A Climatology of Surface Cloud Radiative Effects at the ARM Tropical Western Pacific Sites

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ABSTRACT

Cloud radiative effects on surface downwelling fluxes are investigated using datasets from the Atmospheric Radiation Measurement Program (ARM) sites in the tropical western Pacific Ocean (TWP) region. The Nauru Island (Republic of Nauru) and Darwin, Australia, sites show large variability in sky cover, downwelling radiative fluxes, and surface cloud radiative effect (CRE) that is due to El Niño–Southern Oscillation (ENSO) and the Australian monsoon, respectively, whereas the Manus Island (Papua New Guinea) site shows little intraseasonal or interannual variability. At Nauru, the average shortwave (SW) surface CRE varies from $-38.2 \text{ W m}^{-2}$ during La Niña conditions to $-90.6 \text{ W m}^{-2}$ during El Niño conditions. The average longwave (LW) CRE ranges from 9.5 to 15.8 W m$^{-2}$ during La Niña and El Niño conditions, respectively. At Manus, the average SW and LW CREs vary by less than 5 and 2 W m$^{-2}$, respectively, between the ENSO phases. The variability at Darwin is even larger than at Nauru, with average SW (LW) CRE ranging from $-27.0 \text{ (8.6) W m}^{-2}$ in the dry season to $-95.8 \text{ (17.0) W m}^{-2}$ in the wet season. Cloud radar measurements of cloud-base and cloud-top heights are used to define cloud types to examine the effect of cloud type on the surface CRE. Clouds with low bases contribute 71%–75% of the surface SW CRE and 66%–74% of the surface LW CRE at the three TWP sites, clouds with midlevel bases contribute 8%–9% of the SW CRE and 12%–14% of the LW CRE, and clouds with high bases contribute 16%–19% of the SW CRE and 15%–21% of the LW CRE.

1. Introduction

Understanding and representing the radiative impacts of clouds in climate models is important for accurately simulating Earth’s current energy and water cycles and for predicting cloud radiative feedbacks in simulations of future climate. Details of cloud impacts on the radiation budget depend on both macrophysical (cloud amount, cloud height, and cloud frequency) and microphysical (cloud phase, cloud mass, and particle size) factors. Because many cloud physical processes occur at scales that are smaller than that of a typical global climate model, cloud physical and radiative properties have to be parameterized in these models. Observations are needed to assess whether these parameterizations are accurately reproducing cloud radiative impacts. Global estimates of cloud radiative effect at the top of the atmosphere (TOA) are available from satellite data, but surface observations are much sparser, especially in climatically important, but remote, regions such as the tropics. Estimates of surface radiative forcing from satellite data are possible (e.g., Chen et al. 2000), but most estimates use passive remote sensing techniques, which require assumptions about cloud vertical structure. In addition, satellite studies with passive remote sensors may underestimate the effect of low clouds on the surface radiative budget, as observation of low clouds by the satellite may be blocked by optically thick high clouds. In general, models tend to have larger errors in the surface radiation budget than in the TOA budget, likely because of tuning of cloud properties to match the satellite TOA observations and the sparseness of surface observations (Wild 2005; Wild et al. 2012). Studies have shown that accurate simulation of the TOA radiation budget (as compared with satellite observations) is not a sufficient constraint on cloud properties, because there may be compensating errors in the treatment of clouds in the models that can lead to different partitioning of solar absorption between the surface and atmosphere given the same TOA radiative effect (Stephens 2005).

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The Atmospheric Radiation Measurement Program (ARM) operates a set of long-term sites with measurements of both cloud properties and surface radiation. The simultaneous measurement of surface radiation and cloud properties at the ARM sites (and similar measurement sites such as those operated by CloudNet; Illingworth et al. 2007) enables both assessment of cloud radiative impacts and analysis of how the radiative impacts vary with cloud type and cloud properties. Previous studies have presented comprehensive multiyear climatological descriptions of surface radiation measurements, cloud properties, and cloud radiative effects (CRE) from ground-based measurements at midlatitude (Dong et al. 2005, 2006; Liu et al. 2011) and Arctic sites (Dong et al. 2010); no corresponding study of the tropical region using long-term ground-based measurements exists, however.

The tropical western Pacific Ocean (TWP) region is important to global climate because the absorption of solar energy in the tropics and the transport of that energy poleward are the main driver of the meridional general circulation. In this paper we use multyear measurements from the three ARM sites in the TWP region (Mather et al. 1998; Long et al. 2013) to study the effect of clouds on the surface radiation budget in the tropics. Although all three sites are located in the tropics, they are dominated by different modes of tropical variability, which affect their surface radiation budgets. Previous studies have examined aspects of CRE using ARM tropical data (e.g., Comstock et al. 2012, manuscript submitted to J. Geophys. Res.; Jensen and Del Genio 2003; McFarlane and Evans 2004), but they generally focused on a particular cloud type, only examined a single site, or used much shorter datasets. Here we combine the long-term measurements of surface radiation from broadband radiometers with measurements of cloud vertical structure from active atmospheric remote sensing instruments 1) to characterize the overall mean and variability of surface cloud radiative forcing at several tropical locations and 2) to begin more detailed analysis of tropical cloud radiative forcing by examining differences in cloud radiative forcing as a function of simple cloud type definitions that could be easily applied to climate models.

2. Data and method

The ARM program operates three long-term measuring sites in the TWP region (Fig. 1). The Manus Island (Papua New Guinea) site became operational in late 1996 and is located in the middle of the tropical warm pool, which is important for the prolific convection associated with the upwelling side of the Walker circulation and its impacts on global circulation. In addition, signals
associated with the Madden–Julian oscillation (MJO), the dominant mode of tropical intraseasonal variability, have been detected in the surface radiation measurements at Manus (Wang et al. 2011). The Nauru Island (Republic of Nauru) site became operational in late 1998 and is located on the eastern edge of the warm pool. It exhibits strong variability associated with the El Niño–Southern Oscillation (ENSO) and is an important site for documenting this variability and its effect on the surface radiation budget. The Darwin, Australia, site became operational in early 2002 and is an important example of a tropical coastal site. Along with variability associated with the MJO, it also exhibits strong interseasonal variability, associated with the Australian monsoon (Pope et al. 2009). Taken together, these three sites have been shown to be representative of typical cloud types seen throughout the TWP region (Jakob et al. 2005), although they cannot represent the marine stratus regimes found in the eastern tropical Pacific. Below we describe the ARM measurements and retrieved properties used in this study.

a. Radiation measurements and radiative flux analysis

Surface radiation and meteorological measurements used in the study include downwelling broadband shortwave (SW) diffuse, direct, and total (global) fluxes; downwelling longwave (LW) flux; air temperature; and relative humidity (RH). 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 direct, global, and diffuse flux measurements, respectively, and Eppley Precision Infrared Radiometers for the LW flux to produce 1-min averages from 1-s samples (details about these radiation systems and the instruments used were available online at the time of writing at http://www.arm.gov). Estimates of the 2-sigma (std dev) uncertainties of the 1-min flux measurements are given in Table 1. The radiation measurements were quality controlled using a “surface radiation quality testing methodology” (“QCRad”; Long and Shi 2008). Air temperature and relative humidity measurements, used to produce continuous estimates of the clear-sky downwelling LW flux, are from a Vaisala, Inc., Model HMP35C temperature and humidity probe in a forced-air aspirated enclosure. The estimated uncertainty is 0.6°C for the air temperature and 2%–3% for RH (Ritsche 2006).

The above observations were used as inputs for the “radiative flux analysis,” which is a series of codes that were developed to examine the time series of the measurements and detect periods of clear (i.e., cloudless) skies and then to use the detected clear-sky data to fit appropriate functions, interpolate the fit coefficients across cloudy periods, and thus produce continuous clear-sky irradiance estimates. The resultant measured and clear-sky data are then used to infer various atmospheric and cloud macrophysical properties, including daylight fractional sky cover (effective field of view of 160°), effective cloudy-sky SW transmissivity (calculated as the ratio of the downwelling total SW flux to the corresponding clear-sky total SW flux), and overcast visible optical depth. Details of these algorithms are available in a series of papers by Long et al. (Long and Ackerman 2000; Barnard and Long 2004; Long et al. 2006; Long and Turner 2008; Barnard et al. 2008). Estimates of the uncertainty for clear-sky downwelling total SW flux are given as the root-mean-square error (RMSE) of 2 times the measurement uncertainty (Long and Ackerman 2000); thus, in the case of ARM global SW flux measurements, uncertainties are the larger of 8.5% or 14 W m⁻². Estimated uncertainty for the SW-derived fractional sky cover is less than 10% for an effective field of view of 160° (Long et al. 2006), approximately 3% for the effective transmissivity (Long and Ackerman 2000), and less than 10% for the overcast optical depths (Barnard and Long 2004). The uncertainty for the clear-sky downwelling LW flux is about 4 W m⁻² (Long and Turner 2008).

For the overall radiometer analyses (section 4a), the data used for Manus and Nauru span from January 1999 through December 2010. The start date was chosen as the first full year after the Nauru site became operational for consistency of comparison between the two sites. The Darwin radiometer data span from March 2002 through December 2010.

b. Cloud vertical-profile measurements

Along with the radiation measurements, we use independent measurements of the vertical structure of
clouds from active remote sensors to examine CRE at the surface as a function of cloud type (section 4c). The primary instrument used to define cloud type is the millimeter-wavelength cloud radar (MMCR). Information on cloud existence from a micropulse lidar (MPL) is also used although the MPL is attenuated in optically thick clouds and is unable to see potential overlying layers. In addition, because of issues with the overlap of the lidar detector and receiver, the product used here does not report cloud detections below 1 km (Sivaraman and Comstock 2011). In this work, the MPL is mainly useful for identifying thin midlevel clouds and high cirrus (that are not obscured by underlying clouds) that may not be detected by the MMCR.

The MMCR reflectivity values from the Active Remote Sensing of Cloud Layers product (Clothiaux et al. 2001) and the MPL backscatter are averaged to a common grid that has 120-s temporal resolution and 30-m vertical resolution. The radar reflectivity is corrected for attenuation due to water vapor and then hydrometeors (including cloud, drizzle, and rain) are detected at each grid point on the basis of radar-reflectivity thresholds and gradients in the lidar-backscatter signal (Comstock et al. 2012, manuscript submitted to J. Geophys. Res.). Contiguous blocks of four or more vertical grid points (120 m) that contain hydrometeors identified from the MPL, MMCR, or both are defined as cloud layers, and cloud layers that are less than four vertical bins apart are combined into a single layer. Adjusting the thresholds used for cloud detection would slightly affect the statistics presented in this study but would not significantly affect the primary results.

Missing or bad radar/lidar data are removed through data quality flags in the files, examination of daily maximum reflectivity, and visual inspection of the data. Because of the complicated nature of active remote sensors and the remote locations of the tropical ARM sites, which make instrument repair difficult, the cloud dataset is less complete than the radiation data, particularly at Nauru. The study still includes approximately 578 000 cloud measurements at Manus, 191 000 measurements at Nauru, and 358 000 measurements at Darwin, however. The time series of available radar data is shown in Fig. 2.

3. Results

a. Radiative fluxes and sky cover

In this section we present analysis of the downwelling radiation, sky cover, and downwelling surface CRE (defined as the measured downwelling irradiance at the surface minus the corresponding clear-sky irradiance) at the three TWP sites. We first discuss the Manus and Nauru results, as these two near-equatorial sites are more similar to each other than to Darwin. Figure 3 shows the time series of monthly downwelling all-sky and clear-sky SW and LW fluxes for the three TWP sites for 1999–2010. The clear-sky SW flux time series at Manus (Fig. 3a) and Nauru (Fig. 3b) show two peaks each year, evidence that at locations near the equator the sun passes directly overhead 2 times per year. The downwelling clear-sky SW flux is roughly equivalent for the two sites (Table 2), with overall averages of 300 and
302 W m\(^{-2}\) for Manus and Nauru, respectively. The average all-sky SW flux for Manus (205 W m\(^{-2}\)) is considerably less than that for Nauru (237 W m\(^{-2}\)). This greater SW attenuation due to cloudiness at Manus is also evidenced by the all-sky SW effective transmissivity; the Manus monthly values primarily range between 0.6 and 0.8, whereas the Nauru values exceed 0.8 for approximately one-half of the time. For both the Manus

![Graphs showing monthly downwelling SW and LW irradiances and corresponding SW transmissivities for Manus, Nauru, and Darwin.](image-url)
and Nauru sites, clouds have a limited effect on the downwelling LW flux, adding only about 15 W m\(^{-2}\) to the clear-sky LW flux for Manus and 12 W m\(^{-2}\) for Nauru. Yet for both sites the warm, moist atmosphere produces on average about 408 W m\(^{-2}\) of clear-sky downwelling LW flux, which varies little from month to month.

For the Manus and Nauru plots in Figs. 3 and 4a, the periods of occurrence of El Niño (orange) and La Niña (blue) conditions are denoted on the bottom of the plots. These periods are based on the oceanic Niño index as determined by the National Oceanic and Atmospheric Administration Climate Prediction Center (obtained online at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensoindices/canindex.shtml).

As noted earlier, Nauru is located on the eastern edge of the TWP warm pool, whereas Manus is embedded in the prolific convective center toward the eastern side of the warm pool. Thus Nauru exhibits a much stronger signal associated with ENSO than does Manus. This is evident in Fig. 3 in which values of monthly average effective transmissivity for Nauru tend to be greater than 0.8 during La Niña periods when the most prolific convection migrates farther toward the western side of the warm pool. This essentially leaves the Nauru area embedded in the downwelling side of the Walker circulation with suppressed convective conditions and less average cloudiness (Fig. 4a). During El Niño periods, when the intense convection migrates eastward, the Nauru effective transmissivity values tend to range from 0.6 to 0.8, similar to the Manus values, with average cloudiness also being greater than that during La Niña periods. Although more subtle, there is also a noticeable increase in the effect of clouds on the Nauru downwelling LW flux during El Niño periods. Table 2 also breaks down the overall average SW and LW fluxes for these ENSO periods. For Manus, the downwelling LW CRE is only 1 W m\(^{-2}\) different between El Niño and La Niña conditions, whereas for Nauru clouds increase the LW flux by 16 W m\(^{-2}\) for El Niño as compared with only 10 W m\(^{-2}\) for La Niña. The range in SW CRE for Manus is again fairly small, being only 5 W m\(^{-2}\) different between the ENSO extremes, whereas the Nauru downwelling SW cloud effect is −91 W m\(^{-2}\) for El Niño as compared with −38 W m\(^{-2}\) for La Niña conditions.

For Manus, there is very little difference in occurrence of daylight fractional sky cover or average cloudiness between the two ENSO extremes, with slightly less overcast occurrence and slightly greater occurrence of low (<20%) sky cover (Fig. 4b). For Nauru the difference is much more striking. During La Niña conditions at Nauru, the sky cover is 50% or less during 67% of the observations and only 10% of observations are overcast, indicating the convectively suppressed environment in the area. For El Niño conditions with the migration of the prolific convective center toward the eastern side of the warm pool, the Nauru distribution of sky cover resembles that of Manus, with almost 40% occurrence of overcast and only 5%–7% occurrence across the rest of the sky-cover range.

The Darwin site exhibits strong interseasonal variability and distinct wet and dry seasons associated with the Australian monsoon (Pope et al. 2009). Thus the variability in the downwelling radiation at Darwin (Fig. 3c) is much different from that at Manus and Nauru. The onset and duration of the wet season at Darwin vary from year to year, and various meteorological definitions of the monsoon season have been defined in the literature (e.g., Drosdowsky 1996). For simplicity, we use the months from May through October to represent the dry season for our analysis (denoted as black bars on the Figs. 3c and 4a time series) and the November–April period to represent the wet season. The clear-sky downwelling SW flux for Darwin does not exhibit two peaks as the equatorial sites do. The all-sky SW flux is nearly the same magnitude as the clear-sky SW flux for most of the dry season but is considerably less for the wet season. The SW all-sky effective transmissivity highlights this behavior with values of 0.9 and greater for much of the dry-season periods, whereas the wet-season months have values that are typically less than 0.8. The overall averages for Darwin in Table 2 are taken from April of 2002 through March of 2010 so as to have full years for comparison with the equatorial sites, and the resulting averages are 294 and 234 W m\(^{-2}\) for the clear-sky and all-sky downwelling SW fluxes, respectively. These values result in an overall SW CRE of

| Table 2. Average measured all-sky downwelling SW and LW surface fluxes (labeled SW dn and LW dn), estimated clear-sky downwelling SW and LW fluxes (labeled CSW dn and CLW dn); and estimated surface SW and LW CRE. Average fluxes and CRE are given for each site for the entire analysis period, as well as for subsets by El Niño/La Niña/neutral or wet/dry conditions. |
|------------------|-------|-------|-------|-------|-------|-------|-------|
|                  | SW    | CSW   | SW    | LW    | CLW   | LW    |
|                  | dn    | dn    | CRE   | dn    | dn    | CRE   |
| Manus            | 204.9 | 299.6 | −94.7 | 422.6 | 407.5 | 15.1  |
| El Niño          | 196.9 | 300.4 | −103.5| 422.6 | 406.9 | 15.7  |
| Neutral          | 200.1 | 297.9 | −97.8 | 423.1 | 408.5 | 14.6  |
| La Niña          | 208.7 | 307.8 | −99.1 | 421.5 | 407.4 | 14.1  |
| Nauru            | 237.0 | 302.0 | −65.0 | 420.5 | 408.3 | 12.3  |
| El Niño          | 211.9 | 302.5 | −90.6 | 429.0 | 413.2 | 15.8  |
| Neutral          | 235.1 | 300.6 | −65.5 | 421.9 | 409.6 | 12.3  |
| La Niña          | 268.8 | 307.0 | −38.2 | 410.4 | 400.9 | 9.5   |
| Darwin           | 234.2 | 293.8 | −59.6 | 404.0 | 391.6 | 12.4  |
| Dry              | 239.1 | 266.1 | −27.0 | 385.6 | 377.0 | 8.6   |
| Wet              | 225.3 | 321.1 | −95.8 | 426.1 | 409.1 | 17.0  |
although it varies greatly with season. For the dry season, the clear-sky SW flux is smaller in magnitude and yields an SW cloud effect of $-25$ W m$^{-2}$. The wet season exhibits greater clear-sky SW flux but less all-sky flux, producing an SW cloud effect of $-94$ W m$^{-2}$.

For the downwelling LW flux, unlike the equatorial sites, there is a distinct seasonal variability associated with the large changes in water vapor and cloudiness during the wet and dry seasons (Figs. 4 and 5). In the midlatitudes, about two-thirds of the downwelling clear-sky LW flux is produced by greenhouse gas emission of the lowest 100 m of the atmosphere above the instrument, with 90% being produced in the lowest kilometer (Ohmura 2001). Using the method in Ohmura (2001), we perform radiative transfer calculations with a broadband radiative transfer model (Evans 2007) to understand how the atmospheric temperature and humidity profiles in the lower tropical atmosphere contribute to the observed variability in LW fluxes during different atmospheric conditions. The average temperature and humidity profiles at Darwin (Fig. 5a) show large differences in the magnitude and shape of the humidity profiles in the lower troposphere between the wet and dry seasons. The clear-sky radiative transfer calculations using the average dry and wet atmospheric profiles from Darwin (solid lines in Fig. 5b) are consistent with the Ohmura results, which were calculated for midlatitude atmospheric profiles. Although significantly more LW flux reaches the surface with the
average wet atmospheric profile than with the dry profile, approximately 93% of the downwelling clear-sky LW flux at the surface originates from the lowest kilometer under both wet and dry conditions.

We then include a low cloud (a liquid cloud with a base height of 750 m, a physical thickness of 1000 m, and an optical depth of 10) in the calculations (dashed lines in Fig. 5b). When one considers heights below cloud base, the percentage of the clear-sky downwelling flux at the surface originating from a given height is the same for both the cloudy-sky and clear-sky conditions and is approximately the same for the wet and dry profiles. For heights within and above the cloud, however, there is a distinct difference between the wet and dry profiles. For an optically thick cloud, LW emission originating from a layer within cloud is stronger than from the same layer in clear-sky conditions because of the increase in emissivity that is due to the cloud water. This impact on the surface fluxes is larger for the dry profile than for the wet profile, with an increase in the calculated surface flux of 62 W m\(^{-2}\) (16% of the 381 W m\(^{-2}\) clear-sky value) for the dry case as compared with 36 W m\(^{-2}\) (9% of the 422 W m\(^{-2}\) clear-sky value) for the wet case. We note that an optically thick cloud with a low cloud base is the strongest influence on the surface LW flux—optically thinner clouds or clouds with higher bases have a smaller impact on the surface LW because they emit at colder temperatures. The total impact of clouds on the LW surface flux is a function of atmospheric conditions, cloud amount, cloud type, and frequency of occurrence of particular cloud types.

Overall, the observed clear-sky downwelling LW flux is 32 W m\(^{-2}\) less during the dry season than during the wet season at Darwin, as compared with a 13 W m\(^{-2}\) difference and a 0.5 W m\(^{-2}\) difference between ENSO phases at Nauru and Manus, respectively. The all-sky LW flux and the cloud fraction also vary during the two seasons, however, yielding an average downwelling LW cloud effect at Darwin of 8 W m\(^{-2}\) for the dry season and 17 W m\(^{-2}\) for the wet season that is surprisingly similar to the LW cloud effects at Nauru noted earlier of 10 and 16 W m\(^{-2}\) for La Niña and El Niño periods, respectively.

Also like Nauru, the Darwin site experiences very different cloudiness distributions between the wet and dry periods and also a striking difference in average cloudiness between the two seasons. During the wet season Darwin experiences frequent overcast conditions and larger average cloud amounts, similar to Nauru during El Niño periods and Manus at all times, with lesser sky-cover amounts occurring only 5% of the time and 11% occurrence of clear skies (Fig. 4). For the dry season, however, clear skies occur about 43% of the time and overcast conditions occur only about 7% of the time, whereas 72% of the time the sky cover is 30% or less. This results in average cloudiness values of only 10%–30% during the dry-season months. It is no wonder...
that the Darwin dry season receives 91% of the possible clear-sky downwelling SW flux amount on average, as compared with receiving only 71% of the possible clear-sky amount during the wet season.

**b. Cloud types at TWP sites**

In the previous section, we used the long time series of data from the broadband radiometers to examine the overall surface radiative budget and CRE at the three sites. Those results showed that the CRE at the surface varied considerably among the sites and depended on season (at Darwin) and ENSO conditions (at Nauru). Here we use information on the vertical cloud structure from the radar and lidar measurements to examine how different cloud types contribute to the CRE presented above.

In general, the vertical cloud/hydrometeor frequency distributions at the three TWP sites show similar structures (Fig. 6). All sites show a trimodal distribution (shallow, midlevel, and high clouds) that was described by Johnson et al. (1999), although the midlevel peak in cloud amount is less prominent at Darwin than at the other sites. High cloud is the most frequent, but low and midlevel clouds are also common. The tropical sites often have multilayer clouds, with low or midlevel clouds underneath high ice clouds (Mather and McFarlane 2009). Manus has the highest cloud frequency at all levels, followed by Darwin, and then Nauru. The large cloud amounts at Manus from the radar/lidar observations are consistent with the daylight sky cover and CRE presented previously and are due to Manus’s location in the tropical warm pool, where there is frequent deep convection—either locally or over the “Maritime Continent.” As discussed previously, Nauru and Darwin have more variability in cloud amount, associated with ENSO and the monsoon, respectively. The larger occurrence of high clouds at Darwin than at Nauru may be associated with the fact that high ice clouds are still advected over the Darwin site during the dry season, even if there is not much local cloud formation.

Each cloud layer is assigned a cloud type on the basis of the top, base, and physical thickness of each layer by using typical values identified in previous studies (Johnson et al. 1999; Luo and Rossow 2004). These cloud-type definitions, described in Table 3, identify the majority (97%) of the cloud layers as one of the seven cloud types listed. Since drizzle and rain are included as “cloud” in the radar/lidar classification, the deep convection and congestus categories may actually include cases of stratiform rain with cloud base at the freezing level but rain extending to the surface. We consider this cloud-type definition to be a first step in analyzing the cloud radiative forcing and do not expect these cloud types to correspond exactly to meteorological cloud types, although there are some similarities. Previous studies looking at TOA forcing have used similar categories, but they typically used optical thickness instead of physical thickness (e.g., Chen et al. 2000). An advantage of our simple definition of cloud type is that it can easily be duplicated in models to examine the effect of microphysical and radiative parameterizations on modeled CRE because it depends only on cloud macrophysical quantities.

The frequency distribution of the cloud type for the lowest cloud layer observed at each time is shown in Fig. 7. The lowest cloud layer is used to relate a single cloud type to the surface radiation measurements and to simplify the analysis. Overlying cloud layers may affect the downwelling surface fluxes since the SW CRE depends on the optical thickness of the entire column; in the majority of cases in which multiple layers with

### Table 3. Cloud-type definitions.

<table>
<thead>
<tr>
<th>Cloud type</th>
<th>Cloud base</th>
<th>Cloud top</th>
<th>Cloud thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low clouds</td>
<td>&lt;4 km</td>
<td>&lt;4 km</td>
<td>&lt;4 km</td>
</tr>
<tr>
<td>Congestus</td>
<td>&lt;4 km</td>
<td>4–8 km</td>
<td>≥1.5 km</td>
</tr>
<tr>
<td>Deep convection</td>
<td>&lt;4 km</td>
<td>&gt;8 km</td>
<td>≥1.5 km</td>
</tr>
<tr>
<td>Alto cumulus</td>
<td>4–8 km</td>
<td>4–8 km</td>
<td>&lt;1.5 km</td>
</tr>
<tr>
<td>Altostratus</td>
<td>4–8 km</td>
<td>4–8 km</td>
<td>≥1.5 km</td>
</tr>
<tr>
<td>Cirrostratus/anvil</td>
<td>4–8 km</td>
<td>&gt;8 km</td>
<td>≥1.5 km</td>
</tr>
<tr>
<td>Cirrus</td>
<td>&gt;8 km</td>
<td>&gt;8 km</td>
<td>No restriction</td>
</tr>
</tbody>
</table>
different cloud types exist, however, the overlying cloud layer is either altocumulus or cirrus (which are expected to have the smallest impact on surface fluxes). The cloud-type frequency distribution is similar at all three sites, although the magnitudes vary some among sites. Cirrus and low cloud are the most common cloud types at all sites, followed by altocumulus and deep convection, and altostratus is the least prevalent cloud type at all sites. The lower percentage of cirrus at Manus than at Darwin is due to the existence of more multilayer cloud situations at Manus than at Darwin, and therefore cirrus is less likely to be the lowest cloud type at Manus even though there is a higher frequency of high ice cloud at Manus than at Darwin (Fig. 6).

**c. Shortwave transmissivity by cloud type**

To examine the CRE as a function of cloud type, we use a subset of the radiometer dataset that is matched to the times for which good cloud-type information exists from the radar/lidar (points marked “analysis” in Fig. 2). The radiometer data, which have a 1-min temporal resolution, were first averaged to a 2-min grid to match the temporal resolution of the cloud dataset, and then time periods with good cloud data were retained for the statistics. For comparison with the more complete time series of radiation data discussed in section 3a, the average SW and LW surface fluxes from the radiometer dataset for this subset of data are given in Table 4. Differences in the fluxes relative to the full dataset are due to sampling of different times of the year associated with different incoming SW flux at the TOA (note that Fig. 3 shows that monthly average clear-sky SW flux at the surface can vary by more than 50 W m$^{-2}$ over the year) as well as different water vapor and cloudiness conditions. To reduce the impact of the choice of sampling periods and diurnal changes in the amount of incoming SW radiation on the calculated SW radiative effects, we primarily examine the impact of clouds on the SW transmissivity (measured downwelling SW flux at the surface divided by estimated clear-sky SW flux at the surface).

The distribution of SW transmissivity (Fig. 8) shows large differences as a function of cloud type. Deep convective clouds have the lowest mean transmissivity and narrowest distribution, and cirrus clouds have the highest transmissivity. Except for anvil clouds, all of the high-cloud classes have larger mean transmissivity than do the low-cloud classes. The low-cloud class has the least peaked distribution, indicating the largest variability in transmissivity. All classes show some values of transmissivity that are greater than 1, although it is most frequent in the low-cloud, altocumulus, and altostratus cases. These values of transmissivity of greater than 1 are due to 3D radiative transfer effects in cases in which the direct solar beam is not blocked (either because of broken cloudiness or optically thin clouds) and scattering from nearby clouds enhances the diffuse flux. These effects have been observed in other surface-measurement studies using short-time-scale measurements (Berg et al. 2011; Pfister et al. 2003). In general, these enhanced transmissivity events are of short duration and may disappear from statistics when averages over longer periods are taken. Climate models, which use 1D radiative

![Fig. 7. Cloud-type frequency for the lowest layer at each site.](image)

**Table 4.** As in Table 2, but for the subset of radiometer data for which good radar/lidar data exist. Both SW and LW values include both daytime and nighttime points.

<table>
<thead>
<tr>
<th></th>
<th>SW</th>
<th>CSW</th>
<th>SW CRE</th>
<th>LW</th>
<th>CLW</th>
<th>LW CRE</th>
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</thead>
<tbody>
<tr>
<td>Manus</td>
<td>197.9</td>
<td>298.8</td>
<td>−100.9</td>
<td>423.0</td>
<td>406.6</td>
<td>16.4</td>
</tr>
<tr>
<td>Nauru</td>
<td>221.6</td>
<td>3013</td>
<td>−79.7</td>
<td>425.7</td>
<td>411.0</td>
<td>14.7</td>
</tr>
<tr>
<td>Darwin</td>
<td>233.1</td>
<td>292.9</td>
<td>−59.8</td>
<td>408.8</td>
<td>390.5</td>
<td>13.3</td>
</tr>
</tbody>
</table>
transfer codes are not able to produce transmissivities of greater than 1, however.

As might be expected, much of the SW radiative impact of each cloud type can be explained by its optical-depth distribution. Figure 9 shows the frequency distribution of cloud optical depth derived from the broadband radiometers for overcast cases (as discussed in section 2a) classified by the lowest cloud type at each site, where C1 = Manus, C2 = Nauru, and C3 = Darwin.
site. Note the different axes for the two panels. The clouds with low bases (low clouds, congestus, and deep convection) tend to have larger optical depths and lower transmissivity than do clouds with midlevel or high cloud bases, with the exception of anvil clouds. In general, the optical-depth distributions vary less across site than across cloud type, indicating that the simple breakdown by cloud base, top, and thickness does a reasonable job in separating optically different cloud types. A possible exception is anvil clouds, for which the Darwin site shows a much broader distribution of optical depth than do the other two sites. This may be due to the large seasonal variability in Darwin, with optically thick anvil produced during local convection associated with the active monsoon or with the frequent convection over the Tiwi Islands north of Darwin (Crook 2001) and more optically thin cirrus sampled during the dry season. The optical depth of the cirrus clouds is the most uncertain as only ~20% of cirrus cases are overcast so that optical depth can be retrieved from the radiometers. Cirrus clouds also have the least impact on the surface radiative fluxes, however, because of their high altitude and low optical depths.

Cloud fraction (or sky cover) is also an important determination of cloud SW radiative effects. Figure 10 shows the joint frequency distribution of SW transmissivity and sky cover from the broadband radiometers as a function of cloud type derived from the radar/lidar data. Because of the limited number of cases of some cloud types, we combine results from all sites to increase the statistics. Analysis of individual sites (not shown) indicates that cloud types with large number of cases (such as low, altocumulus, and cirrus) have similar curves of mean transmissivity versus sky cover at all sites. All cloud types show a similar trend of high transmissivity at low sky cover and low transmissivity at high sky cover. A single relationship cannot be used for all cloud types because the magnitude of the mean transmissivity at 100% sky cover, the slope of the curve, and the variability in the midrange of sky cover differ by cloud type. Cirrus clouds have the narrowest frequency distribution, with little variability even at sky cover between 0.4 and 0.8.

d. Longwave radiative effect by cloud type

We also examine the distribution of longwave CRE, which is defined as the measured LW downwelling flux at the surface minus the estimated clear-sky LW flux at the surface. Again, there is a clear distinction between the effects of low and high clouds (Fig. 11), with low clouds having larger LW CRE because of their warmer cloud bases. Optical depth also plays a role, as convective clouds (which have the largest optical depth) have the largest LW CRE of any low cloud type and cirrus clouds have much smaller LW CRE than the optically thicker anvil clouds. The average LW CRE generally decreases with increasing cloud-base altitude (Fig. 12), although there is large variability in the LW CRE associated with each cloud-base height because of the additional impact of cloud optical depth. Variability, especially for the lower cloud-base heights, may also be due to multilayer or broken cloud conditions. The anvil clouds have slightly larger mean LW CRE than the altocumulus clouds despite their higher altitudes because of their larger optical depths (Fig. 9). Low clouds have the broadest distribution of LW CRE, even though they
FIG. 10. Joint frequency distribution of shortwave transmissivity and sky cover for each cloud type over all sites. Frequency is normalized to 1.0 in each sky-cover bin. Bins with frequency of less than 0.001 are not plotted. Mean and median transmissivity for each sky-cover bin are also plotted for cloud-fraction bins that contain at least 0.5% of the total data points for that cloud type.
are typically optically thick (overall mean optical depth of 31), because they are more likely to exist under multilayer or broken cloud conditions than are congestus or deep convection.

The LW cloud effects show more variability by site than the SW cloud effects, with Darwin having the largest LW CRE for all cloud types and Nauru the smallest (except for altostratus). This is likely driven by differences in

![Fig. 11. Longwave CRE as a function of lowest cloud type. Bin widths are 5 W m\(^{-2}\), and the x-axis labels represent the first value of the bin. The legend gives the mean longwave CRE values from MPL at each site, with C1 = Manus, C2 = Nauru, and C3 = Darwin.](image)
both cloud properties and atmospheric conditions at the sites, as the LW surface fluxes are sensitive to both cloud properties and temperature/relative humidity in the lower troposphere (section 3a). For most of the cloud types with low and middle bases (deep convective, congestus, low clouds, and altostratus), the average observed LW CRE at Darwin was larger during the dry season than during the wet season (not shown) because of the broader distribution for LW CRE of those cloud types at Darwin than at the other sites.

e. Overall radiative impact by cloud type

To understand the impact of each cloud type on the overall downwelling surface fluxes, we need to consider the frequency of each cloud type as well as diurnal variability (for the SW fluxes). For instance, although deep convective clouds have the largest mean impact on SW surface fluxes, they are much less frequent than low clouds or cirrus and so may not have large impacts on the overall surface SW radiation budget. To examine the contribution of each cloud type to the total CRE, we multiply the frequency of the cloud type by its mean SW and LW CRE; the results are presented in Fig. 13. For the SW CRE, we only include daytime points and so the mean values given in the legend are larger than the overall SW CRE values given in Table 4.

It is not surprising that low clouds have the largest impact on the SW radiative fluxes at the surface, contributing 35%–47% of the total surface SW CRE at each site, because of the combination of relatively low mean transmissivity and large frequency of occurrence. They are also the biggest factor in the LW CRE because of

![Figure 12](image.png)  
**Fig. 12.** Longwave CRE as a function of lowest cloud-base height. The plot includes data from all three sites. The lowest cloud-base height is binned into 200-m-thick bins. The solid line is the mean LW CRE in each bin, and error bars indicate the standard deviation of LW CRE in each bin.

![Figure 13](image.png)  
**Fig. 13.** Contribution of each cloud type to surface (top) LW CRE and (bottom) SW CRE. Note the different scales of the two figures. Also note that SW CRE values only include daytime points.
their low cloud bases, contributing nearly the same amount (35%–44%) of the total LW CRE at each site as they do the SW CRE. Note that the LW CRE is significantly smaller overall than the SW CRE so that, although the low clouds contribute a similar percentage of each CRE, the impact on the SW fluxes dominates the net surface CRE. Cirrus, which have nearly equal frequency of occurrence to low clouds, have a much smaller impact on the surface radiation because of their high altitudes and low optical depths. They contribute 10%–13% of the SW CRE and 10%–16% of the LW CRE at the surface. The contribution of deep convection is largest at Manus (15% of SW and 21% of LW) and weakest at Darwin. The altostratus clouds have the smallest impact because of their low frequency. Combined, the two midlevel cloud classes (altocumulus and altostratus) contribute 8%–9% of the SW CRE and 12%–14% of the LW CRE at each site. At Darwin, the contribution by cloud type is very different in the dry season (not shown) because of the relative lack of deep convection. During the dry season at Darwin, 72% of the SW CRE and 62% of the LW CRE at the surface are contributed by low clouds and less than 2% is due to deep convection and anvil.

4. Discussion

Overall, we find that clouds with low bases (low, congestus, and deep convection) contribute 71%–75% of the surface SW CRE and 66%–74% of the surface LW CRE at the three TWP sites. Previous studies that have examined CRE by cloud type from satellite data (e.g., Hartmann et al. 1992; Chen et al. 2000; Webb et al. 2001; Futyan et al. 2005; Oreopoulos and Rossow 2011) have mostly focused on top-of-atmosphere, rather than surface, radiative effects, and therefore there are few surface CRE estimates for comparison with our values.

A few estimates of surface CRE are available from satellite-based studies, however. Chen et al. (2000) estimated that clouds with low bases (their cumulus, stratus, and deep convective clouds) contributed 52% of the global surface SW CRE and 59% of the global surface LW CRE. They unfortunately do not break down their estimates by region, and therefore it is difficult to determine whether the difference in the effect of low clouds on the surface CRE between the Chen et al. (2000) study and the current work is due solely to regional differences in cloud amount or properties or is due to differences in defining clouds from satellite and ground-based platforms. They do state that one-half of the surface net CRE in their study is contributed by high-level clouds; their definition of high clouds is based on cloud top and not cloud base, however, and so deep convection is included in their high cloud category. It is likely that the satellite results underestimate the amount of low clouds, especially in the tropics where optically thick anvil may block the satellite’s view of the low clouds. The ground-based measurements likely underestimate the amount of high clouds (for corresponding reasons), but this effect should have less impact on the surface radiative budget estimates.

We note that we have simplified our analysis by classifying the CRE by the lowest observed cloud layer, which could overestimate the radiative effects of clouds with low and middle bases during conditions in which multiple cloud layers exist. To estimate this effect, we compare the mean CRE for the dataset classified by the lowest cloud layer with the mean CRE for periods during which only a single cloud type exists in the column. Mean differences are less than 4% in LW CRE for all cloud types and less than 5% in SW CRE for most cloud types. Altostratus and altocumulus show the largest differences, with SW CRE being approximately 13% higher for all cases when compared with cases with only a single cloud type. For altostratus, however, differences in the clear-sky downwelling flux between the two sets of cases (likely due to sampling of different times or seasons) account for one-half of the difference.

Jakob et al. (2005) examine 2 yr of cloud and radiation data from the Manus ARM site as a function of four large-scale “cloud regimes” or “weather states” (WS) determined from the International Satellite Cloud Climatology Project (ISCCP) geostationary satellite data. The observed radiative properties are 1-h averages around the time of the satellite observation. The mean SW transmissivity in their study ranges from approximately 0.3 for their deep cloud state to 0.95 for their most suppressed state, whereas the values in the current study range from 0.17 for deep convective clouds to 0.80 for cirrus clouds. The larger transmissivity values in the Jakob et al. (2005) study are likely due to the inclusion of clear-sky points within the hour-average time period, whereas in the current study the transmissivities are 2-min averages of cloudy-sky points only. Oreopoulos and Rossow (2011) extend the ISCCP results to eight weather states and examine the CRE using the ISCCP-derived surface and TOA fluxes. They focus primarily on TOA CRE but do present some results for surface LW CRE in the extended tropics (35°S–35°N). Their WS3 (primarily unorganized convection) is the largest contributor to the surface LW CRE (approximately 25% of the total), and a variety of other states containing low clouds (their WS5, WS7, and WS8) contribute approximately 13%–17% each. The states dominated by high clouds (WS1 and WS2) each contribute about 8%–10% of the LW CRE.
5. Summary and conclusions

The Nauru and Darwin ARM sites show considerable variability in sky cover, downwelling radiative fluxes, and surface cloud radiative effect due to El Niño and the Australian monsoon, respectively, and the Manus site shows little intraseasonal or interannual variability. The variability is strongest at Darwin, where the monthly average sky cover is only 10%–20% with a 44% occurrence of clear skies during the peak of the dry-season months, but the average sky cover and frequency distribution during the wet season is similar to that at Manus at all times and to that at Nauru during El Niño periods. This variability in sky cover results in Darwin receiving almost 90% of the possible clear-sky downwelling SW flux during the dry-season months, as compared with only 70% of clear-sky amount during the wet-season months. Nauru monthly average sky cover varies generally from 35%–55% during La Niña periods to 50%–80% during El Niño. The most striking difference for Nauru is the distribution of frequency of occurrence of sky cover, with El Niño periods exhibiting a distribution similar to that of Manus and including almost 40% occurrence of overcast. The La Niña distribution shows a broad peak for the 10%–40% sky-cover range, with two-thirds of the observations having sky-cover values of 50% or less. This results in Nauru receiving about 88% of possible clear-sky downwelling SW flux during La Niña periods, as compared with receiving 78% of clear-sky flux during El Niño. Manus exhibits comparatively smaller differences in monthly average sky cover and frequency distribution and receives 66% and 68% of possible clear-sky downwelling SW flux for El Niño and La Niña periods, respectively.

The monthly average downwelling LW CRE is comparatively small for all three TWP sites. With the exception of Darwin in the dry season, clear-sky downwelling LW flux averages over 400 W m$^{-2}$ for all sites. Clouds then increase the average downwelling LW flux by only about 10–15 W m$^{-2}$ for these periods. For the Darwin dry season, the overall average clear-sky downwelling LW flux of 377 W m$^{-2}$ is increased by only about 9 W m$^{-2}$ by cloudiness because of the frequent occurrence of clear skies and high clouds.

In general, the SW radiative effects vary more by cloud type than by site, indicating that this simple breakdown of cloud type by altitude and thickness can capture key variability in CRE on surface downwelling fluxes in the tropics. An advantage of this analysis is that this simple classification can also be done in models and may identify some issues in model microphysical or radiative parameterizations. Studies have indicated that models often have biases in the frequency or optical properties of one cloud type that cancel out opposing biases in another cloud type to give a reasonable mean radiative budget (Webb et al. 2001). Many of these studies have focused primarily on TOA CRE, but climate models need to be able to simulate both TOA and surface radiative budgets correctly. Qian et al. (2012) examined the surface radiative budget in more than a dozen climate models that participated in the Coupled Model Intercomparison Project (CMIP3). They identified significant differences in cloud fraction and surface SW transmissivity between the observations and the models but did not separate the analysis by cloud type. In future work, we plan to extend that study by analyzing differences in models and observations as a function of cloud type, using the results from the current study.

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