Comparison of the CALIPSO satellite and ground-based observations of cirrus clouds at the ARM TWP sites

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Statistics of ice cloud macrophysical and optical properties from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument on board the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite are compared with those from ground-based lidar observations over a 31 month period. Ground-based lidar observations are taken from the micropulse lidars (MPL) at the three Department of Energy Atmospheric Radiation Measurement (ARM) tropical western pacific (TWP) sites: Manus, Nauru and Darwin. CALIPSO observations show a larger cloud fraction at high altitudes while the ground-based MPLs show a larger cloud fraction at low altitudes. The difference in mean ice cloud top and base heights at the Manus and Nauru sites are all within 0.51 km, although differences are statistically significant. Mean ice cloud geometrical thickness agree to within 0.05 km at the Manus and Nauru sites. Larger differences exist at Darwin due to excessive degradation of the MPL output power during our sampling period. Both sets of observations show thicker clouds during the nighttime which may be real but could also be partially an artifact of the decreased signal-to-noise ratio during the daytime. The number of ice cloud layers per profile are also shown to be consistent after accounting for the difference in spatial resolution. For cloud optical depths, four different retrieval methods are compared, two for each set of observations. All products show that the majority of ice cloud optical depths (~60%) fall below an optical depth of 0.2. For most comparisons all four retrievals agree to within the uncertainty intervals. We find that both CALIPSO retrievals agree best to ground-based optical depths when the lidar ratio in the latter is retrieved instead of set to a fixed value. Also thoroughly compared is the cloud properties for the subset of ice clouds which reside in the tropical tropopause layer (TTL).


1. Introduction

[2] Cirrus clouds alter the radiation budget of the Earth’s climate system through competing greenhouse and albedo effects [e.g., Liou, 1986]. In the tropical atmosphere thin and sub-visible cirrus clouds occur frequently [e.g., Winker and Trepte, 1998; Wang et al., 1998; Fu et al., 2007; Dessler and Yang, 2003; Massie et al., 2010] and play a crucial role in regulating the radiative heating rates in the tropical tropopause layer (TTL) [e.g., Yang et al., 2010]. The TTL is a transitional layer which connects the convective overturning circulation of the Hadley cell in the troposphere to the slow wave-driven up-welling of the lower stratospheric Brewer-Dobson circulation [e.g., Fueglistaler et al., 2009]. Most of the air that enters the stratosphere passes through the TTL providing an important control on stratospheric composition. Recent studies suggest that the radiative energy budget in the TTL places crucial constraints on different atmospheric processes [Hartmann et al., 2001; Gettelman et al., 2004; Corti et al., 2005; Fu et al., 2007].

[3] Resolving the radiative budget in the TTL is dependent on an accurate representation of tropical cirrus clouds. The tenuous nature of tropical thin cirrus provides a challenge to accurately detect with remote sensing instruments. Several datasets of cirrus clouds exist to aid in quantifying their radiative effects. Imaging radiometers such as MODerate resolution Imaging Spectroradiometer (MODIS) [Barnes et al., 1998; Platnick et al., 2003; Ackerman et al., 2008] and the International Satellite Cloud Climatology Project (ISSCP) [Rosow and Schiffer, 1999] provide macrophysical and optical properties of cirrus clouds on a global scale. However, such instruments are limited to a minimum detectable optical depth greater than the optical depths of a portion of cirrus clouds. For example, MODIS’s cloud mask is limited to optical depth greater than about 0.3–0.4 [Ackerman et al., 2008; Marchand et al.,]
2010]. Furthermore, imaging radiometers do not provide detailed information on the vertical cloud structure. Active instruments, such as radar and lidar, provide the vertical cloud structure necessary to calculate radiative heating rate profiles. However, backscatter from small ice crystals is frequently below the detectable threshold of radars. Comparisons of cirrus cloud observations from the millimeter cloud radar (MMCR) and the micropulse lidar (MPL) at the ARM tropical western Pacific (TWP) site Nauru showed that cirrus clouds above 15 km are sufficiently optically thin such that they are detected by the MPL but not the MMCR [Comstock et al., 2002]. The lidar observations from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument on board the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite show that thin and sub-visible cirrus occur frequently in the tropics [e.g., Fu et al., 2007].

4] Lidar observations are required to obtain reliable observations of thin cirrus properties. For the region of interest in this study, i.e. the tropical western Pacific (TWP), we have two sets of lidar observations available: (1) the CALIOP instrument on board the CALIPSO satellite [Winker et al., 2010] and (2) MPLs at the three ARM TWP sites: Manus, Nauru and Darwin [Ackerman and Stokes, 2003]. The ground-based observations provide continuous measurements while CALIPSO, in its sun-synchronous orbit, observes a point only twice during the day (around 1:30 and 13:30 local time). CALIPSO is capable of near-global observations of cirrus clouds whereas the ARM TWP observations provide a point measurement at three sites. While the presence of optically thick low clouds can obscure overlying cirrus clouds from the view of the ground-based lidar, the CALIPSO satellite, with its space-borne viewpoint, virtually eliminates the possibility that the lidar will become fully attenuated before observing a potential cirrus cloud layer. The ARM TWP sites have been collecting MPL observations starting in early 1999 for Manus and Nauru and 2002 at Darwin. CALIPSO was launched in June 2006 into an orbit which passes the same track about every 16 days.

5] The intent of this study is to compare cirrus clouds from these two sets of lidar observations and examine and understand any discrepancies between them. Dupont et al. [2010] performed a similar comparison among CALIPSO observations and four different ground-based lidars located in the midlatitudes. In this study we examine tropical cirrus clouds which play an important role in determining the energy budget in the TTL. A thorough analysis and understanding of the limitations in observing tropical cirrus is needed before an accurate estimation of the radiative energy budget can be made. In addition, the complimentary strengths of each instrument—the temporal coverage of the MPL and the spatial coverage of CALIPSO—could prove useful for the further study of cirrus clouds. Before this is done these datasets need to be evaluated against each other.

6] We focus on comparing statistics of macrophysical and optical properties of cirrus clouds in the vicinity of the three TWP sites. Statistics for the subset of cirrus clouds which reside in the TTL are also examined. Section 2 describes both the CALIPSO and ARM TWP lidar datasets used in this study. The methods used to compare the two sets of observations are given in section 3 and data sampling issues are discussed in section 4. The resulting comparisons of macrophysical and optical properties as well as potential sources of biases are given in section 5. Summary and conclusions are given in section 6.

2. Datasets

2.1. CALIPSO

7] The CALIPSO satellite was launched in April 2006 into a sun-synchronous orbit as part of the A-Train satellite constellation [Winker et al., 2010]. The main instrument on board CALIPSO is CALIOP, a 2-wavelength (532 nm and 1064 nm) polarization sensitive lidar which is capable of detecting clouds with an optical depth of 0.01 or less (with sufficient averaging) and optical depths as large as 5. In this study, we use the CALIPSO L2 v3.01 5 km cloud layer product. The vertical resolution of the CALIPSO data is 30 m from the surface to 8.2 km and 60 m from 8.2 to 20.2 km. Cloud layers are identified by examining the enhancement of the return signal relative to the molecular background using a threshold algorithm [Winker et al., 2009]. The cloud product also reports an opacity flag which determines the point at which the lidar beam has become completely attenuated and no lower return signal (possibly from the surface or a cloud/aerosol layer below) can be identified. Extinction retrievals of cloud and aerosol layers are described by Young and Vaughan [2009]. Further details of the extinction retrieval used in the CALIPSO cloud product are discussed during comparisons of optical depth statistics (section 5.4).

8] The CALIPSO cloud product reports quality flags to indicate the confidence in both the layer classification and extinction retrieval. In this study we do not consider layers with cloud-aerosol discrimination (CAD) scores [Liu et al., 2010] greater than 100, which represent highly uncertain cloud features. The extinction QC flag is used to remove layers with the possibility for large errors (i.e. any of bits 4–9 being set in the extinction QC flag).

9] The CALIPSO L2 v3.01 data products were released in May 2010 and includes several improvements over the previous version of data products, v2.01. Updates relevant to this study include the removal of a software bug which caused a significant overestimate of low cloud fraction [Vaughan et al., 2010]. Also updated is the algorithm used to discriminate between cloud and aerosol [Liu et al., 2010] and improved daytime calibration [Powell et al., 2010] which results in more accurate estimates of layer properties.

10] Cloud and aerosol layers are identified in CALIPSO backscatter using a algorithm called the selective iterative boundary locator (SIBYL) [Vaughan et al., 2009] which detects layers using multiple horizontal resolutions. Multiple passes are made through the data and the amount of horizontal averaging increases with each pass. After cloud layers are identified at a particular horizontal resolution they are removed before moving on to further averaging. In the 5 km L2 v3.01 cloud product three horizontal averages are considered: 5, 20 and 80 km. In this study we consider CALIPSO cloud properties retrieved at all three horizontal averages. All cloud layers, regardless of the amount of averaging performed, are interpolated to a 5 km grid. This multiscale averaging approach can lead to a single cloud layer being reported as multiple layers which overlap in the
vertical. In order to properly compare CALIPSO cloud properties to the ground-based dataset (which does not use a multiscale averaging algorithm) overlapping layers are merged together. Further details on the merging of CALIPSO’s multiresolution layers are given in Appendix A.

[11] Observations from the CALIPSO L2 v3.01 1 km cloud product are also considered in this study. In this data product all data is averaged to 1 km, multiple horizontal resolutions are not used. Cloud optical depths are not retrieved in the 1 km cloud product.

2.2. ARM TWP

[12] The ARM TWP sites consist of three facilities at Manus, Nauru and Darwin the locations of which are shown in Figure 1. Cloud boundaries are determined using the threshold algorithm of Wang and Sassen [2001] and extinction is calculated following Comstock and Sassen [2001]. Details of the ground-based extinction retrievals used in this study are discussed when comparing optical depth statistics (section 5.4).

[13] The MPL operates at a wavelength of 532 nm with a vertical resolution of 30 m. Profiles are averaged from their 30-second native temporal resolution to 1 minute during the night and 5 minutes during the day in order to obtain a signal-to-noise ratio (SNR) sufficient for an accurate extinction and cloud boundary retrieval. Since profiles undergo a larger amount of averaging during the day we are left with a disproportionate amount of night profiles in our set of observations. Therefore, cloud properties retrieved during the daytime are scaled by a factor of five when we consider the dataset as a whole.

[14] Attenuation of the MPL signal is identified following the procedure of Lo et al. [2006]. A profile of the molecular backscatter coefficients at 532 nm are calculated using pressure and temperature observations from collocated radiosonde profiles. Several checks are then implemented to determine signal attenuation. First, the backscatter signal throughout the cloud layer must be greater than the minimum of positive backscatter in the whole profile. Second, the decrease in measured backscatter above the cloud must be proportional to the decrease in the molecular backscatter to within 4%. If at least 4 points (120 m) above the cloud layer conform to this requirement then it is assumed that the MPL signal was not attenuated by the cloud layer. The performance of this method was validated using an alternative method with radar (MMCR) observations at the Darwin site. Attenuation was determined by comparing the MPL cloud top height to the radar cloud top height [Clothiaux et al., 2000]. If the MPL cloud top height is lower than the radar cloud top height by more than 1 km then the MPL signal is assumed to be attenuated. Attenuation determined in this manner at Darwin agreed with the method used in this study 78% of the time.

[15] Cloud optical depths from the ground-based observations are subjected to thresholds to remove uncertain retrievals. Visual inspection of the retrieved cloud boundaries reveal that the MPL is capable of retrieving clouds with \( \tau \sim 3 \) and clouds as thin as \( \tau \sim 5 \times 10^{-3} \). Clouds with optical depths outside this range are considered uncertain and are removed. Imposing this restriction removes less than 2% of all clouds at any of the three TWP sites.

3. Comparison Methodology

[16] We consider 31 months, June 2006–December 2008, of CALIPSO L2 5 km v3.01 and ground-based observations from the ARM TWP sites: Manus, Nauru and Darwin. For CALIPSO data we define a region around each ARM site to compile statistics from—a 1.25° × 5° latitude-by-longitude box centered on each site (Figure 1). Larger spatial domains and different areas were also considered. We found that the spatial domain chosen strikes a balance between an area large enough to collect an adequate number of observations and small enough to be representative of the ground-based site.

[17] Comparisons made between the two sets of lidar observations are done so using two types of datasets: restricted and unrestricted. From a ground-based perspective clouds at higher altitudes are frequently masked by the presence of low water clouds which fully attenuate the lidar signal. While from a space-borne perspective low clouds which attenuate the lidar signal have no effect on the ability to observe high clouds. However, including such cases would introduce a high-cloud bias into the CALIPSO statistics relative to the ground-based observations; i.e., the same profile viewed from a ground-based perspective would not observe high clouds. In the restricted datasets we only include profiles fully transparent to the lidar signal in order to have a fair comparison.

[18] Both instruments have ranges of optical depths for which cloud boundary and extinction retrievals are considered reliable. The MPL can accurately detect clouds with optical depth from approximately \( 5 \times 10^{-3} \) to 3 and CALIOP from 0.01 to 5 [Winker et al., 2009]. Therefore, in the restricted datasets, only clouds whose optical depth fall with the common sensitivity of both instruments are considered—\( 0.01 \leq \tau \leq 3 \).

[19] The unrestricted datasets use all lidar profiles available in each dataset, only profiles where data quality is questionable are excluded.

[20] This study centers on the statistical comparisons of ice and TTL cloud properties. Clouds are defined by the altitude of their cloud base. Both the CALIPSO and ground-based datasets derive cloud altitudes relative to mean sea level. A cloud with a base greater than 7 km is considered as
an ice cloud. Radiosonde observations at the three TWP sites show that an altitude of 7 km corresponds to a mean temperature of $-11.2^\circ$C during the sampling period. The subset of ice clouds which reside in the TTL are defined as clouds with bases greater than 14 km. The mean temperature at 14 km is $-65.7^\circ$C. The standard deviation of the radiosonde temperatures at these two altitudes are less than 2.5°C. Variations in the mean temperature at both 7 km and 14 km among the three TWP sites are less than 0.5°C.

Adopting a simple definition of ice clouds based on the altitude of the cloud base could be problematic. Studies have shown that supercooled and mixed-phase clouds can occur above 7 km in the tropics [e.g., Zhang et al., 2010]. However, these clouds are typically optically thick and therefore would not be included in our restricted datasets. We confirmed this assumption by using the phase information provided in the CALIPSO L2 cloud retrieval. Less then 1.5% of CALIPSO cloud observations in the restricted ice cloud datasets contain water according to the CALIPSO L2 cloud product’s assessment of cloud phase.

While we apply the more general classification of ice clouds to our datasets it is assumed that the majority of these ice clouds are cirrus clouds. Other types of ice clouds, such as those associated with altostratus, nimbostratus, or cumulonimbus, are assumed to be excluded from our datasets by the requirement that the optical depth be less than 3. Therefore it is reasonable to assume that nearly all clouds classified as ice clouds in this study are cirrus clouds. According to this classification 100% of clouds in our restricted ice cloud datasets are cirrus clouds.

4. Sampling Issues

4.1. Availability of Data

Cloud property statistics are taken from observations over an extended period of time. Differences in sampling during this time period can cause observations to favor the cloud characteristics of a particular season. The MPLs at all three TWP sites suffer from occasional data quality issues during our analysis period. Those times are identified and removed. Our analysis period (June 2006–December 2008) does not evenly sample all months; therefore, both the ground-based and CALIPSO observations are more representative of cloud properties from June through December.

Figure 2 shows the sampling per month of all the ground-based and CALIPSO lidar profiles in the unrestricted datasets (top row of panels, labeled “All”). The sampling is given as a percentage of the total number of observations for each dataset, that is Figure 2 gives the fraction of the total number of available profiles which fall within a given month. The top row of panels in Figure 2 shows this fraction relative to the total number of cloudy profiles in the unrestricted datasets (solid line). Both the distribution of all and cloudy profiles agree best at Nauru with an average difference of 1.7%, followed by Manus (2.5%) and Darwin (5%). No ground-based data is available at Darwin for March or April due to

Figure 2. Monthly distribution of profiles available at each ARM TWP site for CALIPSO (black line) and ground-based (red line) observations relative to the total number of profiles (dashed line) and the total number of cloudy profiles (solid line). (top) The distribution of profiles in the unrestricted datasets. The distribution of profiles in the (middle) ice and (bottom) TTL restricted datasets. Percentages in each month are calculated relative to the total number of observations in the entire sampling period.
to poor data quality during both 2007 and 2008. In addition the sample size at Darwin is poor during the months of February and May.

In Figure 2 the panels labeled “Ice” and “TTL” show the distribution of cloudy profiles in the restricted datasets which contain ice and TTL clouds, respectively. Sampling differences are similar to those in the unrestricted datasets. Again Nauru exhibits the best agreement with an average difference of 1.9%, followed by Manus (3.4%) and Darwin (6.9%). Overall these results suggest that the error introduced into cloud property comparisons due to the difference in seasonal sampling could be significant at Darwin and is minimal at both Nauru and Manus.

4.2. Attenuated Profiles

A particular focus in this study is comparisons made using only transparent profiles, i.e. the restricted datasets. Therefore the amount of profiles which are attenuated plays a critical role in determining the overall sampling. Figure 3 shows the percentage of profiles which are attenuated for each month relative to the total number of cloudy profiles. CALIPSO observations are shown in black and ground-based in red. The ground-based observations contain a larger percentage of attenuated profiles (solid red line) relative to CALIPSO (solid black line) over nearly all months and locations. Also shown is the percent of attenuated profiles separated into day (dotted lines) and night (dashed lines) observations. Comparisons of the daytime observations show that the ground-based MPL frequently has difficulty penetrating through the entire atmosphere. Approximately 70% of daytime cloud profiles in the ground-based observations are attenuated. During the night, ground-based and CALIPSO observations show similar fractions of attenuated profiles. The difference between the fraction of attenuated profiles during the daytime and nighttime from CALIPSO is much less than that observed in the ground-based profiles. The impact of the diurnal bias in the ground-based observations is discussed further in section 5.5.

4.3. MPL Data Quality at Darwin

During much of our sampling period the MPL performance at Darwin is sub-optimal. After an upgrade to a polarized version of the MPL at Darwin in August 2006 the output power dropped 40% by December 2006. In May 2007 the MPL at Darwin was replaced to resolve an unrelated issue which restored the output power to normal levels. But the previous decline in output power continued unabated until November 2008 when the installation of a new pump diode restored the output power to normal levels. The reduction in power over a large portion of our observing period reduced the sensitivity significantly. While we still present comparisons at Darwin for completeness, the results at Manus and Nauru are more useful for quantifying differences in cloud properties between CALIPSO and the MPL.

Data quality issues at Darwin preclude ground-based observations during March and April from our analysis. In addition, sample size is greatly reduced during the months of February and May due to data quality. It follows that these underrepresented months could cause larger discrepancies at Darwin and perhaps overwhelm the MPL’s poor output power effect. To test this we assessed the impact of the missing data by removing the same period from the CALIPSO data and by examining monthly statistics (not shown). Doing so showed that the Darwin MPL still showed indications of poorer performance than either the Manus and Nauru MPLs. Therefore we can conclude that underrepresented months in the Darwin dataset are not responsible for the MPL’s poor performance during our sampling period.

4.4. Sampling Uncertainty of CALIPSO Observations

In this study we focus on statistical comparisons between two sets of observations, which requires that we assess the statistical significance of any differences found. Ground-based cloud profiles are retrieved from MPL data every 1 minute (night) or 5 minutes (day) continuously, barring any instrument issues. This creates a large sample size which minimizes the sampling uncertainty in statistics derived from ground-based profiles. CALIPSO observations occurring inside the sampling area (the 1.25° × 5° latitude-by-longitude box centered on each ARM site) provide far fewer observations relative to the ground-based data. In addition to a smaller sample size, CALIPSO profiles along a single transect in the sampling area are strongly correlated with each other. This further reduces an already small sample size into an even smaller number of independent samples since only observations in different overpasses are completely independent of each other. Therefore CALIPSO observations do not comply with the independent sampling assumption and standard statistical tests (e.g. the t-test) cannot be used to determine statistical significance. Note that adjacent ground-based profiles also are strongly correlated with each other, reducing the number of independent
samples. However, the continuous ground-based observations create such a large sample size it can be assumed that the ground-based sampling uncertainty is insignificant.

The bootstrap technique [Efron, 1982] can be used to estimate sampling uncertainty when the independent sampling assumption is not valid. In this method the original data is treated as the parent population. A large number of resamplings are performed using the original data which generates multiple artificial (bootstrap) samples. Each bootstrap sample is constructed to be the same size as the original data. The resampling is performed with replacement so, in general, bootstrap samples contain repeated values of the original dataset and entirely exclude others. The statistic of interest is then calculated for each of the large number of bootstrap samples. The distribution of this statistic calculated from the bootstrap samples can then be used to construct a confidence interval.

For variables such as cloud fields there is considerable autocorrelation which would be destroyed by the bootstrap resampling process. To preserve the correlation inherent to cloud fields the sampling uncertainty of CALIPSO is estimated using the moving-block bootstrap method [Wilks, 1997]. This extension of the bootstrap technique resamples sets of consecutive data (blocks) instead of single points.

Sampling uncertainty is derived for probability density functions (PDFs), means of cloud top height, base height, geometrical thickness, optical depth and the number of cloud layers per profile. An entire CALIPSO profile is considered as a single sample and a block is a consecutive number of profiles along a given transect. Blocks of profiles are resampled many times and the PDF or mean of the cloud property is calculated for each bootstrapped set of profiles. From this distribution of bootstrapped samples a confidence interval is constructed for the mean or, in the case of a PDF, each bin.

### Table 1. Cloud Fraction

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Manus</th>
<th>Nauru</th>
<th>Darwin</th>
</tr>
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<tbody>
<tr>
<td><strong>CALIPSO</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 km</td>
<td>0.871</td>
<td>0.802</td>
<td>0.653</td>
</tr>
<tr>
<td>1 km</td>
<td>0.750</td>
<td>0.574</td>
<td>0.499</td>
</tr>
<tr>
<td>5 km, transparent</td>
<td>0.800</td>
<td>0.763</td>
<td>0.560</td>
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<tr>
<td><strong>ARM</strong></td>
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</tr>
<tr>
<td>1 or 5 min.</td>
<td>0.692</td>
<td>0.534</td>
<td>0.400</td>
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<tr>
<td>5 km “pixel”</td>
<td>0.851</td>
<td>0.740</td>
<td>0.652</td>
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<td>1 or 5 min., transparent</td>
<td>0.551</td>
<td>0.429</td>
<td>0.256</td>
</tr>
<tr>
<td>5 km “pixel”, transparent</td>
<td>0.709</td>
<td>0.613</td>
<td>0.458</td>
</tr>
</tbody>
</table>

### 5. Comparisons of CALIPSO and Ground-Based Lidar Cloud Observations

#### 5.1. Cloud Fraction

We derive cloud fraction from the ground-based and CALIPSO observations using the unrestricted datasets. Clouds from all altitudes are considered in this comparison with the exception of clouds with tops below 1 km. These clouds cannot be detected in the ground-based retrieval since the cloud mask is not implemented below 1 km to avoid difficulties in applying the overlap function. To remain consistent, clouds with tops below 1 km are removed from the CALIPSO dataset. The effect of removing these low clouds from the CALIPSO observations has a minimal effect on the cloud fraction—a reduction of less than 2% for all comparisons presented here.

Comparisons of cloud fraction are given in Table 1. The cloud fractions derived from the unrestricted observations are shown in the row labeled “5 km” for CALIPSO and “1 or 5 min.” for the ground-based observations. CALIPSO observations show a considerably higher cloud fraction (~20%) relative to the ground-based observations. Cloud fraction comparisons are shown separately for the night and day observations in Tables 2 and 3, respectively. For nighttime only observations agreement improves between the CALIPSO (row labeled “5 km” in Table 2) and ground-based (row labeled “1 or 5 min.” in Table 2) observations. Very large differences are present during the daytime with the ground-based cloud fraction significantly smaller than CALIPSO. This is presumably due to the reduction in the MPL sensitivity during the daytime (section 4.2).

Although we compare two 532 nm backscatter lidars, significant differences exist between the two observations and retrieval algorithms which makes a meaningful comparison difficult. For example, CALIPSO’s space-borne viewpoint provides an advantage for observing high clouds. From a ground-based perspective, the atmosphere below, especially the lower cloud layers, reduces the SNR or even totally blocks the lidar from detecting higher clouds, causing

### Table 2. Cloud Fraction, Nighttime Observations Only

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Manus</th>
<th>Nauru</th>
<th>Darwin</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CALIPSO</strong></td>
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</tr>
<tr>
<td>5 km</td>
<td>0.882</td>
<td>0.807</td>
<td>0.677</td>
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<tr>
<td>1 km</td>
<td>0.765</td>
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<td>1 or 5 min.</td>
<td>0.775</td>
<td>0.661</td>
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<td>0.894</td>
<td>0.833</td>
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<td>0.724</td>
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<td>5 km “pixel”, transparent</td>
<td>0.875</td>
<td>0.818</td>
<td>0.619</td>
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### Table 3. Cloud Fraction, Daytime Observations Only

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<th>Nauru</th>
<th>Darwin</th>
</tr>
</thead>
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<td></td>
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</tr>
<tr>
<td>5 km</td>
<td>0.859</td>
<td>0.796</td>
<td>0.628</td>
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<tr>
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<td>0.443</td>
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<td>5 km, transparent</td>
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<td>0.755</td>
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<td><strong>ARM</strong></td>
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<td>1 or 5 min.</td>
<td>0.618</td>
<td>0.436</td>
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<td>0.799</td>
<td>0.634</td>
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<td>1 or 5 min., transparent</td>
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<tr>
<td>5 km “pixel”, transparent</td>
<td>0.493</td>
<td>0.346</td>
<td>0.303</td>
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</table>
them to go undetected. Therefore one would expect the CALIPSO observations to have a larger cloud fraction at higher altitudes relative to the ground-based observations. Other factors that influence cloud fraction include spatial resolution, which affects cloud fraction in a number of ways. For instance, consider the situation of cloud layers separated in the horizontal by a small clear-air gap. Large enough averaging in the horizontal could merge the signal from the individual cloud layers resulting in an increased cloud fraction relative to observations with less horizontal averaging. In addition, under-filled cloud pixels can result in an overestimate of the real cloud fraction. For example, the CALIPSO L2 cloud product contains data on a 5 km horizontal grid. A cloud with an actual horizontal dimension of 2 km (with sufficient backscattering) will be reported in the CALIPSO cloud product as one 5 km cloudy pixel, when the actual cloud fraction in this 5 km region is $\frac{2}{5}$ and not 1. The effect of under-filled cloud pixels is larger for boundary layer clouds since they typically have smaller spatial scales. Our comparison is further complicated by the CALIPSO SIBYL algorithm’s high-resolution cloud clearing [Vaughan et al., 2009]. It removes boundary layer clouds detected at single-shot (2 km) resolution from the 5 km cloud product to ensure that the layers identified are homogeneous features. We examine the impact of this process on our cloud fraction comparison in section 5.1.4. In the next subsection we focus on eliminating the impact of horizontal resolution on our comparison.

### 5.1.1. Effect of Resolution

The ground-based MPL SNR is improved by averaging over time, 1 minute at night and 5 minutes during the day. The equivalent spatial average can be determined by assessing the advection by wind of atmosphere through the field of view of the MPL. For 5 km of atmosphere to be sampled by the MPL in either 1 or 5 minutes would require an unrealistically large wind speed. Given typical wind speeds at the three TWP sites, 1 and 5 minutes of averaging corresponds to a spatial average significantly less than CALIPSO’s 5 km. Therefore the larger cloud fraction in CALIPSO observations may be partially due to differences in resolution due to the effects discussed previously.

Differences in spatial resolution can be accounted for in one of two ways: either reduce the spatial averaging of CALIPSO to better match that of the ground-based data or further average the ground-based observations to 5 km. To achieve the former we can utilize the 1 km CALIPSO cloud product. Cloud fraction derived from the 1 km CALIPSO cloud product is shown in Table 1. Comparisons with the ground-based cloud fraction is much improved over the 5 km cloud product. The lower cloud fraction relative to the 5 km data could also be a result of the reduction in CALIPSO’s cloud detection capability. Less averaging performed in the 1 km data results in less clouds with sufficient SNR to be detectable. Therefore, the reduction of cloud fraction when using the 1 km CALIPSO cloud product is a result of two convoluted effects: the smaller amount of horizontal averaging and the reduced sensitivity to clouds. In section 5.1.2 we will examine which factor dominates. Using radiosonde wind data at each TWP site to approximate the equivalent amount of ground-based spatial averaging (not shown, see section 5.1.2) results in an average value of $\sim 0.4$ km when both night and daytime observations are considered. So the 1 km CALIPSO cloud product still has a larger spatial resolution than the ground-based data.

### 5.1.2. Ground-Based “Pixel”

Instead of reducing the horizontal averaging of CALIPSO we can mimic the horizontal average of CALIPSO in the ground-based data. This method is better suited for comparing the two datasets since we do not need to degrade the cloud detection ability of either retrieval. Cloud fraction derived using the ground-based observations which have been modified to mimic the 5 km resolution of the CALIPSO observations are shown in Table 1 in the row labeled “5 km “pixel”.” The cloud fractions at all three TWP sites agree with the CALIPSO 5 km data to within 0.06. The comparison of cloud fraction during the nighttime (Table 2) shows agreement to within 0.03. During the daytime (Table 3) the comparison of cloud fraction using either resolution shows larger differences with CALIPSO’s cloud fraction being consistently higher. Opposite signs in the differences in cloud fraction between the day and night results in some cancelation of errors when comparing all observations (Table 1). Table 2 indicates that the differences in cloud fraction between the CALIPSO observations (row labeled “CALIPSO 5 km” in Table 1) and the native ground-based observations (row labeled “ARM 1 or 5 min.”) at nighttime could be caused by the difference in resolution alone. The larger differences during the daytime cloud fraction are further evidence of the limited sensitivity of the MPL during the daytime, although resolution may also partially explain the observed differences.

For the preceding results, the ground-based observations are made to mimic CALIPSO’s 5 km horizontal resolution by defining a ground-based “pixel.” A “pixel” is a block of consecutive ground-based profiles which are considered approximately equivalent to a 5 km horizontal domain. Collectively the “pixel” of ground-based profiles is meant to approximate the amount of data that CALIPSO would view as a single profile. The number of consecutive profiles to consider as one “pixel” is determined using radiosonde wind data, which is available at least twice a day at all three TWP sites. Individual radiosonde wind profiles are first linearly interpolated to the vertical resolution of the MPL. Monthly mean wind speed profiles are constructed by averaging the $u$ and $v$ wind components separately across each month of data. The monthly mean wind speed profile is then taken as the magnitude of the resulting monthly mean wind vector at each MPL altitude.

The vertical mean of the monthly mean wind speed profiles is taken in four vertical layers: 0–3.5 km, 3.5–7 km, 7–14 km and 14–20 km. The minimum mean wind speed of these four layers is then used to determine the number of profiles combined to mimic 5 km. Given this mean wind speed, $\bar{U}$, the number of consecutive ground-based profiles is $n = 5 \text{ km}/(\bar{U} \Delta t)$. Where $\Delta t$ is the time average used in the ground-based data (1 minute during the night and 5 minutes during the day). Once the number of ground-based profiles to consider as one “pixel” is determined, the cloud fraction is assessed as follows. If inside this set of profiles there is at least one cloud layer detected then the entire “pixel” is marked as cloudy. Likewise, if no clouds are detected then this is a clear “pixel.” The cloud fraction is then derived relative to the total number of “pixels.”
This procedure results in an average time of 46 minutes (with a standard deviation of 14 minutes) for each 5 km MPL “pixel”. This average (and standard deviation) is derived from all 31 months of data across all three ARM TWP sites. Since the nighttime data is averaged to 1 minute, on average at night a single “pixel” is composed of 46 profiles. During the daytime (5 minute average) this corresponds to 9 profiles per “pixel.”

5.1.3. Transparent Cloud Fraction

Of particular focus in this study is statistical comparisons of observations in which the lidar signal passed completely through the atmosphere. Before placing significance in any statistical comparisons of this subset of observations, we analyze the cloud occurrences. The transparent cloud fraction is given in Table 1. In calculating the cloud fraction using only transparent profiles, profiles in which the lidar becomes fully attenuated are not included. Therefore the cloud fraction becomes the number of transparent cloudy profiles relative to the total number of transparent profiles (i.e. transparent cloudy profiles plus clear profiles).

Differences in the transparent cloud fraction are large and, as discussed above, this may be due to the different spatial resolutions of the two sets of observations. We use the MPL “pixel” method to minimize the uncertainty caused by different horizontal resolutions. A complication arises for determining when a “pixel” is attenuated. Determining this is ambiguous since a “pixel” could be composed of some profiles which are attenuated and some which are completely transparent. Alternatively, one could re-average the original raw backscatter from the MPL to an equivalent spatial average of 5 km and then determine attenuation using this new set of data. However, we would not be testing the MPL’s cloud occurrence at the 1 and 5 minute averages which are used for all other comparisons in this study. Instead we require that more than half of the profiles composing a “pixel” are transparent in order to consider the entire “pixel” as transparent. Rather than comparing this cloud fraction directly to the CALIPSO observations, we perform a sensitivity test using the ground-based observations alone.

Ground-based observations are first combined into “pixels” using the same method outlined previously. All “pixels” that are composed of more than half opaque profiles are not included in this analysis. The results presented here are not sensitive to the details that determine the fraction of opaque profiles. The remaining “pixels” are then used to calculate two different cloud fractions. The first cloud fraction is derived using the individual 1 or 5 minute profiles which make up each “pixel.” The second cloud fraction is derived relative to the total number of “pixels” with a cloudy “pixel” being one which contains at least a single cloud layer. The difference between these two cloud fractions provides an estimate of the effect of spatial resolution on the transparent cloud fraction. This difference can then be used to estimate the true ground-based transparent cloud fraction at an equivalent spatial resolution of 5 km by adding it to the transparent cloud fraction derived using the native 1 and 5 minute profiles (i.e. the row labeled “1 or 5 min., transparent” in Tables 1–3). The resulting cloud fraction is given in Tables 1–3 in the row labeled “5 km ‘pixel’, transparent.”

The transparent cloud fraction comparisons between CALIPSO and the ground-based observations are more consistent after correcting for the effect of resolution. However, the cloud fraction derived using the full set of CALIPSO observations and the MPL “pixel” are more similar than the transparent-only observations. As with previous nighttime ground-based “pixel” comparisons, cloud fraction from CALIPSO and ground-based observations agree well at all three TWP sites. The CALIPSO daytime transparent cloud fraction, shown in Table 3, is significantly larger than that of the ground-based observations even after applying the resolution correction. This suggests that the larger differences in the transparent cloud fraction is due to the MPL’s reduced sensitivity during the daytime.

5.1.4. Cloud Fraction by Altitude

Previous comparisons of cloud fraction may mask disagreement between CALIPSO and ground-based observations by fortuitous error cancelation in cloud fraction at different altitudes. In addition, no assessment has yet been made of CALIPSO’s high-resolution-cloud clearing effect on our cloud fraction comparison. Together this motivates the comparison of cloud fraction by altitude shown in Figure 4 where cloud fraction is calculated in altitude bins of 0.5 km. We eliminate established discrepancies by only using profiles which are completely transparent to the lidar (to sample similar cloud regimes) and only using nighttime observations (when the sensitivities of each set of observations are more similar). The nighttime transparent cloud fraction profile is shown in Figure 4a. To better interpret previous results, the same CALIPSO data is shown in Figures 4a and 4c with the native ground-based cloud fraction in Figure 4a and the ground-based “pixel” cloud fraction in Figure 4c. The corresponding difference profiles between ground-based and CALIPSO observations are shown in Figures 4b and 4d. The method used to calculate the transparent ground-based “pixel” cloud fraction in each altitude bin is analogous to the method used for the total transparent cloud fraction (section 5.1.3).

CALIPSO and native ground-based observations of cloud fraction (Figures 4a and 4b) show significant differences for all three TWP sites. For higher altitudes (≥10 km), the CALIPSO cloud fraction is significantly higher with the maximum differences reaching about 0.3. At lower altitudes (≤7 km), the ground-based cloud fraction is larger with a maximum difference around 0.1. After bringing the two sets of observations onto approximately the same horizontal scale using the ground-based “pixel” method (Figures 4c and 4d) the majority of altitude bins still contain statistically significant differences. The results presented in Figure 4 indicates that the agreement in total cloud fraction between CALIPSO and ground-based observations using the MPL “pixel” method occur by chance, with the difference in cloud fraction changing sign with altitude. Therefore little physical significance is placed in the agreement previously shown for total cloud fraction and, consequently, resolution alone does not explain all of difference in cloud fraction between the two sets of observations.

Figure 4 aids to deduce some of the underlying reasons for differences in cloud fraction. The ground-based “pixel” dataset increases the cloud fraction for all altitudes relative to the native ground-based observations. As a result, the difference between CALIPSO and the ground-based
observations of high cloud fraction is reduced by about half using the ground-based “pixel” method at Manus and Nauru. The inconsistencies at Darwin are larger which is likely due to poor instrument performance (see section 4.3). Thus about half of the difference in high cloud fraction can be explained by resolution. The remaining difference in high cloud fraction may be related to the lower SNR of the ground-based observations at high altitudes. This would particularly become an issue for optically-thin cloud layers.

Comparisons of low cloud fraction between the native ground-based and CALIPSO observations (Figures 4a and 4b) show that the ground-based cloud fraction is significantly larger than CALIPSO for most altitude bins below about 7 km. This demonstrates that clouds with a horizontal dimension less than 5 km in the CALIPSO observations are not causing CALIPSO to overestimate cloud fraction relative to the ground-based observations as previously suggested. CALIPSO’s high-resolution cloud clearing does remove clouds detected at single-shot resolution below 4 km of altitude [Vaughan et al., 2009], which may explain its lower cloud fraction in that altitude range. After applying the “pixel” method to the ground-based data the difference in low cloud fraction becomes even larger (Figures 4c and 4d). While the impact of CALIPSO’s high-resolution cloud clearing could still possibility account for differences below 4 km, significant differences still occur above 4 km. The ground-based “pixel” cloud fraction remains significantly larger than CALIPSO’s cloud fraction up until above 10 km, depending on which TWP site is being examined. One explanation is the ground-based observations contain more smaller-scale clouds than the CALIPSO observations. As a consequence, when the ground-based “pixels” are constructed the cloud fraction in these regions of small-scale clouds is greatly enhanced, resulting in an even larger discrepancies between the two set of observations below 10 km.

Precisely quantifying contributions to discrepancies in cloud fraction between the CALIPSO and ground-based observations shown above is not trivial. The effect that CALIPSO’s high-resolution cloud clearing has on cloud fraction also warrants more in depth scrutiny. Further dissection of the cloud fraction observations from these two instruments is a worthwhile task, but is beyond the scope of this study.

5.2. Cloud Boundaries

CALIPSO and ground-based observations are compared by compiling probability density functions (PDFs) for cloud top height, cloud base height and cloud geometrical thickness for both ice (cloud base > 7 km) and TTL (cloud base > 14 km) clouds. Defined in this manner the TTL cloud observations are a subset of the ice cloud observations. All PDFs are constructed from the restricted datasets. The PDFs of cloud top and cloud base heights are given in Figure 5.

Figure 4. (a and c) Nighttime transparent cloud fraction profiles. CALIPSO cloud fraction (5 km resolution) is given as a solid line for Manus (black), Nauru (blue) and Darwin (red) while the ground-based cloud fraction is given as dashed lines. The shaded regions represent the 95% confidence interval due to CALIPSO’s sampling uncertainty. Cloud fraction is shown for the native (1 and 5 minutes averaged) ground-based observation (Figure 4a) and the cloud fraction derived using the ground-based “pixel” method described in the text (Figure 4c). The difference (ground-based minus CALIPSO) in cloud fraction at each altitude bin is shown for (b) the native ground-based observations and (d) the ground-based “pixel” observations. Regions of statistically significantly differences are indicated by a thick line.
and cloud geometric thickness in Figure 6. The statistics of the distributions are given in Tables 4 and 5.

Cloud boundaries at Manus and Nauru show good consistency between the ground-based and CALIPSO observations with only a few bins falling outside the confidence intervals. More statistically significant differences, particularly for cloud top heights, are found at Darwin. For ice clouds (Figure 5a), the ground-based PDFs of cloud tops and bases are skewed toward lower altitudes relative to the CALIPSO PDFs. Maxima in cloud top and base height occur at higher altitudes in the CALIPSO observations.

Table 4 shows the means and pseudo-standard deviations of the cloud top and cloud base height observations used to compile the PDFs in Figure 5a. Since distributions of cloud top heights, base heights and geometrical thicknesses are not normally distributed, the width of the distribution is described by the pseudo-standard deviation [Lanzante, 1996]. The pseudo-standard deviation is defined as the interquartile range divided by 1.349. The interquartile range is the difference between the third quartile (75th percentile) and the first quartile (25th percentile).

The difference in mean cloud top height and cloud base height are within 0.40 km at Nauru, 0.51 km at Manus and 0.91 km at Darwin. The mean cloud top and base height are higher in the CALIPSO observations and differences are statistically significant at all three TWP sites. The larger
discrepancies at Darwin are presumably due to the MPL’s reduced output power (section 4.3). Pseudo-standard deviations of cloud top and base height distributions are larger in the ground-based observations.

[57] Geometrical thicknesses of ice clouds for the ground-based and CALIPSO observations are shown in Figure 6a. Agreement between datasets is consistent across all three TWP sites. Relative to CALIPSO PDFs, ground-based PDFs show less clouds with a thickness below 1 km and more clouds with a thickness from about 1–3 km. The means and pseudo-standard deviations of cloud geometrical thickness are given in Table 4. The pseudo-standard deviation is larger in the CALIPSO observations at all three TWP sites. Mean geometrical thickness at Nauru differ by 0.05 km and Manus by 0.04 km, neither difference is statistically significant. At Darwin, the difference is statistically

![Figure 6.](image)

**Table 4.** Mean (km) and Pseudo-Standard Deviation (Parentheses, km) of Ice Cloud Tops, Bases, and Geometrical Thickness

<table>
<thead>
<tr>
<th></th>
<th>Base Top</th>
<th>Base Thickness</th>
<th>Top</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARM</td>
<td>CALIPSO</td>
<td>ARM CALIPSO</td>
<td>ARM</td>
<td>CALIPSO</td>
</tr>
<tr>
<td>Manus</td>
<td>11.99 (2.67)</td>
<td>12.46 (2.34) [12.27, 12.63]</td>
<td>14.11 (2.59)</td>
<td>14.62 (2.28) [14.44, 14.79]</td>
</tr>
<tr>
<td>Nauru</td>
<td>12.57 (2.20)</td>
<td>12.97 (1.97) [12.82, 13.13]</td>
<td>14.70 (1.93)</td>
<td>15.05 (1.60) [14.90, 15.20]</td>
</tr>
<tr>
<td>Darwin</td>
<td>12.32 (2.29)</td>
<td>13.04 (2.10) [12.87, 13.22]</td>
<td>14.26 (2.03)</td>
<td>15.17 (1.91) [15.02, 15.33]</td>
</tr>
</tbody>
</table>

*a*The 95% confidence interval for CALIPSO’ sampling uncertainty is given in brackets.
significant with the CALIPSO mean thickness larger by 0.19 km.

PDFs of cloud top height and cloud base height of the subset of ice clouds which reside in the TTL are shown in Figure 5b. Like with the ice cloud comparison, cloud top and base heights at Manus and Nauru agree to within the uncertainty intervals for nearly all PDF bins. More significant differences are found at Darwin, especially for cloud top heights. As discussed in section 4.3 the MPL at Darwin has below-normal output power during much of our sampling period. It follows that this would have the greatest effect on the detection of cloud top height as signal is lost throughout the cloud layer. Means and pseudo-standard deviations of TTL cloud top and base heights are given in Table 5. CALIPSO observations show a higher mean TTL cloud top and base at Manus and Darwin. Nauru TTL mean cloud bases are the same in both sets of observations, cloud tops are higher in the ground-based by 0.11 km. The best cloud top agreement is achieved at Manus (0.08 km) and the mean Darwin cloud top shows the largest difference (0.24 km). Cloud bases heights differ at Darwin by 0.26 km and at Manus by 0.23 km. Differences in the mean TTL cloud base and top height are all statistically significant with the exception of cloud bases at Nauru and cloud tops at Manus. All pseudo-standard deviations except for Nauru cloud bases are larger in the CALIPSO observations.

[59] PDFs of TTL cloud geometrical thicknesses are shown in Figure 6b. Differences at Nauru and Darwin are within the confidence interval for nearly every PDF bin. At Manus several PDF bins have statistically significant differences. Table 5 given the means and pseudo-standard deviations of the two sets of TTL cloud observations. Ground-based mean TTL geometrical thicknesses are larger than CALIPSO at all three TWP sites. Differences at Darwin are greater by 0.02 km, Nauru by 0.12 km and Manus by 0.15 km. The differences at Nauru and Manus are statistically significant.

5.3. Number of Cloud Layers per Profile

[50] When comparing the number of cloud layers per profile we first transform the ground-based observations to an equivalent spatial resolution of 5 km. This is done since the larger horizontal resolution of CALIPSO will have a better chance of detecting a multilayer cloud profile than the finer resolution of the ground-based observations. Similar to the procedure for the cloud fraction, a MPL “pixel” is defined using a block of consecutive profiles. Ideally we would like to make a comparison of the number of cloud layers using the restricted datasets. However, by constructing MPL “pixels” there is the possibility that some profiles within “pixels” could be opaque to the lidar. To deal with this situation, first only “pixels” where at least half of the profiles are transparent to the lidar signal are considered in this analysis. The number of cloud layers is then determined from this new set of “pixels.” To simulate the effect of averaging across each “pixel” cloud layers from adjacent profiles which overlap in the vertical are considered as a single cloud layer. After overlapping cloud layers are combined, the number of cloud layers in each “pixel” is taken as the maximum number of layers from any one profile inside the block. Any opaque profiles which may be present inside a “pixel” are not used for either combining the overlapping cloud layers or for determining the number of cloud layers in each “pixel.”

Comparisons of the number of ice cloud layers per profile are shown in Figure 7 for CALIPSO data and the

<table>
<thead>
<tr>
<th></th>
<th>Base</th>
<th>CALIPSO</th>
<th>Top</th>
<th>CALIPSO</th>
<th>Thickness</th>
<th>CALIPSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manus</td>
<td>14.89 (0.74)</td>
<td>15.12 (1.07)</td>
<td>15.01, 15.24</td>
<td>16.48 (0.76)</td>
<td>16.56 (0.93)</td>
<td>16.44, 16.68</td>
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<tr>
<td></td>
<td>14.91 (0.73)</td>
<td>14.91 (0.69)</td>
<td>14.82, 15.00</td>
<td>16.50 (0.76)</td>
<td>16.39 (0.86)</td>
<td>16.29, 16.49</td>
</tr>
<tr>
<td></td>
<td>14.78 (0.59)</td>
<td>15.04 (0.80)</td>
<td>14.95, 15.13</td>
<td>16.26 (0.70)</td>
<td>16.50 (0.78)</td>
<td>16.40, 16.60</td>
</tr>
</tbody>
</table>

Figure 7. Frequency of the number of ice cloud layers per profile from CALIPSO and ground-based datasets for the three ARM TWP sites. The bounds on CALIPSO’s 95% confidence interval are given as red lines.
Figure 8

(a) Manus, Nauru, Darwin

(b) Manus, Nauru, Darwin

Figure 8
unmodified ground-based data. CALIPSO observations have a higher occurrence of multilayered cloud profiles, as would be expected from a larger amount of horizontal averaging. In Figure 7 the number of layers for the ground-based dataset is also derived using the MPL “pixel” that is equivalent to the CALIPSO 5 km horizontal resolution. The only difference which is statistically significant is for profiles which contain two ice cloud layers at Nauru. In this section we do not present a comparison of the number of TTL cloud layers per profiles since the majority (~97%) of profiles contain only a single TTL cloud layer. This result holds true regardless of observation platform or location.

[62] Inhomogeneous cloud features can lead to the detection of multiple, closely-spaced cloud layers. As a consequence, in the retrieval process cloud layers that are considered too close together are merged together. In the ground-based MPL retrieval cloud layers separated by less than 500 m are combined into a single cloud layer. In the CALIPSO cloud product, the process is more complicated. A different minimum separation is specified for each averaging resolution that the CALIPSO data undergoes (D. Winker, personal communication, 2011). Therefore there is no definitive cutoff for a minimum gap but rather any layers separated by less than 1 km have the possibility of being merged together. This complicates our comparison of the number of cloud layers since differences in how each set of observations closes small gaps in between cloud layers may lead to spurious differences or agreement between the datasets. It cannot be ruled out that the overall good agreement in Figure 7 may be due to differences in how each retrieval defines a unique cloud layer.

5.4. Optical Depth

5.4.1. Retrieval Descriptions

[63] Following the lidar equation given by Platt [1973] the layer-integrated attenuated backscatter \( \gamma' \) is related to the cloud layer optical depth \( \tau \) by

\[
\gamma' = \int \frac{1}{S} \exp(-2\eta \tau) d\tau
\]

where \( \tau \) is the visible optical depth, \( \eta \) is the multiple scatter factor which accounts for multiple scattering effects captured by the lidar receiver and \( S \) is the lidar ratio which is the ratio of the cloud extinction coefficient to the backscatter coefficient. The retrieval of cloud optical depth from lidar measurements requires the estimation of the lidar ratio and the multiple scattering factor.

[64] The CALIPSO cloud product uses three methods to estimate the lidar ratio: (1) the transmittance method which requires a clear air signal below the cloud layer, (2) the lidar equation using a lidar ratio of 25 sr for ice clouds and 19 sr for water clouds and (3) the lidar equation but with an adjustment of the lidar ratio to avoid unphysical optical depths. In CALIPSO L2 v3.01 the multiple scattering factor is set to a constant value of \( \eta = 0.6 \) for all retrieval types (D. Winker, personal communication, 2010). For constrained retrievals Winker et al. [2009] estimate the uncertainty for cloud optical depth to be within a factor of 2 for optical depths less than 5. The large majority (~90%) in the restricted ice cloud datasets of CALIPSO cloud optical depth retrievals use a fixed lidar ratio. In our comparison we consider optical depths derived using any of the three methods for the lidar ratio.

[65] An alternative CALIPSO depth retrieval of Yang et al. [2010] is also considered in our comparison. This retrieval uses a constant multiple scattering factor of 0.5 and a lidar ratio of 34 sr for ice clouds. Optical depth is then calculated using the cloud layer backscatter from the CALIPSO L2 v3.01 cloud product. Using CALIPSO v2.01 data, Yang et al. [2010] estimate a relative uncertainty of 25% in their ice cloud optical depth retrieval.

[66] For the ground-based MPL, extinction is calculated following Comstock and Sassen [2001] with both \( S \) and \( \eta \) fixed at 25 sr and 0.8, respectively. Additionally we make comparisons with \( \eta \) fixed at 0.8 and estimate \( S \) for each profile using the backscatter above the cloud layer as described by Comstock and Sassen [2001].

5.4.2. Optical Depth Results

[67] PDFs of optical depths are shown in Figure 8. Included in Figure 8 is all the optical depth retrievals considered in this study: (1) the official v3.01 CALIPSO retrieval (black line), (2) the CALIPSO retrieval of Yang et al. [2010] (blue line), (3) the ground-based retrieval with \( S = 25 \) and \( \eta = 0.8 \) (red line), and (4) the ground-based retrieval with \( \eta = 0.8 \) and a variable lidar ratio (green line). PDFs are divided into two optical depth ranges: 0.01 < \( \tau < 0.2 \) and 0.2 < \( \tau < 3 \). The mean optical depth in each of these optical depth ranges is denoted with an “x” along the x-axis. The percent of observations which fall within each range are given in the upper-right corner of each plot.

[68] PDFs of ice and TTL cloud optical depth show slight differences between retrieval methods for the same platform. Comparing the two ground-based retrievals, the variable lidar ratio PDF is larger for thicker optical depths, while the fixed lidar ratio PDF is larger in the smaller optical depth bins. For the two CALIPSO retrievals, the Yang et al. [2010] retrieval has less clouds in the thinnest of the optical depth bins relative to the official CALIPSO L2 data.

[69] Examining Figure 8a, agreement between retrieval types for ice cloud optical depth varies across all three TWP sites depending on the range of optical depths being examined. Overall we find that all four retrieval types typically agree within uncertainty intervals. In general, the Yang et al. [2010] retrieval agrees best with the ground-based observations for the thick ice clouds (\( \tau > 0.2 \)). The Yang et al. [2010] retrieval is more consistent in the thin range.
with the ground-based variable lidar ratio retrieval at Manus and Darwin, while the CALIPSO L2 and ground-based fixed lidar ratio retrievals agree better for these two sites. Nauru is the exception, where the thin optical depths in the CALIPSO L2 observations agree best with the ground-based variable lidar ratio retrieval.

[70] The percentages in the upper-right corner of the plots in Figure 8 gives the distribution of optical depths across the two different ranges. The ground-based fixed lidar ratio retrieval contains the most clouds in the thin optical depth category ($\tau < 0.2$) of the four retrieval types. For the thick optical depths ($\tau \geq 0.2$) the ground-based variable lidar ratio retrieval contains the most clouds. Comparing the two CALIPSO retrieval types, the retrieval of Yang et al. [2010] contains more clouds in the thick optical depth range while the CALIPSO L2 retrieval contains more clouds in the thin optical depth range.

[71] TTL cloud optical depth comparisons are given in Figure 8b. As with the comparisons of ice cloud optical depth, we find that typically all four retrieval types agree to within the uncertainty intervals. In the thin optical depth range ($\tau < 0.2$) the ground-based variable lidar ratio retrieval agrees better to both CALIPSO retrievals. Distributions of the optical depths by range reveal that for all four retrievals and all three TWP sites more than 90% of TTL cloud optical depths fall below 0.2.

5.5. Diurnal Biases

[72] Observations using lidar become increasingly difficult during the daytime hours due to increased signal noise. As shown in Figure 3 daytime MPL observations of cloudy profiles are frequently attenuated, about 70% depending on the month and location. During the nighttime the percentage of MPL profiles which are attenuated is much lower than the daytime. Since many comparisons presented in this study focus on transparent profiles only, the resulting ground-based dataset are biased toward nighttime observations. During the night, both the ground-based and CALIPSO observations have similar fractions of attenuated profiles. The fraction of attenuated profiles during the daytime for CALIPSO observations is typical greater than at night. However, differences between day and night are not as severe as those seen in the ground-based observations. The nighttime bias in the ground-based observations motivates the comparison of cloud properties for night and day separately. Comparisons of night-only restricted datasets provides a set of observations which have a similar fraction of cloudy attenuated profiles. In addition, nighttime-only observations provide a comparison free of retrieval complications due to the solar background. In this analysis we only present results for the ice cloud datasets. The comparisons of the diurnal differences of TTL cloud properties show similar results and conclusions drawn from ice cloud results are also generally applicable to TTL cloud observations. For completeness, we present the night and day-only TTL cloud properties in Appendix B.

[73] Night and day-only ice cloud top and base PDFs are shown in Figure 9. Differences between CALIPSO and ground-based nighttime ice cloud PDFs (Figure 9a) are similar to comparisons made using observation from all times (Figure 5a). Much larger differences exist when comparing daytime observations of ice clouds (Figure 9b). During the daytime CALIPSO observations contain more higher ice cloud tops and bases than the ground-based observations. The number of ground-based daytime observations is small enough such that the assumption of insignificant sampling uncertainty may no longer hold true.

[74] Ice cloud PDFs of geometrical thicknesses are given in Figure 10. Unlike the cloud top and base heights, both day and night PDFs show similar discrepancies between the two sets of observations as the full set of observations do (Figure 6a). Thicker clouds are observed during the night in both the CALIPSO and ground-based datasets. Note that the MPL daytime observations of cloud boundaries are much more severely impacted by the solar background. However, similar differences in cloud thickness between the daytime and nighttime from CALIPSO and MPL observations indicate that both ice and TTL clouds may actually be thicker at night. At the same time, this diurnal cycle of geometrical thickness may also be partly the result of the improvement in the SNR during the nighttime hours. A better detection of the cloud base and cloud top at night would result in a geometrically thicker cloud.

[75] The number of ice cloud layers per profile are given in Figure 11 for night and day observations. The MPL “pixel” method described previously is used to calculate the number of ground-based cloud layers. At night the ground-based observations contain more multilayer ice cloud profiles than CALIPSO. While during the day the opposite is true, CALIPSO observes more multilayered ice cloud profiles than the ground-based MPL. The diurnal biases negate each other to some degree when we compare observations from both day and night together (Figure 7). This results in better agreement in the number of cloud layers between the CALIPSO and ground-based observations when comparing both day and night. As discussed in section 5.3 these comparisons may be impacted by differences in how each retrieval defines a unique cloud layer.

[76] Comparisons of daytime and nighttime ice cloud optical depths are given in Figure 12. Overall differences between day and night PDFs are similar to those seen using the full sets of observations. The only significant differences are found for the thinnest few ice cloud optical depth bins. There the daytime observations for all four retrieval types, particularly for the ground-based variable lidar ratio retrieval, have less of the very thinnest optical depths relative to the nighttime observations. This indicates that both sets of observations are more sensitive to clouds with the thinnest optical depths at night, as is expected from SNR considerations.

[77] The statistics derived from day and night observations of cloud top height, base height, geometrical thickness and optical depth are not significantly impacted by the MPL’s diurnal bias in the restricted datasets. However, this diurnal bias could potentially effect the comparisons of the number of cloud layers per profile. While the full set of ground-based observations is more representative of nighttime cloud properties, the actual diurnal cycle of cirrus clouds as represented by CALIPSO observations is too small for this bias to introduce significant differences. The TTL cloud observations also support these conclusions and are given in Appendix B.
An additional complication exists for the comparison of daytime data which arises from how attenuation is determined in the two sets of observations. For a CALIPSO profile to be considered completely transparent then a surface return must be identified in the backscatter profile. For the MPL retrieval if the measured backscatter above the cloud layer does not decrease proportional to the molecular backscatter then the profile is assumed to be attenuated. For a cloudy profile viewed by CALIPSO determining attenuation is more clear-cut since a surface return is a relatively large signal compared to an assessment using the molecular scattering above cloud. This makes the attenuation test for the MPL more sensitive to SNR and could lead to an overestimate of the occurrence of attenuated profiles. During the nighttime, SNR is high and this effect should be less significant. However, during the daytime, when SNR is low, the MPL restricted dataset could exclude cloud profiles which, if hypothetically viewed by CALIPSO, would be included in the CALIPSO restricted dataset.

Comparing the fraction of attenuated cloud profiles (Figure 3) alone gives the impression that this effect could be significant as the fraction of MPL cloud profiles attenuated during the daytime is much larger than CALIPSO’s. During the nighttime both sets of observations show a similar fraction of attenuated cloud profiles. Therefore, it is possible that discrepancies in daytime cloud properties are

Figure 9. PDFs of ice cloud top heights (top row) and cloud base heights (bottom row) from CALIPSO (black line) and ground-based (red line) datasets during the (a) nighttime and (b) daytime. The shaded region represents the 95% confidence interval due to CALIPSO’s sampling uncertainty. The three ARM sites are shown (left to right): Manus, Nauru and Darwin.

[78]
larger due the different attenuation tests. However, this likely does not explain the majority of differences between the two sets of observations during the daytime. Given the same cloud profile, the sensitivity of the MPL attenuation test to lower SNR during the daytime would result in a profile being flagged as attenuated at a thinner optical depth than it would be during the nighttime. This would result in far fewer thicker cloud optical depths in the daytime restricted MPL observations. Examining Figure 12 it is evident that this is not the case. Comparing the MPL PDFs from daytime and nighttime observations show that a similar amount of thicker optical depths occur during the nighttime. This would result in averaging over finer-scale structures of cloud boundaries and variations in optical depth. The higher spatial resolution of the ground-based MPL would capture these finer scale features. Here we perform a similar analysis used for cloud fraction to test the effect of resolution on the PDFs of ice cloud properties.

5.6. Effect of Resolution on PDFs of Cloud Properties

The equivalent spatial resolution of the ground-based MPL is significantly smaller than that of the CALIPSO 5 km observations. This effect was explored when comparing cloud fraction (section 5.1). For statistical comparisons of cloud properties CALIPSO’s larger spatial average could result in averaging over finer-scale structures of cloud boundaries and variations in optical depth. The higher spatial resolution of the ground-based MPL would capture these finer scale features. Here we perform a similar analysis used for cloud fraction to test the effect of resolution on the PDFs of ice cloud properties.

5.6. Effect of Resolution on PDFs of Cloud Properties

The effect of resolution is determined using a method analogous to that used for the transparent cloud fraction. Ground-based observations are first combined into “pixels” using mean radiosonde wind profiles as described in section 5.1. If more than half of the cloud profiles inside a “pixel” are attenuated then that “pixel” is discarded from the set of observations. Our results are not sensitive to the fraction chosen to determine which “pixels” to keep. Cloud properties are then averaged in each of these “pixels.” Since combining multiple cloud layers across profiles in a meaningful way is dubious, we derive column properties. The highest cloud top for each “pixel” is determined by averaging the highest cloud tops from the set of profiles that compose the “pixel.” The lowest cloud base in each “pixel”
is determined in an analogous manner except by averaging the lowest cloud bases. The “pixel” column optical depth is taken as the average of the column optical depths across the set of profiles inside each “pixel.” Figure 13 shows the results of this analysis for the highest cloud top heights and lowest cloud base heights. Figure 14 gives the results for the column optical depth. The dashed lines in Figures 13 and 14 represent the ground-based set of observations which have been averaged into “pixels.” The solid lines shows the column properties derived from the restricted set of CALIPSO and unmodified ground-based observations.

Differences between the ground-based and the averaged ground-based PDFs for the highest ice cloud top and lowest ice cloud base are typically quite small. These small differences between the ground-based PDFs relative to the much larger differences seen when comparing either one of the ground-based PDFs to the CALIPSO PDFs in Figure 13 indicate that resolution alone can not explain the majority of the discrepancies in cloud top and base height. Therefore we conclude that comparisons of cloud top and base height PDFs presented in this study are not significantly impacted by the different spatial resolutions. Physically this means that CALIPSO’s larger amount of horizontal averaging is not large enough to significantly mask variations in ice cloud boundaries. The sensitivity of TTL cloud boundaries was also tested but is not shown here. The results are similar to what is shown for the ice cloud observations.

Column optical depths in Figure 14 include comparisons for all four retrievals considered in this study—the ground-based with a fixed lidar ratio, a variable lidar ratio, the official CALIPSO L2 retrieval, and the CALIPSO retrieval of Yang et al. [2010]. Comparisons of the TTL cloud observations show little change after averaging the ground-based data and are not shown. Discrepancies between the ground-based and the averaged ground-based ice cloud PDFs are prevalent in a few particular areas. Both retrieval types tend to have slightly less clouds with optical depths in the very thinnest bins ($\tau < 0.03$). Most significant is for thicker ice cloud optical depths ($\tau \geq 0.3$) for the variable lidar ratio retrieval. We expect the spatial averaging to play a larger role for the variable lidar ratio since estimating the lidar ratio for each cloud profile results in a greater variability of optical depth from profile to profile. Averaging the fixed lidar ratio retrieval results in a smaller difference when compared with the original ground-based observations. Since the CALIPSO retrieval of Yang et al. [2010] uses a fixed lidar ratio and the majority of clouds in the CALIPSO L2 retrieval use a fixed lidar ratio we can conclude that CALIPSO optical depth PDFs are not significantly affected by spatial resolution. However, in comparing with the ground-based variable lidar ratio retrieval the results shown in Figure 14 need to be taken into consideration. We showed in section 5.4 that the PDFs for thicker optical depth disagreed the most for the variable lidar ratio retrieval. The analysis here suggest that this may be an artifact of the finer spatial resolution of the ground-based observations. For the thinnest of optical depths we showed that the ground-based variable lidar ratio retrieval agreed.
Figure 12
best to either of the two CALIPSO retrievals. Given that the
disagreement at thicker optical depth is a result of different
resolutions we can conclude that optical depths are most
similar between CALIPSO and the variable lidar ratio
ground-based retrieval.

6. Summary and Conclusions

Statistics of CALIPSO and ground-based lidar obser-
vations are compared over a 31 month period. Ground-
based lidar observations are taken from the MPLs at the three
ARM TWP sites: Manus, Nauru and Darwin. CALIPSO’s
sampling uncertainty is nontrivial for the sampling period
chosen and is assessed using the moving block bootstrap
resampling method. Analyzed for consistency is cloud frac-
tion, top height, base height, geometrical thickness, optical
depth and the number of cloud layers per profile. Besides
cloud fraction, cloud properties are compared for ice clouds
only, which we define as a cloud with a base greater than
7 km. Also compared are the subset of ice clouds which
reside in the TTL, defined by a cloud base greater than
14 km. Applications of MPL or CALIPSO observations
to assess atmospheric processes, for instance the delicate
radiative balance of the TTL, requires consideration of the
strengths and weakness of each dataset outlined in this
study.

The cloud fraction derived from the CALIPSO
observations showed a significantly higher cloud fraction—
by up to 0.27—than the native ground-based observations.
After accounting for the difference in resolution using the
ground-based “pixel” method the total cloud fraction agrees
to within 0.06 at all three TWP sites. During the nighttime,
total cloud fraction agrees even better. This is also the case
for the assessment of the occurrence of transparent cloud
profiles. The overall good agreement in total cloud fraction
between CALIPSO and ground-based observations with
a similar horizontal resolution is revealed to be caused by a
fortuitous cancelation of errors from cloud fraction at
different altitudes. For higher altitudes (≥10 km), the
CALIPSO cloud fraction is significantly larger while at
lower altitudes (≤7 km), the ground-based cloud fraction
is significantly larger. CALIPSO’s high-resolution cloud
clearing does remove clouds detected at single-shot reso-
lution below 4 km of altitude, which may explain it’s lower
cloud fraction in that altitude range. However, significant
differences still occur above 4 km. It is possible that

Figure 12. PDFs of ice cloud optical depths from CALIPSO L2 v3.01 cloud product (black line) and the CALIPSO optical
depth retrieval of Yang et al. [2010] (blue line) during the (a) nighttime and (b) daytime. The shaded region on each
CALIPSO retrieval represents the 95% confidence interval due to the sampling uncertainty. Ground-based optical depths
are shown for the lidar ratio fixed at 25 sr (red line) and the variable lidar ratio retrieval (green line). The three ARM TWP
sites are shown (left to right): Manus, Nauru and Darwin. The top row of plots shows the optical depths from 0.01 ≤ \( \tau \) < 0.2
and the bottom row shows 0.2 ≤ \( \tau \) ≤ 3. The upper-right corner of each plot gives the percent of observations which fall
within the plotted optical depth range. The mean optical depth within each range is denoted with an “x” along the x-axis.

Figure 13. PDFs of the (top) highest cloud top heights and (bottom) lowest cloud base heights from
CALIPSO (black line) and ground-based (red line) ice cloud datasets. The dashed line gives the
ground-based ice cloud PDF for the datasets which has been averaged to an equivalent spatial resolution
of 5 km. The shaded region represents the 95% confidence interval due to CALIPSO’s sampling uncer-
tainty. The three ARM sites are shown (left to right): Manus, Nauru and Darwin.
the ground-based observations contain more smaller-scale clouds than the CALIPSO observations. Differences become even larger when the ground-based “pixels” are constructed as the cloud fraction in these regions of small-scale clouds is greatly enhanced. For cloud fraction at higher altitudes, approximately half of the difference can be explained by the difference in spatial resolution. Even after correcting for resolution differences the CALIPSO cloud fraction remains larger at high altitudes. This may be an indication that the MPL is not as sensitive to high clouds during both the nighttime and daytime. All comparisons of daytime cloud fraction show significantly larger differences.

Comparisons of cloud top and base heights show that CALIPSO places clouds at higher altitudes relative to the ground-based observations. The only exception is at Nauru where the mean ground-based TTL cloud top falls just outside the upper bound of CALIPSO’s confidence interval. Mean TTL cloud top and base heights differ by less than...
0.23 km at Manus and 0.11 km at Nauru. Mean ice cloud tops and bases are lower in the ground-based observations by 0.51 km at Manus and 0.47 km at Nauru. Discrepancies in cloud top and base height are larger at Darwin, particular cloud top heights, due to a reduction in the MPL output power during much of our sampling period. At Darwin the ground-based mean cloud top is lower by 0.91 km for ice clouds. We find both in terms of mean and PDFs of cloud top and base heights that the CALIPSO observations are placed at higher altitudes relative to the ground-based observations. This systematic difference can be explained by the different viewpoints of each instrument. Besides the amount of noise, cloud detection is limited by in-cloud attenuation of the lidar beam making the cloud boundary furthest from the lidar more difficult to detect accurately. Measurements with a space-borne lidar are likely to overestimate the cloud base, that is place the cloud base at a higher altitude than it should be. Conversely, the same cloud viewed from a ground-based lidar is likely to underestimate the cloud top, that is place the cloud top at a lower altitude than the actual cloud top. Therefore when comparing the ground-based MPL and space-borne CALIPSO lidar the net of these two effects is that clouds boundaries are shifted to higher altitudes in the CALIPSO observations relative to the ground-based observations. We also determine that CALIPSO’s larger amount of horizontal averaging does not affect comparisons of cloud top and base heights.

All three MPLs have a large fraction of attenuated profiles during the daytime. Therefore the ground-based statistics derived from the restricted datasets are more representative of the characteristics of nighttime clouds. We find that comparisons of cloud top and base heights using observations from both day and night are not affected by the MPL’s diurnal bias. While the full set of ground-based observations is more representative of nighttime cloud properties, the diurnal cycle of cirrus clouds as represented by CALIPSO observations is too small for this to introduce significant differences. During the daytime cloud top and base heights are considerably lower relative to CALIPSO observations.

Mean ice cloud geometrical thicknesses differ significantly only at Darwin where CALIPSO is thicker by 0.19 km. For TTL cloud geometrical thicknesses we find statistically significant differences of 0.15 km at Manus and 0.12 km at Nauru. Geometrical thickness is unaffected by the diurnal bias of the MPL. Day and night observations show similar agreement to the entire sets of observations. CALIPSO and ground-based observations both show the same diurnal cycle with geometrically thicker ice and TTL clouds during the nighttime hours. Given that both instruments have the same diurnal cycle lends credibility that this is a real effect, although it may be partially due to improved SNR at night, which allows for better detection of cloud top and base and therefore a thicker cloud.

The number of ice cloud layers per profile agree well after the effects of resolution is considered. Breaking the datasets into day and night reveals that some of this agreement may be due to different diurnal cycles in each set of observations. The ground-based observations contain more multilayer ice clouds during the nighttime while CALIPSO observations show more during the daytime. Differences between observations in these diurnal comparisons are small and not always statistically significant. The comparison of the number of cloud layers per profile may be impacted by differences in how each retrieval defines a unique cloud layer.

Agreement in ice cloud optical depth varies between the four retrieval types depending on the range of optical depth and TWP site being examined. However, for the majority of the PDF bins all four retrievals agree to within the 95% confidence level. The vast majority of TTL cloud optical depths are less than 0.2, regardless of retrieval type and location. In this optical depth range, the ground-based variable lidar ratio retrieval agrees best with either of the two CALIPSO retrievals. The ground-based fixed lidar ratio retrieval has statistically significant differences in the very thinnest of the optical depth bins. All retrieval types for both sets of observations show slightly more of the very thinnest ice clouds during the nighttime. This is presumably due to an increase in SNR, allowing for the easier detection of optically thin clouds.

Overall, for the thin (τ < 0.2) ice and TTL clouds, both CALIPSO retrievals tend to agree better to the ground-based variable lidar ratio retrieval rather than the fixed lidar ratio. The opposite is true for thick ice clouds (τ ≥ 0.2), with better agreement between either CALIPSO retrieval when using the ground-based fixed lidar ratio retrieval. However, the ground-based variable lidar ratio retrieval PDF is sensitive to the resolution particularly for thicker (τ ≥ 0.3) optical depths. Differences between the PDFs for thicker optical depths may be an artifact of the difference in spatial resolution. Therefore we conclude that the CALIPSO observations of ice and TTL cloud optical depth agree best to the variable lidar ratio ground-based observations.

The lidar ratio of clouds varies primarily due to variations in ice crystal shape [Takano and Liou, 1995]. Therefore, we place greater emphasis on the ground-based retrieval using the variable lidar ratio, as it is more representative of true ice clouds. While the CALIPSO L2 retrieval does retrieve the lidar ratio for a portion of its optical depth retrievals, the vast majority of cloud optical depths are retrieved by using an assumed lidar ratio. In addition, CALIPSO’s optical depth retrieval has to contend with larger multiple scattering effects. Despite these limitations, the CALIPSO observations still agree best to the variable lidar ratio ground-based observations.

While differences in cirrus cloud observations do exist, we typically find good agreement within the uncertainty intervals. The largest discrepancies are found when comparing cloud fraction. Pertinent to this study is the revelation that CALIPSO has a significantly larger cloud fraction at high altitudes. Yet we find that statistics of high-cloud properties agree well. This indicates that despite the MPL’s lower sensitivity to high clouds it obtains enough cloud profiles during our sampling period to produce statistics similar to that of CALIPSO. This is important ramifications since it indicates that the statistics from either set of observations can be used in studies which require ice cloud properties. The complimentary nature of these sets of observations—the near-global coverage of CALIPSO and the long, continuous time series of the MPLs—provides a
useful perspective for assessing the impact of tropical cirrus on the climate system.

Appendix A: Merging CALIPSO’s Multiresolution Layers

Cloud layers in the CALIPSO 5 km products are identified using a multiresolution averaging algorithm called the selective, iterated boundary location (SIBYL) algorithm. SIBYL allows CALIPSO to achieve a balance between the highest possible spatial resolution and a sufficient SNR to accurately retrieve layer properties. Details of CALIPSO’s detection of cloud and aerosol layers are given by Vaughan et al. [2009]. Multiple passes are made through the data and the amount of horizontal averaging increases with each pass. After cloud layers are identified at a particular horizontal resolution they are removed before moving on to further averaging. In the 5 km L2 v3.01 cloud product three horizontal averages are considered: 5, 20 and 80 km. In the first pass the data is averaged to 5 km and cloud layers are identified by comparing to a threshold. The signal associated with cloud layers identified at 5 km are then removed before moving on to further averaged. This step creates a backscatter profile as if the detected cloud layers where never present. Then a second pass is made by averaging the data to 20 km and layer detection and removal is repeated. The process is repeated one last time with the data averaged to 80 km.

Interpreting the layer properties resulting from SIBYL requires an understanding of the output of a multiresolution algorithm. Figure A1 gives a schematic of retrieved cloud boundaries from the 5 km cloud product. This artificial scene shows cloud layers detected at resolutions of 5 km (red, feature A), 20 km (green, features B1, B2 and B3) and 80 km (blue, feature C). Hashing indicates that the region was identified as cloud at more than one horizontal resolution. The CALIPSO 5 km cloud product would report layer properties for each 5 km column and for each feature: A, B1, B2, B3 and C. For example in column 5 the number of cloud layers reported would be three with the feature: A, B1, B2, B3 and C. The boundaries reported from these three layers would overlap in the vertical. It is apparent in column 5 that there is only a single cloud layer but the SIBYL algorithm has caused it to be detected at three different horizontal resolutions. In order to compare to the ground-based data, which performs cloud detection at a single resolution, we combined cloud layers which overlap in the vertical into a single cloud layer. The merged single-layer cloud top is taken as the highest cloud top in the set of overlapping CALIPSO cloud layers (i.e. 9.48 km is column 5 in Figure A1). Likewise, the merged single-layer cloud base is taken as the lowest cloud base in the set of overlapping CALIPSO cloud layers (i.e. 9 km in column 5 in Figure A1). After obtaining the cloud top and base height of the merged single-cloud layer the geometrical thickness becomes the difference between the merged layer’s cloud top and base. The optical depth of a merged single-cloud layer is the sum of all the overlapping CALIPSO cloud layers. Summing the individual optical depths is appropriate since the signal associated with each detected feature is removed before moving on to larger horizontal averages.

In addition to overlapping cloud layers, situations can also arise where the CALIPSO 5 km cloud product produces cloud layers which appear immediately adjacent to each other. Figure A1 shows this situation occurring in columns 13 through 16 where feature B3, detected at 20 km, is adjacent to feature C, detected at 80 km. Columns containing such cloud layers are also merged together as outlined above. It is also possible for cloud layers to be completely contained inside other clouds layers. This situation is shown in columns 8 through 11 in Figure A1 where feature B2, detected at 20 km, is completely contained inside feature C, detected at 80 km. These two layers are also merged into single layers in our CALIPSO dataset.

Ignorance of the CALIPSO 5 km cloud product’s multiresolution retrieval can result in spurious scientific conclusions. To illustrate this point Figure A2 shows the number of ice cloud layers per profile calculated by using the cloud layers reported in the 5 km cloud product at face
value. This is in contrast to Figure 7 which uses the merged CALIPSO ice cloud layers. Merging the overlapping cloud layers results in the reduction of the occurrence of multilayer ice cloud profiles by \( \sim 5\% \).

While we have focused on the detection of cloud layers at multiple resolutions here, this method is also used to identify aerosol layers in the CALIPSO 5 km aerosol product. Therefore the same considerations are applicable to the aerosol layers in the CALIPSO 5 km aerosol product.

Appendix B: TTL Cloud Diurnal Biases

The analysis of the diurnal variations of ice cloud properties presented in section 5.5 is repeated here but for TTL cloud properties. Observations using lidar become increasingly difficult during the daytime hours due to increased signal noise. Nighttime-only observations provide a comparison free of retrieval complications due to the solar background. In addition during the night both the ground-based and CALIPSO observations have similar fractions of attenuated profiles (see section 4.2). While during the daytime MPL cloud profiles are frequently attenuated which results in the restricted ground-based datasets being biased toward nighttime observations. By comparison, a much smaller fraction of CALIPSO daytime cloud profiles are attenuated although the fraction of attenuated profiles during the daytime is typical greater than at night.

Figure B1. PDFs of TTL cloud top heights (top row) and cloud base heights (bottom row) from CALIPSO (black line) and ground-based (red line) datasets during the (a) nighttime and (b) daytime. The shaded region represents the 95% confidence interval due to CALIPSO’s sampling uncertainty. The three ARM sites are shown (left to right): Manus, Nauru and Darwin.
Observations of TTL cloud top and base heights for nighttime and daytime observations are given in Figure B1. Analogous to the ice cloud comparisons in section 5.5, nighttime observations of TTL clouds show similar differences between CALIPSO and the ground-based datasets as the PDFs using both day and night together (Figure 5b). Larger differences exist in daytime-only observations but are less striking than for the ice cloud comparisons. Of interest is Nauru, whose daytime observations agree almost as well as the nighttime observations.

TTL cloud PDFs of geometrical thicknesses are given in Figure B2. Unlike the cloud top and base heights, both day and night PDFs show similar agreement between the two sets of observations as the full set of observations do (Figure 6b). Thicker TTL clouds are observed during the night in both the CALIPSO and ground-based datasets. As discussed in section 5.5 this diurnal cycle is likely part real and partly due to the improved SNR at night.

Comparisons of daytime and nighttime TTL cloud optical depths are given in Figure B3. Overall differences between day and night PDFs are similar to those seen using the full sets of observations. As with the ice cloud observations the daytime observations for all four retrieval types typically have less optical depths in the very thinnest bins.
Figure B3
during the daytime. This result is expected since lidar observations will be more sensitive to clouds with thin optical depths during the nighttime due to increased SNR.

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