PROJECT REPORT

NOAA/OAR Joint Hurricane Testbed

Federal Grant Number: NA15OAR4590205

Probabilistic Prediction of Tropical Cyclone Rapid Intensification Using Satellite Passive Microwave Imagery

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Final Annual Report? No

1. ACCOMPLISHMENTS

The primary **goal** of this project is to improve the probabilistic prediction of rapid intensification (RI) in tropical cyclones (TCs). The framework in which we work is probabilistic models. We specifically are innovating upon existing statistical models that use environmental and TC-centric predictors. The statistical models used in this work include the Statistical Hurricane Intensity Prediction System (SHIPS) RI Index (RII) (Kaplan et al. 2010, Kaplan et al. 2015; *Wea. Forecasting*) and the logistic regression and Bayesian models of Rozoff and Kossin (2011; *Wea. Forecasting*) and Rozoff et al. (2015; *Wea. Forecasting*).

The **objectives** of this project are to update the three statistical models to include a new class of predictors derived from satellite passive microwave imagery (MI) evincing aspects of storm structure relevant to RI, using a comprehensive dataset of MI that includes all available relevant sensors, and using these to develop a more skillful consensus model that can be tested and deployed in real-time operations.

Milestones Since Last Project Report

a. **Updated developmental dataset**

To optimize the use of microwave imagery of a storm for each RI forecast, a few changes were made to the developmental microwave-based predictors. As before, we consider microwave data within 6 h of a forecast. In the case of multiple satellite swaths covering a TC at a given forecast, the following criteria are applied to choose the best swath. From most to least important, we first consider the swath that offers the most complete coverage of the storm. If two or more swaths offer near-equal coverage, then the data coming from the sensor with the highest spatial resolution is chosen. In the unlikely event that two or more passes equally satisfy the previous criteria, then the most recent swath is chosen. In our developmental data, the average swath available is 2.9-h old (with respect to the RI model forecast time), and microwave data are available 63% of the time on average for the model runs in the 1998-2016 time period.

b. **Testing microwave-based predictors**

As described in earlier reports, a variety of microwave predictors were developed. The following types of predictors were found to be useful: SHIPS-like microwave predictors (basic properties for fixed geometric regions), predictors defined for objectively determined eye and eyewall regions (as defined in Rozoff et al. 2015; *Wea. Forecasting*), and some of the principal components (PCs) associated with the two-dimensional empirical orthogonal functions (EOFs) for the microwave data (rotated with respect to the storm motion vector) (e.g., Fig. 1). This project also sought to test ARCHER (Wimmers and Velden 2010; *JAMC*) spiral and ring score predictors, along with inertial stability-based predictors from HWRF, but so far these have not been found to significantly improve the models considered in this study.

(a) 37-GHz (h) EOF 3 **(b)** 37-GHz (h) EOF 5 **(c)** 37-GHz (h) EOF 7 **(d)** 89-GHz (h) EOF 9

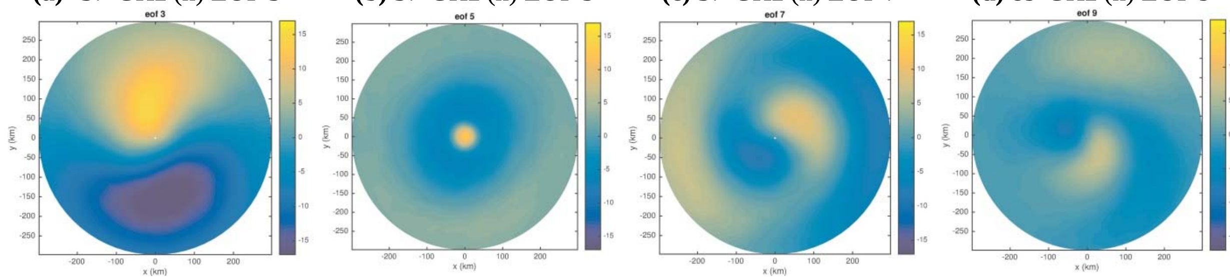

Fig. 1. Some of the PCs/EOFs that improved the microwave models in this project. The 37-GHz (horizontal polarization) EOF 3 of brightness temperatures (a) represents a wavenumber-1 asymmetry, likely related to vertical wind shear or storm motion. More asymmetric storms indicate less likelihood of RI. EOFs 7 (37-GHz, c) and 9 (89-GHz, d) appear to show rainband activity, likely principal rainband structures.

c. **Baseline and New Microwave-Enhanced Models**

With the SHIPS developmental data and new microwave developmental datasets, we have derived new Bayesian, logistic regression, and SHIPS-RII models. To conform with the operational SHIPS-RII consensus model, we derived models for the following RI thresholds: 20 kt / 12 h, 25, 30, 35, and 40 kt / 24 h, 45 kt / 36 h, 55 kt / 48 h, and 65 kt / 72 h. We now show the performance for the microwave-based models for the RI threshold of 35-kt / 24 h. We note that the improvements from microwave data are similar for other thresholds in the 24-h time period, though the microwave predictor information appears to become less impactful at longer lead-times.

Tables 1 and 2 below show the baseline SHIPS predictors and the new microwave-based predictors for the Atlantic RI model suite, while Tables 3 and 4 show the same for the Eastern Pacific model RI suite.

Table 1. Baseline SHIPS predictors used in the Atlantic models at the 35-kt / 24-h RI threshold.

Predictor	Bayesian	Logistic	SHIPS-RII
PER (12-h intensity change observed for the preceding 12 h)	x	x	x
RSST (Reynolds sea surface temperature)		x	
RHCN (Reynolds heat content)			x
U200 (200-hPa zonal wind, r = 200 – 800 km)	x		
RHLO (850-700-hPa relative humidity, r = 200 – 800 km)			x
RHMD (700-500-hPa relative humidity, r = 200 – 800 km)		x	
D200 (200-hPa divergence, r = 0 – 1000 km)			x
EPSS (The q_e difference between parcel/environ, r = 200 – 800 km)	x		
POT (Departure from the storm's potential intensity)	x	x	x
SHDC (850-200-hPa vertical shear after vortex removal, r = 0 – 500 km)			x
SHRG (Generalized 850-200-hPa vertical shear, r = 0 – 500 km)	x	x	
SBTIR1 (Stan. Dev. of GOES BT, r = 50– 200 km)	x		x
SBTIR2 (Stan. Dev. of GOES BT, r = 100 - 300 km)		x	
PCT30 (% area from 50-200 radius with GOES IR BT < -30 C)			x
PCT50 (% area from 50-200 radius with GOES IR BT < -50 C)	x		
MXBT (Maximum GOES IR BT from 0-30 km radius)		x	
IR PC 2		x	

Table 2. Microwave-based predictors use in the Atlantic models at the 35-kt / 24-h RI threshold.

Predictor	Bayesian	Logistic	SHIPS-RII
Mean eyewall brightness temperature (BT) [36.5 horizontal polarization (h)]		x	x
Max. eye BT [36.5 vertical polarization (v)]			x
Mean BT (36.5 v) (r = 30 – 130 km)	x		
Radius of minimum 36.5-GHz Polarization corrected Temperature (PCT) (r = 30 – 130 km)	x		
PC 3 (36.5 v)		x	
PC 3 (36.5 PCT)		x	
PC 7 (36.5 h)		x	
Max. eye BT (89 h)			x
Max. eye BT (89 PCT)		x	
PC 5 (89 h)	x	x	

Table 3. Baseline SHIPS predictors used in the Eastern Pacific models at the 35-kt / 24-h RI threshold.

Predictor	Bayesian	Logistic	SHIPS-RII
PER (12-h intensity change observed for the preceding 12 h)	x	x	x
RHCN (Reynolds heat content)	x		
EPSS (The pos q_e difference between parcel/environment, r = 200 – 800 km)	x		
ENSS (The neg q_e difference between parcel/environment, r = 200 – 800 km)		x	
RHLO (850-700-hPa relative humidity, r = 200 – 800 km)		x	x
D200 (200-hPa divergence, r = 0 – 1000 km)		x	x
POT (Departure from the storm's potential intensity)	x	x	x
SHDC (850-200-hPa vertical shear after vortex removal, r = 0 – 500 km)	x	x	x
SBTIR1 (Stan. Dev. of GOES BT, r = 50– 200 km)			x
SBTIR2 (Stan. Dev. of GOES BT, r = 100 - 300 km)	x	x	
PCT30 (% area from 50-200 radius with GOES IR BT < -30 C)			x
PCT50 (% area from 50-200 radius with GOES IR BT < -50 C)	x	x	
MXBT (Maximum GOES IR BT from 0-30 km radius)		x	

Table 4. Microwave-based predictors used in the Eastern Pacific models at the 35-kt / 24-h threshold.

Predictor	Bayesian	Logistic	SHIPS-RII
Mean eyewall BT (36.5 h)		**x**	**x**
Eyewall Criteria: Percentage of eyewall 36.5 PCT < 270 K			**x**
Mean eye BT (36.5 v)	**x**		
Mean eye BT (36.5 PCT)			**x**
Eye Criteria: Percentage of eyewall BT (36.5 v) < 265 K			**x**
Max. BT (36.5 v) (r = 30 – 130 km)	**x**		
PC 3 (36.5 h)		**x**	**x**
PC 3 (36.5 PCT)	**x**		
Mean eyewall BT (89 h)		**x**	
Max. eye BT (89 PCT)		**x**	
Radius of Min. BT (89 h)	**x**		
PC9 (89 h)		**x**	**x**

The improvements to the RI models by including microwave-based predictors are shown in Fig. 2. The Brier skill score with respect to a climatological baseline is used to evaluate the model skill. The models with and without microwave-based predictors are evaluated for the exact same forecasts over the period 1998-2016 in both the Atlantic and Eastern Pacific using leave-one-year-out cross validation. ***In both basins, and for all models, skill is substantially improved by the inclusion of the microwave-based predictors*** listed in Tables 2 and 4. The consensus produces the highest skill, consistent with the results of the non-microwave-based models in Kaplan et al. (2015; *Wea. Forecasting*).

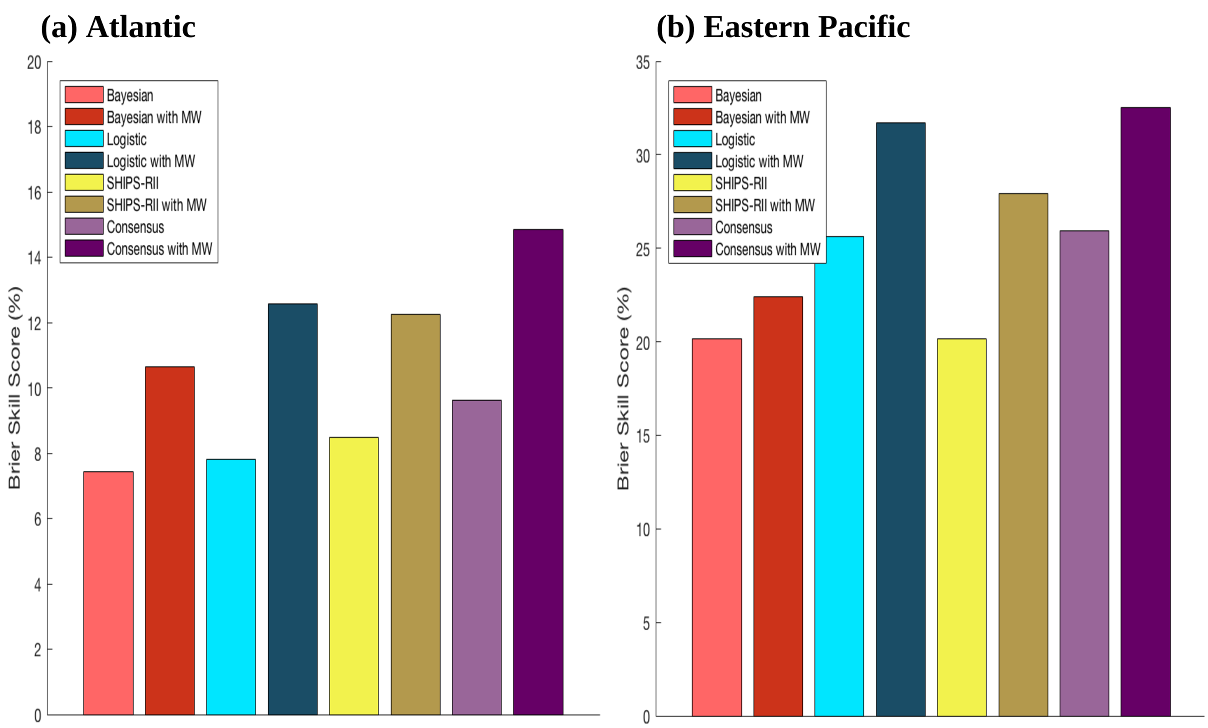

Figure 2. The Brier skill score of the Bayesian, logistic regression, SHIPS-RII, and consensus with and without microwave-based predictors for the (a) Atlantic and (b) Eastern Pacific using leave-one-year-out cross-validation for the years 1998-2016.

d. **Real-time web display**

We are developing a website to display output in real time from the microwave-based RI models during the 2017 hurricane seasons of the Atlantic and Eastern Pacific. The real-time products will be hosted on the CIMSS Tropical Cyclone webpage (http://tropic.ssec.wisc.edu). An example of the webpage output for Hurricane Matthew (2016) is provided at the website: http://www.ssec.wisc.edu/~sarahm/MW_example. An RI table of probabilities will be provided (exactly as provided in the NHC's SHIPS-RII output), along with a display of the storm structure and a "quilt" diagram that shows the intensity history of the storm up to the current forecast time, along with probabilities of the consensus model for each RI threshold (e.g., Fig. 3).

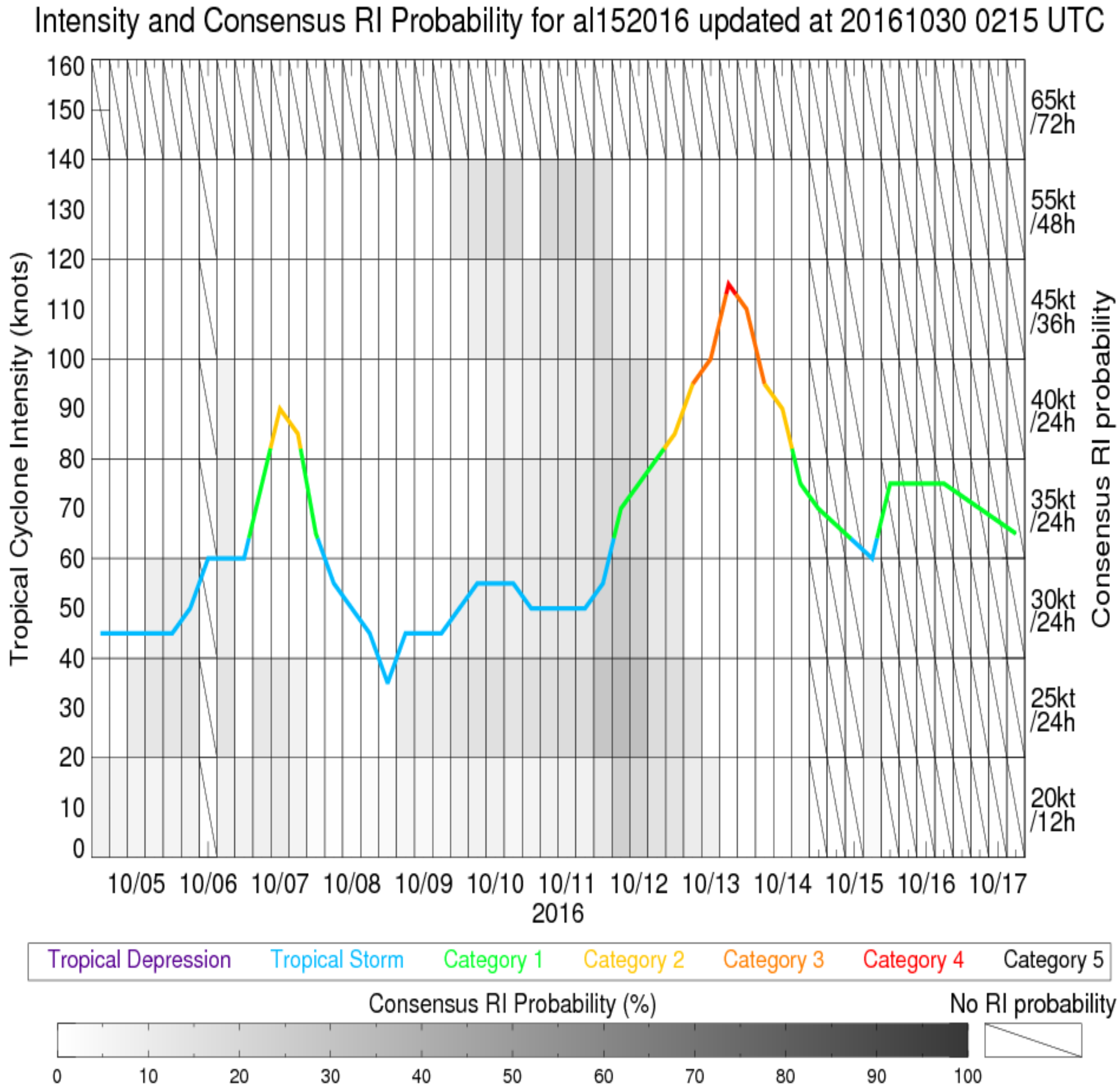

Figure. 3. An example of the RI quilt diagram for Hurricane Nicole (2016). As time progresses forward, the verifying storm intensity is plotted. The quilt diagram shows matching RI probabilities according to the consensus model at each forecast time leading up to the current forecast. Note this is an example for ordinary SHIPS-RII output, not the microwave-enhanced model. The new product will contain probabilities at the 65-kt / 72-h RI threshold as well; however, given microwave swaths will not be available at every forecast time, not every column in the quilt diagram from earlier times will have probabilities available.

Status of Project Tasks / Milestones

Task	Proposed Activity	Status
1	Update developmental dataset to include MI of Atlantic and Eastern Pacific TCs from all available sensors (1998-2016). [September 2015 – January 2017]	Completed (with updates ongoing)
2	Examine and test new MI-based predictors. [September 2015 – January 2016]	Completed
3	Update logistic regression model to incorporate improved MI predictors and evaluate on retrospective and real-time cases. [January – March 2016]	Completed
4	Enhance the Bayesian and linear discriminant analysis-based SHIPS-RII models with up-to-date MI dataset. [January – March 2016]	Completed
5	Evaluation of updated SHIPS-RII and Bayesian models on retrospective dataset. [March – May 2016]	Completed
6	Convert code from Matlab (development framework) to Fortran and C so that code is portable to NCEP operations. [April 2016 – May 2017]	In progress
7	Real-time testing of models in the Atlantic and Eastern Pacific and continue reforecasts of previous seasons (2016) in simulated operational conditions with archived real-time data. [now June – November 2017]	Behind Schedule
8	Evaluation of real-time model performance [now July-December 2017]	Not started
9	Prepare final NCEP-ready code and documentation for running and maintaining models after the conclusion of the project. [November – December 2017]	Not started
10	Prepare final project report [December 2017]	Not started

As can be seen, significant progress has been made on major tasks. We will evaluate the 2016 hurricane season using simulated real-time forecast GFS data as soon as we complete the real-time models, and provide the 2016 and 2017 verification results by the conclusion of this project.

What opportunities for training and professional development has the project provided?
None to report.

How were the results disseminated to communities of interest?
We will provide results on a public webpage and share that webpage with our points of contact at NHC. Preliminary results have been presented at conferences and a publication is planned at the project's completion. We will provide a real-time-capable version of our algorithm to NHC at the end of the project.

What do you plan to do during the next reporting period to accomplish the goals and objectives?
We will complete the real-time implementation of the new models and provide the forecast results on a web page during the 2017 hurricane season. We will also continue to work on developing a real-time Fortran/C-based algorithm that can operate successfully on NOAA computers.

2. PRODUCTS

Presentations in this reporting period

Rozoff, C. M., and C. S. Velden, 2017: JHT Project 4: Probabilistic prediction of tropical cyclone rapid intensification using satellite passive microwave imagery. *Presentation at the 2017 Tropical Cyclone Operations and Research Forum, Miami, FL, 16 March 2016.* [Available online at: http://www.ofcm.gov/meetings/TCORF/ihc17/Session_09/9-4-rozoff_jht_web.pdf]

Publications

None to report. However, we plan to submit a paper (conference and/or journal) on the results of this project after the project's conclusion.

Products

None to report. However, we will submit a Fortran/C-based algorithm that includes the MI-enhanced RI models and capable of running on a NOAA/HPC-designated system at the conclusion of this project, along with supporting documentation.

3. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

What individuals have worked on this project?

Christopher Rozoff (original PI), Christopher Velden (de-facto PI), Sarah Griffin (CIMSS/UW-Madison research assistant)

Has there been a change in the PD/PI(s) or senior/key personnel since the last reporting period?

Yes, the JHT program contacts are aware that PI Christopher Rozoff has accepted a job at the Research Applications Laboratory at the National Center for Atmospheric Research in Boulder, CO. Therefore, Christopher Velden is now serving as the UW-CIMSS PI (was co-I), while Christopher Rozoff continues to lead/advise the project at no-cost.

What other organizations have been involved as partners? Have other collaborators or contacts been involved?

Dr. John Kaplan at the AOML/HRD has been a collaborator on this project. Forecasters at NHC and JHT Program Officials (e.g., Shirley Murillo and Christopher Landsea) have been briefed on the project progress at regular intervals.

4. IMPACT

What was the impact on the development of the principal discipline(s) of the project?

We anticipate that this project will improve one of the NHC's most reliable tools for predicting RI in TCs, thereby helping NHC improve intensity prediction of TCs. While this project is highly applied research, the results may also contribute to increased scientific understanding of intensification processes in TCs.

What was the impact on other disciplines?
Other disciplines often use the types of statistical models we have employed in this project, and therefore researchers may find our project methodology useful.

What was the impact on the development of human resources?
None to report.

What was the impact on teaching and educational experiences?
None to report.

What was the impact on physical, institutional, and information resources that form infrastructure?
None to report.

What was the impact on technology transfer?
None to report.

What was the impact on society beyond science and technology?
Improved TC intensity prediction, especially of RI, is extremely valuable information to society, particularly emergency management and evacuation planning.

What percentage of the award's budget was spent in a foreign country(ies)?
0%.

5. CHANGES/PROBLEMS

The 2016 real-time testing fell behind schedule. Retrospective testing under simulated real-time conditions will be performed to provide an evaluation of the new models for the 2016 hurricane season, along with the evaluation of the actual real-time performance during the upcoming 2017 hurricane season. Therefore, we are requesting a no-cost extension of the project through December 2017 to allow for post-analysis of the results and to better complete the project final report.

6. SPECIAL REPORTING REQUIREMENTS

We report here on the project's Readiness Level as part of the Joint Hurricane Testbed.

Transition to operations activities
The statistical modeling framework is being developed to run in real-time and also in Fortran/C-based code (as opposed to the Matlab developmental framework) so that it will be readily able to run in an operational environment, including the WCOSS high performance computing system.

Summary of testbed-related collaborations, activities, and outcomes
We are working with NHC points of contact Christopher Landsea, John Beven, Daniel Brown, and Dave Roberts with regards to the upcoming real-time analysis and testing.

Has the project been approved for testbed testing yet?
Not yet. A real-time demonstration test is yet to be performed on CIMSS computing platforms before approval considerations can proceed.

What was transitioned to NOAA?
Nothing at this time.

7. BUDGETARY INFORMATION

The project is on budget. A no-cost extension is being requested to complete the remaining tasks.

8. PROJECT OUTCOMES

What are the outcomes of the award?
We have developed a multi-model consensus of probabilistic models that predict the likelihood or rapid intensification in tropical cyclones. In particular, we have updated these models to use new predictors from satellite passive microwave imagery. This consensus model improves forecast skill over its constituent models and over the same models not employing microwave data.

Are performance measures defined in the proposal being achieved and to what extent?
Besides the delay in a real-time demo, performance measures are being otherwise achieved.

NOAA READINESS LEVELS (RLs)

The NOAA Readiness Levels, according to NOAA Administrative Order 216-105A, can be applied to describe this project. The current project has achieved RL 2, but will have RL 2-8 by the conclusion of this project. The readiness levels that will apply to this project include the following:

- RL 2: Applied research: We have conducted an original investigation of new forecast techniques with the practical goal of developing a useful tool in operational forecasting. However, there are applications to basic research from our results as well. [*Completed*]
- RL 3: Proof-of-concept: We plan to show how this product performs in real-time by the conclusion of this project. [*In progress*]
- RL 4: We will set up and evaluate the forecast system at our institution in a real-time environment [*In progress*]
- RL 5: We will evaluate a final algorithm near the end of the project with the goal of having these models proven deployable in a real-time environment. [*To begin later*]
- RL 6: We will demonstrate the forecast scheme in a real-time environment during the 2017 Hurricane season. [*To begin later*]
- RL 7/8: The overall goal is to demonstrate an improved real-time prediction tool for RI that can be used at the NHC, including complete code and documentation and support to implement it in real-time in an operational framework. [*To begin later*]