The Diurnal Cycle of Outgoing Longwave Radiation from Earth Radiation Budget Experiment Measurements

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ABSTRACT

The diurnal cycle of outgoing longwave radiation (OLR) from the earth is analyzed by decomposing satellite observations into a set of empirical orthogonal functions (EOFs). The observations are from the Earth Radiation Budget Experiment (ERBE) scanning radiometer aboard the Earth Radiation Budget Satellite, which had a precessing orbit with 57° inclination. The diurnal cycles of land and ocean differ considerably. The first EOF for land accounts for 73% to 85% of the variance, whereas the first EOF for ocean accounts for only 16% to 20% of the variance, depending on season. The diurnal cycle for land is surprisingly symmetric about local noon for the first EOF, which is approximately a half-sine during day and flat at night. The second EOF describes lead–lag effects due to surface heating and cloud formation. For the ocean, the first EOF and second EOF are similar to that of land, except for spring, when the first ocean EOF is a semidiurnal cycle and the second ocean EOF is the half-sine. The first EOF for land has a daytime peak of about 50 W m⁻², whereas the first ocean EOF peaks at about 25 W m⁻². The geographical and seasonal patterns of OLR diurnal cycle provide insights into the interaction of radiation with the atmosphere and surface and are useful for validating and upgrading circulation models.

1. Introduction

The diurnal and annual cycles of solar irradiance are the two major forcing cycles for our weather and climate system. The outgoing longwave radiation (OLR) responds to this forcing by varying on both an annual and daily basis as a function of time and location. The first satellite measurements relating to the diurnal variation of OLR were analyzed by Raschke and Bandeen (1970). Their data, from a sun-synchronous spacecraft, only allowed computation of near-noon and midnight differences of OLR. Nevertheless, they demonstrated the variation of OLR with local time. In this paper we examine the diurnal cycle of OLR by use of 5 yr of data from the Earth Radiation Budget Experiment (ERBE) scanning radiometer which was aboard the Earth Radiation Budget Satellite (ERBS). This spacecraft, with an inclination of 57°, precessed through all local times every 72 days. The ERBS radiometers provided broadband measurements of OLR and reflected solar radiation, and the data are uniquely suited for study of the diurnal cycle of OLR.

Daily variability of OLR results from interactions of the surface and atmosphere due to temperature, cloud, and humidity variations during the day. These daily variations may be divided into diurnal variations, which repeat periodically, and transient variations due to weather events, which do not repeat on a daily cycle. Accurate knowledge of the diurnal cycle is crucial for several reasons. For sun-synchronous satellites, knowledge of the diurnal cycle is required to use radiometer measurements to compute radiant earth energy budget (Brooks et al. 1986; Barkstrom and Smith 1986). Given that one has measurements at only a few local times for any given region, to compute daily average OLR, it is necessary to make assumptions about variations of OLR across the day. A primary objective of the dedicated ERBS was to define these diurnal variations over the earth so that measurements from instruments in sun-synchronous orbits could be better interpreted. This objective resulted in the orbit design for ERBS by Harrison et al. (1983). Too, the ability of circulation models to simulate the diurnal cycle of OLR depends on how well surface and atmospheric interactions are modeled. Observational knowledge of the diurnal cycle of OLR provides an excellent method for validation of these models.

The present paper uses ERBS scanning radiometer broadband measurement data over a 5-yr period to com-
pute the diurnal cycle of OLR. A grid system of 2.5° regions covering the earth between 55°N and 55°S is used. Diurnal cycles are defined for four 3 month seasons, defined in section 3. This averaging process results in diurnal cycles being defined for over 6000 regions between 55°N and 55°S. To examine these in a systematic manner, the cycles are described in terms of principal components, which use the data to define the dominant patterns. The time variations of the principal components and the geographical patterns of the corresponding empirical orthogonal functions provide a way to describe and understand the cycles in terms of physical processes which create them.

Since the paper by Raschke and Bandeen (1970), a number of articles have dealt with observational studies of the diurnal cycle of clouds and OLR, though some were limited spatially, temporally, or in their use of narrowband measurements. These are reviewed in the next section.

2. Background

This sections deals with the extensive literature available concerning the study of the diurnal cycle of clouds and OLR. Due to the high temporal sampling rates of geosynchronous spacecraft many studies used data from these satellites. This limited these studies to certain regions of the globe and required conversion of narrowband radiances to broadband radiances, usually by correlations. A Meteosat Second Generation (MSG-1), spacecraft carrying the Geosynchronous Earth Radiation Budget (GERB) instrument, a broadband scanning radiometer, was launched in August 2002.

An early paper to study the diurnal cycle of OLR using geostationary data is Saunders and Hunt (1980). They considered four regions using Meteosat data and found diurnal variations depended on scene type. Over ocean, high clouds, and low clouds, OLR remains fairly constant but over desert it varies during the day. They estimated errors of diurnal mean OLR, based on measurements from a sun-synchronous spacecraft with 0900 LST equator crossing, and computed a 9 W m⁻² error for desert if the diurnal cycle is not considered when calculating daily mean OLR. Schmetz and Liu (1988) also used Meteosat data to study the diurnal cycle of four regions. By including the water vapor and 10.5–12.5-μm window channels, they reduced the error of derived OLR by a factor of 2. The marine stratocumulus region was found to have a diurnal cycle due to absorption of sunlight within the clouds, which dissipated by midday allowing OLR to peak in the afternoon. For the Sahara Desert they found a diurnal cycle that peaks near local noon with a range of 62 W m⁻². For the intertropical convergence zone (ITCZ) over Africa, the diurnal cycle has a range of 20 W m⁻² peaking near local noon. For the ITCZ over the Atlantic Ocean the diurnal cycle is very small. Minnis and Harrison (1984), using GOES-East for November 1987, found diurnal variations of 50 W m⁻² over regions with deep convection. Extreme ranges of 100 W m⁻² (Atacama Desert in Peru) to 2 W m⁻² (some ocean regions) were found. In the mean they found the diurnal cycle of OLR follows a half-sine variation, symmetric about noon. This description was incorporated into data processing for ERBE when computing daily average values of OLR. Pinker et al. (1986), using GOES data for May–August 1982 noted a variety of patterns of diurnal cycle of OLR and that a large sample is needed to develop these models.

A dataset beginning June 1974 of nearly continuous data from seven National Oceanic and Atmospheric Administration (NOAA) sun-synchronous satellites was developed by Gruber and Winston (1978) and Gruber and Krueger (1984). This valuable archive was subsequently used by Hartmann and Recker (1986), Gruber and Chen (1988), and Liebmann and Gruber (1988) to study the diurnal cycles of clouds and radiation. Hartmann and Recker (1986) considered OLR for 30°N to 30°S. They determined the ITCZ and South Pacific convergence zone had similar ranges of 6 to 8 W m⁻² and a maximum in the morning (0600–1200 LST) due to convective clouds at ~400 mb. They also found diurnal variations of very high clouds (~100 mb), 180° out of phase with variations at lower levels in atmosphere that reduced the magnitude of the diurnal harmonic. Results were presented as seasonal maps of the first Fourier term of the diurnal cycle, using arrows to indicate magnitude and phase for each region. Gruber and Chen (1988) supplemented the same dataset with Nimbus-7 data to expand the latitudinal range to 55°N to 55°S. Again using harmonic analysis, they showed large seasonal variations of the diurnal harmonic over midlatitude continents. A seasonal difference of 5 W m⁻² at 1200 LST to ~16 W m⁻² at 1400 LST for January and July, respectively, was found. The maximum at local noon is attributed to afternoon cloud growth. Liebmann and Gruber (1988) found a similar seasonal change in the midlatitude diurnal cycle. With respect to the ITCZ they found the maximum amplitude of the diurnal cycle, though small, migrated with the ITCZ along its seasonal path. They point out that the semidiurnal harmonic component (not shown in their paper) often had a significant impact on areas of intense convection.

As ERBE data became available several studies focused on information from this multisatellite radiation budget dataset. Harrison et al. (1988) showed ranges of OLR for all-sky and clear-sky conditions for April 1985 using data from ERBE scanning radiometers aboard NOAA-9 and ERBS. Harrison et al. (1990) and Konrad and Konrad (1993) both showed deserts have peak OLR in early afternoon with minima just before sunrise. For high plateaus and land regions where clouds peak in the afternoon, OLR has midmorning maxima. Tropical land has an evening minimum and the ocean has little response except where there are clouds such as afternoon maxima over areas with morning stratocumulus.
Kondragunta et al. (1993) showed seasonal differences with the winter hemisphere having a smaller diurnal cycle than the summer. Hartmann et al. (1991) used 7 months of ERBS data to compute the diurnal cycle of OLR and albedo and showed the amplitude of the semidiurnal harmonic for boreal winter [December–January–February (DJF)]. They found that, with only 7 months of data for a season, significant weather noise remains in the harmonics.

Duvel and Kandel (1985) provided a good statement of the fundamental assumption implicit in the definition of diurnal cycle. For a given region they expressed the radiance for a given day and local time as a diurnal cycle plus “weather noise.” Diurnal cycle is a function of local time, and does not vary from day to day. Weather noise varies from day to day and with local time. For any region, the diurnal cycle is the OLR for a given local time averaged over a long period, thus weather noise has a zero mean when averaged over time or space. (This latter hypothesis, exchanging time and space averages, is the ergotic assumption.) Several papers above note that a large sample size is required to smooth out the weather noise that affects an analysis of the diurnal cycle of OLR. In section 3 we describe how using the 5-yr span of ERBS data efficiently (though not entirely) averages out much of this noise.

3. Data

This investigation uses 5 yr of OLR fluxes, which were computed using data from the scanning radiometer aboard the ERBS. This spacecraft is in an orbit with a 57° inclination. To reduce possible effects of bidirectional reflectance functions in the derived fluxes, only regions between 55°N and 55°S were considered. This latitude range covers 82% of the earth’s surface. Regions were taken to be 2.5° × 2.5° (equal angle) and hour-box flux values from the S-9 tape data products were used (Barkstrom et al. 1989). These flux values are as measured and no temporal modeling has been applied to them as in daily-mean products.

The orbit tracks of the ERBS over a 36-day period and over a 72-day period are shown by Fig. 1. After 36 days, the spacecraft has not observed all local hours, so it is not productive to compute diurnal cycles on a monthly basis. The spacecraft requires 72 days to precess through all local times, at which point there is good coverage of the earth within 55°N to 55°S. By using data over the period January 1985 through February 1990, seasonal mean diurnal cycles are retrieved well. For this study the seasons were taken to be boreal winter (DJF), spring (MAM), summer (JJA) and fall (SON). Thus, 15 months were available for each season, reducing synoptic noise noted by Duvel and Kandel (1985) and Hartmann et al. (1991).

Another point of Fig. 1 is that the orbits converge at higher latitudes, hence the number of measurements per hour box is larger for higher-latitude regions. Figures 2 and 3 show, for a subtropical and a midlatitude region, (a) the sampling pattern over the five summer seasons, (b) the number of measurements per hour box, and (c) seasonal-mean diurnal cycle for that region. Figure 2b shows that for a region in the Sahara Desert located at 22°N, 5°E, over the five, 3-month periods, approximately 50 measurements are averaged into each hour box. Figure 3b shows the same for a region farther north at 48°N, 5°E, in France. The number of samples for the midlatitude case is two to three times greater than for the low-latitude case in any given hour box. This added sampling is useful for averaging out the synoptic weather patterns that are common in the mid- and higher latitudes. Also, note the number of measurements varies with local time. In summer, for the midlatitude case, there are nearly twice as many measurements at midnight as at noon. Other seasons have different distributions of measurements with local time.

The measurements in each hour box are averaged to give the diurnal cycle for each region, as shown by Figs. 2c and 3c for these two regions. The Sahara case has a strong diurnal cycle, with a peak of more than 40 W m⁻² higher than the minimum. For the region over France, the variation is approximately 20 W m⁻². Even
with 15 months of data for each region weather noise is still evident in the hour-to-hour change in the figures. The diurnal cycles for all 6336 2.5° regions within 55°N to 55°S are computed in this manner.

4. Computation of empirical orthogonal functions

This section discusses details of the method by which the empirical orthogonal functions (EOFs) and principal components were computed. These describe the diurnal variations of OLR. For a given season, for example, boreal winter, for each region in the domain between 55°N and 55°S, the average was computed for each of the 24 h of the day using data over the 5-yr period. A daily average was then computed for each region and subtracted from each of the 24 hourly means to produce a 24-component vector of deviations from the daily mean for each region $k$. Here, $h_i(k)$ is the diurnal cycle at the $i$th hour for the $k$th region. The $24 \times 24$ covariance matrix $G$ was formed by

$$G_{ij} = \frac{\sum_k w(k)h_i(k)h_j(k)}{\sum_k w(k)},$$
Fig. 4. Map of rms value of diurnal cycle of OLR for boreal summer.

Table 1. Variances for land.

<table>
<thead>
<tr>
<th>Order</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
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<tbody>
<tr>
<td>1</td>
<td>0.718</td>
<td>0.752</td>
<td>0.757</td>
<td>0.784</td>
</tr>
<tr>
<td>2</td>
<td>0.095</td>
<td>0.080</td>
<td>0.101</td>
<td>0.078</td>
</tr>
<tr>
<td>3</td>
<td>0.029</td>
<td>0.028</td>
<td>0.021</td>
<td>0.019</td>
</tr>
<tr>
<td>4</td>
<td>0.021</td>
<td>0.021</td>
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<td>0.015</td>
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<tr>
<td>5</td>
<td>0.014</td>
<td>0.016</td>
<td>0.011</td>
<td>0.012</td>
</tr>
<tr>
<td>6</td>
<td>0.012</td>
<td>0.011</td>
<td>0.010</td>
<td>0.009</td>
</tr>
<tr>
<td>Rms, W m⁻²</td>
<td>12.4</td>
<td>13.8</td>
<td>13.3</td>
<td>14.0</td>
</tr>
</tbody>
</table>

$w(k)$ is the area weighting for the $k$th region, and is taken to be the cosine of the latitude of the center of the region; $\Gamma_{ij}$ is the covariance over the domain 55°N to 55°S of the diurnal cycle at hour $i$ with that at hour $j$. Its trace is the total variance of the diurnal cycle, so that $(\sum_i \Gamma_{ii}/24)^{1/2}$ is the root-mean-square deviation over the day. The eigenvalues $\lambda_p$ and eigenvectors $v_p$ of the covariance matrix are computed. The eigenvalue $\lambda_p$ is the variance associated with the $p$th eigenvector. The eigenvectors provide a basis set for describing the diurnal cycles and are called principal components (PCs). They are normalized such that

$$v_p^Tv_q = \delta_{pq} \lambda_p,$$

where $\delta_{pq}$ is the identity operator. One advantage of the orthogonality, in addition to ease of projection of data onto the PC, is that total variance of the distribution is the sum of variances of the individual terms, with no interactions. The geographical distribution corresponding to the $p$th PC is the EOF $\psi_p$, and is computed by

$$\psi_p(k) = \lambda_p^{-1/2} \sum_j v_p(j) h_j(k).$$

Defined in this manner, EOFs satisfy the orthonormality condition that

$$\sum_k w(k) \psi_p(k) \psi_q(k) = \delta_{pq}.$$

From Eqs. (3) and (4) it follows that diurnal variation

$\sum_k w(k) \psi_p(k) \psi_q(k) = \delta_{pq}.$

Fig. 5. The first principal component of diurnal cycle of OLR for land for each season.
Fig. 6. Map of first EOF of diurnal cycle of OLR for land (a) for boreal summer and (b) for boreal winter.
can be expressed in the form of separation of variables in terms of PCs, which are functions of local time, and EOFs which are functions of location, that is, geographical maps, as

$$\mathbf{h}_k(i) = \sum_p \psi_p(i) w_p(j).$$  \hspace{1cm} (5)

There are various ways of defining the PCs and EOFs, resulting in different partitioning of the terms. With the definitions used here, the covariance matrix and eigenvalues have dimensions of watts per square meter squared, so that the PCs have dimensions of watts per square meter. Equation (2) states that over the 24-h period, the sum of squares of the components of each PC is the variance described by that pattern. The PC is the standard deviation at time $i$ for the pattern. Likewise, Eq. (4) states that the EOFs are dimensionless and the area-weighted sum of squares of the components for each EOF is unity. An EOF is the number of standard deviations by which a region $k$ varies.

5. Results

Figure 4 is a map of the rms of the diurnal cycle for boreal summer. Over land, rms reaches 30 W m$^{-2}$ for desert regions. Over ocean, there are vast areas where the rms is less than 4 W m$^{-2}$ and for most of the remaining ocean rms is less than 8 W m$^{-2}$. There are small areas in the Indian Ocean where the rms is as high as 16 W m$^{-2}$. This is in agreement with Harrison et al. (1988), who showed that the diurnal range of OLR over land is an order of magnitude greater than over ocean. We thus partitioned the earth between 55°N and 55°S into land or ocean so that each type could better manifest its characteristics. Any region containing both land and ocean was discarded; there are 301 such regions, accounting for slightly less than 5% of the number of regions. There are 1536 land regions and 4499 ocean regions in the domain. The land and ocean within the 55°S to 55°N zone cover 78% of the earth’s surface.

a. Diurnal cycle over land

Table 1 lists the fraction of variance for the first six PCs, listed in order of decreasing eigenvalue, or variance. The first and second PCs describe 72% to 78% and 8% to 10% of the variance respectively. The 22 higher-order PCs account for the remaining 12% to 18% of variance. Thus, the first two PCs are adequate to describe the diurnal cycles over land fairly accurately. The rms of the diurnal cycle, computed from the trace of the covariance matrix, is listed in the bottom row of Table 1 for land. Differences of rms from minimum to maximum are about 10%. Root-mean-square for land is highest during spring and fall, when Northern and Southern Hemispheres have strong insolation. Root-mean-square is lowest during boreal winter due to the greater fraction of land area in the Northern Hemisphere, when insolation and diurnal cycle are least at this time of year.

Figure 5 shows PC(1) for land for each season and has dimensions of watts per square meter. Since the daily mean was initially subtracted, the daily average of each PC is zero. The first PC describes the response of solar heating during the day as the surface and atmosphere heat up and radiate, then cool down at night. The four curves are extremely similar. One reason is that, for any season, PC(1) must describe the response of land in both Northern and Southern Hemispheres. Because seasons of the two hemispheres are 180° out of phase, seasonal effects will tend to cancel. The peak values are approximately 20 W m$^{-2}$ and occur between 1100 and 1300 LST. The curves are symmetrical about the peak. The minima are at night and are near -10 W m$^{-2}$. Because EOF(1) dominates the diurnal cycle for land, most regions’ time variations will be quite similar PC(1) for land is essentially the same half-sine wave result found by Minnis and Harrison (1984).

Figure 6a is a map of the first EOF for boreal summer as the number of standard deviations for each region. The largest values are over the Atacama Desert of Chile and middle eastern deserts, where the diurnal cycle has a range of 60 to 70 W m$^{-2}$, followed by the Sahara and Kalahari Deserts. For these regions there is little moisture to permit solar heating to be converted into latent heat, so that the surface heats up greatly, and there is little cloud cover or water vapor to attenuate the resulting large surface and lower tropospheric radiation. The next largest values are over deserts of Australia, steppe regions of Central Asia, North American plains, and the savanna areas of Africa. Interestingly, the Himalayas have a negative value for EOF(1); this negative value is explained after the discussion of EOF(2). Figure 6b is the EOF(1) map for boreal winter. The Chilean desert has a range of over 80 W m$^{-2}$, and the pattern over the Great Australian Desert intensifies to a maximum. The maximum across the middle eastern deserts moderates and, over the Sahara Desert, moves southward. Most of North Africa has a diurnal cycle of 30 W m$^{-2}$ or greater and remaining areas of the Northern Hemisphere have a diurnal cycle range near 15 to 30 W m$^{-2}$.

Figure 7 shows the second PC for each season for

![Fig. 7. The second principal component of diurnal cycle of OLR for land for each season.](image-url)
Fig. 8. Map of second empirical orthogonal component of diurnal cycle of OLR for land (a) for boreal summer and (b) for boreal winter.
land. Again, the four curves are quite similar. They are sine-like and have a peak value of approximately 8 W m$^{-2}$ near 1600 LST and a minimum of approximately $-5$ W m$^{-2}$ near 0800 LST, about 4 h out of phase with PC(1). Whereas PC(1) is nearly symmetric about noon, PC(2) is fairly skew symmetric about noon. The effect of PC(2) is to refine the shape of the diurnal cycle given by PC(1) so as to make the maximum and minimum occur either earlier or later, depending on the sign of the second EOF for the region.

Figure 8 is a map of EOF(2) for boreal summer for land and is due to a mixture of effects of clouds, surface, and orography. There are maxima over northern Africa, the Kalahari Desert, and the Middle Eastern deserts. These regions have diurnal cycles with maxima well past noon due to the heating of the surface and lower troposphere. When PC(2) × EOF(2) is added to the first pattern for a region PC(1) × EOF(1), the effect of the positive EOF(2) is to shift the maximum of the diurnal cycle to afternoon. Deep convective regions of Brazil and central Africa have negative values of EOF(2). These negative values shift the maximum of the diurnal cycle to the morning. The OLR diurnal cycle has its maximum in the morning due to afternoon buildup of high clouds. Over eastern India/Bangladesh, EOF(2) has a very low value. This is the monsoon season, and low EOF(2) indicates an afternoon increase of high clouds. Afternoon thunderstorms east of the Rocky Mountains and near Florida exhibit similar behavior. Boreal winter shown in Fig. 8b is equally complex. Minima are located over the Amazon and south of the Congo basin and Borneo, where deep convection regions are located for boreal winter. For most of Eurasia and North America EOF values are between $-1$ and 1. North Africa and other tropical regions have values between 1 and 2.

Figure 9 shows the diurnal cycles of regions downslope of (a) the Himalayas and (b) the Amazon. They are reconstructed using the first four PCs (solid), which shows the diurnal cycle minus the weather noise and all 24 PCs (dotted), which returns the region’s original diurnal cycle. For the Amazon, one finds a familiar near-noon peak with an early morning minimum between 0200 and 0600 LST. For the Himalaya region, where the minimum occurs near local noon, the cycle consists mainly of PC(2), but here EOF(1) must be negative to shift the phase of PC(2) to a later time (near 1200 LST), explaining the near-noon negative value of EOF(1) for this and nearby regions.

Figure 10 shows PC(3) for land for the four seasons. These account for 2% to 3% of the variance, are sinusoidal with two cycles though the day, and have an amplitude less than 5 W m$^{-2}$. PC(3) serves to describe the diurnal cycle for a region with two maxima during the day. Figure 11 is a map of EOF(3) for boreal summer. It is small except for a region near the northeast coast of South America and across the Congo Basin and extending northeast from there. These regions are associated with deep convection during this season. Grey and Jacobson (1977) discuss regions with two maxima in the diurnal cycle of rainfall from deep convection; this double maximum will be marked by a double maximum in OLR also.

b. Diurnal cycle over ocean

Table 2 shows for ocean the fraction of variance described by each of the first six EOFs and the rms for each season. As for land, the rms for ocean varies by about 10% from minimum to maximum. The minimum is in boreal summer, when the sun is in the north where most land is located. The remaining three seasons have very close values. The fraction of variance described by the first PC is 16% to 19% and the second PC describes 10% to 12%. The remaining terms decrease slowly with increasing order and account for 69% to 74% of the variance. Whereas for land, two PCs were sufficient to describe the diurnal cycles fairly accurately, for ocean many terms are required, indicating a greater variety of diurnal cycle shapes. This is in agreement with the finding of Liebmann and Gruber (1988) that over ocean there is a large variety of diurnal cycle forms. Also, the diurnal cycle over ocean is much smaller than for land, and thus the effects of “synoptic noise” are much stronger in the sampling error for the ocean PCs and EOFs. Although the noise is not of interest, its presence in the diurnal cycles, which are computed from observations, requires many terms for its description.
Figure 12 shows PC(1) for ocean. Rather than being a half-sine during day and nearly constant during night, as it was for land, this PC(1) has a sinusoidal shape with a maximum of 5 W m\(^{-2}\) near noon and a lesser maximum of 1 W m\(^{-2}\) near midnight. Minima of -3 W m\(^{-2}\) occur near sunrise and sunset. The shape differs from that for land because the processes causing the cycle are different. The ocean surface does not heat significantly during the day as for land. Over ocean, sunlight is absorbed by the clouds, causing them to dissipate during the day, allowing radiation from the warmer ocean surface to escape. The minima indicate increased cloudiness at these times. Grey and Jacobson (1977) discuss oceanic regions that have double maxima. Although clouds absorb sunlight over land also, this effect is smaller than that of surface heating of the land.

Figure 13 is a map of EOF(1) for ocean for boreal summer. For most of the oceans, EOF(1) is between -1 and 1. The northeast Pacific and Atlantic Oceans and portions of the Indian Ocean have large expanses with EOF(1) between 1 and 3. In the Bay of Bengal and south there are regions for which EOF(1) is between 3 and 5. These are regions that have much monsoon activity during this period. For the remaining seasons, the EOF(1) maps have similar ranges though the patterns differ.
PC(2) for ocean is shown by Fig. 14 for four seasons. They are sinusoidal waves also but with smaller amplitudes. They are out of phase with PC(1), as required by orthogonality, and serve to shift the phase of the diurnal cycle. Figure 15 shows EOF(2) for ocean for boreal summer. For most of the ocean the EOF is between −1 and 1. The major interest is in the equatorial Indian Ocean, where this EOF exceeds 3. In this area the effect of EOF(2) is to shift diurnal maxima to early afternoon and flatten the cycle during night. In boreal spring this feature is not present over the Indian Ocean. Over the southwest Pacific convergence zone, EOF(2) exceeds 3, having the same effect in that area. There is a region in the Atlantic Ocean just east of the U.S. coast where EOF(2) is negative. This region is generally over the Gulf Stream and indicates development of cloudiness in day and dissipation at night. There is a similar region in the Indian Ocean southeast of the Horn of Africa.

Grey and Jacobson (1977) demonstrated that in regions of intense deep convection in the Tropics, there are large diurnal cycles, typically with maximum rainfall in the morning around 1000 LST. In regions with low-level clouds, the diurnal range is much smaller. These variations of rainfall from deep convective system are accompanied by changes in the height of the top of the clouds, and thus changes of the OLR. In the regions of the monsoons in the Indian Ocean during the summer and over the southwest Pacific convergence zone during boreal spring, there are intense organized convective systems. Here, there are strong diurnal cycles of the OLR, corresponding to the diurnal cycles of rainfall discussed by Grey and Jacobson (1977).

6. Discussion

The validity of the PCs and EOFs presented here must be considered. North et al. (1982) developed a criterion
for the validity of EOFs. EOFs (or equivalently PCs, by duality) are necessarily computed from a finite number of realizations and thus are statistical samples, with variance due to sampling error. On this basis they derived a criterion for the validity of a computed EOF, assuming that each realization is independent. This standard deviation of the error of the eigenvalue $\lambda_p$ is defined as $\delta \lambda_p = \lambda_p (2/N)^{1/2}$. For the present study, $N$ is the number of regions for land (1536) or ocean (4499).

North et al. (1982) considered the computed EOF to be valid if it contained mainly the corresponding population EOF with only a “small” admixture of other EOFs. (An EOF would be considered valid if $\delta \lambda_p < \Delta \lambda = \lambda_p - \lambda_{p+1}$.) Though often in application to geophysical data, the independence assumption does not hold, the validity of EOFs/PCs calculated here is born out by this criterion as shown in Table 3. There one finds that the first four EOFs for both land and ocean have $\delta \lambda_p < \Delta \lambda$.

Note these numbers are normalized by the trace of the covariance matrix to match the variances shown in Tables 1 and 2. Another indication of the validity of the PCs is the similarity of the PCs for each order for each of the four seasons.

In the average over the globe, the diurnal cycle is very nearly symmetric. This is found in the near symmetry of PC(1) about noon for both land and ocean and raises a question. Is this symmetry a coincidence or the result of an underlying principle? Because only two PCs account for 82% to 87% of the variance of diurnal cycles over land, these two PCs describe most of the forms of diurnal cycles for OLR and the variety of these forms is highly restricted. Over ocean, the greater variety of forms of diurnal cycles does not permit dominance by only two terms. Figures 9a and 9b show that the diurnal

**Table 3.** North et al. (1982) criteria for validity of PCs.

<table>
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<th>Order</th>
<th>$\delta \lambda$</th>
<th>$\Delta \lambda$</th>
<th>$\delta \lambda$</th>
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<td>0.623</td>
<td>0.003</td>
<td>0.048</td>
<td>0.004</td>
<td>0.079</td>
</tr>
<tr>
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<td>0.080</td>
<td>0.003</td>
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<td>0.016</td>
<td>0.002</td>
<td>0.016</td>
</tr>
<tr>
<td>3</td>
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<td>0.004</td>
<td>0.001</td>
<td>0.008</td>
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<td>0.002</td>
<td>0.012</td>
</tr>
<tr>
<td>4</td>
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<td>0.001</td>
<td>0.013</td>
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</tr>
</tbody>
</table>
cycle computed for each region using this dataset still includes weather “noise.” This noise typically is described by the higher-order PCs and can be suppressed by using only significant PCs to reconstruct the diurnal cycle.

These results cover latitudes up to 55° from the equator. With the ERBS orbit inclination of 57°, the period of precession through all local times is 72 days. For this reason we used four 3-month seasons as the basis for the analysis. If there is a strong annual or semiannual cycle in the diurnal cycle for a region, the seasonal mean diurnal cycle will be less than the peak value.

In order to retrieve measurements at higher latitudes through all local times with a single spacecraft, the orbit must have a higher inclination, with resulting longer precession period. This long precession cycle would result in mixing of the seasonal and diurnal cycles in the measurements. The best way to determine diurnal cycles at high latitudes may be to use data from multiple spacecraft in near-polar orbits. Because insolation is constant through the entire day at the poles, one expects that the diurnal cycle will vanish at those two points. Likewise, with latitude increasing from 55° to 90°, one may expect that the diurnal cycle will decrease in magnitude, though not necessarily monotonically.

A knowledge of the diurnal cycle helps to understand the physical processes that occur at a daily timescale. It is at this timescale that solar energy is transferred from the surface to the atmosphere. Slingo et al. (1987) and Lin et al. (2000) point out that knowledge of the diurnal cycle helps to validate and improve GCMs. The diurnal cycle of OLR is affected by heating of the surface and lower troposphere and, in some regions, the development of clouds. The ability of a GCM to replicate the diurnal cycle of OLR depends on the simulation of the diurnal cycles of these temperatures and clouds. In addition, the description of the diurnal cycles is needed to assess temporal sampling errors and to evaluate the adequacy of temporal interpolation and averaging methods in processing and analysis of satellite measurements of OLR.

7. Conclusions

The diurnal cycle of outgoing longwave radiation from the earth is computed using 5 yr of data from the Earth Radiation Budget Experiment scanning radiometer aboard the Earth Radiation Budget Satellite, covering the earth from 55°N to 55°S. Regions of 2.5° latitude by 2.5° longitude are used, excluding coastal regions. Results cover 78% of the earth’s surface. A principal component analysis is applied to the cycle for each region. Diurnal cycles of land and ocean differ considerably. The first PC for land accounts for 72% to 78% of the variance, whereas PC(1) for ocean accounts for only 16% to 19% of the variance, depending on season. The diurnal cycle for land is surprisingly symmetric about local noon for the first PC, which is approximately a half-sine during day and flat at night. The second PC describes lead–lag effects. For the ocean, the first PC is similar but has a secondary maximum near midnight. The second PC for ocean describes a semidiurnal cycle that is out of phase with the first PC. The first PC for land has an average daytime peak of about 20 W m⁻², whereas the first ocean PC peaks at about 5 W m⁻².

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REFERENCES


