P2B.11 TROPICAL INTENSITY FORECASTING USING A SATELLITE-BASED TOTAL PRECIPITABLE WATER PRODUCT

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1. INTRODUCTION

Over the past several decades there have been only modest improvements in operational intensity forecasts (DeMaria et al, 2007), despite the fact that track errors have decreased significantly. Because of the complexity of the physical processes affecting intensity changes, the Statistical Hurricane Intensity Prediction Scheme (SHIPS) has generally been the most skillful of NHC's operational intensity forecast models over the past 10 years.

The SHIPS model includes dynamical effects on intensity change through the environmental vertical shear and upper-level divergence predictors calculated from the NCEP global forecasting system (GFS) model (DeMaria et al, 2005). SHIPS also includes a mid-level moisture predictor, which is also calculated from the GFS fields. However, the moisture predictor is only marginally significant and has a very small impact on the forecast. The small impact is inconsistent with observational studies which suggest that moisture variability in the storm environment, especially those associated with the Saharan Air Layer (SAL), can have a large effect on TC intensity (Dunion and Velden 2004). It is possible that the lack of impact in SHIPS is due to the difficulty with analyzing and forecasting moisture in the GFS.

In this study, the impact of environmental moisture on intensity changes is evaluated using an advanced satellite-based total precipitable water (TPW) product (Smith et al 2008). The impact on intensity change is determined by calculating various parameters from the TPW fields and then determining whether they provide additional predictive information in SHIPS. The TPW product is described in section 2, the SHIPS model is briefly summarized in section 3, and the TPW predictors are evaluated in section 4. Azimuthally averaged TPW fields are evaluated first, followed by asymmetric variables.

2. THE TPW PRODUCT

The TPW product was developed by Remote Sensing Systems (RSS) and uses a unified, physically based algorithm to estimate atmospheric water vapor from highly calibrated microwave radiometers. The water vapor values from SSM/I, TMI and AMSR-E instruments are combined to create maps four times per day. The maps are mostly filled but still contain some data gaps. To produce a more filled map in the earlier years, the maps consist of 12-hour averages (1987 to 1995), while in later years, a 6-hour average is produced (1996 to 2007). For this study, the TPW fields from 1997 to 2006 on a domain from 0 to 60^{o}N and 100 to 0^{o}W at 6 h intervals were used.

A time-weighted average of the satellite water vapor retrievals falling within a given 0.25 degree cell is produced. Empty cells are spatially filled using a 9x9 moving window and remaining holes are filled using satellite data from the map before or after (this essentially makes the map a +/- 9 hour data set though one can access the +/- 3 hour data). Any remaining small holes are again spatially filled using a 9x9 window. Information on filling process is retained. The resulting maps are over 99.8% complete for years after 2002. Further details are available from Smith et al (2008) and www.remss.com.

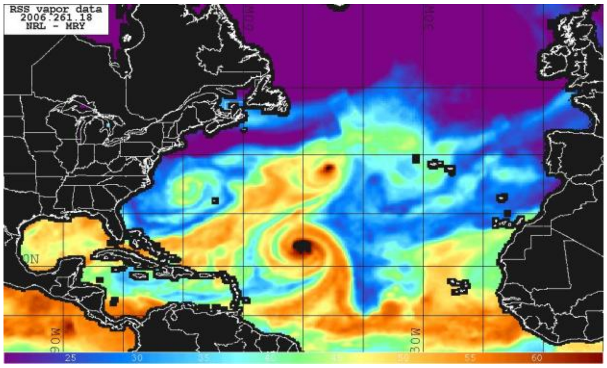

Figure 1. The TPW product at 18 UTC on 18 September 2006.

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Figure 1 shows an example of the TPW product on the domain used in this study. The values range from near zero to more than 60 mm. Hurricane Gordon was located near 38^{o}N and 48^{o}W and Hurricane Helene was near 24^{o}N and 50^{o}W in Fig. 1. Moist (TPW / 45 mm) and dry (TPW . 45 mm) bands can be seen around both storms. The dry air in the periphery of Gordon was mid-latitude in origin, while the dry air surrounding Helene was associated with the SAL.

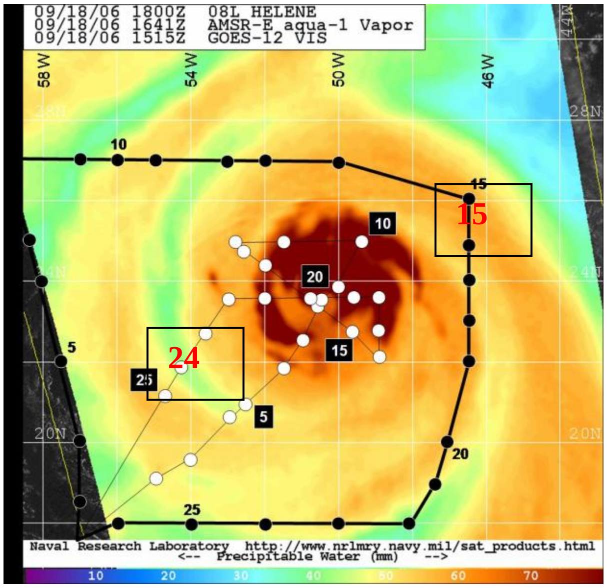

Figure 2. The NRL TPW product (similar to the RSS product) around Hurricane Helene (2006) along the swath of AMSR-E. The locations of dropwindsonde #24 from the NOAA P-3 and dropwindsonde #15 from the NOAA G-IV are indicated by the red numbers.

Figure 2 shows a close up view of the NRL TPW product for Hurricane Helene. In this version, the product along a single swath of AMSR-E is shown. The banding structure in the TPW product is readily seen. For comparison, temperature and moisture soundings from aircraft dropwindsondes are shown in Figs. 3 and 4. As indicated in Fig. 2, dropwindsonde #15 was in a moist band and #24 was in a dry band. Figures 3 and 4 shows that there are very large differences in the mid-level moisture in these two soundings, providing confirmation that the TPW product can be used to evaluation moisture variations around tropical cyclones.

3. THE SHIPS MODEL

SHIPS uses a multiple regression technique to predict intensity change (in terms of a maximum wind change) out to 5 days (DeMaria et al 2005). Predictors include climatology, persistence and atmospheric and oceanic variables. The atmospheric predictors are determined from the GFS analyses for the model development and from GFS forecasts in real time. The primary oceanic predictor is the maximum potential intensity (MPI) estimated from the sea surface temperature (SST) along the storm track. The 2007 version of SHIPS included 18 basic predictors. The prediction with the 18 predictors is then modified in a “correction” step using three additional predictors from GOES imagery and oceanic heat content (OHC) analysis determined from satellite altimetry. The satellite predictors are added as a correction because they were not available for the full development sample (1982-2006) for the 2007 model.

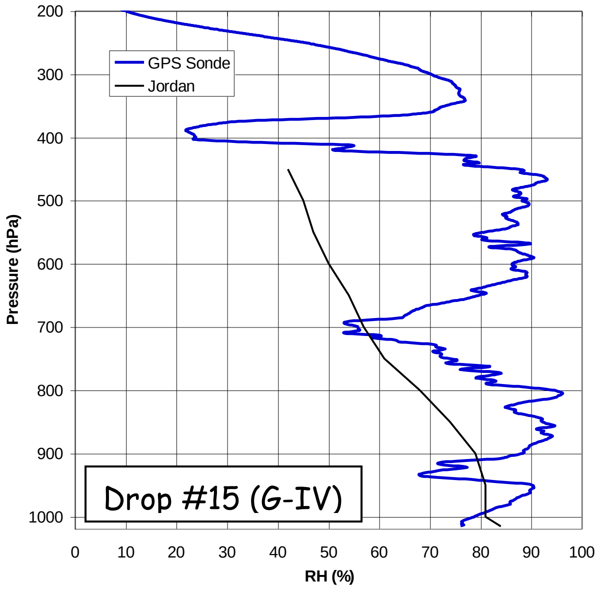

Figure 3. The relative humidity (RH) versus pressure from the GPS sounding #15 at the location shown in Fig. 2. The RH from the Jordan mean sounding is indicated by the black line.

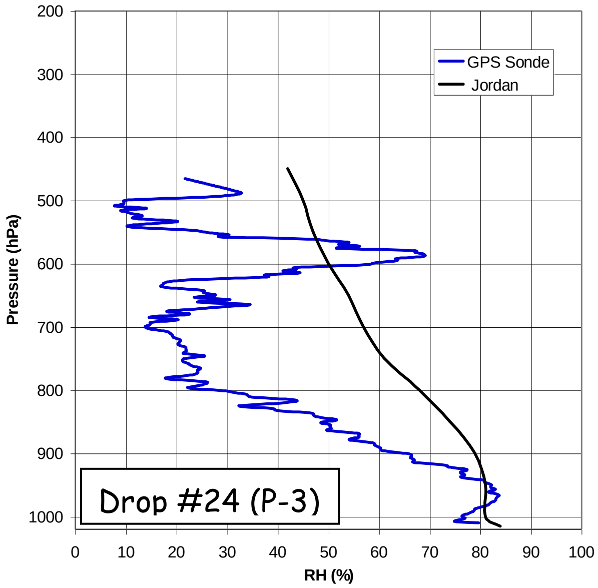

Figure 4. The relative humidity (RH) versus pressure from the GPS sounding #24 at the location shown in Fig. 2. The RH from the Jordan mean sounding is indicated by the black line.

The SHIPS predictors can be classified into “static”, which are only available at the beginning of the forecast, and “time dependent”, which are available for the entire forecast period. The static predictors include variables such as the initial storm intensity, persistence (determined from the previous 12 h intensity change), and the variables from the GOES imagery. Time dependent predictors include variables such as the vertical shear in the storm environment from the GFS forecasts and the MPI along the storm track.

4. EVALUATION OF TPW VARIABLES

The starting point of the TPW product evaluation is the basic version of the Atlantic SHIPS model that was run in real time in 2007. The correction step with the GOES and OHC input is not considered because the satellite data is not always available and would limit the sample size for the TPW evaluation, which is already restricted to a 10 year sample. The most important of the 18 predictors include the MPI, persistence, the environmental vertical shear and the environmental 200 hPa temperature.

Variables from the TPW analyses were added to the 18 predictors already included in SHIPS, as will be described in sections 4.1 and 4.2. The sample is then restricted to only those cases that include the TPW variables. For the period from 1997 to 2006 with TPW analysis, the sample includes 3004 cases with at least a 12 h forecast, decreasing to 971 cases with a 120 h forecast. The impact of the TPW variables is evaluated by determining the additional variance explained when they are added and by a statistical significance test of the regression coefficients. For this evaluation the regression coefficient is considered statistically significant if the null hypothesis that the coefficient is zero can be rejected at the 95% level, using a standard F-test.

As an example of this procedure, the 200 hPa divergence SHIPS predictor (D200) was evaluated. The regression coefficients for D200 were statistically significant at all time periods from 12 to 120 h. The magnitudes of the normalized regression coefficients were roughly in the middle of the 18 predictors, so D200 can be viewed as a fairly typical predictor. Figure 5 shows the total variance explained by the 18 SHIPS predictors, which ranges from about 36% at 12 h to 75% at 120 h. The values are available every 6 h, but are shown at 12 h intervals in Fig. 5 for simplicity. SHIPS predicts the intensity change over the entire forecast intervals, which helps to explain why the variance explained increases with interval length. Figure 6 shows the increase in variance explained when the D200 predictor is added to the other 17. D200 is a time dependent predictor and has the maximum impact on the 72 h forecast. The variance increase is not very large (less than 1%), but D200 is still important for the prediction.

4.1 Symmetric TPW Predictors

As can be seen in Fig. 2, the TPW values are generally largest near the storm center and have considerable variability with radius away from the center. For this reason, the TPW values were azimuthally averaged in 200 km wide radial bands out to 1100 km from the storm center. The averaged TPW in each band was added separately to the 18 SHIPS predictors to determine the radial location of the strongest predictive signal. The TPW values were also averaged over circular areas from r=0 to 100, r=0 to 200, …, r=0 to 1000 km radius as an initial evaluation of their predictive information. For simplicity, the variance explained was averaged over three time periods (0 to 36 h, 42 to 72 h and 78 to 120 h) rather than at each 6 h forecast interval. Because the TPW variables are static predictors, it might be expected that their maximum impact would be for the shorter forecast periods.

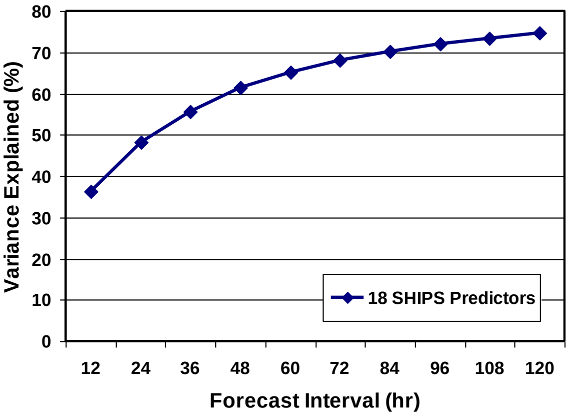

Figure 5. The variance explained by the 18 SHIPS predictors for the 1997-2006 sample.

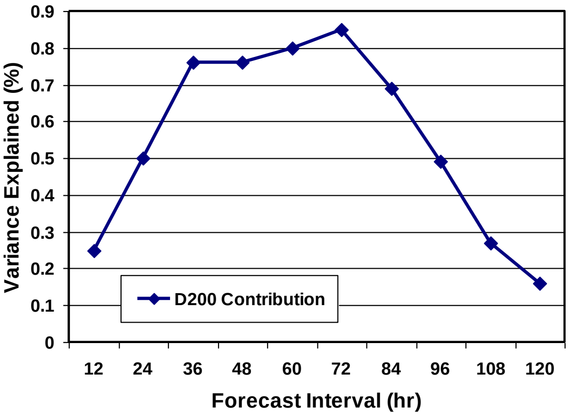

Figure 6. The variance explained when the 200 hPa divergence predictor is added to the other 17 SHIPS predictors.

Figures 7 and 8 show that the TPW increases the variance explained for the short term SHIPS predictions.

The largest increases are when the averaging area is very close to the storm center. For the smallest radii, the correlation of TPW with intensity change is statistically significant at the 95% level at all forecast times from 6 to 42 h. The regression coefficients are positive at these times, indicating that higher TPW values result in a greater intensity increase. This result indicates that the TPW product can provide intensity prediction information beyond what is already included in the basic SHIPS model.

There is hint of a secondary maximum in the variance explained for the 42-72 h predictions for radii near 300 km for the annular average in Fig. 7 and near 500 km for the circular average in Fig. 8. This region is near where the banding features were apparent for the Hurricane Helene case in Fig. 2. In the next sub-section, asymmetric predictors are tested to determine if there are better methods for quantifying the TPW structure in the storm environment.

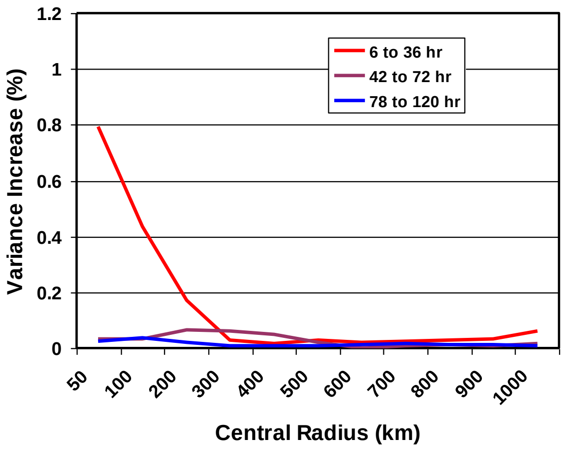

Figure 7. The increase in variance of the intensity changes explained when the TPW averaged over a 200 km wide annulus is added as a predictor, as a function of the central radius. For the first point, the annulus is 100 km in width.

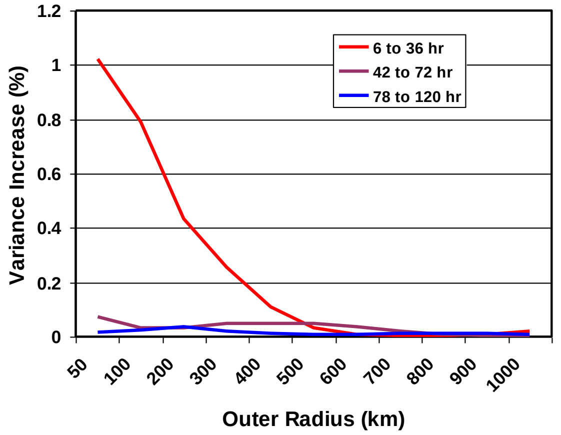

Figure 8. The increase in variance of the intensity changes explained when the TPW averaged over a circular area from centered on the storm, as a function of the outer radius.

4.2 Asymmetric TPW Predictors

The analysis of the azimuthally averaged TPW shows that the strongest predictive signal came from the regions closest to the storm center. It is possible that the information in the outer regions is not properly captured because the dry and moist bands occur at different radii for different storms, and at different times for the same storm. Also, the dry bands usually do not extend all the way around the storm, so the azimuthally average values are not representative of the driest regions.

As a first test of asymmetric TPW predictors, the percentage of the area drier than a specified threshold was calculated over the same annular regions used in Fig. 7. In this calculation, the dry regions will be accounted for even if they are present over only a small azimuthal interval. Figure 9 shows the variance increase when the areas with TPW < 50 mm were used as the predictors. The maximum response is for the 42-72 h predictions when the annulus is centered at 600 km radius. The regression coefficients were statistically significant at 24-78 h for this radius and the coefficients were all negative, indicating that larger dry areas lead to smaller intensity increases.

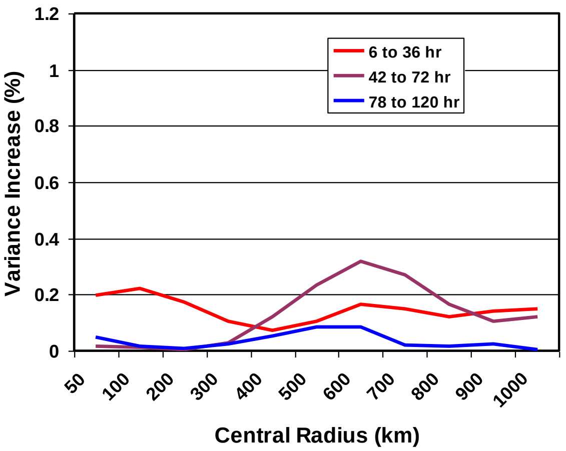

Figure 9. The increase in variance of the intensity changes explained when the percent area of a 200 km wide annulus with TPW less than 50 mm was added as a predictor, as a function of the central radius. For the first point, the annulus is 100 km in width.

5. CONCLUSIONS AND FUTURE PLANS

An advanced satellite-based total precipitable water (TPW) product was tested for its use in tropical cyclone intensity prediction. A 10-year (1997-2006) dataset at 6 h intervals over the Atlantic basin was obtained for the test. Several variables were calculated and added to the input to the 2007 version of the Statistical Hurricane Intensity Prediction Scheme (SHIPS). The predictive value of the TPW variables was evaluated by calculating the increase in the variance of the observed intensity changes explained when the TPW predictors were added. This method provides a test of the usefulness of the TPW information, relative to what is already included in SHIPS.

Results showed that the average TPW near the storm center has a statistically significant positive correlation with intensity change for the 6 to 42 h predictions. Results also showed that the percent of the area with TPW < 50 mm in an annulus centered at 600 km has a statistically significant negative correlation with intensity change for the 24-78 h prediction. Thus, the TPW product has the potential to improve the SHIPS model.

In the preliminary results presented in this paper, a few radial intervals were tested, and a single threshold (50 mm) was used to identify dry regions. Many other combinations could be tested to determine the regions and TPW thresholds that provide the most increase in explained variance. Many other TPW variables could also be tested including the driest values in a ring, average values in a quadrant, and measures of the TPW asymmetry.

All of the results shown here are for the dependent sample. To confirm the predictive value of the TPW product, the best choice of variables would need to be tested on independent cases, and with only the information that is available in real time. The quality of the TPW product would be similar in real time, but most of the other SHIPS predictors would be degraded since they would be evaluated along the forecast track, rather than the best track, and from GFS forecast fields from rather than the GFS analyses used in the dependent sample.

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REFERENCES

DeMaria, M., J.A. Knaff, and C.R. Sampson, 2007: Evaluation of Long-Term Trends in Operational Tropical Cyclone Intensity Forecasts. *Meteor. and Atmos. Phys.*, **59**, 19-28.

_____, M. Mainelli, L.K. Shay, J.A. Knaff and J. Kaplan, 2005: Further Improvements in the Statistical Hurricane Intensity Prediction Scheme (SHIPS). *Wea. Forecasting*, **20**, 531-543.

Dunion, J.P., and C.S. Velden (2004): The impact of the Saharan Air Layer (SAL) on Atlantic tropical cyclone activity. *Bull. Amer. Meteor. Soc*., **85**, 353-364.

Smith, D.K., K. Hilburn, and F.J. Wentz, 2008: DISCOVER merged water vapor product validation. 22nd Conf. on Hydrology, New Orleans, LA, paper P3.4.