NOAA/OAR Joint Hurricane Testbed

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Improved Eyewall Replacement Cycle Forecasting Using a Modified Microwave-Based Algorithm (ARCHER)

PI: Anthony Wimmers, wimmers@ssec.wisc.edu, 403-629-2428

Submitting Official: Jenny Hackel, Asst. Director, jenny.hackel@ssec.wisc.edu

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Cooperative Institute for Satellite Meteorological Studies (CIMSS)
University of Wisconsin-Madison
1225 West Dayton Street
Madison, WI 53706

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Final Report

Executive Summary: For this final report, we present summaries of the accomplishments from this project over each of the project milestones. The period of work extends from July 2015 to September 2018. Over this time we have developed **1)** A revision of ARCHER that generates ERC-relevant eyewall statistics from 85-92 GHz microwave imagery, **2)** A predictive model of ERC initiation in the North Atlantic from these ARCHER statistics, and **3)** An online graphical/text display of this model with documentation. The model has performed successfully and has been cited several times in official hurricane forecasts during periods of high-impact potential. Final integration into operations will be possible when ARCHER is integrated into the GeoIPS framework under a current JPSS supported multi-institutional project.

1. ACCOMPLISHMENTS DURING THIS PERIOD

Milestones/Deliverables

Milestone	Start Date	Forecasted Completion	Actual Completion	% Complete
1. Create a double eyewall module for ARCHER	July 2015	Dec 2015	Dec 2015	100%
2. Create real-time online display of ARCHER-ERC output	Jan 2016	June 2016	June 2016	100%
3. Evaluate performance of online ARCHER module display	Jan 2016	June 2016	June 2016	100%
4. Produce initial online technical documentation	Jan 2016	June 2016	June 2016	100%
5. Calibrate/validate the ERC probability product	Jan 2016	June 2016	Feb 2017	100%
6. Finalize double eyewall ARCHER module to optimize performance	July 2016	Dec 2016	Dec 2016	100%
7. Finalize online display of algorithm	July 2016	Dec 2016	May 2017	100%
8. Complete online technical documentation	Jan 2017	June 2017	Feb 2018	100%
9. Deliver ERC module for SHIPS	Jan 2017	Feb 2018	TBD	50%
10. Create real-time online text file output of ERC module for SHIPS	Jan 2017	Feb 2018	June 2018	100%

Milestone 1. Double eyewall module for ARCHER

Before the start of this project, the ARCHER algorithm used a "Ring Score" measurement to provide a form of fine-scale center-fixing guidance in Cat 1-5 TCs in 85-92 GHz satellite imagery. The Ring Score is approximately an azimuthal average of brightness temperature image gradients in the radial direction, which provides an effective pattern-matching signal for finding the center of an eyewall. As part of this project, we have unfolded this approach into an enhanced eyewall-detection signal. Our new ARCHER algorithm includes output for Ring Score as a function of radius from the center-fix, so that this new array of values can be analyzed for secondary maxima that indicate either a developed or emerging secondary eyewall (Figure 1).

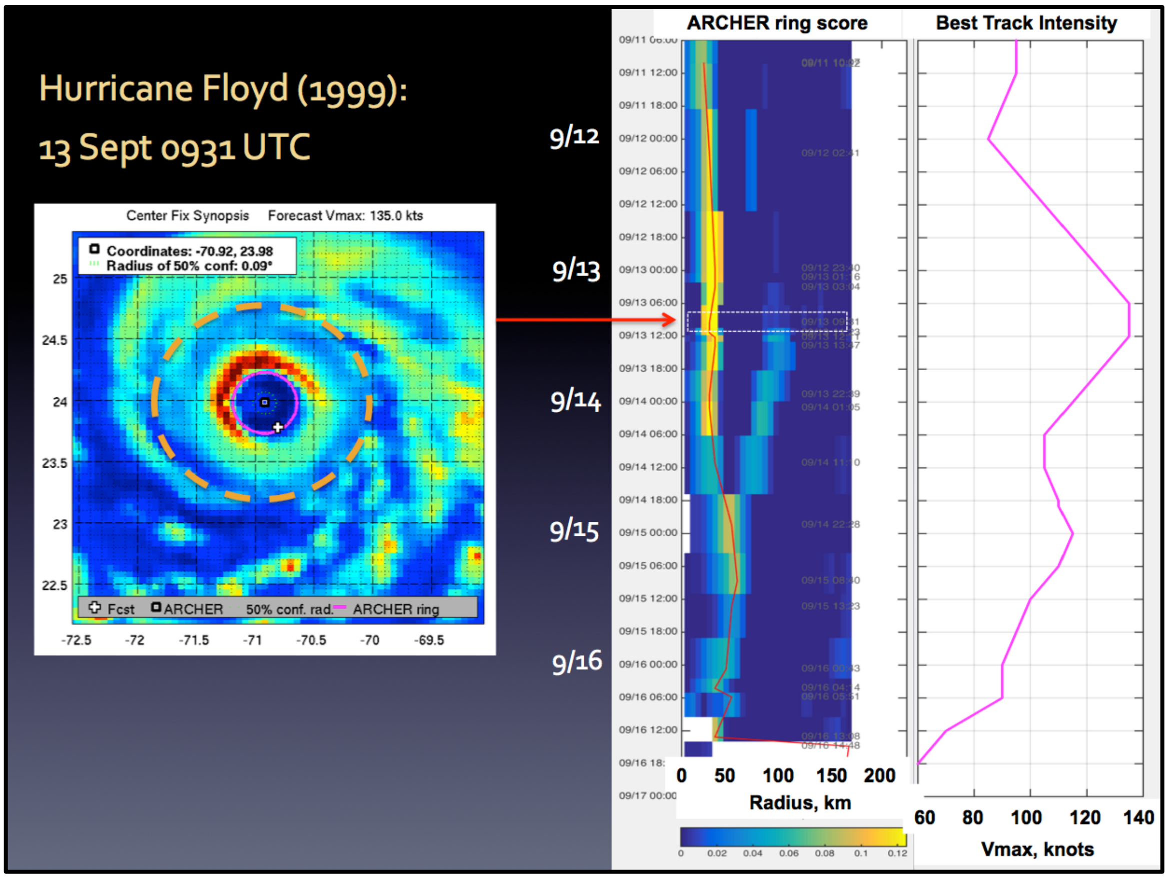


Figure 1. Left: 85-92 GHz microwave image of Hurricane Floyd (1999) with a magenta ring at the maximum ARCHER Ring Score, and a dashed orange ring at the secondary maximum. Center: Hovmöller diagram of ARCHER Ring Score with time for Hurricane Floyd. Right: NHC Best Track intensity at matching times.

The Hovmöller plot from Figure 1 shows that an eyewall replacement cycle (ERC) is readily apparent in the time series of Ring Scores. (This was not as evident in the comparisons we made with azimuthally-averaged *brightness temperature*.) The primary eyewall forms a column of maximum Ring Score values at radii normally less than 75 km. The secondary eyewall emerges as a second branch of lower Ring Score values at higher radii, which ultimately contracts and converges with the primary eyewall after 24-48 hours.

Milestones 2&3. Create real-time online display of ARCHER-ERC output, and evaluate performance.

An operational script produces ERC guidance imagery from ARCHER results in real-time, linked from the original ARCHER page. The ERC guidance page includes a Hovmoller chart of ARCHER ring score, azimuthal brightness temperature and operational/forecast maximum wind. (More information on the forecasting utility of this product is described further below.) This product was on time for the 2016 North Atlantic hurricane season.

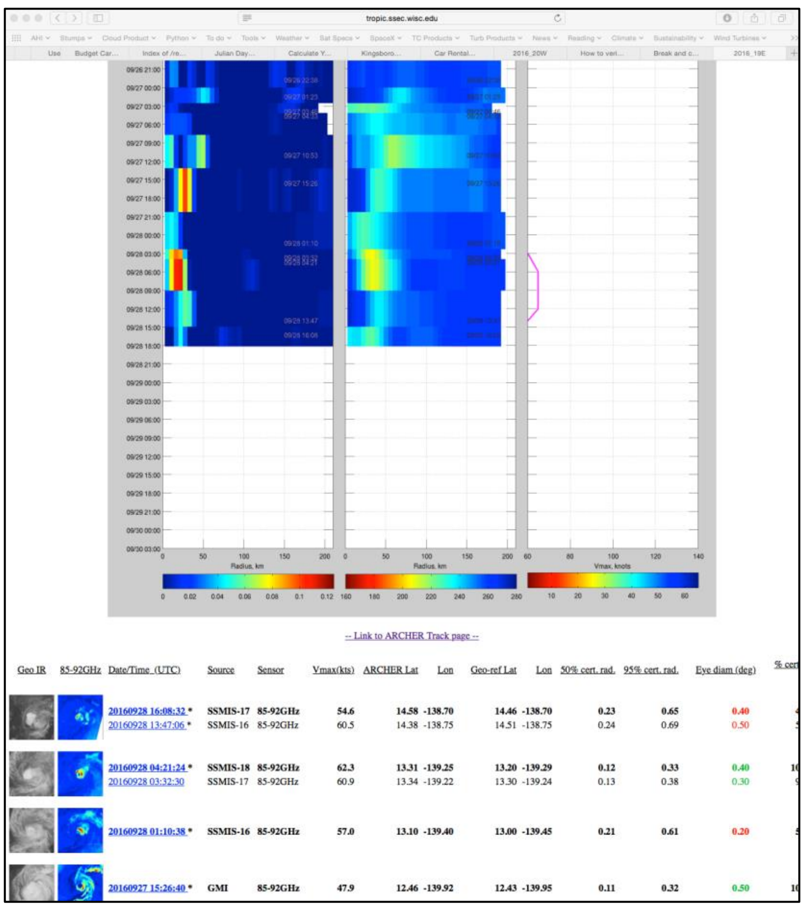


Figure 2. Screenshot of ERC guidance page for Hurricane Ulika (2016 19E).

Milestone 4. Produce initial online technical documentation

We have composed a short introduction to the ERC guidance product page, linked from the main ARCHER-ERC webpage. It describes the elements of the product images and offers an initial suggestion on how to interpret the trends in eyewall development to produce an ERC forecast.

Figure 3. Screenshot of the online ARCHER-ERC Product Description.

Milestone 5. Calibrate/Validate the ERC Probability Product

As we introduced earlier, the ARCHER model provides radial profiles of "Ring Score" calculated from brightness temperatures in satellite microwave imagery. A time evolution of these profiles is shown in Figure 4.

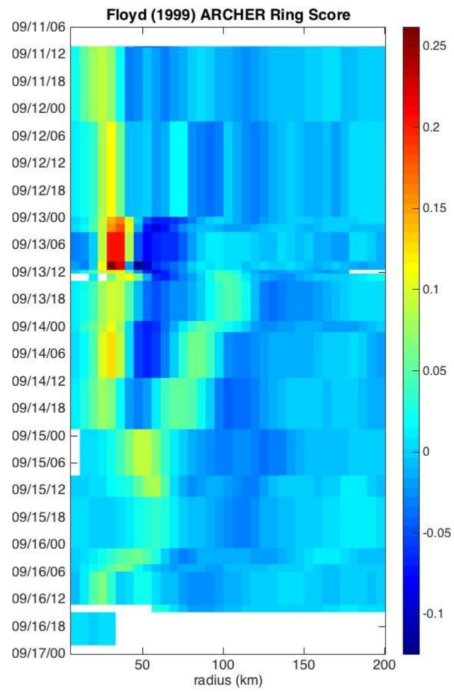


Figure 4. Hovmöller diagram of ARCHER Ring Score profiles in Hurricane Floyd (1999). Radius is distance from storm center in km. An outer eyewall starts to form on Sep 12–13, then becomes stronger in Ring Score and contracts, eventually "replacing" the inner eyewall on Sep 15.

A typical Ring Score (RS) profile in a storm with a single eyewall is shown in the left panel of Figure 5. The maximum RS is found in the eyewall, and there is a minimum outside the eyewall in the subsidence region of the moat. A typical RS profile in a storm with concentric eyewalls is shown in the right panel of Figure 5. Here the maximum is in the inner eyewall and a secondary maximum is located in the outer eyewall, and the moat is confined between these two maxima.

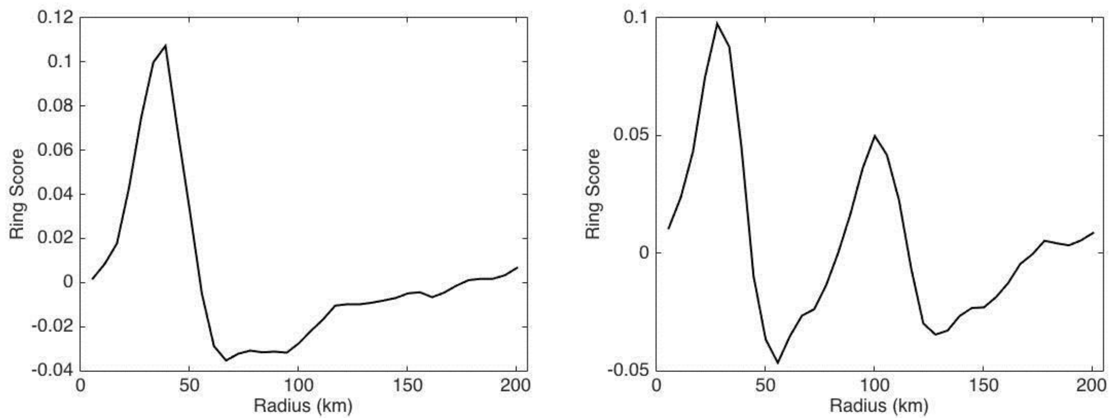


Figure 5: Typical Ring Score profile in a storm with a single primary eyewall (left) and a storm with concentric eyewalls (right).

The temporal evolution of these profiles during an eyewall replacement cycle (ERC) is intuitive; the inner RS maximum decreases while the outer maximum increases and contracts radially inward. The moat can become very pronounced when both eyewalls are convectively active. As the ERC evolves, the inner maximum eventually vanishes as the contracting outer eyewall "replaces" it.

So, to diagnose the onset of an ERC, there should be quite a lot of information in this temporal evolution of the RS profiles. After considering and exploring a number of methods to objectively capture this information (e.g., using Peaks Analysis software), we have arrived at a method that is comparatively simple and seems to be highly effective. The RS profiles for all times in all storms that we have data for (about 1500 profiles) were first decomposed into a set of Empirical Orthogonal Functions (EOFs). The profiles were first standardized to avoid too much focus on the high variability region of the inner eyewall. The first 8 EOFs, which can also be referred to as "RS profile loading patterns", are shown in Figure 6, and they do a good job of capturing the radial variability of the RS profiles.

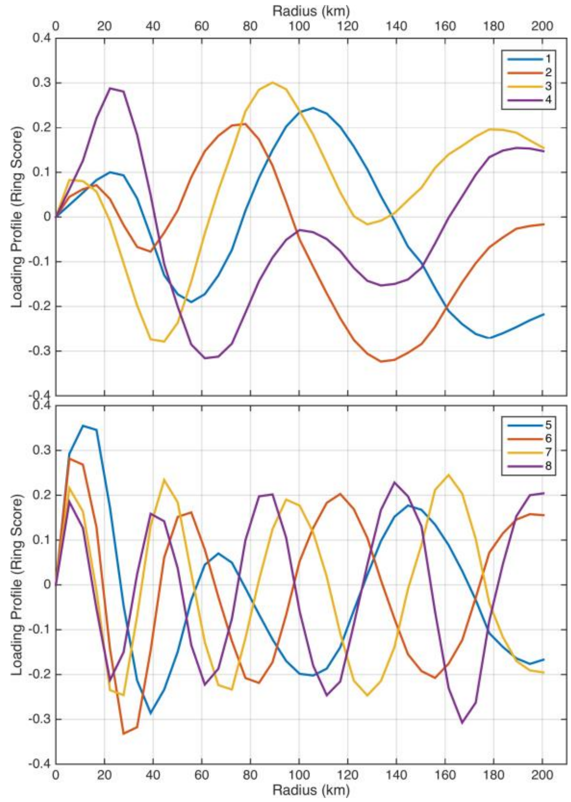


Figure 6: RS profile loading patterns determined using Principal Component Analysis. Any RS profile can be largely reconstructed by summing over these profiles with the appropriate weights.

When the loading patterns are projected onto an RS profile, each of the 8 projections will provide a different "weight" (or, alternatively, principal component or PC) so that the eight PCs together describe the shape of that profile. By looking at these PCs and how they evolve over time, we can objectively isolate the behavior seen in the Hovmöller diagram of Figure 4.

Our goal is to provide a probability of ERC onset using these PCs as predictors. We also use storm intensity as a predictor because of its known relationship to ERC onset. The two methods that we have used in the past are to construct a Bayesian model and/or a binomial regression model, which is simpler to implement. Here we chose to first explore the binomial regression model with the thought that we could potentially create a second Bayesian model in the future.

One of the great advantages of using PCs as predictors in a regression is that they are completely independent of each other by construction (the EOFs are orthogonal). So issues of predictor cross-correlation are completely eliminated and this makes for a very "clean" model. The addition of the intensity-based predictors does introduce some cross-correlation back into the model since the PCs are also likely to be correlated with intensity, but this should be comparatively minimal. The model predictand (response variable) is an ERC-onset flag that was determined subjectively using microwave imagery. The flag is 1 at ERC-onset, 2 during the ERC, and 0 everywhere else. Using the flag = 2 during the ERC allows us to exclude those times from model training and testing. Our thinking is that the forecaster wouldn't be interested in the model-estimated probability of ERC-onset during an ERC.

Our model development and implementation procedure is as follows: We begin with a predictor pool consisting of the first 8 PCs and current intensity (in knots) for all times in all storms. The previous 6, 12, 18, and 24 h change in these 9 predictors form the remainder of the 45-predictor candidate suite. A backward stepping routine is used to reduce the predictor pool, which selected 38 predictors. If the current intensity is less than 65 kt, a probability of zero is assigned. We also constructed a second model for comparison that uses only the intensity-based predictors (no microwave information).

In a dependent test, the model, which we are calling M-PERC, explains 48% of the variance of the ERC-onset flag and the Brier Skill Score is 49%, which is actually quite remarkable. Some examples of the model performance are shown in Figure 7. In these plots, the solid line is the new M-PERC model and the dashed line is the intensity-based model. The colored lines show the ERC events deduced subjectively using the microwave imagery. ERC-onset is at the earliest point on each of the colored lines, and the line spans the period of the ERC duration. The lines are green, yellow, and red for high, medium, and low confidence in the true existence of the ERC events.

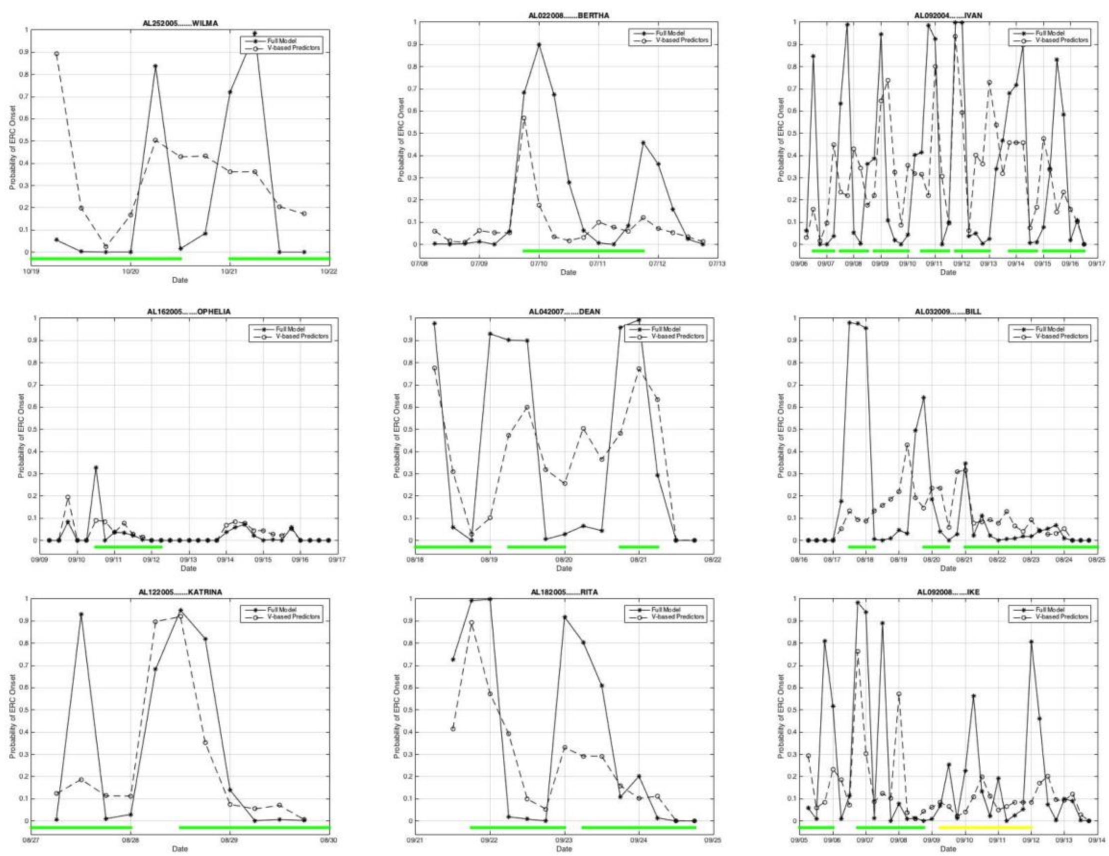


Figure 7: M-PERC diagnostic estimate of probability of ERC-onset in a few storms. In some cases (e.g., Wilma, Dean, Katrina, Ike), the model is started during an ongoing ERC, and the estimates during the ERC should be ignored. That is, only the earliest point of the colored lines are relevant to ERC-onset, and only periods with no colored lines are relevant for non-ERC cases.

In summary, we have completed a working model to diagnose ERC-onset using microwave information. We are calling it the M-PERC model, and it appears to perform remarkably well, at least in dependent testing. The main challenges to the operational implementation of M-PERC will lie in the data availability and latency constraints, but that is nothing new.

Milestone 6. Finalize double eyewall ARCHER module to optimize performance.

During the calibration/validation of M-PERC, it remained an option to revise ARCHER to work more effectively in the objective ERC scheme, and we explored this option while the calibration/validation was underway. However, M-PERC worked very effectively with the existing ARCHER modifications, so any extra effort to revise ARCHER was not necessary, and the existing version is now considered final.

Milestone 7. Finalize online display of algorithm

The online display has now reached its intended form, with three columns of plots for forecaster guidance. This is shown below for a six-day period of Hurricane Irma (Figure 8). On the left is the Hovmoller diagram of ARCHER ring score, which clarifies the progression of eyewall and proto-eyewall inner edges with time. In the center is the M-PERC "probability of an imminent ERC" using a probabilistic model of ARCHER scores and Vmax history ("Full model": *), and also using Vmax history only (o). On the right is the operational Vmax, which helps to contextualize the M-PERC scores in the progress of a TC's intensification or de-intensification. This is situated within a directory of microwave images through the TC's history, as shown in earlier reports.

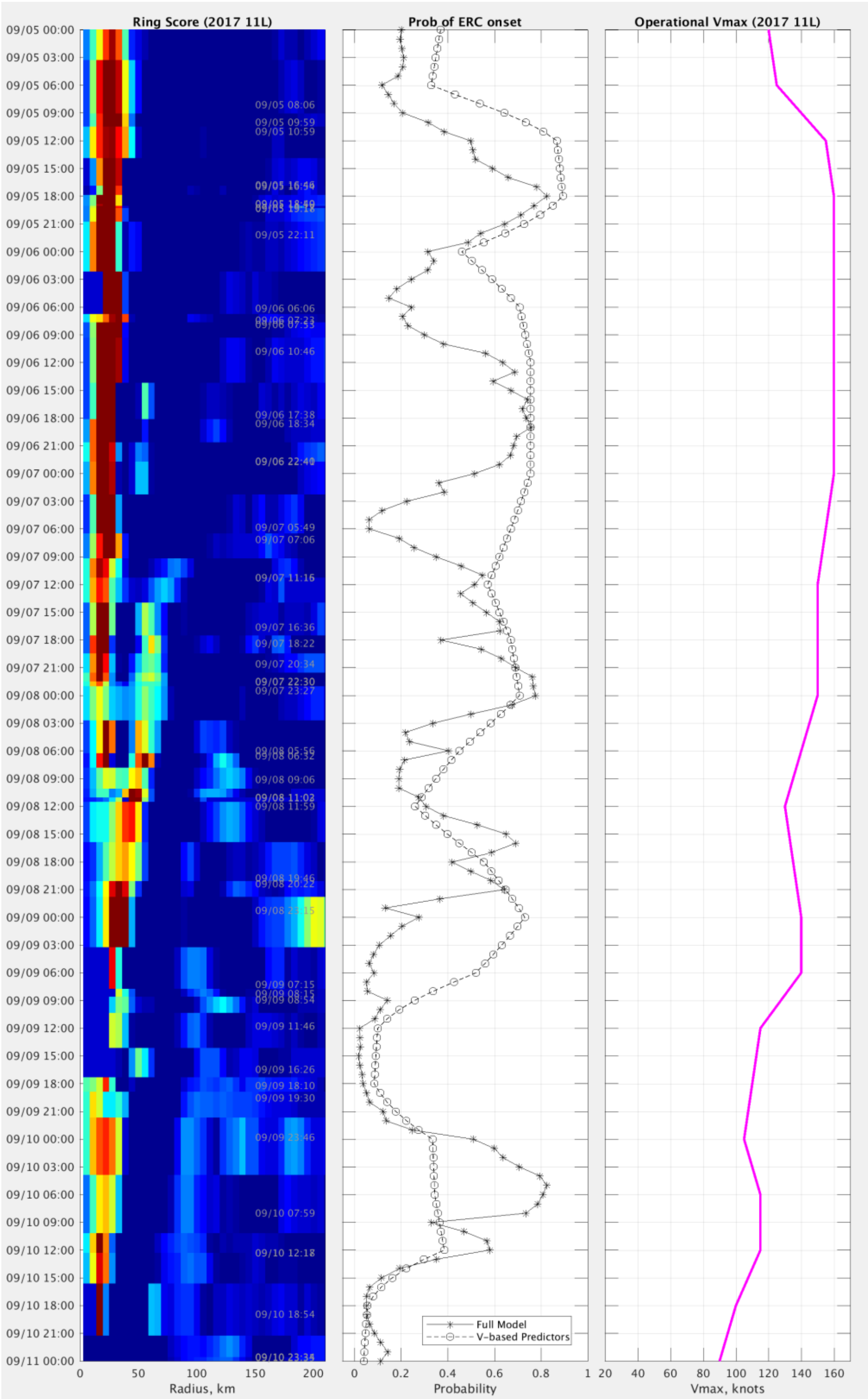


Figure 8: Example of real-time display of ERC guidance for six days of Hurricane Irma (2017). Details explained in text.

We have been following the performance of this product in real time during each of the North Atlantic tropical storms to evaluate the effectiveness of these probabilistic predictions. The example from above is a reasonably good case of typical performance. Below we discuss the details of this performance, with annotations shown in Figure 9.

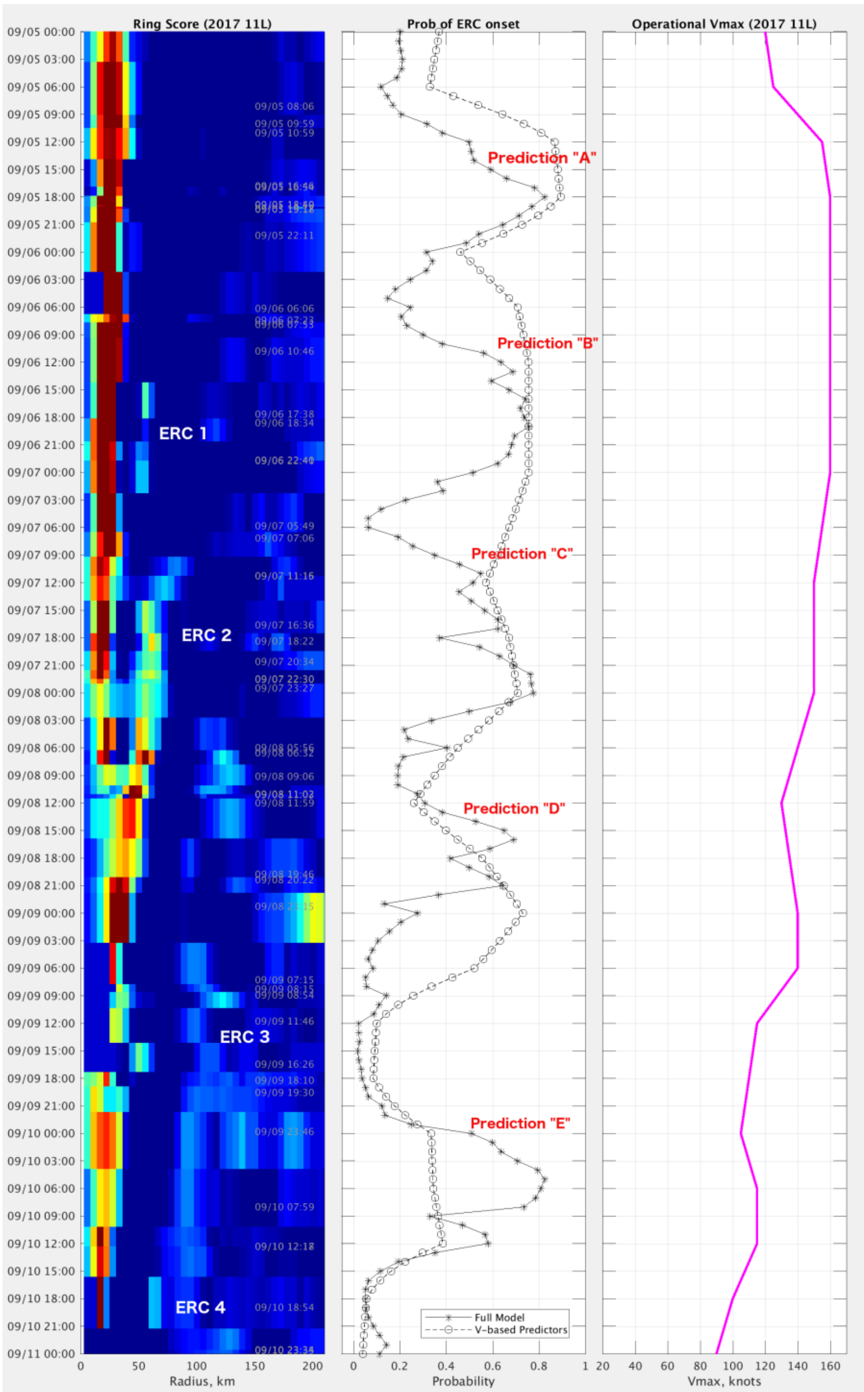


Figure 9: Annotation of the real-time display of ERC guidance for six days of Hurricane Irma (2017). Details explained in text.

During this particularly intense period in the evolution of Hurricane Irma (2017), four ERCs took place in the span of these six days. The ERCs are labeled and numbered in the ARCHER ring score Hovmoller plot in the left of Figure 9. Although each ERC is unique, they can be identified by their common characteristic of an outer branch of relative maximum scores merging with the more intense inner branch and increasing the radius of the new eye.

Here we classify a "Prediction" of an imminent ERC from the M-PERC model as a moment in which the M-PERC Full Model reaches above a 50% probability. In four out of five cases, the prediction is verified with an ERC completing approximately 18-24 hours later. The one exception is "Prediction A" at about 9/15 15Z. Here we can see that the less accurate "V-based" model is much more aggressively predicting an ERC, and it is clear that the influence of the sudden increase in Vmax in the intense hurricane was responsible for directing the Full Model toward a positive prediction. However, this can be easily discounted by a user because of the complete absence of a secondary eye feature in the microwave imagery. (This can be seen in the Hovmoller plot at that time, in the dark blue area throughout the outside of the eyewall.)

Milestone 8. Complete online technical documentation

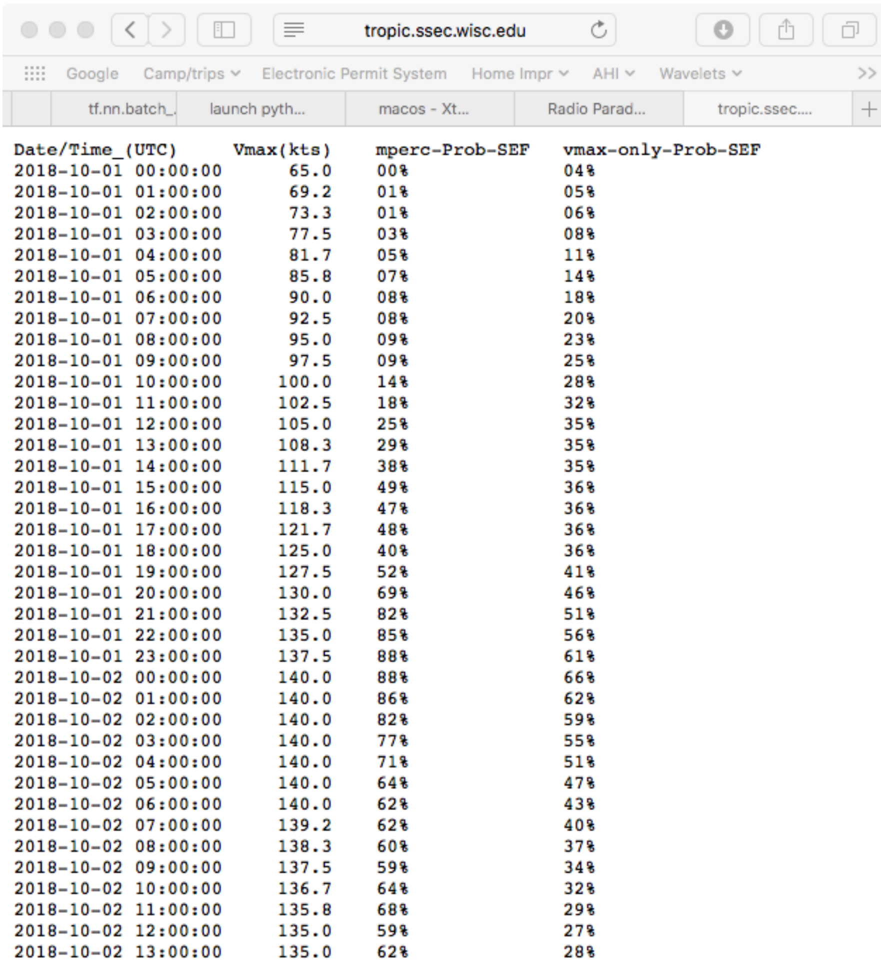
The online technical documentation was produced as a wiki collaborative document hosted at SSEC (https://groups.ssec.wisc.edu/groups/archer/archer-erc-introduction), and linked from the ARCHER-ERC page. The documentation is complete, and we have found that the guidelines for interpreting the probabilistic model are consistent with our experience of the 2017 and 2018 hurricane seasons.

Milestone 9. Deliver ERC module for SHIPS

It is now increasingly clear that properly delivering an ERC module to NHC will require an operational software platform at NHC to ingest and stage microwave imagery for the ARCHER algorithm. This is being supported (July 2018 to July 2021) under the JPSS Risk Reduction grant to incorporate ARCHER into a real-time data processing environment for NHC, CPHC and JTWC ("Real-time acquisition, processing, analysis, and operational integration of TC-centric polar orbiting data. Part II: Serving forecasters with advanced satellite-based TC center-fixing and intensity information", UW-CIMSS). When this platform is running at NHC, it will be a simple and straightforward task to add the ERC module as well. But in the meantime, this milestone is listed as TBD.

Milestone 10. Create real-time online text file output of ERC module for SHIPS

We are now producing online text file versions of the M-PERC output for automated reading (Figure 10). This is useful for future incorporation into SHIPS, into other automated algorithms, and as a more precise report for viewers of the online graphical output. In this output, the "Vmax" column is the operational track intensity, interpolated to one hour resolution, the next column is the M-PERC probability of an imminent ERC, and the final column is the “default” probability of ERC (using Vmax trends only).



Date/Time_(UTC)	Vmax(kts)	mperc-Prob-SEF	vmax-only-Prob-SEF
2018-10-01 00:00:00	65.0	00%	04%
2018-10-01 01:00:00	69.2	01%	05%
2018-10-01 02:00:00	73.3	01%	06%
2018-10-01 03:00:00	77.5	03%	08%
2018-10-01 04:00:00	81.7	05%	11%
2018-10-01 05:00:00	85.8	07%	14%
2018-10-01 06:00:00	90.0	08%	18%
2018-10-01 07:00:00	92.5	08%	20%
2018-10-01 08:00:00	95.0	09%	23%
2018-10-01 09:00:00	97.5	09%	25%
2018-10-01 10:00:00	100.0	14%	28%
2018-10-01 11:00:00	102.5	18%	32%
2018-10-01 12:00:00	105.0	25%	35%
2018-10-01 13:00:00	108.3	29%	35%
2018-10-01 14:00:00	111.7	38%	35%
2018-10-01 15:00:00	115.0	49%	36%
2018-10-01 16:00:00	118.3	47%	36%
2018-10-01 17:00:00	121.7	48%	36%
2018-10-01 18:00:00	125.0	40%	36%
2018-10-01 19:00:00	127.5	52%	41%
2018-10-01 20:00:00	130.0	69%	46%
2018-10-01 21:00:00	132.5	82%	51%
2018-10-01 22:00:00	135.0	85%	56%
2018-10-01 23:00:00	137.5	88%	61%
2018-10-02 00:00:00	140.0	88%	66%
2018-10-02 01:00:00	140.0	86%	62%
2018-10-02 02:00:00	140.0	82%	59%
2018-10-02 03:00:00	140.0	77%	55%
2018-10-02 04:00:00	140.0	71%	51%
2018-10-02 05:00:00	140.0	64%	47%
2018-10-02 06:00:00	140.0	62%	43%
2018-10-02 07:00:00	139.2	62%	40%
2018-10-02 08:00:00	138.3	60%	37%
2018-10-02 09:00:00	137.5	59%	34%
2018-10-02 10:00:00	136.7	64%	32%
2018-10-02 11:00:00	135.8	68%	29%
2018-10-02 12:00:00	135.0	59%	27%
2018-10-02 13:00:00	135.0	62%	28%

Figure 10. Example text file M-PERC output for Hurricane Walaka (2018 01C).

2. PRODUCTS

As described in Section 1, we have completed the following deliverables/products during this the project:

a. The ARCHER-ERC real-time graphical guidance webpage, at http://tropic.ssec.wisc.edu/real-time/archerOnline/web/index_erc.shtml
b. The ARCHER-ERC Product Description page, at https://groups.ssec.wisc.edu/groups/archer/archer-erc-introduction

c. The ERC-Probability model algorithm,
d. The real-time M-PERC online text file output.

3. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

As this is a fairly small project, we have kept the activity limited to the three original participants – Anthony Wimmers, Derrick Herndon and Jim Kossin. We have provided regular updates to our colleagues at the NHC.

4. IMPACT

The expected impact of this project is to improve the forecasting accuracy for intense hurricanes in one of the current areas of need for the NHC: understanding and predicting eyewall replacement cycles. We attempt to do this using an automated analysis of eyewall (and developing eyewall) sizes and trends from 85-92 GHz microwave imagery. The information is organized into real-time online graphics and an associated probabilistic model. These new tools offer a more rigorous analysis of a phenomenon that requires greater understanding and analysis to provide adequate warning during weather-related emergencies.

5. CHANGES/PROBLEMS

We have encountered no significant obstacles in this project to meet our original objectives.

6. SPECIAL REPORTING REQUIREMENTS

Test Plans for the ARCHER-ERC / M-PERC Project

We will continue to run the automated ARCHER-ERC and MPERC for the real-time website at CIMSS through the next year and beyond.

The primary criterion for success is a positive review from NHC participants within the JHT. Their decision will be based on quantitative performance metrics compiled by the CIMSS team (accuracy, Brier Skill Score), case histories, as well as the NHC's professional judgment of the skill of the algorithm in real-time.

Project Readiness Level

The online tools (Milestones 2 and 3) and the M-PERC probability model can be considered "RL 7: Prototype system." (This is 7 of 9). These tools are currently working in an operational environment in a demonstration phase and user documentation is online. The remaining criterion for reaching the next level is receiving the operator approval.

Transition to Operations Activities

In preparation for transition to operations, we are demonstrating the final products in real time on the CIMSS TC webpage, and continue to explore options for recoding the full ARCHER system into a format that is compatible with the NHC system.

Testbed Approval

The decision to transition to operations will occur after the close of the project, anticipated sometime in 2019.

7. BUDGETARY INFORMATION

We have spent the full $80,299 budget for this project in sync with the completed deliverables.

8. PROJECT OUTCOMES

The outcome of this project is a new system to automatically analyze near real-time microwave imagery of hurricanes and provide comprehensive forecaster guidance on the potential for an upcoming eyewall replacement cycle. This guidance will take the form of an online graphical depiction of the relevant image characteristics, and a probabilistic model using microwave image information in the same fashion as the pERC model.

REFERENCES

n/a