Determination of precipitable water and cloud liquid water over oceans from the NOAA 15 advanced microwave sounding unit

Norman Grody,1 Jiang Zhao,2 Ralph Ferraro,1 Fuzhong Weng,1 and Reinout Boers3

Abstract. The advanced microwave sounding unit (AMSU) was finally launched in May 1998 aboard the NOAA 15 satellite. Algorithms are provided for retrieving the total precipitable water (TPW) and cloud liquid water (CLW) over oceans using the AMSU measurements at 23.8 and 31.4 GHz. Extensive comparisons are made between the AMSU retrievals of CLW and TPW and those obtained using other satellite instruments (Special Sensor Microwave Imager (SSM/I) and Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI)) and ground-based radiometers. The AMSU TPW is also compared against radiosonde data, where all of the results are in good agreement with rms differences less than 3 mm and biases less than 1 mm over the range between 5 and 60 mm. The CLW comparisons show greater variability, although the time series of the AMSU and ground-based sensors follow each other and cover the same dynamic range of 0 – 0.5 mm. The AMSU CLW also compares well with the other satellite measurements, although a bias exists between AMSU and TMI when the CLW exceeds 0.5 mm.

1. Introduction

Microwave radiometers aboard satellites have been used to measure a wide variety of atmospheric and surface parameters. This paper is concerned with two of the most directly measured parameters, the total precipitable water (TPW) and cloud liquid water (CLW) over oceans [Grody et al., 1980]. Much of our knowledge about the spatial distribution of TPW and CLW is acquired from satellite microwave radiometers [e.g., Prabhakara et al., 1983; Weng and Grody, 1994]. For moist areas such as the Intertropical Convergence Zone the TPW and CLW exceed 50 mm and 1 mm, respectively. Conversely, the TPW and CLW are less than 10 mm and 0.1 mm, respectively, in areas having persistent subsidence (e.g., subtropical high). Some of the most extensive analysis of these parameters was obtained following the launch of the Special Sensor Microwave Imager (SSM/I) aboard the DMSP satellites. Both statistical and physical algorithms were developed and validated using different data sets [Alishouse et al., 1990a, 1990b; Greenwald et al., 1993; Weng and Grody, 1994; Wentz, 1997]. These efforts promoted the application of the TPW and CLW by numerical models [Deblonde and Wagneur, 1997] and climate analysis [Jackson and Stephens, 1995; Trenberth and Guillemot, 1995].

This study uses data from the latest microwave instrument, called the advanced microwave sounding unit (AMSU). The instrument was launched in May 1998 aboard the NOAA 15 satellite and consists of three separate radiometers, where one is a dual-frequency radiometer operating at 23.8 and 31.4 GHz. This dual-frequency radiometer is used to determine the TPW and CLW over oceans as well as other parameters [Grody et al., 2000]. The algorithms are developed in section 3, and the TPW is validated in section 4 using radiosonde data and ground-based radiometer measurements. Comparisons are also made between the AMSU, SSM/I, and Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) measurements of TPW. Section 5 describes the validation of the CLW, using ground-based microwave radiometer measurements. Additional AMSU comparisons of CLW are made in section 6 using the SSM/I and TMI.

2. AMSU Instrument

The advanced microwave sounding unit (AMSU) is the second, and most advanced, microwave instrument launched by NOAA. It contains 20 channels and is a replacement of the four-channel microwave sounding unit (MSU), which was first launched on TIROS-N in 1978. The AMSU was primarily designed to obtain soundings, i.e., vertical profiles of atmospheric temperature and water vapor. As such, the AMSU contains 12 channels within the 50 – 60 GHz oxygen band and five channels around the 183 GHz water vapor line. In order to improve the soundings near the surface, AMSU also contains window channels at 23.8, 31.4, and 89 GHz.

To optimize the sensors performance, the 20 channels are divided among three separate total power radiometers, AMSU-A1, AMSU-A2, and AMSU-B. Each radiometer uses a cross-track scanner to view Earth, where AMSU-A1 and -A2 (denoted collectively as AMSU-A) have an instantaneous field of view (IFOV) of 50 km at nadir, while AMSU-B has an IFOV of 16 km. Figure 1 shows the three AMSU modules along with their channel frequencies and IFOV at nadir. More detailed information is given in Table 1 and will be discussed later. The AMSU-B module contains three channels around the 183 GHz water vapor line for water vapor profiling, while the 89 and 150 GHz channels are used mainly to identify
precipitation. The AMSU-A1 module contains 12 channels within the 50–60 GHz portion of the oxygen band for deriving temperature profiles, in addition to an 89 GHz channel. Of particular importance to this study is the AMSU-A2 module, which has channels at 23.8 and 31.4 GHz to obtain the TPW and CLW over oceans. As mentioned next, these channels are also used in combination with the 89 GHz channel on the AMSU-A1 module to obtain rain rates, snow cover, and sea ice concentration.

At the present time, AMSU covers the largest spectral range of any microwave instrument launched in space. This is shown in Figure 2, by displaying the 20 AMSU channels (including their bandwidths) on the overall brightness temperature spectra seen from space (top graph). An expanded portion is given in the bottom graph for the 50–60 GHz oxygen band. Figure 2 was generated using clear atmosphere simulations over land ($\varepsilon_s = 0.95$) and ocean ($\varepsilon_s = 0.5$). Of particular importance here are the two lowest frequency channels (1 and 2), which occupy the most transparent regions of the spectrum, so that the brightness temperatures depend strongly on surface emissivity $\varepsilon_s$ as well as the emission from the intervening atmosphere by water vapor and clouds. As mentioned above, these lowest-frequency channels were originally included to improve the soundings near the surface. However, they are now used together with those at higher frequencies (15, 16, and 17) to derive a number of hydrological products ([Grody et al., 2000]). These products include rainfall, snow cover, total precipitable water, and cloud liquid water, which when combined with those derived from other instruments (e.g., SSM/I), can expand the spatial and temporal coverage available from polar-orbiting satellites.

Table 1 lists some of the main channel characteristics of AMSU-A, including the channel central frequencies, number of bands, bandwidth, and radiometric temperature sensitivity (or noise equivalent delta temperature (NEDT)) for each channel. The main beam and cross-polarization beam efficiencies as well as beam widths for each AMSU-A channel were calculated using measured antenna patterns ([Mo, 1999]) and are also listed in Table 1. Each of the AMSU-A antenna systems has a nominal IFOV of 3.3° at the half-power points and scans across the Earth within a maximum angle of ±48° (beam centers) from the nadir direction. The antenna reflectors rotate one complete revolution every 8 s, during which 30 Earth scene resolution cells (also referred to as beam positions, each separated by 3°20') will be sampled in a stepped-scan fashion. Onboard calibration is obtained by viewing the cold space cosmic background temperature (2.7 K) and an internal blackbody target every 8 s for each scan line. Beam positions 1 and 30 are the extreme scan positions of the Earth views, while beam positions 15 and 16 are at 1°40' and -1°40' from the nadir direction, respectively. Table 1 also lists for reference the channel characteristics of AMSU-B, which has one third the IFOV of AMSU-A and 90 beam positions.

The thermal radiation emitted by the Earth’s surface acquires a preferential orientation of polarization depending on the surface geometry (i.e., its roughness). The projection parallel to the surface is called the horizontal component, while the other is referred to as the vertical component. For the

Table 1. Characteristics and Specifications of AMSU^a

<table>
<thead>
<tr>
<th>Center Frequency, MHz</th>
<th>Number of Bands</th>
<th>Bandwidth (3 dB Measured), MHz</th>
<th>NEDT (Measured), K</th>
<th>Beam Efficiency (Cross-Polarization), %</th>
<th>Nadir</th>
<th>Beamwidth (3 dB Measured), deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 23,800</td>
<td>1</td>
<td>251</td>
<td>0.30 (0.21)</td>
<td>95 (1.6)</td>
<td>V</td>
<td>3.5</td>
</tr>
<tr>
<td>2 31,400</td>
<td>1</td>
<td>161</td>
<td>0.30 (0.26)</td>
<td>97 (1.2)</td>
<td>V</td>
<td>3.4</td>
</tr>
<tr>
<td>3 50,299</td>
<td>1</td>
<td>161</td>
<td>0.40 (0.22)</td>
<td>95 (2.4)</td>
<td>V</td>
<td>3.7</td>
</tr>
<tr>
<td>4 52,799</td>
<td>1</td>
<td>380</td>
<td>0.25 (0.14)</td>
<td>95 (1.2)</td>
<td>V</td>
<td>3.7</td>
</tr>
<tr>
<td>5 53,596 ± 115</td>
<td>2</td>
<td>168, 168</td>
<td>0.25 (0.15)</td>
<td>95 (1.4)</td>
<td>H</td>
<td>3.7</td>
</tr>
<tr>
<td>6 54,400</td>
<td>1</td>
<td>380</td>
<td>0.25 (0.13)</td>
<td>95 (1.6)</td>
<td>H</td>
<td>3.6</td>
</tr>
<tr>
<td>7 54,940</td>
<td>1</td>
<td>380</td>
<td>0.25 (0.14)</td>
<td>95 (1.5)</td>
<td>V</td>
<td>3.6</td>
</tr>
<tr>
<td>8 55,500</td>
<td>1</td>
<td>310</td>
<td>0.25 (0.23)</td>
<td>95 (1.4)</td>
<td>H</td>
<td>3.6</td>
</tr>
<tr>
<td>9 $f_c = 57,290,344$</td>
<td>1</td>
<td>310</td>
<td>0.25 (0.25)</td>
<td>96 (1.3)</td>
<td>H</td>
<td>3.5</td>
</tr>
<tr>
<td>10 $f_c = 217$</td>
<td>2</td>
<td>75, 76</td>
<td>0.40 (0.28)</td>
<td>96 (1.3)</td>
<td>H</td>
<td>3.5</td>
</tr>
<tr>
<td>11 $f_c = 322.2 ± 48$</td>
<td>4</td>
<td>35, 35, 35, 35</td>
<td>0.40 (0.40)</td>
<td>96 (1.3)</td>
<td>H</td>
<td>3.5</td>
</tr>
<tr>
<td>12 $f_c = 322.2 ± 22$</td>
<td>4</td>
<td>15, 15, 15, 15</td>
<td>0.60 (0.54)</td>
<td>96 (1.3)</td>
<td>H</td>
<td>3.5</td>
</tr>
<tr>
<td>13 $f_c = 322.2 ± 10$</td>
<td>4</td>
<td>8.8, 8.8, 8.8</td>
<td>0.80 (0.91)</td>
<td>96 (1.3)</td>
<td>H</td>
<td>3.5</td>
</tr>
<tr>
<td>14 $f_c = 322.2 ± 4.5$</td>
<td>4</td>
<td>3.3, 3.3</td>
<td>1.20 (0.91)</td>
<td>96 (1.3)</td>
<td>H</td>
<td>3.5</td>
</tr>
<tr>
<td>15 89,000</td>
<td>1</td>
<td>2000</td>
<td>0.50 (0.17)</td>
<td>98 (1.4)</td>
<td>V</td>
<td>3.5</td>
</tr>
<tr>
<td>16 89,000</td>
<td>1</td>
<td>1000</td>
<td>1.0 (0.37)</td>
<td>&gt;95</td>
<td>V</td>
<td>1.1</td>
</tr>
<tr>
<td>17 150,000</td>
<td>1</td>
<td>1000</td>
<td>1.0 (0.84)</td>
<td>&gt;95</td>
<td>V</td>
<td>1.1</td>
</tr>
<tr>
<td>18 183,000 ± 1000</td>
<td>2</td>
<td>500, 500</td>
<td>1.1 (1.06)</td>
<td>&gt;95</td>
<td>V</td>
<td>1.1</td>
</tr>
<tr>
<td>19 183,000 ± 3000</td>
<td>2</td>
<td>1000, 1000</td>
<td>1.0 (0.70)</td>
<td>&gt;95</td>
<td>V</td>
<td>1.1</td>
</tr>
<tr>
<td>20 183,000 ± 7000</td>
<td>2</td>
<td>2000, 2000</td>
<td>1.2 (0.60)</td>
<td>&gt;95</td>
<td>V</td>
<td>1.1</td>
</tr>
</tbody>
</table>

^aNEDT, noise equivalent delta temperature; V, vertical; H, horizontal.
AMSU instrument the received polarization varies with scan angle because of the rotating-reflector/fixed-feed horn antenna design. This is different from that of a conical scanning radiometer such as the SSM/I, which receives a fixed polarization independent of scan. At a given scan angle \( \theta_s \), the normalized surface emitted radiation (i.e., emissivity) \( \varepsilon_s \) seen by AMSU contains mixed vertical, \( \varepsilon_V \), and horizontal, \( \varepsilon_H \), polarization's (the very small cross-polarized contribution is neglected, which is because of imperfect cross-polarization isolation in the antenna), i.e.,

\[
\varepsilon_s = \varepsilon_V(\theta) \cos^2 \theta_s + \varepsilon_H(\theta) \sin^2 \theta_s,
\]

where the local zenith angle \( \theta \) varies as a function of scan angle \( \theta_s \). The two angles are related by \( \theta = \sin^{-1} \left[ (1 + H/R) \sin \theta_s \right] \), where \( R \) is the Earth's radius of 6371.2 km and \( H \) is the height of the satellite, which is approximately 870 km for the NOAA-KLM series.

Equation (1) is used to define the emissivity for the 23.8, 31.4, and 50.3 GHz channels. For a sea surface the emissivity components \( \varepsilon_V \) and \( \varepsilon_H \) can be calculated using the Fresnel formula for calm seas [Klein and Swift, 1977] together with an empirical model that includes the effects of wind-driven foam and surface roughness on emissivity [e.g., Wentz et al., 1986]. Figure 3 shows the calculated emissivity at the three frequencies for a calm ocean surface at a temperature of 285 K and salinity of 36 parts per thousand. It should be noted that the emissivity is vertically polarized at nadir (\( \theta_s = 0^\circ \)) and varies slightly with zenith angle.

### 3. Algorithm Formulation

The theoretical development of the TPW and CLW algorithms given here closely follows the process used to derive the algorithms for the SSM/I, but is modified to allow some differences between the SSM/I and AMSU. Besides the differences in frequencies (i.e., SSM/I channels are at 19.35, 22.23, 37, and 85 GHz), the SSM/I views Earth at a fixed local zenith angle of 53.1°, while AMSU-A views Earth with local zenith angle varying as a function of scan angle.

Figure 2. Simulated brightness temperatures over land (\( \varepsilon_s = 0.95 \)) and ocean (\( \varepsilon_s = 0.5 \)) for a cloud-free, standard atmosphere having 25 mm of H\(_2\)O vapor. (top) Full spectrum. (bottom) An expanded portion around the O\(_2\) band. The 20 AMSU channels are indicated in both graphs.
angles ranging from 1.2° to 57.3° from the nadir direction. The varying zenith angle alters the surface emissivity, increases the path length through the atmosphere (i.e., limb effect), and enlarges the footprint as the instrument scans from nadir. All of these factors except the effect of varying footprint size were included in the radiative transfer simulations used to generate the prelaunch algorithms [Grody et al., 2000].

The brightness temperatures measured by AMSU-A contain three contributions, the surface emission, the upwelling atmospheric radiation, and the downwelling atmospheric radiation reflected at the surface. For window channels where only the spheric radiation, and the downwelling atmospheric radiation three contributions, the surface emission, the upwelling atmospheric radiation and surface conditions.

The atmospheric transmittance depends primarily on the atmospheric absorptions due to water vapor and liquid water. As such, the emissivity in (4) is constant, so that the brightness temperature at frequency $\nu$ can be approximated as

$$T_B \approx T_s \{1 - \tau_s \exp (1 - e_s)\},$$

where $T_s$ is the surface temperature and $\tau_s$ is the atmospheric transmittance. Surface emissivity depends on frequency, polarization, and local zenith and scan angles and is given by (1). The atmospheric transmittance depends primarily on the TPW, and CLW and can be expressed as

$$\tau_s = \exp \left\{ -\left(\frac{TPW}{V_s} + CLW/Q_s + \kappa_s\right)\right\},$$

where the parameters $V_s$ and $Q_s$ are a function of frequency $\nu$. The parameter $Q_s$ also depends on the cloud temperature and drop size distribution. In the simulations discussed at the end of this section, the temperature dependence of $Q_s$ is included, but the drop size dependence is neglected by only modeling nonprecipitating clouds whose drops are much smaller than the radiation wavelength. Also included in (3) is the absorption to oxygen, $\kappa_s$, which is only a function of frequency.

After combining (2) and (3) we obtain the expression

$$\begin{align*}
TPW & = C_0 + C_1 \ln \left[ T_s - T_B(\nu_1) \right] \\
& + C_1 \ln \left[ T_s - T_B(\nu_2) \right], \\
CLW & = D_0 + D_1 \ln \left[ T_s - T_B(\nu_1) \right] \\
& + D_2 \ln \left[ T_s - T_B(\nu_2) \right].
\end{align*}$$

The major angle dependence in (5a) and (5b) arises from the common factor $\cos \theta$. Because of the oxygen absorption term in (4) the coefficients $C_0$ and $D_0$ are also a function of $\theta$ and can be accurately represented as a quadratic function of $\cos \theta$,

$$C_0 = \alpha + \beta \cos \theta + \gamma \cos^2 \theta,$$

where all of the coefficients in (5a), (5b), (6a), and (6b) are obtained using radiative transfer simulations of the AMSU measurements for a variety of zenith angles and atmospheric and surface conditions.

Equations (5a) and (5b) suggest that any two-window channels can be used to retrieve the TPW and CLW with equal accuracy for isothermal atmospheres. In general, however, for nonisothermal atmospheres, (2) and (4) contain an additional terms that depend on the difference between surface and cloud temperature. This temperature difference cannot be inferred from the AMSU measurements and therefore represents a noise source. Fortunately, the effect of this “noise” on retrieval accuracy can be reduced by properly choosing the channels. The optimal channel combination is obtained by performing regression analysis on the simulated AMSU measurements. Of all the AMSU channels, the 23.8 and 31.4 GHz channels generally perform the best. As discussed next, the coefficients in (5a) and (5b) are obtained by performing regression analysis on the simulated AMSU-A2 channel measurements with $T_s$ set to 285 K.

Simulated brightness temperatures at 23.8 and 31.4 GHz were obtained using the radiative transfer equation with the latest absorption models for oxygen and water vapor [Rosenkranz, 1998]. Brightness temperatures are calculated using radiosonde profiles of temperature and water vapor from the midlatitudes to the tropics so that the TPW varied from 5 to 70 mm. For each profile, nonprecipitating clouds were introduced at low, middle, and high levels, and the corresponding CLW varied from 0 to a maximum of 0.5 mm for warm clouds. Also, for each data set the sea surface emissivity was varied using winds at 0, 5, 10, and 15 m/s. To cover the range of AMSU-A scan positions, each set of simulations were performed at seven local zenith angles, from 0° to 60° with 10° steps. At each angle a total of 752 different combinations of atmospheric and surface conditions were used to produce the simulated brightness temperatures for each channel frequency. The coefficients in (5a), (5b), (6a), and (6b) are obtained by regressing the dependent variables of TPW/$\cos \theta$ and CLW/$\cos \theta$ against the predictors $\ln \left[ T_s - T_B(\nu) \right]$ at the two frequencies. To ensure that $T_s > T_B(\nu)$ under all conditions, $T_s = 285$ K is chosen. The resulting algorithms are given by (5a) and (5b) with $\nu_1 = 23.8$ GHz and $\nu_2 = 31.4$ GHz, and the coefficients are found to be
The simulated data set (used in determining the coefficients). The total number of data in both plots is 5264 (752 \times 7 ranges) with a mean TPW of 23.4 mm and a mean CLW of 0.17 mm. The resulting rms error of the retrieved TPW is 0.76 mm (top graph) while the rms error of the CLW is 0.048 mm (bottom graph).

\[ C_0 = 247.92 - [69.235 - 44.177 \cos(\theta)] \cos(\theta), \quad (7a) \]
\[ C_1 = -116.27, \quad C_2 = 73.409 \quad (7b) \]
\[ D_0 = 8.240 - [2.622 - 1.846 \cos(\theta)] \cos(\theta), \quad (7c) \]
\[ D_1 = 0.754, \quad D_2 = -2.265. \quad (7d) \]

Figure 4 shows the scatterplots of the retrieved precipitable water and cloud liquid water against the values contained in Figure 4. (a) Retrieved precipitable water using equations (7a) and (7b) versus the actual values in the data set. (b) Retrieved cloud liquid water using equations (7c) and (7d) versus the actual data values. Other TPW products. An adjustment to the algorithm was implemented based on a four-month rain-free (CLW < 0.2 mm) RAOB match-up. The adjustment of (5a) is given as

\[ TPW_{adj} = 0.942\ TPW - 2.17, \quad (8) \]

where the 0.942 slope parameter can be physically related to a model transmittance error at 23.8 GHz while the -2.17 intercept parameter can be associated with sensor calibration errors. The adjustment coefficients are consistent with those found using independent match-up data obtained following the adjustment. As such, these adjustments are considered stable so that (8) is the operational algorithm currently used by NOAA.

During the SSM/I TPW validation [Alishouse et al., 1990a] it was discovered that there were potential sources of errors in both the satellite data and the RAOB data that could not be accounted for. By assuming that the errors are normally distributed, a statistical trim was used to reduce the errors. A similar trim procedure was implemented in the AMSU validation with RAOB data. Figure 6 shows the scatterplot of the AMSU TPW against RAOB TPW for the ±3 hour data set. The 5% worst match-up data from both sides of the distribution (which are also shown in the plot) were excluded. This reduces the effects of poor quality match-up data on the validation. In this plot and in our current operational system we produce AMSU TPW only under the condition that the CLW is less than 0.6 mm to reduce precipitation contamination, although it is not clear yet how precipitation affects the TPW retrieval. The scatterplot shows good agreement between the two data sets with a 0.9 mm bias and a 3 mm rms difference. We should also mention that during our validation work we found that the bias varies at different geographical locations.
For example, the AMSU TPW usually produces a positive bias in the tropical Pacific sites but has a negative bias in the North Atlantic sites. We suspect that this is maybe due to the different RAOBs but have not performed any further analysis at this time.

4.2. Validation With ARM MWR Data

The ARM sites are located at Manus Island (147.43°E, 2.05°S) and Nauru Island (166.916°E, 0.521°S). At each of these sites, ground-based microwave radiometers (MWR) make observations every 20 s at the AMSU-A2 frequencies of 23.8 and 31.4 GHz and are used to derive the TPW and CLW [Han and Westwater, 1995]. The accuracy of the TPW measurements relative to RAOBs was less than 1.3 mm for Denver, Colorado. Compared to satellite instruments, which view the ocean background, ground-based microwave radiometers observe the colder and more stable space as a background. This should result in a greater accuracy for the MWR compared to satellite measurements. Westwater et al. [1999] compared the MWR observations of TPW during PROBE in the tropical western Pacific with RAOB data and obtained a 3.7 mm rms difference between two data sets. It is interesting to note that although the ground-based measurements are expected to be more accurate than the satellite observations, both the MWR and AMSU measurements result in nearly the same rms difference when compared against RAOB measurements for the western Pacific region. This ~3 mm difference is much larger than the ~1 mm algorithm errors determined from simulations, which suggests that much of the difference is attributed to the RAOBs.

When using the MWR for validation of AMSU, it is possible to account for the different spatial scales of the two sensors by time averaging the MWR measurements [Weng and Grody, 1994]. In this study, 1 hour average MWR data were used. Also, to avoid the contamination effect due to heavy precipitation, the match-up data are filtered out when either the MWR or AMSU CLW is greater than 0.6 mm.

The daily MWR data at the Manus ARM site were processed from July 1998 to March 1999. It is found that the large size of Manus Island can produce land contamination if the AMSU footprint approaches the island. Therefore the AMSU measurements closest to the ARM site may not provide good validation. If land contamination is suspected on the basis of geographical distances, we therefore switch to the next closest AMSU measurement and check again until we find a “clean” IFOV within 100 km of the ARM site. Figures 7 and 8 show scatterplots and time series of the MWR and selected AMSU TPW, with most footprints within 0.5–1.0° of the ARM site. Figure 7 is for the descending (~1930 local time (LT)), and Figure 8 is for ascending orbits (~0730 LT). The results show that both the magnitude and the temporal changes of the AMSU TPW agree very well with the MWR measurements. Statistical analysis of the scatterplots results in an AMSU bias of ~0.5 mm with an rms difference of less than 3 mm compared to the ARM data. Since the statistical results are about the same for the ascending and descending AMSU measure-
ments, only the descending orbital data will be shown from here on.

The daily MWR data were also processed at the Nauru ARM site from November 1998 to July 1999. Unlike Manus Island, Nauru is a small island compared with the AMSU FOV (Nauru is ~30 km²), so that land contamination is not a problem and we can simply use the closest AMSU measurements. Figure 9 shows the plots obtained for the descending AMSU match-ups. For this ARM site the bias is 0.1 mm, and the rms difference is 1.5 mm. These smaller differences may be attributed to the fact that the AMSU measurements are closer to the Nauru site than for the Manus validation.

4.3. Validation With Cape Grim MWR Data

Another independent data set of TPW was obtained using the MWR from Cape Grim, Tasmania. This site is in a different climatic region than are the ARM sites. Data from August to September 1998 were collected and reanalyzed into hourly averages. Considering the geographic and meteorological features of Cape Grim, we decided to compare the MWR data with AMSU measurements north or west to the cape. As in the Manus Island site, the AMSU data very close to the cape were excluded from the match-up data to avoid land contamination.

Figure 10 shows the time series and scatterplot of the two data sets for the AMSU footprints located north of Cape Grim. The plots combine both the ascending and descending match-up data. Effects due to heavy precipitation are eliminated by filtering out the match-ups when the AMSU CLW is greater than 0.6 mm. Both the time series and the scatterplots compare well in most cases, although the AMSU TPW is generally higher than the MWR measurements by 1.86 mm. This bias is likely due to the elevation (~300 m) of the Cape Grim MWR measurement, which results in a 1.8 mm underestimation of TPW compared to sea level observations.

4.4. Intercomparison of AMSU TPW With Other Sensors

The AMSU TPW was also compared with that obtained from the SSM/I and TMI. Daily global images from the different satellite instruments are found to exhibit similar spatial patterns. In order to obtain a quantitative comparison we calculated the zonal means and produced scatterplots. As an example, Figure 11 shows the daily zonal means (averaging ascending and descending data) in the Northern Hemisphere for August 16, 1999 (Figure 11a), and February 3, 2000 (Figure 11b). The SSM/I (F-13) and TMI products were obtained from Remote Sensing System’s Web site; their SSM/I products were calculated on the basis of the temperature data record (TDR) [Wentz, 1997]. Figure 11 shows that the AMSU, TMI, and
SSM/I have very similar latitudinal distributions. Since the SSM/I and AMSU have a gap in the time of observation while TMI may have some records matching the AMSU time, we also performed a space-time match-up of AMSU against the TMI data. Figure 12 is the scatterplot of the matched AMSU and TMI for August 16, 1999 (Figure 12a), and February 3, 2000 (Figure 12b). Ascending and descending data are combined here, and the time difference between the two observations is less than 10 min. Generally, the two products agree well, having rms differences of less than 3 mm. The largest differences appear in the midrange of TPW (30–50 mm).

5. Validation of AMSU CLW

After examining numerous AMSU measurements over clear ocean areas a bias of 0.03 mm was found in the algorithm. The adjustment of (5b) is therefore given as

\[ \text{CLW}_{\text{adj}} = \text{CLW} - 0.03. \]  

Validation of the AMSU CLW is difficult because of the lack of direct observations. Just as in the case of TPW, the best remote observations of CLW are obtained using ground-based microwave radiometers. In sections 5.1 and 5.2, the CLW measurements are validated against the MWR data from the ARM sites and Cape Grim. The AMSU measurements are also compared against the CLW measured from the SSM/I and TMI.

5.1. Validation With MWR Data

As part of the SSM/I validation effort, MWR observations were used to validate and improve the CLW algorithm [Alishouse et al., 1990b; Weng and Grody, 1994]. In these studies, coincident observations of SSM/I and MWR data were intercompared. To compensate for the large IFOV of the satellite measurements, the ground-based data were time averaged. In our validation, time-averaged MWR data are also used to account for the large IFOV of the AMSU measurements. However, for periods when the MWR CLW showed large temporal variability within the hour, we only used the instantaneous ARM data. For the Cape Grim data, CSIRO provided carefully processed 1 hour averaged MWR measurements, and we simply interpolated the data to the AMSU ascending and descending times.

Since the clouds over the ARM sites are often tropical cumulus, they are generally small relative to the AMSU IFOV with little uniformity. Also, as mentioned in section 4.2, land contamination is a problem for the Manus Island site since the AMSU match-ups cannot be very close to the island. This presents a match-up problem since the CLW can be highly variable over short distances. Therefore, instead of selecting the closest “clean” footprint (as for the TPW validation) we chose the best matched AMSU CLW within a 1° latitude-longitude distance of the site. The match-up plots of the two products are given in Figure 13 for the descending AMSU data. These plots show relatively good agreement between the AMSU and MWR CLW. To be consistent, we analyzed the Nauru data the same way as for Manus Island. Figure 14 shows the scatterplots of the descending and ascending AMSU data matched up with the MWR measurements over Nauru. The differences between the satellite and ground-based CLW measurements are similar to those of the Manus Island match-ups.

Figure 15 shows the match-ups of AMSU and the MWR measurements of CLW for the Cape Grim site over the period...
between August and September 1998. In Figure 15 we filtered out the match-up data when AMSU CLW is greater than 0.6 mm. In general, the time series of the AMSU and MWR CLW agree with one another. However, the scatterplot shows that AMSU has a slight negative bias, especially for high CLW amounts.

5.2. Intercomparison of CLW From Different Satellites

The AMSU measurements of CLW were also intercompared with SSM/I and TMI measurements. Although the spatial variability is not a large problem for satellite data, the temporal variability of CLW makes the validation difficult when the satellites have different orbit times. To obtain quantitative comparisons, the daily averaged zonal mean CLW from AMSU, SSM/I, and TMI are compared in Figure 16. The plots show the zonal means for August 16, 1999 (Figure 16a), and February 3, 2000 (Figure 16b). All three satellite instruments display similar latitude distribution, but there are differences in magnitude between the different instruments. Changing the scale factor in the CLW algorithms can minimize these differences. For example, in the case of the AMSU algorithm (9) this adjustment could take the form $CLW_{\text{adj}} = \text{const}(CLW - 0.03)$.

As we did for the TPW, comparisons are made between the AMSU and TMI CLW measurements. Though the time differences between the two satellite observations are kept within 10 min, large differences were still found between the two products. In order to study the differences between the two measurements the data are grouped according to the TMI CLW. Figure 17 shows the average and standard deviation of satellite measurements. The diamonds, connected by dashed lines, show the mean of the grouped CLW data, with the horizontal lines indicating the range of each group. The verti-

![Figure 12](scatterplot_of_AMSU_and_TMI_TPW_for(a)August_16_1999,(b)February_3_2000.png)

**Figure 12.** Scatterplot of AMSU and TMI TPW for (a) August 16, 1999, and (b) February 3, 2000.

![Figure 13](scatterplot_of_best_matched_descending_AMSU_and_Manus_MWR_CLW.png)

**Figure 13.** (a) Time series and (b) scatterplot of best matched descending AMSU and Manus MWR CLW.

![Figure 14](scatterplots_of_descending_and_ascending_AMSU_versus_Nauru_MWR_CLW.png)

**Figure 14.** Scatterplots of (a) descending and (b) ascending AMSU versus Nauru MWR CLW.
cal lines define the standard deviation of the AMSU CLW within each group. From these plots it seems that AMSU CLW is nearly the same as the TMI CLW for CLW < 0.5 mm. However, the two products diverge for larger CLW. This difference for large liquid water may be due to the smaller IFOV for TMI (15 km) compared to AMSU.

6. Conclusions

Over the past 2 years, much work has been done on the validation and improvement of the AMSU TPW and CLW algorithms. The AMSU TPW has been compared against measurements from RAOBs and ground-based microwave radiometers (MWR) as well as other microwave satellite instruments (SSM/I and TMI). All of these data were in good agreement, with scatterplots showing rms differences of less than 3 mm and biases of less than 1 mm over the range between 5 and 60 mm. In addition to the use of scatterplots the AMSU measurements also displayed zonal means similar to those of the other satellite instruments.

Because of the large variability of CLW in both space and time and the lack of good-quality independent data, validation of the AMSU CLW is more difficult than that of TPW. The best source of validation is MWR measurements. However, it was difficult to compare the AMSU measurements close to the MWR site without encountering contamination by large land bodies. Therefore, in some cases (i.e., Manus Island) we used the best match-ups within 100 km of the site. Also, in tropical areas like the ARM sites, small-scaled and quick-changing cloud make the comparison even more complicated. Though the validation results are not as good as those of TPW, the time...
series of AMSU and MWR CLW generally follow each other quite well and are in the same range. The AMSU also matches well with other satellite CLW products, although a bias exists between the AMSU and TMI for high CLW amounts.

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