Spatial Variability of Outgoing Longwave Radiation

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ABSTRACT

Data from the Earth Radiation Budget Experiment scanning radiometer aboard the NOAA-9 operational meteorological satellite are used to investigate the spatial variability of outgoing longwave radiation (OLR). Daily and monthly radiation maps at 2.5° latitude-longitude scale are used as a basis for the study. The regions of greatest variability are in the tropics and subtropics. Storm tracks such as the South Pacific convergence zone appear as regions of high OLR variability. Spatial spectra in longitude show two regimes of OLR. At large scales (wavenumbers less than 6), the spatial spectrum is flat. For wavenumbers greater than 10, the spectra decrease as wavenumber to the −3 power. The spatial spectrum of daily anomalies from the mean is a strong function of latitude and season, with interesting features. Correlations of daily anomalies from the monthly mean decrease exponentially in latitude but have a damped-wave structure in longitude. The spatial variability of the daily maps, as measured by degree variance, have 10 times the power at degree 24 than the monthly maps, but at scales between 1 and 10, the degree variance is practically the same for daily as for monthly.

1. Introduction

In the present paper, we examine the spatial variations of the daily outgoing longwave radiation (OLR). The objective of the study is to quantify the spatial distributions of the day-to-day variations. These variations are of interest in two areas of research. First, they help to define the interaction of radiation with other processes on the order of a day. Second, a knowledge of the space and time variability of the field is needed for sampling studies for the evaluation of errors in existing satellite data and in design studies of future radiation budget measurement systems.

Most studies of OLR distributions to date have concentrated on the monthly average distribution (e.g., Heddinhaus and Krueger 1981; Smith and Bess 1983). Only a few investigations have considered the OLR distributions on time scales of a few days (e.g., Cahalan et al. 1982; Charlock et al. 1988; Charlock et al. 1989; Bess and Charlock 1990).

The day-to-day variations are considered to be rapidly varying random fields superimposed over a more slowly varying field, which may be characterized adequately by the monthly mean field. As random fields, the day-to-day variations are described statistically.

Suitable measures for such random fields are variances, power spectra, autocorrelation, and degree variances. Semantically, the individual realizations of the day-to-day variations are weather, but their statistical properties are an aspect of climate.

Data from the Earth Radiation Budget Experiment (ERBE) scanning radiometer (Barkstrom and Smith 1986) aboard the NOAA-9 operational meteorological satellite in the form of daily and monthly radiation maps at 2.5° latitude-longitude scale are the basis for the study. These data provide daily average global maps of flux, which have been analyzed to account for radiance anisotropy and diurnal variability (Smith et al. 1986; Brooks et al. 1986). The consideration of these effects in the analysis of the data produces daily maps that are of sufficiently high quality as to be useful for the present investigation. The results shown in this paper are for April, July, and October 1985 and January 1986 (the ERBE validation months).

2. Variances

Figures 1a through 1d show the distributions of the monthly mean OLR for April, July, and October 1985 and January 1986. These months were selected because they follow the equinoxes and solstices by about a month, and the atmosphere appears to lag the solar forcing by slightly more than a month. For each month there are major zonal variations within the Tropics. These zonal variations follow the sun’s north-south
Fig. 1a. Monthly mean OLR map for April 1985 (W m⁻²).

Fig. 1b. Monthly mean OLR map for July 1985 (W m⁻²).
Fig. 1c. Monthly mean OLR map for October 1985 (W m⁻²).

Fig. 1d. Monthly mean OLR map for January 1986 (W m⁻²).
movement through the year. Outside the Tropics the mean OLR has little zonal structure.

In the middle and high latitudes, on any given day there are weather features that cause a great deal of zonal variability of OLR, as Fig. 2 shows for 28 October 1985. These features are due primarily to clouds and temperature variations and, to a small degree, humidity variations. They move with the prevailing westerlies in the midlatitudes, so that the monthly mean map is much smoother than the daily map.

The standard deviations of the daily OLR about the monthly means are shown in Figs. 3a through 3d. The midlatitudes have standard deviations of 10 to 20 W m\(^{-2}\). The “roaring forties” of the southern oceans, that is, the zone between 40\(^\circ\) and 60\(^\circ\) S, has a remarkably uniform standard deviation of 10 to 20 W m\(^{-2}\) for all months. Regions of OLR extrema have low variability. For example, the polar regions have OLR minima and very small variability. Also, the high OLR region of the tropical east Pacific Ocean has a small variability. The major subsidence regions, that is, the deserts of North Africa, Saudi Arabia, and the equatorial Atlantic and eastern Pacific Oceans, are fairly constant, with standard deviations in the range 4 to 10 W m\(^{-2}\). A comparison of maps of standard deviation with maps of monthly mean OLR shows that regions of high variability are associated with regions where the OLR has large gradients. One example is the storm track (or baroclinic waveguide) of the South Pacific convergence zone, with a standard deviation of 39 to 52 W m\(^{-2}\) for various months. The Indian Ocean has a very complex pattern of variability, especially in the western part. There is also a high variability region in the neighborhood of Uruguay. This region of high variability is a storm track. It moves slightly with the season to follow the sun and has a variability of 35 to 47 W m\(^{-2}\).

Each of the four months has unique variability features. April (Fig. 3a) is a transition month. There are bands of high variability regions at 30\(^\circ\) N and 30\(^\circ\) S around the earth. This includes the global high variability region over the western Sahara desert. This variability is due to an influx of clouds across the area during the last ten days of the month. These clouds reduced the mean OLR and its diurnal range (Harrison et al. 1988). There are high variability regions across the Pacific Ocean at 30\(^\circ\) N. The storm track of the Southern Pacific convergence zone is a part of the band at 30\(^\circ\) S. Along the equator is a region of high variability where high clouds flow eastward from Amazonia. Afghanistan is another region of high variability.

July (Fig. 3b), as the peak of the Northern Hemisphere summer and Southern Hemisphere winter, has a variability quite different from that of April. Over the Northern Hemisphere the daily variation has increased since spring, but there is less variation over the Tropics. The bands of high variability at 30\(^\circ\)N and 30\(^\circ\)S that were present in April do not appear. The region of high-
Fig. 3a. Map of OLR standard deviations for April 1985 (W m$^{-2}$).

Fig. 3b. Map of OLR standard deviations for July 1985 (W m$^{-2}$).
Fig. 3c. Map of OLR standard deviations for October 1985 (W m\(^{-2}\)).

Fig. 3d. Map of OLR standard deviations for January 1986 (W m\(^{-2}\)).
est variability over the globe is in the western Pacific Ocean at 20°N, 150°E, with a standard deviation of 56 W m⁻². This is a storm track with its source in the Indonesia—Philippines region. The high variability that was over Afghanistan in April has moved over Pakistan. The Sahara desert, which had a high variability over its western part during April, has a low variability over its full extent. There is another low variability region over the Azores, matching the high OLR of the Azores high pressure cell. Directly south is another low variability region at 10°S, where in April there was a highly variable region. There is also a region of low variability formed over Siberia. Poleward of 60° in both the Northern and Southern Hemispheres, the standard deviations are below 10 W m⁻².

October (Fig. 3c) is the transition month following the autumnal equinox. The band of high variability regions that was at 30°N in April has reappeared at 10°N. To a large degree, this band is due to movements of deep clouds associated with the intertropical convergence zone. It extends from the west coast of Africa across the Indian Ocean to the South China Sea from the equator to approximately 5°N. The beginning of the rainy season over the Congo causes the OLR in that region to be highly variable. The high variability region over Afghanistan in April and over Pakistan in July is now over India and the Bay of Bengal, and with 58 W m⁻², the global high. This high variability is due to the withdrawal of the monsoons from India and Bangladesh during the month. The high that appeared in July over the western Pacific Ocean has moved over the Philippines, with 53 W m⁻².

January (Fig. 3d) exhibits a lack of structure except for the Indian Ocean region and the ubiquitous storm tracks of the South Pacific convergence zone and over Uruguay. The global high-variability region is northwest of Australia, having moved from the Philippines. The high variability region that was over India in October has moved over Sri Lanka. The poles and Siberia are regions of very low variability, with standard deviations of 3.8 to 7 W m⁻². Most other areas of the earth have standard deviations in the range 10 to 20 W m⁻².

The low variability of OLR over the Arctic and Siberian regions is caused by the low variability of the meteorological conditions. The Arctic tropopause is low and much of the cloud variability is due to stratuscumulus. Wallace et al. (1988) have shown that the 500-mb and 1000-mb height fields have low variability over these regions during the winter. Also, because of the reduced lapse rate in polar winter, clouds have a smaller effect on OLR.

3. Longitudinal variability

In this section the structure of the longitudinal variability is examined. First, the magnitude of variations is defined. Next, the longitudinal variability is defined by computing the power spectrum of the OLR around a latitude circle. Finally, the autocorrelation of the OLR in the longitudinal direction is examined.

a. Zonal variance

In order to describe variances, the notation of Oort (1983) will be used, whereby an overbar denotes monthly mean and brackets denote zonal mean. The zonal variance of the monthly mean map is defined as

\[ \sigma_{\text{an}}^2 = \langle (\bar{M} - \langle \bar{M} \rangle)^2 \rangle. \]

The zonal variance of the monthly mean map for each 2.5° zonal band is shown in Fig. 4a (dashed line) for April. The monthly mean variations are quite strong at the equator due to the deep convection zones of the Amazon, the Congo, and Indonesia, alternating with the subsidence zones between them. Antarctica also causes a strong variation because of its high glacial plateau over half of the zone and the ocean over the other half of the zone.

The zonal variance of the daily maps is defined as

\[ \sigma_1^2 = \langle (M - \langle M \rangle)^2 \rangle. \]

This daily mean zonal variance is shown in Fig. 4a as a solid line for each 2.5° zonal band. This line is the zonal average of the point variances presented as a map in Fig. 3a. Individual peaks in the daily mean zonal variance imply variable weather patterns, for example, changing cloudiness. These peaks result, for example, from large convective activity due to tropical storms or influx/reduction of clouds over areas normally very clear/cloudy. The troughs are primarily caused by a persistence in either clear or cloudy conditions over a given latitude. Figure 4a also shows the difference between the daily variance and the monthly variance, which is the same as the variance of the difference between the daily maps and the monthly maps:

\[ \sigma_1^2 - \sigma_{\text{an}}^2 = \langle \bar{M}^2 \rangle - \langle \bar{M}^2 \rangle. \]

This difference is a measure of the effect of short-term dynamics on the OLR. Because the zonal variances of the monthly mean map and the variances of the day-to-day variances simply add to produce the total zonal variance, it is useful to consider the variances rather than the standard deviations. The short-term variations are concentrated strongly in the low latitudes.

Figure 4b shows that in July, the zonal variability maxima of OLR move into the Northern Hemisphere, for both monthly mean and day-to-day variations. There is also a peak of day-to-day variability (dashed line) at 30°S due to the storm track of the South Pacific convergence zone and the storm track out of Uruguay. Another maximum occurs near 5°N due to several high variance regions along that latitude. Figure 4c shows reduction of the zonal variance of the monthly mean OLR distribution in the Northern Hemisphere in October. This is due to the movement of the sun south-
ward, which reduces the OLR contrast of the northern continents against the oceans. The day-to-day variations again have two distinct maxima, at 30°S and near 15°N. For January, Fig. 4d shows a very strong and sharp maximum of zonal variance near the equator for both the monthly mean map and for the daily averaged variability. In a study of motions in the Northern Hemisphere, Kao and Wendell (1970) noted a maximum of kinetic energy of zonal and meridional transient motions near 40°N in all seasons. This compares with the maxima noted in Figs. 4a–d.

b. Longitudinal spectra

The OLR field may be expressed as

\[ M(\alpha, \phi, t) = \sum_{n=-\infty}^{\infty} c_n(\alpha, t) e^{-in\phi}, \]

where \( \alpha \) denotes latitude, \( \phi \) longitude, and \( t \) the day of the month. The \( c_n(\alpha, t) \) is the \( n \)th complex Fourier coefficient for the expansion of the OLR field and can be computed from

\[ c_n(\alpha, t) = \frac{1}{2\pi} \int_0^{2\pi} M(\alpha, \phi, t) e^{in\phi} d\phi, \quad n \neq 0. \]

Because \( M(\alpha, \phi, t) \) is real, \( c_{-n}(\alpha, t) \) is the complex conjugate of \( c_n(\alpha, t) \). The average power in the \( n \)th wave at latitude \( \alpha \) is then defined as

\[ P_n(\alpha) = \frac{1}{T} \sum_{t=1}^{T} \{ |c_n(\alpha, t)|^2 + |c_{-n}(\alpha, t)|^2 \}, \]

where \( T \) is the number of days in the month. Figures 5a–d show the distribution of spectral power of the daily anomalies about the monthly mean with latitude for wavenumbers 1 through 6 for each of the validation months. There are necessarily peaks of power where the variance shows peaks (Fig. 3), since the sum of the average power over all wavenumbers plus the square of the monthly mean zonal mean is the variance at a given latitude:

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**Fig. 4.** Distribution of longitudinal variance with latitude for (a) April 1985, (b) July 1985, (c) October 1985, and (d) January 1986.
Fig. 5. Distribution of spectral power with latitude for (a) April 1985, (b) July 1985.
Fig. 5. (Continued) (c) October 1985, and (d) January 1986.
\[ P(\alpha) = [M^2] = [\overline{M}]^2 + \sum_{n=0}^\infty P_n(\alpha). \]

The variations of OLR during a month are markedly greater in the subtropics than in the middle and high latitudes. This is shown by the zonal variance in Fig. 4 and by the spectral power in Fig. 5. The low latitudes have a large amount of activity in the lower wavenumbers, corresponding to variations with longitudinally extensive correlations. Poleward of 60º, the power in all but wavenumber 1 drops off quickly in both hemispheres. This is a consequence of the polar coordinate system for which the \( n \)th wave of an analytic function must vanish as \( \theta^n \) in the neighborhood of the pole (Bowman and Bell 1987). The peaks of wavenumber 1 power near the poles are presumably due to Greenland in the north and the topography of Antarctica in the south. There are strong peaks of spectral power at 30ºN to 40ºN, 10ºN, and 30ºS, with well-defined minima between them. These peaks and minima define belts of activity and inactivity. The peak at 30ºN to 40ºN may be due to the undulations of the jet stream as highs and lows move along it.

In October (one month after equinox) the spectral power is roughly symmetric in latitude (Fig. 5c). The distribution is skewed to the south in January (Fig. 5d) and to the north in July (Fig. 5b). In April (Fig. 5a), the distribution is skewed to the Northern Hemisphere, although this is the month after equinox. This disruption in April of the pattern of the spectral power following the sun through the year is due to a strong component of wavenumber 2 in April.

Figure 6 shows the spectral power of the daily anomalies as a function of wavenumber for several latitudes for October. The spectral power for the other months is quite similar except for the lowest six waves, which vary strongly with season. The spectra in longitude show two regimes of OLR. At large scales, that is, wavenumbers less than 6, the spatial spectrum is roughly flat. For wavenumbers greater than 10, the spectrum decreases approximately as \( n^{-3} \). Salby (1982) demonstrated that one cannot unambiguously retrieve longitudinal Fourier components with wavenumbers greater than 6 from sun-synchronous satellite data. It can be shown that a “smooth” spectrum nevertheless manifests itself in the computed spectrum. Although individual Fourier components cannot be retrieved, the spectrum is a statistical quantity. The computed spectrum is smaller than the “true” spectrum by a factor on the order of 3.

A similarity of the OLR variation to that of the dynamics of the atmosphere is expected. Radiative interactions of the clouds and latent heat release within the clouds due to condensation and freezing of water are important diabatic processes, which couple clouds to the dynamics. Also, the dynamics create the conditions favorable for clouds, which are the strongest modulators of OLR. Temperature and humidity also affect OLR, and these quantities are also closely coupled to the dynamics. The ranges seen in Fig. 6 suggest the model for the eddy kinetic energy spectrum presented by Gifford (1988), based in turn on Golitsyn (1973). Planetary waves, that is, wavenumbers 1 through 6, are driven by diabatic pro-
cesses and by upscale cascading of eddy kinetic energy. Baroclinic processes dominate the range between wavenumbers 6 to 15. Wavenumbers greater than 15 make up the energy cascade range. The energy cascade range extends to a much smaller scale than is resolvable with the present dataset, with its $2.5^\circ \times 2.5^\circ$ resolution.

Studies of the spectra of motions of the atmosphere, for example, by Kao and Wendell (1970), show that the spectrum of the eddy kinetic energy decreases as $n^{-3}$. Thiebaux (1981) has shown that the spectrum of eddy kinetic energy is related to that of the geopotential height field such that the spectrum of the geopotential height decreases faster with $n$ than does the spectrum of the eddy kinetic energy. Thus, the spectrum of the geopotential height decreases faster with $n$ than does the spectrum of OLR. This is in agreement with the observation by Cahalan et al. (1982) that the geopotential field has a greater spatial correlation length than does OLR. Charlock and Rose (1991) also found that clouds, which are the strongest modulators of OLR, have a shorter range structure than does geopotential height.

4. Correlations

a. Latitudinal correlations

The correlation of OLR in latitude was formed by computing the correlation of daily anomalies between a given point and points directly north and south over a one-month period, and then averaging these correlations around the latitude circle. Figure 7 shows the resulting correlation between points on a north–south axis for October. The shapes for each case are very nearly exponential, with the correlation decreasing to
$1/e$ over 500 to 800 km. This kind of behavior was seen in single-point correlations in the 500-mb height field by Thiebaux (1976) and by Blackmon et al. (1984) for time scales of 2.5 to 6 days. The cusp at latitude difference of 0 km does not appear in the geopotential correlations; it is due to significant variability of OLR over spatial scales smaller than the grid box size of 2.5°, which was used for the present data.

b. **Longitudinal correlations**

The correlation in the longitudinal direction was computed in the same manner as for the correlation in latitude, and the results are shown in Fig. 8. The correlations decrease exponentially from the reference point, with wavetype structure manifesting itself as a negative minimum at a distance of 1500 to 4000 km. The 45° case in each hemisphere closely resembles the
5. Degree variances

One useful measure of spatial variability of a field on a sphere is the degree variance, which is the analog of the Fourier spectrum appropriate for a sphere (e.g., North and Cahalan 1981; Smith and Green 1981; North et al. 1982). The degree variance of monthly mean OLR maps based on the Earth Radiation Budget instrument aboard the Nimbus-6 spacecraft was investigated by Smith and Bess (1983). In this section, the degree variance of daily OLR maps is considered.

The OLR distribution may be expressed in terms of spherical harmonics as

\[ M(\theta, \phi) = \sum_{n=0}^{\infty} \sum_{\ell=-n}^{n} C_n^\ell Y_n^\ell(\theta, \phi), \]

where \( \theta \) is colatitude. The \( C_n^\ell \) are expansion coefficients and are complex. Because \( M(\theta, \phi) \) is real, \( C_n^\ell \) is the complex conjugate of \( C_n^{-\ell} \). The degree variance is defined by

\[ \sigma_n^2 = 2 \sum_{\ell=0}^{n} |C_n^\ell|^2. \]

Degree variance is most useful for processes that are isotropic with respect to rotation of the sphere. Although this assumption is not valid for large-scale processes on earth, such as planetary waves, it is a useful approximation for smaller scales, that is, synoptic and smaller.

Degree variances are computed for each daily map. The degree variances are then averaged over the month and are shown in Fig. 9 as a dash-dot line. The bars in the plot indicate the mean plus/minus one standard deviation. The degree variance for the monthly mean map is shown as a dotted line. The strongest feature of the degree variance is the peak for degree 2, which is due to the coefficient of \( P_0^2(\cos \theta) \). This term describes the equator-to-pole variation of OLR and varies very little with time. The most variable degree variance is for degree 1. The \( C_1^0 \) describes the pole-to-pole gradient and has the strongest annual cycle of all terms. From degree 3 through 8, the degree variance stays in the range 20 to 120 \( \text{W}^2 \text{m}^{-4} \), after which it forms a fairly smooth line with exponential decrease with degree. This line may be approximated by

\[ \sigma_8^2 = 138 e^{-0.121n}. \]

For degree variance greater than 10, the standard deviation of the degree variance for any given day about the mean degree variance is about 30% of the mean. This expression is inconsistent with the power law distribution found for the longitudinal spectra of daily variations under the assumption of isotropy with respect to rotation.

The spatial variability at wavenumbers between 1 and 10 is practically the same for daily maps as for
monthly, but for degree greater than 10 the degree variance of the monthly mean map decreases much more rapidly than does the degree variance for daily maps. The daily maps have 10 times more power at degree 24 than do the monthly maps. Physically, this indicates that at small scales as characterized by wavenumbers on the order of 24, there is much detailed structure on the daily maps, as is demonstrated by Fig. 2. Most of this fine detail is transitory, so that the monthly mean map is much smoother, that is, has much less power at these wavenumbers. For large features, described by wave numbers of 10 or less, the structure is predominantly that of the monthly mean map. The degree variance of the monthly mean OLR maps for wavenumbers greater than 12 is approximated by

\[ \sigma_n^2 = 68e^{-0.16n^2} \]

The degree variance for April 1985 is approximately 30% higher for wavenumbers of 10 to 15 than for the other months studied. This may be due to April being a month when large transitions typically occur.

6. Conclusions

Daily and monthly radiation maps at 2.5° latitude—longitude scale from the Earth Radiation Budget Experiment scanning radiometer aboard the NOAA-9 operational meteorological satellite have been used to investigate the spatial variability of outgoing longwave radiation (OLR). The regions of greatest variability are in the tropics and subtropics. Storm tracks such as the South Pacific convergence zone appear as regions of high OLR variability. Spatial spectra in longitude show two regimes of OLR. At large scales (wavenumbers less than 6), the spatial spectrum is flat, but for wavenumbers greater than 10, the spectra decrease rapidly. The spatial spectrum of daily anomalies from the mean is a strong function of latitude and season. Correlations of daily anomalies of OLR from the monthly mean decrease exponentially in latitude and longitude. The spatial variability of the daily maps, as measured by degree variance, has 10 times the power at degree 24 than that of the monthly maps, but at scales between 1 and 10, the degree variance is practically the same for daily as for monthly.

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