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Diurnal variation of the outgoing long-wave radiation: as revealed by the E.R.B.E.

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ABSTRACT

The diurnal variation of the Outgoing Longwave Radiation (OLR) and its annual variation were studied using scanner products from the Earth Radiation Budget Experiment (ERBE). Data from the combination of sun synchronous polar orbiter NOAA-9 and mid-inclined precessing orbit Earth Radiation Budget Satellite (ERBS), which provide the best diurnal global coverage, were used for the period of March 1985 to February 1986. Harmonic analysis was performed on monthly mean hourly OLR for both average sky and clear sky conditions in order to obtain the amplitude and phase of the OLR diurnal cycle. Large diurnal amplitudes are noticed mostly over desert regions. Over oceans, convectively active regions like the Inter Tropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ) show noticeable diurnal variation compared to the rest of the regions. Annual variation of the OLR diurnal amplitude was compared with annual variation of the various earth radiation budget parameters. A good relationship was found between the OLR diurnal amplitude and the monthly mean net radiation and incoming solar radiation.

1. Introduction

The knowledge of spatial and temporal variations of the earth radiation budget is crucial to the understanding of climate, because the earth's circulation system depends on the sources and sinks of energy. The earth's radiation budget parameters vary on various time scales. Some of the well known variations are inter annual, intra-annual, intra-seasonal and diurnal variations. The diurnal variation is perhaps the least understood, mainly because of inadequate sampling of the entire earth on this time scale. Geostationary satellites can sample the earth with high temporal resolution, but they are limited by spatial resolution, as they can only view a limited region of the earth. On the other hand, polar orbiting satellites can sample the entire earth, but they are limited by poor temporal resolution, as they can view any particular region only twice a day, once during ascending node and once during descending node. In order to monitor major portion of the earth with better spatial and temporal resolution, either many geostationary satellites covering the entire earth or many polar orbiting satellites with different equator crossing times are required. Since either approach would require a lot of effort and money, an alternative with some compromise was obtained through the Earth Radiation Budget Experiment (ERBE). The ERBE is a multi satellite system consisting of two polar orbiting satellites with different equator crossing times and one precessing satellite with 57° inclination to the equator.

Many efforts were made in the past to study the diurnal variation of the earth's atmosphere using earth's top of the atmosphere radiation budget parameters with the then available satellite data. Gruber and Chen (1988) and Liebmann and Gruber (1988) analyzed global Outgoing Longwave Radiation (OLR) to examine the diurnal cycle using a composite daily cycle obtained from a series of sun-synchronous polar orbiting satellites which flew in different years with ten different equator crossing times. Hartmann and Recker (1986) also have computed the diurnal harmonic with similar data. Meisner and Arkin

(1987), McGarry and Reed (1978) and Duvel (1989) studied some aspects of diurnal variation using infrared data from geostationary satellites. Minnis and Harrison (1984b) studied extensively the diurnal variability of visible and infrared radiation data from GOES-East (Geostationary Operational Environmental Satellite, East) during November 1978.

The above studies suffer from one or more problems. Some of them are (i) the temporal sampling was sometimes not adequate enough to get good diurnal estimates, (ii) the radiances sampled do not include the complete emission bands of the Earth and (iii) some studies covered only a portion of the globe. One of the main objectives of the Earth Radiation Budget Experiment is to obtain better diurnal sampling. In addition to the better sampling, ERBE has implemented better inversion algorithms, many of which depend on model sets derived from Nimbus-7 ERB experiment. An additional advantage of the ERBE data set over the earlier ones is that the ERBE science team decided to process clear sky radiances as separate parameters, with which one can differentiate the role of clouds on the Earth's radiation budget.

In this study, we made an attempt to understand the diurnal variation of OLR, its annual and spatial variation making use of the ERBE data. Through its relationship to deep convection, OLR is related to the latent heat of condensation released which is the primary energy source for driving the general circulation. Gruber and Chen (1988) noticed annual variation in phase of the diurnal cycle of OLR, earlier phases with larger amplitude occurring in the summer months and later phases with smaller amplitude occurring in winter months over few selected places. This suggests some relationship between diurnal amplitude and phase of the OLR with Sun's position. Understanding of diurnal cycle of OLR and its annual variation will help proper incorporation of cloud mechanisms in the general circulation models. Diurnal variation of OLR can be caused by the diurnal variation of the cloud cover, surface and atmospheric temperatures and water vapor content in the atmosphere. Where ever appropriate, we compared our results with other diurnal studies made in the past. Many studies in the past have utilized ship and land station data to examine the diurnal cycle of rainfall measurements and may not be in good agreement with some other diurnal rainfall results, because of the fact that every type of cloud cannot produce rain. Deep towering cumulonimbus clouds, which are rain producers, especially in the tropics, are often too small in spatial scale to be resolved by the ERBE data. Another point is that cirrus from the deep cumulus clouds may extend for several miles from the original cloud cluster and last longer than the original cumulus cloud. The light rain, if any, from these cirrus shields may not contribute much to the diurnal variation of surface rainfall measurements, but contributes significantly to the diurnal variation of OLR. So the diurnal variations in rainfall measured at surface may not always agree with the diurnal variations in OLR.

Data and analysis procedures are discussed in Section 2. Section three is devoted to results and discussion. Section 3 is divided into many subsections, in which annual mean diurnal harmonics, seasonal mean diurnal harmonics and relationship between the diurnal variation of OLR and the other earth radiation budget parameters are discussed in each subsection. Final conclusions are drawn in Section 4.

2. Data and analysis procedures

2.1. *Data*

The source of data for this study is the Earth Radiation Budget Experiment (ERBE). One of the objectives of the ERBE is to obtain better diurnal sampling of broadband measurements of the earth radiation budget parameters. ERBE is a three satellite system, two Sun synchronous satellites with different equator crossing times (NOAA-9 and NOAA-10) and the NASA Earth Radiation Budget Satellite (ERBS) which is in a non Sun synchronous precessing orbit (57°). Each of these satellites carry a scanner and a non-scanner package. The scanner observes radiation in three channels (total, shortwave and longwave) with wavelength ranges of 0.2 μm–50 μm, 0.2 μm–5 μm and 5 μm–50 μm, respectively. For details of the ERBE instruments, calibration, and top of the atmosphere inversion algorithms the reader is referred to Barkstrom (1984), Brooks et al. (1986) and Smith et al. (1986).

In this study, we utilized scanner data processed from the ERBS and NOAA-9 satellite combination (S-4 products). Harrison et al. (1983) showed that a combination of at least one sun synchronous satellite and a precessing orbit satellite with an inclination of 46° or 57° is needed to obtain the best global coverage over a period of a month. In a simulation study, Brooks and Minnis (1984) have shown that a single satellite in a Sun-synchronous orbit and a mid-inclined (57°) satellite in a precessing orbit are good enough to unravel diurnal variations from synoptic and seasonal variations. So the combination of NOAA-9 with equatorial crossing times at 0230 and 1430 solar time (LST) and ERBS with an inclination of 57° to the equator, precessing through all local hours at the equator in 36 days, provides the best temporal and global coverage for the diurnal variation studies. Monthly mean Outgoing Longwave Radiation (OLR), net radiation and solar insolation and monthly mean hourly OLR for both average (clear plus cloudy) and clear sky conditions covering the period from March 1985 to February 1986 at 2.5° latitude by 2.5° longitude resolution were analyzed. The ERBE hourly data processing algorithm uses a half-sine model centered about the local solar noon over land and deserts when certain restrictive criteria are met. When a half-sine model cannot be used, linear interpolation between hours is used (Brooks and Minnis, 1984). A maximum likelihood estimate technique (Wielicki and Green, 1989) was used to identify clear and cloudy scenes. Here 5% or less cloud cover is considered as clear scene.

2.2. Analysis procedures

The monthly time and space averaging system of ERBE accumulates data for each 2.5° latitude by 2.5° longitude grid areas from each satellite and obtains monthly mean hourly data by averaging all values in a month for any particular hour. Harmonic analysis (Fourier analysis) was performed on this monthly hourly data to obtain amplitude and phase of the diurnal cycle of OLR. Seasonal and annual mean hourly data were obtained by averaging monthly hourly OLR data of all the months of the season/year for any particular hour. Again, seasonal/annual mean hourly data were subjected to harmonic analysis to obtain the seasonal/annual mean diurnal cycle of OLR. A standard procedure (Panofsky and Brier, 1957) was followed to compute harmonic coefficients, amplitude and phase of the diurnal cycle of OLR. A statistical significance test, as described in Brooks and Carruthers (1953), was applied to the diurnal amplitude obtained by harmonic analysis. The computed diurnal amplitude at each 2.5° by 2.5° grid box was compared against a value A, which is obtained by

$$A = 2\sigma[(\log_e 20 \cdot n)/N]^{1/2},$$

where σ is the standard deviation of the N values and n is the number of harmonics computed. In this case $N = 24$ and $n = 12$. If the diurnal amplitude exceeds the value A, then that amplitude is taken as statistically significant at 5% level. The quantity A, computed in the above equation comes out to be close to one standard deviation.

3. Results and discussion

3.1. Annual mean harmonic analysis

The annual mean (March 1985 to February 1986) diurnal harmonic is presented in Fig. 1. In the figures, length of the arrows is directly proportional to the amplitude of diurnal cycle up to 5 W/m^2, and constant beyond 5 W/m^2. Amplitudes greater than 5 W/m^2 are contoured at the interval of 10 W/m^2. Phase of the diurnal cycle is indicated by the direction of the arrow. Arrows pointing northward indicate midnight or 0000 LST, arrows pointing eastward indicate 0600 LST, arrows pointing southward indicate 1200 LST and arrows pointing westward indicate 1800 LST. Here the phase of the diurnal cycle indicates the time of the day at which maximum OLR emission occurs. Since OLR is considered as proxy to cloudiness, especially in the tropics, and since lower OLR values correspond to cloudiness, the time at which minimum OLR occurs is of prime interest for discussion.

The annual mean diurnal harmonic (Fig. 1) shows large amplitudes over land compared to oceanic regions. Over oceans, convectively active regions show greater amplitudes compared to non-convective regions. Over land, amplitudes greater than 15 W/m^2 are found over desert regions like Sahara, Kalahari in Africa, Arabia, Afghanistan, Pakistan, Gobi in Eurasia, Australian desert in Australia, Southwestern United States and northern Mexico in North America, and Atacama in South America. Over most of these desert regions,

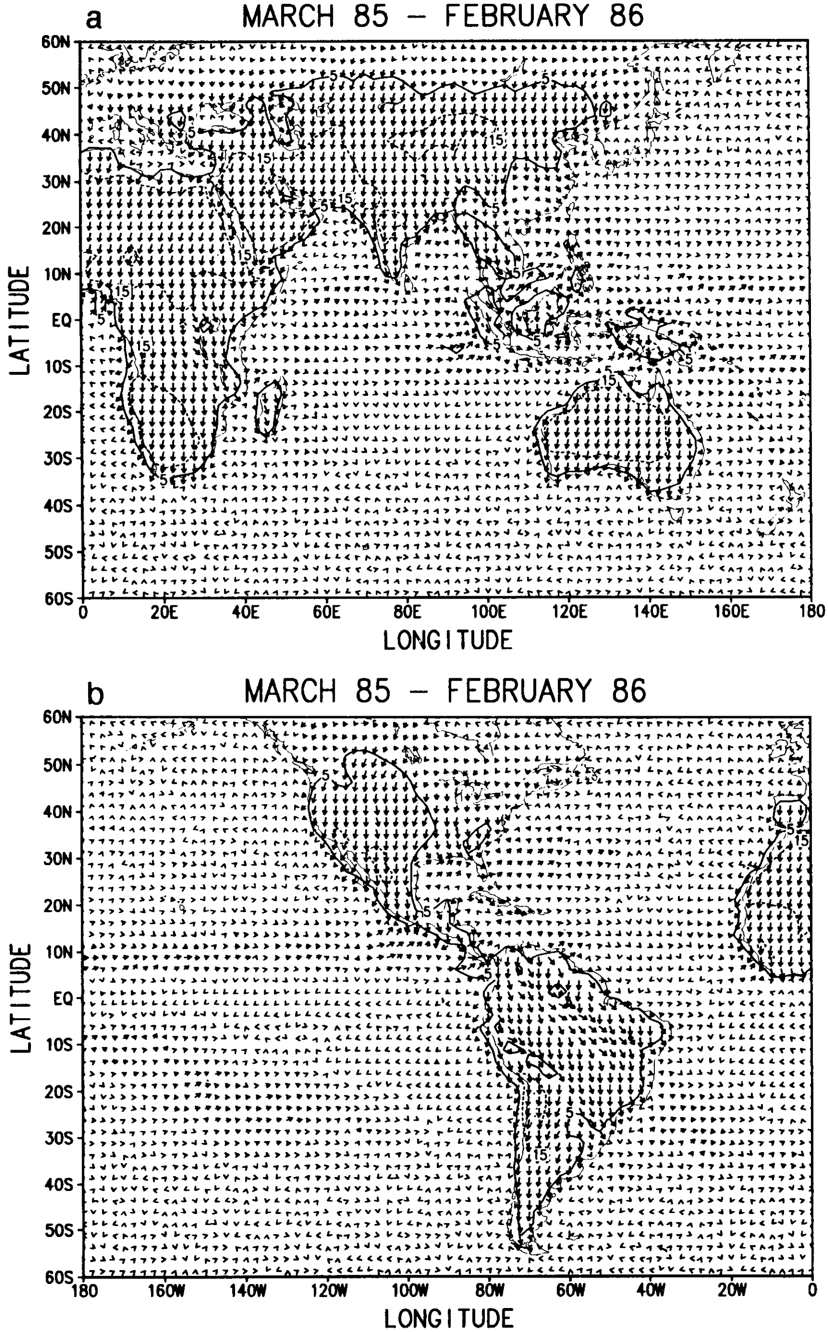


Fig. 1. (a) Amplitude and phase of the diurnal cycle of Outgoing Longwave Radiation for the year March 1985 to February 1986 for the eastern hemisphere. The length of the arrow is proportional to the amplitude up to 5 Wm^{-2} and constant above that. Solid contour is 5 Wm^{-2}, dashed contour is 15 Wm^{-2} and dotted contour is 25 Wm^{-2}. Arrow pointing northward indicate maximum longwave emission occurring at 0000 LST, eastward 0600 LST, southward 1200 LST and westward 1800 LST. (b) Same as (a), except for the western hemisphere.

maximum OLR occurs in the afternoon. Because of low humidity and cloud cover, diurnal variation in OLR over desert regions is mostly due to the diurnal variation in surface temperature which in turn is due to diurnal cycle of solar insolation. After sunrise, solar insolation heats the desert soil causing the surface temperature to increase gradually to its peak slightly after midday. After this the surface temperature starts decreasing as the solar zenith increases. By evening, solar radiation reaches zero, but surface temperature continues decreasing due to radiational cooling until sunrise the next day morning. The phase (peak OLR emission) of OLR diurnal cycle occurs in the afternoon because surface temperature reaches its peak in the afternoon over desert regions. This afternoon phase could also be influenced by the half-sine model fit used over desert regions in the ERBE monthly hourly data processing algorithm.

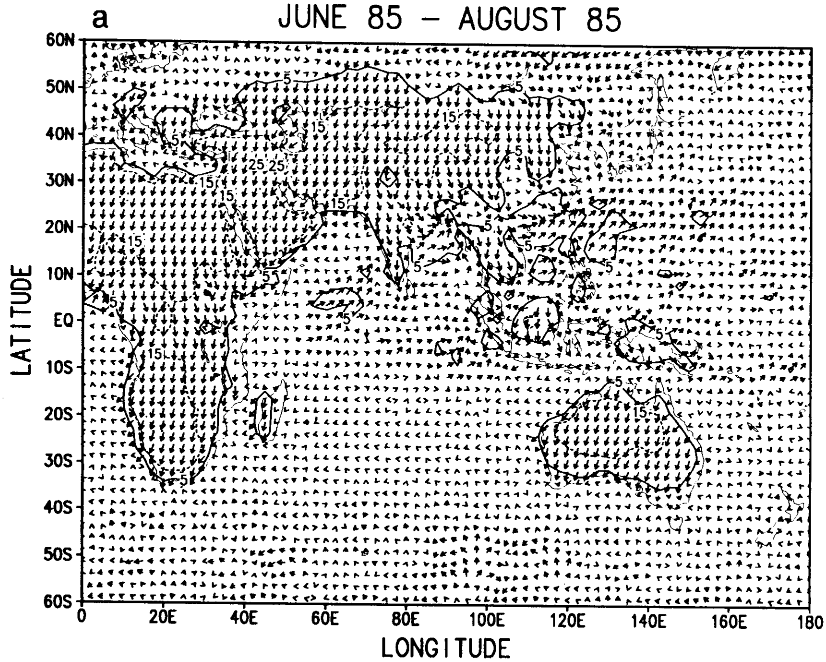
OLR diurnal variation is different over convectively active land regions. Over these regions the OLR diurnal variation results from the fact that the presence of clouds alters the longwave emission to space. Over the Amazon river basin, Mexico, Central America, Congo river basin, Madagascar, Indonesia, Indo-China, Malaysia, Eastern China, and Eastern part of India amplitudes are greater than 5 W/m^2 and phase occurs before noon. It is well known that these land regions are affected by monsoonal cloudiness, and before noon OLR maximum suggests before midnight cloudiness. A detailed discussion is given in the seasonal mean field section.

Diurnal variation is small over almost all oceanic regions compared to land. Intuitively one can understand this because oceans have large heat capacity and hence sea surface temperature does not change on daily basis. However, there are some oceanic regions where OLR undergoes significant diurnal variations. These are low level convergence regions like the Inter Tropical Convergence Zone (ITCZ), South Pacific Convergence Zone (SPCZ), and South Atlantic Convergence Zone (SACZ); low level stratus regions off west coast of South America; and high sea surface temperature regions like the Gulf stream and northwestern Pacific. The cloudiness over these regions is seasonally dependent and detailed discussion is presented in the next section. Off the west coast of South America where low level stratus clouds are present during southern hemisphere summer, amplitudes are large and the phase occurs in the afternoon. Afternoon phase over this region indicates early morning cloudiness. Minnis and Harrison (1984a) noticed that the stratus cloudiness over this region reached a maximum in the early morning hours (0300–0600 LST) and a minimum in the afternoon (around 1530 LST) for the month of November 1978.

Results presented here are consistent with the earlier studies most of which used narrow band measurements (Gruber and Chen, 1988; and Liebmann and Gruber, 1988). Though Minnis and Harrison (1984b) converted GOES narrowband measurements to broadband radiances, they suggested that their transfer functions should be used only in the absence of direct broadband measurements from the radiometers. It is interesting to note that even in the annual mean sense, the variable but seasonally large diurnal amplitudes over oceanic regions like ITCZ, SPCZ, SACZ, Gulf stream, and low level stratus regions off South America are clearly delineated. There is an advantage in looking at the annual mean diurnal variation in OLR using ERBE data. The annual map clearly shows regions where persistent large scale diurnal cycles occur. Large seasonal OLR phase and amplitude changes occur even in regions not prominent on the annual map. This is particularly true over the ocean. These changes are examined in the next section. Hartmann et al. (1991) studied data from the ERBS satellite alone and found that a sampling bias existed which was introduced by the satellite's precessing orbit. Product combining the NOAA-9 and ERBS data tends to minimize this problem on a seasonal basis and is even more effective in annual averages.

3.2. Seasonal mean harmonic analysis

Figs. 2a, b are northern hemisphere summer and Figs. 2c, d are northern hemisphere winter mean diurnal harmonic maps, respectively. During northern summer large amplitudes greater than 15 W/m^2 are noticed over most of the United States, northern parts of Mexico, Atacama desert in South America, Sahara and Kalahari deserts in Africa, Saudi Arabia, Middle east, Tibetan Plateau and Gobi desert in Eurasia, and the Australian desert in Australia. All these regions come under a subtropical high pressure belt where strong large scale subsidence prevents cloud formation so that solar radiation can directly heat the ground and



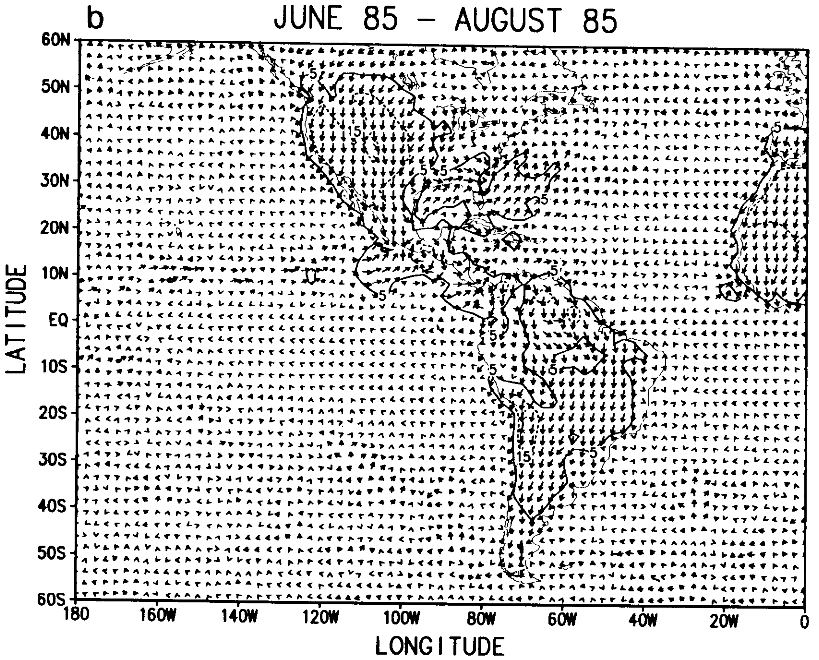
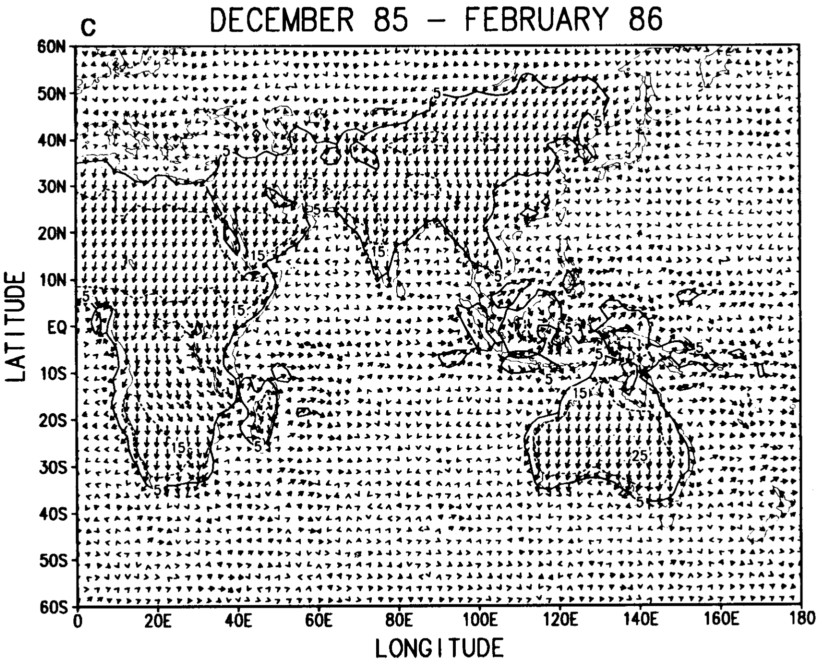


Fig. 2. (a) Same as Fig. 1a, except for June 1985–August 1985. (b) Same as Fig. 1b, except for June 1985–August 1985. (c) Same as Fig. 1a, except for December 1985–February 1986. (d) Same as Fig. 1b, except for December 1985–February 1986.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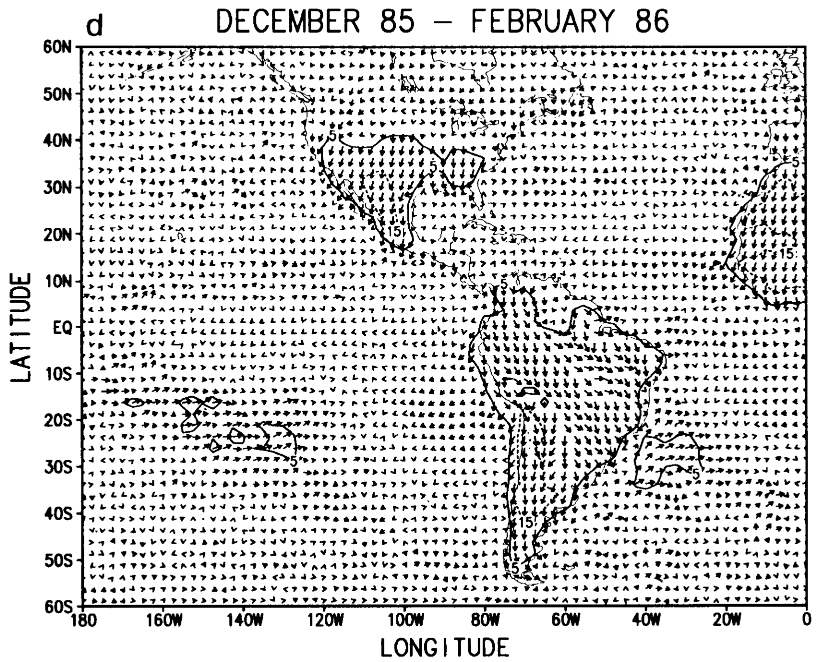
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Fig. 2. (cont'd).

cause diurnal variation in surface temperature. Because of low humidity over these regions, this diurnal variation in surface temperature is in turn reflected in OLR. Maximum OLR occurs in the afternoon over most of these regions. The explanation for the afternoon phase is same as previously noted in Subsection 3.1. Amplitudes greater than 5 W/m^2 are noticed over most of the land regions between 45° N and 45° S with a few exceptions like Peru, parts of China, and parts of the eastern United States. Clear land regions undergo large diurnal variation in OLR, but the magnitude of the amplitude is smaller than deserts. Phase occurs in the afternoon over these regions by the same mechanism as in deserts. A different kind of diurnal pattern is noticed over plateau or high land regions such as the Tibetan plateau, Rocky mountain plains in the central US, and eastern equatorial Africa. Over these regions maximum OLR occurs in the mid morning. This may be because convection starts earlier in the day over the high plains compared to the adjacent lowland and these convective clouds block the solar heating of the surface around noon (Harrison et al., 1988).

Over cloudy land regions, the diurnal cycle in OLR is due to diurnal changes in cloudiness. These are mostly northern hemisphere summer monsoon regions like India, Indochina, Central America, and equatorial western Africa. Over India, Indochina, and Central America phase occurs in the mid morning around 1000 LST indicating minimum longwave emission in late evening. This suggests evening cloudiness in the monsoon land regions. It is cautioned here that, in reality, the maximum and minimum OLR may not occur exactly 12 hours apart as created artificially by the harmonic analysis, but tend to be separated in the vicinity of 12 hours. Nocturnal precipitation maxima were recorded in many monsoonal land stations over monsoon region (Ramage, 1971). This may also mean that cloud height changes from morning to evening, with low or mid level clouds in the morning and deep cumulus clouds in the evening. Over monsoon regions persistent cloudiness inhibits the radiative heating of the surface in the mornings. However, in the evenings radiational cooling from the cloud tops and warming at the cloud base causes instability in the cloud layer. This unstable situation leads to the development of deep convective clouds and nocturnal rainfall in monsoon land regions. Similar diurnal variation in cloud top altitude, rather than a change in cloud amount is also noticed over Amazon during November 1978 (Minnis and Harrison, 1984b).

Diurnal amplitudes are also significantly large over some of the oceanic regions like North Equatorial Indian Ocean, Bay of Bengal, North Equatorial Western Pacific, Eastern Equatorial Pacific near Central America, Gulf of Mexico, North Western Atlantic in the Gulf stream region, and north equatorial Atlantic off Africa (GARP Atlantic Tropical Experiment (GATE) region). All of these regions are deep convective regions and the convective activity over these regions is seasonally dependent. In all of these regions phase occurs in the early morning which indicates maximum OLR in the early morning and deep cloudiness in the afternoon. From the climatological point of view, these regions of high sea surface temperature favor deep convection in the afternoon. Diurnal variation was extensively studied over the GATE region. Amplitudes greater than 5 W/m^2 with early morning phase are noticed in the tropical eastern Atlantic off North Africa. This suggests afternoon convection over that region. This is in agreement with the study of McGarry and Reed (1978) and Reed and Jaffe (1981) who utilized Synchronous Meteorological Satellite (SMS) infrared images over the GATE region.

Local effects play a great rôle in diurnal variation. Afternoon maxima in cloudiness is observed in many places over land close to the ocean. For example, Florida and some of the Central American land regions show afternoon maxima in cloudiness by showing early morning maxima peak in OLR. This may be due to local land sea breeze effects. In the summer hemisphere over land this afternoon convection may be due to daytime heating of the boundary layer which is destabilized by afternoon and becomes conducive to cloudiness.

During northern hemisphere winter (Figs. 2c, d) the diurnal amplitude over northern hemisphere desert regions decreases, while the amplitude increases over southern hemisphere deserts such as the Australian and Atacama deserts. Over the oceans, especially over the Indian and Pacific Oceans, a substantial shift is noticed in the regions of large diurnal amplitude from the northern hemisphere to the southern hemisphere. This shift in amplitude is due to seasonal shift in cloud belts from northern summer to southern summer which follow the Sun's movement. Noticeably large amplitudes are found in the southern Pacific and southern Atlantic Oceans. These regions correspond to the South Pacific Convergence Zone and South Atlantic Convergence Zone. Phase in these regions around 5000 to 6000 LST suggests that deep convective clouds occur in the evening.

Diurnal variation is larger during northern summer than winter over Central America, northern Indian Ocean and northwestern Pacific. Over most of these regions phase occurs between midnight and early morning. Significant diurnal variation over the Amazon river basin is more widespread during southern summer than southern winter. Phase occurs between morning and noon over most of the Amazon river basin during southern summer, whereas during southern winter phase occurs in the afternoon mainly because it is less cloudy during southern winter. The mid morning phase during southern summer is mainly due to change in cloud height from morning to evening. In the morning, cloud altitude is low and maximum longwave emission comes from low clouds. By afternoon, cloud tops rise and hence longwave emission decreases. Though there is little change in cloud amount diurnally, change in cloud altitude drives the diurnal variation in OLR over Amazon basin during southern summer (Minnis and Harrison, 1984a). Of particular interest off western coasts of South America and Southern Africa are the diurnal amplitudes greater than 2 W/m^2. These regions correspond to low level stratus deck regions, which form over the cold sea surface temperature regions. Over these regions phase occurs around 1600 LST suggesting morning cloudiness. Of course, phase for amplitudes less than 5 W/m^2 may not be significant. Over Pacific stratus regions Minnis and Harrison (1984a) noticed that cloud coverage decreased from near 90% at 0600 LST to about 50% in the early afternoon in the month of November. So in these oceanic stratus regions evening OLR phase is mainly due to a decrease in stratus cloud amount from morning to evening.

Though there is no appreciable change in amplitude, there is noticeable change in phase from summer to winter over southeastern Africa south of the equator. During winter, phase occurs in the afternoon over this region and during summer phase occurs around mid-morning. Similar changes in phase from summer to winter occur over the eastern United States. Over the southeastern United States, maximum OLR occurs near noon during winter as against early morning during summer. Late evening clouds and thunderstorms during summer over southeastern United States are probably responsible for low OLR values in the evening and early morning OLR maximum. In summer warm moist air from the Gulf of Mexico moves over the heated land in the afternoon, making the environment unstable and conducive to the development of high cumulus clouds or thunderstorms by evening. Amplitudes and phase changes are also noticed over the southwestern Indian Ocean and eastern equatorial Indian Ocean from summer to winter, southern summer being larger in amplitude. Phase occurs around mid-morning over this region during southern summer.

3.3. *Relationship between diurnal amplitude and earth radiation budget parameters*

So far we have discussed some of the regional features of the diurnal cycle of OLR and its annual variation. In this section we relate the diurnal amplitude with the other Earth Radiation Budget parameters. We establish a relationship between the monthly mean net radiation and the diurnal amplitude of OLR. Here we first separate the diurnal amplitude of OLR and the other radiation budget parameters (monthly mean longwave, net radiation and solar insolation) based on geographic scene types like desert, land, and ocean and then examine their annual variation in a latitudinal band average sense.

Presented in Fig. 3 are the time series' of the diurnal amplitude of OLR, monthly mean OLR, solar insolation, and net radiation averaged over tropical and subtropical latitude bands for both average and clear sky desert scenes. Over deserts in all latitude bands solar insolation and net radiation undergo systematic annual variation and the agreement between these two is excellent. Since solar insolation follows the position of the Sun, its annual variation can be easily understood. The net energy at the top of the earth's atmosphere also follows the position of the Sun. Since the solar insolation is the energy source for the Earth's

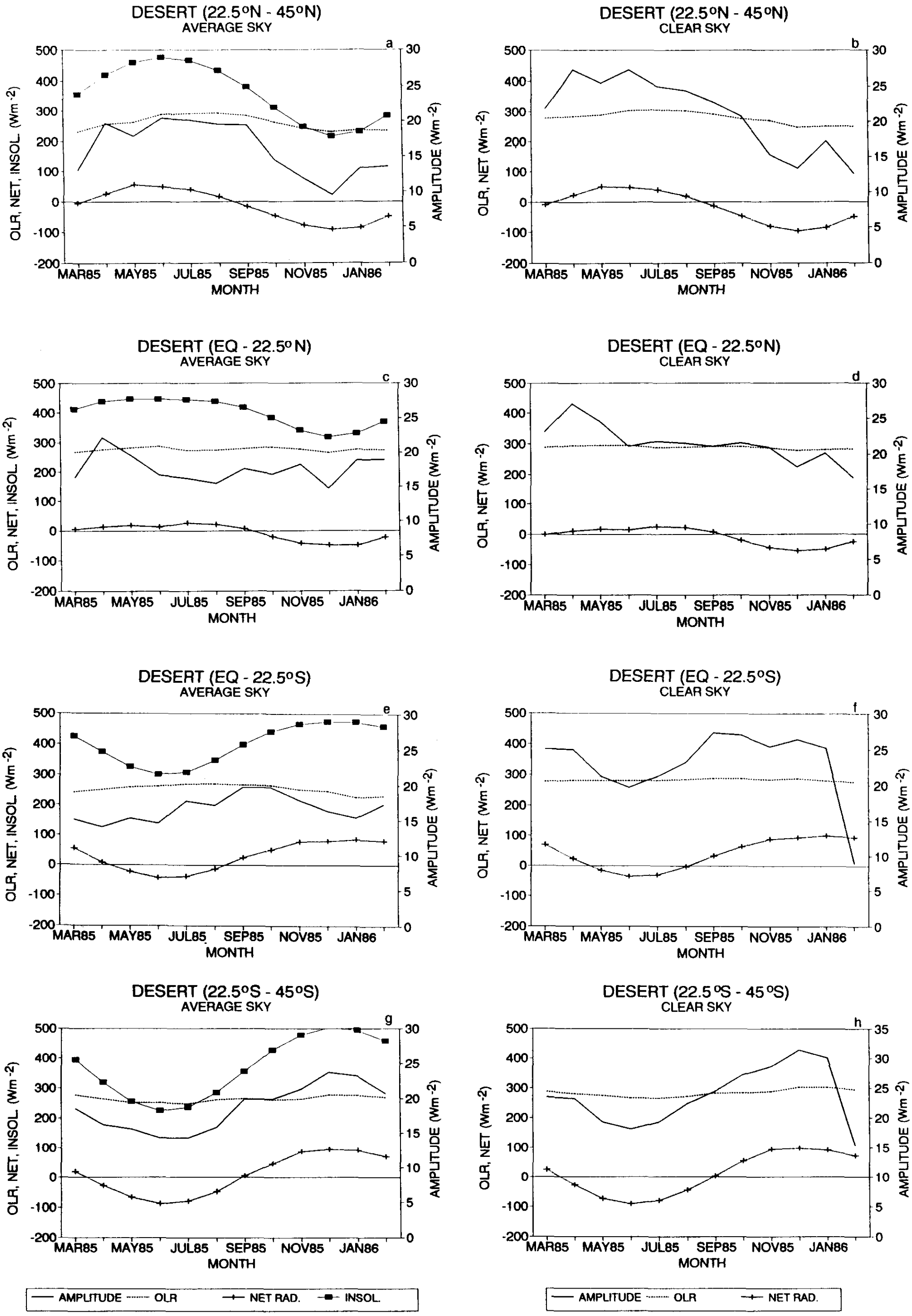

Fig. 3. Time series' of diurnal amplitude and monthly mean OLR, net radiation and solar insolation averaged over deserts.

climate system, the agreement between the solar insolation and net radiation is no surprise. Of particular interest is the remarkable agreement between the net radiation or solar insolation and the diurnal amplitude of OLR in the subtropics (Figs. 3a, g). This indicates during summer time over subtropical deserts (June to August in Fig. 3a and December to February in Fig. 3g), net radiation reaches its peak and this high net radiation drives the variations in OLR diurnal amplitude. However, over tropical deserts (Figs. 3c, e), though the net radiation is at its peak during summer time, the diurnal amplitude is not. This is because tropical deserts are relatively more cloudy than subtropical deserts in the summer and these clouds moderate the diurnal amplitude in OLR. The diurnal amplitude of OLR variation over clear sky deserts also follows net radiation. However, the magnitude of diurnal amplitude is larger over clear sky deserts compared to average sky deserts in all latitude bands. Though the difference between clear sky and average sky net radiation is small, the difference between clear sky and average sky diurnal amplitude is large especially in the tropics. This suggests that clouds moderate the diurnal amplitude of OLR over deserts. While in the subtropics peaks in the diurnal amplitude are in agreement with the solar insolation maximum, this does not occur in the tropics, even in clear sky conditions. This could be because of the absorption of longwave radiation in the water vapor absorption band by the water vapor which is abundant in the tropical atmosphere or due to cloud contamination of the clear sky longwave data processed by the ERBE. It is well known that though the tropical deserts regions are less cloudy than the non desert regions, they are not completely devoid of moisture. The source of moisture over these desert regions may not be local, but transported from elsewhere. Not the moisture, but the lack of ascending motion is the main culprit in inhibiting the cloud formation over the deserts.

Driven by the annual cycle of the Sun, monthly mean OLR does vary annually and this variation is larger in the average sky conditions than in clear sky condition, though the magnitude of clear sky emission itself is large. If plotted on an enlarged scale, the agreement between the monthly mean OLR and the diurnal OLR amplitude can be easily seen. In what follows, diurnal amplitude of OLR obtained from harmonic analysis is compared with diurnal range of OLR which is the difference between the maximum and minimum OLR. Over deserts diurnal amplitude is of the order of 15 to 20 W/m^2 for average sky conditions and 20 to 25 W/m^2 for clear sky conditions. On the other hand diurnal range is of the order of 65 W/m^2 for average sky and 75 W/m^{-2} for clear sky condition (Harrison et al., 1990). Remember that diurnal amplitude is half of the diurnal range. Also the first harmonic, i.e., diurnal harmonic explains only part, though a major part, of the total variance. Though the harmonics higher than third harmonic may not explain much variance, second harmonic may explain some significant variance. In summary, our diurnal harmonic results are in close agreement with the diurnal range obtained by Harrison et al. (1990).

Fig. 4 shows the time series' of diurnal amplitude of OLR, monthly means of OLR, net radiation and solar insolation averaged over tropical and subtropical land scenes for both clear and average sky conditions. As explained earlier in the case of deserts, the agreement between solar insolation and net radiation is excellent and the same mechanism applies here too. While the agreement between the net radiation and the diurnal amplitude of OLR is excellent in the subtropics, it breaks down in the tropics both for average and clear sky conditions. In the case of average sky conditions in tropics, clouds reduce the diurnal amplitude in OLR, because diurnal variation of OLR from cloudy regions is small. It is of interest to note that while the clear sky amplitude is larger than the average sky amplitude in the subtropics, the clear sky amplitude is smaller than the average sky amplitude in the tropics, especially in the summer. It is our conjecture that the tropical atmosphere, rich in water vapor, absorbs part of the longwave radiation emitted by the earth's surface in the water vapor absorption band so that the longwave emission at the top of the atmosphere is small. Smaller clear sky diurnal amplitudes in the tropics could be due to the absorption of longwave by water vapor or due to misidentification of clear sky conditions by the ERBE algorithms. OLR variations follow diurnal amplitude over most of the places, except in the southern tropics. Diurnal amplitude over the land is of the order of 8 to 12 W/m^2 for average sky, whereas, diurnal range is of the order of 20–40 W/m^2 (Harrison et al., 1990). Since the diurnal cycle in OLR over the

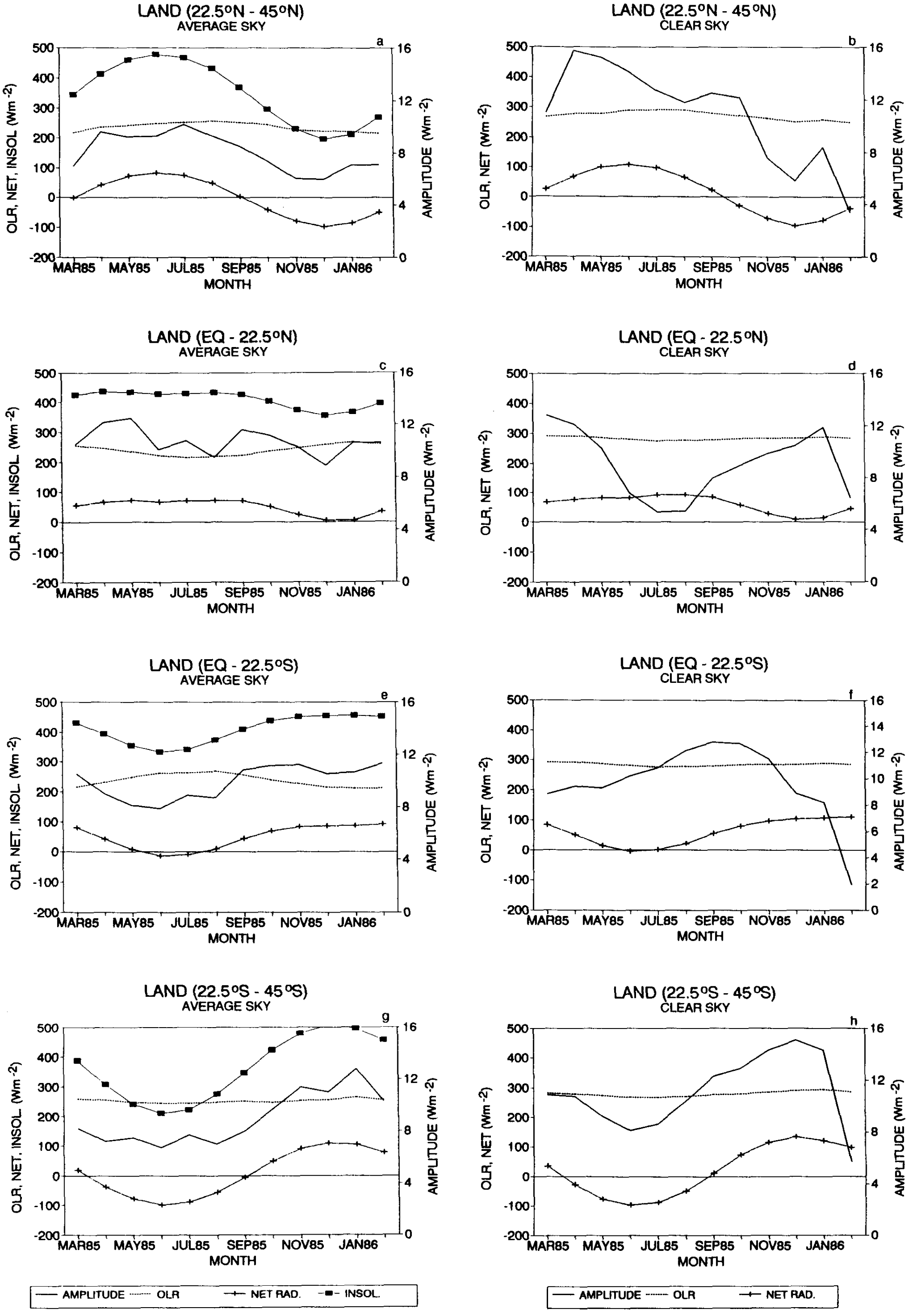

Fig. 4. Same as Fig. 3, except averaged over land.

oceanic clear sky regions is insignificant, time series' averaged over oceanic regions are not shown. Measurement programs must of necessity consider the relationship between diurnal cycles and the mean values of the components of the Earth's radiation budget. The measured components are the OLR, reflected shortwave radiation and the solar irradiance. Both the OLR and reflected shortwave have strong diurnal cycles which vary with season, surface type, and the regional diurnal cloud cycle. A Sun synchronous polar orbiter with near noon and midnight equator crossing times yields good measurements for a single satellite. The top of the atmosphere solar insolation peaks at local noon while, over most land areas, the OLR maximum is close to 1300 LST (Figs. 2). Regionally however, Figs. 1, 2 indicate that a single satellite would have numerous seasonal and some annual problems. Seasonally the ITCZ, the SPCZ, the Gulf of Mexico and the neighboring Atlantic, much of Brazil, parts of Africa plus other regions show OLR maxima between 0300 and 0900 local time. Some regions in north central Brazil and in the ocean off southeast Asia show these morning OLR maxima even in the annual maps (Fig. 1b). The morning maxima are caused by the regional cloud cycle which has fewer or at least lower clouds in the morning compared to the rest of the day.

4. Concluding remarks

Diurnal variation of the OLR was studied by utilizing the best global data set ever produced from sampling point of view. OLR diurnal harmonic analyses presented here reconfirms most of the earlier findings which used narrow band measurements. OLR diurnal amplitudes are largest over clear sky desert regions and this diurnal variation is mostly due to surface temperature variations. The phase over these regions occurs in the afternoon. The phase over non-cloudy land and desert regions is biased toward noon due to half-sine diurnal model fit used by the ERBE data processing system. Convectively active land regions like the Amazon basin, Congo basin, and Indian monsoon regions also undergo large diurnal variations in OLR, though the amplitudes are smaller than clear sky land regions. The phase over these regions occurs in the mid-morning. The mid morning phase over these regions may be due to the nocturnal cloudiness of cloud altitude changes from lower in the day to higher during the night. Convectively active oceanic regions undergo significant diurnal variation in OLR. Large diurnal amplitudes over the oceanic convective regions like ITCZ, SPCZ, and SACZ are clearly delineated.

Annual variation of the diurnal amplitude of OLR follows annual variation of the monthly mean solar insolation, net radiation, and OLR itself over land and desert regions with few exceptions. Broad band measurements with the help of clear sky radiant fluxes provided some new information on the diurnal behavior of OLR. Relationships between OLR diurnal amplitude and the other top of the atmosphere ERB parameters indicate that the annual variation of OLR diurnal amplitude is driven by the net radiation, which in turn is driven by the solar insolation. Diurnal amplitude is moderated by the presence of clouds over the land and desert regions. In clear sky tropical regions, reduced diurnal amplitude may be due to misidentification of clear sky conditions by the ERBE data processing algorithms.

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