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IMPROVEMENTS IN THE PROBABILISTIC PREDICTION OF TROPICAL CYCLONE RAPID INTENSIFICATION RESULTING FROM INCLUSION OF SATELLITE PASSIVE MICROWAVE OBSERVATIONS

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1. INTRODUCTION

The physical processes accompanying rapid intensification (RI, defined as an increase in the analyzed maximum sustained surface winds by at least 25 kt in 24 h) in tropical cyclones (TCs) remain unresolved. Moreover, predicting these events is one of the most challenging aspects of intensity forecasting. Improving the prediction of RI is a top priority at NOAA's National Hurricane Center and Central Pacific Hurricane Center.

Probabilistic RI schemes incorporating environmental data and GOES-IR imagery have improved RI prediction (Kaplan et al. 2010; Rozoff and Kossin 2011). Environmental data, such as a TC's potential intensity, ocean heat content, and vertical wind shear, represent some of the kinds of variables found in empirical forecast schemes for RI as these features describe whether the necessary background conditions for RI exist. GOES-IR-based predictors also describe aspects of the environment such as vertical wind shear and upper-level divergence, but are particularly useful in depicting certain cloud structures relevant to RI. It is generally believed that RI is strongly tied to the organization of and relationships between precipitation and the kinematic structure of a TC. It is therefore not surprising that GOES-IR imagery adds forecast skill to empirical RI prediction. A primary shortcoming of IR imagery is that it often cannot discern the organization of inner-core TC precipitation due to the fact that upper-level cirrus clouds obscure the detection of such internal structure.

Although microwave imagery (MI) has lower temporal coverage in comparison to IR imagery, MI can more readily resolve precipitation patterns underneath the cirrus canopy. Therefore, the use of MI in RI prediction is believed to be quite advantageous and recent studies suggest MI-based predictors may add significant skill to probabilistic RI models (e.g., Velden et al. 2010; Harnos and Nesbitt 2011; Jiang et al. 2011, 2012).

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The goal of this study is to improve the statistical prediction of RI using a variety of predictors derived from passive MI. To this end, we have created physically based statistical features exploiting information about the distribution and intensity of precipitation, including warm-rain and ice hydrometeors, in the inner core of developing and mature TCs. From there, we have adapted statistical models to incorporate the most skillful predictors.

2. METHODOLOGY

Three probabilistic RI models are used to study the potential forecast improvements achieved by MI-based predictors. These models include the Statistical Hurricane Intensity Prediction Scheme (SHIPS) Rapid Intensification Index (RII) (Kaplan et al. 2010) and also the Bayesian and logistic regression models described in Rozoff et al. (2011). The following results are all based on the logistic regression model, although MI-based predictors add significant skill to the other models as well.

The logistic regression model uses optimal environmental and GOES-IR-based predictors from the SHIPS developmental dataset (DeMaria et al. 2005). The SHIPS-based predictors for the logistic regression model in the current study are identical to those described in Rozoff and Kossin (2011).

A new developmental dataset of MI brightness temperatures (T_b) at 18.7-19.4, 36.5-37.0, and 85.5-89.0 GHz from the Special Sensor Microwave/Imager (SSM/I), Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), the Advanced Microwave Scanning Radiometer-EOS (AMSR-E), and WindSat was assembled for our experiments. The effective field of view for each instrument at each channel used in this study is shown in Table 1. Currently, the MI dataset covers the Atlantic and eastern Pacific Ocean basins over the period of 1998-2008.

Table 1. The effective field of view for each sensor and channel used in this study.

SSM/I	TMI	AMSR-E	WindSat
43 x 69 km *19.4 GHz*	18 x 30 km *19.4 GHz*	16 x 27 km *18.7 GHz*	16 x 27 km *18.7 GHz*
38 x 40 km *37.0 GHz*	9 x 16 km *37.0 GHz*	8 x 14 km *36.5 km*	8 x 13 km *37.0 GHz*
13 x 15 km *85.5 GHz*	5 x 7 km *85.5 GHz*	4 x 6 km *89.0 GHz*	

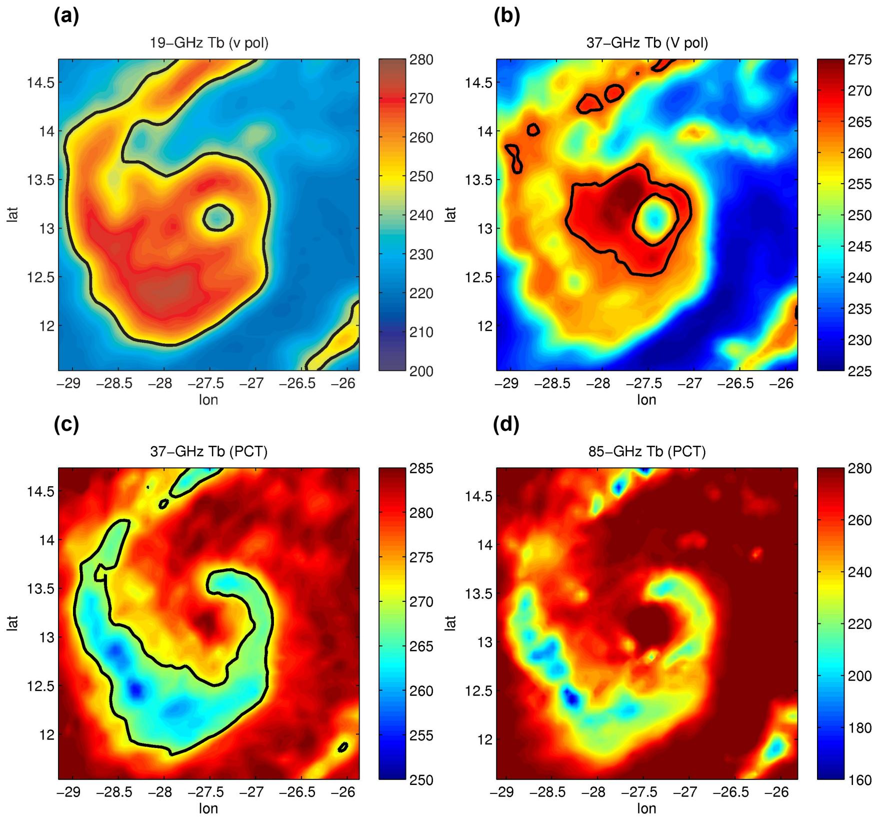

Figure 1. Atlantic Hurricane Danielle at 1527 UTC 14 August 2004 as depicted by TMI's (a) 19-GHz $T_{b,v}$, (b) 37-GHz $T_{b,v}$, (c) 37-GHz PCT, and (d) 85-GHz PCT.

Multiple MI channels are chosen for this study because of each channel's unique perspective on storm structure. Low frequency channels, including the 19.4- and 37.0-GHz channels, measure the emission of microwave radiation from liquid hydrometeors. These channels can often capture the precipitation structure of TCs at lower levels of the troposphere. On the other hand, the higher frequency channels, including the 37.0-GHz and 85.5-GHz channels, capture ice scattering from precipitation at higher levels of the TC. Figure 1 shows an example of these different perspectives for Atlantic Hurricane Danielle (2004) at a stage in which it was undergoing RI. While the 19-GHz channel suffers from lower spatial resolution compared to the other channels, both the vertically polarized T_b ($T_{b,v}$) (Fig. 1a) and the horizontally polarized T_b ($T_{b,h}$) (not shown) indicate Danielle has a ring structure around the storm center at 1527 UTC 14 August. This structure is also seen in the intermediate-resolution 37-GHz $T_{b,v}$. However, using the polarization-corrected temperature (PCT) at 37 GHz and 85 GHz (Figs. 1c,d), we can see ice scattering associated with deeper convective clouds. Thus, the storm structure is asymmetric aloft even though the degree of symmetry at lower levels of the storm is consistent with eyewall formation and TC intensification.

To create predictors from satellites measuring slightly different microwave frequencies from one another, a correction resulting from an empirical histogram matching technique similar to Jones and Cecil (2006) is applied to AMSR-E and WINDSAT T_b to ensure they have similar cumulative distribution functions to TMI and SSM/I T_b. Once this procedure has been carried out to adjust AMSR-E and WINDSAT T_b, simple MI predictors were defined.

To define MI-based predictors, accurate center estimates are necessary. All center fixes are based on the objective technique of Wimmers and Velden (2010). For the 19.4- and 37.0-GHz MI, we use the 37.0-GHz channel for centering, whereas the TC centers in 85.5-GHz MI are found using the 85.5-GHz $T_{b,h}$. These choices reduce parallax errors between 37.0 and 85.5-GHz channels. The 37.0-GHz-based center for 19.4-GHz MI is beneficial due to the lower spatial resolution of 19.4-GHz MI.

Two types of MI-based predictors are defined. First, similar to the GOES-IR predictors in the SHIPS developmental dataset, a variety of fixed-geometry predictors are defined. A second set of predictors is based on an objective estimate of the nascent or mature eye and eyewall regions and is derived from the algorithm of Wimmers and Velden (2010). As a whole, MI-based predictors include the minimum, average, standard deviation, and maximum of $T_{b,v}$ and $T_{b,h}$ in regions depicting the eye, eyewall, and general inner- and outer-cores.

Statistically independent predictors that maximize the Brier skill score (BSS) of the logistic regression model are chosen for the RI thresholds of 25, 30, and

35 kt per 24 h in the Atlantic and eastern Pacific Ocean basins. Model skill is evaluated using the independent testing technique of leave-one-season-out cross validation (e.g., Rozoff and Kossin 2011) over the years of 1998-2008. In order for an MI-based predictor to be considered, the difference in the composite means of the RI and non-RI samples must be statistically significant at the 95% level according to a two-sided student-*t* test. To properly compare the BSS of the MI-enhanced RI model with the MI-free version, both models are trained and evaluated on only the forecast times in which all the SHIPS-based and optimal MI-based predictors are available.

Now, while the BSS can be markedly improved by making forecasts closest to the time of a satellite overpass and restricting our forecasts to higher-resolution sensors (i.e., TMI, AMSR-E, WINDSAT), NOAA forecasts are typically issued at the synoptic times of 00, 06, 12, and 18 UTC. Forecasts at these fixed times are a challenge since sufficiently recent MI may not be available at the time of the forecast. In this study, forecasts are made at synoptic times only when the MI is available and less than 6-h old. (Sensitivity tests are ongoing to resolve which cut-off times and which sensors, in the case of multiple satellite passes, add the most skill.) With only the use of TMI, AMSR-E, SSM/I, and WINDSAT, depending on the quality-control criteria used in defining a microwave predictor, MI-based predictors are available 40-60% of the time in our training sample.

3. RESULTS

As an example of the improvements that can be achieved by including simple MI-based predictors in the logistic regression RI model, we focus our attention on RI prediction for an RI threshold of 35 kt per 24 h. The higher RI threshold typically yields a lower BSS than those of the lower RI thresholds, giving it the most potential for improvement (Kaplan et al. 2010; Rozoff and Kossin 2011). Table 2 shows the optimal, statistically independent MI-based predictors for the logistic scheme in the North Atlantic. Overall, the composite means of the RI and non-RI samples show that precipitation is more intense and centralized in TCs that are currently or about to undergo RI, which is consistent with the results of Vigh et al. (2009) and Rogers (2010). Interestingly, only 19.4- and 37.0-GHz predictors are found to be optimal in this model.

Table 2. Microwave-determined features applied to the logistic regression model in the North Atlantic Ocean. Also shown are the relative values of the predictor means for the RI sample relative to the non-RI sample.

Feature Description	RI ave
19.4-GHz ave $T_{b,v}$ (r = 100–300 km)	higher
19.4-GHz min eye $T_{b,v}$	higher
19.4-GHz ave ring $T_{b,h}$	higher
37.0-GHz radius of max $T_{b,h}$	lower
37.0-GHz ave $T_{b,v}$ (r = 0–100 km)	higher

Table 3 shows the BSS for the logistic regression-based RI model with and without MI-based predictors. Whether we consider TCs with current intensities of $v_{max} \geq 25$ kt or only those with $v_{max} \geq 45$ kt, the BSS is substantially improved by the inclusion of MI-based predictors. A reliability diagram (not shown) shows one notable improvement is that the MI-enhanced RI model can more often produce higher probabilities of RI and with a degree of accuracy. Figure 2 shows that the BSS can be improved at other RI thresholds as well, although the greatest relative improvement in forecast skill is achieved for higher RI thresholds.

Table 3. The Brier skill score for TCs tested in the North Atlantic Ocean for an RI threshold of 35 kt per 24 h for the logistic regression model. Results are shown for the model incorporating TCs with $v_{max} \geq 25$ kt (N = 1360) and TCs with $v_{max} \geq 45$ kt (N = 1013).

Model	Brier Skill Score
$v_{max} \geq 25$ kt without MI	7.5%
$v_{max} \geq 25$ kt with MI	19.6%
$v_{max} \geq 45$ kt without MI	11.9%
$v_{max} \geq 45$ kt with MI	24.7%

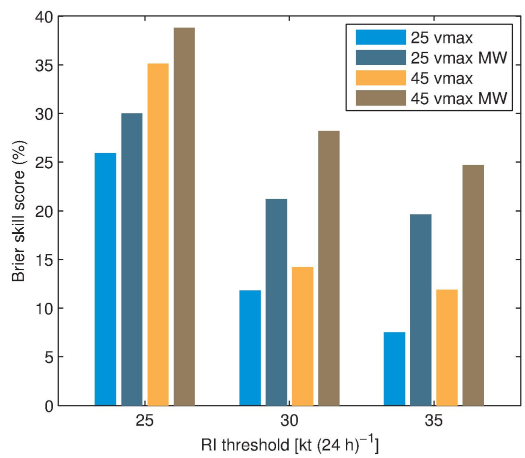

Figure 2. Brier skill scores for Atlantic TCs with RI thresholds of 25, 30, and 35 kt per 24 h for the RI model excluding MI predictors (light blue and orange for TCs with $v_{max} \geq 25$ kt and $v_{max} \geq 45$ kt, respectively) and including MI predictors (dark blue and brown for TCs with $v_{max} \geq 25$ kt and $v_{max} \geq 45$ kt, respectively).

The optimal predictors for the eastern Pacific Ocean differ from the Atlantic for the 35 kt per 24 h RI threshold (Table 4). In this case, predictors from each of the 3 tested channels are found to improve the forecast skill of the logistic regression model. Similar to before, more intense convection is favorable to RI. Moreover, in the RI sample, the convection tends to be more widespread. At first glance, it is counterintuitive that the RI sample shows more asymmetry at both 19.4 and 85.5 GHz. Studying individual cases suggest this may be due to strong convective bursts dominating the signal, but further study of this impact is necessary. Table 5 indicates that MI-based predictors improve the BSS in the eastern Pacific as well. However, the relative improvement is far less than in the Atlantic. This lack of relative improvement may be, in part, due to the already elevated BSS for the RI model that does not use MI-based predictors. In other words, MI-based predictors may be most beneficial for less predictable ocean basins such as the Atlantic.

Table 4. Same as Table 3, but for the east Pacific Ocean.

Feature Description	RI ave
19.4-GHz std dev $T_{b,h}$ (r = 0–100 km)	Higher
19.4-GHz % area $T_{b,v}$>245K (r = 50-200 km)	Higher
37.0-GHz ave. $T_{b,h}$ (r = 100–300 km)	Higher
85.5-GHz std dev $T_{b,v}$ (r = 100–300 km)	Higher

Table 5. The Brier skill score for TCs tested in the east Pacific Ocean for an RI threshold of 35 kt per 24 h for the logistic regression model. Results are shown for the model incorporating TCs with $v_{max} \geq 25$ kt (N = 1470) and TCs with $v_{max} \geq 45$ kt (N = 939).

Model	Brier Skill Score
$v_{max} \geq 25$ kt without MI	24.7%
$v_{max} \geq 25$ kt with MI	28.2%
$v_{max} \geq 45$ kt without MI	24.2%
$v_{max} \geq 45$ kt with MI	27.5%

4. FUTURE WORK

Currently, efforts are underway to expand the MI predictor developmental dataset to include data from 2009 onward. We are also augmenting our developmental dataset with Special Sensor Microwave Imager/Sounder (SSMI/S) MI (at 19.4, 37.0, and 91.7 GHz) and Advanced Microwave Sounding Unit-B (AMSU-B) MI (at 89.9 GHz).

In addition, we have been recently supported by NOAA's Joint Hurricane Testbed to test a real-time version of the MI-enhanced RI models for operational forecasting. As such, we are developing real-time versions of these models to be tested in the 2012 and 2013 Atlantic and Eastern Pacific hurricane seasons.

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