EVALUATION OF ADVANCED MICROWAVE SOUNDING UNIT TROPICAL CYCLONE INTENSITY AND SIZE ESTIMATION ALGORITHMS

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Abstract

Advanced Microwave Sounding Unit (AMSU) data are used to provide objective estimates of one-minute maximum sustained surface winds, minimum sea level pressure, and the radii of 34-, 50-, and 64-kt winds in the northeast, southeast, southwest, and northwest quadrants of tropical cyclones. The algorithms are derived from AMSU temperature, pressure, and wind retrievals from all tropical cyclones occurring in the Atlantic and East Pacific basins during 1999–2001. National Hurricane Center best track intensity and operational radii estimates are used as dependent variables in a multiple regression approach.

The intensity algorithms are evaluated for the developmental sample using a jackknife procedure and independent cases from the 2002 hurricane season. Jackknife results for the maximum winds and minimum sea level pressure estimates are mean absolute errors (MAE) of 11.0 kt and 6.7 hPa, respectively, and root mean square errors (RMSE) of 14.1 kt and 9.3 hPa, respectively. For cases with corresponding reconnaissance data, the MAE are 10.7 kt and 6.1 hPa, and the RMSE are 14.9 kt and 9.2 hPa. The independent cases for 2002 have errors only slighty larger than those from the developmental sample.

Results from the jackknife evaluation of the 34, 50, and 64 kt radii show mean errors of 30, 24, and 14 n mi, respectively. The results for the independent sample from 2002 are generally comparable to the developmental sample, except for the 64 kt wind radii, which have larger errors. The radii errors for the 2002 sample with aircraft reconnaissance data available are all comparable to the errors from the jackknife sample, including the 64 kt radii.

1. Introduction

Upon discontinuation of aircraft reconnaissance in the western north Pacific in 1987, the Atlantic became the only tropical cyclone basin with routine in situ tropical cyclone (TC) observations. Accordingly, the worldwide standard for TC intensity monitoring, especially when reconnaissance data are not available, is based on a method developed by Dvorak (1975) in the mid-1970s and enhanced in the mid-80s (Dvorak 1984). The Dvorak technique uses visible (VIS) and infrared (IR) satellite imagery to observe the central and banding features of TCs and cloud top temperatures near the eye. Although the methods are augmented by a set of empirical rules, interpretations of TC attributes are subjective and can result in different intensity estimates of the same storm. The technique generally is successful, but large errors sometimes are possible. Velden et al. (1998) extended Dvorak's work, developing an automated version of the IR technique, for which the only subjectivity is the user's selection of the storm center location. With a reported RMSE of 8.34 hPa and a slight bias (0.33) toward underestimation, theirs is a good technique for estimating TC intensity. However, it is not applicable to tropical depressions (TDs) or weak tropical storms (TSs), and further limitations exist when a central dense overcast is present or there is strong vertical wind shear. Results of both works suggest it advantageous to have an alternative TC intensity estimation technique that is not based solely on the Dvorak method.

Estimates of TC structure via the extent of 34-, 50-, and 64-kt surface winds also are challenging but necessary, as many commercial and military users need accurate measurements of surface winds near TCs. As such, the National Hurricane Center (NHC) estimates and reports these statistics at six-hour intervals for every tropical system in their area of responsibility. Wind radii observations are obtained from reconnaissance data, ship reports, buoys, or satellite-borne scatterometers, but many of these data sources have spatial limitations or occur opportunistically. In their absence, conservative overestimates of the wind radii commonly are reported as symmetric circular and semi-circular advisories when, in fact, large asymmetries may exist. The applicability of scatterometers for wind observations has led to a surge in its usage, yet Jones et al. (1999) note many effects that degrade the wind retrieval accuracy, especially near the region of peak winds.

Due to the shortcomings of estimating TC intensity and wind structure, an alternate method is desired that is entirely objective and applicable to tropical depressions, tropical storms, and hurricanes. VIS and IR imagery have desirable horizontal resolution, but information cannot be obtained below the cloud top layer, and VIS imagery has additional temporal limitations. Alternatively, passive microwave remote sensing is suitable for TC studies because (1) microwaves penetrate most clouds beyond the top layer, a beneficial feature when a central dense overcast exists; (2) they are unaffected by hydrometeor contamination except in heavily precipitating regions; and (3) microwave sensing is not limited to a certain time of day.

Several studies have capitalized on the utility of microwave sensing for objective analyses of tropical cyclones after the pioneering work by Kidder (1979) and Kidder et al. (1978, 1980). Bankert and Tag (2002) describe a method to estimate TC intensity objectively using 15 features derived from Special Sensor Microwave/Imager 85 GHz data and rain rate imagery. Although their technique shows promise, the RMSE are large, on the order of 20 kt for independent data. In another study, Merrill (1995) used data from the Microwave Sounding Unit (MSU) and Special Sensor Microwave/Temperature (SSM/T) instruments to estimate TC intensity. The 55-GHz band data are sensitive to upper tropospheric temperature, which is hydrostatically related to the sea level pressure of a TC. The primary limitation of his technique was the poor horizontal resolution of the data, which is around 110 km for MSU data and 175 km for SSM/T data, at best.

In May 1998, the MSU's successor, the first Advanced Microwave Sounding Unit (AMSU), was launched aboard the NOAA-15 satellite. The multi-platform AMSU has more channels (15 on AMSU-A and 5 on AMSU-B), and increased horizontal resolution (48 km and 16 km at nadir for AMSU-A and -B, respectively) relative to the previous generation MSU. The primary objective of AMSU-A is to provide temperature soundings between the surface and 1 hPa, but it also is useful in deriving other TC parameters of interest, including cloud liquid water and rain rate. The primary task of AMSU-B is to provide moisture soundings. For more details of the AMSU instrument and its applicability to tropical cyclones, see Kidder and Vonder Haar (1995) and Kidder et al. (2000).

Despite its usefulness, there are some disadvantages to using AMSU data. Polar-orbiting satellites only pass over the same location up to twice daily, meaning there can be long stretches of time between subsequent passes. However, the deployment of three additional AMSU instruments – aboard NOAA-16 (launched September 2000), Aqua (May 2002), and NOAA-17 (June 2002) – helps alleviate this problem. The path of polar-orbiting satellites also leads to noncontiguous coverage near the equator causing some tropical cyclones to be unobserved.

The efficacy of the AMSU has prompted several recent TC studies. Spencer and Braswell (2001) used limb-adjusted brightness temperatures to statistically relate six AMSU-derived parameters – four with temperature information and two for correcting hydrometeor contamination – to the maximum sustained winds of Atlantic basin TCs. Their results, reported as the average error standard deviation, correspond closely with reconnaissance data (9.1 kt), but they degrade markedly (14.6 kt) for all other cases. Similar to Merill's (1995) work, Brueske and Velden (2003) developed a TC estimation algorithm with Channel 7 (55 GHz) AMSU data. After initially correcting for sub-sampled upper tropospheric warm anomalies (UTWA), they statistically related the adjusted UTWA to in situ observations of TC mean sea level pressure. They enhanced their retrieval technique by using AMSU-B data to determine TC eye size and NHC data to determine TC position. However, their retrievals are sensitive to the eye size parameter, thus a version of their algorithm is under development where the eye size is determined by NHC.

In this study, a method is described for estimating TC intensity – measured by one-minute maximum sustained winds (MSW) and minimum sea level pressure (MSLP) – and size (via the wind radii) utilizing AMSU-A data from 1999–2001. AMSU-A temperature retrievals are used to determine the geopotential height and surface pressure fields from the hydrostatic equation, and the gradient wind equation is used to estimate the azimuthally averaged tangential wind. Parameters from these fields are used as input to statistical relationships for estimation of the MSW, MSLP, and azimuthally averaged radii of 34-, 50-, and 64-kt winds. Additionally, the asymmetric wind radii are determined by fitting the mean wind radii to an idealized symmetric vortex with an added asymmetry factor related to the storm motion vector. A jackknifing procedure is used for evaluation of the intensity estimates against NHC post-season best track data, and wind radii estimates are evaluated against NHC tropical cyclone operational forecast advisory data issued every six hours. An additional 100 cases from the developmental data with coincident air reconnaissance data provide another source of evaluation. Finally, a brief independent evaluation is done against NHC post-season best track data from the 2002 tropical season.

2. Data

The AMSU-A (hereafter referred to as AMSU) radiances were collected in real-time for all storms in the Atlantic and East Pacific basins during the 1999–2001 tropical cyclone seasons. Data from the NOAA-15 satellite were available from 1999-2001, and additional data from NOAA-16 were collected in 2001. The analysis process was begun by obtaining current and 12-h old TC position estimates at six-hourly intervals from the NHC. The storm position is interpolated to the time of the most recent AMSU data, which typically is within six hours of the storm position estimate. Although the cross-track scanning AMSU swaths are nearly 2200 km wide, the analyses were limited to those where the storm center fell within 600 km of the swath center. The AMSU data are analyzed over a domain with a 600 km radius (chosen to include the gale radius of the largest Atlantic tropical cyclones). The storm center is restricted to within 600 km of nadir to minimize the domain area that is outside of the AMSU swath. When the center falls at or near the 600 km threshold, there is a small portion of the analysis domain with no data. This is not a problem because the analysis procedure extrapolates data from neighboring data points. The maximum resolution (48 km) occurs when the storm is near the center of the AMSU data swath. At 600 km from the swath center, the data resolution is ~80 km. Figure 1 shows examples of the data coverage for storms near and 600 km from the center of the AMSU swath.

a. The Temperature Retrieval

Prior to the temperature retrieval, two corrections to the NOAA-15 data were made for scan position and viewing angles as described by Goldberg et al. (2001). For NOAA-16, only the viewing angle correction was applied because the scan position correction was negligible for that satellite (Goldberg 2002, personal communication). After the corrections, the normalized radiances were used as input to a statistical temperature retrieval (Goldberg et al. 2001 and Knaff et al. 2000), which provides temperature as a function of pressure at 40 levels from 1000 to 0.1 hPa. However, only 23 pressure levels between 920 and 50 hPa were used in this study. The former constraint is due to the 1000-hPa level generally being below the surface in the center of strong TCs; the levels above 50 hPa also were disregarded as they were assumed to be above the storm circulation. The cloud liquid water (CLW) is also estimated from the AMSU-A data as part of the statistical retrieval algorithm.

Although microwave soundings provide information below the cloud-top layer, utilization in strongly convective regions of TCs is problematic due to hydrometeor attenuation. Because of their relatively large sizes, CLW droplets and ice crystals absorb and scatter microwave radiation, resulting in anomalously cold retrieved temperatures, which consequently cause erroneously high pressures and reduced pressure gradients. Preliminary investigations of the retrieved fields showed these detrimental effects (Figure A2 a,c,e), thus two corrections – one each for attenuation by CLW and ice scattering – were applied using vertically integrated CLW values retrieved at each footprint (Appendix).

The initial correction (for CLW) was applied to the temperature profiles at the AMSU swath points. A two-pass distance-weighted averaging method (Barnes 1964) then was applied to interpolate the unevenly spaced temperature and CLW data on the swath to an evenly spaced 12º by 12º grid with 0.2º grid spacing. By the nature of this process, the data is smoothed, the degree to which is controlled by the e-folding radius of the response function in the Barnes analysis. Based upon the behavior of the response function and by experimentation, an e-folding radius of 100 km was chosen for all of the Barnes analyses. Values of 50-150 km were tested and it was found that the minimum value that sufficiently smoothed the retrieved fields (determined subjectively from contour plots) was 100 km. Results also showed that the statistical intensity estimation procedure described in Section 3 was not very sensitive to the choice of the e-folding radius within the range 75-150 km. After the interpolation of temperature and CLW to the grid, the second hydrometeor correction was applied for ice scattering (Appendix).

b. The Wind Retrieval

There are several assumptions underlying the retrieval of the horizontal wind field from the AMSU temperature data, including those of hydrostatic and gradient balance. The hydrometeor corrected temperature data at all 23 pressure levels between 920 and 50 hPa were interpolated to a radial grid and azimuthally averaged, with the TC center located at the origin, so that temperature is a function of pressure and radius, extending outward 600 km. No surface temperature information can be derived from the AMSU, so it was obtained from the National Center for Environmental Prediction (NCEP) global analysis closest in time to the AMSU swath, though not more than six hours old. The AMSU algorithm is not very insensitive to the NCEP surface temperatures, because the data are used only as a lower boundary condition to derive the surface pressure and pressure gradient. Nearly all of the surface pressure gradient comes from temperature structure above the surface through the downward integration of the hydrostatic equation.

Next, the geopotential height field was derived as a function of pressure using hydrostatic integration. In doing so, additional assumptions were made that (1) temperature varies linearly with height between two pressure levels; (2) variations in gravity with height can be neglected so that height and geopotential height are equivalent; and (3) virtual temperature effects can be neglected. The last assumption could cause errors of a few hPa in the surface pressure calculation, and in reality, the moisture soundings from the AMSU-B could be used to calculate virtual temperature. The AMSU-B instrument on NOAA-15 was not functioning properly, however, so the data were not available consistently before 2001. Nevertheless, wind is related to the pressure gradient rather than the pressure itself, and errors in the pressure gradient due to neglecting virtual temperature effects are proportional to the moisture gradient rather than the total moisture. Thus, the moisture gradient errors are less than those of the total moisture.

The hydrostatic integration was begun at the surface at the outer radius of the domain, where the surface pressure boundary condition was determined from the same NCEP analysis used for the surface temperature. The equation was integrated upward to give the height of the first AMSU pressure level (920 hPa) at r = 600 km, then upward again to acquire the height of the next pressure level, and so forth up to 50 hPa. A final assumption then was made that the 50 hPa level is above all perturbations associated with the TC so that the height of this level is constant at all radii. Hence, the hydrostatic equation can be integrated downward from 50 hPa to 920 hPa at all radii to give the height of each pressure level in the interior of the domain. With the height and temperature of the 920-hPa level, as well as the surface temperature from NCEP, the hydrostatic equation then was integrated downward to compute the surface pressure at all points inside the outer boundary. Again, assuming a linear variation in temperature with height between the AMSU data levels, the temperature and pressure as a function of height were calculated at 1 km intervals from the surface to 20 km, and the density at each level was calculated via the ideal gas equation.

With the pressure and density known as a function of height and radius, the wind field was determined assuming gradient balance (1), where the radial pressure gradient was calculated using centered finite differences (with one-sided differences at r=0 and 600 km), and the Coriolis parameter was evaluated at the storm center.

$$\frac{V^2}{r} + fV = \frac{1}{\rho}\frac{\partial p}{\partial r} \qquad (1)$$

$$V = \frac{-rf}{2} \pm \sqrt{\left(\frac{rf}{2}\right)^2 + \frac{r}{\rho}\frac{\partial p}{\partial r}} \tag{2}$$

Occasionally, the radial pressure gradient is negative in some upper level regions (2), preventing a real solution of the gradient wind equation; for these points, the magnitude of the pressure gradient was reduced until the radicand was positive, providing a real solution.

An example of the AMSU-retrieved temperature perturbation and derived gradient winds is shown in radial-height cross-sections of Hurricane Gert (Figure 2) corresponding to the swath plot in Figure 1b. The temperature anomalies were calculated at each level by subtracting the retrieved temperatures at r=600 km from the temperature at each radius. The hurricane had MSW of 115 kt at this time, however, the coarse resolution of the AMSU and the smoothing of the data resulted in retrieved MSW of approximately 60 kt. The retrieved upper tropospheric warm anomaly of approximately 6 ºC also is likely a tempered estimate of the true magnitude.

c. AMSU Cases

The temperature, pressure, and gradient winds as a function of radius and height and the CLW as a function of latitude/longitude were determined from AMSU data for all available cases from 1999–2001. Cases where the storm center was within 100 km of a major land mass were excluded based on the desire to have at least one AMSU footprint near the storm center over open water for accurate retrievals.

A summary of all the AMSU cases included in this study is shown in Figure 3, where the reported intensities are from the NHC best track. The distribution of storm intensities in the developmental data set (1999–2001) was representative of climatology. The data included 473 cases from 89 TCs for analyzing the intensity, of which 247 were from the Atlantic and 226 were from the East Pacific. Over two-thirds are at the TD (123 cases) and TS (199 cases) intensities, and the remaining cases are at hurricane-strength (151 cases) wind speeds. Of the latter, 102 cases are Category 1 or 2 storms (Simpson 1974), and 49 are Category 3 or 4 storms; there were no AMSU passes over TCs when at the Category 5 level. The number of cases for estimating the wind radii is reduced, as will be discussed in Section 4, leaving 129 cases from 31 TCs for the 34-kt wind radii; 92 cases from 23 TCs for the 50-kt wind radii; and 68 cases from 19 TCs for the 64-kt wind radii.

The independent sample from 2002 is comprised of 288 cases of which 64 were within six hours of reconnaissance. The 288 cases came from 30 TCs, and of them, 143 were from the Atlantic and 145 from the East Pacific. Ninety-five cases are TDs, 140 are TSs, and 53 are Hurricanes. Of the latter, 36 are Category 1 or 2, and 17 are Category 3 or higher. For the wind radii estimations, there were 218 cases from 24 TCs for the 34-kt wind radii; 120 cases from 16 TCs for the 50-kt wind radii; and 67 cases from 10 TCs for the 64-kt wind radii.

3. Tropical Cyclone Intensity Estimation

Although the horizontal resolution of the AMSU is more than double that of the MSU, it still is too coarse to observe tropical cyclones without subsampling problems. According to Weatherford and Gray (1988), the eye diameter of an Atlantic tropical cyclone can range from 8 km to over 200 km, but the majority fall between 30 and 60 km. Even if a TC falls near the ideal nadir position, the 48 km resolution is not sufficient to resolve the tight pressure gradient associated with the radius of maximum wind. However, as shown in this study, several parameters can be derived from the AMSU temperature, pressure, and wind retrievals. Combined with other parameters available in real time, these data can be related statistically to NHC-reported MSW and MSLP of TCs, providing objective estimates of each. The development of these algorithms is explained in this section, followed by a cross-evaluation to examine their performance as well as an independent evaluation against 2002 data.

a. Methods

Eighteen parameters derived from the AMSU data and one additional non-AMSU-derived parameter available in real time served as possible estimators of tropical cyclone intensity (Table 1). The parameters relay information from various vertical levels about retrieved pressures, winds, temperature anomalies, swath spacing, and cloud liquid water values. The combined 19 variables make up the independent data set used as potential estimators of TC intensity via the MSW and MSLP; excepting CLWPER, all AMSU-derived parameters were azimuthally averaged.

The dependent data for the TC intensity estimations are from the NHC best track (BT) linearly interpolated to the time of the AMSU swath. However, the best track data are not all "ground truth". BT intensity estimates are determined from available Dvorak satellite estimates, ship reports, buoy data, land stations, aircraft reconnaissance measurements, and satellite cloud track winds, scatterometer and passive microwave (SSM/I) surface winds. Nearly all of the aircraft observations are from the Atlantic. While a validation data set consisting entirely of in situ data is preferable, AMSU and reconnaissance data were coincident within six hours only 100 times from 1999–2001. This is a marginal amount of cases from which to develop a statistical algorithm with 19 potential estimators, so until a larger data set becomes available, the best track data is the best alternative for stable development. The reconnaissance data set was used for a separate evaluation.

While all the parameters in Table 1 seem relevant to TC intensity, the actual significance of each one is not explicit. Therefore, the relationship between the estimators and the predictands was analyzed via multiple linear regressions. It generally is not prudent to include every possible estimator in the regression equation; some may not be valuable in estimating the predictand or some may be mutually correlated (i.e., changes in one tend to be associated with changes in another), thus providing redundant information. Consequently, the list of potential estimators was shortened initially by correlating each variable against the predictands. If the correlation coefficient was less than 0.5, then that variable was excluded initially.

A backward stepwise regression with a one-percent significance level (α= 0.01) then was used to select a set of estimators from the remaining variables. It is possible, though, that some variables removed by the initial correlation step could improve the variance explained; while a given variable may not be correlated with the MSW or the MSLP, it may be correlated with the residuals of the estimative algorithms. For instance, the AMSU footprint resolution at the storm center (SS) has no direct physical relationship to TC intensity, but as the resolution worsens, the intensity is underestimated by the AMSU data. Thus, there is a relationship between SS and the residuals from the backward stepwise regression. So as not to exclude these relevant connections, each of the variables removed by the initial correlation was analyzed against the residuals. All parameters for which a trend with the residuals existed were added back to the potential estimator pool, a backward stepwise regression was reanalyzed, and the variables retained were the final set used in the algorithms to estimate the MSW and the MSLP.

The intensity estimators selected using the 1999–2001 data were evaluated using a "storm jackknife" procedure. The typical jackknife method develops regression equations on n-1 cases and tests the algorithm on the withheld case. However, numerous cases from a given TC can exist, potentially weighting the developmental data set and underestimating the error on the "independent" case. To prevent this bias, all cases for a given storm were withheld, the algorithms to estimate the MSW and MSLP were developed with the remaining cases, and then the algorithms were independently tested on all the withheld cases from that storm.

The accuracy of the AMSU-derived estimations of MSW and the MSLP was evaluated with three measures: (1) the coefficient of determination (R^2), which denotes the proportion of the variation of the predictand that is described by the regression; (2) the mean absolute error (MAE), which is the average of the absolute differences between the estimated and NHC-reported values; and (3) the root mean square error (RMSE), which is the square root of the average of the squared differences between the estimated and NHC-reported values (Wilks 1995).

b. Results

1) DEPENDENT DATA RESULTS

The final regressions provide two simple and robust formulas to estimate the MSW and MSLP of tropical cyclones. Of the initial parameter pool, seven AMSU-derived variables are retained, explaining 72.3 percent of the variance in the MSW data; an additional parameter is retained to explain 76.5 percent of the variance in the reported MSLP (Table 2).

To facilitate the comparison of the coefficients for each estimator, normalized coefficients were calculated from non-dimensional dependent and independent variables calculated by mean centering and then dividing by the standard deviation. Each normalized coefficient has a comparable magnitude for MSW and MSLP, suggesting that the parameters work similarly in estimating each; the signs are opposite, however, since MSW and MSLP are inversely related. The normalized coefficients illustrate that the AMSU-derived tangential winds at a height of five kilometers from 0-250 km (VBI5) is the most influential parameter in estimating both MSW and MSLP, followed closely by the pressure drop at the surface (DP0).

VBI5 probably was selected instead of VBI3 or VBI0 because the height and wind fields in the domain interior are derived via a downward integration, and noise and errors accumulate near the surface. Additionally, hydrometeor effects worsen closer to the surface. DP0 is an influential parameter, partly because the area-averaged pressure drop is strongly related to intensity, and also because it is calculated over a large radial interval allowing it to include a significant amount of data in regard to the coarse AMSU resolution.

The two estimators with lower normalized coefficients, SS and RMX3, were the only ones added back to the estimator pool by the residual analyses. While SS is not physically related to TC intensity, it helps correct for resolution variations by increasing the estimated intensity when SS is large. Similarly, the estimated intensity decreases as RMX3 increases because the AMSU better resolves larger storms. RMX3 probably was chosen over RMX0 for the same reasons described above for VBI5.

The MAE (RMSE) on the development data set is 10.6 (13.5) kt for estimating MSW and 6.5 (8.8) hPa for MSLP (Table 3). These statistics deteriorate only slightly on the storm jackknife data, suggesting that the artificial skill is minimal. The RMSE of 14.1 kt for the MSW estimates is smaller than Bankert and Tag's (2002) RMSE of 19.7 kt. The RMSE of the MSLP is 9.3 hPa, which is 1.0 hPa higher than the reported ODT RMSE (Velden et al. 1998). However, restricting the AMSU cases to only Atlantic storms as Velden et al. did, the resultant RMSE of 8.2 hPa is comparable to their findings. The standard deviation of the MSW jackknife residuals is 14.1 kt, akin to 14.6 kt from Spencer and Braswell (2001). Therefore, the intensity estimation equations developed in this study have errors comparable to those from other methods, with the advantage that they estimate MSW and MSLP for tropical disturbances of all strengths. A comparison for a homogeneous sample would be required to determine which method is best.

When the storm jackknife data were compared only to the 100 cases with reconnaissance data within six hours, all but one of the statistical measures improves (Table 3). When estimating MSW, the explained variance increased to 74.3 percent, and the MAE and standard deviation of the residuals decreased to 10.7 and 13.7 kt, respectively. However, the RMSE increased slightly to 14.9 kt when compared to the in situ data, likely signifying that there are a few cases with large errors, which are skewing the RMSE on this smaller data set, but that there are many more cases with small errors, keeping the MAE down and raising the coefficient of determination. When estimating MSLP for the cases with reconnaissance data, the variance explained increased to 83.1 percent, the MAE (RMSE) decreased slightly to 6.1 (9.2) hPa, and the residual standard deviation decreased to 9.0 hPa.

The distribution of residuals (Figure 4) shows that 72.5 percent of the errors fall within 15 kt and only 13 percent of errors are more than 20 kt. For the MSLP estimates, the residual distribution (Figure 5) shows that 78.4 percent lie within 10 hPa with only 4.4 percent exceeding 20 hPa. The fact that the maximum wind error exceeded 20 kt in only about 13% of the cases is encouraging. Brown and Franklin (2002) showed that the errors in the Dvorak estimates exceed 20 kt in about 10 percent of the cases. These results suggest that the AMSU can provide intensity estimates comparable to the Dvorak method, but are independent of visible and IR imagery. Because of this independence, a method that combined both types of data would likely lead to even more accurate intensity estimates.

A closer examination of the residuals revealed six storms that were underestimated by the AMSU algorithm in excess of 30 kt, with a maximum error of 57 kt. Half of these were from Hurricane Iris, and another was from Hurricane Juliette. Based upon their appearance in IR imagery, both were small storms. Aircraft data for Iris near the time of its peak intensity indicated a radius of maximum wind as small as 8 km, confirming this was a very small storm. These results indicate that the algorithm does not perform well in such cases due to its limited horizontal resolution. The other two underestimated cases were from Hurricane Lenny, which seems to have been ill affected by inaccurate temperature retrievals in and around the elevated terrain of the Caribbean islands. Additionally, it appeared that the AMSU footprint locations occurred on either side of the warm core associated with the storm, so that the most intense region was not sampled.

There are 14 cases in which the AMSU algorithm overestimates TC intensity by more than 25 kt, the greatest overestimation being 32.4 kt. These large overestimations likely occur for two reasons: (1) when TCs intensify rapidly, the warm core seems to appear before it, influencing the wind field accordingly, and (2) when TCs lose all convection, the warm core is exposed. The latter occurs most often in the East Pacific, which is where 64 percent of the large overestimations occurred. A possible way to correct for this in the future would be to use IR data as part of a multi-platform algorithm.

2) INDEPENDENT DATA RESULTS

Although the jackknife sample provides a better estimate of the potential operational performance of the algorithm than the dependent cases, an evaluation on cases that were not used in the model development is still needed. For this purpose, the algorithm developed from the 1999-2001 cases was run in real-time during the 2002 hurricane season, and results were compared to the 2002 NHC post-season best track data. As shown in Table 4, the performance of the algorithm is robust, with only a very small increase in error relative to the developmental data set. The algorithms explain 69.0 percent of the variance in the MSW data and 67.5 percent of the variance in the MSLP data. Furthermore, the MAE (RMSE) is 10.9 (14.1) kt for estimating the MSW, and 7.5 (10.5) hPa for estimating the MSLP. When evaluated against only the 64 cases with reconnaissance data, the results again are consistent with the developmental data set compared to reconnaissance, with 72.3 and 83.4 percent of the variance explained for MSW and MSLP, respectively. Additionally, the MAE and RMSE of the reconnaissance-only evaluation are very similar to the errors of the entire 2002 data set.

4. Tropical Cyclone Wind Radii Estimation

The basic assumptions underlying the objective estimation of tropical cyclone wind radii with AMSU data are the same as those for estimating intensity. Again, because the AMSU resolution is too coarse for direct use, and also because the wind retrievals are symmetric averages, a statistical procedure utilizing AMSU-derived parameters was employed to approximate the azimuthally averaged (hereafter referred to as AA) radii of 34-, 50-, and 64-kt winds (when applicable) in the Atlantic and East Pacific basins. The AMSU-derived AA estimates subsequently were used with a simple surface wind model – given as the sum of a constant vector proportional to TC motion plus a modified Rankine vortex model – to make asymmetric estimations of the wind radii in the northeast (NE), southeast (SE), southwest (SW), and northwest (NW) quadrants relative to the TC center, as are reported by the NHC operational forecast advisories every six hours. The developments of the symmetric and asymmetric wind radii techniques are described in this section; the former are cross-evaluated via the same storm jackknife procedure used for the intensity evaluation, and the asymmetric estimates were evaluated against the NHC advisories closest in time to the AMSU swath data (with a maximum three hour difference) for both the developmental and the 2002 independent data sets.

a. Methods

The NHC operational MSW estimates, as opposed to the AMSU estimated MSW, were used to determine which wind radii were to be estimated. For example, if the operational estimate of the MSW is 65 kt, the 34-, 50-, and 64-kt wind radii all are to be estimated, even if the AMSU estimate is below 65 kt. This was done in order to maintain consistency with the NHC's reported TC intensity estimate.

The same 19 potential parameters used for the intensity estimation (Table 1) as well as the operational estimate of intensity, make up the independent variables (estimators) for the AA 34-, 50-, and 64-kt wind radii estimations. The dependent variable, reported in nautical miles (n mi), is the AA of the wind radii from the operational forecast advisories issued every six hours by the NHC. The radii closest in time to the AMSU swath were used with no more than three hours difference. Because there is no systematic technique analogous to the Dvorak method for estimating the wind radii from satellite data, the wind radii data in the NHC advisories are derived from available surface and remotely sensed data as well as aircraft reconnaissance data. As with the best track data, the majority of the "ground truth" data for the wind radii are not in situ measurements. Unlike the BT data, however, there is no post-season analysis of the wind radii measurements, suggesting that large errors may be inherent in the evaluation data set. Therefore, the data for developing the wind radii equations were restricted to Atlantic cases west of 55^{o}W, which has the best coverage of aircraft reconnaissance, buoys, ships, and island stations. The East Pacific cases that had reconnaissance data also were included.

The same four-step statistical method with the same significance levels used in developing the intensity estimation algorithms was used to create three wind radii algorithms, one each for the AA 34-, 50-, and 64-kt winds. After the initial correlation (removing those with a coefficient less than 0.5) of each estimator with the predictand, a backward stepwise regression was employed with the resulting variables (α = 0.01), followed by an examination of the residuals against the parameters removed at the outset by the correlation. Again, any parameters showing a relationship with the residuals were added back to the potential estimator pool, and the regression was reanalyzed.

With the AMSU-derived AA wind radii estimates, the wind radii in the NE, SE, SW, and NW quadrants were determined by using a modified Rankine vortex (Depperman 1947) applied to a polar coordinate system, where the surface wind speed (V) outside the radius of MSW (r_m) is given by a simple model,

$$V(r,\theta) = (V_m - \gamma)\left(\frac{r}{r_m}\right)^{-x} + \gamma\cos(\theta - \theta_0) \qquad (3)$$

where r is the radius from the TC center; θ is the angle measured from a direction 90 degrees to the right of the storm heading; V_m is the maximum sustained wind speed; γ is the asymmetry factor due to the storm translational speed (Schwerdt et al. 1979); and x is a unitless, positive number that determines the rate at which the wind speed decays with radius. Application of (3) to the best track MSW and observed wind radii in each quadrant for the 1999–2000 data indicated that the best fit is obtained when γ is 60 percent of the asymmetry factor and θ_0=0, indicating that the MSW generally are 90 degrees to the right of the direction of motion.

With θ_0 and γ specified and V_m set to the operational estimate of MSW, the AMSU-estimated AA wind radii then were used to determine the two remaining free parameters, r_m and x, by solving (3) for r and applying an azimuthal average to give

$$\bar{r} = \frac{r_m}{2\pi}\int_0^{2\pi}\left(\frac{V_m - a}{V - a\cos(\theta - \theta_0)}\right)^{1/x} d\theta \qquad (4)$$

There are three possible scenarios for finding r_m and x: (1) when the MSW of a TC is greater than 34 kt but less than 50 kt, providing only an AMSU estimate of the AA 34-kt wind radii; (2) when the MSW is greater than 50 kt but less than 64 kt, resulting in AMSU estimates of the AA 50- and 64-kt wind radii; and (3) when the MSW is greater than 64 kt, providing all three AMSU estimates of the AA wind radii. The second case is ideal in that (4) can be evaluated twice, once each for the AA 34- and 50-kt wind radii, resulting in two equations to solve for the two unknowns, r_m and x. The dilemma occurs when the MSW is less than 50 kt, since only the mean 34-kt wind radius is known, and when the wind is 64 kt or greater, since three average wind radii are available.

To remedy these problems, the parameters x and r_m were determined using a variational approach where a cost function, $C(r_m,x)$, is minimized. The cost function is given by

$$C = \frac{(r_{34} - R_{34})^2}{\sigma_{34}^2} + \frac{(r_{50} - R_{50})^2}{\sigma_{50}^2} + \frac{(r_{64} - R_{64})^2}{\sigma_{64}^2} + \lambda_x \frac{(x - x_c)^2}{\sigma_x^2} + \lambda_{rm} \frac{(r_m - r_{mc})^2}{\sigma_{rm}^2} \qquad (5)$$

where r_{34} is the average 34-kt wind radius determined from (4), R_{34} is the average 34-kt wind radius from the statistical algorithm, σ_{34} is the standard deviation of a sample of mean 34-kt wind radii, (and similarly for the 50- and 64-kt wind radii), x_c is the climatological value of x, r_{mc} is the climatological value of r_m, and σ_x and σ_{rm} are the sample standard deviations of x and r_m, respectively. The climatological variables and standard deviations were determined from NHC operational estimates of wind radii for all storms from 1988–2000 that were west of 55°W. The sample again was restricted by longitude, because most of the TCs in the western Atlantic basin had aircraft reconnaissance and surface data available to more accurately estimate the wind radii. The standard deviations in (5) are constants, but the climatological values of x and r_m are a function of the TC MSW, where r_{mc} decreases and x_c increases for stronger storms.

The last two terms on the right side of (5) are “penalty terms” that prevent the values of x and r_m from deviating too far from the climatological values as determined by λ_x and λ_{rm}. Values of 0.1 for both parameters were chosen based upon an analysis of the behavior of the minimization of (5) for idealized wind profiles. With these values of λ, the penalty terms have only a small influence on the solution expect in the special cases where the storm maximum wind is very close to one of the wind radii thresholds (34, 50 or 64 kt) and the speed of motion is large. In these cases, the wind radii are zero for a fairly large span of azimuth for the highest wind threshold. This makes the azimuthal mean radius in (4) very small. In the minimization procedure, unrealistic values of x and r_m are required to compensate. The penalty terms prevent this unrealistic solution from being selected.

Once r_m and x are known, they can be used in (3) to determine the radius for any wind speed (V) at any azimuth (θ). The value of V is set depending on which wind radii magnitude is sought (i.e., when determining the asymmetric 34-kt wind radii, V=34), and θ is determined by rotating the desired geographic direction into the storm-motion relative coordinate system.

b. Results

1) AZIMUTHALLY AVERAGED WIND RADII

The final regressions provide three equations for estimating the azimuthally averaged 34-, 50-, and 64-kt wind radii (Table 5). Four to five variables are used to account for approximately 66 to 81 percent of the variations in the reported NHC wind data. The set of estimative parameters varies based on which wind radius is being approximated. The 50 and 64 kt radii equations have two estimators in common, while the 50 and 34 kt radii equations have no common estimators.

The error statistics for these three wind radii based on the developmental and storm jackknife data sets are shown in Table 6. For the AA 34- and 64-kt wind radii, the results of the jackknife data set decline modestly, suggesting that the AMSU-derived algorithms are without artificial skill. However, the 50-kt wind radii are not estimated as well. There is large scatter (R^2 = 39.3%) and a bias of -9.9 n mi, indicating that the AMSU algorithms are underestimating the extent of 50-kt winds. Whether these errors are valid or a result of conservatively overestimated evaluation data presently is unclear; this ambiguity will be resolved once a large enough reconnaissance data set is acquired for comparison. However, the lower reliability of the AA 50-kt wind radii may be less of a problem when the asymmetric wind radii are calculated, since the cost function blends this information with the AA 34- and 64-kt wind radii.

2) ASYMMETRIC WIND RADII

(i) Dependent Data Results

The AMSU-derived AA wind radii approximations used in conjunction with the Rankine vortex model generally provide good estimates of the NHC asymmetric wind radii (Tables 7 and 8), although large differences occurred in a few cases (the maximum differences are on the order of 200 n mi for the 34-kt radii, 150 n mi for 50-kt radii, and 90 n mi for 64-kt wind radii). The assumption that the wind field asymmetries are solely the result of motion may be the cause of such large differences, particularly when a storm is imbedded in an environment containing strong horizontal wind shear. Once again, without a data set consisting only of in situ observations, it is difficult to determine whether outliers are due to the statistical estimation or uncertainties in the NHC evaluation data.

To better illustrate the asymmetric wind radii estimation, two specific examples are discussed below: (1) a small but highly asymmetric storm that validates well with concurrent reconnaissance data, and (2) a large storm without current aircraft reconnaissance data.

On 1152 UTC 6 October 2001, Tropical Storm Iris had MSW of 55 kt and was moving west-northwest at 15 kt. Since Iris was south of the Greater Antilles, reconnaissance data were coincident with this time. With an intensity so close to the 50-kt wind radii threshold and a rapid translation speed, 50-kt winds are not expected to encircle the TC, rather they exist only in the NE and NW quadrants (Figure 6). Both the AMSU-derived and NHC radii estimates show this asymmetry very well, although they differ in magnitude by about 10 n mi.

The case of Hurricane Gert on 1132 UTC 22 September 1999 shows how uncertainties in the evaluation data complicate the assessment of errors. The NHC radii estimates for this case were almost exactly the same as those determined from a reconnaissance flight nearly 36 hours prior. However, between the flight and the time of this case, the TC weakened from 96 to 71 kt and speed of motion increased from 9 to 21 kt. Consequently, there is no estimate of 64-kt winds in the NW or SW quadrants from the AMSU data, yet the NHC continues to report 64-kt wind radii of 90 and 50 n mi, respectively, in those quadrants (Figure 7). It is unclear which radii estimates are more accurate in this case.

Despite the uncertainties in the NHC wind radii for Hurricane Gert, both the AMSU and NHC 34- and 50-kt radii are much larger for Gert than for Iris (Figures 6 and 7). Based upon aircraft data and satellite imagery, Gert was a much larger storm than Iris, indicating that the AMSU algorithm can distinguish between storms of different sizes. Additionally, the radius of maximum wind is estimated as part of the asymmetric wind radii estimation procedure; although these were not evaluated in this study, the values for these Gert and Iris examples were 69 and 29 n mi, respectively, again distinguishing between the large and small storms.

(ii) Independent Data Results

Table 9 shows the radii error statistics for the 2002 independent sample. Comparing Tables 7 and 9 shows that the errors of the AMSU estimates of the 34 and 50 kt asymmetric wind radii for the 2002 independent cases are comparable to the results with the jackknife sample, although the biases are a little larger. For the 64 kt radii, the performance for the total 2002 sample degrades compared to the jackknife results, but the performance for the 2002 sample with reconnaissance data is comparable. It is possible that the degradation of the 64 kt radii estimates for the total 2002 sample is partially due to uncertainties in the operational radii estimates, since this sample includes east Pacific as well as Atlantic storms. The 64 kt wind radii are the most difficult to estimate because the satellite winds (QuikSCAT and SSM/I) are less valid for higher wind speeds, and there is generally less in situ data near the storm center. When a large enough sample becomes available, the radii algorithm (especially for the 64 kt wind) should be re-derived and evaluated using only those cases that include aircraft reconnaissance as ground truth. Nevertheless, the general consistency of the radii errors between the jackknife and independent samples suggest that the performance of the radii algorithm was probably not overly influenced by the choice of the developmental sample, and the method can be used to provide radii estimates that explain 45-60% of the variability of the NHC operational estimates.

5. Summary and Conclusions

This study used data from the Advanced Microwave Sounding Unit to estimate two measures of tropical cyclone intensity – MSW and MSLP – and wind structure via the azimuthally averaged radii of 34-, 50-, and 64-kt winds. The physically based part of the algorithms provide a spatially smoothed view of tropical cyclone parameters, which are input to statistical models to provide the desired intensity and wind estimates. The estimative algorithms were developed from 1999-2001 cases with a combined correlation-multiple linear regression-residual analysis technique, and a storm jackknife evaluation was employed to remove the artificial skill of the models. The azimuthally averaged wind radii subsequently were used in conjunction with a simple surface wind model (the sum of a modified Rankine vortex and a constant vector proportional to the storm motion) to estimate the wind radii asymmetrically, in the northeast, southeast, southwest, and northwest quadrants of TCs. The intensity estimates were evaluated with post-season best track analyses; for the wind radii, evaluation was with NHC operational forecast advisory estimates. In addition to the jackknife evaluations of the developmental data, a subsequent independent evaluation was performed using cases from the 2002 hurricane season.

In general, the intensity estimates described in this study have errors comparable to the objective Dvorak method. However, the method described here provides intensity estimates for all ranges of tropical cyclones intensity, while the objective Dvorak method is restricted to storms of minimal hurricane strength or greater. The intensity estimates in this study also have errors comparable to those from other AMSU-based intensity techniques. An advantage of the current technique, however, is that the method also provides estimates of the wind structure, through the radii of 34, 50 and 64 kt winds. These radii estimates explain 45-60% of the variability of the wind radii in the operational NHC forecast advisories.

Work is underway to extend the intensity and wind-radii estimation algorithms globally to all other tropical basins. Other future work may include enhancing the asymmetric wind estimations by using a nonlinear balance equation to derive the three-dimensional wind field rather than forcing the maximum wind to be 90 degrees to the right of the storm motion, thus accounting for cases when the tropical cyclone is embedded in an environment containing strong horizontal wind shear. AMSU-B and IR imagery also may be used to determine TC size so that the AMSU-derived estimative parameters can be scaled accordingly. Finally, when a sufficient number of AMSU cases with coincident reconnaissance data exist, the intensity and radii estimative algorithms may be redeveloped so that they are based entirely on "ground truth" and are completely independent of the Dvorak method.

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Appendix

In order to more accurately represent the retrieved tropical cyclone temperature, pressure, and wind fields, a correction for hydrometeor affects is necessary. Modifications for absorption in areas of high CLW content and scattering by ice were developed based upon the method described by Linstid (2000).

Both corrections are implemented at 12 pressure levels between 350 and 920 hPa (i.e., 350, 400, 430, 475, 500, 570, 620, 670, 700, 780, 850, and 920 hPa) at which AMSU temperatures are retrieved. As will be seen, the attenuation affects of CLW at the lower pressure levels are minimal, so that only a correspondingly slight adjustment is done. The data used in developing the correction come from 64 AMSU passes over Atlantic and East Pacific storms from the 1999 tropical season. Despite the 154 total passes over tropical disturbances that year, only those are used where the analysis domain is completely over the ocean in order to provide homogeneity in the sample.

a) CLW Correction

The basis of the CLW correction is to remove the artificial relationship between lower derived temperatures and large amounts of CLW. The temperature data utilized in the correction consist of all AMSU swath points (footprints) within a 12º by 12º storm-centered grid. This number varies depending on where in the AMSU swath a TC falls, such that more points are included when the TC falls near nadir as opposed to further out in the swath.

Each footprint location has an associated temperature profile and CLW value. Initially, at each pressure level, the mean temperature of all the swath points is calculated for each storm and subsequently used to find the temperature deviation,

$$T_{dev}(i) = T_{mean} - T(i) \quad [A1]$$

at each footprint. A linear regression then is performed at each of the 12 pressure levels, using the data points from all 64 AMSU passes with the temperature deviations as the dependent variable and the associated CLW values as the independent variable. Next, the slopes of the 12 regression lines are plotted against their corresponding pressure level (m_p), and a quadratic curve is fit to the data (Figure A1). At 350 hPa, the slope is nearly zero, indicating CLW does not affect temperature due to less CLW at this level. In contrast, the magnitude of the slope is largest at 920 hPa, representing the decrease in temperature due to the abundance of CLW at this level.

Not all swath points are affected by CLW, so only those with a corresponding CLW value greater than 0.3 mm are corrected for attenuation effects. The correction is given by

$$T_{corrected}(i) = T_{original}(i) + m_p * CLW(i) \quad [A2]$$

where m_p is the slope for a given pressure level.

b) Ice Correction

Succeeding the CLW correction, the temperature data are corrected further for scattering by ice crystals via the method described by Linstid (2000) with minor modifications. Prior to the ice correction, a distance-weighted averaging method (Barnes 1964) is used to interpolate the unevenly spaced swath data to an evenly spaced 12º by 12º grid with 0.2º grid spacing. It would be preferable to perform the ice correction on the swath data, as with the CLW correction, because the Barnes analysis smoothes the data. However, the Laplacian method utilized by Linstid (2000), described as follows, requires that the data be evenly spaced.

At each of the 12 aforementioned pressure levels, the mean temperature unaffected by ice is calculated only using points where the associated CLW value is less than 0.2 mm. This constraint is based on the assumption that cloud ice does not occur where there is little or no CLW. If the temperature at a given grid point is less than the mean temperature minus 0.5 ºC, the data point is considered too cold due to ice attenuation, and it is flagged to be corrected.

Following Linstid (2002), once all the points affected by ice are flagged at each pressure level, Laplace's equation [A3] is used to fix the corrupted data, because it provides a smooth temperature field using uncorrupted data points.

$$\nabla^2 T = 0 \qquad \text{[A3]}$$

Equation A3 is solved by iteratively replacing each flagged data point with the average of its nearest neighbors, of which there are four if the point is in the center of the domain, three if it is on the side, and two if it is in the corner. This correction procedure is continued until the temperatures of all the flagged data points converge such that the difference in the temperatures between the previous and current iteration are less than 0.005 ºC.

In Figure A2 are the uncorrected versus the hydrometeor corrected plots of the radial-height cross-sections of temperature anomaly (ºC) and azimuthally averaged gradient wind (kt) as well as the horizontal distribution of surface pressure (hPa) of Hurricane Gert when it was a Category 4 storm with MSW of 115 kt. The corrections greatly reduced the large area of low-level cold temperatures and the large area of surface high pressure. The adjusted wind profile is much more realistic than the uncorrected version, with the anticyclonic area at the storm's edge removed.

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Table Captions

Table 1. Potential estimators of tropical cyclone intensity, where *r* is the radius and *z* is height.

*LAT is the only parameter not derived from AMSU data.

Table 2. Regression variables and their corresponding coefficients, normalized coefficients, and p-values retained to estimate best track reports of MSW (kt) and MSLP (hPa).

Table 3. Comparison of the results for estimations of MSW (kt) and MSLP (hPa) using the AMSU-derived intensity algorithms for the developmental, storm jackknife, and storm jackknife against reconnaissance data sets.

Table 4. Comparison of the results for independent estimations of MSW (kt) and MSLP (hPa) using the AMSU-derived intensity algorithms for all 2002 data and only data with reconnaissance.

Table 5. Regression variables and their corresponding coefficients, normalized coefficients, and p-values retained to estimate NHC reports of the azimuthally averaged 34-, 50-, and 64-kt wind radii (n mi).

*BTMSW is the best track estimate of the maximum sustained winds; in real time, the operational estimate will be used.

Table 6. Comparison of the results for estimating the azimuthally averaged 34-, 50-, and 64-kt wind radii (n mi) with AMSU-derived algorithms for the developmental and storm jackknife data sets.

Table 7. Comparison of the results for estimating the asymmetric wind radii (n mi) of 34-, 50-, and 64-kt winds using AMSU-derived estimates of the azimuthally averaged wind radii with a Rankine vortex model; all quadrants have been combined into one sample.

Table 8. Comparison of the results, shown by quadrant, for estimating the asymmetric wind radii (n mi) of 34-, 50-, and 64-kt winds using AMSU-derived estimates of the azimuthally averaged wind radii with a Rankine vortex model.

Table 9. Comparison of the results for independent estimations of the asymmetric wind radii (n mi) of 34-, 50-, and 64-kt winds for 2002 data using AMSU-derived estimates of the azimuthally averaged wind radii with a Rankine vortex model; all quadrants have been averaged into one. Results are shown for all cases and for cases when reconnaissance observations were made within 3 hours of the AMSU observation.

Figure Captions

Figure 1. A portion of the AMSU swath showing (a) Hurricane Isaac near nadir on 21 Sep 2000, and (b) Hurricane Gert near the 600 km threshold of the swath center on 16 Sep 1999.

Figure 2. Radial-height cross sections for Hurricane Gert on 16 Sep 1999 of AMSU-retrieved (a) temperature anomalies (^{o}C) showing the warm core at a height of approximately 12 km, and (b) gradient winds (kt) showing that the MSW occur at approximately 175 km from the storm center.

Figure 3. Histogram of all AMSU cases from 1999–2001, binned by intensity and basin of occurrence.

Figure 4. Histogram of residuals (best track minus AMSU-estimated) for estimates of MSW (kt) from 1999–2001 storm jackknife data.

Figure 5. Histogram of residuals (best track minus AMSU-estimated) for estimates of MSLP (hPa) from 1999–2001 storm jackknife data.

Figure 6. Comparison of AMSU-derived and NHC reports of asymmetric 34- and 50-kt wind radii (n mi) for Tropical Storm Iris (1152 UTC 6 Oct 2001), where the arrow denotes direction of storm translation.

Figure 7. Comparison of AMSU-derived and NHC reports of asymmetric 34-, 50-, and 64-kt wind radii (n mi) for Hurricane Gert (1132 UTC 22 Sep 1999), where the arrow denotes direction of storm translation.

Figure A1. The slope of the cloud liquid water versus temperature deviation regression versus the corresponding pressure level, fit with a quadratic curve.

Figure A2. Non-hydrometeor corrected (a,c,e) and hydrometeor corrected (b,d,f) plots for Hurricane Gert (115 kt) from 1148 UTC 17 Sep 1999 showing: (a,b) radial-height cross-section of temperature anomalies in ºC; (c,d) lat-lon profile of surface pressure in hPa; (e,f) radial-height profile of azimuthally-averaged gradient wind in kt.