AN ANALYSIS OF TROPICAL CYCLONE INTENSITY ESTIMATES OF THE ADVANCED MICROWAVE SOUNDING UNIT (AMSU), 2005-2008

Corey Walton
University of Miami, Coral Gables, FL

INTRODUCTION

Analysis and forecasts of tropical cyclones involve two main foci: location and intensity. In order to make a good forecast it is essential that the current conditions of a storm be accurately known. This is a more difficult task than it seems. While there are numerous surface observations over land, they are scarce over the ocean where the majority of storms originate. Ship observations are available, but again they are sparse. Ships also tend to avoid steering into storms. This leads to other methods of data retrieval to help determine the current conditions of a tropical system. Aircraft reconnaissance data is an extremely useful and accurate tool. On the downside, the cost of a flight and the small number of planes available limits the amount of potential data from this method of retrieval.

Also, half of the tropical cyclones in the Atlantic are too far away to be reached by aircraft. With this lack of continuous data, forecasters are led to look for other methods to help determine the current conditions of a storm. Since hurricane forecasting began there have been numerous improvements and technological enhancements, but there still remain difficulties within each area, especially intensity forecasting.

The emergence of satellite imagery in the early 1960’s was a great breakthrough for hurricane forecasting. Forecasters were able to locate more storms, as they were now able to see over the oceans, where surface data were not available. Satellite pictures became operational in the mid-1960’s with about one picture a day available for analysis. (Timchalk et al., 1965; Fett, 1964). As more frequent satellite pictures became available specific patterns were noticed, and by the early 1970’s a method for using satellite pictures to determine current intensity was developed (Dvorak, 1973). What has become known as the Dvorak technique looks at satellite pictures to determine a cloud pattern type as seen in Fig. 1. From the cloud pattern a corresponding T-number and current intensity can be determined. The method has improved over the years with some changes such as including infrared satellite pictures, but it remains very similar to the first process that came out. This method has proven quite accurate; however, it has its downfalls. Each classification is based off a previous one, and certain restrictions are made that will not allow a current intensity to increase or decrease past a certain amount than the previous estimate made. Also, when storms are first forming the cloud patterns can be ambiguous making it difficult to make an accurate classification.

Pitfalls such as these have led researchers to look for alternative or complementary ways of estimating current intensity. The difficulties present in specifying the current intensity may be one of the reasons why since 1990, there has been little change in the accuracy of intensity forecasts (Rappaport et al., 2008). This study looks at a relatively recent method of current intensity estimation using the Advanced Microwave Sounding Unit (AMSU).

The first AMSU was launched on 13 May 1998 on the NOAA-15 polar orbiting satellite (Kidder et al., 2000). The AMSU is a microwave radiometer that detects earth and atmosphere emitted radiation in the microwave part of the electromagnetic spectrum (UW-CIMSS, 2008). Microwave sounders have the advantage of penetrating through clouds, which geostationary visible and infrared satellites cannot do. Each channel senses a different microwave frequency, which corresponds to a different layer of the atmosphere. The combination of data from the different channels gives a vertical structure of a tropical system. This is unlike the Dvorak technique, which only views the top of the cloud. The resolution of the AMSU at nadir, meaning the pass is centered directly over the storm center,
is 50 km, and at the limbs or when a pass is at the side of the storm, is 100 km. This will be important to remember when looking at the analysis involving the core size of a storm. While the AMSU soundings provide data that can be used for numerous types of atmospheric analysis, tropical cyclone intensity is most concerned with brightness temperature (Tb). The AMSU cannot detect temperature directly but it can derive Tb. A warm brightness temperature anomaly is indicative of the actual warm core of a tropical system. As a storm intensifies, the warm brightness temperature anomaly will increase, especially near the center or eye of the storm (UW-CIMSS, 2008). Fig. 2 shows an example of the vertical storm structure that can be derived from the AMSU data.

This study compares AMSU intensity estimates from two institutions, the Cooperative Institute for Meteorological Satellite Studies (CIMSS) and the Cooperative Institute for Research of the Atmosphere (CIRA). While each institute uses the same instrument, each selects different information and uses separate algorithms to determine an intensity estimate. The CIMSS Algorithm uses AMSU-A channels 5 through 8 and AMSU-B channel 16. It applies corrections to account for sub-sampling (storm size is smaller than instrument resolution) and scan geometry (instrument at limb, not at nadir). The CIMSS AMSU also considers the radius of maximum wind (RMW), which is indicative of the storm core size, and the environmental pressure for boundary conditions. To obtain a wind estimate, first, the mean sea level pressure (MSLP) is determined from a multiple regression scheme that directly uses the AMSU channels. The MSLP is then used to obtain a corresponding maximum sustained wind speed (MSW) estimate. Finally, the CIMSS algorithm is updated annually in hopes of yearly improvement. The CIRA Algorithm uses the AMSU channels to get temperature and wind fields, and then a multiple regression scheme to get the MSLP and MSW separately. The last CIRA update was in 2005. The differences in the two algorithms account for the differences in the intensity estimates. In this study, the two algorithms are analyzed separately.

**METHODOLOGY**

**Data Retrieval**

For this study, all data used for analysis were obtained from the Automated Tropical Cyclone Forecasting system (ATCF). A total of four parameters are analyzed: CIMSS AMSU, CIRA AMSU, TAFB Dvorak, and SAB Dvorak. TAFB is NOAA’s Tropical Analysis and Forecast Branch and SAB is NOAA’s Satellite Analysis Branch. While the raw data set includes analysis of all four parameters separately, for comparison, the wind estimates of the TAFB and SAB Dvorak method are averaged to get an overall Dvorak wind estimate. It is important to know that by averaging the two Dvorak estimates, this generally provides a smaller error than using them each separately. Best track data listed in the Tropical Cyclone Reports (Jarvinen et al., 1984) issued by the National Hurricane Center is used to verify the parameter estimates. The parameter estimates are operational, meaning that the data values used in this study are the same as those available when the actual forecasts were made. Data points from both the Atlantic and Eastern Pacific basins were used.

**Data Requirements**

The complete raw data set contains more data points than were used for final analysis. First, the time of each AMSU pass had to be within two hours of a reconnaissance flight in order for the data to be used. This is required to ensure that the best track data used to verify the data set is based from in situ data, and not the estimates being analyzed. This requirement eliminates the majority of Eastern Pacific basin data as well as many Atlantic data points. From here, the data was required to be homogeneous meaning that for each time of an AMSU pass all four parameters (CIMSS AMSU, CIRA AMSU, TAFB Dvorak, SAB Dvorak) had to be available. This ensures that when comparing the analysis of each parameter the same set of storms and times are being compared. This is important, as no two storms are identical. Dvorak estimates and best track values are only given every six hours, so the six hourly data closest to the time of the AMSU pass was used for each AMSU pass time. Best track data is also available at every 6-hour interval. Since the Dvorak technique estimates have the advantage of being at the same times as the best track values used for verification, interpolated best track values were determined for the time of each AMSU pass. The AMSU data was then verified using the interpolated best track data.
Data Divisions

Once the data set was completed, it was subdivided to provide a complete analysis. The combined data (2005-2008) was first analyzed as one complete set, and then it was split into a multi-stratification of intensity and core size. For this multi-stratification, the intensity, determined by maximum sustained wind speed (MSW), was divided into weak systems (MSW 63 kts and less), and strong systems (MSW 64 kts and greater). The core size, determined by radius of maximum wind (RMW), was divided into small core systems (RMW 25 nm and less), and large core systems (RMW 30 nm and greater). RMW is operationally estimated to the nearest 5 nm. These divisions roughly split the size and intensity samples into halves, and led to a total of four sets: small/weak systems (SW), large/weak systems (LW), small/strong systems (SS) and large/strong systems (LS). Due to the interpolated best track data used for AMSU verification, the sample sizes for the intensity and size stratification may vary slightly between the Dvorak and AMSU parameters. This happens if a best track value is on the border between two categories and upon interpolation, the value falls into the other category causing different sample sizes.

Statistical Measures Used

For each of the aforementioned categories three statistical measures are used to analyze the data. The first of these is the mean bias error (MBE) also known as the total error. For each data point the bias error (BE) is given by:

\[
BE = x_{\text{experimental}} - x_{\text{true}},
\]

where \(x_{\text{experimental}}\) is the parameter wind estimate, and \(x_{\text{true}}\) is the best track wind or interpolated best track wind. The MBE is the average of all the BEs for a given parameter. The closer the MBE is to zero the better. The advantage of this measure is that it can determine whether a parameter overestimates or underestimates the true value on average. The disadvantage is that a dataset can have huge individual bias errors, but if there are similar magnitudes of positive and negative errors, the mean bias error can come out to zero.

This leads to the importance of the second statistical measure, mean absolute error (MAE). The absolute error (AE) for each data point is the absolute value of the bias error, given by:

\[
AE = |x_{\text{experimental}} - x_{\text{true}}|
\]

The MAE is the average of all the individual AEs. The MAE helps rule out the disadvantage of the MBE. Here, since all values are positive, if there are large individual absolute errors, they will be reflected in the mean value.

The final statistical measure used is the correlation coefficient, also called an R-value. It measures the strength and direction of a linear relationship between two variables, which in this study are the best track or interpolated best track wind and each parameter’s wind estimate. The correlation R-value is given by:

\[
r = \frac{n\Sigma x_i^* x_i - \Sigma x_i^* \Sigma x_i}{\sqrt{(n\Sigma x_i^2 - (\Sigma x_i^2)^2)^{1/2}} \sqrt{(n\Sigma x_i^2 - (\Sigma x_i^2)^2)^{1/2}}}, \quad i = 1, \ldots, n,
\]

where \(x_i^*\) is the parameter estimate, \(x_i\) is the best track value, and \(n\) is the sample size. In this case, the closer the value is to 1 the better the correlation is. MBE, MAE and an R-value together can give an idea of what a data set looks like and how accurate it is.

Significance Testing

One of the overall purposes of this study is to determine the situations where one AMSU technique does better than the other (CIMSS vs. CIRA), and where the two AMSU techniques outperform, are competitive with, or are outperformed by the Dvorak technique (CIMSS, CIRA AMSU vs. Dvorak). While looking at the statistical measures alone is helpful, it is important to perform statistical significance testing to determine if the differences seen between the parameters is enough to make an overall conclusion. To perform the statistical significance testing, a one-tailed z-test was performed between each of the parameters for each of the three statistical measures MBE, MAE and correlation r-value (Spiegel, 1990.) For the MBE z-value, first the standard deviation, \(\sigma\), needs to be found for each parameter. The formula for \(\sigma\) is as follows:

\[
\sigma = \sqrt{(\Sigma(BE_i - MBE)^2 / n)},
\]

where \(\Sigma\) signifies the sum over all \(i\), BE, are the individual bias errors of the parameter for \(i = 1, 2, \ldots, n\), and \(n\) is the sample size. Comparing, for example, parameter 1 with MBE1 and \(\sigma_1\), and parameter 2 with MBE2 and \(\sigma_2\), a comparative standard deviation \(\sigma_{MBE1-MBE2}\) is found. The formula for this standard deviation is:

\[
\sigma_{MBE1-MBE2} = \sqrt{\left(\sigma_1^2/n_1 + \sigma_2^2/n_2\right)}.
\]
Then, the $z$ value is found by:

$$z = (|MBE_1| - |MBE_2|)/\sigma_{MBE1-MBE2}.$$ 

Since mean bias error can be either negative or positive, the absolute value is taken so that only the magnitude is compared. For example, a MBE of 1 kt or -1 kt is the same distance from zero. Thus, when comparing those there is no difference between the magnitudes leading to a value of 0 for $z$. If the absolute value were not taken then $z$ would not be zero leading to an inaccurate result. Finding a $z$ value for MAE comparison uses the same equations for the standard deviations and $z$ value substituting MAE for MBE, and $AE_i$ for $BE_i$, where $AE_i$ is the individual absolute error for each $i = 1, 2, \ldots, n$. Since MAE is always positive, taking the absolute value is not necessary.

Once a $z$ value is found, several things can be determined. First, the sign of the $z$ value tells which parameter is outperforming. Since for MBE and MAE the lower or closer the value is to zero, the better the parameter is doing, then a negative $z$ value indicates that parameter 1 is outperforming. If $z$ is positive, the opposite is occurring and thus parameter 2 is outperforming. Next, there are critical values of $z$ that help determine the level of significance. If $z$ is equal to or less than -1.645 or equal to or greater than 1.645, the sign depending on which parameter outperforms, then the outperforming parameter is significantly better to a .05 level. Following the same principle, if the $z$-value is -2.33 or 2.33, then the parameter is significant to a .01 level. The lower the level, the more significant the outperformance is. More critical values of $z$ are found in Table 1. If a $z$ value is significant at the .05 level, but not at the .01 level it is considered probably significant. A value significant at the .01 level or any lower level, then it is considered highly significant. If the level of significance is greater than .05, then there is no significant difference between the two parameters being compared.

For correlation coefficient comparison, a similar $z$ value is found of which the significance level analysis is the same as for MBE and MAE; however, the formula to determine the $z$ value is different. First, a $Z$ value is determined for each parameter using the formula:

$$Z = 0.5*\ln[(1+r)/(1-r)],$$

where $r$ is the correlation coefficient. Then a corresponding $\sigma_z$ is determined where,

$$\sigma_z = 1/\sqrt{(n-3)},$$

where $n$ is the sample size. Similar to $\sigma_{MBE1-MBE2}$, a $\sigma_{z1-z2}$ is determined by:

$$\sigma_{z1-z2} = \sqrt{(\sigma_{z1}^2 + \sigma_{z2}^2)}.$$

Then,

$$z = (Z_1 - Z_2)/\sigma_{z1-z2}.$$ 

The interpretation of this $z$ value is the same as before except when analyzing the sign of the $z$ value. With correlation, the higher the value the better, so in this case a positive $z$ value indicates that parameter 1 is outperforming, while a negative $z$ value indicates that parameter 2 is outperforming. The levels of significance are the same as before and found in Table 1.

**CIMSS AMSU VS. CIRA AMSU ANALYSIS AND DISCUSSION**

In this section, the analysis of the CIMSS AMSU and the CIRA AMSU will be discussed and compared to determine if either of the techniques is better than the other.

**Combined Data Set (2005-2008)**

Combining all the individual years into one data set gives a total sample size of 199 data values. Table 2 shows the breakdown of the dataset by each hurricane season.

The combined data set analysis indicates that the CIMSS AMSU has the lowest values of MBE and MAE as indicated in Fig. 3a. The CIMSS AMSU MBE, with a value of -4.1 kts, is almost half the value of the CIRA AMSU MBE with -8.0 kts, and based on the significance testing found in Table 3, is significantly lower than the CIRA MBE. The

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>68</td>
</tr>
<tr>
<td>2006</td>
<td>33</td>
</tr>
<tr>
<td>2007</td>
<td>27</td>
</tr>
<tr>
<td>2008</td>
<td>71</td>
</tr>
</tbody>
</table>

**Table 2. Breakdown of the total data set sample size by individual hurricane season**
CIMSS MAE is also significantly lower than the CIRA MAE. Looking at Fig. 3b and Fig. 3c, both parameters show a pattern of underestimating the true intensity at higher intensities. The CIMSS AMSU, however, does show more data points that provide a better estimate at the higher intensities than the CIRA AMSU does, which would account for the CIMSS AMSU having a lower MBE. Also, the CIMSS AMSU best-fit line appears to be more parallel with the perfect fit line, which also corresponds to the higher correlation value. The CIMSS r-value is also significantly higher than the CIRA as indicated in Table 3. Overall, for the combined data set, the CIMSS AMSU outperforms the CIRA AMSU based on the significant differences between all three statistical measures.

<table>
<thead>
<tr>
<th>Stratification</th>
<th>MBE Z</th>
<th>Significance Level</th>
<th>MAE Z</th>
<th>Significance Level</th>
<th>Correlation Z</th>
<th>Significance Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined 2005-2008</td>
<td>-2.770</td>
<td>CIMSS Sig to .005</td>
<td>-2.668</td>
<td>CIMSS Sig to .005</td>
<td>1.970</td>
<td>CIMSS Sig to .005</td>
</tr>
<tr>
<td>Large/Strong</td>
<td>-0.646</td>
<td>No difference</td>
<td>-0.520</td>
<td>No Difference</td>
<td>-0.128</td>
<td>No Difference</td>
</tr>
<tr>
<td>Large/Weak</td>
<td>-0.509</td>
<td>No Difference</td>
<td>-1.663</td>
<td>CIMSS Sig to .05</td>
<td>0.753</td>
<td>No Difference</td>
</tr>
<tr>
<td>Small/Strong</td>
<td>-2.698</td>
<td>CIMSS Sig to .005</td>
<td>-2.068</td>
<td>CIMSS Sig to .05</td>
<td>1.058</td>
<td>No Difference</td>
</tr>
<tr>
<td>Small/Weak</td>
<td>-2.802</td>
<td>CIMSS Sig to .005</td>
<td>-1.882</td>
<td>CIMSS Sig to .05</td>
<td>0.721</td>
<td>No Difference</td>
</tr>
</tbody>
</table>

**TABLE 3.** Displays the z values and corresponding significance levels when comparing the CIMSS AMSU with the CIRA AMSU for each stratification. Any category highlighted in gray depicts a situation where one of the AMSU parameters’ corresponding statistical measures is better than the other AMSU parameter to a significant level.

**FIG. 3.** a) Displays mean bias error (MBE) in blue and mean absolute error (MAE) in red for the CIMSS AMSU, CIRA AMSU, and Dvorak for the 2005-2008 Combined division. b) Displays best fit linear regression lines and corresponding correlation coefficient R-value for each parameters’ wind speed estimates and best track winds for the 2005-2008 Combined division: CIMSS AMSU (blue), CIRA AMSU (red), Dvorak (green). Black line is a perfect fit line displaying what a perfect correlation is. c) Displays the individual bias errors versus best track winds for the CIMSS AMSU (blue), CIRA AMSU(red), and the Dvorak (green) for the 2005-2008 Combined Division.

**Multi-Stratification by Core Size and Intensity**

For the multiple stratification by intensity and core size, there were a total of four divisions: large/strong (LS), large/weak (LW), small/strong (SS), and small/weak (SW). For this stratification, it is important to remember the resolution of the AMSU instrument, which is the same as an RMW of about 25 nm. The criterion for the small stratification for RMW is 25 nm and less. For these small systems, it is suspected that the AMSU resolution may not be reliable enough to accurately resolve the intensity.

Starting first with the large/strong systems, the sample size was the smallest out of any of the divisions with only 19 data values. For this division, the CIMSS AMSU had close to zero bias with a MBE.
of -.2 kts, which is the lower MBE of the two AMSU parameters as indicated in Figure 4a. Also, the CIRA AMSU MBE is positive indicating that the parameter overestimates on average for this division. The CIMSS AMSU also has a lower MAE as seen in Figure 4a. However, looking at Table 3, these differences are not significant. While it is difficult to see a strong pattern in Figure 4b and Figure 4c due to the small sample size, the CIMSS AMSU appears to have a similar number of overestimations, as there are underestimations, which explains why the CIMSS AMSU had a MBE near zero. This also would explain why the best-fit line is practically on top of the perfect fit line. However, due to some variability the correlation coefficient is not high. The CIRA AMSU has a few more overestimations overall, which is why the best-fit line is above the perfect fit line. The CIRA AMSU has a slightly higher correlation coefficient of the two AMSU parameters. However, the r-values between the two parameters are very similar which is confirmed with the lack of a significant difference indicated in Table 3. Overall, there is no significant difference between the CIMSS and CIRA intensity estimates for large/strong storms.

Moving to large/weak systems, the sample size for this division is much higher than the previous division with 67 data points. The CIMSS AMSU again has a low MBE as viewed in Figure 5a. The CIRA AMSU underestimates by slightly more, but the difference between the two AMSU parameters’ MBEs is not significant as indicated in Table 3. The CIMSS AMSU also has a lower MAE, which when compared to the CIRA AMSU is significant at the .05 level, which indicates that the CIMSS AMSU MAE is probably significantly lower than the CIRA AMSU MAE. The patterns in Figure 5b are much different than previous divisions. The best-fit lines for both the CIMSS and CIRA AMSU do not parallel the perfect fit line well. Each parameter appears to overestimate at wind speeds less than 40 kts, and then begins to underestimate at wind speeds above 40 kts. The large variability that shows up in Figure 5c also corresponds to the lower correlation coefficients. The CIMSS AMSU does have a higher r-value, but the difference between the r-values is not significant as seen in Table 3. Overall, this gives a mixed result since the CIMSS AMSU had a probably significantly lower MAE than the CIRA, but a lack of significant difference of the other two statistical measures. This gives only a suggestion that the CIMSS AMSU is the better performer of the two AMSU parameters for large/weak storms.

For small/strong systems, the sample size was 85, the largest of the divisions for this stratification. For this division, both AMSU parameters have large MBEs and MAEs compared with previous divisions. Looking at Figure 6a, of the two AMSU parameters, the CIMSS AMSU has the lower MBE and MAE. Table 3 confirms that the differences in MBE and MAE of the CIMSS and CIRA are significant. However, the correlation coefficients are not significantly different. Figure 6b and Figure 6c give some insight into why this may be. The CIRA AMSU shows a larger underestimation as indicated in the MBE, but the CIMSS AMSU shows a lot more variability at higher wind speeds. It is this variability that most likely is the cause for the lack of a large difference in the r-values despite the significant differences in MBE and

FIG. 4. a-c) Same as for Fig. 3, but for the Large/Strong Storm division. Refer to Fig. 3 for figure details.
MAE between the two parameters. Overall, since the CIMSS AMSU has a significantly lower MBE and MAE, the CIMSS AMSU outperforms the CIRA AMSU for small/strong systems.

Finally, the last division, small/weak systems, has a small sample size of only 28. Comparing the two AMSU parameters, the CIMSS AMSU has a lower MBE and MAE as illustrated in Figure 7a. There is a large difference between the two MBEs, and Table 3 indicates that the difference is highly significant. The difference between the MAEs is less than that of the MBEs, and based on the significance level the difference is only probably significant. While the actual values of the MBEs and MAEs don’t stand out as being horrible, the low correlation values of both parameters show that small/weak storm intensities are difficult to estimate. The CIMSS r-value does break .5, while the CIRA AMSU r-value does not, but the difference is not significant. This may be due to the small sample size. Figure 7c shows that both parameters have a lot of variability, which helps explain the low correlation values. As displayed in Figure 7b, the CIMSS AMSU best-fit line parallels the perfect fit line much better than the CIRA AMSU does. The CIRA AMSU has very few overestimations of the true intensity as indicated by the best-fit line being entirely below the perfect fit line. Overall, since the CIMSS AMSU does have a significantly lower MBE and a probably significant MAE, the CIMSS AMSU outperforms the CIRA AMSU for small/weak systems.

CIMSS/CIRA AMSU VS. DVORAK
ANALYSIS AND DISCUSSION

In this chapter, both AMSU parameters, CIMSS and CIRA, are compared to the Dvorak to determine the situations where either AMSU parameter is competitive with the Dvorak or outperforms the Dvorak. It should be noted again that the sample sizes between the AMSU parameters and Dvorak vary slightly due to the differences between the best track data used to verify the Dvorak estimates and the interpolated best track data used to verify the AMSU estimates. If a best track value is on the border between two divisions by intensity, when interpolated, the data value might fall into the other division.

Combined Data Set (2005-2008)
Looking at the entire 2005-2008 combined data set, in comparison to the Dvorak, neither of the AMSU parameters outperforms the Dvorak, and in fact based on the significance testing in Table 4, neither is even competitive with the Dvorak. Figure 3a shows that the Dvorak technique has very little bias error, and this is reconfirmed in Figure 3b as the Dvorak best-fit line parallels the perfect fit line very well. This is indicative in the high correlation value of .95 as well. The Dvorak parallels the perfect fit line, whereas both AMSU techniques tend to underestimate the true intensity at the higher wind speeds, with the CIRA AMSU underestimating at a greater magnitude than the CIMSS AMSU. From this data, and the significance testing, it appears that both the CIMSS and CIRA AMSU methods are not competitive with the Dvorak technique. However, the AMSU method should not be completely discarded as a valuable intensity analysis tool based solely on this conclusion. The following multi-stratification analysis shows...
Multi-Stratification by Intensity and Core Size

Beginning with the large/strong systems, the Dvorak sample size was the same as the AMSU with 19 data values, the smallest sample of any division. While the Dvorak has a larger magnitude MBE compared with the CIMSS AMSU, the Dvorak has a lower MAE than both AMSU parameters as indicated in Figure 4a. Table 4 shows that these differences are not significant. Figure 4b shows that the Dvorak best-fit line follows the perfect fit line fairly well. It does show a slight underestimation at the higher wind speeds, but overall it has a higher correlation value than either AMSU parameter. This most likely is due to the Dvorak having less variability than the other two parameters as seen in Figure 4c. However, overall the r-value differences are not significant. This shows that overall both AMSU parameters are competitive with the Dvorak technique for large/strong systems based on the lack of significant differences between all three parameters.

For large/weak systems, the sample size for the Dvorak was again the same as the AMSU with 67 data values. While the Dvorak has lower values of MBE and MAE than the CIRA AMSU, and higher values compared with the CIMSS AMSU as illustrated in Figure 5a, the differences between the Dvorak and both AMSU parameters’ MBE and MAE are not significant as indicated in Table 4. Figure 5b shows a similar pattern for the Dvorak best-fit line as it did for both the CIMSS and CIRA AMSU best-fit lines.

<table>
<thead>
<tr>
<th>Stratification</th>
<th>Parameter</th>
<th>MBE with Dvorak Z</th>
<th>Significance Level</th>
<th>MAE with Dvorak Z</th>
<th>Significance Level</th>
<th>R with Dvorak</th>
<th>Significance Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined 2005-2008</td>
<td>CIMSS AMSU</td>
<td>2.744</td>
<td>Dvorak Sig to .005</td>
<td>3.021</td>
<td>Dvorak Sig to .002</td>
<td>-2.943</td>
<td>Dvorak Sig to .002</td>
</tr>
<tr>
<td>Large/Strong</td>
<td>CIMSS AMSU</td>
<td>-0.077</td>
<td>No Difference</td>
<td>1.035</td>
<td>No Difference</td>
<td>-0.360</td>
<td>No Difference</td>
</tr>
<tr>
<td>Large/Weak</td>
<td>CIMSS AMSU</td>
<td>0.646</td>
<td>No Difference</td>
<td>1.539</td>
<td>No Difference</td>
<td>-0.232</td>
<td>No Difference</td>
</tr>
<tr>
<td>Small/Strong</td>
<td>CIMSS AMSU</td>
<td>3.700</td>
<td>Dvorak Sig to .001</td>
<td>3.504</td>
<td>Dvorak Sig to .000</td>
<td>-4.099</td>
<td>Dvorak Sig to .000</td>
</tr>
<tr>
<td>Small/Weak</td>
<td>CIMSS AMSU</td>
<td>3.700</td>
<td>Dvorak Sig to .001</td>
<td>3.504</td>
<td>Dvorak Sig to .000</td>
<td>-4.099</td>
<td>Dvorak Sig to .000</td>
</tr>
</tbody>
</table>

Table 4. Displays the z values and corresponding significance levels when comparing the CIMSS and CIRA AMSU with the Dvorak technique for each stratification. Any category highlighted in gray depicts a situation where the AMSU parameters’ corresponding statistical measures shows no difference or is better than the Dvorak statistical measures.

However, the Dvorak line does appear to be more parallel to the perfect fit line. The Dvorak still overestimates at lower wind speeds and underestimates at the higher wind speeds, but not to the amount that the AMSU parameters appears to be doing. This is illustrated in Figure 5c. The magnitudes of the errors for the AMSU parameters are greater than that of the Dvorak, especially for the lower wind speeds. However, the correlation coefficient of the Dvorak is not significantly higher than either AMSU parameter as indicated in Table 4. The overall low correlation values of all three parameters shows that this is a storm type that all three parameters need to improve on estimating the intensity for. Based on the lack of significant differences between the parameters’ statistical analysis values, both the CIMSS and CIRA AMSU are competitive with the Dvorak for large/weak storms.

For small/strong systems the Dvorak had a sample size of 88, which is slightly higher than that of the AMSU. Looking at Figure 6a, the Dvorak clearly has a lower MBE and MAE than both AMSU parameters for small/strong systems. The Dvorak MBE is practically zero at -1.1 kts. Table 4 indicates that the differences are highly significant. Figure 6b shows a much better correlation of the Dvorak with the best track wind. The Dvorak underestimates the true intensity some at the higher wind speeds, but not nearly to the magnitude of the AMSU parameters. Also, there appears to be less variability in the Dvorak estimates than with the AMSU parameters as viewed in Figure 6c. These factors explain why the Dvorak correlation value is significantly higher than both AMSU parameters. Overall, the Dvorak outperforms
both the CIMSS and CIRA AMSU for small/strong storms. However, as previously mentioned, this is expected due to the known knowledge of the AMSU instrument resolution. Also, this is the largest division out of the multi-stratification divisions. The fact that a high percentage of the data values are small/strong systems explains why the AMSU did not appear to be competitive with the Dvorak when just looking at the combined 2005-2008 data analysis.

Finally, for small/weak systems, the Dvorak sample size of 25 was slightly less than...
that of the AMSU. Looking back at Figure 7a, the Dvorak parameter has the lowest MBE, but the highest MAE. Figure 7c indicates why this is the case. There appear to be an equal number of overestimations and underestimations by the Dvorak, which would lead to the low MBE. However, the magnitudes of these errors are larger than many of the AMSU errors, which lead to the high MAE. Table 4 indicates that the Dvorak has a probably significantly lower MBE than the CIRA AMSU, while there is no significant difference between the Dvorak and CIMSS AMSU MBEs. For the MAEs, the CIMSS AMSU MAE is probably significantly lower than the Dvorak, while there is no significant difference between the CIRA AMSU MAE and the Dvorak MAE. Figure 7b shows that the Dvorak estimates have almost no correlation with the best track winds. The Dvorak r-value is .15, which is the lowest of all the correlation coefficients found in this entire study. The Dvorak best-fit line is almost horizontal, indicating a poor relationship with the best track winds. The CIMSS AMSU correlation coefficient is probably significantly higher than the Dvorak, while the CIRA AMSU r-value is not significantly different from the Dvorak. The lack of a significant difference between the Dvorak r-value and the CIRA AMSU r-value, despite the large actual difference, is probably due to the low sample size. Overall, the CIMSS AMSU outperforms the Dvorak for small/weak systems based on the probably significantly lower MAE and probably significantly higher correlation coefficient. The CIRA AMSU is competitive with the Dvorak for small/weak systems based on the lack of a significant difference of MAEs and r-values.

CONCLUSIONS

As mentioned previously, the purpose of this study is to determine the specific situations in which the AMSU parameters, CIMSS and CIRA, either outperform the Dvorak technique, are competitive with the Dvorak technique, or the Dvorak technique outperforms them. By determining this information, forecasters can better decide which method of intensity estimation to use when knowing certain criteria about a tropical system.

1) Comparing just the CIMSS and CIRA AMSU, the CIMSS AMSU outperforms the CIRA AMSU for the majority of the divisions analyzed. 2) For the combined 2005-2008 dataset, the Dvorak outperformed both AMSU parameters. This result does not give a favorable outcome in declaring the AMSU a reliable intensity estimator. However, upon further analysis of different stratifications a different set of results followed. 3) For the multi-stratification by intensity and core size, it was shown that the CIMSS and CIRA AMSU are competitive with the Dvorak for both large/strong systems (RMW > 25 nm, MSW > 63 kts) and large/weak systems (RMW > 25 nm, MSW < 64 kts). This shows that both AMSU parameters are in fact competitive for all systems with an RMW greater than 25 nm for any intensity level. 4) Also, the CIMSS AMSU outperformed the Dvorak for small/weak systems (RMW 25 nm and less, MSW < 64 kts), while the CIRA AMSU was competitive with the Dvorak for this same division. This information shows that the AMSU parameters are competitive with the Dvorak for all weak systems with wind speeds less than 64 knots, regardless of size. 5) While not shown, yearly alterations to the CIMSS technique were responsible for improving performance of the CIMSS AMSU relative to the CIRA AMSU in 2007-2008 relative to 2005 and 2006. These conclusions give an overall idea of which systems the AMSU should be used for.

While there was only one division in which one of the AMSU parameters outperformed the Dvorak technique, the AMSU parameters estimates still provide valuable information to forecasters. By knowing the types of storms that the AMSU is competitive with the Dvorak, then in those situations, the data from each of the parameters can be used as confirmation for the others. This follows along the premise that the more data available the better, especially as the AMSU is completely independent of the Dvorak technique in its methodology. Also, since the Dvorak technique only provides estimates every six hours, an AMSU pass might occur between that time span, and can help provide a more current estimate. This can be helpful in rapidly intensifying or weakening systems in which the intensity can change significantly over only 6 hours.

Overall, the AMSU method for estimating intensity is a valuable tool for the analysis of tropical systems. This study provides the specific situations in which the CIMSS and CIRA AMSU can be used alongside the Dvorak technique to aid forecasters’ analysis of current storm intensity.

ACKNOWLEDGMENTS

I would like to thank my thesis advisor Sharan Majumdar of the University of Miami with aiding me in the process of scientific writing. Also, I would like to thank Jack Beven and Chris Landsea of the National Hurricane
Center for their guidance in the research topic of tropical cyclone intensity estimates, and the constant feedback and help I received throughout the research process.

REFERENCES


