Quantification of the Impact of Nauru Island on ARM Measurements

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ABSTRACT

Nauru Island at times generates low clouds that impact low-level cloud statistics and downwelling shortwave radiation measurements made at the Atmospheric Radiation Measurement Program (ARM) site. This study uses five years of Nauru data to quantify the island impact on the site measurements. The results indicate that the solar-heating-produced Nauru island effect occurs about 11% of the time during daylight hours. The island effect increases the 500–1000-m cloud base occurrence by 15%–20% when clouds occur, but because the island effect only occurs 11% of the time the overall increase in daylight low-cloud statistics is 2%, or 1% for 24-h statistics. In a similar way, the island effect produces a reduction of about 17% in the downwelling shortwave (SW) radiation across the daylight hours during the 11% of the time it occurs, an overall 2% daylight (or 1% for 24 h) average reduction. The island effect produces frequent positive downwelling SW cloud effects, in particular during the morning, which tend to somewhat mitigate the overall decrease in downwelling SW radiation that is due to clouds. This produces 17 W m^{-2} less daylight average SW cloud effect relative to non-island-effect times, in particular for the convectively suppressed regime that typifies island-effect-producing conditions. For long-term overall statistical studies such as model and satellite comparisons, the 2% daylight (or 1% per 24 h) average increase in low-level cloud occurrence and decrease in downwelling SW are not of large concern as long as researchers are aware of them. For shorter-term studies, however, or those that separate data by conditions such as convectively active/suppressed regimes, the Nauru island effect can have significant impacts.

1. Introduction

An atmospheric radiation and cloud station was established on the island of Nauru by the U.S. Department of Energy Atmospheric Radiation Measurement Program (ARM; Mather et al. 1998). Nauru is a remote, small island that is roughly 6 km long by 4 km wide and is located in the equatorial western Pacific Ocean at 0.5°S, 166.9°E. Nauru was chosen as an ARM site because its location experiences both the upwelling and downwelling portions of the east–west equatorial general circulation (i.e., the Walker circulation), and with its small size it was hoped that the measurements made there would be primarily representative of the larger surrounding oceanic environment. The Nauru ARM site is located on the westward edge of the island, bordering the sea at a height of about 7 m above sea level. Observations at the Nauru ARM site started in December of 1998, and a month-long field campaign (Nauru99) ran from mid-June to mid-July of 1999 (see online at http://www.arm.gov/science/nauru99/index.html).

During the Nauru99 campaign, it was observed that small cumulus clouds often formed over the island and grew into what is commonly referred to as a ‘‘cloud street’’ or ‘‘cloud plume’’ downstream from the island. A subsequent study by Nordeen et al. (2001) using 1-km-resolution visible satellite images concluded that when the Nauru cloud plume occurs it typically extends downwind and grows during the day to a mean length of 125 km by late afternoon, with a maximum observed length of 425 km during the study period. This generation of cloud plumes is not unique to Nauru; it occurs for many small islands in the tropics under the right conditions (Dorman 1994; Yang et al. 2008). A study by Matthews et al. (2007) concluded that solar heating during daylight produces a surface layer over Nauru Island that is warmer and deeper than the surrounding oceanic surface layer. This condition then acts to promote low-level cloud formation over the island. Figure 1 presents a simple conceptual model of the Nauru island effect.

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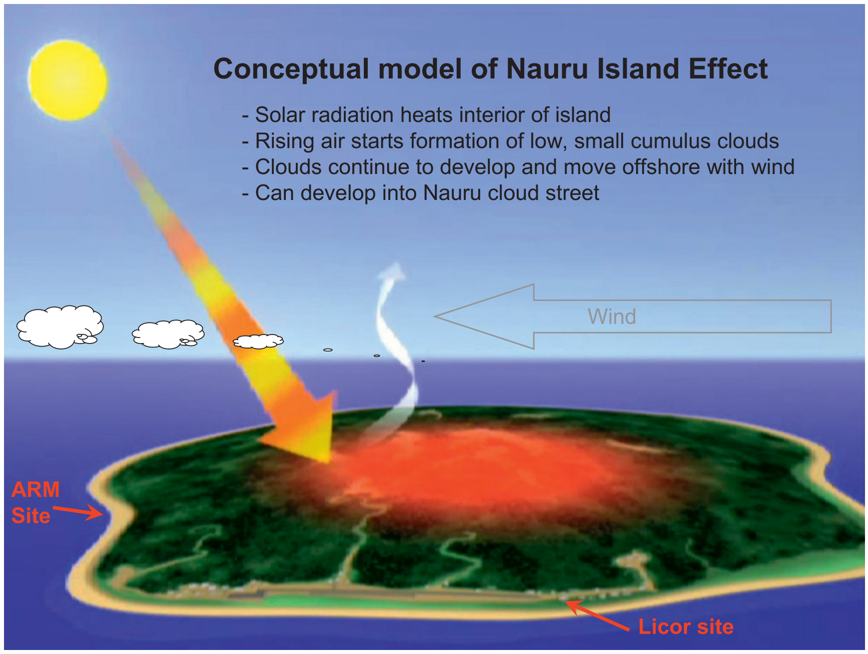

FIG. 1. Conceptual model of the Nauru island effect and production of a cloud plume. The approximate Nauru ARM site location is shown on the western side of the island, and the Li-Cor radiometer site is visible shown on the southern end. The background island image is provided through the courtesy of the ARM image library.

Analysis of the Nauru99 data showed that the formation of the Nauru island cloud plume had a sporadic impact on the ARM measurements located on the leeward side of the island and thus to some unknown extent caused the ARM measurements to diverge from representing the surrounding oceanic area. The Nauru Island Effect Study (NIES) was conducted from September 2002 to June 2003 to study the phenomenon with an added aim of possibly developing a method to detect any "island effect" occurrence (Long 2001). McFarlane et al. (2005) reported on the analysis of the 9 months of NIES data. They found that the effects of the island-induced clouds were confined primarily to the low-level-cloud-occurrence statistics and the downwelling shortwave (SW) radiation received at the surface. In addition, a method was developed that used surface-based downwelling SW radiation measurements and standard meteorological measurements of wind direction and air temperature to detect the occurrence of the island effect. As a result, a simple Li-Cor, Inc., pyranometer system was deployed in September of 2005 near the airport on the southern end of the island (Fig. 1) to use for island-effect detection. In this study, we use the five years of data gathered from September 2005 through September 2010 and apply the McFarlane et al. (2005) island-effect detection method to help to quantify what influence that Nauru Island has had on the ARM measurements during this time. By examining five years of data—a period that includes a larger range of large-scale conditions than did the previous 9-month study, we expect this study to quantify more accurately the effects of the island-induced clouds on the ARM measurements over longer-term scales.

2. Data and detection methods

Data used in this study include downwelling broadband diffuse, direct, and total (global) SW and downwelling longwave (LW) radiation, air temperature, wind direction, and the lowest cloud-base height from a ceilometer, all measured at the Nauru ARM site. Additional downwelling broadband SW radiation data measured with Li-Cor model LI-200 pyranometers are used from the "Li-Cor site." The ARM-site radiation systems use Eppley Laboratory, Inc., normal incidence pyrheliometers, precision spectral pyranometers, and shaded model 8-48 "black and white" pyranometers for the SW measurements and Eppley precision infrared radiometers for the LW measurements to produce 1-min averages from 1-s samples. (Details about these radiation systems and the instruments used are available online at http://www.arm.gov.) Estimates of the two-sigma (standard deviation) uncertainties of the measurements are 3% or 4 W m^{-2}, 6% or 20 W m^{-2}, 6% or 10 W m^{-2}, and 2.5% or 4 W m^{-2} (whichever value, the given watts per meter squared or percent of signal, is largest for each) for the downwelling diffuse SW, direct normal SW, total (global) SW, and LW measurements, respectively (Stoffel 2005). The radiation measurements were quality tested using the surface radiation quality testing methodology (QCRad) of Long and Shi (2008). For the Li-Cor pyranometers, the manufacturer claims that under most conditions of natural daylight the error is 5% or less. King and Myers (1997) estimate that errors up to 10% are possible, however, because of the silicone detector spectral range being limited to wavelengths of 1 μm and less.

The air temperature measurements are from a Campbell Scientific, Inc., model HMP35C temperature and humidity probe (manufactured by Vaisala, Inc.) in an aspirated enclosure. Wind direction measurements come from a propeller anemometer and wind vane, an R. M. Young Company model 05103 wind monitor. The estimated uncertainty is 0.6°C for the temperatures and ±5° for the wind direction (Ritsche 2006).

Lowest-level cloud-base heights are determined using a Vaisala ceilometer (model CT25K), with a maximum detection height of 25 000 ft (7.5 km) with 15-m vertical resolution and data produced every 15 s. Estimated uncertainty in comparison with collocated ARM micropulse lidars is about 75 m (Flynn 2004).

The island-effect detection used in this analysis is a revised version of the McFarlane et al. (2005) method. The differences are that, first, there was a small error in perceived orientation of the island in the McFarlane et al. study. With the correct orientation, the angles of wind direction from which airflow will significantly cross over the island before reaching the ARM site range from 60° to 200°, as opposed to the range of 50°–180° used in the McFarlane et al. study. The second difference is that in this study we use a 30-min average of wind direction up to the time of interest, rather than a 60-min average centered on the time of interest as was done in the McFarlane et al. study, reasoning that clouds need to be formed and advected over the ARM site to influence the measurements, which is a process that takes only a relatively short amount of time—on the order of 5–10 min. As a consequence, wind direction much after the time of interest is not likely to have an important effect on the ARM site measurements through island-induced low-level clouds. We also note that in this study the Li-Cor site is located on the south side of the island, whereas the Li-Cor data collected during the NIES experiment and analyzed in McFarlane et al. were from instruments that located on the eastern side of the island. For this study, the island effect is deemed to be occurring if

1) the wind is from across island (direction between 60° and 200°), using an average of 30 min up to the time of interest (air must pass over the island for the island to influence it),
2) the air temperature is greater than 302 K at the time of interest at the Nauru ARM site (warmer air temperatures are indicative of strong island heating),
3) the 1-h-average SW correlation between the Li-Cor site and the Nauru ARM site is less than 0.8 using a 60-min correlation centered on the time of interest (indicating that the two sites are experiencing significantly differing SW variability), and
4) the 60-min standard deviation (centered on time of interest) in downwelling SW radiation is at least 10% greater at the Nauru ARM site than at the Li-Cor site (indicating that the ARM site is being influenced significantly more by cloud-generated variability in the SW measurements).

The data from 22 September 2005 through 28 September 2010 were processed with all times classified as either being or not being island influenced on the basis of the above criteria. The analyses that follow are based on this classification. We note that because the detection method uses specific thresholds, a weak island effect may be present even if conditions are close to, but do not exceed, one of the threshold values used.

3. Analysis

As illustrated in Fig. 1 and described in Matthews et al. (2007), the Nauru island effect is generated by solar heating of the island surface and thus is a daytime phenomenon. McFarlane et al. found no clear signal in ceilometer detections of low-cloud frequency at night. Although small island cloud plumes are not uncommon, Nauru may be more susceptible than most islands to solar heating owing to the decades of phosphate mining that have left large unvegetated karst fields as the predominant land surface over most of the center of the island. Figure 2 shows the time series of daily daylight percent of time that an island effect on the ARM site measurements was detected using the method described in the previous section. A 30-day running mean is included to illustrate the longer-term pattern. On a few days an island effect occurs for more than 60% of the daylight hours, but for 78% of the days the occurrence is for 20% of the daylight hours or less. Overall, the island effect occurs for an average of 11% of the daylight hours during the study period.

To examine how the island effect might affect the low-level cloud statistics, we use the detected lowest cloud-base height from the ceilometer. Figure 3 shows the frequency of occurrence during daylight hours for times with and without an island effect. Of the daylight times at which clouds are detected by the ceilometer, cloud bases

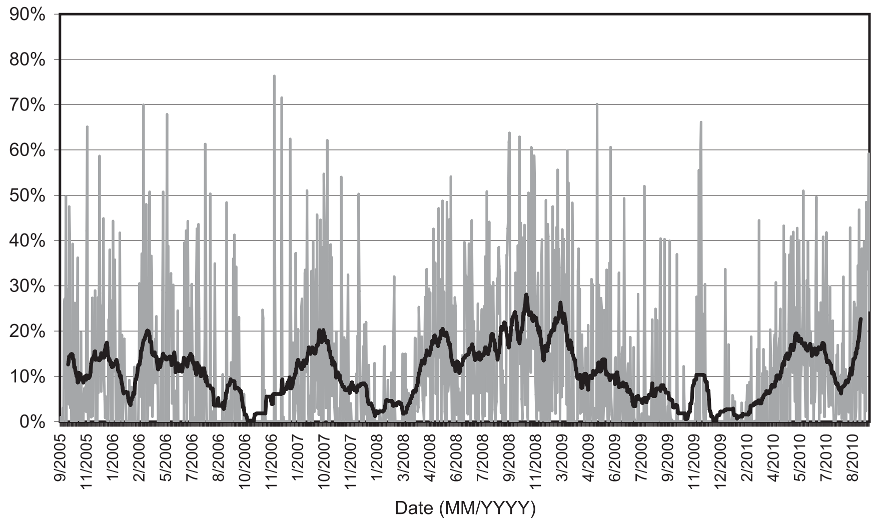

FIG. 2. Daily daylight percent of time that the Nauru island effect was detected (gray bars), and the 30-day running mean (black line).

in the 500–1000-m height range occur 15%–20% more often when an island cloud effect is occurring than when one is not occurring (Fig. 3, left panel). The values in this range are larger than the relative difference of 7%–13% seen in the McFarlane et al. analysis, a result that might be due to the slightly revised definition of the island cloud effect or to the much shorter time period (9 months) examined in that study. During the current study period, no island effect occurs for 89% of the daylight time; therefore, the aggregate effect on the low-level cloud statistics is only to increase the daylight low cloud amount by about 2% over that if there were no cloud influence ever on the ARM site measurements.

The Nauru island-effect periods do exhibit a different frequency distribution of fractional sky cover than do times without an island effect. Figure 4 shows the frequency for fractional sky cover during daylight hours, derived from the shortwave radiometer measurements using the Long and Ackerman (2000) and Long et al. (2006) sky-cover retrieval method. Because the island effect is caused by solar heating, it stands to reason that it occurs on days with relatively smaller cloud amounts and little if any deep convection and occurs most often under convectively suppressed conditions. The convectively suppressed regime is typified by small, top-of-boundary-layer cumulous clouds (Cu), and the island effect is even more pronounced under these conditions (Matthews et al. 2007; McFarlane et al. 2005). Thus, as Fig. 4 illustrates, the frequency distribution of sky cover is shifted toward smaller cloud amounts with a peak between 30% and 50% sky cover and amounts of 0%–60% sky cover accounting for 76% of the time. In addition, during island-effect conditions, the sky is overcast only about 5% of the time as compared with 23% of the time with no island effect, and there is almost no occurrence of sky cover of less than 10% for island-effect conditions, whereas sky cover of less than 10% occurs 15% of the time when there is no island effect.

The importance of convectively suppressed conditions in favoring an island-effect occurrence is also exemplified by noting the periods of minimum occurrence of the island effect in Fig. 2. On the basis of data from the National Center for Atmospheric Research Climate and Global Dynamics Division (obtained online at http://www.cgd.ucar.edu/cas/ENSO/enso.html), their analysis of the oceanic Niño index, a 3-month running mean of SST anomalies in the Niño-3.4 region spanning 5°N–5°S and 120°–170°W, shows that the minimum periods in the Nauru island-effect occurrence corresponds to El Niño occurrences. Specifically, El Niño periods from their analysis occurred during August 2006–January 2007, September 2007–May 2008, and June 2009–April 2010. This makes physical sense in that with an El Niño the center of convection in the equatorial Pacific migrates toward the central Pacific (i.e., toward Nauru). As we have noted, it is the convectively suppressed regime that favors the Nauru island effect; thus, increased convective activity at Nauru due to El Niño tends to decrease the conditions that favor island-effect occurrence.

The cloudiness characteristics of the island-effect regime in Fig. 4 produce an interesting phenomenon with respect to the downwelling SW radiation. As reported by Berg et al. (2011), small Cu cloud fields frequently produce surface SW measurements that exceed the corresponding clear-sky amount, even when averaged up to 60 min and more (although generally the longer

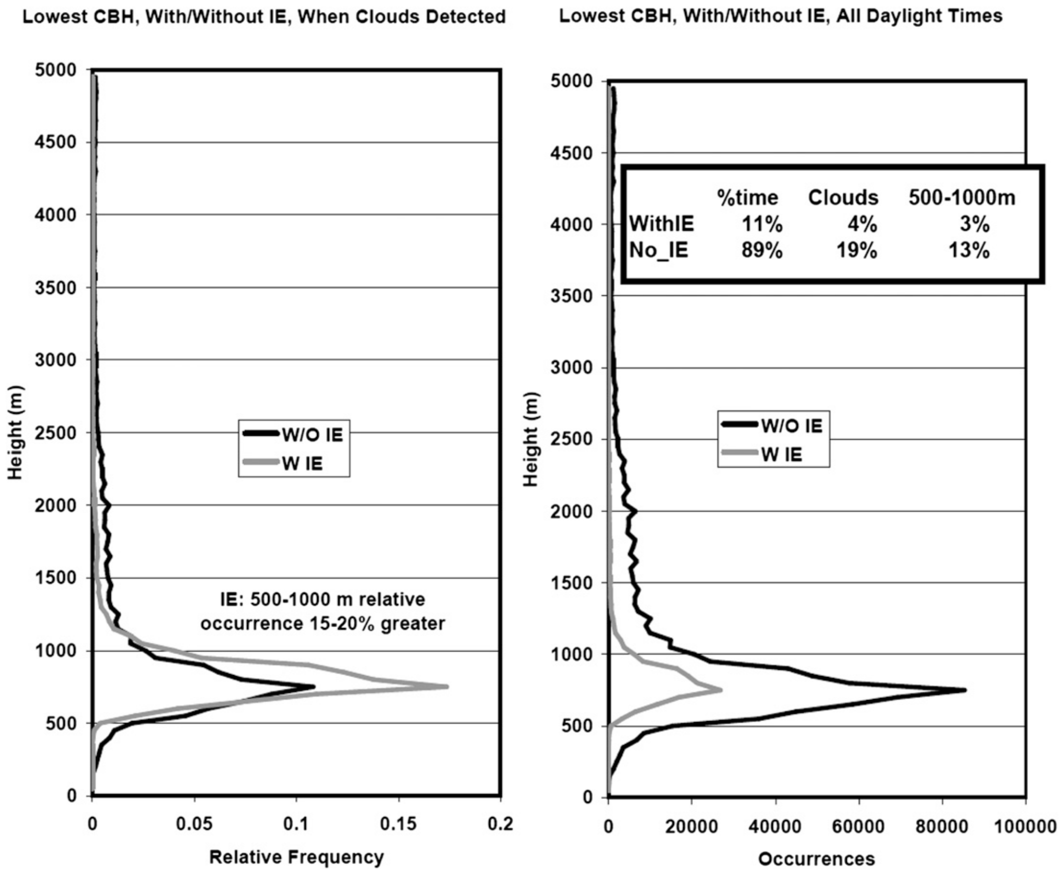

FIG. 3. (left) Relative frequency of occurrence of lowest cloud-base heights for times at which low clouds are detected and (right) number of occurrences of lowest cloud-base heights during all daylight times for times with (gray lines) and without (black lines) an island effect.

the averaging time is, the smaller is the magnitude). This downwelling ''positive cloud effect'' occurs because the presence of clouds (except for very dark, optically thick clouds) generally increases the magnitude of the diffuse SW radiation (Long and Ackerman 2000; Long et al. 2006; Berg et al. 2011). For times at which the direct SW component is not blocked by cloud, then, the sum of the direct plus diffuse SW radiation exceeds that for clear skies, and for 1-min data it can exceed the clear-sky amount by hundreds of watts per meter squared. This positive cloud effect for an extreme case in which the island effect occurred during most of the daylight period is illustrated in Fig. 5. Although the Li-Cor data show only occasional variation on this day, the ARM data show frequent variability that is at times both less than and greater than the corresponding clear-sky amount. For our analyses, all clear-sky SW estimates are produced using the Long and Ackerman (2000) method. Also note that on this day there are more positive-cloud-effect events in the morning than in the afternoon, indicating that the direct beam was less often obscured by cloud in the morning but that the direct beam was blocked most of the time from about 1400 LST on at the ARM site but not at the Li-Cor site. This is not an unusual circumstance with respect to the Nauru island effect, as is discussed further below.

Figure 6 shows the relative frequency of the downwelling SW cloud effect for times at which the island effect is and is not occurring and separated into morning (labeled as ''am'') and afternoon (labeled as ''pm'') analyses. For times at which there is no island effect, the relative distributions are nearly identical, with the peak frequency centered on zero cloud effect. For the times with a cloud effect occurring, however, both the am and pm distributions show the peak frequency as occurring for positive 20–40 W m^{-2}. The am distribution shows more frequent occurrence of larger positive events than the pm distribution does, with positive events occurring 46% of the time in the morning as compared with 26% of the time in the afternoon. The am island-effect distribution also shows more frequent large negative excursions (<-500 W m^{-2}) than does the pm distribution.

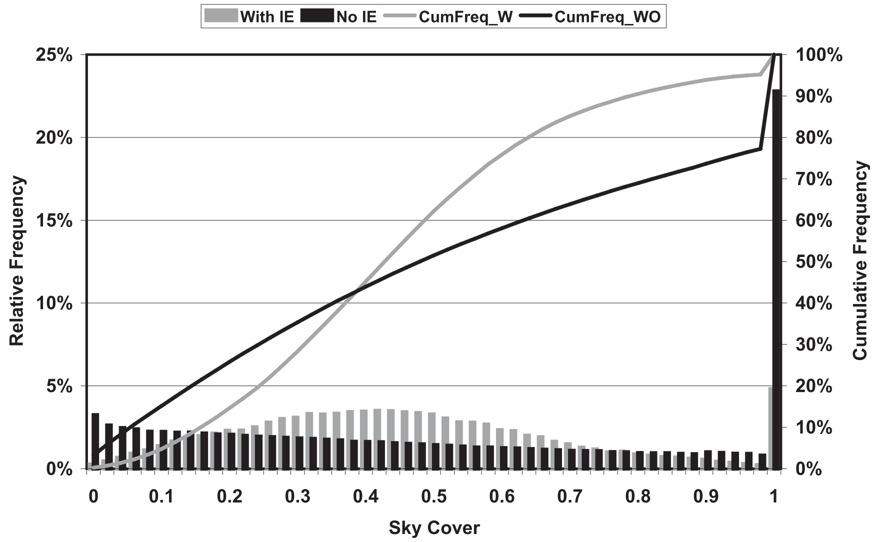

FIG. 4. Relative frequency of occurrence of daylight fractional sky cover (left axis; bars) for times with (gray bars) and without (black bars) an island effect, and the corresponding cumulative frequency (right axis; solid lines).

The result of the differences in occurrence of downwelling SW cloud effects can be seen in Fig. 7, which shows the average daylight diurnal cycle for times with and without an island effect during the study period. The frequent positive-cloud-effect occurrences somewhat mitigate the total cloud effect in the morning, producing less of a negative average than for times without an island effect. The afternoon average cloud effect is about the same with and without an island effect occurring, however. Thus, in the aggregate, the total daylight downwelling SW cloud effect for times with an island cloud effect is smaller in magnitude across the day (-113 W m^{-2}) than it is for times at which there is no island effect (-130 W m^{-2}), although the shift in distribution of fractional sky cover (Fig. 4) is also a factor.

These characteristics of the island effect with respect to influence on the downwelling SW radiation are easily understood by reference to Fig. 1. The ARM site is located

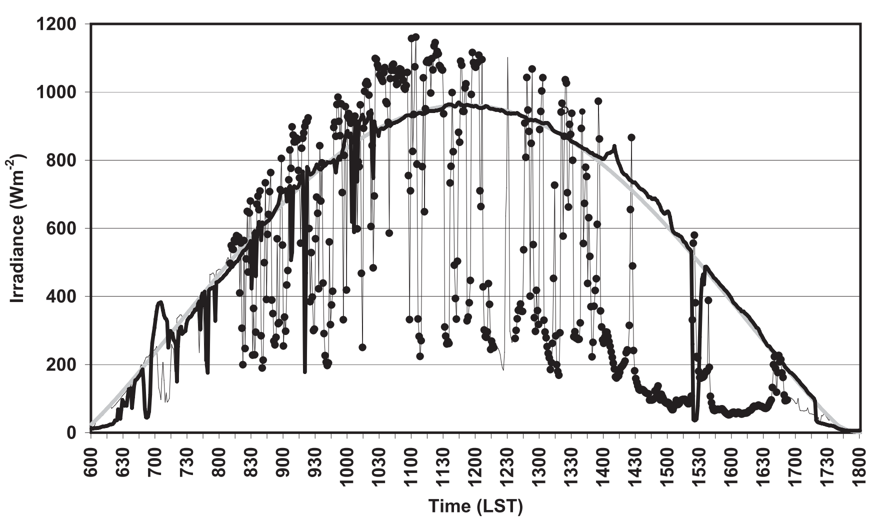

FIG. 5. Example day with extreme Nauru island effect occurring (12 May 2009), showing the downwelling SW radiation measured at the ARM (thin black line) and Li-Cor (thick black line) sites. The light-gray line corresponds to estimated clear-sky SW radiation, and black dots are detected island-effect occurrences superimposed on the 1-min ARM SW radiation measurements.

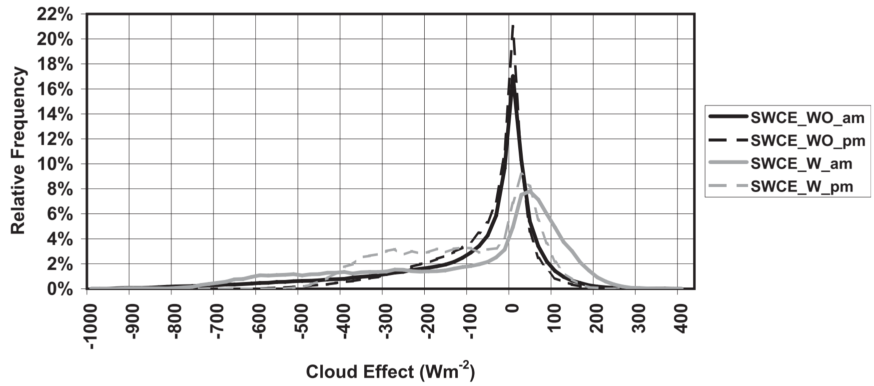

FIG. 6. Relative frequency of occurrence of daylight downwelling SW cloud effect for times with (gray solid line for am; gray dashed line for pm) and without (black solid line for am; black dashed line for pm) an island effect.

on the western side of Nauru Island, and the island effect on the ARM measurements only occurs when the wind has a significant easterly component (McFarlane et al. 2005). Island-produced clouds form and are advected toward the west. In the morning, when the sun is located toward the east, the enhanced cloudiness to the west of the ARM site is unlikely to block the direct sunlight, yet there is enhanced diffuse SW radiation because of the presence of clouds. In the afternoon, there is still enhanced diffuse SW radiation, but now the enhanced cloudiness to the west has more of a chance of blocking the direct sun in the western sky. In addition, the clouds generated by the island are in the early stages of formation and tend to be smaller and optically thinner than other convective cloudiness nearby. Thus, when the sun is blocked in the morning, it is typically by optically thicker (non–island generated) clouds that produce larger negative-cloud-effect values (as shown in Fig. 6), as compared with the less attenuated but more frequent sun blockage in the afternoon by the island-generated clouds that produce more frequent but smaller-magnitude negative cloud effects. As shown by Nordeen et al. (2001), the island effect often produces cloud streets that can extend for hundreds of kilometers downstream of the island, thus increasing the blockage of the late afternoon sun as it gets nearer to the horizon and the gaps between the clouds disappear from the line of sight from that viewing angle.

The difference in cloud amounts and cloud-effect characteristics between the island-effect and non-island-effect regimes does not illustrate the overall effect of the increased cloudiness produced by the island on the ARM downwelling SW measurements. To quantify this overall island effect on the surface SW measurements, Fig. 8 shows the aggregate daylight diurnal average ratio of the ARM downwelling SW radiation over the corresponding

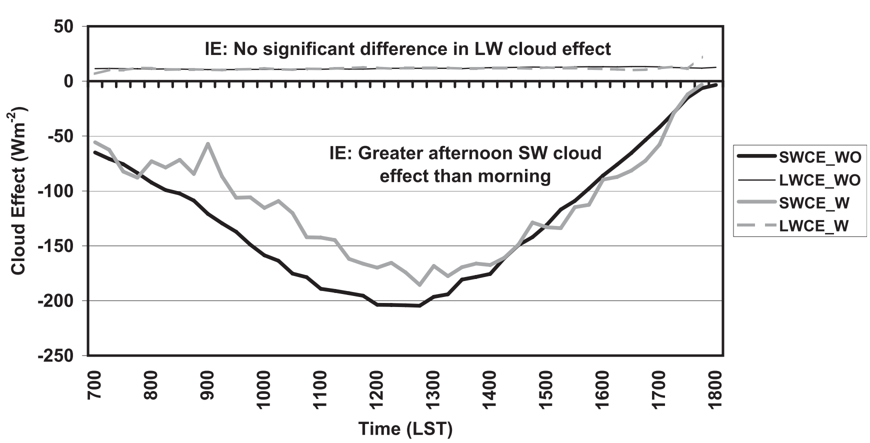

FIG. 7. Average daylight diurnal cycle of the downwelling cloud effect for times with (gray solid line for SW; gray dashed line for LW) and without (thick black line for SW; thin black line for LW) an island effect.

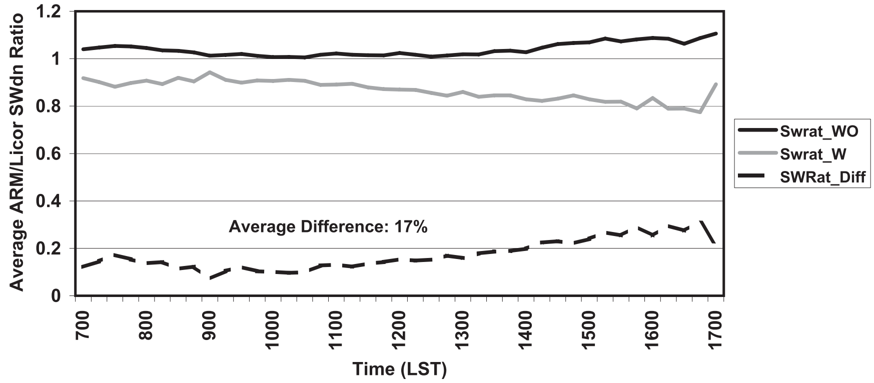

FIG. 8. Average daylight diurnal cycle of the ratio of ARM-site downwelling SW radiation over the corresponding downwelling SW radiation at the Li-Cor site for times with (gray line) and without (black line) an island effect, and the difference between the two (dashed line).

Li-Cor measurements. For non-island-effect times, the ratio is nearly 1, with minor differences due to differing instrument characteristics such as cosine response and calibration differences. Thus, the ARM and Li-Cor sites are effectively ‘‘seeing’’ the same overall downwelling SW input at the surface. For times with an island effect, however, the ARM site downwelling SW radiation is on average about 17% less across the daylight period than that at the Li-Cor site, equivalent to about 82 W m^{-2} less daylight SW radiation for the ARM site, with greater differences in the afternoon than in the morning hours. Similar to the result for low-level cloud occurrence, when weighted by the 11% occurrence of the island effect overall (Fig. 2), this produces a 2% aggregate total overall decrease in the daylight average downwelling SW radiation (about 9 W m^{-2}) reaching the surface for the ARM-site measurements, or about 1% (4–5 W m^{-2}) in the 24-h averages.

As reported by McFarlane et al. (2005), we find in this longer analysis that indeed the island effect has no appreciable influence on the average downwelling longwave irradiance. This is shown in Fig. 7 as no significant difference in the average LW cloud effect between times with and without an island effect. The large column water vapor amounts that typify the tropical western Pacific warm-pool area produce a large downwelling LW irradiance already, and clouds generally have only a small (typically $<$50 W m^{-2}) influence in increasing the irradiance reaching the surface. Thus, the result that the total daylight average difference in LW cloud effect is less than 1 W m^{-2} is not surprising.

4. Conclusions

As noted in McFarlane et al. (2005), the Nauru island effect only influences the low-level cloud occurrence statistics and the downwelling SW radiation measured at the ARM site when an island effect is occurring. Our current study spans five years of data and shows that the island effect occurred on average for 11% of the daylight time during the study period. The island effect increased the frequency of lowest cloud-base height on average by 15%–20% when it occurred, but, because it only occurs 11% of the time during daylight periods, the aggregate effect is only about a 2% increase in overall daylight low-level cloud statistics or about 1% in the 24-h average. The island-effect periods do exhibit a frequency distribution of fractional sky cover that is peaked toward smaller sky-cover amounts between 10% and 60% (Fig. 4), which in turn produces more frequent positive-cloud-effect occurrences, but this sky-cover distribution likely is also due to the influence of convectively suppressed conditions resulting from large-scale subsidence when significant periods of the island effect occur.

For the effect of clouds on the downwelling SW radiation, the island effect produces more frequent positive cloud effects in the morning than in the afternoon, which in turn produces less overall average negative cloud effect in the morning than in the afternoon for the island-effect regime. Overall, the morning aggregate SW cloud effect is smaller in magnitude for times with an island effect than for times without an island effect, but both are of about the same magnitude in the afternoon hours. The net result is that a daylight average SW cloud effect of -113 W m^{-2} is 17 W m^{-2} smaller in magnitude than at the corresponding non-island-effect times (-130 W m^{-2}) for the convectively suppressed regime that typifies conditions that produce the island effect. Nevertheless, the increased cloudiness generated by the island over the ARM site does produce an overall 2% daylight reduction in the measured downwelling SW radiation, or about 1% in the 24-h average. There is no significant impact on downwelling LW radiation.

For studies such as model and satellite comparisons using long-term overall statistics, the 2% daylight (or 1% per 24 h) average increase in low-level cloud occurrence and decrease in downwelling SW radiation are not of large concern as long as researchers are aware of them. For shorter-term process studies or those that separate data by conditions such as convectively active/suppressed regimes, however, the Nauru island effect can have significant impacts. To help all researchers using Nauru data, the ARM Tropical Western Pacific Site Scientist Team has processed Nauru data as a value-added product the 1-min resolution output files of which include a flag denoting whether an island effect is occurring. As of the time of writing, these files are available as an ARM ''PI product'' through the ARM archive (online at http://archive.arm.gov).

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