11.11 A SURFACE BASED CLIMATOLOGY OF IRRADIANCE, CLOUD EFFECT AND CLOUD AMOUNT AT THE ARM SITES

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INTRODUCTION

Clouds, along with column water vapor, are the principal control of the surface radiation budget. Clouds simultaneously reduce the amount of shortwave (SW) radiation and increase the amount of longwave (LW) radiation reaching the surface. While the effect of clouds on the top-of-atmosphere radiation budget has been well documented, the effect of clouds on the surface radiation budget has been much less well studied. Here we outline a methodology to address this problem. Our goal when designing the methodology was to use only broad-band radiometer and surface meteorology measurements so that it could be applied to any surface site with well-maintained radiometers. Here, we illustrate our method using data from the fixed sites of the Atmospheric Radiation Measurement (ARM) Program (Ackerman and Stokes, 2003). The sites we consider here are the Southern Great Plains (SGP) site in Oklahoma; the North Slope of Alaska (NSA) site in Pt. Barrow, Alaska; and the Manus Island and Nauru sites in the Tropical Western Pacific (TWP).

Our primary motivation in carrying out this research is to understand and document the effect of clouds on the surface radiation balance. A strong secondary motivation is to provide data that can be used to evaluate and improve the treatment of clouds and radiation in global climate and numerical weather forecasting models. This application of our results is discussed below.

1. METHODOLOGY

Our methodology follows the same general approach as developed by the Earth Radiation Budget Experiment (ERBE) Science Team (Harrison et al., 1988). The initial step in determining the effect of clouds on the surface radiation budget is to develop a continuous estimation of clear sky irradiance, i. e., the downwelling irradiance from a cloudless sky for both shortwave and longwave radiation. We then subtract each of these from the actual measured irradiance values in order to determine the cloud effect. We call this value the *cloud effect* to distinguish it from cloud forcing. This latter term is, in our estimation, unfortunately named because it is not really a forcing. It includes the changes in the upwelling irradiances at the surface in the presence of clouds, which we do not discuss here.

In an earlier study (Long and Ackerman, 2000) we documented our use of measured total and diffuse shortwave radiation to identify periods of cloudless sky. We then fit these periods with a simple function of the solar zenith angle that depends on two parameters. During periods of cloudy skies we find the clear sky irradiance by interpolating the values of these two parameters and calculating the irradiance from the simple function. More recently, we have developed a similar approach for longwave irradiance. The function we use in this case is the Brutsaert equation (Brutsaert, 1975). The methodology for the longwave analysis is described in Long (2004). As discussed in a companion conference paper (Long et al, 2005), we can use these data to infer both shortwave and longwave cloud amount values, which have an accuracy of about ±0.1.

2. RESULTS

Figure 1 shows our results from the ARM SGP site for the period from May 1995 to January 2004. The values plotted are monthly means but these means are averaged from 1 minute values of both observed and cloudless sky values. One can clearly see the march of the annual cycle. It is interesting to note the lag of the LW relative to the SW, which is due to the lag in atmospheric warming relative to the solstice maximum.

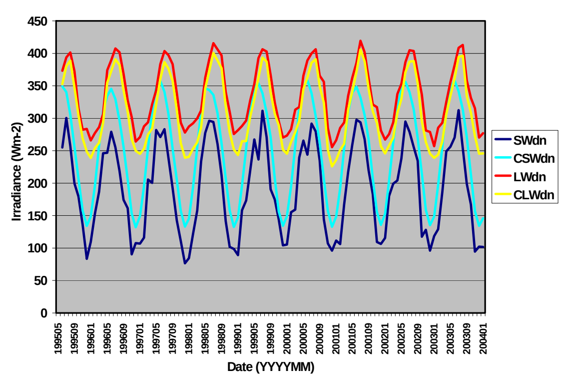

Figure 1. Monthly-mean downward shortwave and longwave observed and clear sky irradiances at the ARM SGP site. Observed SW and cloudless sky SW are in dark blue and cyan, respectively. Observed LW and cloudless sky LW are in yellow and red respectively.

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Monthly mean values of cloud amount are shown in Figure 2. Because we use measured irradiance to infer cloud amount, this cloud amount is somewhat different than cloud fraction. Cloud fraction is the fractional area of a region that is covered by the vertical projection of clouds. Cloud amount is the line-of-sight cloud amount weighted by the cosine of the zenith angle along that line of sight. Cloud amount includes both cloud base and visible cloud sides, but weights overhead clouds more heavily than clouds near the horizon. Cloud amount values are typically around 0.5 with minimum values in the late summer and maximum values in the late winter and spring. We expect some differences in the curves because the SW values are daylight hours only while the LW values are 24-hour averages The SW values are almost always larger than the LW values. We anticipate this because the LW irradiance values which are used to infer cloud cover are not very sensitive to high clouds, particularly when they are optically thin.

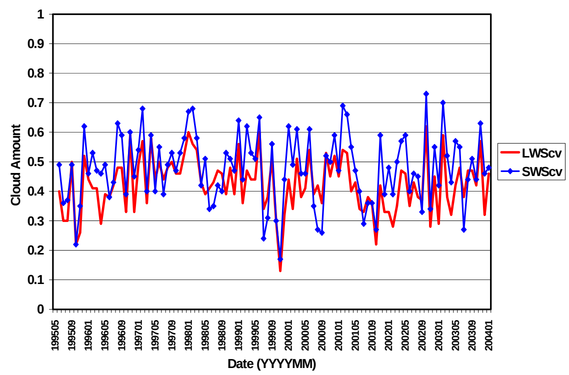

Figure 2. Monthly-mean values of cloud amount deduced from SW (blue) and LW (red) irradiance values.

Differencing the two sets of curves in Figure 1 produces the SW and LW cloud effect (Figure 3). These can then be added to give the net cloud effect. The SW cloud effect averaged over the entire record is -59 W/m^2. This value is adjusted to a 24 hour day to make it directly comparable to the LW cloud effect, which is 23 W/m^2, and the net is then -35 W/m^2. Since the mean value of the SW irradiance is around 200 W/m^2, the cloud effect at the SGP reduces the downwelling SW by about 30%. The mean value of the LW is about 325 W/m^2, so the cloud effect increases the LW by only some 7%.

The values in Figure 3 are illustrative of the effect of clouds on the surface radiation budget and can be compared directly with output from numerical weather models. However, they are not particularly useful for comparison with climate models because these models attempt to simulate the statistical features of climate. Next we present frequency distributions of the daily values of the four downward irradiances (Figure 4). Clouds shift the clear sky SW values to smaller values and extend the range of values. The impact on LW values is smaller with a slight shift to larger values. We can also create distributions of the actual cloud effect values. Climate models can be tested against these results. If the models have the appropriate cloud-radiation interactions, they should be able to reproduce these irradiance distributions and their relative shifts due to clouds.

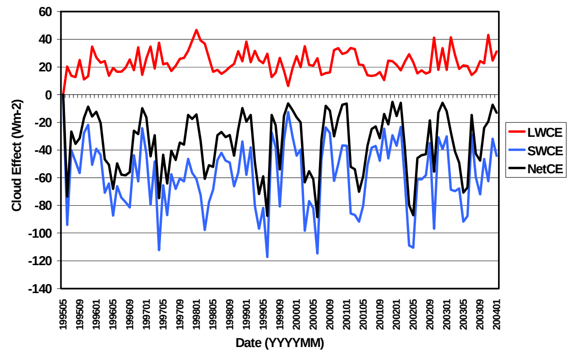

Figure 3. Monthly-mean values of SW (blue), LW (red) and net (black) cloud effect calculated from the curves in Figure 1.

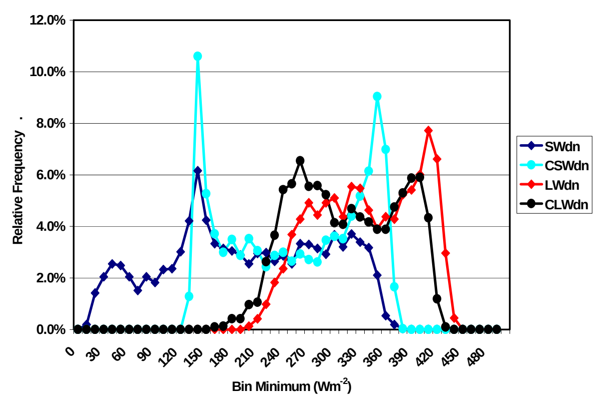

Figure 4. Frequency distributions of daily values of downwelling irradiances for the SGP time series shown in Figure 1.

In Figure 5, we show time series of irradiances for Manus Island and Nauru in the TWP. Manus Island is located in the Maritime Continent and experiences frequent convection and extensive cloud cover. The Manus series runs from 1996 to 2004. The annual cycle can be seen in the SW cloudless sky series. It looks a bit unusual to midlatitude observers because the sun passes overhead twice a year for an equatorial site. There is little sign of an annual cycle or interannual variability in the observed SW time series or in either LW series. There is little LW cloud effect because there is such a large cloudless sky irradiance driven by the large precipitable water values in this region. The Nauru time series are similar except for the observed SW series, where we see a distinct transition occur in the second half of 2001. This transition is associated with the ENSO cycle. During the early part of the series, the TWP was in a strong La Nina phase. During this phase Nauru experiences large-scale subsidence, little active convection, and modest cloud cover. The second part of the record is associated with an El Nino event, during which the active convection moves eastward. Nauru experiences considerably more convection and a higher incidence of cloud cover.

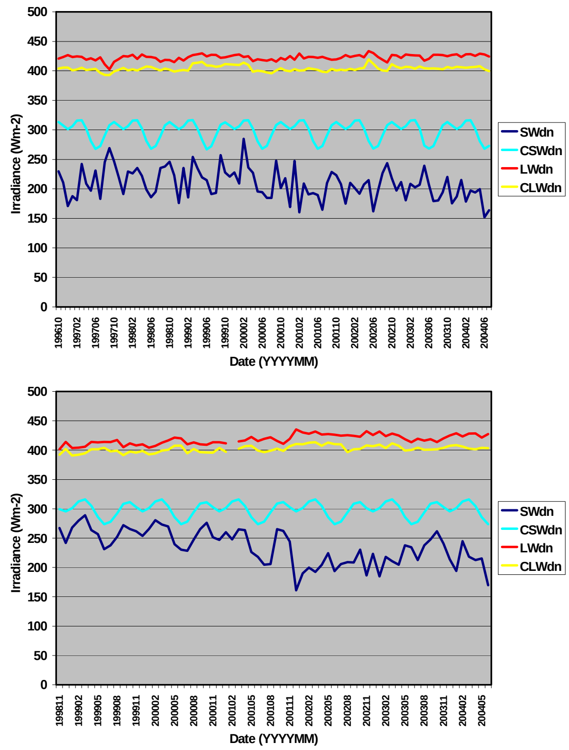

Figure 5. Same as Figure 1 but for Manus Island (upper panel) and Nauru (lower panel).

The corresponding cloud effect time series are shown in Figure 6. As expected the cloud effect series for Manus shows relatively little annual or interannual variability. The LW cloud effect is particularly notable for its constant values. For Nauru, both the SW and LW cloud effect series show the transition from relatively clear to relatively cloudy. The series average SW cloud effect values are -90 W/m^2 for Manus and -64 W/m^{2}for Nauru. Average LW cloud effect values are 19 W/m^2 for Manus and 16 W/m^2 for Nauru. Clearly the dominant signal in the tropics is found in the SW.

Frequency distributions for the two sites are quite interesting (Figure 7). The observed SW distribution at Manus (dark blue points, top panel) is distinctly different from the clear sky distribution (cyan). The range is much larger, the distribution is much flatter, and the median is considerably reduced. The center panel is the distribution for the first half of the time series at Nauru. The observed SW is broadened and displaced to smaller values. Note, however, that it is considerably different than the Manus distribution. The SW distribution for the second half of the Nauru series (bottom panel) looks very similar to the Manus distribution. The somewhat more jagged appearance is due to the more limited number of points in this curve.

The upper and lower panels show the signature of active convection, namely significantly reduced solar irradiance and a very broad distribution. The middle panel shows the signature of a convectively suppressed regime dominated by optically thinner clouds. In all three panels, the LW observed distributions are very similar in shape to the cloudless sky values, but slightly shifted upward in value.

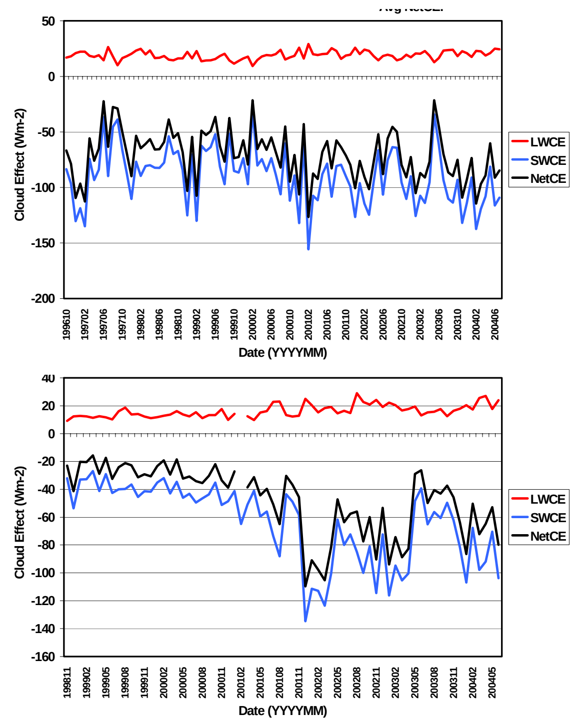

Figure 6. Same as Figure 2 but for Manus Island (upper panel) and Nauru (lower panel).

Similar plots of the time series values for the NSA site at Pt. Barrow are shown in Figure 8. These figures are strikingly different with their very pronounced annual cycle and larger difference between LW cloudless and observed values (top panel). The cloud effect (middle panel) time series has periods each winter in which the cloud effect is positive due to the absence of solar radiation. The mean cloud effect values are -46 W/m^2 for the SW, 33 W/m^2 for the LW, and then -11 W/m^2 for the total. The breaks in the curves are the result of missing data which prevent us from providing a statistically significant value of the LW cloud effect for the month. The distributions (bottom panel) are again quite different. Both SW distributions are elongated with a high frequency of very low values as a result of the long artic winter. The observed LW distribution has pronounced summer enhancement due to the prevalence of thick overcast clouds.

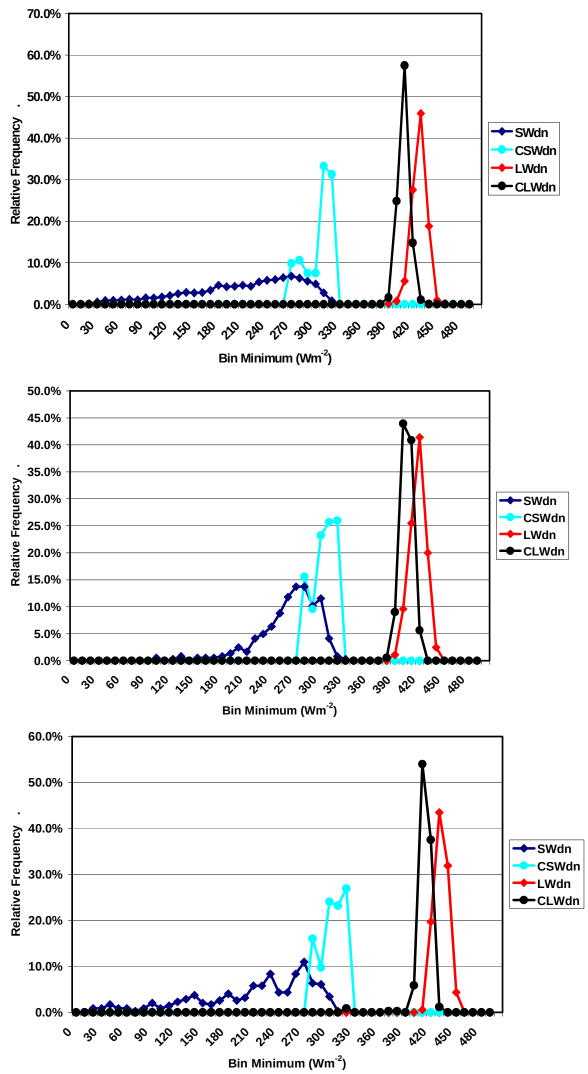

Figure 7. Frequency distributions of daily values of downwelling irradiances for the Manus Island time series (top panel), for the first half of the Nauru time series (middle panel) and second half of the Nauru time series (bottom panel).

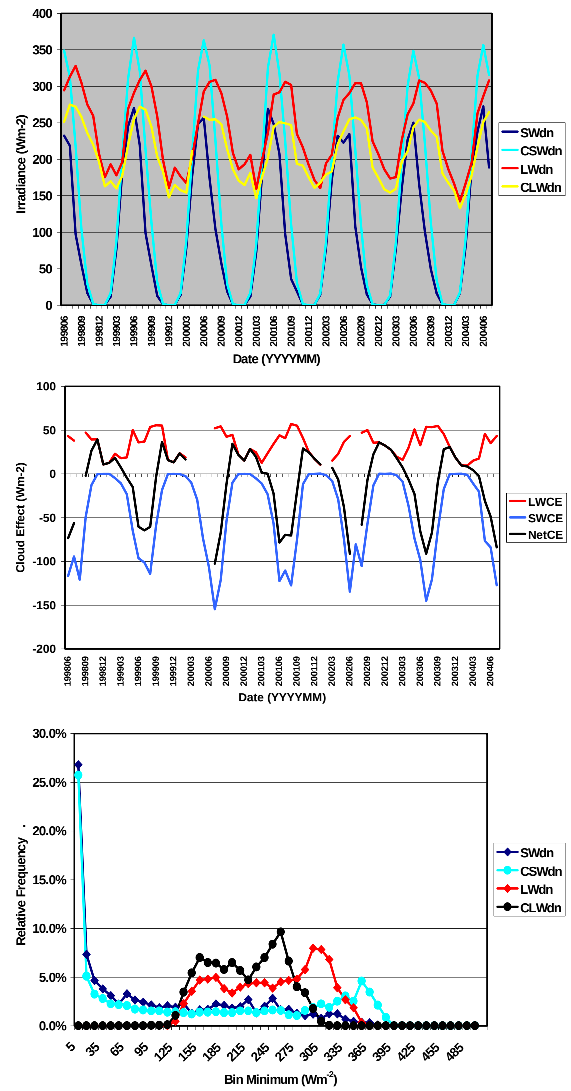

Figure 8. Data from the NSA site at Pt. Barrow: Irradiance time series (top panel), cloud effect time series (middle panel), and frequency distributions of the irradiance series (bottom panel).

Figure 9 summarizes the cloud effect results for the four sites. As expected the SW cloud effect is most pronounced for the most convective site, Manus, and the smallest in the arctic. Values in the arctic are roughly half those in the convective tropics. The LW cloud effect values are a bit more surprising. There is actually very little difference in the values, particularly between the tropical sites and the SGP. The value in the NSA is larger by only about 10 to 12 W/m^2. As a result, the net cloud effect is dominated by the SW effect and is always negative on average.

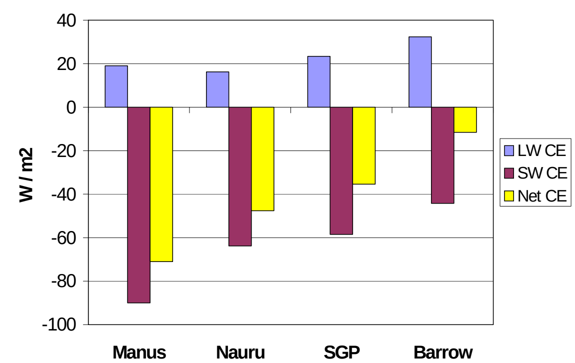

Figure 9. Summary of cloud effect values at the four ARM sites considered here. The net value is simply the sum of SW and LW values.

Neglecting for the moment that these figures are for the downwelling irradiance, it is interesting to consider them in the context of TOA irradiance values. The ERBE analysis showed that net TOA cloud forcing (their term) in the maritime continent is nearly zero because large values of reflected SW are nearly balanced by large decreases in the outgoing LW. These results for Manus show that the SW effect is correspondingly large for the surface but that the LW effect is small. The conclusion then is that clouds may have a small impact on the TOA budget in the convective tropics but they have a substantial effect on the distribution of the energy between atmosphere and ocean. Clouds decrease the radiation energy being deposited in the ocean by some 70 W/m^2 and increase the radiation energy in the atmospheric column by about this same amount. These numbers are relatively unaffected by considering net irradiances at the surface because the ocean albedo and emitted LW irradiance are not strongly affected by the presence of clouds.

3. SUMMARY

The results described here are based on an analysis of surface broad-band irradiance measurements. Similar analyses can be performed on any data set that has simultaneous measurements of total and diffuse SW, total LW irradiance, and surface meteorology. Our approach allows us to deduce the effect of clouds on both SW and LW radiation budgets and values of both cloud amount, and optical depth. (The latter is not discussed here, but in the companion paper by Long et al., 2005).

This study is primarily intended to improve our understanding of the role clouds play in determining the surface radiation budget. We think, however, that these results, particularly the frequency distributions, are a valuable way of evaluating climate and weather models. The frequency distributions presented here are based on daily values. We can produce distributions at a much higher time resolution if desired.

We realize that the analysis shown here is restricted to single sites widely separated in space, which calls into question the representative nature of the results. Previous investigations of this question indicate that the statistical characteristics of a well-located single site are representative of a larger area on the scale of tens to a hundred kilometers. The ARM SGP site has a network of radiometer sites scattered across an area of northern Oklahoma and southern Kansas that is about 300 x 300 km in size. We are currently carrying out a similar analysis for each of these locations and will use this to improve our understanding of this question.

The next step in our analysis is to match TOA irradiances with our surface irradiances on a daily basis. This will allow us to refine our understanding of the role of clouds on the column energy balance.

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