Satellite-Based Tropical Cyclone Intensity Estimation Using the NOAA-KLM Series Advanced Microwave Sounding Unit (AMSU)

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ABSTRACT

Satellite-borne passive microwave radiometers, such as the Advanced Microwave Sounding Unit (AMSU) on the NOAA polar-orbiting series, are well suited to monitor tropical cyclones (TCs) by virtue of their ability to assess changes in tropospheric warm core structure in the presence of clouds. The temporal variability in TC upper-tropospheric warm anomaly (UTWA) size, structure, and magnitude provides vital information on changes in kinematic structure and minimum sea level pressure (MSLP) through well-established thermodynamic and dynamic principles. This study outlines the aspects of several factors affecting the effective AMSU measurement accuracy of UTWAs, including the practical application of a previously developed maximum likelihood regression algorithm designed to explicitly correct for TC scan geometry and UTWA–antenna gain pattern interaction issues (UTWA subsampling) unique to TC warm core applications. This single-channel AMSU approach (54.96 GHz) is the first step toward a more elaborate multichannel application that is currently under study. Independent application of the single-channel algorithm in the Atlantic and eastern Pacific basins in 2000 and 2001 demonstrates that AMSU-derived UTWAs are moderately correlated with coincident TC MSLP. In addition, further improvements in correlation, and MSLP estimate accuracy, are possible through application of the proposed corrective retrieval algorithm, provided that 1) accurate estimates of TC eye size (a proxy for the UTWA horizontal dimension) are available and 2) the peak upper-tropospheric warming represented by the AMSU-A 54.94-GHz radiances corresponds with the actual TC thermal structure. This study recommends potential remedies for both of these algorithm skill prerequisites that include the incorporation of improved eye size estimates from ancillary data sources and/or the utilization of additional AMSU-A upper-tropospheric sounding channels.

1. Introduction

The 2001 Northern Hemisphere hurricane season marked the third year of passive microwave warm core observations using the National Oceanic and Atmospheric Administration’s K, L, and M satellite series (NOAA-KLM) Advanced Microwave Sounding Unit (AMSU). Over the past two decades, several authors (Kidder et al. 1978, 2000; Velden et al. 1991; Spencer and Braswell 2001) have documented the virtues of monitoring tropical cyclone (TC) intensity using satellite-borne passive microwave radiance data. In all of these studies, measurements (55-GHz region) of TC upper-tropospheric warm anomalies (UTWAs) are linked to either surface wind structure or minimum sea level pressure (MSLP) using thermodynamic and dynamic constraints on the TC scale (i.e., several hundred kilometers). With the launch of AMSU in May 1998, vertical cross sections of mature TCs derived from 48-km horizontal resolution (nadir) AMSU-A radiance observations are now possible (Fig. 1). These observations are often strikingly similar to classic composites created using aircraft and radiosonde data (Koteswaram 1967; Hawkins and Rubsam 1968).

Merrill (1995) first introduced the concept of passive microwave radiometer observation “effective accuracy” and demonstrated that, for a variable horizontal resolution instrument like the AMSU-A, the TC UTWA resolving limit is a complex function of several parameters including AMSU-A scan angle (ϕ), AMSU-A scan angle off-axis angle (θ), UTWA horizontal scale (R), and scattering by mixed-phase hydrometeors. Due to the ephemeral nature of TC position within the AMSU-A scan swath (ϕ, θ) and variation in UTWA horizontal scale (R) between successive AMSU-A observations (Fig. 2), there exists a component of the measured UTWA temporal variability that is purely instrument related versus change that reflects actual thermodynamic (and TC intensity) structure change. This introduces er-
Fig. 1. Hurricane Floyd 1238 UTC 14 Sep 1999 temperature anomaly (contour interval 2°C) derived from NOAA-15 AMSU-A radiance data. An UTWA of approximately 18°C was observed at 250 hPa. Aircraft reconnaissance reported an MSLP value of 924 hPa at 1113 UTC.

Fig. 2. A schematic diagram illustrating the complex interaction between a TC UTWA and the AMSU-A antenna gain pattern as a function of instrument scan angle ($\phi$), off-axis angle ($\theta$), and UTWA horizontal scale.

ror into statistical regression schemes that attempt to directly relate 55-GHz-region UTWA observations with TC MSLP or maximum surface wind ($V_{\text{max}}$). The aforementioned effects are nontrivial and have limited past attempts to develop and implement satellite-based TC passive microwave intensity estimation techniques.

The remainder of this paper describes the adaptation, test, and evaluation of an algorithm designed to explicitly model and ameliorate the effects of AMSU-A instrument scan geometry according to the methodology prescribed by Merrill (1995). Section 2 describes the satellite data and in situ observations used in this study followed by a description in section 3 of the salient features of the maximum likelihood retrieval algorithm. Section 4 describes the results of fully automated, independent algorithm tests in the Atlantic (ATL) and eastern Pacific (EPAC) basins during 2000/01 where TC MSLP was estimated using raw and scan-geometry-corrected (hereafter referred to as retrieved) UTWA information derived from limb-corrected AMSU-A 54.94-GHz brightness temperature data. Notable TC cases are discussed and the impact of ancillary information used to optimize the algorithm’s analytic UTWA first-guess structure function is investigated. A summary and concluding remarks, including a discussion of near-future initiatives, are provided in section 5.
2. Data

Global AMSU temperature (AMSU-A) and moisture sounder (AMSU-B) earth observation radiance data are routinely provided by NOAA/National Environmental Satellite, Data, and Information Service (NESDIS) to the University of Wisconsin—Madison (UW) Space Science and Engineering Center (SSEC) Cooperative Institute for Meteorological Satellite Studies (CIMSS) in near–real time. Average time delays between AMSU TC observation and SSEC/CIMSS receipt range from 1 to 3 h based on several factors including TC location, internal NOAA/NESDIS processing and quality control, telecommunications network load, etc. The time delay rarely exceeds 3 h.

Development of the 1999 dependent dataset required the identification and manual retrieval of NOAA-15 AMSU-A/B orbits providing TC coverage. Visualization of orbit coverage (near–real time and postevent) and determination of precise TC overpass time (UTC) were made possible using the UW—SSEC Man—computer Interactive Data Access System (McIDAS) (Suomi et al. 1983). The entire satellite navigation/acquisition process was automated for independent test processing, as well as in support of future research and development activities, and is discussed in more detail in section 4. Radio frequency interference with the NOAA-15 AMSU-B instrument in 1998 (subsequently fixed in 1999) prohibited inclusion of 1998 data into the retrieval development sample.

ATL and EPAC basin TC reconnaissance observations from the United States Air Force Reserve 53rd Weather Reconnaissance Squadron and NOAA were used to 1) develop dependent test regression coefficients relating raw/retrieved AMSU-A UTWAs to aircraft reconnaissance estimates of MSLP and 2) validate independent test results. The selection of AMSU/aircraft reconnaissance “match pairs,” for both dependent and independent samples, were based on the time difference between aircraft reconnaissance and AMSU-A observations, and environmental conditions. Only those observations that occurred within ±6 h and during which time the TC was not undergoing significant intensity change due to interaction with land, wind shear, etc. were considered.

3. Forward model

As discussed in section 1, AMSU-A horizontal resolution varies from approximately 48 km near satellite nadir to over 100 km near scan limb (see Fig. 2). As TCs intensify, the combined effects of eye subsidence and high inertial stability within the inner-eyewall region increasingly constrain the horizontal dimensions of peak TC UTWA warming (Schubert and Hack 1982) to scales less than possible even under the most optimal AMSU-A viewing conditions (i.e., $\phi = 0^\circ$, $\theta = 0^\circ$). As a result, the true magnitude of TC UTWAs will typically be subsampled for all but a small minority of TCs possessing large eyes (and corresponding UTWA horizontal scales) or for average-sized systems that happen to fall fortuitously at the center of an AMSU-A Field of View (FOV) near satellite nadir. In reality, TCs are characterized by a wide variety of horizontal scales and can fall anywhere within the AMSU-A scan swath; therefore, knowledge of the effects of storm horizontal scale and instrument scan geometry ($\phi$, $\theta$) are vital steps toward “correcting” the TC UTWA measurements and obtaining more accurate MSLP estimates.

The approach used in this study is based on the methodology proposed by Merrill (1995) using previous-generation Microwave Sounding Unit (MSU) data. Adopting Merrill’s technique for use with AMSU-A, the observed 54.94-GHz horizontal brightness temperature distribution $B_{\text{obs}}(x, y)$, using a storm-centered cross-hair pattern of nine AMSU-A FOVs from which the TC UTWA is estimated, is considered a convolution of the true upper-tropospheric thermal distribution $B_{\text{true}}(x, y)$ and the antenna gain pattern $F(x, y, \nu)$ (Fig. 3). This can be represented mathematically as

$$B_{\text{obs}}(x, y, \nu) = \int \int B_{\text{true}}(x, y) F(x, y, \nu) \, dA,$$  

assuming that 1) the atmosphere is sufficiently opaque at $\nu = 54.94$ GHz so that the surface emission term can be neglected, 2) the frequency-dependent weighting function does not vary significantly over the atmospheric layer depth characterized by the peak upper-tropospheric warming, and 3) scattering by mixed-phase hydrometeors is negligible (see section 5). The antenna gain pattern $F(x, y, \nu)$ for off-nadir scan angle $\phi$ is uniquely prescribed based on the diffraction pattern of a uniformly illuminated circular aperture:

$$F(\phi, \theta, \nu) \sim 4[J_1(\nu d \sin \theta)/\nu d \sin \theta]^2,$$  

where $J_1$ is a Bessel function (first kind, order one), $\nu$ is the frequency of incident radiation (54.94 GHz), $d$ is the AMSU-A instrument bore sight aperture (m), and $\theta$ is the scan angle off-axis angle defined by the displacement of the TC low-level circulation center (LLCC) from the center of the AMSU-A FOV containing the peak UTWA warming (see Fig. 2). Finally, $dA$ represents the area formed by the intersection of the AMSU-A antenna gain pattern with the earth’s surface (see Fig. 3c).

With the premise that TCs are in hydrostatic balance at the storm scale, the true upper-tropospheric thermal distribution $B_{\text{true}}(x, y)$ is assumed to mirror the surface pressure distribution. A first-order approximation of $B_{\text{true}}(x, y)$ is modeled after Holland (1980):

$$B_{\text{true}}(x, y) \sim B(x, y, \mathbf{X}) = B_{\text{env}} + \text{delta}_x B[1 - \exp(-R/r)] + B_x(x - x_0)B_y(y - y_0),$$  

where $B_{\text{env}}$ represents the background thermal distribution, $\text{delta}_x$ is the horizontal scale of the UTWA, $R$ is the radius of the TC eye (m), $r$ is the radial distance from the eye center (m), and $B_x$ and $B_y$ are the horizontal scales of the UTWA in the $x$ and $y$ directions, respectively.
Fig. 3. A schematic diagram illustrating the concept of true TC UTWA convolution with the AMSU-A antenna gain pattern for Hurricane Floyd at 1238 UTC 14 Sep 1999. (a) NOAA-15 advanced very high resolution radiometer (AVHRR) multispectral image, (b) hypothetical “true” upper-tropospheric thermal structure for select AMSU-A FOVs, (c) spatial dimension of individual AMSU-A FOVs as a function of scan angle, and (d) convolution of (b) and (c). AVHRR image courtesy of D. Santek, UW—SSEC.

where $B_{\text{env}}$ represents undisturbed environmental conditions, $\Delta B$ the UTWA magnitude for a mature TC, and $B_x$, $B_y$, the storm environmental derivatives (baroclinic terms), $x$ and $y$ the position relative to TC center $(x_c, y_c)$, and $r = (|x - x_c|^2 + |y - y_c|^2)^{1/2}$. The term within curly brackets $\{ \}$ defines the shape of the radial distribution of the UTWA as a function of distance $r$ from the TC center. In addition, $R$, which represents the horizontal scale of peak warming, is a vital component of (3) and must be prescribed accurately in order to maximize the representativeness of $B_{\text{true}}(x, y)$ in the forward model; $\gamma$ is a dimensionless shape factor whose magnitude influences the slope of the UTWA as a function of distance $r$ from the storm center; and $X$ represents a tunable TC UTWA horizontal structure function (column vector) consisting of eight parameters,

$$X = [B_{\text{env}}, \Delta B, R, \gamma, B_x, B_y, x_c, y_c]^T,$$

all of which, with the exception of $R$, $x_c$, and $y_c$, are initially assigned a priori constraint ($X_{\text{con}}$) mean values and error variances based on satellite- or aircraft-reconnaissance-derived parameter climatologies (Merrill 1995). In this study, the TC UTWA horizontal scale parameter $R$ is defined through the spatial analysis of AMSU-B 89.0-GHz moisture sounder window channel radiance data (Fig. 4). AMSU-B 89.0-GHz radiances are strongly attenuated by convection within the TC eyewall region (Kidder et al. 2000) and therefore can be used as a proxy for eye size. A fourth-degree newton interpolating polynomial (Cheney and Kincaid 1985) $F(r)$ is fit to the radial distribution of AMSU-B 89.0-GHz radiance data and $R$ is assigned at the first occurrence of $|\delta^2F(r)/\delta r^2| = 0$ (inflection point) coincident with reduced AMSU-B 89.0-GHz brightness temperatures characteristic of hydrometeor scattering within the eyewall region. The final $R$ value is found by averaging up to four separate $R$ estimates from each radial direction in AMSU-B brightness temperature array line-element space. The TC position $(x_c, y_c)$ is determined using published forecast discussion bulletins generated by the National Hurricane Center (NHC) with finescale adjustments based on linear extrapolation of position based on projected TC translation velocity and the time differential between the initial position assessment and the time of AMSU observation.

Once the constraint structure vector $X_{\text{con}}$ (4) is specified, it is used by the forward model to estimate the expected radiance distribution $B_{\text{true}}^m(x, y, X_m)$, where $X_m$ is the $m$th iterated storm structure vector. This process is repeated until the difference between the observed AMSU-A radiance distributions $B_{\text{obs}}(x, y, X_m)$ are minimized. At each iterative step, $X_m$ is perturbed according to the method proposed by Rodgers (1976):
$X_{m+1} = X^\text{con} + S^\text{con} K^m (K^m S^\text{con} K^m + S_{yy})^{-1} \times [Y_{\text{obs}} - Y_m - K_m (X^\text{con} - X_m)],$ (5)

where $X^\text{con}$ is the constraint (a priori) storm structure vector, $S^\text{con}$ the constraint structure error covariance, $K_m$ the forward model sensitivity to changes in the structure vector (i.e., $\partial B^\text{con}(x, y, X_m)/\partial X_m$), and $S_{yy}$ the AMSU-A observation error covariance. Based on (5), the maximum likelihood solution for the storm structure function $X^\text{con}(X_m, m \rightarrow \infty)$, including the retrieved UTWA (delta $\delta B^\text{con}$), occurs when the differences between the observed AMSU-A radiances $B_{\text{obs}}$ and forward model radiances $B_{\text{con}}$ and the forward model sensitivity-weighted difference between the constraint storm structure $X^\text{con}$ and $m$th iteration structure $X_m$ are the same. Finally, the scan geometry and diffraction-corrected UTWA (delta $\delta B^\text{con}$) are retrieved through inversion of the solution structure function $X^\text{con}$.

At this point it is assumed that the retrieved TC UTWA (represented by delta $\delta B^\text{con}$) represents the best estimate of true upper-tropospheric thermal structure and, therefore, is optimized for statistical regression against in situ MSLP observations with minimum variance. The ability of the retrieval algorithm (5) to resolve $X^\text{con}$, and therefore $\delta B^\text{con}$, depends highly on the accuracy of the constraint storm structure $X^\text{con}$. As noted by Merrill (1995), the solution storm structure $X^\text{con}$ will always fall between $X^\text{con}$ and the value of $X$ that best produces the AMSU-A observed radiance distribution $B_{\text{obs}}$. Whether the actual AMSU-A observation or constraint is favored depends upon the expected constraint structure error covariance $S^\text{con}$, the expected observation variance (noise) $S_{yy}$, and the sensitivity of the forward model to changes in the storm structure $K_m$. Here, $S^\text{con} \rightarrow 0$ implies that $X^\text{con}$ is a good estimate of the storm structure and the solution will favor the constraint with zero variance. On the other hand, $S^\text{con} \rightarrow \infty$ implies $X^\text{con}$ is a poor estimate of the storm structure and the solution tends toward the inversion of the forward model. Both $S_{yy}$ and $K_m$ are coupled in the sense that accurate AMSU-A observations (i.e., $S_{yy} \rightarrow 0$) or large forward model sensitivities $K_m$ (i.e., favorable viewing geometry $\rightarrow$ satellite nadir, FOV centered) cause the algorithm to favor the solution of the forward model whereas $S_{yy} \rightarrow \infty$ or small $K_m$ (i.e., unfavorable view geometry $\rightarrow$ satellite limb, non-FOV-centered) favor the constraint $X^\text{con}$.

During 1999, 22 ATL cases that satisfied the criteria specified in section 2 were used to develop dependent sample regression coefficients and equations relating AMSU TC UTWA observations to MSLP. Three parallel experiments were conducted using identical NOAA-15 AMSU-A and in situ MSLP datasets (Fig. 5). The first experiment relates the raw AMSU-A 54.94-GHz-derived UTWA (delta $\delta B$) with in situ MSLP estimates while the other two experiments relate the retrieved UTWA (delta $\delta B^\text{con}$) with in situ MSLP estimates after explicitly treating and removing the scan geometry and diffraction effects. Of the two experiments in which the retrieval algorithm was applied, one used a fixed climatological horizontal scale parameter of 24 km (Weatherford and Gray 1988) while the other used variable $R$ values derived using AMSU-B 89.0-GHz radiance data. The test results demonstrate that while some degree of correlation ($R^2 = 0.58$) exists between raw delta $\delta B$ and MSLP, improvements are possible using the retrieval with either fixed ($R^2 = 0.64$) or AMSU-B 89.0-GHz-derived $R$ values ($R^2 = 0.74$).

In summary, the results of the 1999 dependent test—enhanced TC UTWA sampling leading to improved correlation with reconnaissance MSLP estimates—appear to validate Merrill’s earlier hypothesis on the nature and degree of passive microwave TC UTWA subsampling and support the application of the proposed retrieval algorithm. Owing to the relative success of the depen-
dent test on TC cases in 1999, a series of independent tests were conducted on cases in 2000 and 2001 and are described in detail in the next section.

4. Independent algorithm tests

A series of independent tests were performed using TC cases from 2000 and 2001 (Atlantic and east Pacific). A fully automated, objective processing scheme was employed (Fig. 6). The TC MSLP was diagnosed in 2000 using the following regression coefficients derived from the 1999 dependent sample,

\[
\begin{align*}
\text{MSLP}_{\text{ret}} &= (157.9 - \delta B_{\text{ret}}) / 0.16 \\
\text{MSLP}_{\text{raw}} &= (68.9 - \delta B_{\text{raw}}) / 0.07,
\end{align*}
\]  

whereas a slightly modified set of regression equations was used in 2001,

\[
\begin{align*}
\text{MSLP}_{\text{ret}} &= (150.7 - \delta B_{\text{ret}}) / 0.15 \\
\text{MSLP}_{\text{raw}} &= (65.4 - \delta B_{\text{raw}}) / 0.07,
\end{align*}
\]  

based on the increased 1999 + 2000 sample size \((N = 53)\). Processing during both seasons was “event driven”, based on TC position estimates provided within NHC/Joint Typhoon Warning Center (JTWC) forecast discussion bulletins (step 1). Based on TC position, AMSU-A/B observation data were acquired, the size parameter \(R\) determined, and the forward model run using AMSU-A FOV scan angles (\(\phi\)) and off-axis angles (\(\theta\)) (step 2) leading to estimates of raw (\(\delta B_{\text{raw}}\)) and retrieved (\(\delta B_{\text{ret}}\)) UTWA (step 3) magnitudes. During the final step (step 4), TC MSLP was diagnosed using the aforementioned regression equations.

Overall, the 2000 ATL–EPAC independent test was successful and further reinforced the 1999-dependent test results (Fig. 7). Application of the retrieval yielded \(\delta B_{\text{ret}}\) values more highly correlated with reconnaissance estimates of MSLP than using the raw \(\delta B_{\text{raw}}\) values (\(R^2 = 0.86\) versus 0.62). It is also noteworthy that the retrieval algorithm appears to reinforce the linear relationship between passive-microwave-observed TC UTWAs and MSLP.

Based on the findings in 2000, a “hybrid” approach was adopted in which MSLP was diagnosed using the raw AMSU equations when the UTWA magnitude was less than 1°C, and the retrieved MSLP estimates when the UTWA magnitude exceeded 1°C. While the 1°C raw UTWA threshold is empirically based, it is founded on the underlying principles of when explicit correction for UTWA subsampling is required using AMSU. For example, during the incipient stages of TC genesis (raw values usually <1°C), the UTWA scale is relatively large owing to the lack of an eyewall that horizontally constrains peak inner core region warming (subsidence branch from secondary circulation). Therefore, attempts to correct for AMSU subsampling during the early stages of TC growth are not necessary.

The results of the 2001 independent test (Fig. 8) were generally inferior to those of 2000. Several suspected factors contributing to poor hybrid retrieval performance in 2001 include the following:

- an unusual number of TC eye sizes were significantly smaller than the limits of AMSU resolvability (“pinhole” eyes),
- nonrepresentative automated eye size estimates using the proposed AMSU-B 89.0-GHz technique, and
- inability of the single-channel approach and associated horizontal structure function to account for UTWA warming observed at levels other than resolved by AMSU-A 54.94 GHz.

A good example of the AMSU TC MSLP retrieval
Fig. 6. A diagram illustrating 2000/2001 independent test automated processing. Clockwise from the upper-left-hand corner: determination of AMSU TC coverage and data acquisition based on NHC (or JTWC) forecast discussion bulletin initial/12-h forecast positioning, determination of $R$, AMSU-A FOV navigation, and convolution of structure function $X$ with the AMSU-A antenna gain pattern, determination of $\Delta \theta_B$ and $\Delta \theta_B^\text{ret}$, and raw/retrieved MSLP using 1999/2000 regression coefficients.

Fig. 7. A comparison of 2000 ATL–EPAC AMSU-A 54.94-GHz (channel 7) raw (red diamonds) and retrieved TC UTWA (blue circles) magnitude (°C) vs aircraft-reconnaissance-observed MSLP (hPa).
algorithm sensitivity to eye size is illustrated by Hurricane Juliette (EPAC), 21 September–3 October 2001 (Fig. 9a). Hurricane Juliette rapidly intensified on 25 September 2001, attaining an MSLP of 923 hPa with a reported eye as small as 10 n mi (18 km) in diameter (Fig. 9b). Under these circumstances, the horizontal scale of Juliette’s UTWA is considerably smaller than even the most optimal horizontal resolution of the AMSU-A (48 km at nadir), resulting in significant underestimation of MSLP using raw (and subsampled) UTWA observations (green line). The lack of retrieved MSLP estimates (blue line) from 1200 UTC 25 September to 0000 UTC 27 September 2001 reflects automated processing constraints, namely that no retrieval was attempted for TCs positioned on the limb of the AMSU-A scan swath due to a lack of confidence in AMSU-B 89.0-GHz-derived eye size estimates under those circumstances. Even when Juliette’s position within each instrument scan swath is nonlimb in character, horizontal resolution limits of the AMSU-B (16.3 km at nadir, degrading as scan angle $\phi$ increases) preclude accurate eye size estimation for systems like Juliette with unusually small, or pinhole, eyes (Fig. 9c). When improved eye size information is made available to the retrieval algorithm [e.g., from the Automated Tropical Cyclone Forecast (ATCF) package (C. R. Sampson 2001, personal communication)], the retrieval performance improves dramatically (red line) and provides a much more realistic assessment of intensity.

Owing to the potential positive impact of ancillary eye size information on the retrieval performance for Hurricane Juliette, and in the context of the degraded 2001 independent test results, the authors investigated the incorporation of ATCF eye size information for each case processed in 2001 (all other factors being held constant). The ATCF eye size values are obtained from the global TC forecast centers and are a result of careful interrogation of multiple data sources. The results are summarized in Table 1. In general, access and incorporation of ancillary ATCF eye size information improves the performance of the retrieval MSLP estimates with mean error and standard deviations reduced below both raw and original retrieval (using AMSU-B 89.0-GHz-derived eye size estimates) values. Of paramount importance is the fact that the availability of accurate eye size estimates, when coupled with the retrieval, leads to superior MSLP estimate skill relative to what is possible using raw AMSU-A 54.94-GHz UTWA observations alone.

A detailed investigation of Hurricane Michelle, 31 October–6 November 2001, suggests that the current form of the AMSU MSLP retrieval algorithm (based solely on single-channel 54.94-GHz TC UTWA observations) may occasionally be limited during circumstances in which the TC upper-tropospheric warming is not adequately represented by the AMSU-A 54.94-GHz channel (Fig. 10). This can occur from two scenarios: 1) Scattering from hydrometeors (precipitation contamination) can occasionally creep into the signal in very deep convection, resulting in a “cooling” of the radiances. If this convection is very near the eye, the contamination may bleed into the eye field of view, thereby reducing the UTWA signal. 2) The actual peak warming in the TC may be occurring at levels other than that sensed by the 54.96-GHz channel. During Hurricane Michelle’s period of maximum intensification near 1800 UTC 2 November 2001 until approximately 1800 UTC 4 November 2001, the AMSU-A 55.5-GHz (channel 8

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**Figure 8.** A comparison of 2001 ATL–EPAL AMSU-A 54.94-GHz (channel 7) raw (red diamonds), retrieved (black triangles, using AMSU-B 89-GHz-derived $R$ values), retrieved (blue circles, using ATCF-derived $R$ values) TC UTWA magnitude ($^\circ$C) vs aircraft reconnaissance observed MSLP (hPa). A comparison with AMSU-A 55.5-GHz (channel 8) raw TC UTWA (green squares) vs aircraft-reconnaissance-observed MSLP (hPa) is also provided.
with higher-altitude weighting function peak ~150 hPa) UTWA exceeds that observed in AMSU-A 54.94-GHz (channel 7) data. Under these circumstances, even with improved eye size estimates, the retrieval algorithm will have difficulty adequately deducing MSLP since the UTWA observed by the 54.94-GHz channel no longer represents the true level of peak warming.

5. Summary and conclusions

An algorithm to retrieve TC intensity (MSLP) from single-channel AMSU observations has been developed and tested. The algorithm attempts to explicitly correct for the undersampling of TC upper-level warm anomalies due to the relatively coarse resolution of the AMSU footprints. After applying and evaluating the retrieval algorithm over a 3-yr period (the first year to train the algorithm followed by two years of independent testing), results indicate the microwave technique has promise for offering an alternative satellite-based method to complement the commonly utilized Dvorak IR technique (Dvorak 1975). Several factors have been identified that can affect AMSU retrieval performance including 1) accuracy of the automated specification of TC position at the time of AMSU observation, 2) the accuracy of the automated objective estimation of TC eye size (proxy for UTWA scaling), and 3) circumstances in which peak upper-tropospheric warming associated with the TC is not fully characterized by the single-channel (54.94 GHz) observations. A factor associated with factor 3 involves the occasional impact of hydrometeor scattering within the eyewall region and the associated
Table 1. Independent test results for 2000 and 2001: AMSU-derived MSLP estimate mean error and standard deviation. Raw represents MSLP estimates derived using raw delta_B values, Ret (AMSU-B) represents hybrid MSLP estimates derived using both raw (delta_B < 1°C) and retrieved UTWA values (delta_B ≥ 1°C) based on AMSU-B 89.0-GHz eye size estimates, Ret (ATCF) represents hybrid MSLP estimates derived using both raw (delta_B < 1°C) and retrieved UTWA values (delta_B ≥ 1°C) based on ATCF eye size estimates. Dvorak estimate mean error and standard deviation are provided for comparison. Note: Dvorak MSLP values are based on T-number averages from NOAA/NESDIS Satellite Analysis Branch, the U.S. Air Force Weather Agency (AFWA), and NOAA/TPC/NHC when available. The increased sample size (N) in 2001 reflects the availability of both NOAA-15 and NOAA-16 AMSU data.

<table>
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<th>Year</th>
<th>Error (hPa)</th>
<th>Raw</th>
<th>Ret (AMSU-B)</th>
<th>Ret (ATCF)</th>
<th>Dvorak</th>
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“cooling” effect on 54.94-GHz upper-tropospheric brightness temperatures. Three years of AMSU TC warm core observations suggest that this issue, assumed negligible in Eq. (1) (section 3), is occasionally violated particularly during periods when exceptionally deep convection (e.g., convective bursts) occurs close to the TC low-level circulation center (LLCC). Under these circumstances, AMSU-A 54.94-GHz radiances can be attenuated to the point of affecting the magnitude of the UTWA. This will in turn lead to suspect TC MSLP estimates.

While the merits of the proposed AMSU TC intensity estimation algorithm have been demonstrated, early indications of the value of ancillary, albeit subjective, position and eye size information must be recognized and considered in the context of potential future operational use. Besides reconnaissance aircraft in the Atlantic, several excellent sources of passive microwave TC position and eye size information are currently available in near–real time. These include the Tropical Rainfall Measurement Mission (TRMM) and the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) as discussed by Hawkins et al. (2001). These tools are now being utilized at global forecast centers and the TC parameters disseminated to potential users via such vehicles as the ATCF package. Owing to the increased accessibility and diversity of near-real-time satellite databases, the potential to improve TC MSLP intensity estimates using passive microwave radiance information from the AMSU appears entirely within reach. Finally, work is under way on the development of a multiple-channel form of the AMSU algorithm that includes the explicit treatment and removal of hydrometeor scattering effects on AMSU radiance information.

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