Retrieval and characterization of cloud liquid water path using airborne passive microwave data during INDOEX

Guosheng Liu
Department of Meteorology, Florida State University, Tallahassee, Florida

Judith A. Curry and Julie A. Haggerty
Program in Atmospheric and Oceanic Sciences, University of Colorado, Boulder, Colorado

Yunfei Fu
Department of Meteorology, Florida State University, Tallahassee, Florida

Abstract. During the 1999 intensive observation period of the Indian Ocean Experiment (INDOEX), the Airborne Imaging Microwave Radiometer (AIMR) was deployed on the National Center for Atmospheric Research (NCAR) C-130 aircraft to measure upwelling microwave radiation that can be used to retrieve cloud liquid water path (LWP). In this study, we present a LWP retrieval algorithm that is optimized for tropical atmospheric conditions, typical of conditions observed in INDOEX. Radiative transfer modeling and error analysis are conducted for the four AIMR channels, to guide selection of AIMR channels used for the LWP retrievals. Results show that the horizontal polarization channels outperform vertical polarization channels at both 37 and 90 GHz. Additionally, for LWP less than ~300 g m\(^{-2}\), the best results are expected from the 90 GHz horizontal polarization channel, while the 37 GHz horizontal polarization channel performs better for higher LWPs. On the basis of these findings we formulated the LWP retrieval algorithm from the combination of the retrievals of 37 and 90 GHz horizontal polarization channels. Results of several indirect validations show that in nearly clear condition the LWP retrievals have essentially no bias and a random error of about 28 g m\(^{-2}\). The image of the retrieved LWP compares well with observations by a 0.64 μm visible channel, and the magnitude of the retrieved LWP for large convective cells is comparable to the estimation based on in situ measurements. It is also shown that the retrieved LWPs for convective cells are smaller than those estimated by assuming adiabatic process while the two have a similar trend in the LWP versus cloud top temperature diagram. By analyzing all available AIMR observations, it is found that the mean LWP for cloudy pixels measured during the INDOEX experiment is about 50 g m\(^{-2}\). A significant north-south gradient of the mean LWP is found in INDOEX domain during this period, with the mean LWP in the region south of 5°S being twice as high as that in the region north of 5°N. The LWP frequency distribution shows that clouds with larger LWPs occur more often in the southern region than in the northern region.

1. Introduction

The Indian Ocean Experiment (INDOEX) is motivated by the increasing awareness of the importance of both anthropogenic and natural aerosols to the Earth’s radiation budget [e.g., Charlson et al., 1992; Andreae, 1995]. The radiative effect of aerosols arises both from the direct effect, i.e., the direct scattering and absorption of sunlight by the particles, and also from the indirect radiative effect, which arises from the effect of sulfate aerosols on cloud microphysical processes and hence influences the radiative properties of the clouds [e.g., Coakley et al., 1987; Radke et al., 1989]. The INDOEX experiment is designed to quantitatively assess the aerosols’ effects on the Earth’s radiation through measuring the radiation budget, aerosol concentration, and clouds over the Indian Ocean.

The Indian Ocean region was selected for this experiment because during the winter monsoon (January–March) the region provides a nearly ideal natural laboratory for observing the direct aerosol radiative forcing. Polluted air flows off the Indian and Southeast Asian subcontinents in the northeasterly flow over the Bay of Bengal, and the Arabian Sea, which for this time of year often have large cloud-free regions. Stratuscumulus that form in the offshore flow are broken and thin, and the cloud cover fraction is typically small. The contrast between the high rates of aerosol emission over the Indian subcontinent and the low rates of emission near intertropical convergence zone, only 1500 km south of the continent, has been observed to give rise to strong gradients in aerosol concentrations [Rhoads et al., 1997; Jayaraman et al., 1998], and is hypothesized to be associated with corresponding gradients in cloud microphysical and optical characteristics.

Copyright 2001 by the American Geophysical Union.

Paper number 2000JD900782.
0148-0227/01/2000JD900782$09.00
Table 1. Main Characteristics of AIMR

<table>
<thead>
<tr>
<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequencies</td>
<td>37 and 90 GHz</td>
</tr>
<tr>
<td>Polarizations</td>
<td>H and V</td>
</tr>
<tr>
<td>Beam width</td>
<td>1° × 2° for 90 GHz, 2.8° for 37 GHz</td>
</tr>
<tr>
<td>Scan mode</td>
<td>Cross scanning ±60° from nadir</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>&lt;1.0 K</td>
</tr>
</tbody>
</table>

In relation to the aerosols’ indirect effect on radiation, the focus of this study is to retrieve and characterize the cloud liquid water path (LWP; vertically integrated cloud liquid water content) using data observed from Airborne Imaging Microwave Radiometer (AIMR) that flew on the National Center for Atmospheric Research (NCAR) C-130 aircraft during INDOEX. Compared to measurements by in situ instruments, AIMR observations cover a much larger area by scanning from -60° to 60° off nadir. Therefore it serves to provide an overall picture of the cloud water characteristics during the experiment.

The emissivity of ocean surface at microwave frequencies is much less than unity although it depends on viewing angles and polarizations [Wilheit et al., 1994]. Thus the presence of cloud liquid water leads to a warmer brightness temperature observed from an aircraft or satellite. Using this property of microwave radiations, a number of physically based algorithms have been developed to retrieve hydrometeor profiles over ocean [e.g., Kummerow and Giglio, 1994; Evans et al., 1995]. Additionally, the intensity of microwave emission from a nonprecipitating liquid water cloud is a function of cloud LWP regardless of the drop size distribution since the drops are Rayleigh scatterers at these wavelengths [Takeda and Liu, 1987]. This property allows us to retrieve cloud LWP without knowing the drop size distribution (Note: this is not the case for precipitating clouds). LWP retrieval algorithms using satellite microwave data, particularly those of Special Sensor Microwave Imager (SSMI), have been developed by several investigators [e.g., Petty, 1990; Greenwald et al., 1993; Liu and Curry, 1993; Lin and Rossow, 1994; Weng and Grody, 1994; Wentz, 1997]. Since the AIMR has different frequencies and scanning mechanism from previous satellite radiometers as described later in section 2, LWP retrieval algorithm has to be developed specifically for AIMR data. In this study, we inherit some of the techniques developed by Liu and Curry [1993], and modify their algorithm for AIMR measurements.

The main focus of this study is to develop a LWP retrieval algorithm that works optimally for AIMR data observed during INDOEX. The targeted clouds are shallow cumulus in a tropical environment. Therefore the developed algorithm will work optimally for tropical shallow convective clouds although it may easily modified for other cloud types and climatological regions. The retrieved LWP products will be archived in INDOEX data center for related studies. We also describe the LWP characteristics of the cumulus clouds observed during INDOEX.

2. Data

The AIMR is a dual-frequency, dual-polarization total power radiometer that measures radiances at 37 and 90 GHz [Collins et al., 1996]. It was originally designed and built for applications to the remote sensing of sea ice. This device was first flown on the NCAR C-130 aircraft during autumn 1994 for the Beaufort Arctic Storms Experiment and later during the Marine Stratocumulus Tops Experiment. After upgrading certain hardware, it was flown during Surface Heat Budget of the Arctic Ocean (SHEBA) experiment in 1998. The INDOEX field experiment provides the first opportunity to examine how well AIMR performs in a tropical environment.

In AIMR brightness temperatures arise due to calibration uncertainties and polarization conversion from the raw data that are a mixture of horizontal and vertical signals. Collins et al. [1996] estimated that the total error is on the order of 0.7 K for 37 GHz and 0.8 K for 90 GHz. Error caused by separating polarizations during data processing increases as the incidence angle approaches zero where the distinction between horizontal and vertical polarization breaks down. However, at nadir the brightness temperatures at horizontal and vertical polarizations should be the same and equal to the mixed raw brightness temperature. To avoid introducing this additional error by polarization conversion, for between plus and minus 10° off nadir we use the mixed raw brightness temperature to retrieve LWP. The retrieval algorithm of this study is capable of being applied to either a single polarization component or a mixture of both polarizations.

![Figure 1. Radiative transfer model simulated relationships between brightness temperatures and scanning angles at the for AIMR channels for liquid water path from 0 to 1015 g m⁻². A standard tropical atmosphere is assumed in the model simulation.](image-url)
Eighteen flights by C-130 aircraft were conducted during the INDOEX experiment from February 16 to March 25, 1999. The region covered by these flights is approximately 10°S–14°N, 66°–76°E. AIMR data were collected, processed, and archived by NCAR Atmospheric Technology Division. For LWP retrieval, only the data collected when C-130 was flying at a fixed altitude over cloud top are usable. All data are from scattered clouds with clear openings, which allows us to derive clear-sky radiance from observed data nearby the clouds.

3. Retrieval Algorithm

3.1. Sensitivity of AIMR Channels to Cloud Liquid Water

To investigate how the AIMR channels respond to cloud liquid water, we first conduct radiative transfer simulations under a similar atmospheric condition to INDOEX. Results of the simulations serve as the theoretical basis for the LWP retrieval algorithm development. The radiative transfer model used here is described by Liu [1998]. The simulated brightness temperatures received by a cross scanning radiometer at 6 km are shown in Figure 1 as a function of LWP and scanning angles (0° to 60°). Brightness temperatures from 0° to -60° (not shown) are symmetric to those from 0° to 60°. A standard tropical atmosphere with the cloud located between 1 and 3 km is assumed. The sea surface temperature used in the model is 300 K, and the surface wind speed is 5 m s⁻¹. Brightness temperatures vary with scanning angle, especially for the 37 GHz vertical polarization channel, because microwave emission from the ocean surface depends on scanning angle and polarization. Vertical polarization channels have greater angular dependence than the horizontal polarization channels. Figure 1 shows that brightness temperature increases with LWP for all channels. For 90 GHz, brightness temperature saturates around 285 K, where the cloud becomes a blackbody at this frequency.

Sensitivity to LWP of these channels is shown in Figure 2, which is defined by the brightness temperature change $\Delta T_B$ caused by an increase of 100 g m⁻² of LWP; that is,

$$S = \frac{\Delta T_B}{\Delta \text{LWP}} \times 100 \quad \text{K gm}^{-2},$$

where $T_B$ is the brightness temperature. From this figure we can draw the following conclusions: First, besides LWP, the sensitivity also depends on scanning angle for all the channels although this dependence is relatively small for the 90 GHz horizontal polarization when LWP is lower than 200 g m⁻². Second, horizontal polarization channels are superior to
vertical polarization channels for all LWP and scanning angle combinations. Because sea surface emissivity is smaller at horizontal polarizations than at vertical polarizations, the background radiation at horizontal polarizations is less; therefore, the dynamic range for brightness temperature to vary with LWP is greater. A drawback of the horizontal polarization channels is that they are more sensitive to surface wind speed. However, this high wind sensitivity is not a major problem for this study, because surface wind speed is low in the INDOEX region and high concentration of low-level water vapor masks some of the brightness temperature variations caused by wind. Finally, the sensitivity is the highest at 90 GHz when LWP is low. As LWP increases, the sensitivity at 37 GHz becomes higher than that at 90 GHz, with the turning point near LWP~300 g m\(^{-2}\) at nadir. For very high scanning angles, 37 GHz has a higher sensitivity than 90 GHz because brightness temperatures at 90 GHz are close to saturation due to the very long slant path at these angles. It should be mentioned that the high water vapor density in the tropics does not improve the overall signal-to-noise ratio of the retrieval by masking the surface wind influence because it also reduces the sensitivity of microwave radiation to LWP, particularly at 90 GHz.

3.2. Description of the Retrieval Algorithm

The framework of the LWP retrieval algorithm is based on the SSM/I version of Liu and Curry [1993]. Unlike most of the other algorithms that are instrument-specific, this algorithm is flexible to be modified for observations at any frequencies, polarizations, and scanning geometries. The cross-scanning nature of the AIMR makes it difficult for other published algorithms to be applied.

On the basis of Liu and Curry [1993], LWP can be expressed as

\[
LWP = \frac{1}{k} \ln \left( \frac{1}{1 - \varepsilon_c} \right) \cos \theta, \tag{2}
\]

where \(k\) is the absorption coefficient for liquid water, and a function of frequency and cloud mean temperature, \(\varepsilon_c\) is the emissivity of the cloud, and \(\theta\) is the incidence angle (0°-60° for AIMR observations). The cloud emissivity \(\varepsilon_c\) is derived from a quadratic equation as follows:

\[
a\varepsilon_c^2 + b\varepsilon_c + c = 0 \tag{3}
\]

and
Table 2. Uncertainties Assumed in Monte Carlo Error Analysis

<table>
<thead>
<tr>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty</td>
</tr>
<tr>
<td>$T_B$</td>
</tr>
<tr>
<td>$T_{B0}$</td>
</tr>
<tr>
<td>$T_C$</td>
</tr>
<tr>
<td>$T_a$</td>
</tr>
<tr>
<td>$T_s$</td>
</tr>
</tbody>
</table>

\[
a = \chi T_c \\
b = T_{B0} - (1 + \chi) T_c \\
c = T_B - T_{B0} \\
\chi = 1 - \frac{T_{B0}}{2} \left( \frac{1}{T_a} + \frac{1}{T_s} \right) \tag{4}
\]

where $T_B$ is the observed brightness temperature over the cloud, $T_{B0}$ is the brightness temperature under clear-sky conditions, $T_c$, $T_a$, and $T_s$ are the temperatures of the cloud (mean), lower atmosphere (weighted by absorption coefficients), and sea surface, respectively. For this study, $T_c$, $T_a$, and $T_s$ are derived on a case-by-case basis from data observed by temperature and humidity probes, and $T_s$ is obtained from a downward looking narrowband infrared radiometer on-board C-130. $T_{B0}$ is derived from the AIMR observed brightness temperatures over the clear regions nearby the clouds, but at the same scanning angles. Since microwave radiation from the ocean surface varies with scanning angle, we have to derive $T_{B0}$ for every scanning angle from $-60^\circ$ to $60^\circ$ off nadir. This is fundamentally different from the algorithms for SSM/I, in which the incidence angles are always the same during a scan due to its conical scan mechanism. Because we derive $T_{B0}$ from AIMR observed brightness temperatures, systematic error (bias) in brightness temperatures (if any) will be cancelled out in our retrieval algorithm, so that it does not affect the retrieved LWP.

Using (2) to (4), LWP can be calculated for each of the four AIMR channels. Next, we will determine the best channel or channel combinations for a specific cloud condition.

3.3. Error Analysis and Final Retrieval Selection

Several approximations have been introduced in developing (2) to (4), for example, assuming that cloud layer emits radiation with a uniform temperature and ignoring the atmospheric emission above cloud layer in part of the

Figure 4. Root mean square (rms) error caused by uncertainties in algorithm’s input variables. These errors are calculated by a Monte Carlo procedure in each all input variables are randomly perturbed within their typical uncertainty range for $10^6$ times. The unit is g m$^{-2}$.
equation [see Liu and Curry, 1993 (A9)]. The error caused by these approximations is assessed by the following procedure. First, we calculate the brightness temperatures under tropical atmospheric conditions using the exact solution of the radiative transfer model. Then (2) to (4) are used to “retrieve” LWP from these calculated brightness temperatures. The retrieved LWPs are then compared to the ones used originally in the radiative transfer model as model input. The difference (retrieved LWP minus original input) is shown in Figure 3 as a function of LWP and scanning angle for the four AIMR channels. This is the error caused by simplifying the exact radiative transfer equation to equations of (2) to (4). At 37 GHz the error caused by these approximations is less than 10 g m$^{-2}$ for any combinations of LWP and scanning angle. At 90 GHz it is less than 10 g m$^{-2}$ for most of the region with LWP<400 g m$^{-2}$. However, there is a sharp increase toward greater LWPs at large viewing angles. Recalling Figures 1 and 2, brightness temperatures at 90 GHz for large LWPs and at large scanning angles are near saturation and have little sensitivity to LWP. Thus, even a small error in the input variables can result in a large error in the retrieved LWP values. Therefore retrieval of LWP using 90 GHz data for large LWPs at large viewing angles should be avoided. It should be mentioned that the error associated with these approximations should be smaller at high latitudes where water vapor concentration is low and the 90 GHz radiation is far from saturation.

The greater error of the retrieval algorithm comes from the uncertainties of input variables in (2) to (4), i.e., $T_b$, $T_{80}$, $T_C$, $T_A$, and $T_S$. The typical uncertainties of these variables are listed in Table 2. $T_b$ is the observed brightness temperature, which has an accuracy of better than ±1 K according to manufacturer’s specification. $T_{80}$ is the clear-sky brightness temperature, which is derived from observations next to the cloudy area. We assume an uncertainty in $T_{80}$ of ±2 K, i.e., twice of that in $T_b$. $T_C$ is the mean temperature of the cloud. It is determined by comparing temperature and humidity data when the aircraft was doing a slant ascent/descent. Because $T_C$ depends on cloud depth, it varies from cloud to cloud. Considering the cloud depth is typically less than 1 km, we assume an uncertainty of ±3 K. Because $T_S$ and $T_A$ are less variable in the tropics, their uncertainties should be small (~±2 K for $T_A$ and ±1 K for $T_S$).

Random error caused by the aforementioned uncertainties can be assessed by a Monte Carlo procedure in which we randomly add noise to the input values within the range specified in Table 2, and compare the “retrieved” to the true (input) LWP. A similar procedure was used by Liu and Curry [2000] in analyzing random error in ice water path retrievals. Figure 4 shows the root mean square (rms) error by randomly perturbing the input variables for 10$^6$ times (We also did the same procedure for 10$^5$ and 10$^7$ times. Those results are very similar to Figure 4). Again, horizontal polarization channels outperform vertical polarization channels for both 37 and 90 GHz. For 37 GHz horizontal polarization channel, the rms error ranges from 10 to 35 g m$^{-2}$ with greater error at low scanning angles and high LWPs. The rms error for 90 GHz horizontal polarization channel ranges from 10 to 45 g m$^{-2}$ with greater error toward larger LWPs. Another error that was not included in the error analysis above arises from the fact that clouds observed during INDOEX have small horizontal scale, so that the radiation at radiometer’s direct line-of-sight is different from that at the reflected line-of-sight for off-nadir viewing observations. This error is very difficult to be assessed although it should decreases as clouds become more uniformly distributed (such as stratocumulus). Additionally, possible error occurs when the relative humidity outside the cloud is much below 100%. This will cause derived $T_{80}$ smaller than actual $T_{80}$ of the cloudy area where the air has a relative humidity of 100%.

From Figures 3 and 4 we may conclude the following: (1) It is preferred to use horizontal polarizations in LWP retrieval algorithms. This is particularly true for tropical and sub-tropical regions, where surface wind speed is generally low.
Plate 1. February 27, 1999, case. (left) MCR 0.64 visible channel image. (right) Image of LWP retrievals. The image covers approximately 12 km (width) by 20 km (length) area.
and water vapor concentration is high. (2) The 90 GHz channel outperforms 37 GHz channel only for clouds with low LWP values, for example, LWP<200 g m$^{-2}$. The saturation of this frequency limits its ability to retrieve high LWPs at high scanning angles. This limitation may be only severe for the tropics. For high latitudes where water vapor concentrations are low, 90 GHz should outperform 37 GHz in a larger range.

On the basis of these results we formulate the final LWP algorithm as following:

\[
\text{LWP}_{90H} = \begin{cases} 
\text{LWP}_{90H} & \text{if LWP}_{90H} < 200 \text{ g m}^{-2}, \\
 f \times \text{LWP}_{90H} + (1-f) \times \text{LWP}_{37H} & \text{if } 200 \leq \text{LWP}_{90H} \leq 400 \text{ g m}^{-2}, \\
\text{LWP}_{90H} & \text{if LWP}_{90H} > 400 \text{ g m}^{-2},
\end{cases}
\]

where $f = 1 - (\text{LWP}_{90H} - 200)/200$, LWP$_{90H}$ and LWP$_{37H}$ are the LWP retrievals for 90 and 37 GHz horizontal polarization channels, respectively. This formulation takes the advantage of the better sensitivity of 90 GHz at low LWPs and the better sensitivity of 37 GHz at high LWPs while keeping a gradual transition.

Figure 6. Vertical profiles of (a) air temperature and dew point, and (b) liquid water content (from four cloud liquid water probes) for an aircraft descent in the area shown in Plate 1.
3.4. Validation

Validation for LWP retrievals has always been the greatest challenge for cloud remote sensing because of the difficulties in obtaining “truth” data. This is particularly the case for the INDOEX study, in which clouds are small in horizontal scale (several hundred meters to several kilometers). It is virtually impossible to sample the vertical profile of liquid water content for the same cloud from aircraft in situ measurements. A slant ascending or descending of an aircraft always crosses several cells and measures liquid water content for these cells at different altitudes. For this reason, we are unable to conduct a direct validation for the retrieved LWP. Instead, we show some indirect evidence that supports the validity of our retrievals.

First, we check whether the algorithm produces zero LWP under clear conditions. From all available AIMR data, we selected 11 time intervals (each time interval corresponds to one original AIMR data file), during which we find little clouds from the nadir looking infrared radiometer data, or mostly clear conditions. These 11 time intervals contain 1,068,869 AIMR pixels for each channel. Using the retrieval algorithm, LWP values are calculated and their frequency distribution is given in Figure 5. The frequency is defined by the percentage ratio of number of pixels in each 10 g m\(^{-2}\) LWP bin to total pixel number in all bins. The LWP values show a normal distribution with maximum frequency near zero. The mean and standard deviation of the retrievals are 7 g m\(^{-2}\) and 28 g m\(^{-2}\), respectively. Since there might be clouds off nadir in these “clear” scenes (note: the frequency distribution is slightly skewed toward positive side), the slight positive bias may not be a problem for the algorithm. The standard deviation is an indication of the magnitude of the random error in the retrievals, which is about 28 g m\(^{-2}\). Therefore we may conclude that for small LWP values the algorithm does not have significant systematic error (or bias) while its random error is about 28 g m\(^{-2}\). The random error seems to be somewhat larger than our theoretical estimation (10 to 20 g m\(^{-2}\)) as shown in the error analysis section. However, considering that there may be uncertainties unaccounted for in the error analysis, particularly the noise in the raw radiometer data introduced by either hardware problem or during initial data processing (as shown below), we believe that the magnitude of the random error shown here is within the predicted range. For large LWP values these errors can increase as shown in the error analysis section, although it is difficult to assess their actual magnitude.

Next, we conduct a case study to examine the performance of the algorithm. In Plate 1, we show the images of 0.64 μm (visible) instrument counts (left) that is proportional to reflected radiance from Multi-Channel Radiometer (MCR) and the retrieved LWP values (right) for 0654Z to 0657Z on February 27, 1999. The width of the image corresponds to ~12 km, while the length is about 20 km. Since the MCR has a better spatial resolution (~35 m versus ~100 m for 90 GHz and ~200 for 37 GHz of AIMR) and greater sensitivity for thinner clouds, the visible image shows sharp cloud outlines compared to AIMR image. Despite this difference, the general patterns of the clouds (even for some very small cells) are the same. This consistency implies that the retrievals are at least qualitatively correct in identifying clouds. It is also noticed that the AIMR LWP image is noisier than the visible image, e.g., the horizontal stripes. The stripes can also be seen in the brightness temperature data, so are not introduced in the retrieval algorithm. It is not clear that they are introduced mechanically by the instrument or during post-observation data processing. Further investigation in this area is desired to improve quality of AIMR data. In any case, this noise adds random error shown in Figure 5. By improving the brightness temperature data, the retrieval algorithm could reduce random error to better than 28 g m\(^{-2}\).

Soon after taking this image, the aircraft made a slant descent to survey the clouds just observed from above cloud top. Figure 6 shows the vertical profiles of temperature and dew point (Figure 6a), and liquid water content (from four cloud water probes) (Figure 6b) during the descent. It is seen that the aircraft first encounters the cloud around 0710:00 at an altitude of ~1300 m. The liquid water content at that point is ~1.2 g m\(^{-2}\). It continues to encounter clouds until 0714:00 at an altitude of ~700 m. Because it is a slant descent, the liquid water contents are not from the same cloud at different times. It is more likely that each spike of the liquid water content in the profile corresponds to an individual cloud, separated by clear areas in between. However, it is reasonable to assume that most of the clouds have a similar cloud base height. Therefore the tallest cloud encountered by the aircraft is about 600 m in depth (i.e., from 700 to 1300 m) and has 1.2 g m\(^{-2}\) liquid water content near its top. Since liquid water content in cumulus clouds usually increases linearly with height, we may roughly estimate the liquid water path for this cell to be about 360 g m\(^{-2}\) [i.e., 600×(1.2+0.0)/2 = 360 g m\(^{-2}\)]. This value is comparable to the largest LWP values from several of the biggest cells shown in Plate 1. This comparison is a very crude and indirect verification, because there is no guarantee that the tallest cell encountered by the aircraft is similar to those in Plate 1. However, given the fact that no other more adequate validation data are available, this comparison at least indicates that the retrieved LWP for large cumuli are not unreasonable.
assumed that pixels with retrieved LWP smaller than 7 g m$^{-2}$ are clear-sky pixels, and they are not included in the statistics. The frequency distribution of the retrieved LWP values is shown in Figure 8. To better show the contributions of large LWPs, a logarithmic scale is used for the frequency axis. Clouds with the smallest LWP have the highest frequency, which is consistent with earlier satellite observations [e.g., Curry et al., 1990; Lin and Rosow, 1994]. The mean LWP for all these cloudy pixels is 50 g m$^{-2}$. The frequency of occurrence for clouds with LWP greater than 100 g m$^{-2}$ is on the order of 1% or less.

One of the major goals of INDOEX is to study the north-south gradient of radiative effect due to the gradient in aerosol concentration. To understand the north-south gradient of aerosol indirect radiative effect, we need to know the difference in cloud liquid water between northern and southern part of the region because cloud albedo varies with both LWP and cloud particle size [Han et al., 1998]. In Figure 9, we show the latitudinal distribution of the mean LWP in every 5° increment. The mean LWP increases from northern to southern part of the region with the southermost region having twice as much cloud liquid water compared to the northermmost region. This trend can also be seen in the LWP frequency distributions shown in Figure 10. The frequency for larger LWP values is greater in the southern regions than in the northern regions, while the northern part of the region contains more clouds with low LWP values. This difference may be mainly due to the fact that convections in the northern part are suppressed by the large-scale subsidence in the subtropical anticyclone. It is not clear how this difference plays a role in determining the effective particle size of cloud droplets. However, it is plausible that a deeper cloud has both

4. Characteristics of Liquid Water Path During INDOEX

Using the algorithm presented in section 3, LWP retrievals have been done for AIMR data collected during INDOEX. A total of 11,230,177 pixels are determined by the algorithm as cloudy pixels (i.e., LWP>7 g m$^{-2}$, the bias of clear-sky LWPs), which count about half of the total pixels observed. We
a higher LWP and a larger effective radius. If this is the case, we would expect that the effective radius in southern part is larger than that in northern part, even without including the aerosol effect. The aerosol effect is also likely to cause smaller cloud particles in the northern part because of the higher aerosol concentration. It is necessary to keep this natural variability in mind when interpreting the effect of aerosol on cloud particle size and cloud radiative effect.

5. Conclusions

A LWP retrieval algorithm for AIMR observations is presented in this study. Although this algorithm can be applied to other atmospheric conditions, it is optimized here for tropical and subtropical conditions. Radiative transfer simulations have been conducted first to investigate the response of brightness temperatures to LWP variations at the four AIMR channels. The results indicate that at the same frequency horizontal polarization channels have higher sensitivities than vertical polarization channels. Of the two horizontal polarization channels, the sensitivity at 90 GHz is higher for LWP less than 300 g m\(^{-2}\), while brightness temperatures at 37 GHz become more sensitive for larger LWPs. The low sensitivity at 90 GHz for high LWPs arises from the brightness temperature saturation, especially for high scanning angles.

The framework of the retrieval algorithm is based on the SSM/I version of Liu and Curry [1993], but with substantial modifications. The biggest difference of AIMR from SSM/I is its cross-scanning mechanism, which causes the background sea surface emission to change constantly with scanning angle. Before selecting which channel is optimal for a certain cloud condition, we first conducted error analysis for the four AIMR channels. It is found that the horizontal polarization channels outperform vertical polarization channels at both 37 and 90 GHz. Additionally, for LWP less than 300 g m\(^{-2}\), the best results are expected from 90 GHz horizontal polarization channel, while 37 GHz horizontal polarization works better for higher LWPs. On the basis of these findings we formulated the final LWP retrieval as a combination of the retrievals from 37 and 90 GHz horizontal polarization channels.

The following indirect validations have been done: analyzing retrieved LWP values under clear conditions, and comparing with visible reflectivity images, in situ liquid water content measurements and cloud top temperatures. The results show that near clear conditions the retrievals do not have significant bias and the random error is about 28 g m\(^{-2}\); the image of retrieved LWP compares well with the cloud cells observed by 0.64 μm visible channel; and the magnitude of retrieved LWP for large convective cells is comparable to the estimation based on in situ measurements of liquid water content. It is also shown that the retrieved LWPs for convective cells are smaller than those estimated by assuming adiabatic process while the two have a similar trend in the LWP versus cloud top temperature diagram. It should be mentioned that the validation conducted in the study is not ideal although we could not find a better way given the data that were available. As LWP is an important parameter in determining the cloud radiative effect, it is highly desired to have a special experiment in the future that is dedicated to the algorithm validation.

The mean LWP for cloudy pixels measured during the INDOEX experiment is about 50 g m\(^{-2}\). A large north-south gradient of the mean LWP is found in the INDOEX domain during this period, with the mean LWP south of 5°S being about twice as high as those north of 5°N. By examining the LWP frequency distributions, it is found that clouds with larger LWPs occur more often in the southern region. It is argued that cloud particle size in the southern clouds may also be larger because these clouds are deeper. This difference in microphysical properties between northern and southern parts in the INDOEX domain should be considered when interpreting the aerosol effect on cloud properties.

In this study, we mainly focused on the LWP retrieval using AIMR data. In the future, cloud LWP data from AIMR and cloud reflectivity data from MCR will be jointly analyzed to retrieve both LWP and particle effective radius. The variation of the retrieved effective radius will be examined in the context of aerosol effects on cloud microphysics and on cloud radiative properties, which is one of central themes of INDOEX.

Acknowledgments. We thank scientists and engineers at NCAR, especially Craig Walther, in collecting the AIMR data during INDOEX and processing them after the experiment. James Coakley Jr. kindly provided the MCR image for the case study. Comments from two anonymous reviewers are very helpful. This research has been supported by NSF INDOEX grants ATM-9910640 and ATM-0002860. J. Curry’s participation in this project was funded by a grant from DOE ARM.

References


J. A. Curry and J. A. Haggerty, Program in Atmospheric and oceanic Sciences, University of Colorado, Boulder, CO.

Y. Fu and G. Liu (corresponding author), Department of Meteorology, Florida State University, Tallahassee, FL 32306-4520. (liug@met.fsu.edu)

(Received July 20, 2000; revised October 17, 2000; accepted October 27, 2000.)