PROJECT Final REPORT

NOAA/OAR Joint Hurricane Testbed

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

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Final Annual Report? Yes

1. ACCOMPLISHMENTS

The primary goal of this project was to improve the probabilistic prediction of rapid intensification (RI) in tropical cyclones (TCs). The framework in which we worked was with probabilistic models. We specifically innovated upon existing statistical models that use environmental and TC-centric predictors. The statistical models used in this work included the Statistical Hurricane Intensity Prediction System (SHIPS) RI Index (RII) (Kaplan et al. 2015) and the logistic regression and Bayesian models of Rozoff and Kossin (2011) and Rozoff et al. (2015).

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

Milestones

a. **Revised model framework**

Earlier this year, models using predictors from the Fischer et al. (2018) brightness temperature normalization technique were developed since predictors from Rozoff et al. (2015) were not sufficiently improving the real-time performance of the models. The procedure to create normalized fields was done with respect to a TC's current intensity, such that the climatological microwave imagery structure for a given intensity bin is subtracted from each microwave image in the same intensity bin. Each difference field is then normalized by the standard deviation of the climatological structure. This analysis was done on imagery rotated with respect to the deep-layer shear vector. The 37-GHz (horizontal polarization) and 85-GHz polarization corrected temperatures were evaluated and found to be the most useful to detect robust RI structures. Robust anomaly structures were found in the normalized brightness temperature fields for weakening, steady, slowly intensifying, and rapidly intensifying storms. Simple tests were conducted in Fischer et al. (2018) showing that simple azimuthal means of the normalized fields over some radial range can provide skillful RI predictions.

Given these promising results, we discarded the previous MI-based predictors (from Rozoff et al. 2015) and tested a small set of predictors using the normalized 37-GHz and 85-GHz fields of Fischer et al. (2018), including azimuthal mean brightness temperatures for the radial ranges of r = 0 to 50, 75, 100, and 150 km and quadrant average brightness temperatures for r = 100 km, where the quadrants were defined with respect to the deep-layer shear vector. Models were developed for the logistic regression, Bayesian, and SHIPS-RII model. It turns out, for each model and threshold in both basins, one 37 GHz-based predictor and sometimes a second 85-GHz predictor always benefited the model compared to an equivalent model not possessing a MI-based predictor. More often than not, the upshear-left and upshear-right quadrants of the normalized 37-GHz imagery provides the most useful predictors, indicating a more anomalously active convective region upshear of the storm is more conducive to RI (i.e., the storm is more symmetric).

The Brier skill scores for the revised Bayesian, logistic regression, and SHIPS-RII models, along with a three-model consensus, for the Atlantic and Eastern Pacific are provided in Fig. 1. At every threshold, the MI-based predictors add significant skill, although the consensus is not always better than individual models, with the logistic regression model generally performing best of all models. As in previous studies (e.g., Kaplan et al. 2015), the Eastern Pacific offers much higher skill except at the 65 kt per 72 h threshold.

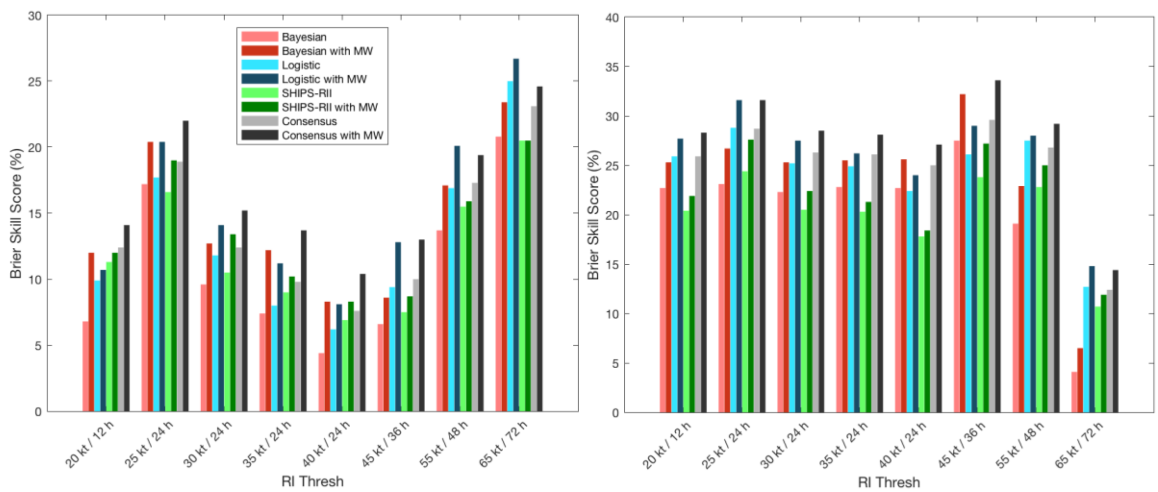


Figure 1. The Brier skill scores of the Bayesian model, logistic regression model, SHIPS-RII and their consensus with and without microwave-based predictors for the Atlantic (left) and Eastern Pacific (right) using leave-one-year-out cross-validation for the years 1998-2016.

For the 2017 season, a real-time trial was conducted. These results are shown in Fig. 2 and briefly summarized here. A homogeneous comparison of the Brier skill scores of all the new MI-enhanced RI models run in real-time (with real-time quality data) vs. their non-MI-based operational counterparts is shown in Fig. 2, along with a version of the models using the same non-MI predictors as the MI-version of the models. In the Atlantic, the logistic regression and Bayesian models both outperformed the non-MI versions at the 65 kt / 72 h threshold, while the logistic regression outperformed at the 35 kt / 24 hour threshold and the Bayesian outperformed the non-MI version of the Bayesian model at the 35 kt / 24 h and 45 kt / 36 h thresholds. The Eastern Pacific was also a mixed bag, with the consensus doing best at the 25, 30, and 35 kt / 24-h thresholds and the 65 kt / 72-h threshold.

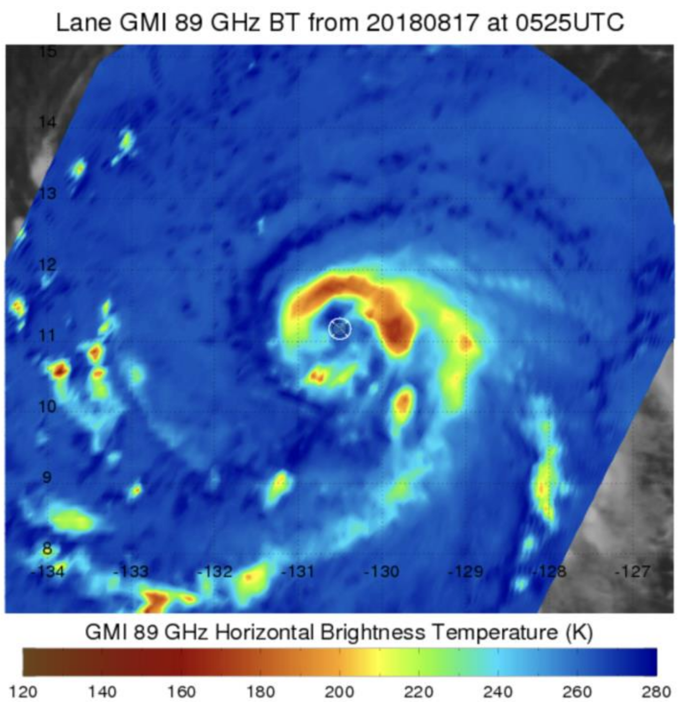
Fig. 3. Brier skill scores for the logistic regression, Bayesian, and consensus models for versions of the models with MI data (red), the operational models without MI data (blue), and a version of the MI models without MI data (since the operational and MI-version of the models have slightly different non-MI predictors) (black) for the Atlantic (left) and Eastern Pacific (right)

b. **Real-time testing of models during 2018 Atlantic and Eastern Pacific hurricane seasons**

An experimental website was developed to demonstrate and allow a quick assessment of the probabilities of RI with the updated models and the inclusion of the new microwave predictors in real-time. The site can be found at http://tropic.ssec.wisc.edu/real-time/mw-ri-prob/. Four different microwave sensors were used in this real-time demonstration:

1) Special Sensor Microwave Imager (SSM/I) from the Defense Meteorological Satellite Program (DMSP) F15 satellite
2) Special Sensor Microwave Imager/Sounder (SSMI/S) from the DMSP F16, F17, and F18 satellites
3) Advanced Microwave Scanning Radiometer 2 (AMSR2)
4) Global Precipitation Measurement (GPM) Microwave Imager (GMI)

An example of the real-time website from 0600 UTC 17 August 2018 during Hurricane Lane is illustrated in Fig. 2. The top panel of Fig. 2 shows the GMI presentation around the time of the forecast. The bottom panel shows the predicted probabilities of RI at various RI thresholds. The probabilities of RI with microwave predictors are displayed in the left table, and the concurrent non-MI (same models, no MI data) RI model probabilities are displayed in the right table. Both probabilities are shaded based on percentages. Past probabilities can be viewed in the chart below the left table. Boxes are shaded based on consensus RI probabilities using microwave data. White boxes indicate probabilities were not available due to the lack of microwave (MI) data in that analysis cycle. In addition, no RI probabilities are calculated using microwave data if the TC center is too close to land. Overall, the MI-based models perform better in this particular example by correctly showing higher probabilities for RI at the 24-hour and 36 hour lead-times, although the MI-based models incorrectly showed a slightly decreased probability at the 12-hour lead-time. Both sets of models correctly decreased probabilities of RI at the 48 and 72 hour lead-times, with the MI versions of the models showing slightly lower probabilities.



Lane at 08/17/18 06 UTC. Intensity = 70 kts, MPI = 132 kts

Experimental Matrix of RI probabilities
(WITH MICROWAVE -- GMI)

RI (kt / h)	20/12	25/24	30/24	35/24	40/24	45/36	55/48	65/72
SHIPS-RII	10.4%	42.8%	28.0%	17.4%	10.5%	23.3%	13.6%	3.1%
Logistic	22.9%	56.9%	52.9%	44.4%	22.9%	29.7%	6.5%	4.4%
Bayesian	23.4%	57.3%	35.9%	27.0%	13.6%	34.3%	1.4%	0.0%
Consensus	18.9%	52.3%	38.9%	29.6%	15.7%	29.1%	7.2%	2.5%

SHIPS Matrix of RI probabilities
(NO MICROWAVE)

RI (kt / h)	20/12	25/24	30/24	35/24	40/24	45/36	55/48	65/72
SHIPS-RII	27.0%	35.0%	32.6%	24.6%	14.8%	22.0%	19.5%	7.8%
Logistic	23.2%	46.5%	36.8%	29.1%	11.9%	18.5%	7.1%	1.5%
Bayesian	23.4%	42.3%	24.4%	14.0%	4.3%	13.8%	1.2%	0.0%
Consensus	24.5%	41.3%	31.3%	22.6%	10.4%	18.1%	9.3%	3.1%

Fig. 2. Example of the real-time RI prediction at 06 UTC 17 August 2018 from the TC CIMSS website, for rapidly intensifying TC Lane in the Eastern Pacific. (Top) GMI image of Lane near the time of the forecast. (Bottom) Probabilities from the MI and non-MI versions of the RI models for RI at the various thresholds. Lane intensified by 20 kt, 45 kt, 50 kt, 40 kt, and 40 kt over the following 12, 24, 36, 48, and 72 hours.

Status of Project Tasks / Milestones

The following table summarizes the tasks originally proposed with some updated dates due to a NCE, and the status of these tasks.

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
2	Examine and test for significance of 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 – December 2017]	Completed
7	In-house real-time testing of models in the Atlantic and Eastern Pacific and continue reforecasts of previous seasons in simulated operational conditions with archived real-time data. [June – November 2017]	Completed
8	Evaluation of models and model updates. [January – December 2017]	Completed
9	Prepare final NCEP-ready code and documentation for running and maintaining models at the conclusion of the project. [February – December 2017]	Awaiting feedback from NOAA/JHT
10	Operational demo real-time test. [June – August 2018]	Completed

Item 9 will be completed pending review from the JHT.

For future directions, we might suggest a hybrid approach to post-processing model output (like HWRF), combined with microwave imagery obs, to improve upon HWRF RI prediction, or we could try a convolutional neural network approach in either a purely empirical based framework (including microwave imagery and other observational fields) or in the aforementioned hybrid technique using both model and observations.

References

Fischer, M. S., B. H. Tang, K. L. Corbosiero, and C. M. Rozoff, 2018: Normalized convective characteristics of tropical cyclone rapid intensification events in the North Atlantic and Eastern North Pacific. *Mon. Wea. Rev.*, **146**, 1133-1155.

Kaplan, J., C. M. Rozoff, and Co-Authors, 2015: Evaluating environmental impacts of tropical cyclone rapid intensification predictability utilizing statistical models. *Wea. Forecasting*, **30**, 1374-1396.

Rozoff, C. M., and J. P. Kossin, 2011: New probabilistic forecast models for the prediction of tropical cyclone rapid intensification. *Wea. Forecasting*, **26**, 677-689.

Rozoff, C. M., C. S. Velden, J. Kaplan, J. P. Kossin, and A. J. Wimmers, 2015: Improvements in the probabilistic prediction of tropical cyclone rapid intensification with passive microwave observations. *Wea. Forecasting*, **30**, 1016-1038.

What opportunities for training and professional development has the project provided?
If the project is accepted by JHT for implementation for operations, we will provide training for forecasters on the use/interpretation of the MI-based probabilistic RI models.

How were the results disseminated to communities of interest?
We provided the real-time results on a shared webpage with our points of contact at NHC. Prior results have been presented at conferences.

What do you plan to do during the next reporting period to accomplish the goals and objectives?
This is our final report on the current project. We await directions from the JHT POCs on whether there will be any further support for this project.

2. PRODUCTS

Presentations in this reporting period
Poster presentation at the 33rd AMS Conference on Hurricanes and Tropical Meteorology, led by Sarah Griffin (CIMSS).

Publications
None to report.

Products
Pending JHT directions, we will submit a Fortran/C-based algorithm of the MI-enhanced RI models to be run on NOAA HPC systems.

3. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

What individuals have worked on this project?
Christopher Rozoff (Co-PI), Christopher Velden (co-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?
No

What other organizations have been involved as partners? Have other collaborators or contacts been involved?
Forecasters and Program Officials (e.g., Shirley Murillo and Christopher Landsea and all other NHC points of contact) at the National Hurricane Center/Joint Hurricane Testbed have been briefed on the project progress.

4. IMPACT

What was the impact on the development of the principal discipline(s) of the project?
We anticipated that this project would help improve on one of the NHC's most difficult task, that of predicting RI in TCs. While this project's aims were operationally oriented, the findings may also contribute to increased scientific understanding of intensification processes in TCs.

What was the impact on other disciplines?
While the impact may be minimal, other disciplines often use the types of statistical models we have used 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 RI, will be extremely valuable to society, particularly emergency management planning.

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

5. CHANGES/PROBLEMS

The original set of MI-based models did not perform up to our expectations, so efforts were made to try out new innovations in the analysis of microwave imagery with respect to storm intensification.

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 was tested 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 have communicated with points of contact (POC) Christopher Landsea, John Beven, Daniel Brown, and Dave Roberts at the NHC for real-time analysis and testing during the 2017 hurricane season. They also requested results from the 2018 hurricane season given our difficulties with an earlier version of our RI models.

Has the project been approved for testbed testing yet?
The 2017 and 2018 real-time testing was performed on CIMSS computing platforms.

What was transitioned to NOAA?
Nothing yet at this time.

Thus, the project's ***Readiness Level (RL) is at level 6***.

7. BUDGETARY INFORMATION

A NCE was granted to extend the project in order to perform real-time testing. This project will wrap up 8/31/18.

8. PROJECT OUTCOMES

What were 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 was shown to improve forecast skill over its constituent models and over the same models not employing microwave data in leave-one-year-out cross validation, but did not consistently outperform operational versions of the same models that do not use MI-based imagery. A simpler and more elegant set of MI-based models were more recently developed that also produced mixed results, with the model able to outperform the operational non-microwave version of the model at certain lead-times and thresholds.

Are performance measures defined in the proposal being achieved and to what extent?

There were delays in real-time testing and also due to reformulation of the models after a first generation of models failed to outperform operational models.