1}{12} \sum_{m=1}^{12} y(x, m),
\]

and the seasonal cycle is

\[
V(x, m) = y(x, m) - \bar{y}(x).
\]

The units of \( y, \bar{y} \), and \( V \) are watts per meter squared.
FIG. 1. Annual-mean maps of (a) ASR, (b) OLR, and (c) net radiation (W m$^{-2}$).
To quantify the seasonal cycle for tens of thousands of regions, principal component analysis is used. The first step is to form a covariance matrix as

$$
\Gamma(m, m') = \sum_{x \in G} w(x) V(x, m) V(x, m'),
$$

(3)

where $G$ is the set of land or ocean regions, $V(x, m)$ denotes the seasonal cycle at region $x$ for month $m$, and $w(x)$ is the area weighting for region $x$. In the CERES grid system there are 21,259 land regions and 39,734 ocean regions. The 3,807 mixed regions are not considered. Because there are 12 monthly means in this study, the covariance matrix is $12 \times 12$. The elements of $\Gamma(m, m')$ and its eigenvalues $\lambda_n$ have the dimensions of watts squared per meters to the fourth power. The eigenvectors $u_n(m)$ are dimensionless and normalized such that

$$
\sum_{m=1}^{12} u_n^2(m) = 1.
$$

(4)

It is useful to define the principal component $PC_n(m)$ as

$$
PC_n(m) = \lambda_n^{1/2} u_n(m),
$$

so that $PC_n(m)$ has the dimension of watts per meter squared and has variance $\lambda_n$. The sum of the eigenvalues is the mean variance of the seasonal cycle. The principal components describe the temporal patterns of the seasonal cycle.

For ASR and for OLR, the 12 eigenvectors $u_n(m)$ are projected onto the $V(x, m)$, and the result is multiplied by $\lambda_n^{-1/2}$ to obtain the empirical orthogonal functions, EOF$_n(x)$, which are the spatial coefficients associated with each PC:

$$
EOF_n(x) = \lambda_n^{-1/2} \sum_{m=1}^{12} u_n(m) V(x, m).
$$

(5)

The EOFs are nondimensional and normalized such that

$$
\sum_{x \in G} w(x) EOF_n^2(x) = 1.
$$

(6)

Thus, the seasonal cycle of a flux at region $x$ and month $m$ can be represented by

$$
V(x, m) = \sum_{n=1}^{12} EOF_n(x) PC_n(m).
$$

(7)

3. Global time and space variations

a. Annual-mean maps of TOA fluxes

The global annual-mean ASR is 240 W m$^{-2}$ (Table 1), and Fig. 1a shows the geographical distribution of this mean. The dominant feature is the zonal variation due to insolation at TOA, but the longitudinal variations over ocean are due to clouds. In general, the mean ASR is highest over the oceans, which have low albedos.

![Fig. 2. First three PCs of the seasonal cycle of ASR over (a) land and (b) ocean (W m$^{-2}$).](image-url)
Subsidence areas near the equator have large values because of the lack of clouds. The high ASR over the equatorial Pacific Ocean and the west equatorial Indian Ocean also indicates the paucity of cloud over these regions. A strip of lower values just north of the equator indicates the ITCZ and its associated cloudiness. At the equator, the convective regions of the Amazon basin, the Congo basin, and the “Maritime Continent” are low relative to the rest of the zone. The deserts of North Africa and the Middle East have low annual-mean ASR relative to the rest of that latitudinal zone because of their high albedos. Greenland also has a high albedo that is due to its ice/snow cover, which is apparent in its lower ASR values.

Figure 1b is a map of the annual-mean OLR, and the global annual mean is 239 W m$^{-2}$. Like the annual-mean ASR, the main pattern is zonal in the extratropics, but cloud effects are prominent elsewhere. The cold cloud tops in the ITCZ reduce OLR just above the equator. The subsidence zones over the oceans and deserts have the greatest annual-mean OLR. As with annual-mean ASR, the three convective regions over South America, the Congo, and the Maritime Continent have local minima of annual-mean OLR in their zones. Although the Greenland Plateau has the lowest annual-mean OLR in the Northern Hemisphere, eastern Antarctica has even lower values associated with its high elevations.

Figure 1c is a map of the annual-mean net radiation, and its global mean is 1 W m$^{-2}$. Because the mean net flux is the difference between the mean ASR and the mean OLR, it is strongly zonal as well, with longitudinal differences due to variations in clouds. The mean net flux is negative over the North African and Middle Eastern deserts, showing net cooling in these subsidence regions (Charney 1975). The mean net flux over the Australian desert is also lower than its zonal mean, although the contrast is not as large as over the Northern Hemisphere deserts. Off the west coasts of South America and southern Africa, the mean net flux has features that are likely due to low-level maritime cloudiness. Overall, the
annual-mean net radiation goes from a surplus to a deficit at 40° latitude in each hemisphere.

The global-average net radiation is 1 W m\(^{-2}\), which was set in the EBAF dataset by the adjustments described in section 2. Because of its low albedo, ocean absorbs more insolation than land does. Much of Earth’s landmass is at high latitude, and thus the global-average OLR for land is 11 W m\(^{-2}\) less than for ocean. The net radiation flux for land is a deficit of 19 W m\(^{-2}\) whereas the ocean has a surplus of 9 W m\(^{-2}\). The atmosphere carries this surplus energy from the ocean to the land as latent and sensible heat. The landmasses then act as radiators for the heat engine, emitting the heat over such places as the deserts of North Africa and the Middle East and over continental high pressure regions during winter.

b. Root-mean-square of seasonal cycles

Over land, the seasonal cycle of ASR has an RMS of 73 W m\(^{-2}\), as shown in Table 1. This RMS value is a measure of the amplitude of the cycle. In the absence of storage or transport of heat, OLR would equal ASR locally and instantaneously, so that the RMS of the OLR seasonal cycle would equal that of ASR, and the RMS of the net radiation seasonal cycle would be very small. The RMS values in Table 1 show that this is not the case, however. Given strong transport, surplus heat in low latitudes is quickly moved to high latitudes and therefore becomes part of the annual mean, flattening the annual-mean map of OLR and causing the seasonal cycle of OLR (21 W m\(^{-2}\)) to be smaller than that of ASR (73 W m\(^{-2}\)). Also, storage of heat attenuates the OLR cycle. With a small cycle of OLR, the net radiation seasonal cycle would then be close to the ASR cycle. The RMS values of the net and OLR cycles are thus a measure of the transport and storage of heat.

For ocean, the storage of heat is large, and the cycles of surface temperature and therefore OLR are small. The seasonal cycle of OLR has an RMS of 12 W m\(^{-2}\) (Table 1). As a consequence, the seasonal cycle of net radiation is close to that of ASR, and here the difference

**Fig. 4.** Second EOF of the seasonal cycle of ASR over (a) land and (b) ocean.
between the ASR and net RMS values is only 4 W m\(^{-2}\).
The heat transport is also large in the ocean, but the relatively small size of the OLR cycle can be explained simply by the heat storage. It remains to partition the effects of storage and transport of heat. The annual-mean meridional transport of heat can be deduced from the zonal-mean profile of net radiation over land and ocean, as has been done by Oort and Vonder Haar (1976) and more recently by Fasullo and Trenberth (2008).

c. Principal component analysis of ASR

Table 2 shows the first four eigenvalues of the seasonal cycle of ASR. These normalized eigenvalues are very similar for land and ocean. The first PC describes about 96% of the variability of ASR, and thus PC\(_1\) explains most of the seasonal cycle of ASR for both land and ocean. The second PC describes 2%–3%, leaving little other variation to be described by higher-order terms.

Figure 2 shows the first three principal components of the seasonal cycle of ASR over land and ocean as a function of month of the year. PC\(_1\) for land (Fig. 2a) is very sinusoidal in shape with an amplitude of 100 W m\(^{-2}\) and a peak in June, and it represents most of the annual cycle of ASR. PC\(_2\) is a wavenumber 2 with maxima of about 16 W m\(^{-2}\) near the solstices and minima of \(-18\) W m\(^{-2}\) in March and \(-12\) W m\(^{-2}\) in September, and it represents a semianual cycle. These first two PCs behave similarly to the annual cycle of insolation as described with principal components by Smith et al. (1990). Over most of the globe, the insolation varies sinusoidally with time. In the polar regions, the extended zero values of polar night require a second term to describe them, namely PC\(_3\). PC\(_3\) is a wavenumber-1 sine, out of phase with PC\(_1\), and it has an amplitude of about 10 W m\(^{-2}\). It is due to cloud and snow effects that lag the solar declination. The amplitude and phase of the annual cycle of a region are expressed by PC\(_1\) and PC\(_3\) as weighted by the EOF\(_1\) and EOF\(_3\) coefficients of the region. The first three PCs for ASR over ocean (Fig. 2b) are very similar to those for land. This similarity indicates that on a global scale the variation of clouds over ocean is much like that over land, especially in terms of lead and lag.

The geographical distribution of coefficients that corresponds to PC\(_1\) for ASR over land is EOF\(_1\), shown in Fig. 3a. EOF\(_1\) is nearly zonal, with values ranging from nearly 2 at high northern latitudes to nearly \(-2\) at high southern latitudes, except across Eurasia, which has a more complex variation with longitude. The positive EOF\(_1\) values of the Northern Hemisphere, when multiplied by PC\(_1\), show an increase in ASR from March through September. Conversely, the negative values of EOF\(_1\) in the Southern Hemisphere show an increase there in ASR from September through March. This is exactly what is expected, since PC\(_1\) explains over 95% of the seasonal cycle of ASR and is mainly a representation of the changing insolation throughout the year. EOF\(_1\) is small near the equator because insolation there does not vary as much as at higher latitudes. The Greenland plateau and Antarctica have smaller variations of ASR because of their relatively more constant high albedo. EOF\(_1\) for ASR over ocean is shown in Fig. 3b. It displays the same zonal structure that EOF\(_1\)
for land does. The longitudinal variations in the tropics for
the annual mean (Fig. 1a) are not seen here.

Figure 4a shows the EOF2 of ASR over land. EOF2
represents the coefficients of the semiannual PC2, which
explains only 2.9% of the seasonal cycle. Values be-
tween 60°N and 60°S are generally small. Larger positive
values at high latitudes show that there is more absorption
of shortwave radiation during the summer months and
that ASR goes to zero in the winter months. EOF2 has
local minima over Central America, equatorial Africa,
and southern Asia, indicating a reduction in ASR during
June and July, the time of the monsoons. EOF2 over ocean
(Fig. 4b) shows the same zonal structure as EOF2 over
land. The Bermuda–Azores high shows over the North
Atlantic Ocean. The dark-green bands near the equator
indicate the north–south motions of the ITCZ throughout
the year. Movements of the associated subsidence zones
also appear. Except for these movements of cloud systems
and subsidence zones, EOF2 of ASR is very similar to
that for TOA insolation noted by Smith et al. (1990).

d. Principal component analysis of OLR

OLR is the response of the surface and atmosphere to
ASR; therefore, it is expected that similarities will exist
in the principal components and EOFs of the seasonal
cycles of the two fluxes. Table 3 shows that the first ei-
genvalues of the seasonal cycle of OLR are 0.88 for land
and 0.79 for ocean. These values indicate that the first
PC strongly dominates and describes most of the sea-
sonal cycle.

Figure 5a shows the first three PCs of the seasonal
cycle of OLR over land. Like PC1 for ASR, PC1 for OLR
is sinusoidal in shape and is an annual cycle. Its amplitude
is smaller, about 27 W m⁻², and it has a maximum in July
and a minimum in January, so that it lags the PC1 for ASR
by a month. PC1 for the seasonal cycle of OLR over
ocean is shown in Fig. 5b. Its shape is similar to PC1 for
land, but its amplitude is smaller (15 W m⁻²).

For ASR, the principal components of any given
order for both land and ocean are nearly identical. For

![Fig. 6. First EOF of the seasonal cycle of OLR over (a) land and (b) ocean.](image_url)
OLR, however, this is not the case. PC2 of OLR over land is similar to PC3 of OLR over ocean. Both are wavenumber 2 and represent the semiannual cycle, as does PC2 of ASR. These PCs explain about 5% of the variance in the OLR seasonal cycle. They have local maxima in January and July/August, but the minima in PC3 over ocean lag those in PC2 over land by 0.5–1 month. PC3 over land and PC2 over ocean are similar. Both are a wavenumber 1, out of phase with PC1, lagging by 3 months, and they have amplitudes of about 6 W m$^{-2}$.

Figure 6a shows EOF1 of OLR over land, the geographical distribution of coefficients corresponding to PC1. This map and the map of EOF1 over ocean (Fig. 6b) show a pattern in the extratropics that is a function of the sine of the latitude, similar to that of EOF1 of ASR (Fig. 3), with high positive values over northern latitudes and high negative values over southern latitudes. Longitudinal variations are superimposed on this latitudinal variation. In the tropics, the movement of deep convective centers (e.g., from the Congo basin to equatorial Africa) dominates EOF1 over land and is shown by negative-to-positive bands across the equator. These same bands are also found in EOF1 over ocean and indicate the north–south movements of cloud systems and the associated subsidence zones as they follow the sun. For example, note the dark blue areas over India and the surrounding ocean. These negative EOF1 values when multiplied with PC1 show that OLR is reduced during the summer monsoon season, as one would expect with cold convective cloud tops.

EOF2 for land and EOF3 for ocean corresponding to the semiannual cycle of OLR are shown in Fig. 7. Most of the variation over land and ocean occurs from 30°N to 30°S. The negative-to-positive-to-negative bands can be clearly seen over Africa and over the Indian Ocean. This pattern represents the north–south movements of clouds throughout the year.
e. Principal component analysis of net radiation

Like ASR, the eigenvalues of the seasonal cycle of net radiation show that the first principal components for both land and ocean explain more than 95% of the variability in the cycle (Table 4). In addition, PC2 describes 2%–3%, as for ASR.

The first three PCs of the seasonal cycle of net flux over land are shown in Fig. 8a. PC1 is sinusoidal in nature, matching the temporal pattern of PC1 for ASR over land. The amplitude is somewhat smaller because, for net flux, OLR is subtracted from ASR. The next two PCs represent the semiannual cycle and the out-of-phase annual cycle, respectively, and these are in phase with those for ASR. Because the second and third eigenvalues are so small, PC2 and PC3 account for very little of the variation of the seasonal cycle, and they are nearly identical to those of ASR. The PCs over ocean are shown in Fig. 8b and are very similar to those for ASR because the OLR has a small RMS relative to ASR. PC1 over ocean has a slightly larger cycle of net radiation than over land because its cycle of OLR is smaller.

EOF1 for the net flux over land is shown in Fig. 9a. The pattern is nearly zonal, just like that of EOF1 for ASR. Figure 9b shows EOF1 over ocean, which is also zonal and corresponds well to EOF1 over land. Some deviations from the zonal pattern can be seen near the west coasts of North America, South America, and southern Africa. The EOF2 maps over land and ocean that correspond to the semiannual cycle are shown in Fig. 10. These are also nearly the same as those for ASR.

f. Temporal relations among ASR, OLR, and net radiation

Because the first principal components of ASR and OLR describe so much of their temporal variations, the PCs can be used to examine the relations between ASR and OLR. Figure 11 shows the PC1 of OLR as a function of PC1 of ASR over land. Both PCs are very nearly sine waves; therefore, this hodograph figure is very nearly an ellipse. The phase angle is computed from the dot product of the PCs, and OLR lags ASR by 25.8°, or 26 days. Figure 12 is a similar plot for radiation over ocean. Over ocean the phase angle is 41.6°, or 42.2 days, a lag of OLR behind ASR. Mlynczak et al. (2011) found that PC1 for the upward longwave flux from the ocean lags the net shortwave flux at the surface by about 2 months but that, while the downward longwave flux lags the shortwave flux, it leads the upward longwave flux. Thus, the contribution to OLR from the ocean surface has a large lag due to its great thermal inertia. The atmospheric temperature increases more rapidly, so that at TOA the total OLR lags ASR by 42 days, less than the corresponding lag of the surface upward longwave flux over ocean.

Figures 13 and 14 are plots of PC1 of net radiation flux at TOA as a function of PC1 of ASR for land and for ocean. In Fig. 13, the maximum vertical distance between the upper and lower sides of the ellipse is about 25 W m⁻² and the horizontal range is 200 W m⁻², and therefore the ellipse is narrow, and the range of PC1 of net radiation is approximately 0.85 times that of ASR. The vertical distance between the upper and lower parts of the curve is the difference between OLR at the two times of year when the ASR takes a given value. This vertical distance in Figs. 13 and 14 corresponds to that

<table>
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<tr>
<th>Table 4. The normalized eigenvalues of, or fraction of variance explained by, the first four PCs of the seasonal cycle of net radiation.</th>
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<tbody>
<tr>
<td><strong>Eigenvalues</strong></td>
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<tr>
<td>1</td>
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<td><strong>Sum, 1–4</strong></td>
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in Figs. 11 and 12. Figures 13 and 14 emphasize that the OLR cycle is small relative to the ASR cycle and that most of the variation of net radiation is due to ASR.

4. Discussion

This study has used monthly mean maps that have been averaged over 10 yr. Use of monthly mean maps reduces the vagaries of synoptic variations. Averaging over a decade reduces the effects of intraseasonal and interannual variations, at least those effects with shorter time scales relative to the averaging time of 10 yr. Inherent in this rationale are the assumptions that the seasonal cycles are forced by the annual cycle of insolation and that the intraseasonal and interannual variations are free modes of the dynamical system. The possibility that variations that are either shorter or longer than a year may affect the seasonal cycle is not excluded. Indeed, synoptic processes transporting heat from low to high latitudes profoundly influence the annual mean and seasonal cycle of the OLR distribution.

The effects of using the EBAF data product rather than the SYN product are now considered. The salient factors are described in the second paragraph of section 2. For shortwave flux, the change in the solar constant from 1365 W m$^{-2}$ to a daily-varying SORCE value with an annual average of 1361 W m$^{-2}$ results in a decrease of the annual-average global-mean SW of 1 W m$^{-2}$ but only affects the seasonal cycles by a variation of $\pm 0.02$ W m$^{-2}$ because of the eccentricity of Earth’s orbit. The factor of 1.017 that is applied to the reflected SW causes the seasonal-cycle results that would have been computed using SYN to be changed by that factor so as to agree with these results using EBAF—that is, about a difference of 1 W m$^{-2}$ for the RMS of the annual cycle. In a similar way, because the annual-average global mean is subtracted from the OLR, the only effect of the difference between the EBAF and SYN datasets will be that the

Fig. 9. First EOF of the seasonal cycle of net radiation over (a) land and (b) ocean.
seasonal-cycle results for EBAF are greater than those from SYN by a factor of 1.0029, which is negligible. These changes apply to the principal components. Because the changes are multiplicative, their effects apply only to the principal components, and the EOFs are not affected.

Earlier studies of the seasonal cycle of TOA radiation fluxes (Bess et al. 1992; Smith et al. 1990) did not separate land and ocean because of the low resolution (15°) of the wide-field-of-view data products that were used. As a consequence, the time responses of land and ocean were mixed in the principal components. The 1° resolution of the CERES data products permits the separation of land and ocean so that their different characteristics can be seen.

The seasonal cycles of ASR, OLR, and net radiation flux are greatly affected by heat transfer and storage by land, air, and sea. In converse, a description of these cycles provides information about the transport and storage of heat. Consider a planet with no storage or transport of heat. For this case the OLR would have to equal the ASR at every point. Now consider a planet with storage. The temperature would result in an OLR that would increase with ASR but with a lag and amplitude depending on the thermal inertia. The amplitude of the OLR cycle would equal that of the ASR. The present results show that for Earth there is some storage but that the transport dominates the radiation cycle.

The inertia of the ocean is so immense that the circulation on the planetary scale has only a small seasonal cycle. Also, the heat storage capacity is so great that the seasonal cycles of temperature and OLR are relatively small. Thus, the seasonal cycle of heat transport of the ocean is small relative to that of the atmosphere. The annual-mean transport accounts for most of the transport of heat by the ocean. A model is required to separate the heat storage and transport effects. Also, these results provide information with which to validate the results of the model.

These observational results for the amplitude and lag of OLR in response to the periodic forcing by ASR should provide insight into the heat capacities and...
sensitivities of the Earth climate system for studies such as Schwartz (2007) and Dickinson and Schaudt (1998). Further investigations are needed in these directions.

5. Conclusions

The annual-mean net radiation flux for land is a deficit of 19 W m\(^{-2}\), whereas the ocean has a surplus of 9 W m\(^{-2}\). Atmospheric circulation redistributes the energy between ocean and land.

The first principal component PC\(_1\) describes more than 95% of the variance in the seasonal cycle of the absorbed solar radiation and the net radiation fluxes. The time and space variation of outgoing longwave radiation is more complex, and PC\(_1\) accounts for 88% of the variance over land and 79% over ocean. PC\(_1\) is an annual cycle for ASR, net radiation, and OLR. The corresponding geographical distribution EOF\(_1\) is zonal outside the tropics. Because PC\(_1\) describes such a preponderance of the variance, principal component analysis is very useful for describing these seasonal cycles. The annual cycles of ASR are about 100 W m\(^{-2}\) over land and ocean, but the amplitude of OLR is about 27 W m\(^{-2}\) over land and 15 W m\(^{-2}\) over ocean. The second principal component for OLR over ocean is an annual cycle that is out of phase with PC\(_1\) and represents 8% of the variance. Over land, the second principal component represents the semiannual cycle and accounts for 2.9% of the variance for ASR and 5% for OLR. EOF\(_2\) is small except in polar regions and in the tropics for ASR and for OLR over land. Over ocean, the semiannual cycle is represented by PC\(_2\) for ASR and PC\(_3\) for OLR.

FIG. 11. Monthly mean values of the first PC of OLR as a function of monthly mean values of first PC of ASR over land. The dashed line is an ellipse fit to the data.

FIG. 12. As in Fig. 11, but over ocean.

FIG. 13. Monthly mean values of the first PC of net radiation as a function of monthly mean values of the first PC of ASR over land.

FIG. 14. As in Fig. 13, but over ocean.
The magnitude of OLR and its time lag relative to that of ASR are important descriptors of the climate system and are computed for the first principal components. OLR lags ASR by about 26 days over land and 42 days over ocean. The principal components are useful for comparing the observed radiation budget with that computed by a model.

Acknowledgments. The authors gratefully acknowledge support by the CERES program from the NASA Science Mission Directorate through Langley Research Center to Science Systems and Applications, Inc. They also acknowledge the CERES project at NASA Langley for access to the dataset. They thank the reviewers for their insightful comments and suggestions, which have improved this paper.

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