Improvements in the Probabilistic Prediction of Tropical Cyclone Rapid Intensification Resulting from Inclusion of Satellite Passive Microwave Observations

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Project goals

1. Improve the statistical prediction of RI using a variety of predictors derived from passive microwave imagery

- Create 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 tropical cyclones.
- Adapt statistical models to incorporate the most skillful predictors

** Nearly completed work supported by GOES-RRR/NOAA JHT*

2. Evaluate new models in real-time

** Ongoing work supported by NOAA JHT*

Methodology : Datasets

- SHIPS developmental dataset (DeMaria et al. 2005)
  - Includes environmental and GOES-IR predictors
- New Development Data (1998 – 2008):
  - SSM/I : 19.4, 37.0, 85.5 GHz

    Spatial resolution : 43 x 69 km, 38 x 40 km, 13 x 15 km
  - TRMM TMI : 19.4, 37.0, 85.5 GHz

    Spatial resolution : 18 x 30 km, 16 x 19 km, 5 x 7 km
  - AMSR-E : 18.7, 36.5, 89.0 GHz

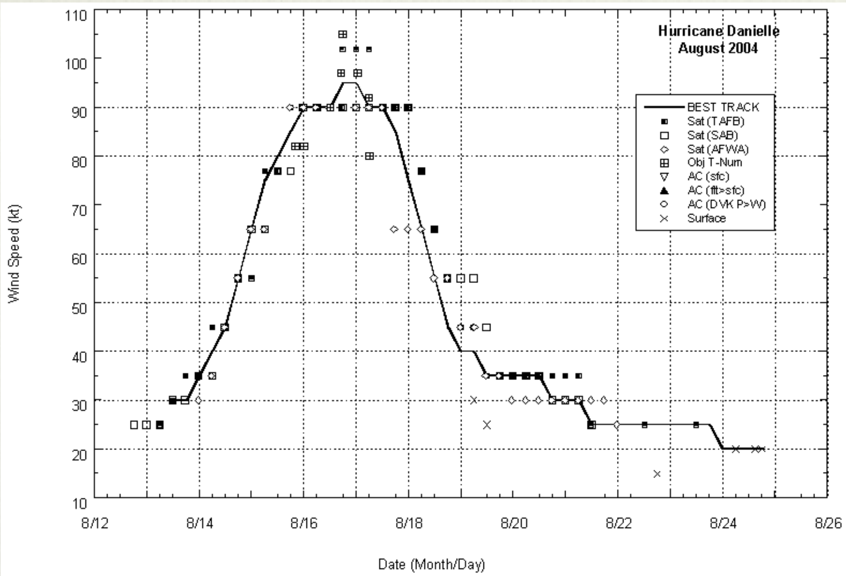
    Spatial resolution : 16 x 27 km, 8 x 14 km, 4 x 6 km
  - WINDSAT : 18.7, and 37.0 GHz

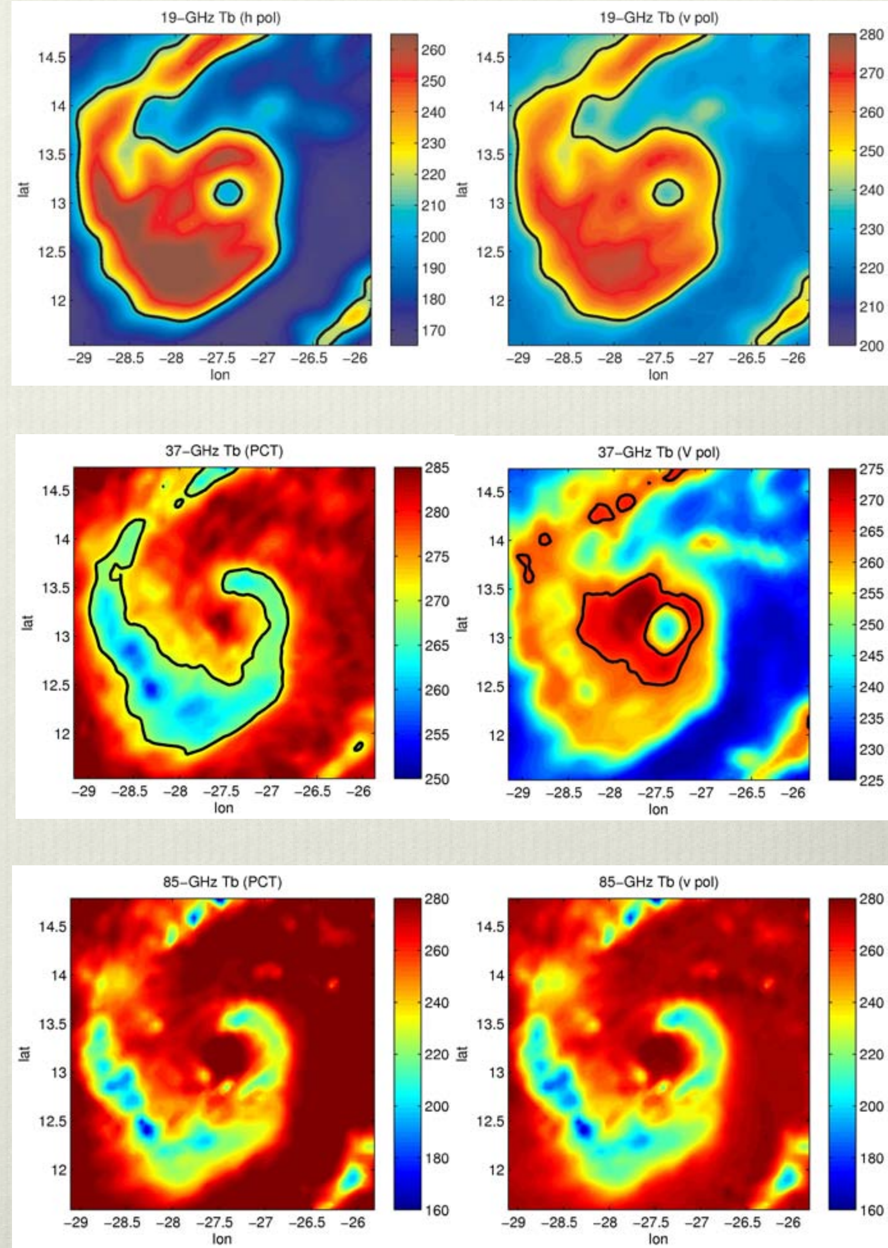
    Spatial resolution : 16 x 27 km, 8 x 13 km

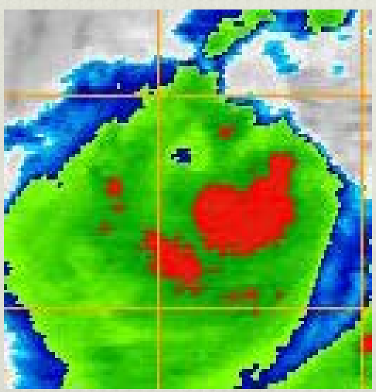
** SSMI/S (19.4, 37.0, 85.5 GHz) and AMSU-B (89 GHz) will be used in the real-time model*

Structure at 19.4, 37, and 85.5-GHz (TMI)

Hurricane Danielle (14 Aug 04; 1527 UTC)







GOES-12 IR 1445 UTC

Methodology : Models

- Models:
  - Logistic regression (Rozoff and Kossin 2011; *WAF*)
  - Bayesian model (Rozoff and Kossin 2011; *WAF*)
  - SHIPS-RII (Kaplan et al. 2010; *WAF*)
  - Consensus model (Logistic, Bayesian, and SHIPS-RII)
- In this presentation, we shall focus on the logistic regression model results

$$p_L\left(\Delta v_{\max} / \Delta t \geq a\right) = \frac{1}{1 + \exp\left(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{N_L} x_{N_L}\right)}$$

here, the $\mathbf{x}_L = (x_1, x_2, \ldots, x_N)$ represent certain environmental and GOES-IR features,
β_i represent the fitted coefficients obtained from a least-squares technique, and
a represents the RI threshold of 25, 30, and 35-kt intensity change per 24 h

Logistic Regression Model

- Optimal predictors

Feature Description (ATL)	RI Preference
Previous 12-h intensity change	higher
Reynolds sea surface temperature	higher
200-hPa divergence (r = 0 – 1000 km)	higher
800-200-hPa vertical wind shear magnitude (r = 200 – 800 km	lower
Departure from the TC's max. potential intensity	higher
Stand. dev. Of IR cloud-top BT (r = 100 – 300 km)	lower
Ave. IR cloud-top BT (r = 0 – 30 km)	lower

Feature Description (EPAC)	RI Preference
Previous 12-h intensity change	higher
Ver. ave. of neg. diff. between θ_e of parcel lifted from sfc and θ_e* (r = 200-800 km)	higher
800-200-hPa vertical wind shear magnitude (r = 200 – 800 km)	lower
Departure from the TC's max. potential intensity	higher
IR cloud-top BT (r = 100 – 300 km)	lower
Stand. Dev. Of IR cloud-top BT (r = 50 – 200 km)	lower
Max. IR cloud-top BT (r = 0 – 30 km)	lower

***Note, in all of the following microwave-based models, these predictors are part of the models.**

Methodology : Predictor development

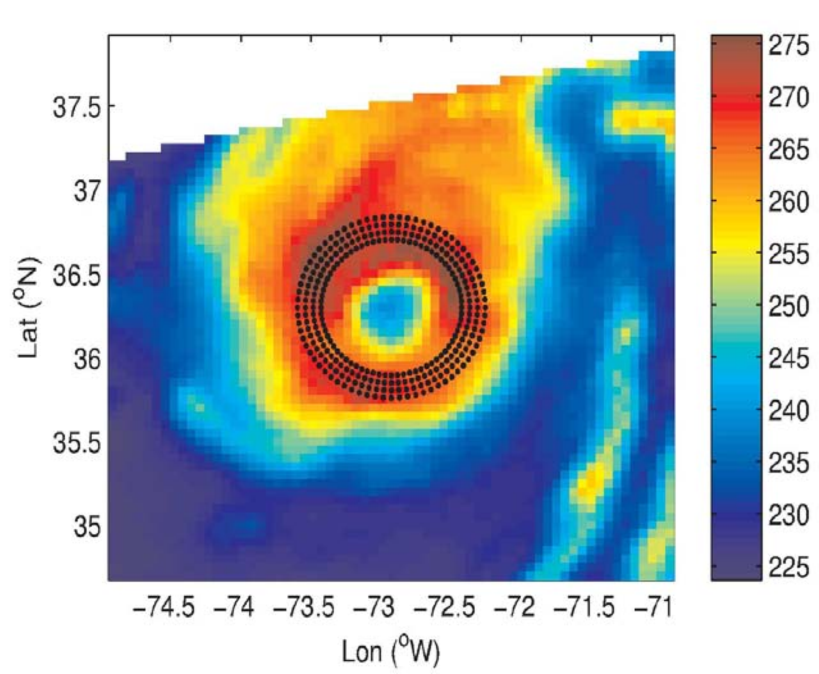
- Histogram matching was performed to calibrate AMSR-E 18.7-, 36.5-, and 89.0-GHz $T_{b,v}$ and $T_{b,h}$ to be comparable to 19.4-, 37.0- and 85.5-GHz values from other sensors (e.g., TMI, SSM/I).

- Center finding accomplished with **ARCHER** (Wimmers & Velden 2010) using $T_{b,h}$. For the 19.4- and 37.0-GHz channels, we use the 37.0-GHz channel for centering, whereas 85.5-GHz centers are found using 85.5-GHz $T_{b,h}$.
  - This reduces parallax issues between 37.0 and 85.5-GHz channels, while the 19.4-GHz channel has lower spatial resolution, which allows the 37.0-GHz channel to provide a more accurate center for 19.4 GHz

Methodology : Predictors

- *Nascent eyewall/eye-based predictors:* Objective nascent eyewall/eye detection is carried out on each channel using optimal BT thresholds for each channel.

Hurricane Alex (4 Aug 2004) (37 GHz v pol BT)



- *Fixed-geometry predictors* (similar to the GOES-IR predictors in the SHIPS developmental dataset) were developed as well.

Forecasts at satellite times

- Tests have revealed that 19 and 37-GHz-based microwave predictors add significant skill to the logistic model when making forecasts at the times of a satellite overpass, with increases in the Brier skill score exceeding 20%.
  - Predictors based on high-resolution sensors showed increases in the Brier skill score of around 35% for the 35 kt per 24 h RI threshold.
- 85-GHz based predictors generally added relatively marginal skill to the logistic model at satellite overpass times.

Forecasts : Synoptic Times

- Many NOAA forecast products are issued at synoptic times of 00, 06, 12, 18 UTC.

- Challenges
  - Sufficiently recent low-earth orbiting satellite imagery will not always be captured before the forecast model needs to run
  - Data latency
  - For times when multiple sensors are available, which one is the best choice?

- For now, RI forecasts incorporating microwave data are issued at synoptic times only when data are less than 6-h old. The most recent imagery is used.
  - Forecasts are validated with leave-one-year-out cross validation from 1998 – 2008 and compared with forecasts having no microwave data.
  - TMI, AMSR-E, SSM/I, and WINDSAT are used, which, depending on whether a predictor meets certain quality-control criteria, can lead to microwave predictors being available roughly 40-60 % of the time in our training period/sample.
  - Models at all RI thresholds show significant increased skill using certain microwave predictors, but can even have more skill if optimal predictors are chosen for each RI threshold, which will be shown in the following results

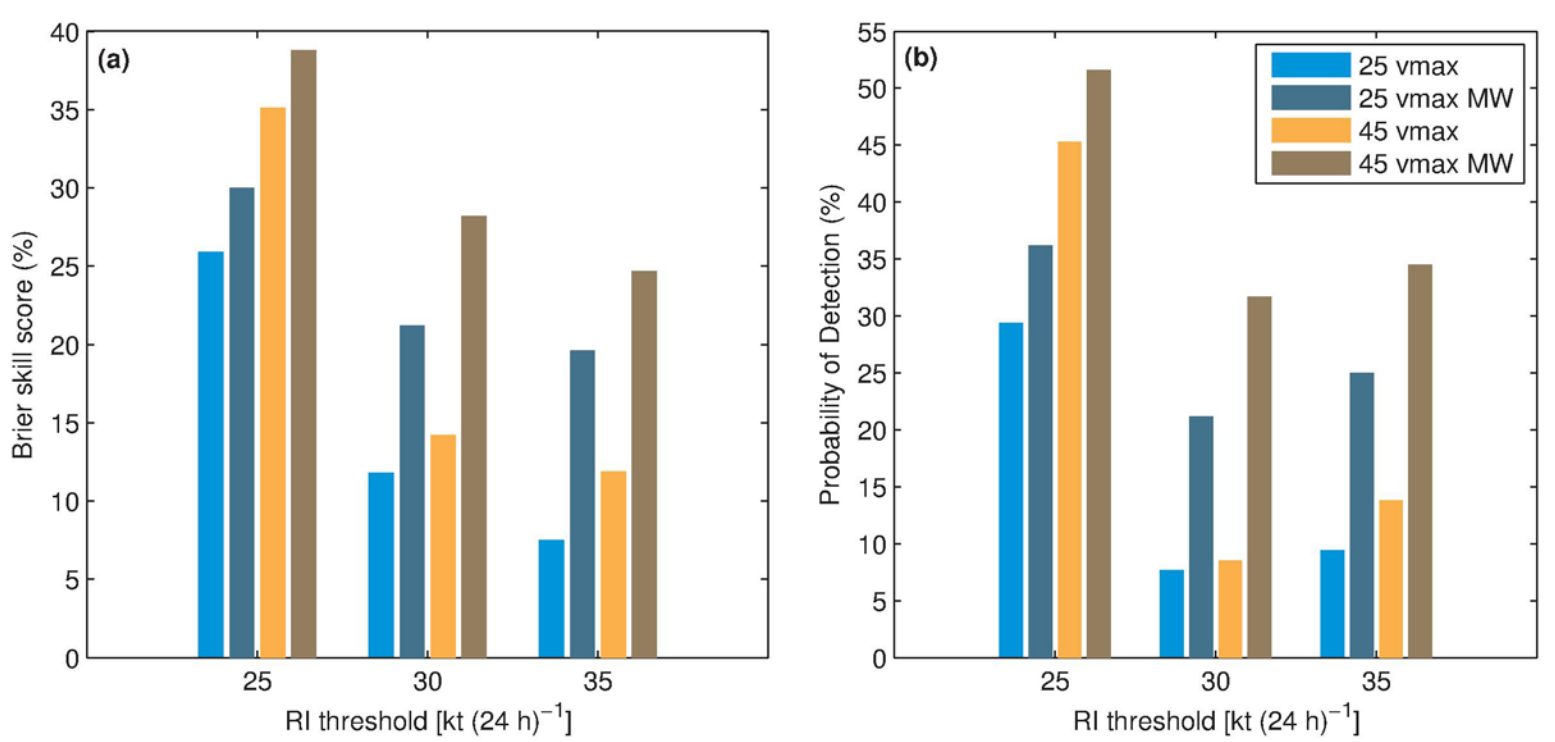
ATL Forecasts (19.4, 37, 85.5 GHz)

Synoptic Times (00, 06, 12, 18 UTC)

Feature Description	RI Threshold	RI Preference
19.4-GHz ave BT (h pol) *r* = 0 – 100 km	25	higher
19.4-GHz percent area BT (vpol) > 245 K	25	higher
19.4-GHz max eye BT (h pol)	30	higher
19.4-GHz ave BT (v pol) *r* = 0 – 100 km	30	higher
19.4-GHz ave BT (h pol) *r* = 100 – 300 km	30	higher
19.4-GHz ave BT (v pol) *r* = 100 – 300 km	30, 35	higher
19.4-GHz eye min. BT (v pol)	35	higher
19.4-GHz ring ave. BT (h pol)	35	higher
37.0-GHz min eye BT (h pol)	25, 30	higher
37.0-GHz ring stan. dev BT (h pol)	30	lower
37.0-GHz radius of max BT (h pol)	35	lower
37.0-GHz ave BT (v pol) *r* = 0 100 km	35	higher
85.5-GHz ave eye BT (h pol)	25	lower
85.5-GHz eye radius	25	lower
85.5-GHz percent area PCT < 250	25	higher
85.5-GHz ave BT (v pol) *r* = 30 – 130 km	25, 30	lower

ATL Forecasts (19.4, 37, 85.5 GHz)

Synoptic Times (00, 06, 12, 18 UTC)



*N = 1360 for $V_{max} \geq 25$ m s^{-1} and N = 1013 for $V_{max} \geq 45$ m s^{-1} (for 25 kt/24-h RI)

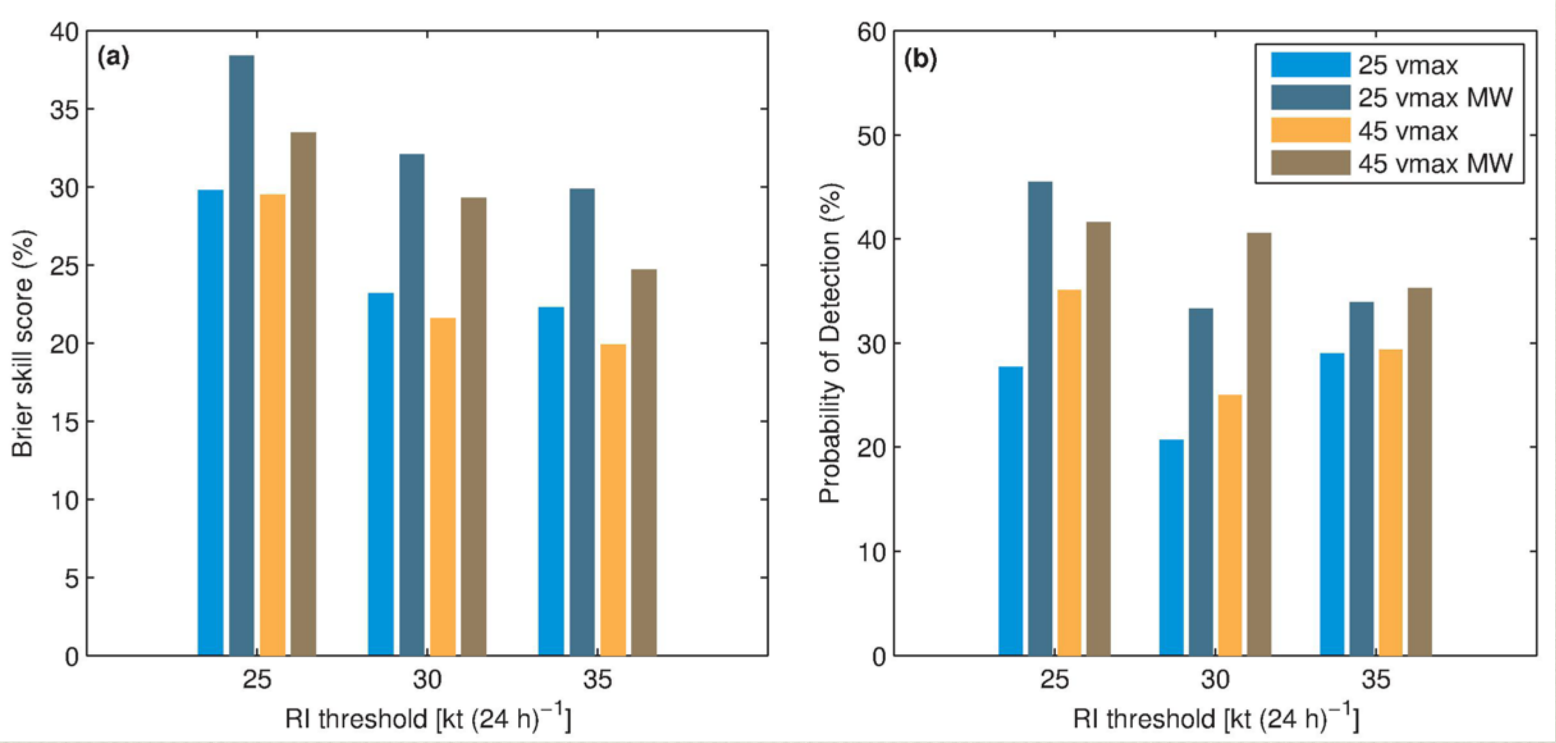
EPAC Forecasts (19.4, 37, 85.5 GHz)

Synoptic Times (00, 06, 12, 18 UTC)

Feature Description	RI Threshold	RI Preference
19.0-GHz ave BT (v pol) (*r* = 0 – 100 km)	25	higher
19.0-GHz std. dev. BT (h pol) (*r* = 0 – 100 km)	30, 35	higher
19.0-GHz % area BT (v pol) > 245 K (*r* = 50 – 200 km)	25, 30, 35	higher
37.0-GHz % eye with BT (vpol) < 265 K; PCT > 270 K	25, 30	lower
37.0-GHz ave ring PCT	30	lower
37.0-GHz ave PCT (*r* = 100 – 300 km)	30	lower
37.0-GHz max ring PCT	35	lower
37.0-GHz ring width	35	lower
37.0-GHz ave. BT (v pol) (*r* = 100 – 300 km)	35	higher
37.0-GHz ave. BT (h pol) (*r* = 100 – 300 km)	25, 35	higher
85.5-GHz std. dev eye BT (h pol)	25	higher
85.5-GHz ave. ring BT (h pol)	25, 30	lower
85.5-GHz std. dev ring BT (h pol)	25	higher
85.5-GHz % area BT (v pol) < 250 K (*r* = 50 – 200 km)	30	higher
85.0-GHz std. dev. BT (v pol) (*r* = 100 – 300 km)	30, 35	higher

EPAC Forecasts (19.4, 37, 85.5 GHz)

Synoptic Times (00, 06, 12, 18 UTC)



*N = 1120 for $V_{max} \geq 25$ m s^{-1} and N = 733 for $V_{max} \geq 45$ m s^{-1} (for 25 kt/24-h RI)

Conclusions

- At synoptic forecast times, the inclusion of optimal microwave predictors into the logistic RI model improves forecast skill by anywhere from
  - 16 - 160 % in the Atlantic ($V_{max} \geq 25$ m s^{-1})
  - 29 - 38 % in the East Pacific ($V_{max} \geq 25$ m s^{-1})

Ongoing development

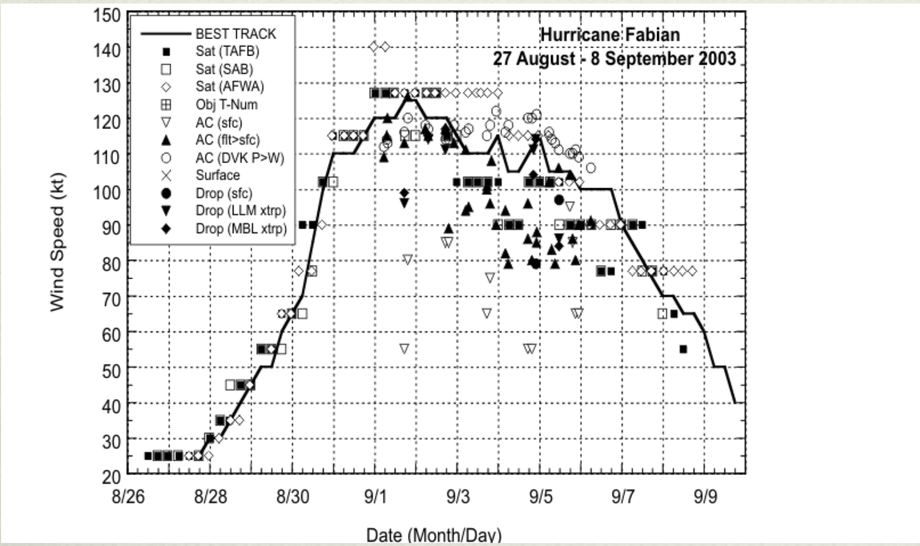
- Complete microwave versions of Bayesian and SHIPS-RII models
- Update training data to include 2009-2011.
- Continue improvements to structural predictors at all frequencies
- More experiments with data latency

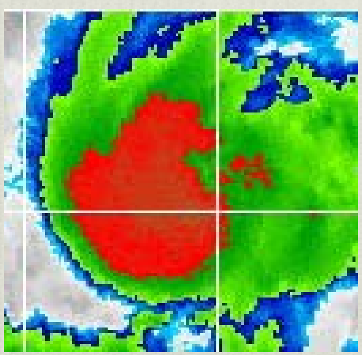
Real-time forecasts

- Project goal:
  - In-house demo of real-time model in 2012
  - All Atlantic and East Pacific real-time models completed (June 2013)
  - Operational testing (Jun – Dec 2013)
- So far, real-time NESDIS/NASA data feeds have been established at SSEC:
  - SSMI/S
  - AMSU-B
  - SSM/I (F15)
  - WINDSAT
  - TRMM-TMI

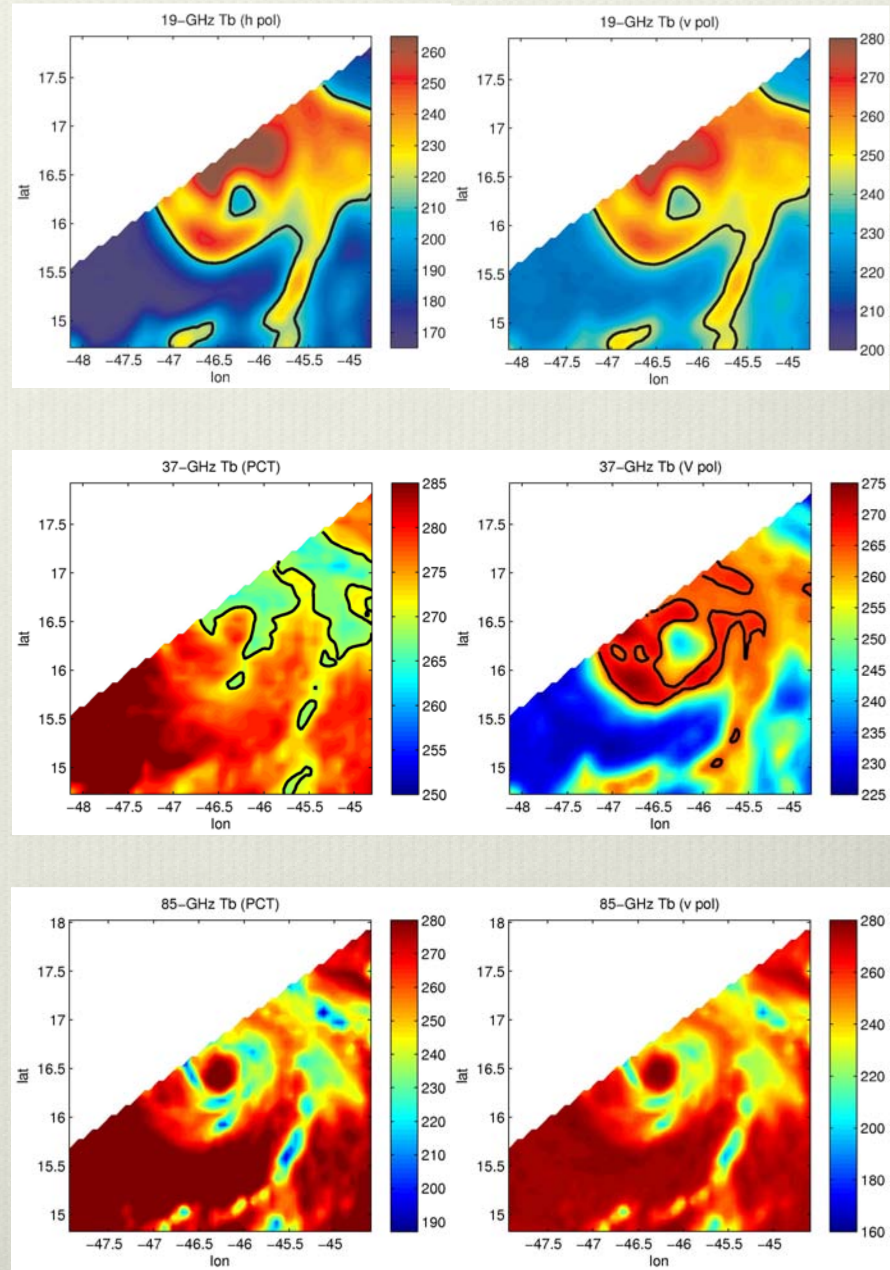
Structure at 19.4, 37, and 85.5-GHz (TMI)

Hurricane Fabian (30 Aug 03; 0217 UTC)





GOES-12 IR 0215UTC



Methodology : Histogram Matching

- Histogram matching was performed to calibrate AMSR-E 18.7-, 36.5-, and 89.0-GHz $T_{b,v}$ and $T_{b,h}$ to be comparable to 19.4-, 37.0- and 85.5-GHz values from other sensors (e.g., TMI, SSM/I).

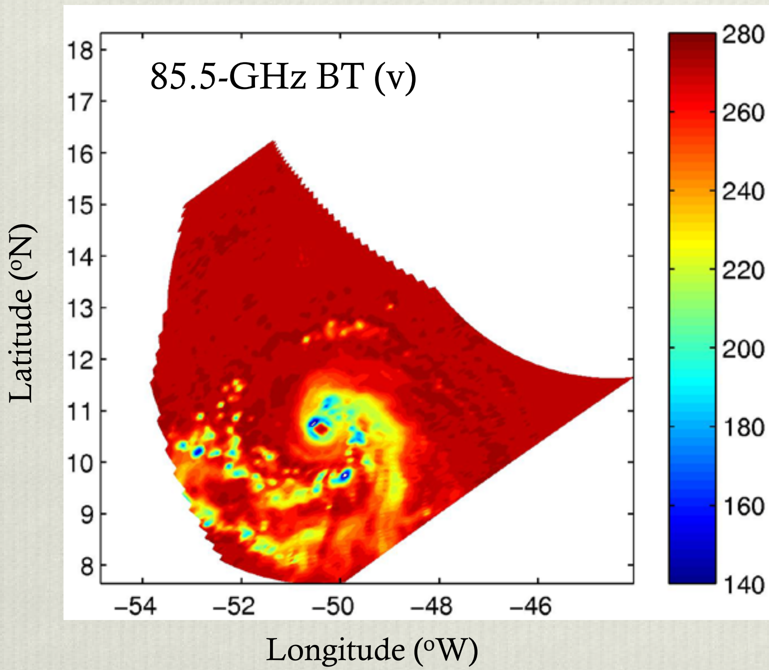
Match AMSR-E cases to TMI (similar spatial resolution)

Storm Name	AMSR-E	TMI
1. Ivan – 9/6/04	0445 UTC	0530 UTC
2. Jeanne – 9/20/04	0632 UTC	0707 UTC
3. Jeanne – 9/22/04	0619 UTC	0655 UTC
4. Dennis – 7/7/05	0620 UTC	0542 UTC
5. Emily – 7/11/05	1645 UTC	1658 UTC
6. Ophelia – 9/11/05	1842 UTC	1826 UTC
7. Rita – 9/22/05	0726 UTC	0810 UTC
8. Bertha – 7/10/08	1701 UTC	1728 UTC
9. Bertha – 7/17/08	1709 UTC	1732 UTC
10. Bertha – 7/18/08	1614 UTC	1637 UTC
11. Ike – 9/7/08	1820 UTC	1833 UTC

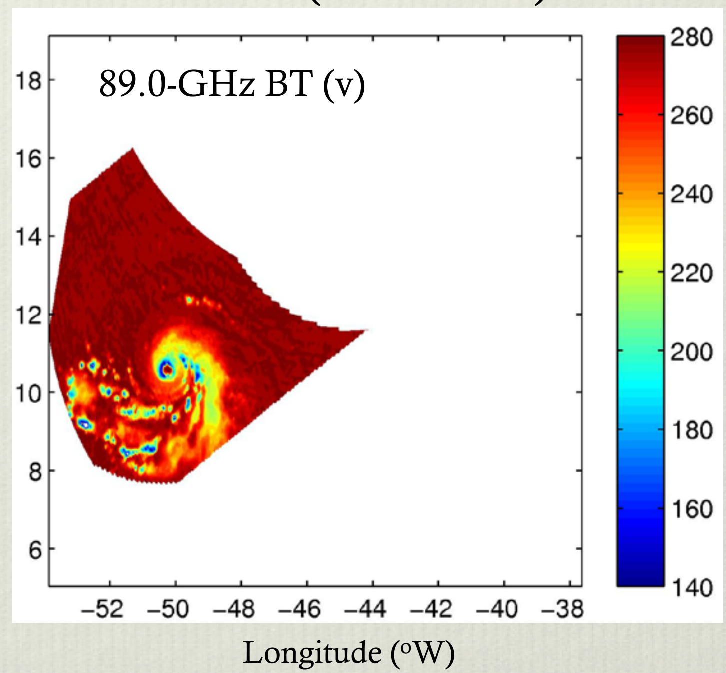
Histogram Matching

- The geometric intersection of satellite swath segments are used to compare data. For example, for the Hurricane Ivan (2004) imagery below, we only use the common data data for TMI & AMSRE swaths to use in our histogram matching calibration.

TMI (0530 UTC)



AMSRE (0445 UTC)



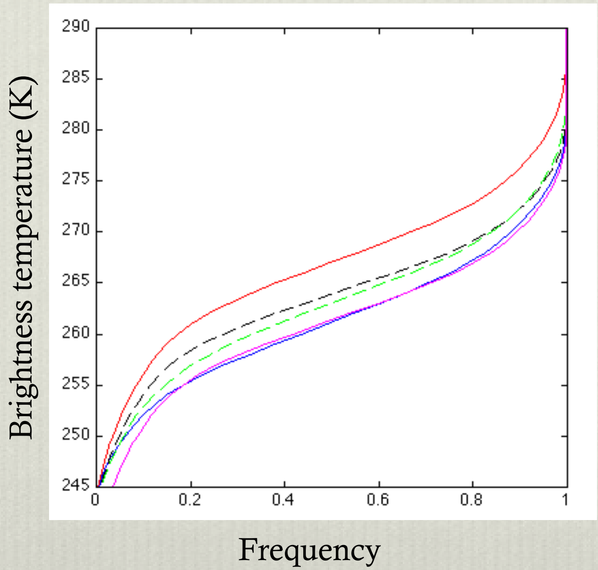
- Data are then interpolated to a common grid of 0.05 degree grid spacing before performing histogram matching

Histogram Matching

- We seek linear calibrations for AMSRE brightness temperatures such that the cumulative distribution functions of AMSRE and TMI match. (This approach is similar that of Jones and Cecil 2006)

$$T_{b,(h,v),correct} = a + b\,T_{b,(h,v)}$$

- For example, the 85-GHz BT (h pol), we find $a = 5.1073$ and $b = 0.9597$ for $T_b \geq 245$ K. (No adjustment below 245 K is done.)



Red: Original AMSRE
Blue: TMI
Black: Jones & Cecil (2006) corrected AMSRE
Green: Wimmers corrected AMSRE
Magenta: our scheme corrected AMSRE

Methodology : Predictors

- *Nascent eyewall/eye-based predictors:* Objective nascent eyewall/eye detection is carried out on each channel using optimal BT thresholds.
  - $T_{b,h} \geq 215$ K and $T_{b,v} \geq 245$ K (19.4 GHz)
  - $T_{b,v} \geq 265$ K or PCT ≤ 270 K (37.0 GHz) [PCT = $2.18\ T_{b,v} - 1.18\ T_{b,h}$]
    - Numbers supported by work of Jiang, Kieper, et al. (2011; *IHC*)
  - PCT ≤ 250 K (85.5 GHz) [PCT = $1.82\ T_{b,v} - 0.82\ T_{b,h}$]
    - Number supported by work of Harnos and Nesbitt (2011; *GRL*)
- *Fixed-geometry predictors* (similar to the GOES-IR predictors in the SHIPS developmental dataset) were developed as well.

Forecasts (19 GHz) : Satellite Times

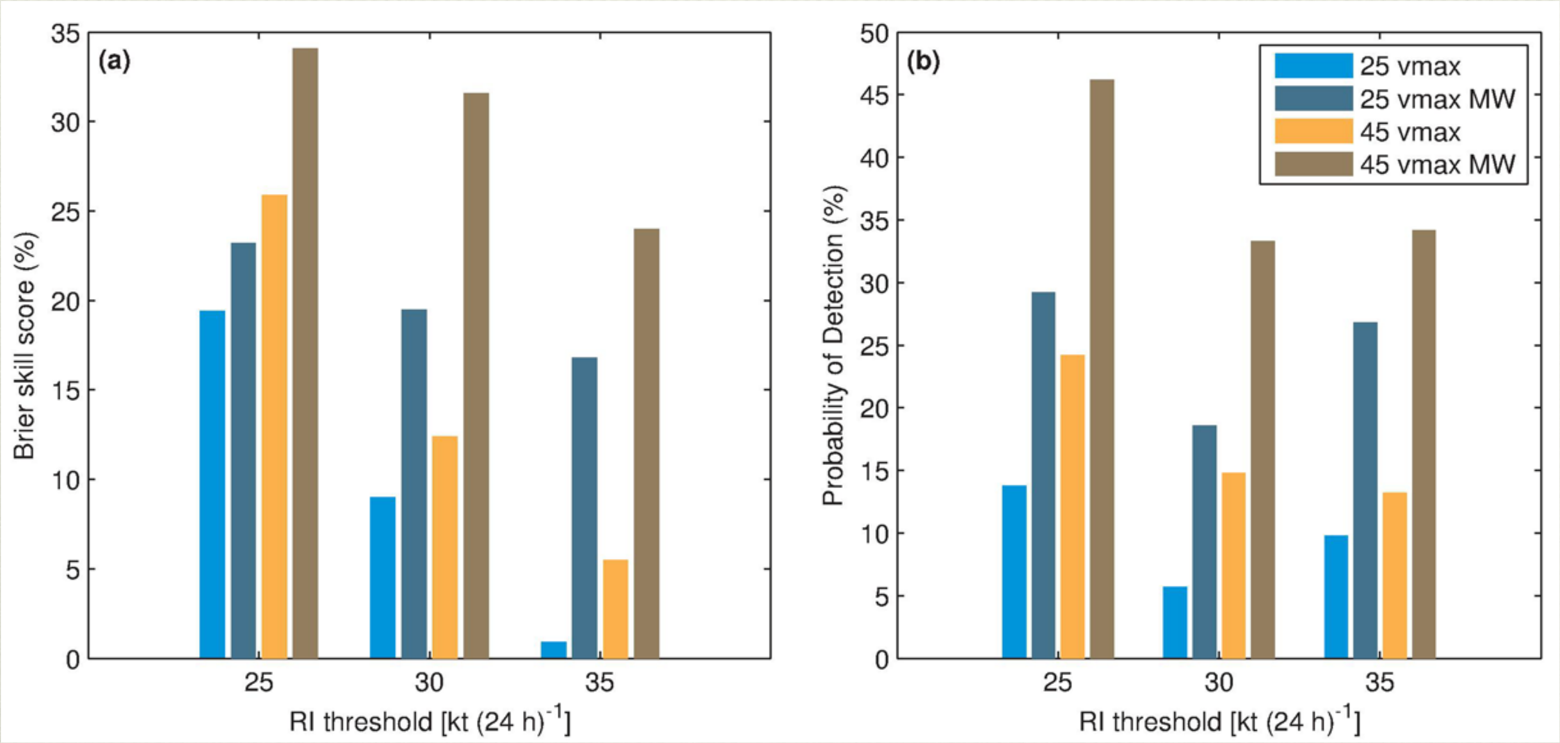
ATL (SSM/I, AMSR-E, TMI)

- Optimal predictors – tested with the logistic regression model containing environmental/GOES-IR predictors

Feature Description	**RI Preference**
ave. eye BT (h pol)	higher
ave. ring BT (h pol)	higher
BT of the eye – BT of the ring	more negative
ave. BT (r = 0 – 30 km) (v pol)	higher
ave. BT (r = 0 – 100 km) (v pol)	higher
% area BT (v pol) > 255 K	higher

Forecasts (19 GHz) : Satellite Times

All Sensors (SSM/I, AMSR-E, TMI)



*N = 1650 for $V_{max} \geq 25$ m s^{-1} and N = 1212 for $V_{max} \geq 45$ m s^{-1}

Forecasts (37 GHz) : Satellite Times

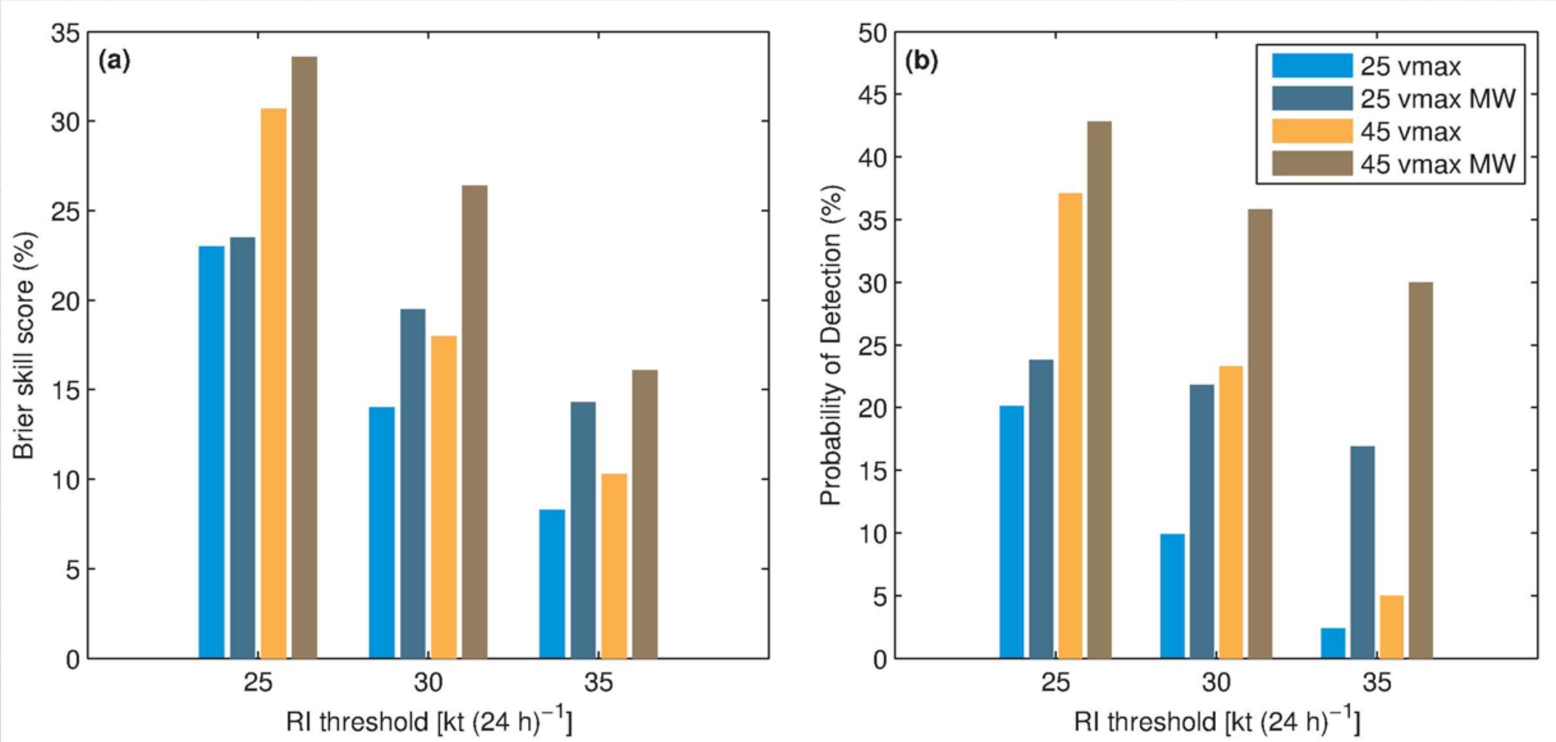
ATL (SSM/I, WINDSAT, AMSR-E, TMI)

- Optimal predictors – tested with the logistic regression model containing environmental/GOES-IR predictors

Feature Description	RI Preference
max eye BT (h pol)	higher
ring fullness parameter	higher
eye fullness parameter	lower
radius of min BT from 0 to 30 km radius (v pol)	smaller
ave BT from 30 to 130 km radius (v pol)	higher
radius of min PCT from 30 – 130 km	smaller
stan. dev. Of PCT from 100 – 300 km	higher
percent area PCT < 275 K	higher

Forecasts (37 GHz) : Satellite Times

ATL - all Sensors (SSM/I, WINDSAT, AMSR-E, TMI)



*N = 2720 for $V_{max} \geq 25$ m s^{-1} and N = 2050 for $V_{max} \geq 45$ m s^{-1}

Forecasts (37 GHz) : Satellite Times

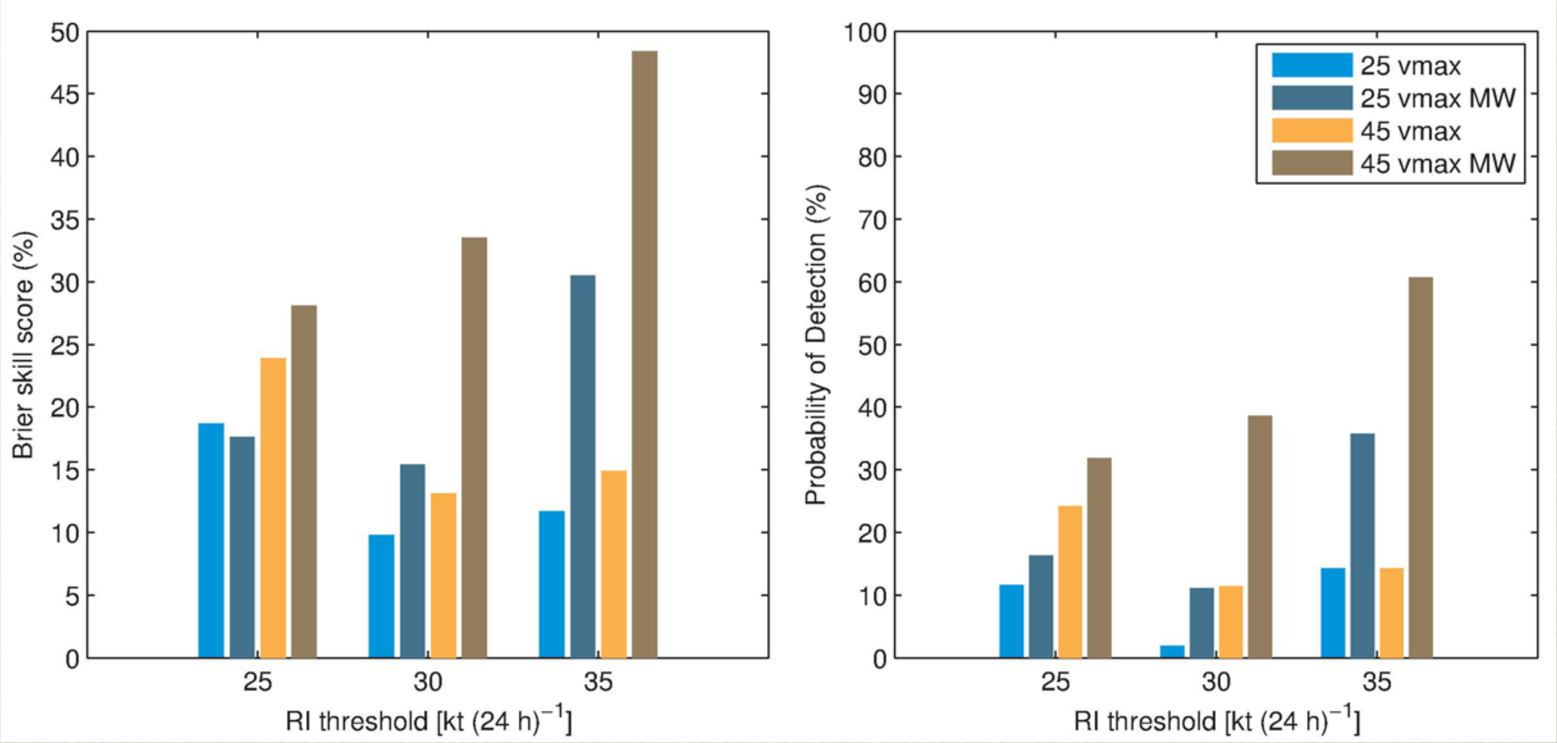
High-resolution Sensors (AMSR-E, TMI)

- Optimal predictors – tested with the logistic regression model containing environmental/GOES-IR predictors

Feature Description	RI preference
max eye BT (h pol)	higher
max ring BT (h pol)	higher
eye BT – ring BT (PCT)	higher
radius of min BT from 0 to 30 km radius (h pol)	smaller
radius of min BT from 30 to 130 km radius (PCT)	smaller
ave. BT (h pol) $r = 0 – 100$ km	higher
percent area r = 50 – 200 km of BT > 275 K (h pol)	lower

Forecasts (37 GHz) : Satellite Times

ATL high-resolution Sensors (AMSR-E, TMI)



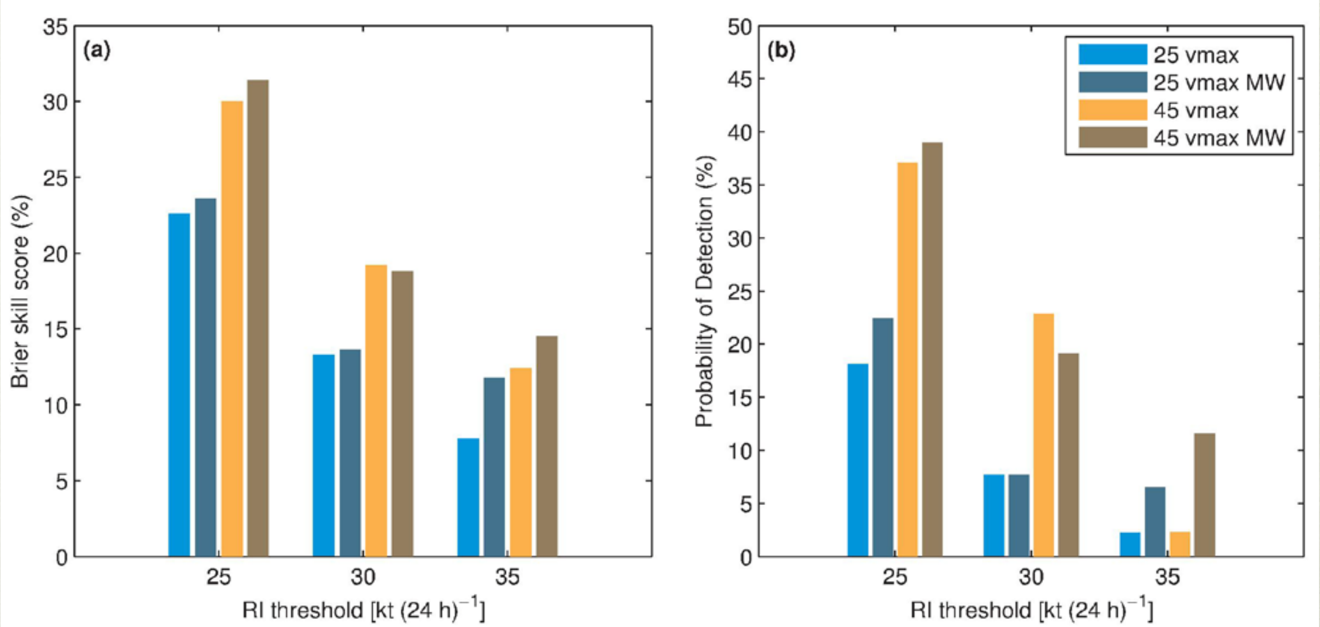
*N = 1155 for $V_{max} \geq 25$ m s^{-1} and N = 873 for $V_{max} \geq 45$ m s^{-1}

Forecasts (85 GHz) : Satellite Times

All Sensors (SSM/I, AMSR-E, TMI)

- Optimal predictors – tested with the logistic regression model containing environmental/GOES-IR predictors

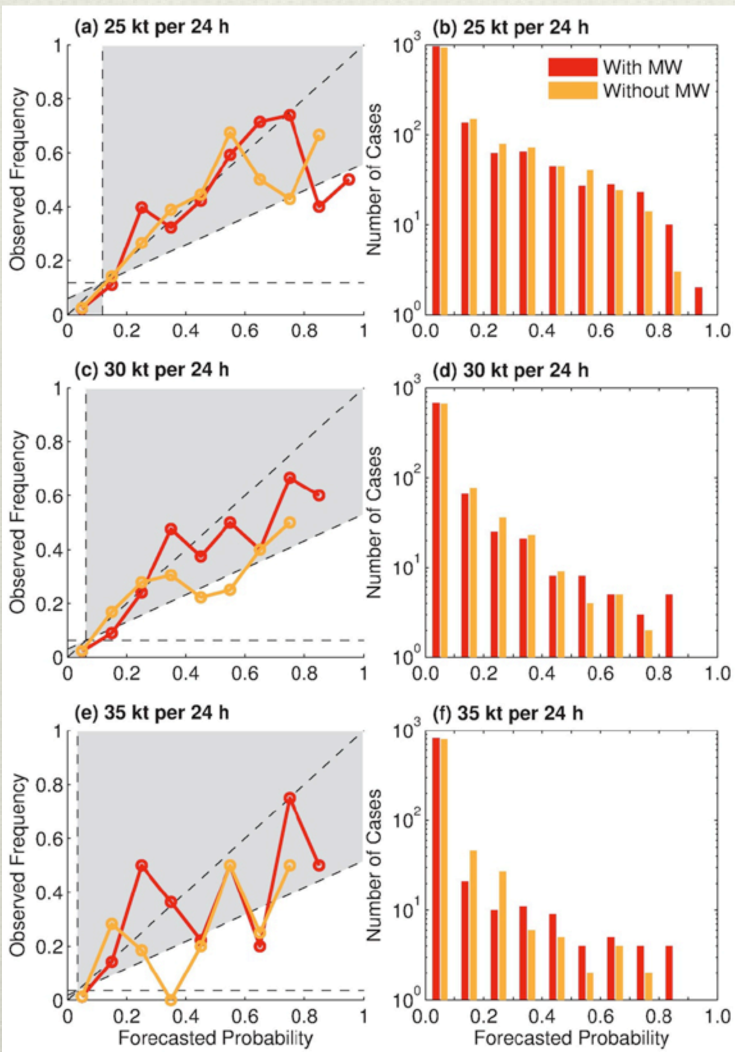
Feature Description	RI Preference
stan. dev. of eye BT (h pol)	lower
Radius of min BT (h pol)	smaller
Stan. dev. Of BT from 100 – 300 km radius (v pol)	lower
% BT (h pol) < 240 K	higher
% BT (v pol) < 240 K	higher
% PCT < 250 K	higher



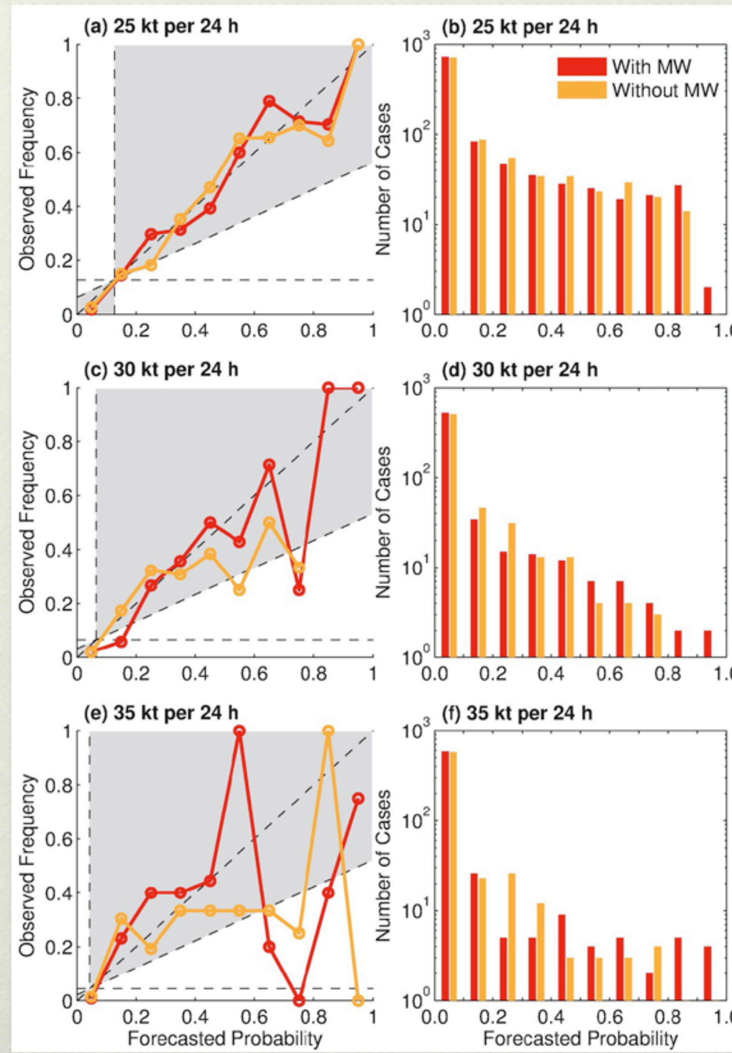
*N = 2743 for $V_{max} \geq 25$ m s^{-1} and N = 2045 for $V_{max} \geq 45$ m s^{-1}

ATL Forecasts (19.4, 37, 85.5 GHz) : Synoptic Times (00, 06, 12, 18 UTC)
Reliability

$V_{max} \geq 25$ m s^{-1}



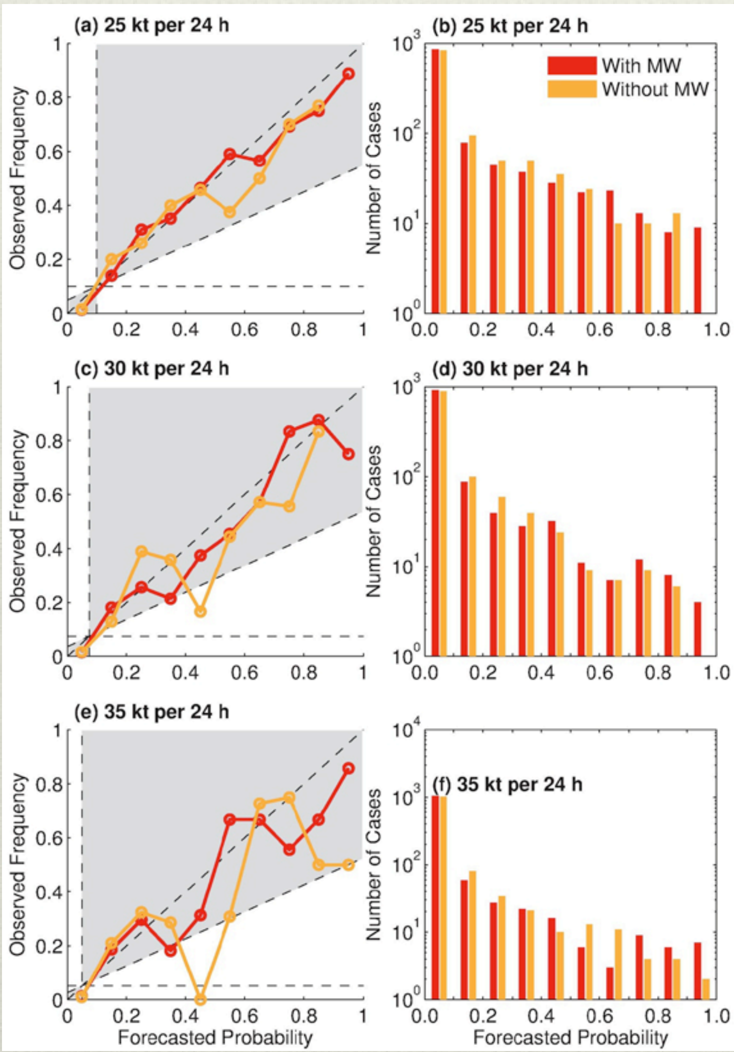
$V_{max} \geq 45$ m s^{-1}



EPAC Forecasts (19.4, 37, 85.5 GHz) : Synoptic Times (00, 06, 12, 18 UTC)

Reliability

$V_{max} \geq 25$ m s^{-1}



$V_{max} \geq 45$ m s^{-1}