NOTES AND CORRESPONDENCE

On the Interannual Variation of the Earth Radiation Balance

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ABSTRACT

The interannual variability of the top of the atmosphere net radiation budget as measured from the Nimbus-7 Earth Radiation Budget instruments was calculated for an eight year period 1979–1986. The largest fluctuations are shown to occur in three tropical areas: the Atlantic off the west coast of Africa, the eastern Pacific near South America, and the western Pacific northeast of Indonesia. The variability in the Atlantic was 20% greater than in the eastern Pacific and 35% greater than in the Indonesian area. The maximum anomalies in these two Pacific regions occurred during the El Niño year 1982–1983, while the maximum Atlantic anomalies, south of the Gulf of Guinea, were during 1984. An independent dataset of derived cloud type and amount from the Temperature Humidity Infrared Radiometer (THIR) and the Total Ozone Mapping Spectrometer (TOMS) instruments shows interannual changes in multilevel convective cloud systems have a minimal effect of the net balance. However changes in middle and low clouds drastically effect the balance, and are the most likely cause of the maximum radiation balance variability in the Gulf of Guinea region. This observed interannual variation of the top of the atmosphere net balance, reported in the present study, denotes the most variable "cloud radiative forcing" situation observed to date.

1. Introduction

The top of the atmosphere net radiation balance (NET) is calculated by differencing the emitted longwave and absorbed shortwave irradiances. This measurement defines deficit or surplus energy in the earth/atmosphere column that can be used in other energy transformations. The effect of clouds, referred to as cloud radiative forcing, is derived by differencing an actual scene with clouds and the defined clear sky irradiances. Cess (1976), Ellis (1978), Hartmann and Short (1980), and Ohring and Clapp (1980) have made estimates of the effect of cloud changes on the radiation balance and atmospheric temperature with sometimes conflicting results. Most recently Ramanathan et al. (1989) used early results from the Earth Radiation Budget Experiment (ERBE) and showed that clouds, in general, tend to cool the planet. The net radiative effect of course depends on the cloud type as well as total cloud amount. In general a change in large scale convective cloudiness results in little variation of the NET due to the reciprocity of the albedo and the emitted flux. When the cloud amount and albedo increase, the emitting temperature and flux decreases, thus producing little NET change. However changes in certain cloud types do cause significant NET variation. An increase in low-level stratiform clouds can greatly affect the balance by decreasing the absorbed shortwave radiation. Since they are near the earth's surface, little change in emitted flux is observed. Another example is high level cirrus clouds which affect the emitted flux but are often not well observed at the visible wavelengths.

In addition to calculation of the radiative forcing it is important to identify areas where changes in cloudiness and forcing occur. The variability of these regions and their relative heating or cooling can modify the atmospheric energetics and have an effect on the general circulation. Studies (Liebmann and Hartmann 1984; Hendon and Hartmann 1982; Hoskins and Karoly 1981) point to changes in the midlatitude circulation patterns caused by tropical heat sources and sinks. Calculation of NET anomalies can help define these areas. The area off the west coast of Africa is shown to vary, in the annual average case, more than any other area in the world, and thus its effect as a changing tropical heat source is of interest. An anomaly in the NET may also contribute to anomalies in sea surface temperature (SST), as there is often a positive NET anomaly in conjunction with large scale SST warming. Such highly variable regions are also of interest to circulation modelers as recent studies of the radiation budget with respect to model verification have shown the necessity of correctly modeling the large scale radiation variability as well as the overall patterns (Smith and Vonder Haar 1989; Charlock et al. 1988; Ramanathan 1987).

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2. Data

The earth radiation budget (ERB) data are from the sun-synchronous Nimbus-7 satellite which has ERB as well as other instrument packages. The ERB wide field-of-view (WFOV) four-channel fixed hemispheric radiometers are broadband instruments that measure global radiation parameters (Jacobowitz et al. 1984). One channel is a total broadband instrument from <0.2->50 μm, another was limited to the shortwave from 0.2–3.8 μm. The longwave flux was calculated by differencing these two measurements. The WFOV instruments have an effective half power resolution of near 10°, but for the time and space averaged products, the data are binned into 2070, approximately equal 500 km^2 areas. The unmatched length of the ERB dataset makes possible interannual studies and included here are eight years of data, November 1978–October 1986. Monthly averaged ERB observations, almost continuous with the exception of two months in 1986, were averaged into eight annual averages, which became the basis of this study.

A global multilevel cloud climatology has been derived, independent from the ERB observations, from two other Nimbus-7 instruments–THIR and TOMS. The cloud algorithms and methods are completely described by Stowe et al. (1988). The THIR is a scanning radiometer which measures thermal radiation in two spectral bands centered on 11.5 and 6.7 μm (Hwang 1982). The TOMS instrument measures ultraviolet backscattered radiation at six wavelengths, however only two of these wavelengths, 0.36 and 0.38 μm, are used to compute a directional albedo (Heath et al. 1978). Cloud amounts are derived during the day (ascending node) using a combination of both these algorithms. Only the THIR algorithm is used during the night time (descending node) passes. Also included in the cloud algorithm are terrain, snow and ice, and surface temperature analysis from the Air Force 3-D Cloud Nephanalysis that are used to compute a cloud/no cloud threshold. Global cloud amounts for three different levels are produced for daily as well as monthly means. The data was conveniently binned into identical areas and with concurrent times as the ERB data allowing for easy comparison between these datasets.

3. Variability of the net balance

The interannual variability of the net radiative balance was calculated by first computing eight annual averages and then the standard deviation using these eight samples. Each annual average follows the Nimbus-7 satellite year from November 1–October 31. The standard deviation map that results is presented in Fig. 1, and clearly shows three areas of highest NET variation: the Gulf of Guinea region off the west coast of Africa, the eastern Pacific near the west coast of South America, and the western Pacific northeast of Indonesia. The greatest NET variation occurs in the Gulf of Guinea area where the maximum standard deviation is 6.2 Wm^{-2} compared to only 5.0 Wm^{-2} in the eastern Pacific, and 4.4 Wm^{-2} near Indonesia. Some regions poleward of 70° have similar variability but due to the severe fluctuation of the albedo during times of near zero incident radiation, these areas are suspect. Similar standard deviation calculations might be made to highlight areas that have high monthly variability. Yet the purpose here is to present variability on the interannual time scale.

Examining the time series of the NET variability of the three areas, Fig. 2, clearly shows the largest Pacific anomalies were during the El Niño in late 1982 into 1983. Near Indonesia the NET dropped rapidly after October 1982 to an almost 25 Wm^{-2} decrease in February 1983. After an initial rise of over 20 Wm^{-2} in late 1982, the NET in the eastern Pacific near the coast of South America dropped 25 Wm^{-2} only to rise again later in the year. In the Gulf of Guinea region there was a decrease in the NET during 1983 of 15 Wm^{-2}, but the largest anomalies of the eight year time period occurred during 1984—the year after the Pacific El Niño. Twice during 1984, in January and September, the anomaly grew to over 20 Wm^{-2}, and at times during 1982 the anomalies were 10–20 Wm^{-2} below normal.

The components of the NET calculation are the incident radiation, the albedo, and the outgoing longwave radiation (OLR). Since our computation of the standard deviation involves annual averages, the incident radiation is constant, and therefore all the variation must be from the reflected and emitted irradiances. Figure 3 presents the time series of the albedo and OLR anomalies concurrent with the NET anomalies in Fig. 2. Generally, for an individual time period, the albedo and the OLR anomalies are reversed. For example, when the albedo increases (usually more cloud), the OLR will decrease due to the cooler temperatures of the cloud tops. This especially holds true in areas of strong convection, when there is a positive anomaly in one parameter causing the other to be negative. During times of low to moderate anomalies these two effects balance out so no great change in the NET is observed. However if there are large anomalies in the albedo and OLR, the resulting NET anomaly can be confusing. In the Indonesian area during the El Niño, the albedo strongly decreased while the OLR strongly increased resulting in a sharp decline in the NET. During this same year the reverse anomalies of albedo and OLR were observed in the eastern Pacific. In May and June, while the albedo anomaly was positive and the OLR anomaly was negative, the NET anomaly remained near zero. In these areas of tropical convection, when dealing with large changes in the radiation budget quantities (OLR and albedo), the results on the NET are unpredictable. In the Atlantic (Gulf of Guinea area) the magnitude of the anomalies in Fig. 3 are only half of the other areas (note the ordinate scale). These anomalies are much different than the Pacific areas in

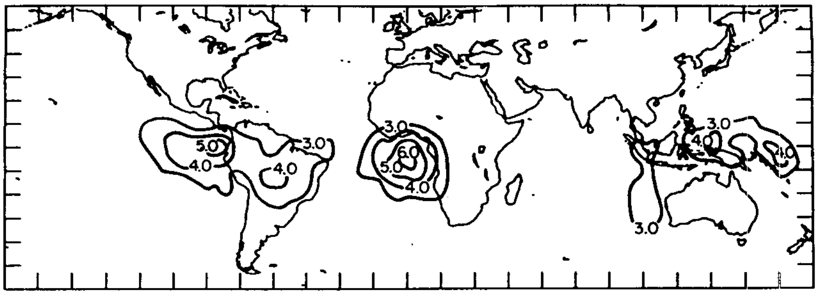

FIG. 1. Standard deviation (Wm^{-2}) of the annual averaged net radiation balance from Nimbus-7 from 11/1978–10/1986.

that the albedo and OLR anomalies are usually of the same sign. Even though the albedo and OLR anomalies are not as great, this effect causes the largest fluctuations in the NET and is the reason behind this region's maximum NET variability.

The high variability of the ERB in the eastern and western Pacific is not unexpected, as the El Niño during 1982 and 1983 has previously been shown to produce large changes in the OLR (Ardanay and Kyle 1986). The Indonesian area is normally dominated by decreased OLR, indicative of strong vertically developed convection. This was reversed during early 1983. The eastern Pacific region generally has OLR values representative of little enhanced convection except during the El Niño year when this was the norm. Similar to the eastern Pacific, the OLR and albedo in the Atlantic area usually show no evidence of convective clouds. The Atlantic intertropical convergence zone (ITCZ) and its associated strong convection rarely moves far enough south of the equator to have a direct effect on our defined region. Therefore the changes in clouds, which must be the cause of NET variability, are very different in each of the three areas. In the next section, the cloud changes that lead to the radiation budget parameter anomalies will be examined.

4. Cloud variability

The Nimbus-7 global cloud climatology is available for the first five and a half years of the ERB time series, and the examination of cloud versus ERB anomalies is the next logical step. Three cloud levels are used

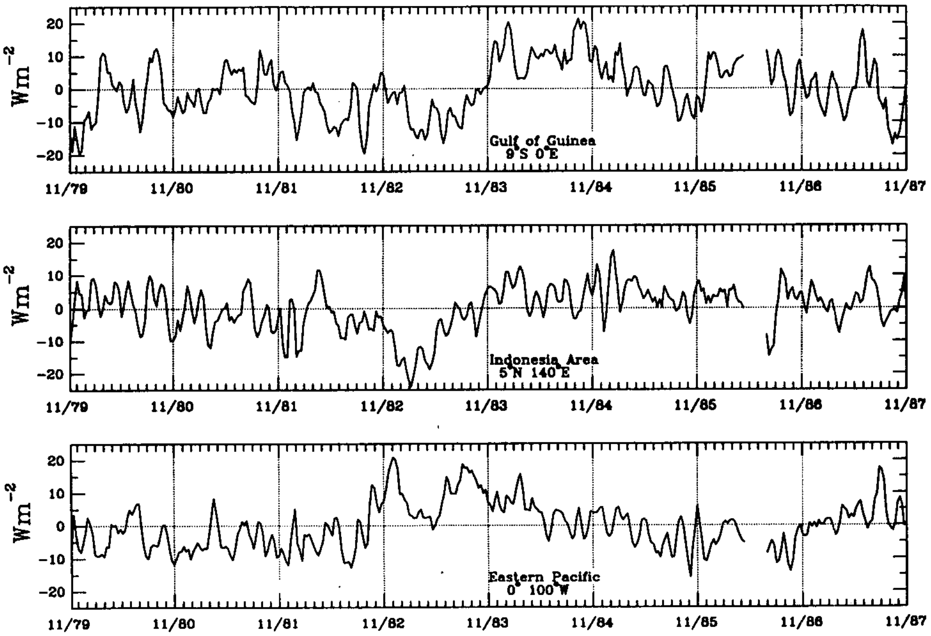

FIG. 2. Weekly net radiation balance anomalies (Wm^{-2}) from Nimbus-7 earth radiation budget for 11/1979–10/1987 for the three areas of highest annual averaged NET variability. To assist in analysis a four week running mean was applied. The largest variations occurred during the 1982–1983 El Niño for the Indonesian and Eastern Pacific areas and during 1983–1984 for the Gulf of Guinea off Africa.

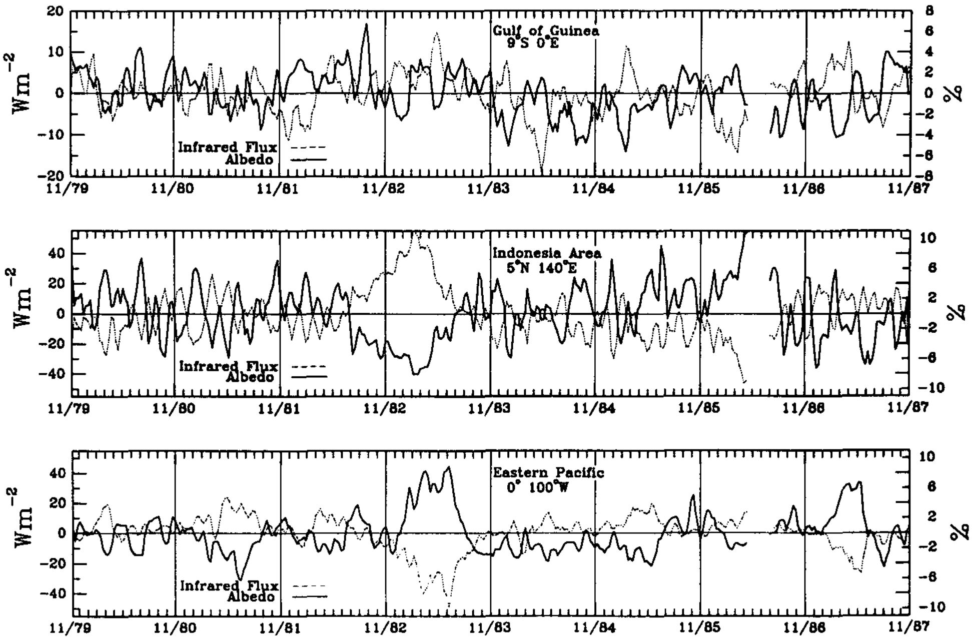

FIG. 3. Same as Fig. 2 except for the infrared flux (OLR) and albedo anomalies.

from the cloud climatology as well as a total cloud amount (TCA). Low level clouds (LLC) are defined as clouds less than 2 km in height. The boundry height of the middle level clouds (MLC) and high level cloud (HLC) varies with latitude; but in the tropics, equatorward of 30°, the boundary is set at 7 km. Therefore MLC are defined as those from 2–7 km, and HLC are those above 7 km. TCA in the Indonesian area ranged from a normal 80% to less than 30% in April 1983. The eastern Pacific TCA was normally near 40% but in April 1983 was near 90%. The Gulf of Guinea region TCA was near 50%. Cloud anomalies in these three areas of high NET standard deviation were assembled and are presented in Figs. 4 and 5. In the Pacific areas during the El Niño, the HLC and MLC changed drastically while the LLC anomaly was reversed. Convective systems with large vertical extent often mask the lowest level cloud amount, so that when the convective clouds are absent, an increase in the LLC anomaly becomes suspect. In contrast to large changes in the Pacific areas, the TCA in the Gulf of Guinea region varied by only 20%. The only significant changes were in the MLC (±15%) and LLC (±10%). During 1982–83 the TCA remained normal while there was an increase in the LLC and a decrease in the MLC. This increased the albedo and OLR and therefore dropped the NET. There was also a rise in the MLC during the following year, reaching a maximum anomaly of +10% in April 1984.

5. Discussion and conclusions

It quickly became apparent that the three areas of greatest net radiation balance variability have quite different cloud characteristics. The two Pacific areas, one near South America, the other near Indonesia, were greatly influenced by cloud changes which occurred during the 1982–83 El Niño event. The Indonesian area is normally 80% cloud filled, with low OLR and high albedo, and with considerable cloud amounts at all three levels. This area of strong convection had a interannual NET deviation of 4.4 Wm^{-2} with the largest variations during the El Niño year when a sharp decrease in the TCA, HLC, and MLC occurred. At this time the NET dropped sharply as anomalies in the emitted radiation were greater than those in the absorbed. Because this area still had significant cloud filled area, the albedo did not change enough to offset the large increase in OLR caused by much warmer than normal emitting temperatures. The decrease in the HLC and MLC clouds were significant enough to allow the majority of emission to occur at lower altitudes.

The eastern Pacific region off the west coast of South America usually has around 40% TCA consisting of only MLC and LLC. By March 1983, the TCA had increased by over 40% with a sharp increase in the HLC and MLC. The albedo increased, the OLR decreased, but the NET anomaly was near 0.0 Wm^{-2}. The major enhanced convection was already occurring, as evident in the TCA increase, but the reciprocity of the albedo and OLR anomalies had cancelled any NET anomaly. The maximum NET anomalies were in December 1982 and August 1983 before and after the convective event. In these months the albedo and OLR anomalies were concurrently negative. This again points out the importance to the NET anomaly of relative minor changes in the OLR and albedo—when

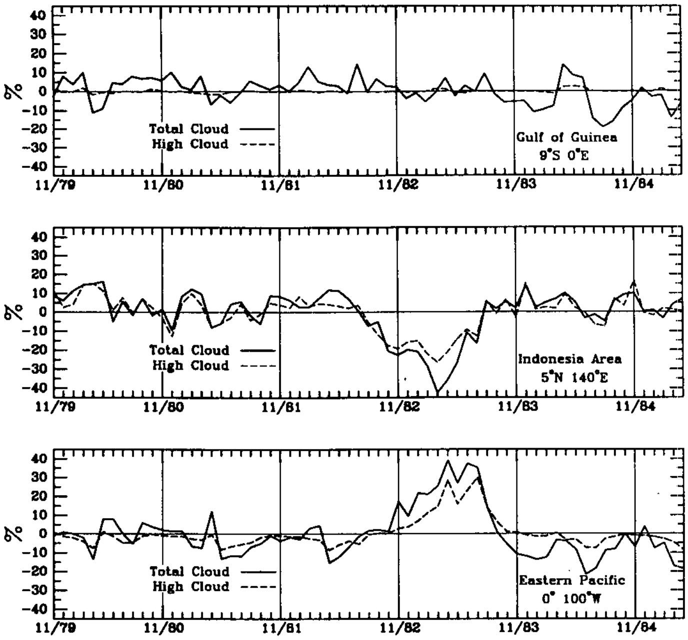

FIG. 4. Total and High cloud amount anomalies (%) from the Nimbus-7 cloud climatology for 11/1979–4/1985 for the three areas of highest annual averaged NET variability.

these are of the same sign. For the El Niño year this area had a positive NET anomaly of almost 10.0 Wm^{-2}, and was an area of warmer than average SST. This "surplus" energy in the ocean–earth–atmosphere column may have contributed to the increase and maintenance of the high SST. The El Niño event provided the most significant contribution to this region's high NET variability, (5.0 Wm^{-2}), but the following year the NET was still above average. Other than these years the NET was remarkably constant.

The region which had the highest interannual variability of the NET, 6.2 Wm^{-2}, is off the west coast of Africa south the Gulf of Guinea. Only MLC and LLC dominate this area's cloud climatology. As previously

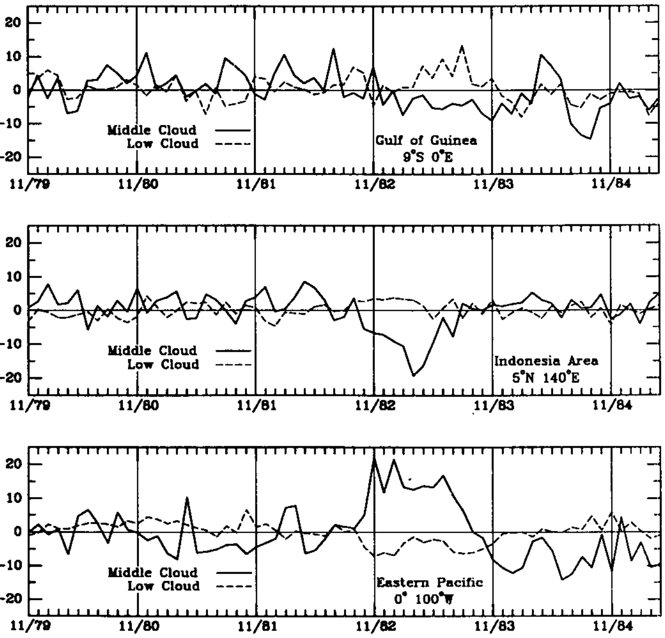

FIG. 5. Same as Fig. 4 except for the Low and Middle level clouds.

discussed, when these cloud amounts fluctuated, the anomalies of albedo and OLR often had the same sign, thus causing the large changes in the NET. The NET variability was greatest in 1984, the year after the Pacific El Niño, when the anomalies of MLC and LLC were widely varying. An Atlantic SST warming event similar to the Pacific El Niño occurred in 1984 (Weisberg and Colin 1986). In June of that year the SST in our defined area was 3°–4°C warmer than the previous year. By this time there had been seven months of above normal NET, averaging near 10 Wm^{-2}. As in the Pacific this surplus energy may have contributed to the rise and maintenance of the SST anomaly.

An associated displacement of the Atlantic ITCZ southward from normal (Philander 1986; Horel et al. 1986) may account for the cloud and NET variability observed during 1984. In January and August the NET anomaly was +20 Wm^{-2}, caused by large negative albedo anomalies and minimal increases in OLR. A sharp decline in the MLC and LLC caused these radiation changes. The ITCZ is normally furthest north in August allowing the southern hemisphere subtropical high pressure systems to shift north. The resulting large scale subsidence is critical to the formation of persistent low and midlevel stratiform clouds that characterize this region. When the ITCZ is displaced southward, this high pressure system cannot move north to its normal location and the MLC and LLC decrease. During April the ITCZ is normally at its most southern latitude. In 1984 the southerly shift caused abnormally high MLC, resulting in decreased OLR and positive NET anomalies.

The areas off the west coast of South America and Africa have been shown to have the greatest variability in the annual average net radiation balance. The NET variation in both were caused not by changes in large scale convective cloud changes, but instead by changes in middle and low level clouds. These cloud types alter the normal reciprocity of the albedo and OLR found in multilevel convective clouds. There are other midlatitude areas which have similar stratiform cloud characteristics, but these tend to be interannually stable. There is high NET variability in the tropical stratiform areas because these areas are affected by interannual global scale circulation changes such as El Niño.

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