Opportunities to Improve Tropical Cyclone Forecasts with JPSS and GOES-R

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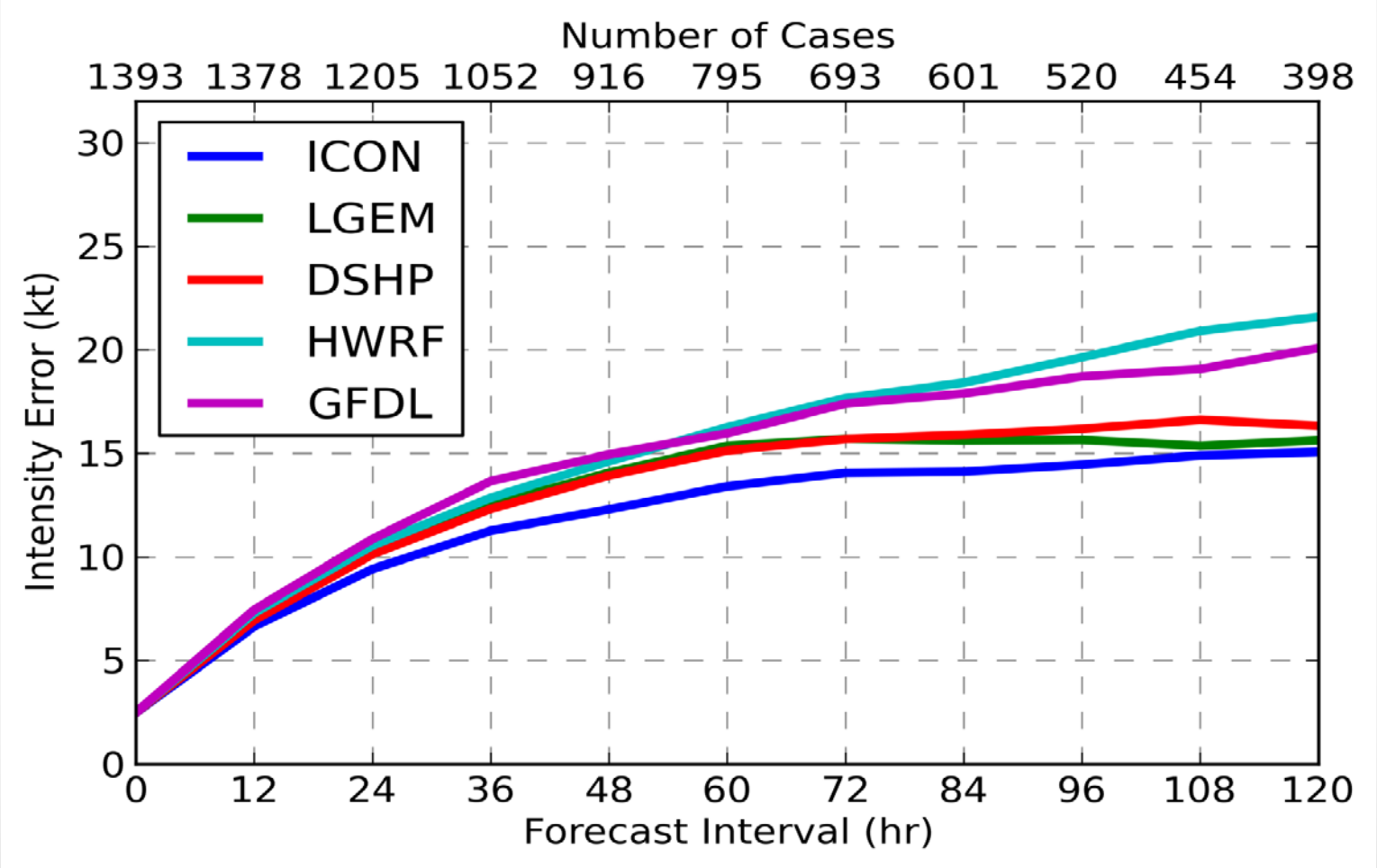
Introduction

- **Tropical Cyclone (TC) Group at CIRA is working on multiple projects using JPSS and GOES data/proxies:**
  1. **Improving TC track and intensity forecasting with JPSS imager and sounder data**:
     - ✓ Use ATMS and CrIS data to improve intensity forecast (SHIPS, LGEM, RII)
     - ✓ Use ATMS and VIIRS data to develop an objective center fixing and eye detection algorithms
  2. **ATMS TC intensity and structure algorithm:**
     - ✓ Is being transitioned to operations
  3. **Cal/Val:** validating ATMS soundings/ TC algorithms
  4. **Lightning** for improving **rapid intensification** and genesis anticipation
  5. **GOES-R and JPSS** to improve **TC structure** diagnosis
  6. **VIIRS Day-Night Band** for TC applications

Focus: Improving Intensity Forecasts

Improving Statistical-Dynamical Models (SHIPS, LGEM, & RII)

2009-2013 Mean Atlantic Intensity Errors



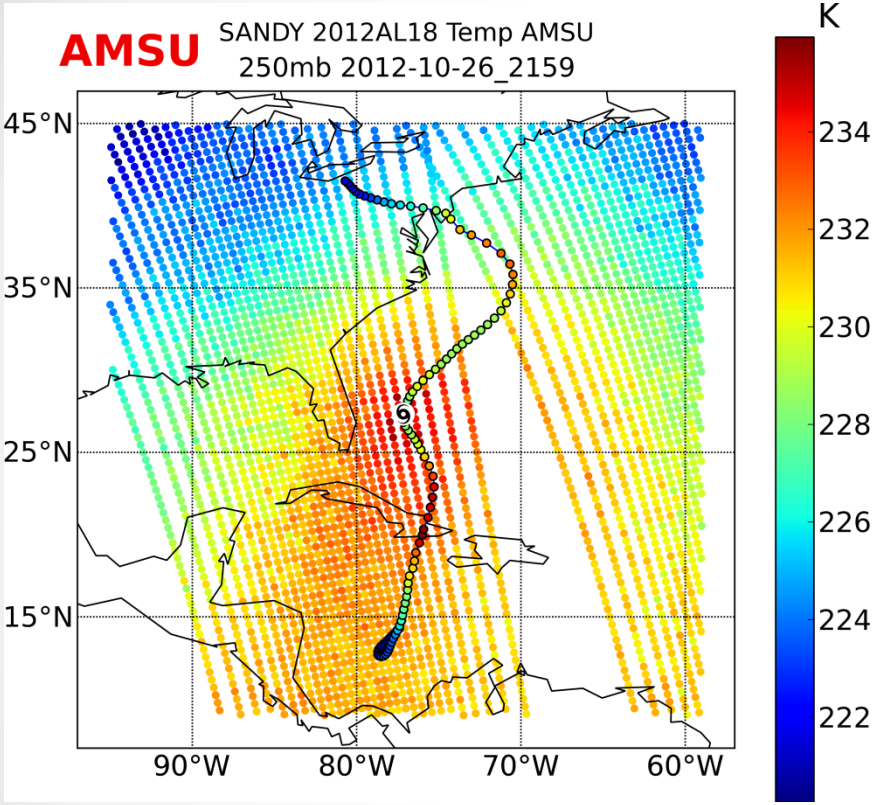
Maximum Potential Intensity (MPI) Estimates

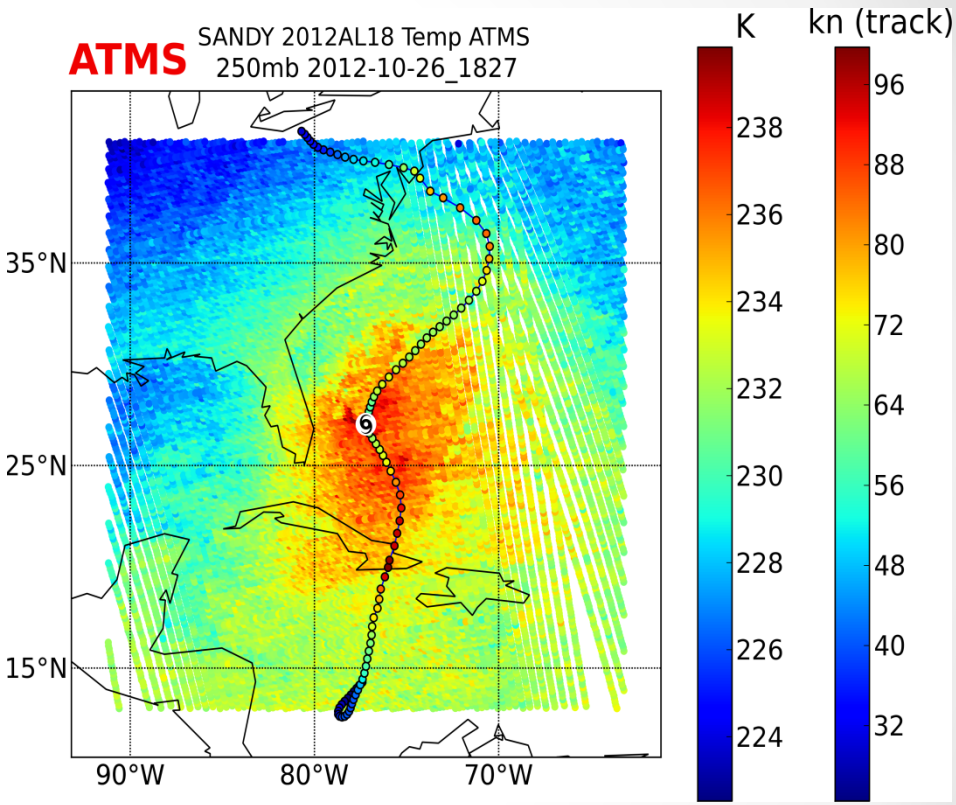
- **A key parameter in the statistical-dynamical models is the Maximum Potential Intensity (MPI)**
- **Currently MPI is empirical**ly calculated from SST only
- Our work **uses ATMS-MIRS T, Q, SLP retrievals** together with SST **to estimate MPI** from ATMS and SST using algorithm by Emanuel (1988), Bister and Emanuel (1998):

$$(MPI)^2 = \frac{T_s - T_o}{T_o} \frac{C_k}{C_D} (k^* - k)$$

  - T_s, T_o, k^*, and k: estimated from SST, sounding
  - C_k/C_D: specified ratio of surface exchange coefficients
- Incorporate **improved MPI estimates** into :
  1) Statistical Hurricane Intensity Prediction Scheme (**SHIPS**) Model
  2) Rapid Intensification Index (**RII**)
  3) Logistic Growth Equation Model (**LGEM**)

Resolution: ATMS vs. AMSU

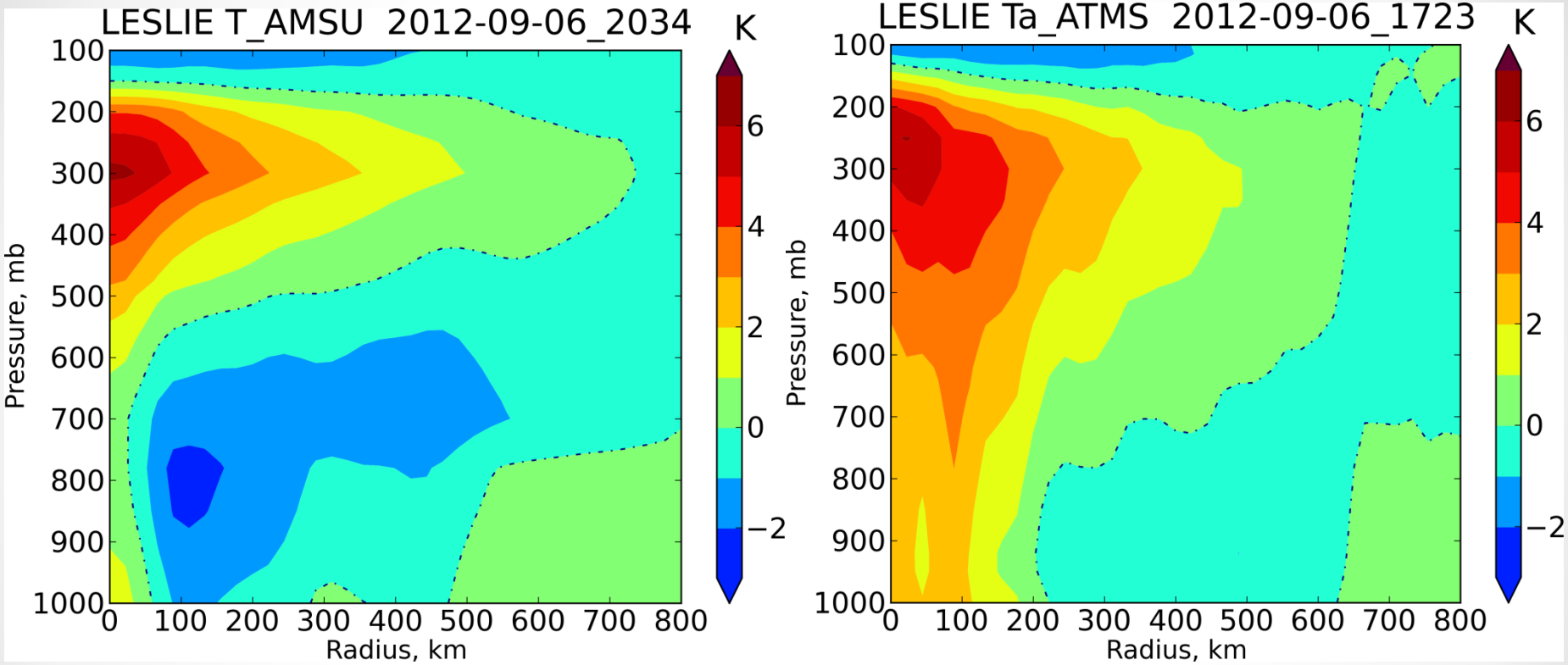




ATMS:

- Higher resolution
- Wider swath
- Smaller gaps between passes

Temperature Profile: ATMS vs AMSU

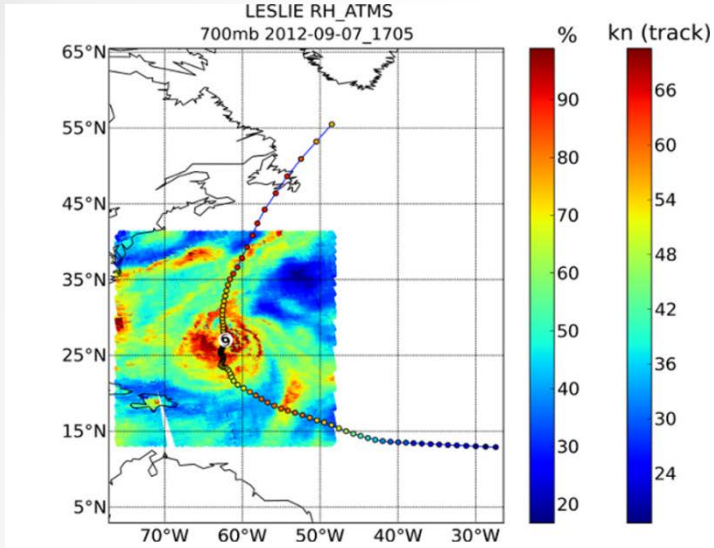


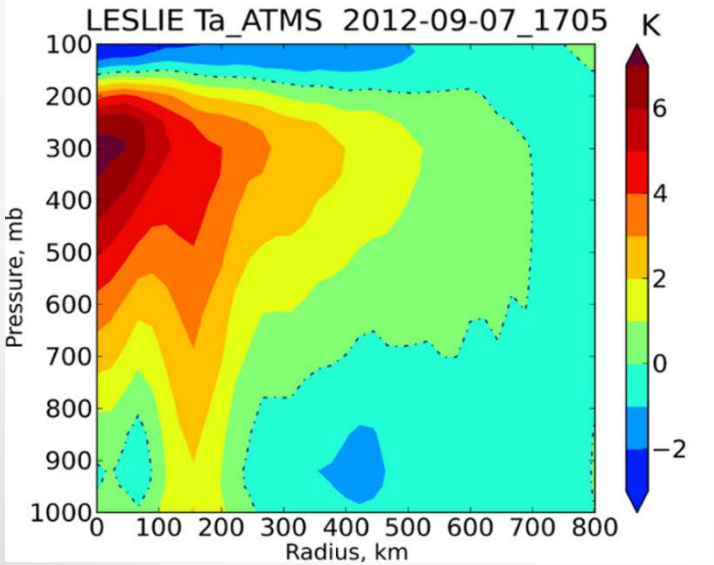
MIRS Retrievals

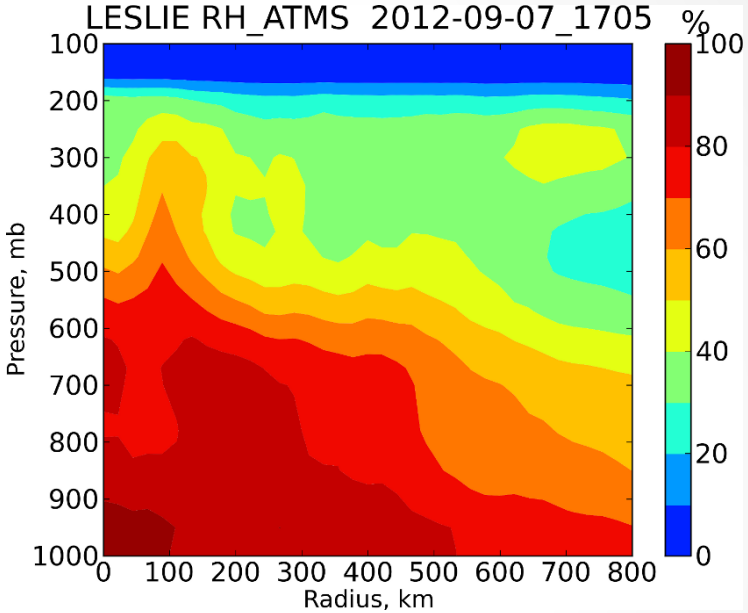
ATMS:

- Better resolves warm core
- No additional T corrections needed at low levels

Temperature and RH profiles: Leslie

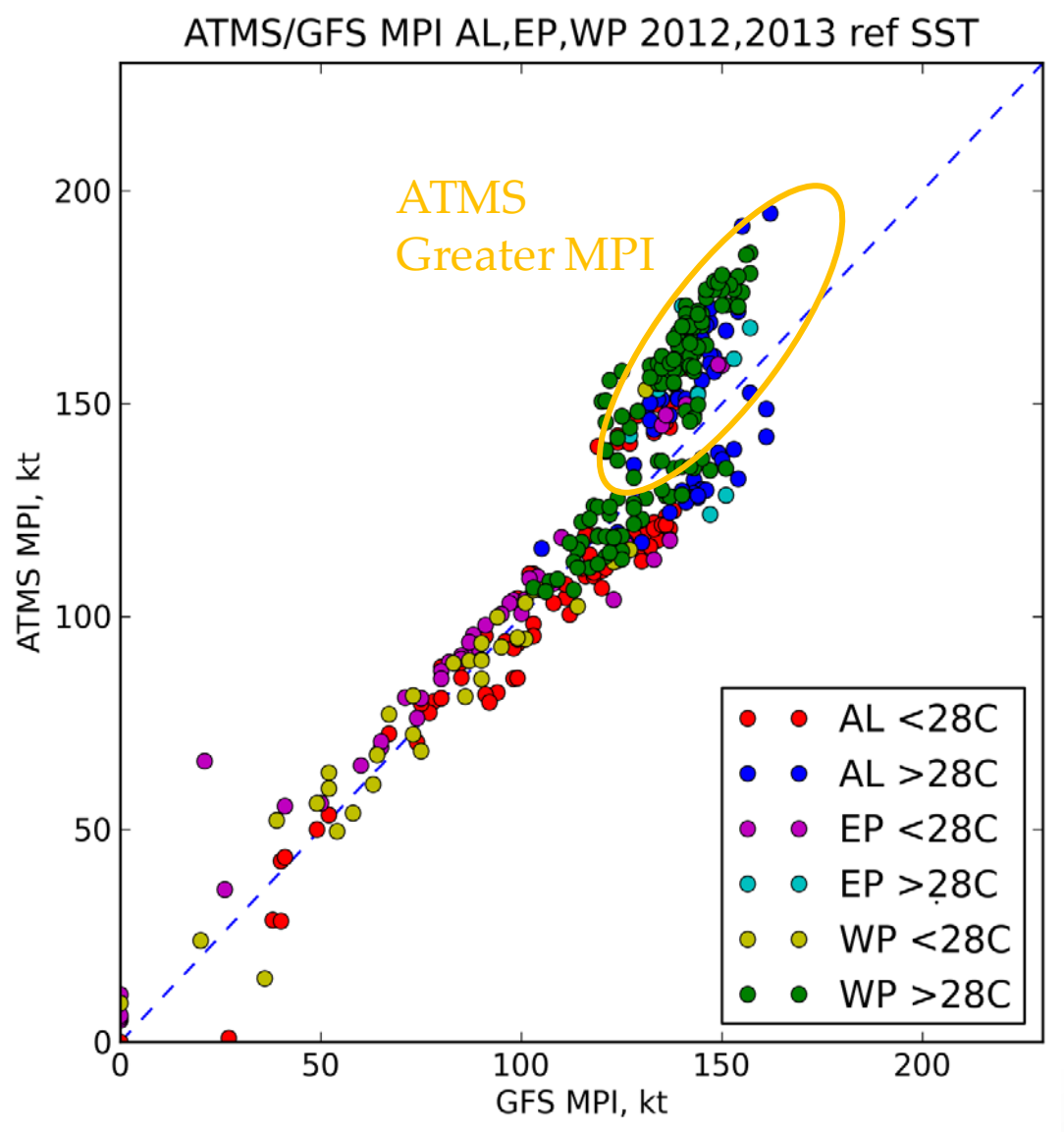






1. Average T, RH between r = 200 to 800 km to get $\overline{T}(p), \overline{RH}(p)$
2. Input $\overline{T}(p), \overline{RH}(p)$ environmental profiles to Emanuel (1988) MPI algorithm
3. Replace empirical MPI with ATMS MPI in RII and models
4. A similar procedure is done with GFS-based soundings to serve as a baseline

MPI Findings: ATMS vs. GFS profile



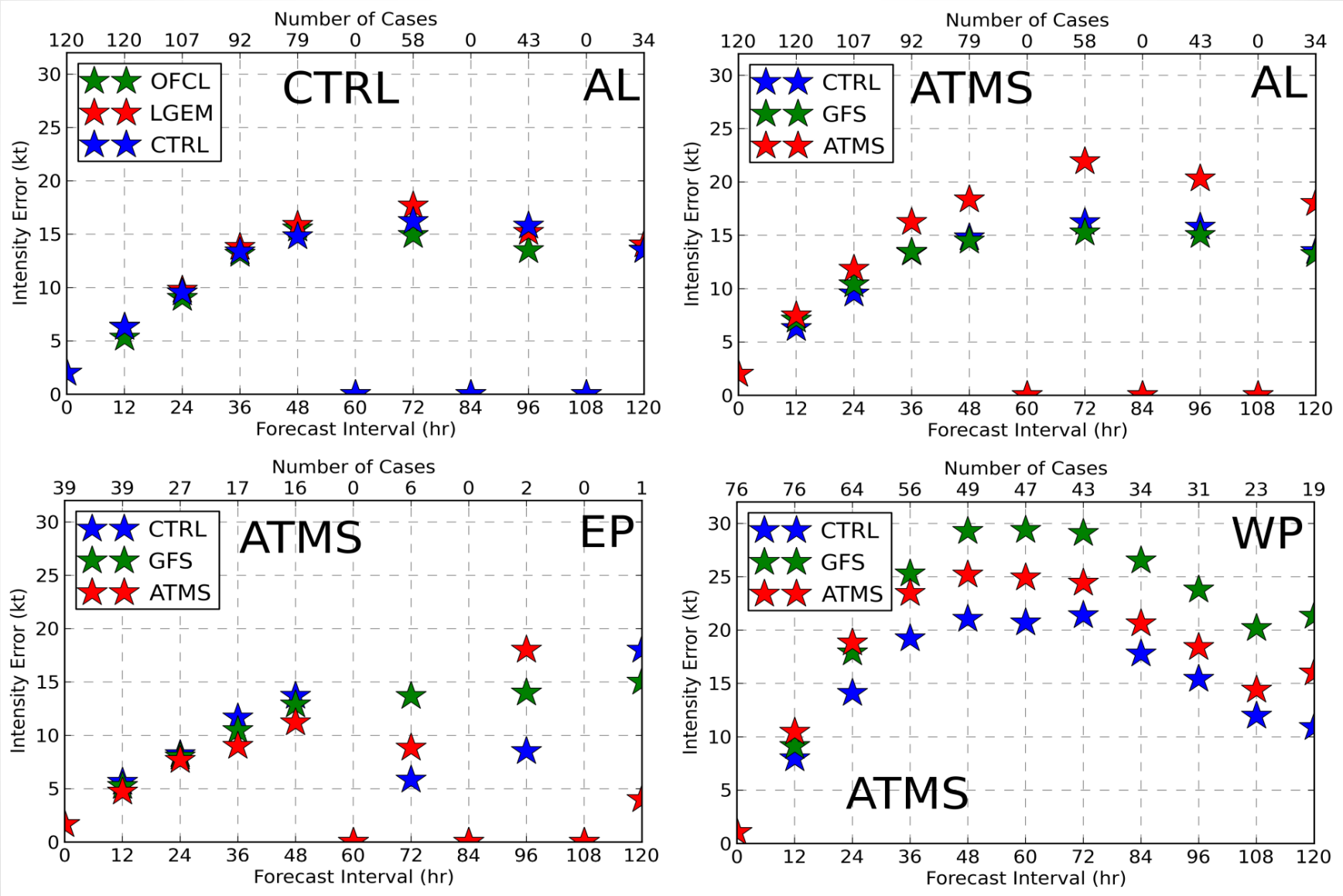
- T,q profiles calculated by azimuthally averaging T,q at 200 800km
- All other parameters same as operational, including weekly Reynolds SST
- In some cases using ATMS data significantly changes MPI values

RII Statistics: GFS vs ATMS

Basin		BS GFS	BS ATMS	BS Mean	BSS A/G	BSS G/M	BSS A/M	Bias GFS	Bias ATMS	# Cases	#RII
AL	25kt	964.55	957.98	854.27	0.68	-12.91	-12.14	1.63	1.44	130	13
	30kt	723.53	718.46	667.83	0.70	-8.34	-7.58	1.30	1.15	130	10
	35kt	477.11	467.65	413.10	1.98	-15.49	-13.20	1.26	1.00	130	6
	40kt	248.40	243.55	211.88	1.95	-17.24	-14.95	1.63	1.37	130	3
WP	30kt	1044.39	996.30	1586.00	4.60	34.15	37.18	0.56	0.61	176	31

1) Statistics is preliminary: based on very small number of cases
2) **AL: Improved with ATMS**
   - Brier Score: ATMS < GFS
   - Brier Skill Score: ATMS/GFS > 0
   - Bias: ATMS better than GFS
3) **EP:** only 1 (one) RI cases available, unable to calculate statistics
4) **WP: Improved with ATMS**
   - Brier Score: ATMS < GFS
   - Brier Skill Score: ATMS/GFS > 0
   - Bias: ATMS better than GFS

LGEM Intensity Verification



Summary and Future Plans

Improving RII, LGEM and SHIPS forecasts

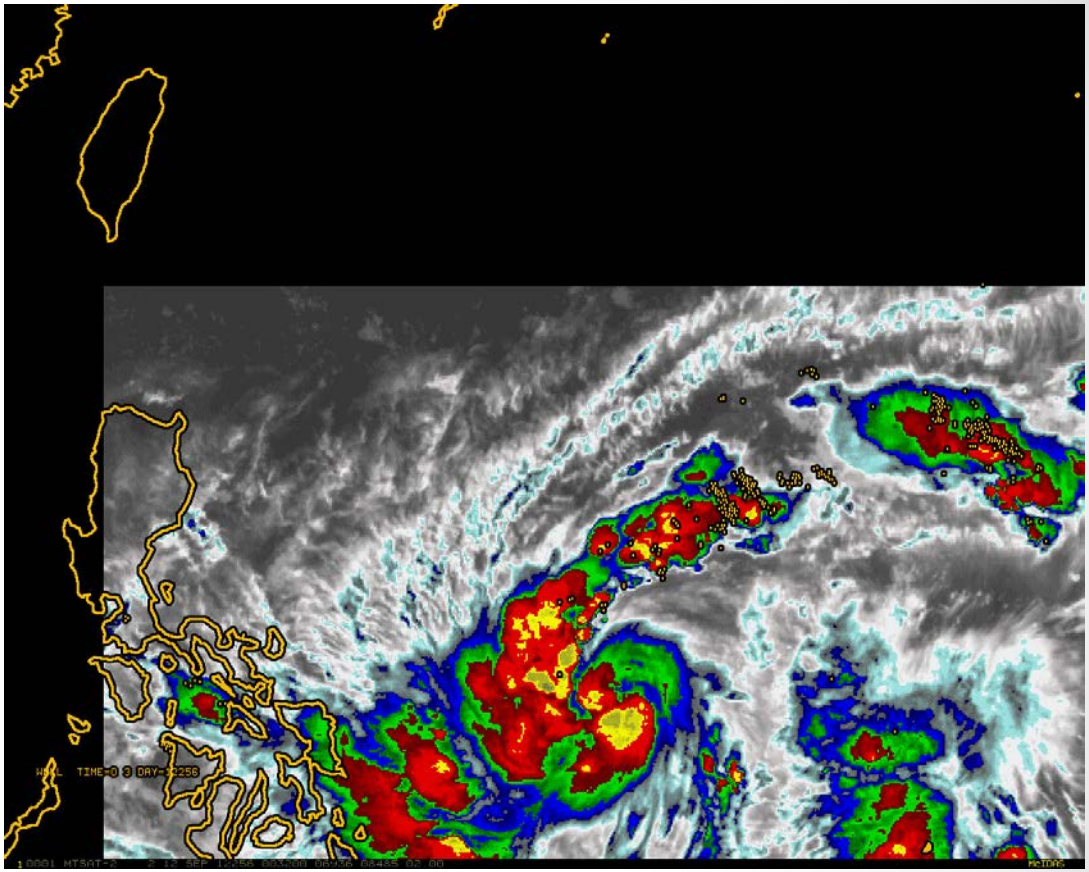
- ATMS data provide more realistic TC structures than AMSU
- Rapid Intensification forecasts (RII) are slightly improved AL,EP,WP
- LGEM, SHIPS Intensity forecast: AL - worse; WP,EP - better in some cases

Future Plans

- **Obtain more ATMS cases** for further testing and reliable statistics
- Compare ATMS data to dropsondes in AL, apply bias correction if needed **(i.e., CAL/VAL)**
- **Combine GFS and ATMS data** to obtain most realistic environmental soundings

Focus: Lightning and Rapid Intensification

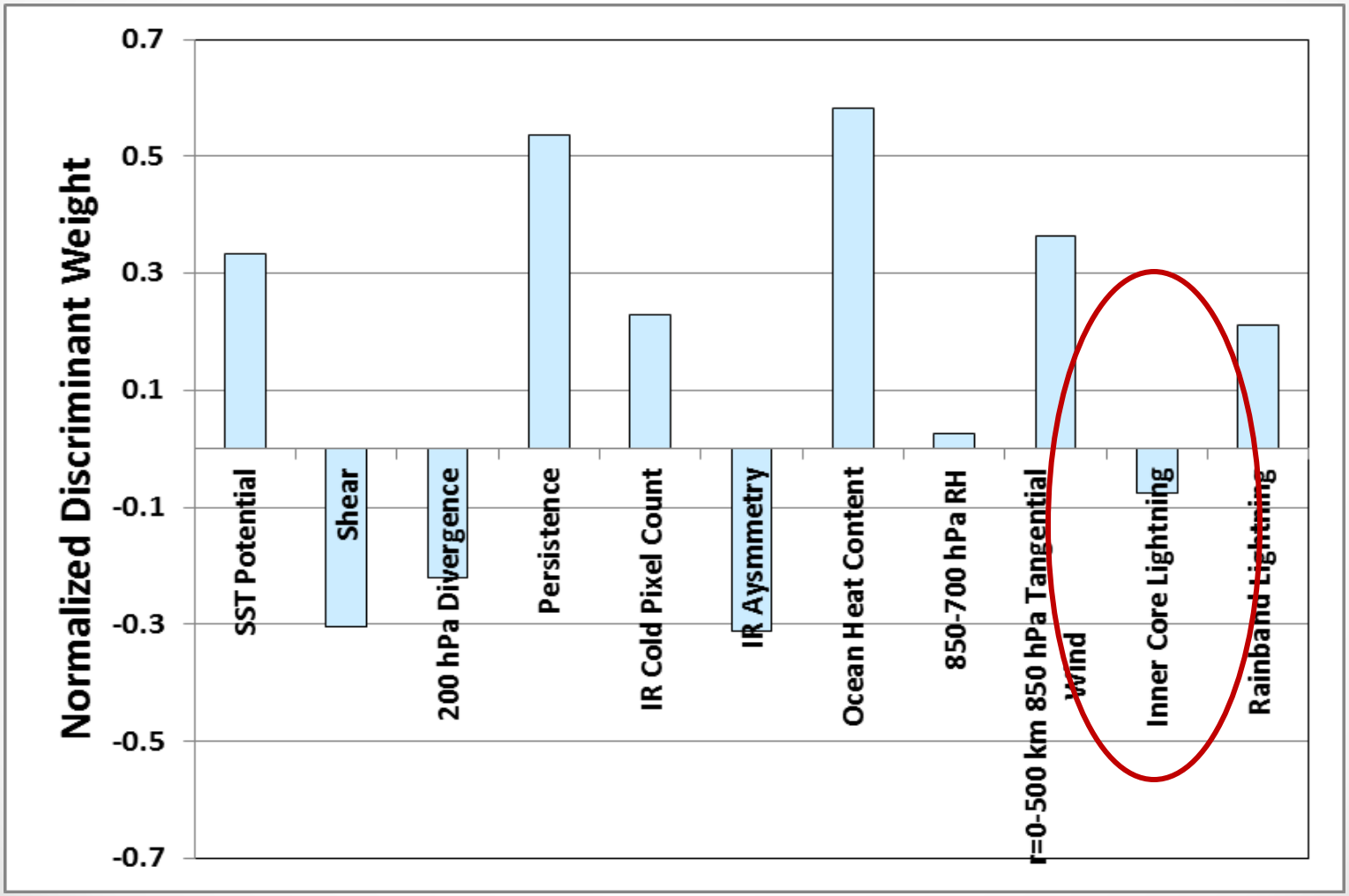
- Lightning and Rapid Intensification analyzed for Atlantic and east Pacific TCs
- Ground-based WWLLN data utilized
- RI is favored when lightning is in rain band region (200-400 km)
- Inner core lightning signals end of RI period
- West Pacific data analysis shows similar results



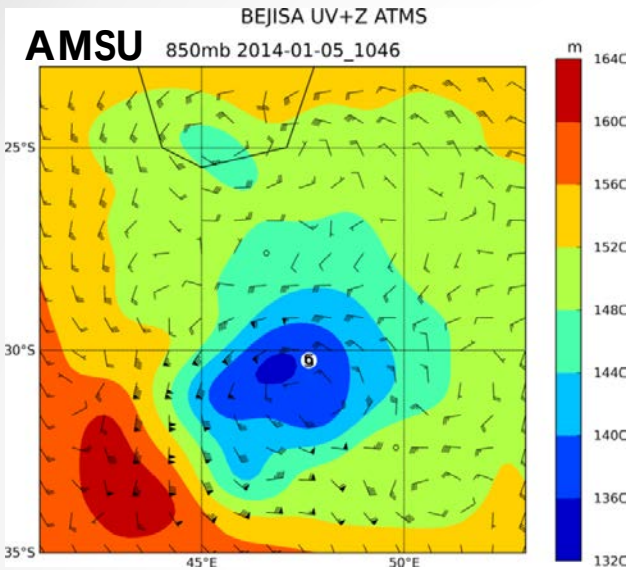
IR Image and WWLLN Lightning Locations Typhoon Sanba 2012 (wp172012)

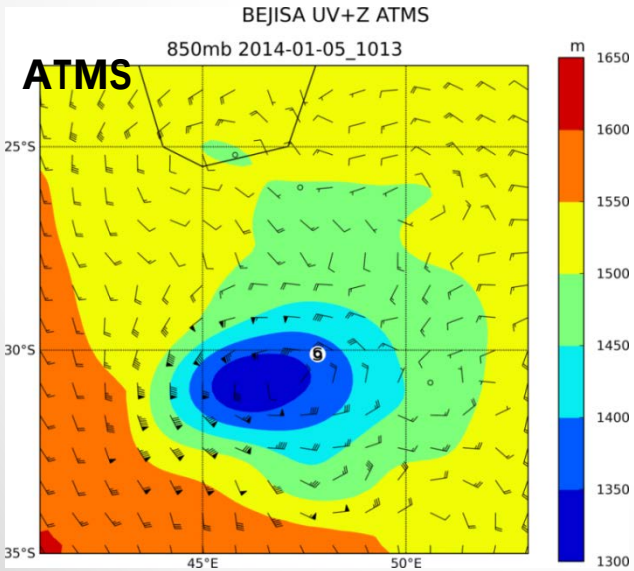
Normalized Predictor Weights West Pacific RII

2005-2012 Sample



Focus: MIRS ATMS-based Tropical Cyclone Intensity and Structure Estimates





- AMSU-based intensity and structure estimates (Legacy Product)
  - Statistical algorithm (MLR) uses storm-environment predictors
  - Predicts MSW, MSLP, azimuthal average R34, R50, and R64
  - Operational at NCEP since 2006 (Demuth et al. 2004; 2006)

- Adapted AMSU-based product to use S-NPP MIRS ATMS data
  - **Ensures continuity** of guidance (AMSU has limited lifetime)
  - Enhanced resolution and coverage expected to improve accuracy of product estimates
  - **Uses** Microwave Integrated Retrieval System (**MIRS**) temperature retrievals

Summary and Future Plans

ATMS Intensity and Structure

- The method has met most of the operational requirements

ATMS-based Estimate	N	MAE	Project Goal
Vmax	225	12.9 kt	13.5 kt
Min P	225	8.9 hPa	9 hPa
R34	170	41 nmi	32 nmi
R50	109	19 nmi	18 nmi
R64	67	16 nmi	10 nmi

Future Plans

- Transition method to operations (August 2014) and make text estimates (i.e., fixes) available via ATCF at JTWC, NHC, CPHC
- Continue verification efforts as more data come available
- Conduct more extensive calibration and validation of the algorithm
- Update the algorithm

Focus: Automated eye-detection/center-fixing

Motivation:

- **Center fixing/finding is the first, yet time consuming, step in the forecast process**
- **Accurate center estimate impacts all downstream forecasts**
- Nearly all existing center fixing methods are subjective
  - Exception: CIMSS ARCHER method that fits spiral patterns to microwave imagery
- Aircraft and RADAR fixes are infrequent
- There are many geostationary images to provide center fixes
- Automatic method for estimating TC location is highly desirable

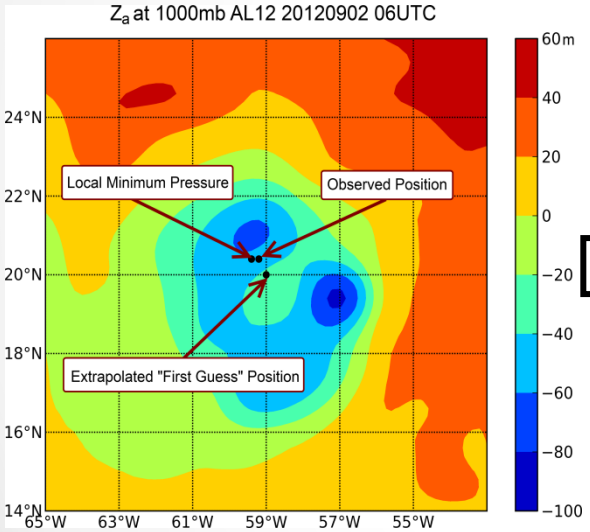
Method: Combine MW, Visible, and IR data to develop objective center-fix and eye-detection algorithms:

- **Use Quadratic Discriminant Analysis (QDA)** to obtain center-location from MW images (ATMS, AMSU), refine center location using hi-resolution visible imagery (VIIRS)
- **Use Circular Hough Transform (CHT)** (computer vision technique) for automatic center-fixing and eye detection
- **Use Principal Component Analysis (PCA) and machine learning** to develop automated eye-detection algorithm using IR images

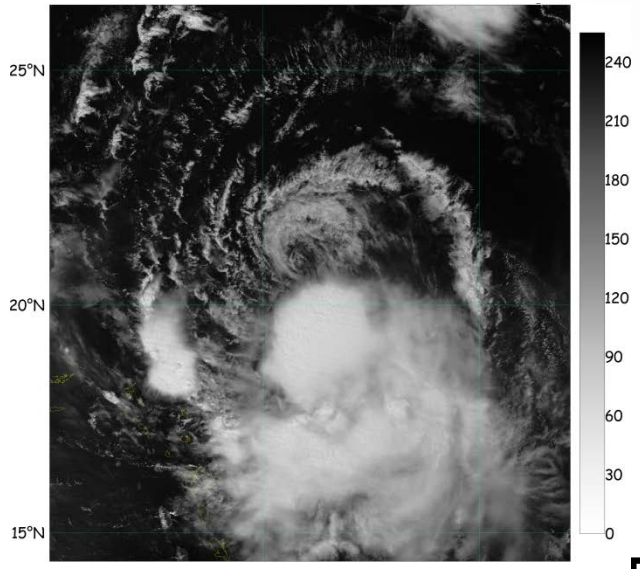
MW data: Center Fix Algorithm using QDA

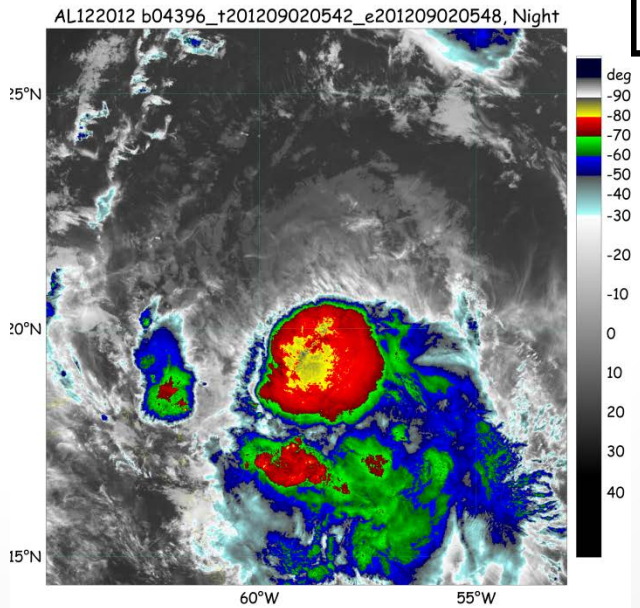
COMPLETED

- First guess from extrapolation of operational info
- Analysis of MIRS soundings



- Extract features (pressure gradients, etc.)
- Refine the fix with QDA





FUTURE

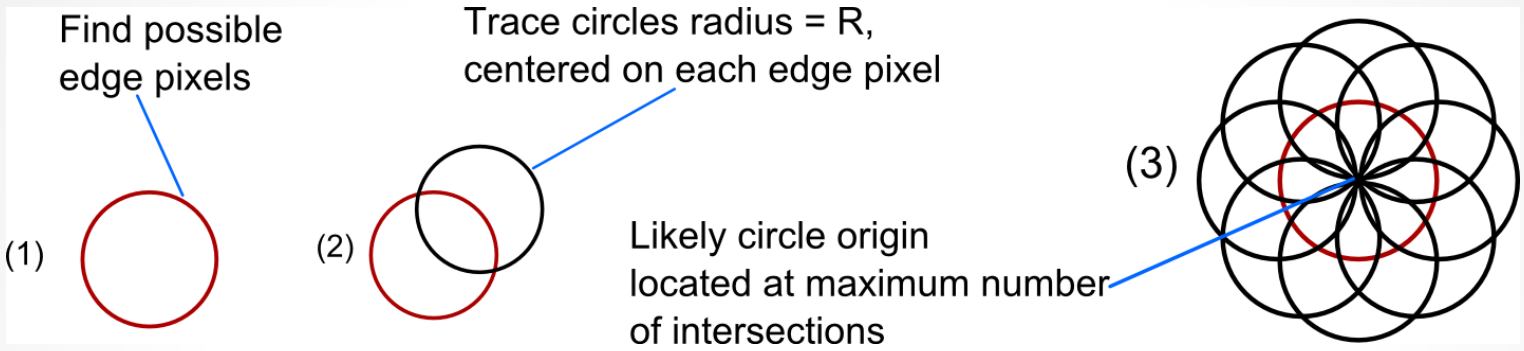
- Refine fixes with high-res Vis/DNB and IR information (e.g., CHT)

Machine Learning Algorithm to give final lat/lon of low-level circulation center

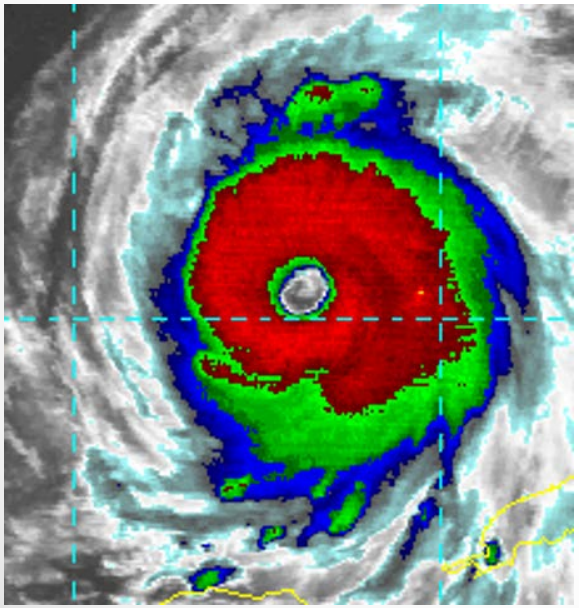
Example from Hurricane Leslie Sept 02,2012 06UTC

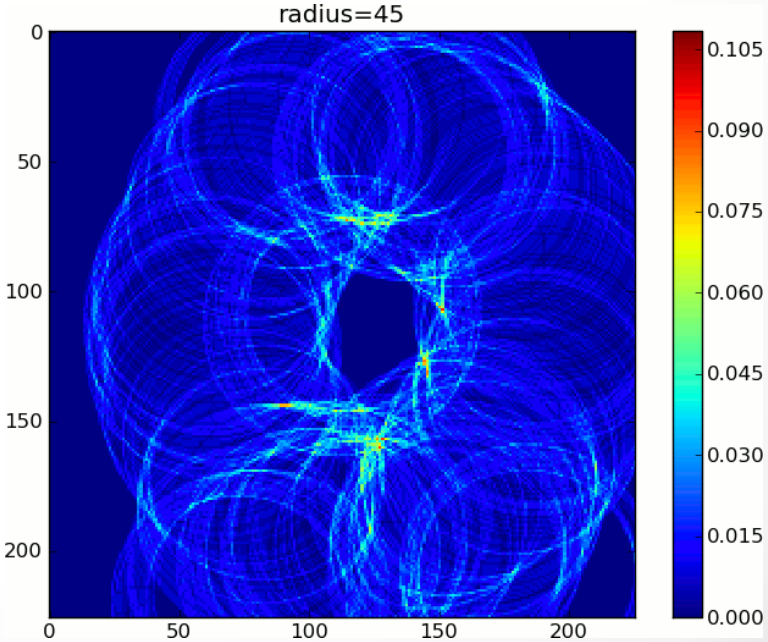
Circular Hough Transform (CHT)

Visual Example: Katrina



- If R is not known, perform CHT for range of R. Select R, origin from max number of intersections (accumulation matricies)





Eye or No Eye

Image without an eye

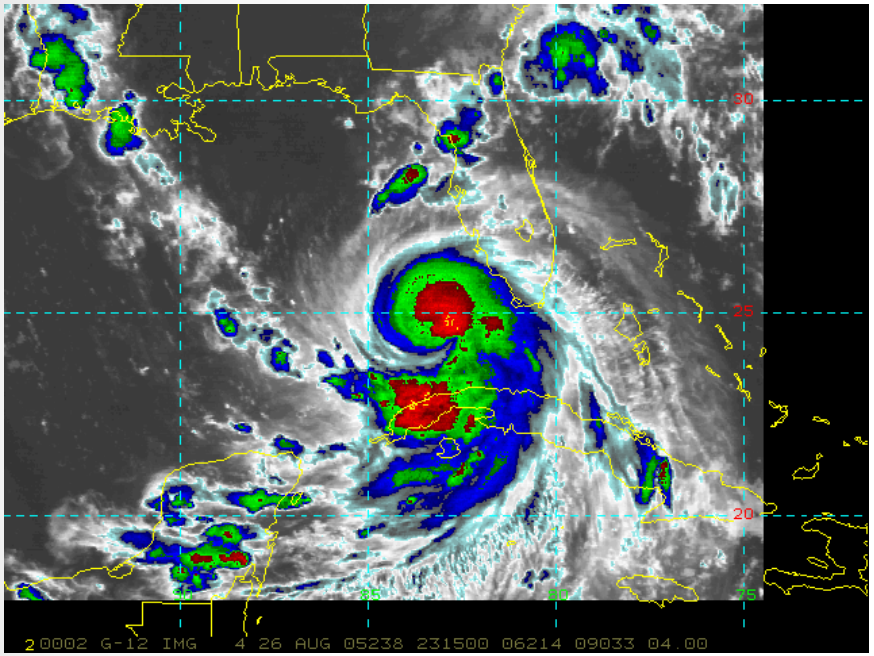
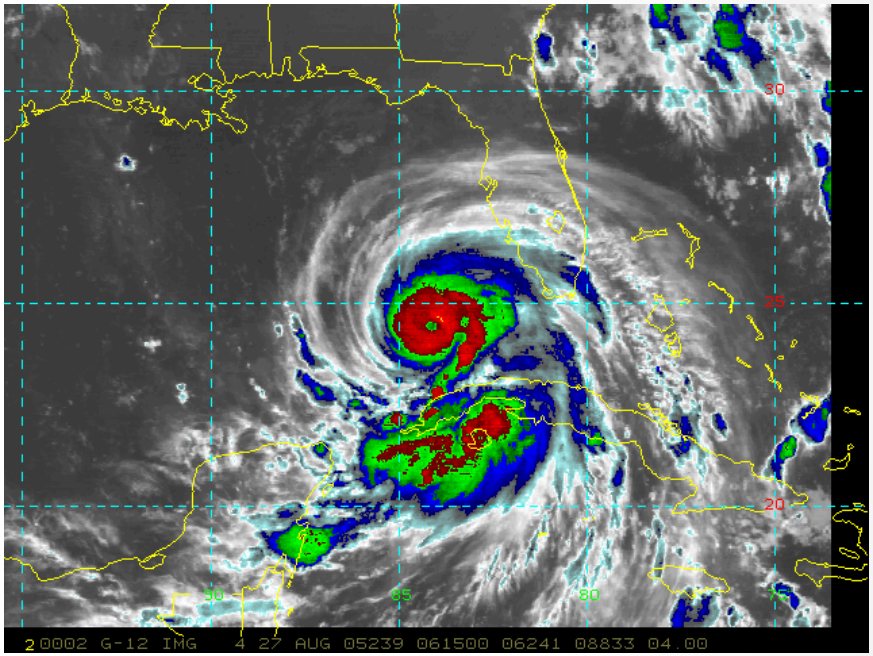


Image with an eye



- Subjective eye classification (from historical Dvorak fixes) data set six-hourly 1989-2013. (DONE!)
- Train machine-learning algorithm for automated eye-detection
- Create an objective eye dataset for all images.
- Use eye vs. no-eye information to develop eye formation forecasting (GOES R), eye climatology etc…

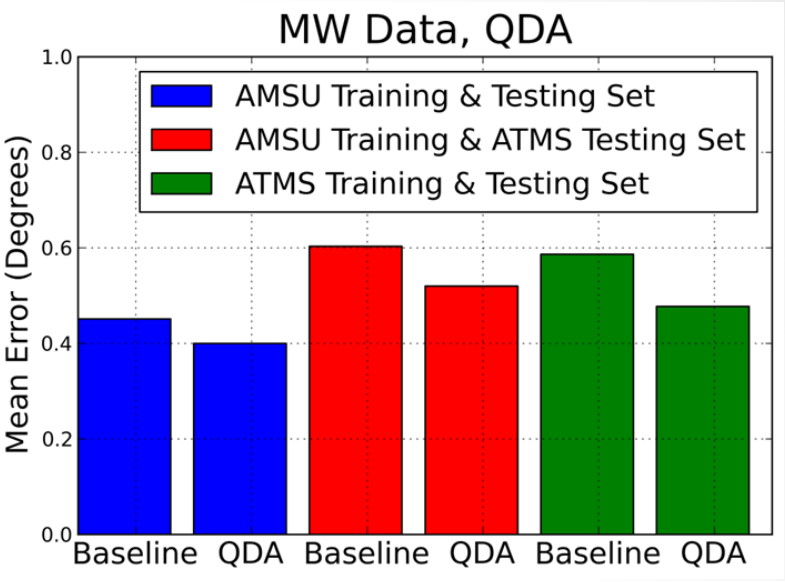
Summary and Future Plans

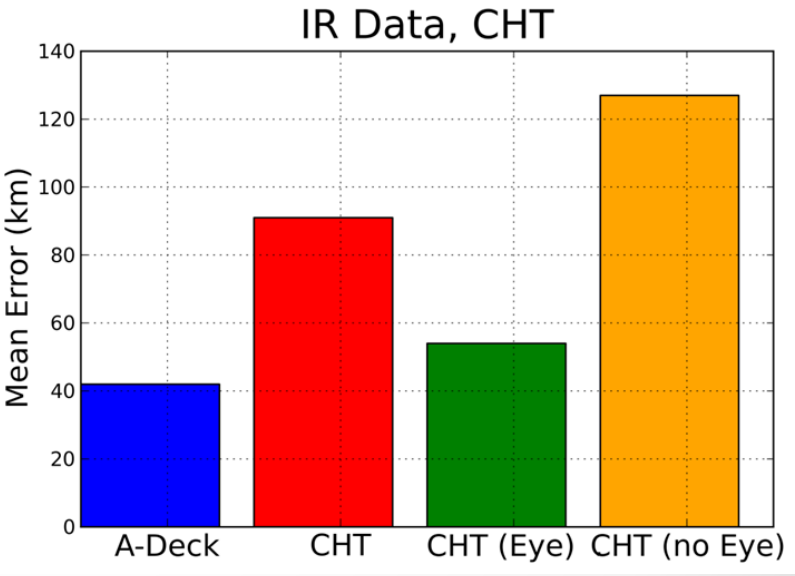
Center Fix/Eye detection – QDA, CHT, PCA

- Quadratic Discriminant Analysis:
  - up to 19 % improvement in center location from MW
- Circular Hough Transform:
  - Good for storms with eye, poor for sheared storms
  - Accumulation matrices may be useful for eye detection
- A subjective eye/no-eye data set has been created and is being used to train eye detection algorithms (PCA Machine Learning)

Future Plans

- Use CHT from IR data as 1st guess for visible algorithm
- Combine CHT with other information (shear vector, MW, DNB)
- Apply PCA machine-learning to database of IR images for objective eye detection
- Use objective eye detection for eye formation algorithms (GOES – R3 project)



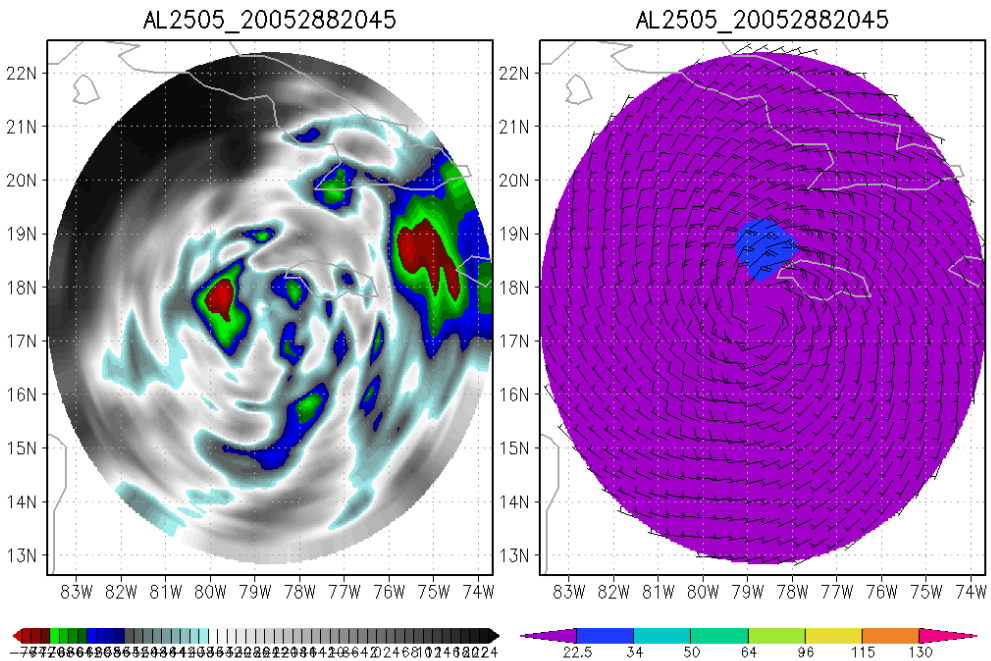


Focus: Inferring TC structure from IR Imagery

- GOES-R work led to the development of a method to estimate aircraft-based TC wind fields based on
  - Current Intensity
  - Current motion
  - One IR image

- The algorithm uses a **single field principle component analysis methodology** that relates principle components to wind fields (aircraft)

- This algorithm will likely **transition to operations via the multi-platform TC wind analysis (MTCSWA, Knaff et al. 2011)**



Three-hourly loop of IR images (left) and estimates of surface winds (right) for Hurricane Wilma (2005). Surface winds are estimated using the current intensity, current motion, and a single IR image. More information can be found in Knaff et al. (2014, J. Appl. Meteor. Climatol., conditionally accepted).

MTCSWA : http://www.ssd.noaa.gov/PS/TROP/mtcswa.html

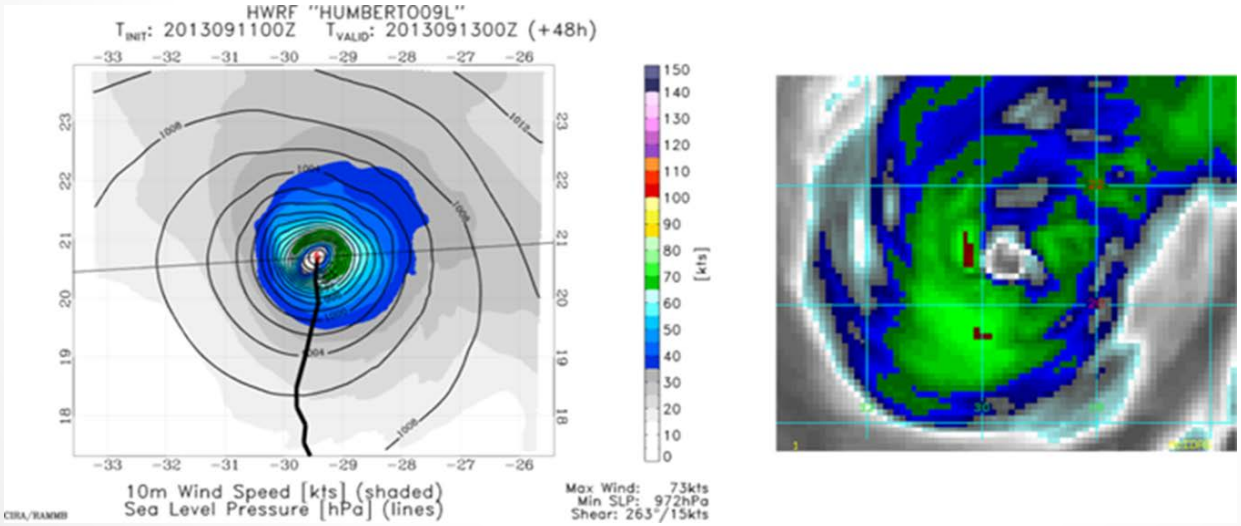
Summary and Future Plans

Inferring TC structure from IR Imagery

- This method is able to estimate the azimuthal wavenumber 0 and 1 components of the wind field and significantly improves on methods currently used in operations

Future Plans

- Use this method with HWRF model output where the wind field is better known (GOES-R3)



HWRF surface wind field (left) and matching synthetic IR imagery (11 μm) for Hurricane Humberto (2013). Both fields are from the 48h forecast initialized 11 Sept 00UTC and valid at 13 Sept. 00UTC.

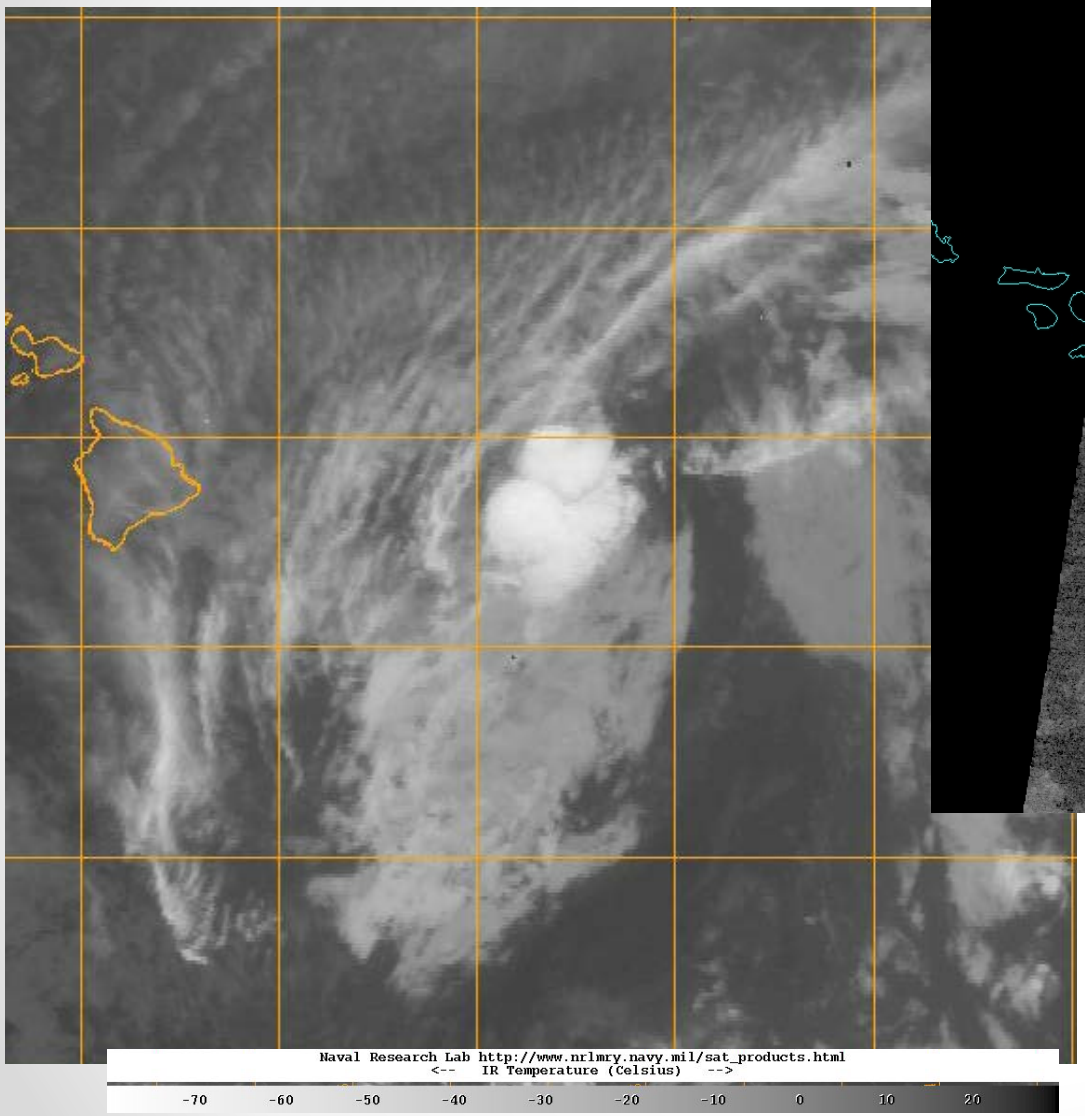
Summary

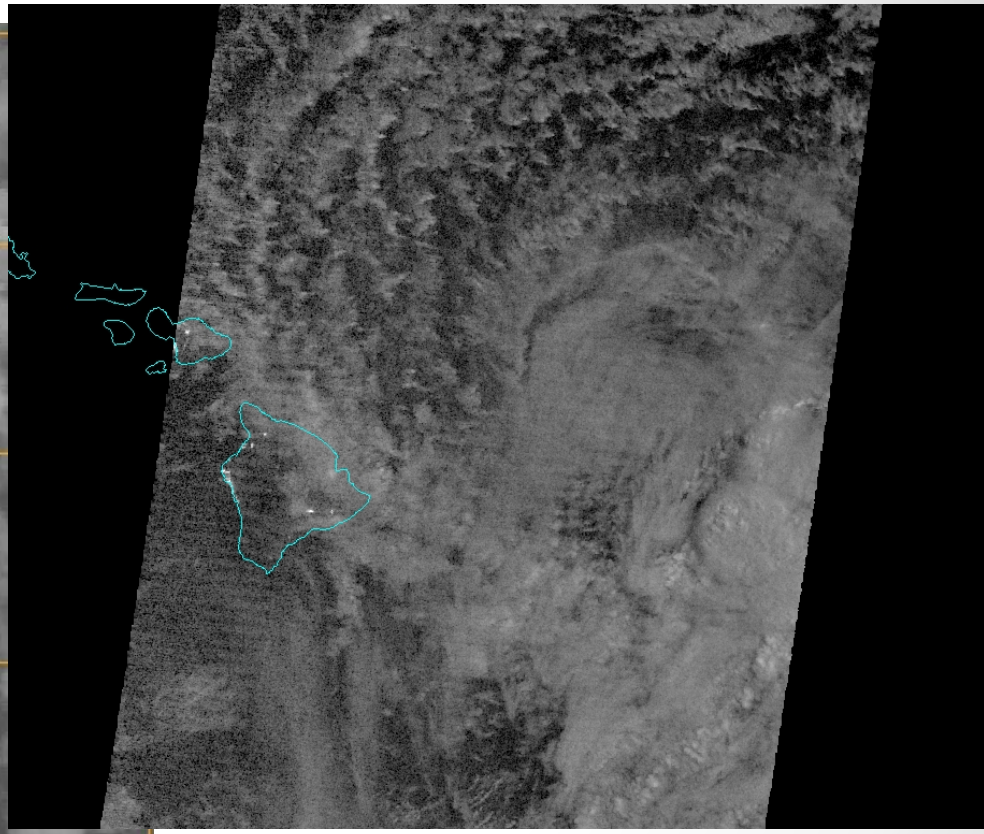
- JPSS and GOES-R data are being used in a variety of ways to improve TC forecasting and diagnosis
- Use of **ATMS** data that have much better resolution compared to AMSU was shown to **improve TC structure estimates, intensity forecast, and TC center estimation**
- Use of **VIIRS** data, especially **DNB** images, provides **additional information, not available from other sources**, which could be used to improve TC forecasts
- **Lightning information is uniquely related to physical processes** and not available from other sources.
- There are **many opportunities to use advanced statistical and machine learning methods to help TC forecasters** (e.g. eye detection and formation, relating satellite information to TC structure and intensity)

Five DNB TC Cases

food for discussion

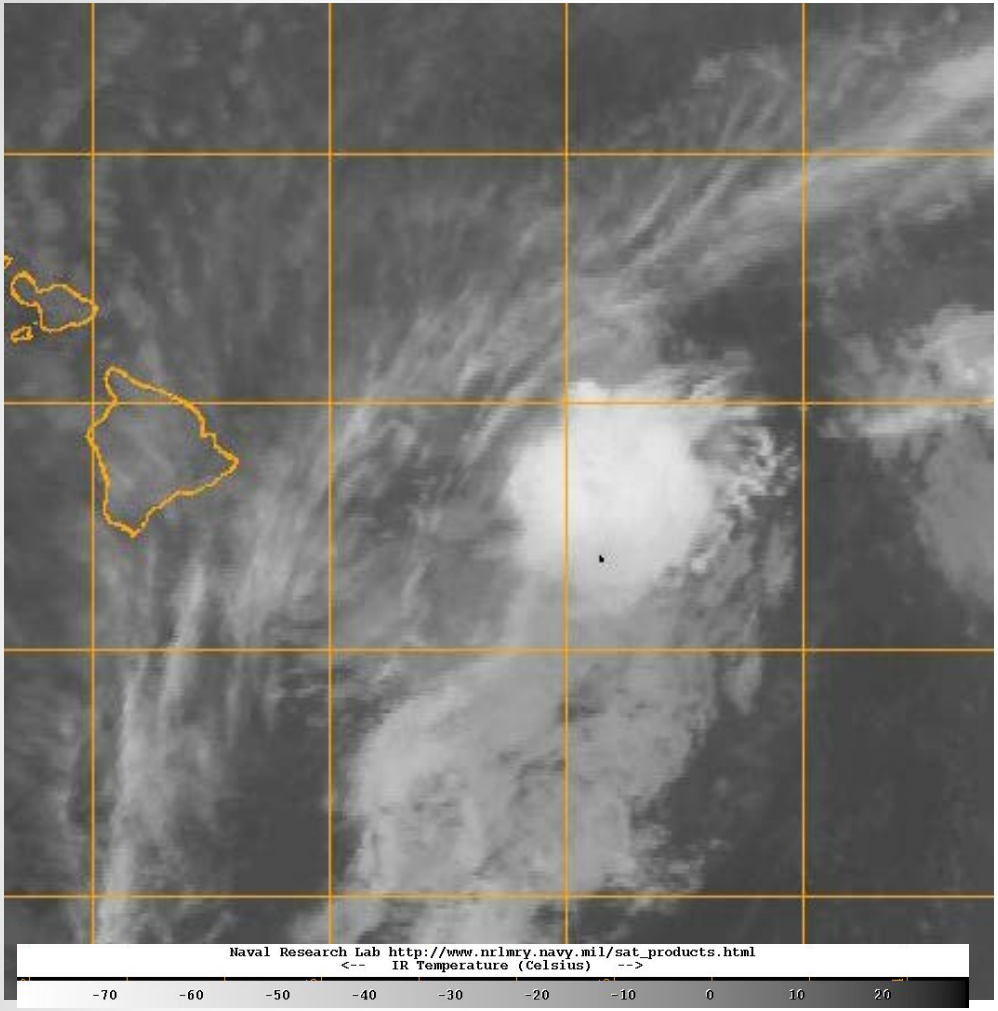
GOES-15 IR & VIIRS DNB image ~1100Z

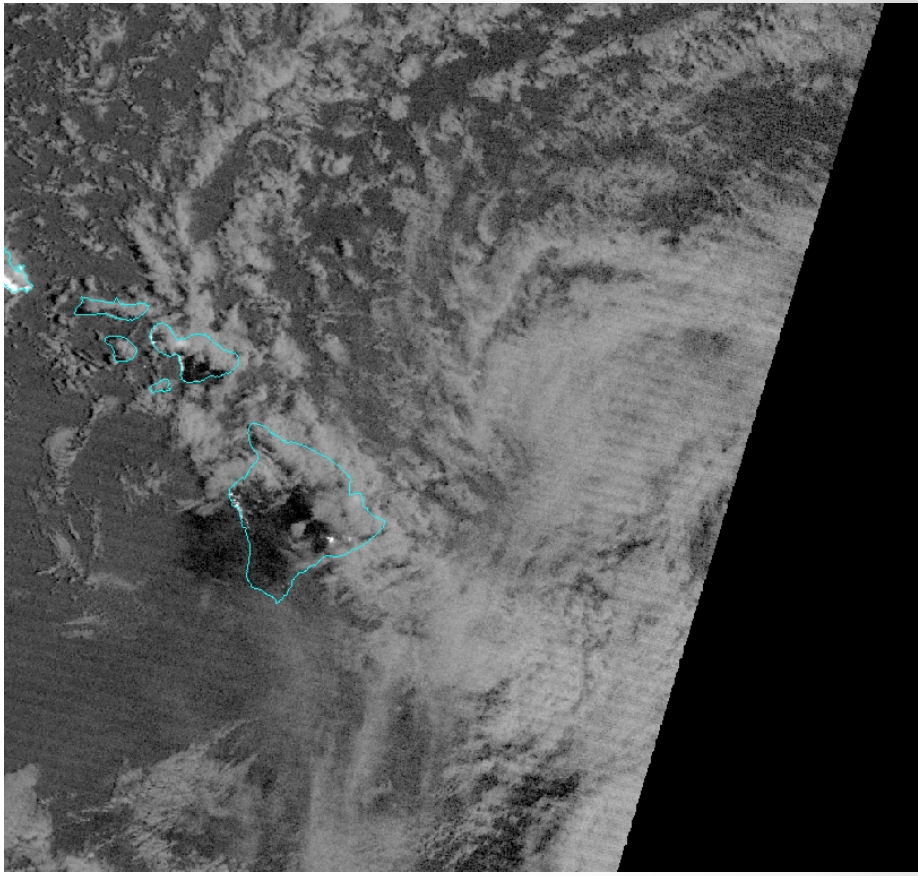




From R. Ballard , 2014

GOES-15 IR & VIIRS DNB around 1245Z

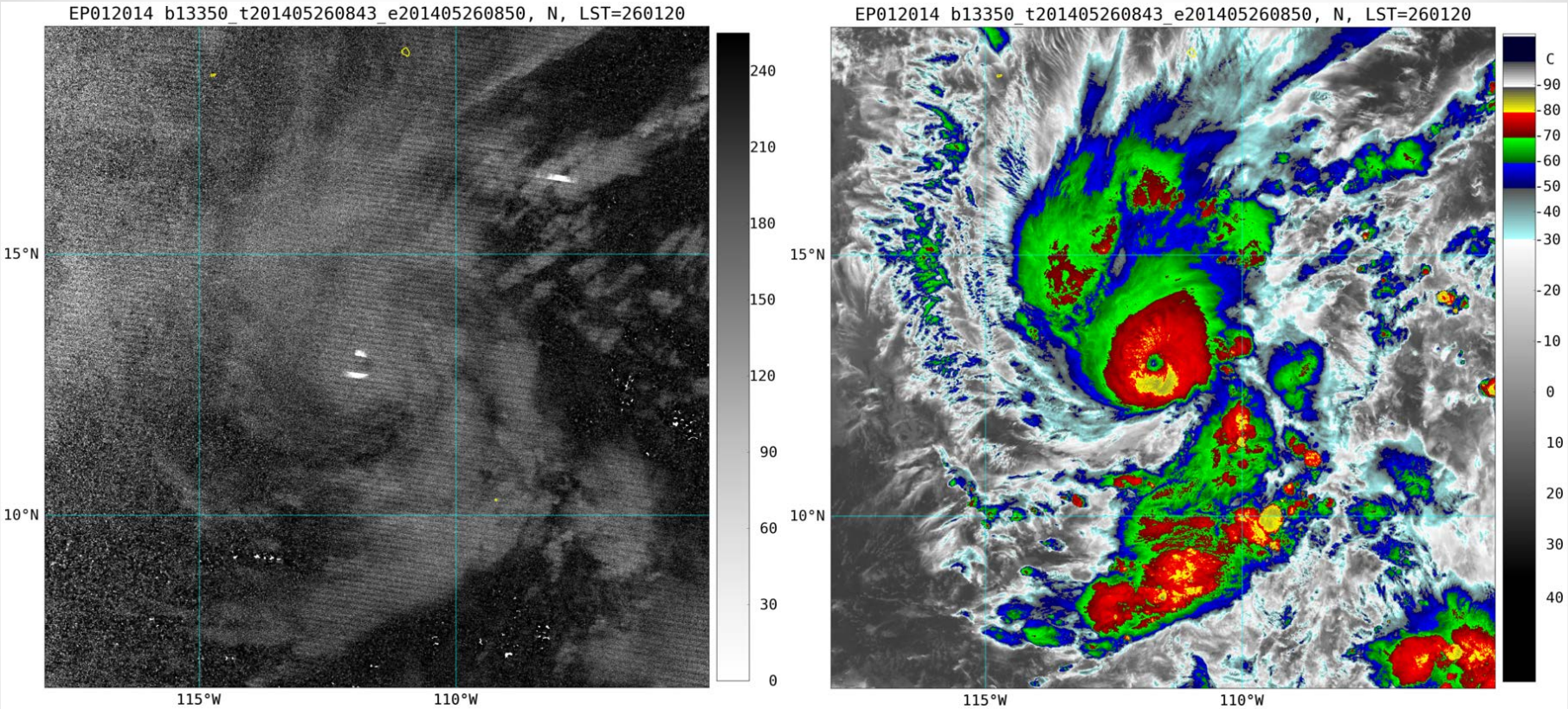




From R. Ballard , 2014

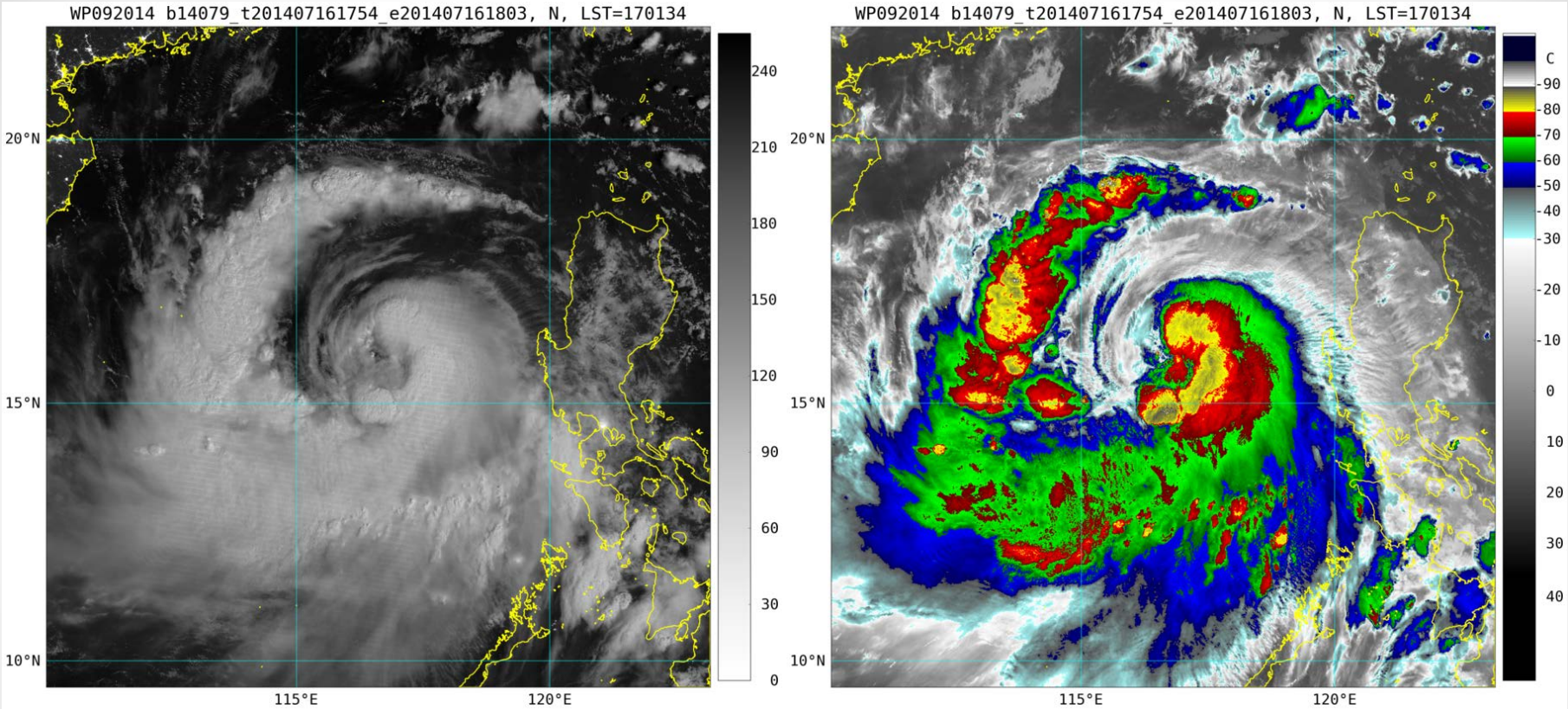
"The center of Flossie was hidden by high clouds most of the night before VIIRS nighttime visual satellite imagery revealed an exposed low level circulation center farther north than expected. We re-bested the 06 UTC position based on the visible data." – CPHC 5 am 7/29/13

VIIRS Day-Night Band Imagery



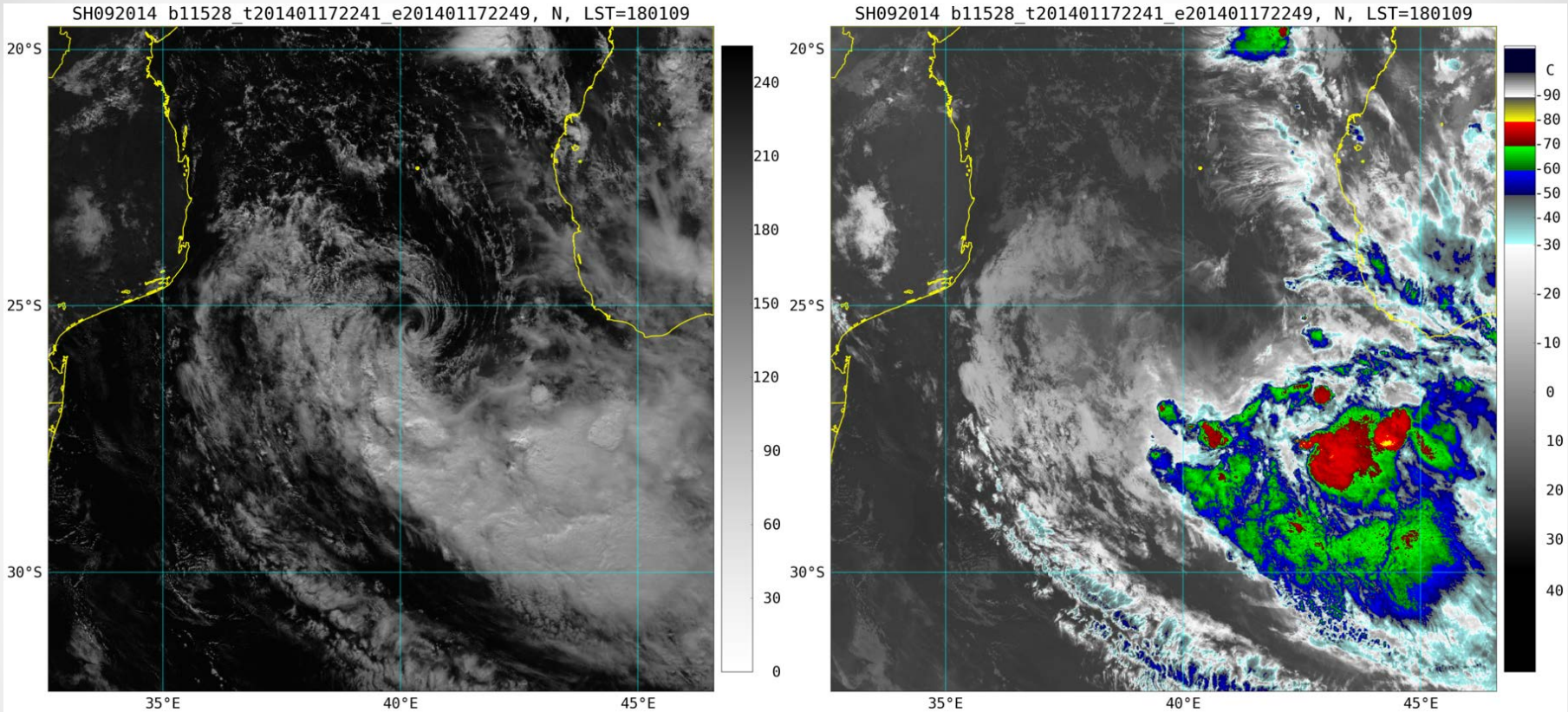
- Lightning strikes around the eye - peaking intensity? (see DeMaria et al.. 2012)

VIIRS Day-Night Band Imagery



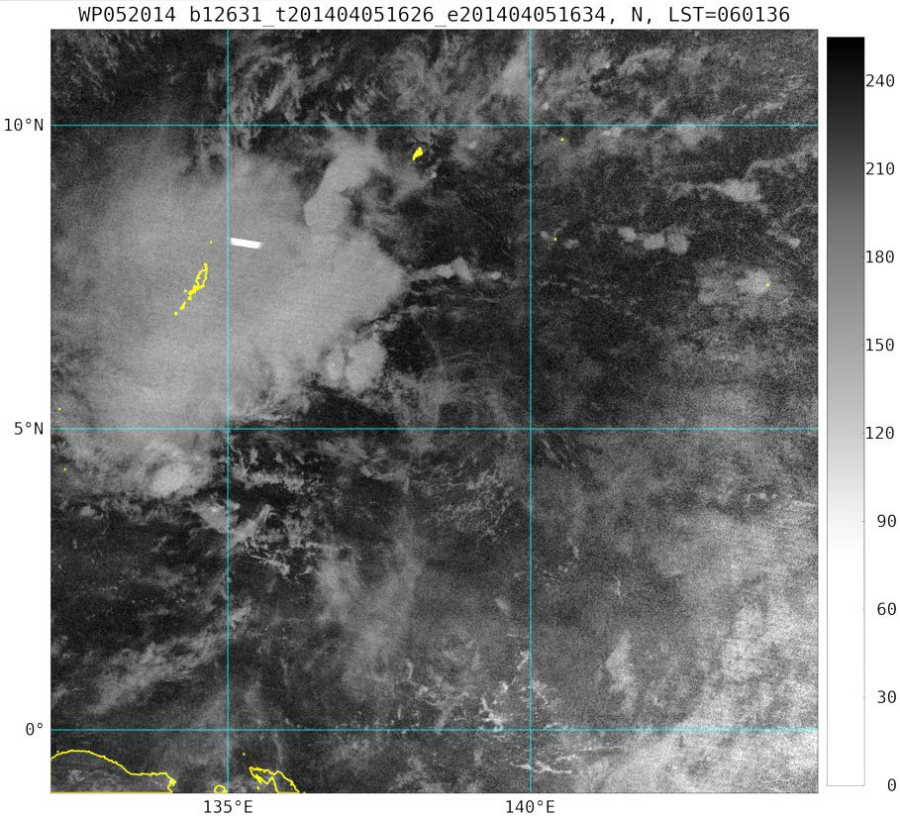
- Eye is clearly visible on night-time DNB image
- It's not obvious if eye is present based on the IR image alone

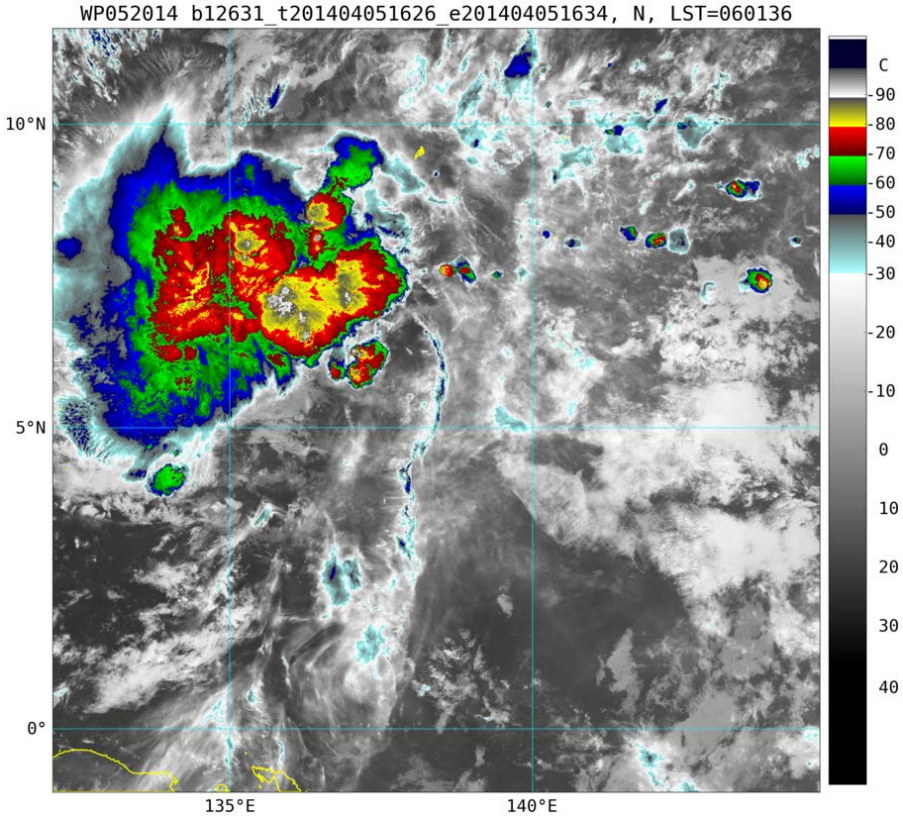
VIIRS Day-Night Band Imagery



- Low level circulation center visible only on DNB image
- Hard to see the center location from the IR image alone

VIIRS Day-Night Band Imagery





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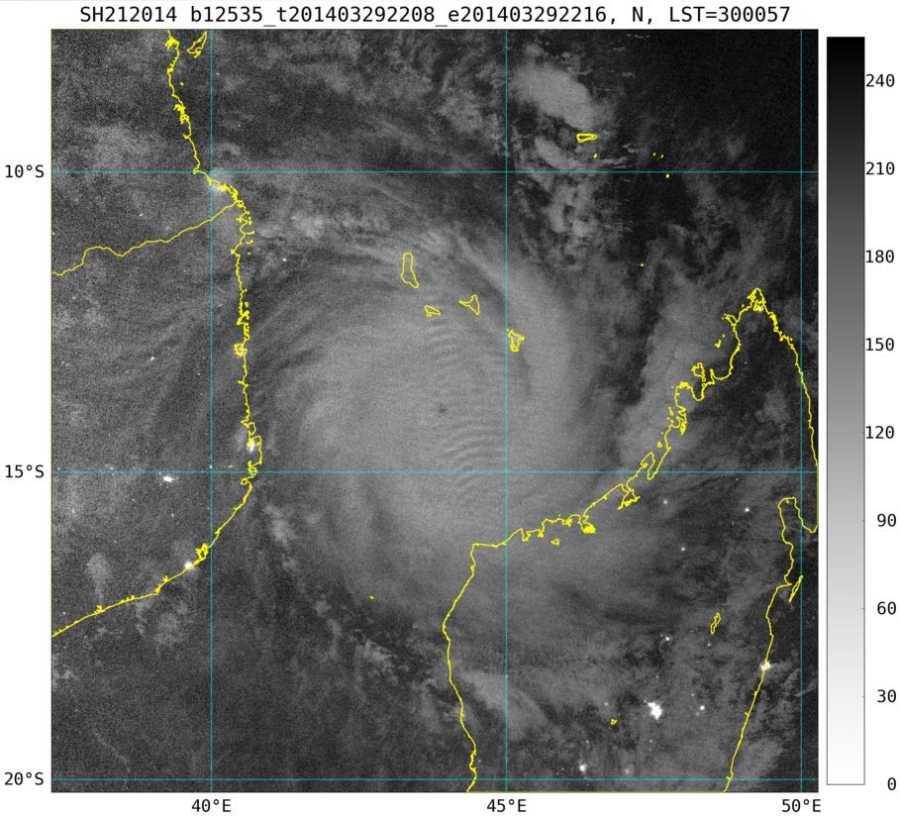
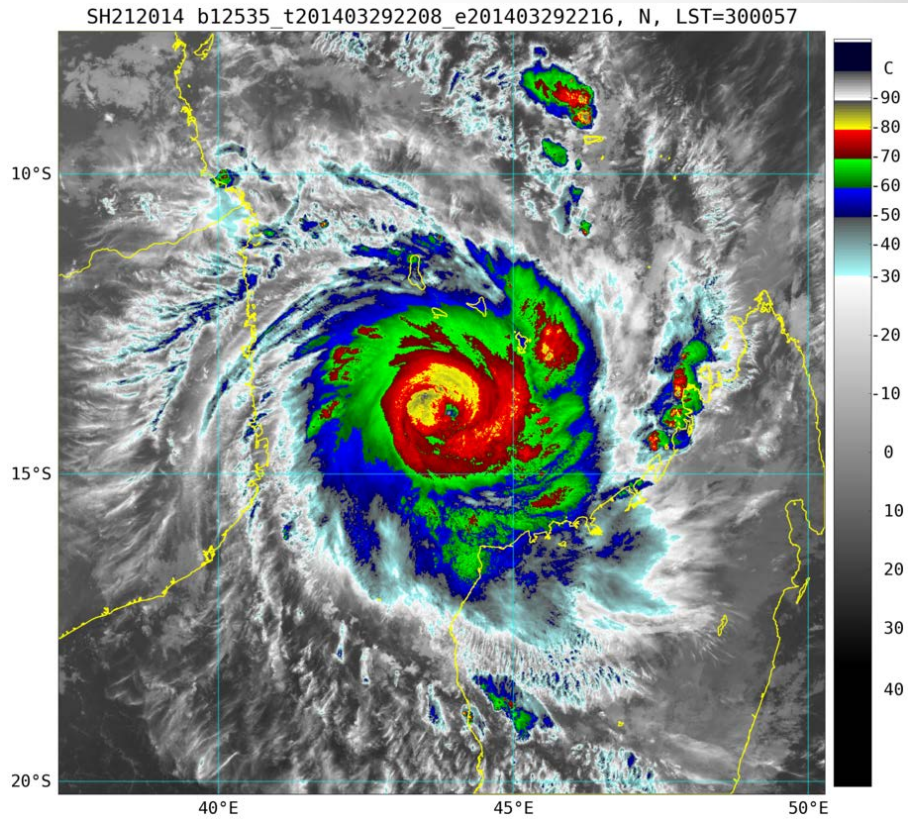
VIIRS Day-Night Band Imagery





- Gravity waves observed in nightglow on DNB images (Yue et al. 2014)

References:

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Yue,J. S. D. Miller, L. Hoffmann and W. C. Straka, 2014: Stratospheric and mesospheric concentric gravity waves over tropical cyclone Mahasen: Joint AIRS and VIIRS satellite observations. *Journal of Atmospheric and Solar-Terrestrial Physics*, http://dx.doi.org/10.1016/j.jastp.2014.07.003

Knaff, J.A., S.P. Longmore, R.T DeMaria, D.A. Molenar, 2014: Improved Tropical Cyclone Near-Surface Wind Estimates Using Routine Infrared Satellite Reconnaissance. Accepted *J. App. Meteor. Climate*.

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Knaff, J. A., M. DeMaria, D. A. Molenar, C. R. Sampson and M. G. Seybold, 2011: An automated, objective, multi-satellite platform tropical cyclone surface wind analysis. J. Appl. Meteorol. Climatol. **50**:10, 2149-2166. doi: 10.1175/2011JAMC2673.1

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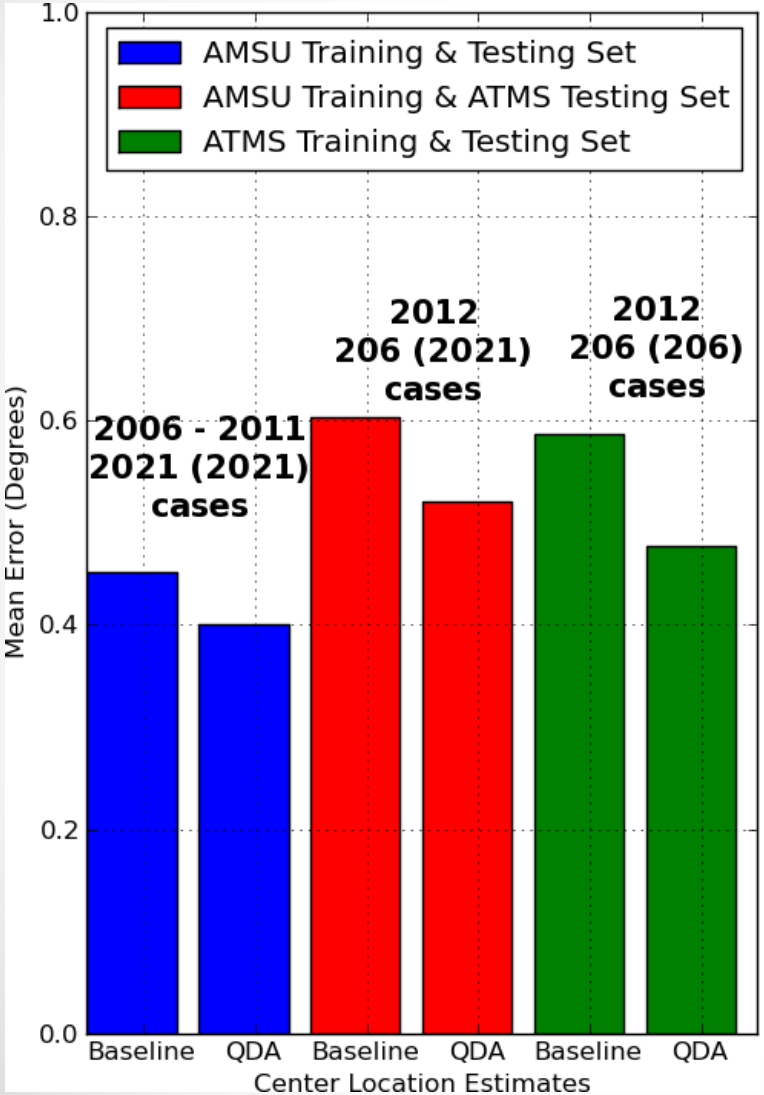
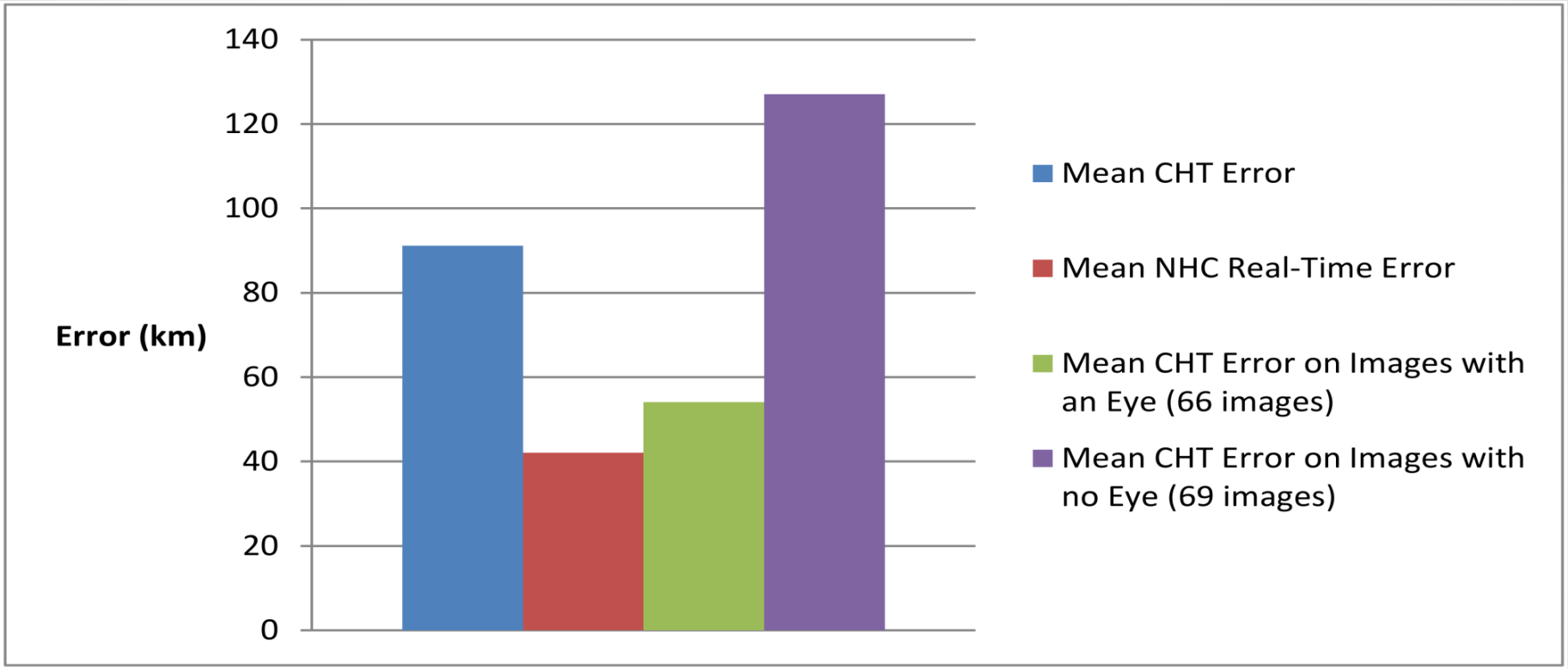
Additional Slides

Validation: QDA-based Center Fix Estimates



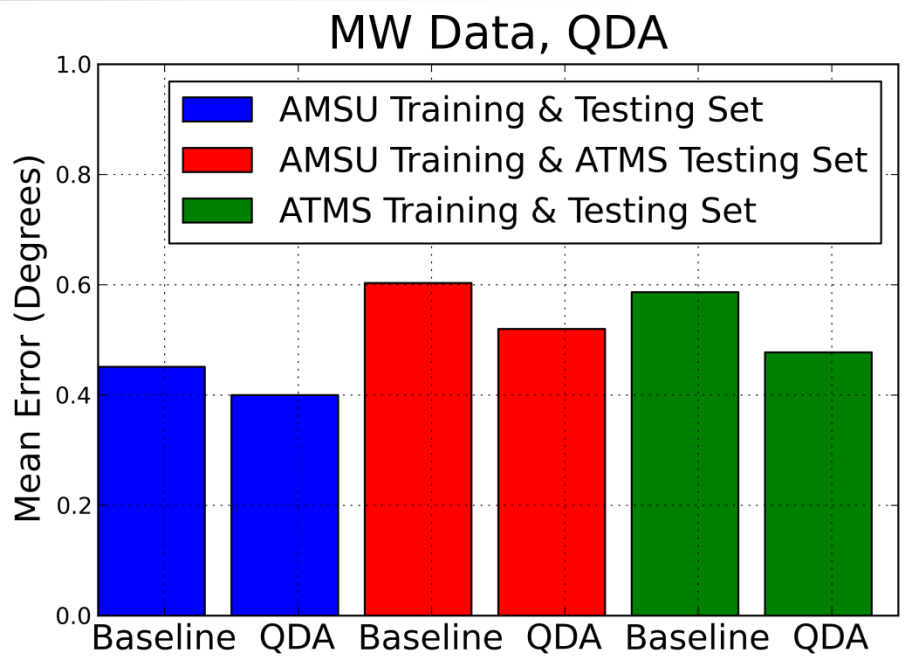
- Baseline
  - estimated storm position extrapolated from storm track
  - provided by NHC as current best guess available in real time (CARQ line)
- Quadratic Discriminant Analysis(QDA)
  - trained and tested against various sets of data
- Results (% improvement)
  - AMSU (AMSU_tr) 10%
  - AMSU (ATMS_tr) 13%
  - ATMS (ATMS_tr) 20%

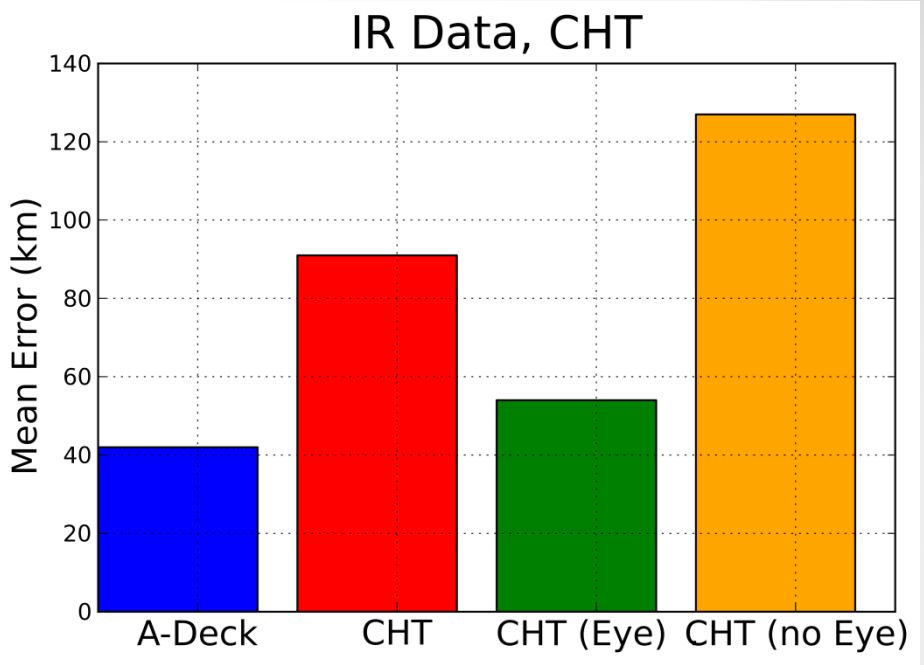
CHT: Results



- 135 Images from Sandy, Earl, Erika, Charley, Katrina
- Mean CHT error: 91 km; for storms with eye: 54 km
- Bias X: 6km, Bias Y: 8.5 km; Bias explained by Parallax

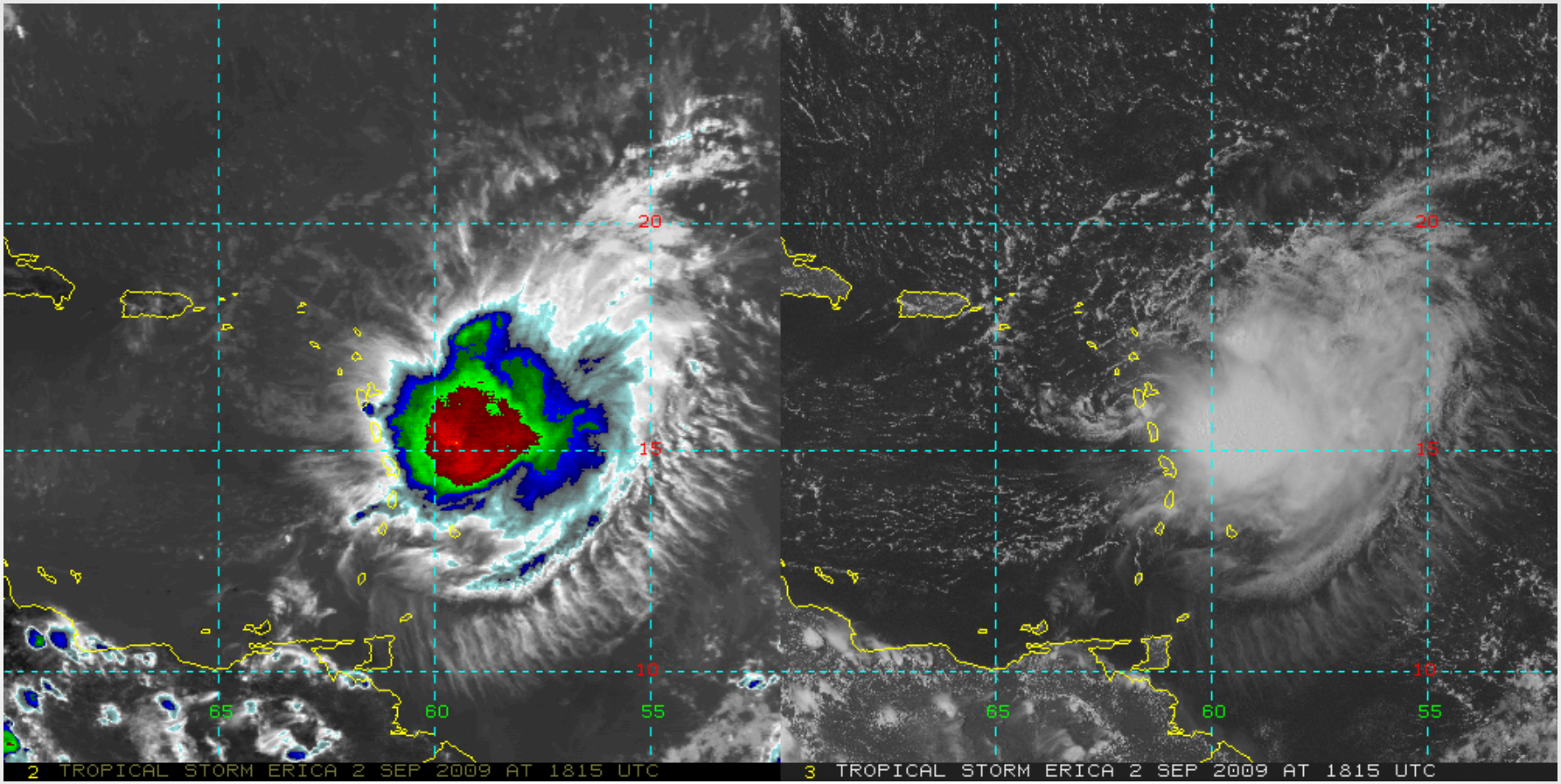
Key Results: Center Fix





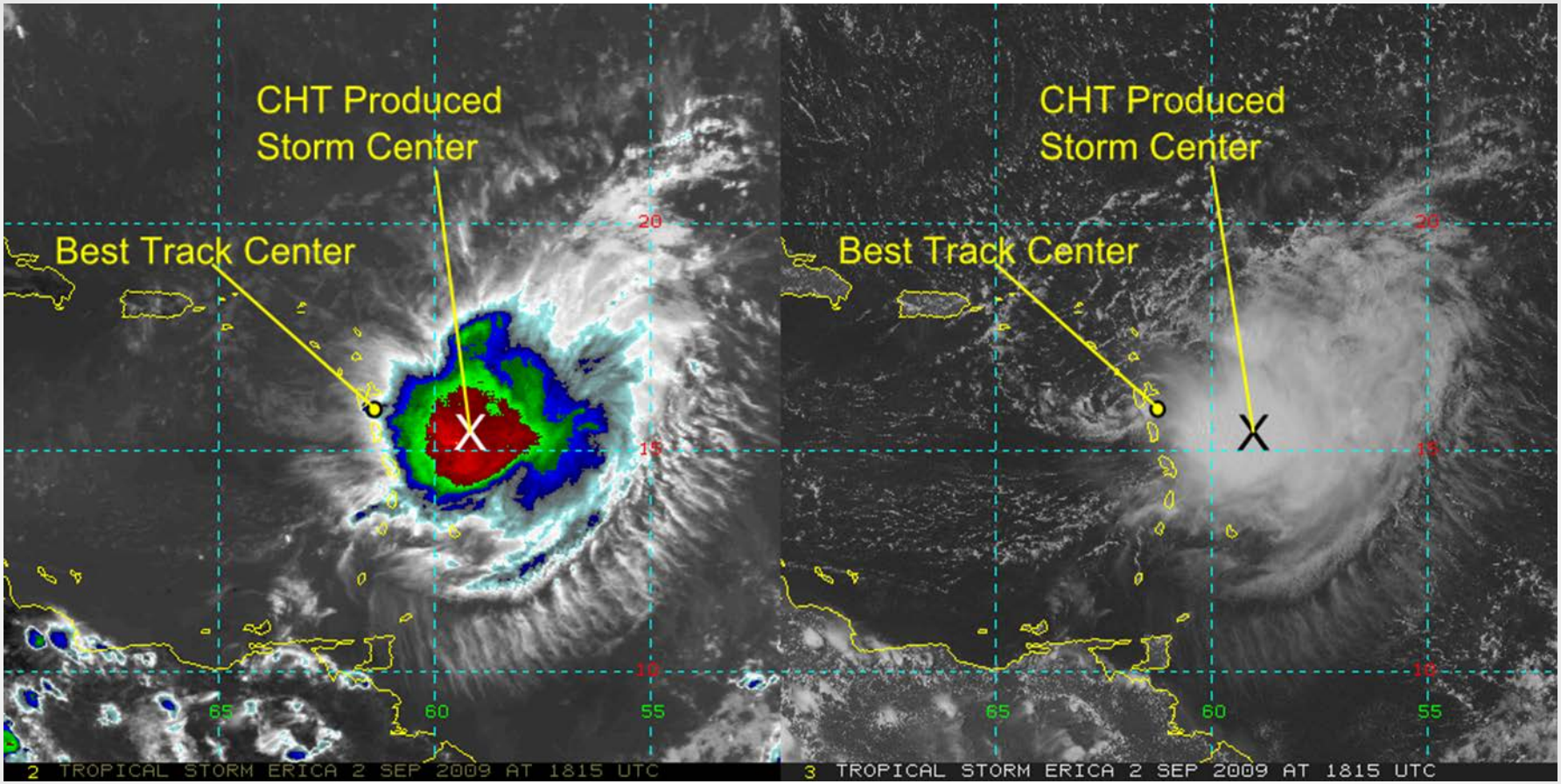
- **QDA (MW Data):**
  - up to 19% increase in accuracy over extrapolated A-Deck positions
- **CHT (IR Data):**
  - Effectively finds cloud shield center/center of eyes
  - Produces large errors for sheared storms
  - Could be combined with other methods and used for automated eye detection

CHT: TC Erica



- In the case of sheared storm center of the coldest clouds is found instead of the storm center

CHT: TC Erica



- In the case of sheared storm center of the coldest clouds is found instead of the storm center

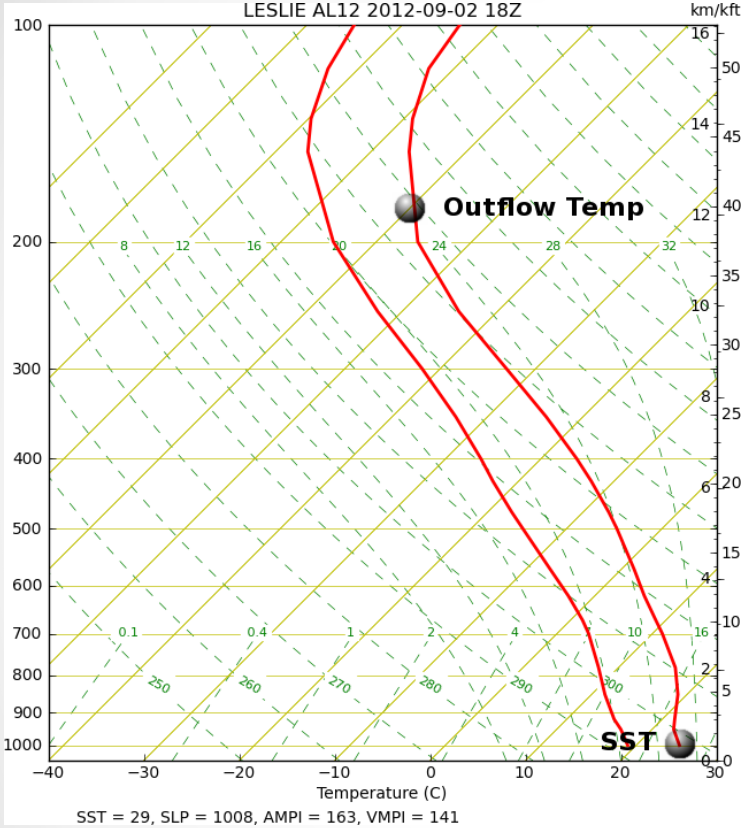
ATMS vs AMSU

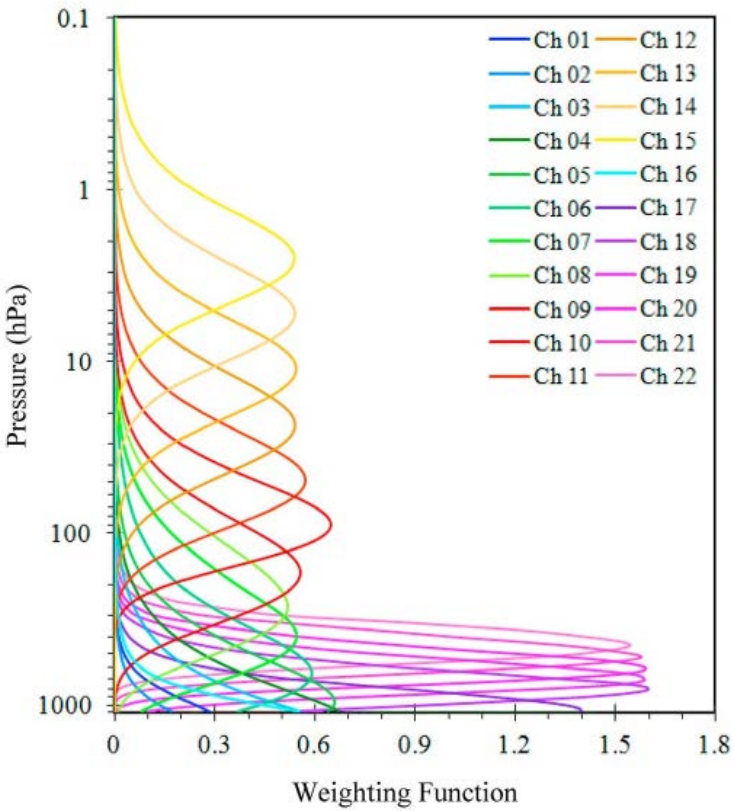
	AMSU	ATMS
Channels	15	22
Frequencies	23 - 89GHz	23-183GHz
Orbit	NOAA-19, 870km	Suomi NPP, 824km; sun synchronous
Swath width	2200km	2503km

ATMS:

- Additional channels:
  - 51.7 GHz, channel 4, lower troposphere T
  - 183 ± 1:8GHz - close to H2O absorption line, channels 19
  - 183 ± 4:5GHz, channel 21
- Oversampling of coarse resolution channels
- First 16 channels for T sounding from surface to 1hPa (≈ 45km)
- Remaining channels for Q sounding from surface to 200hPa (≈ 10km)

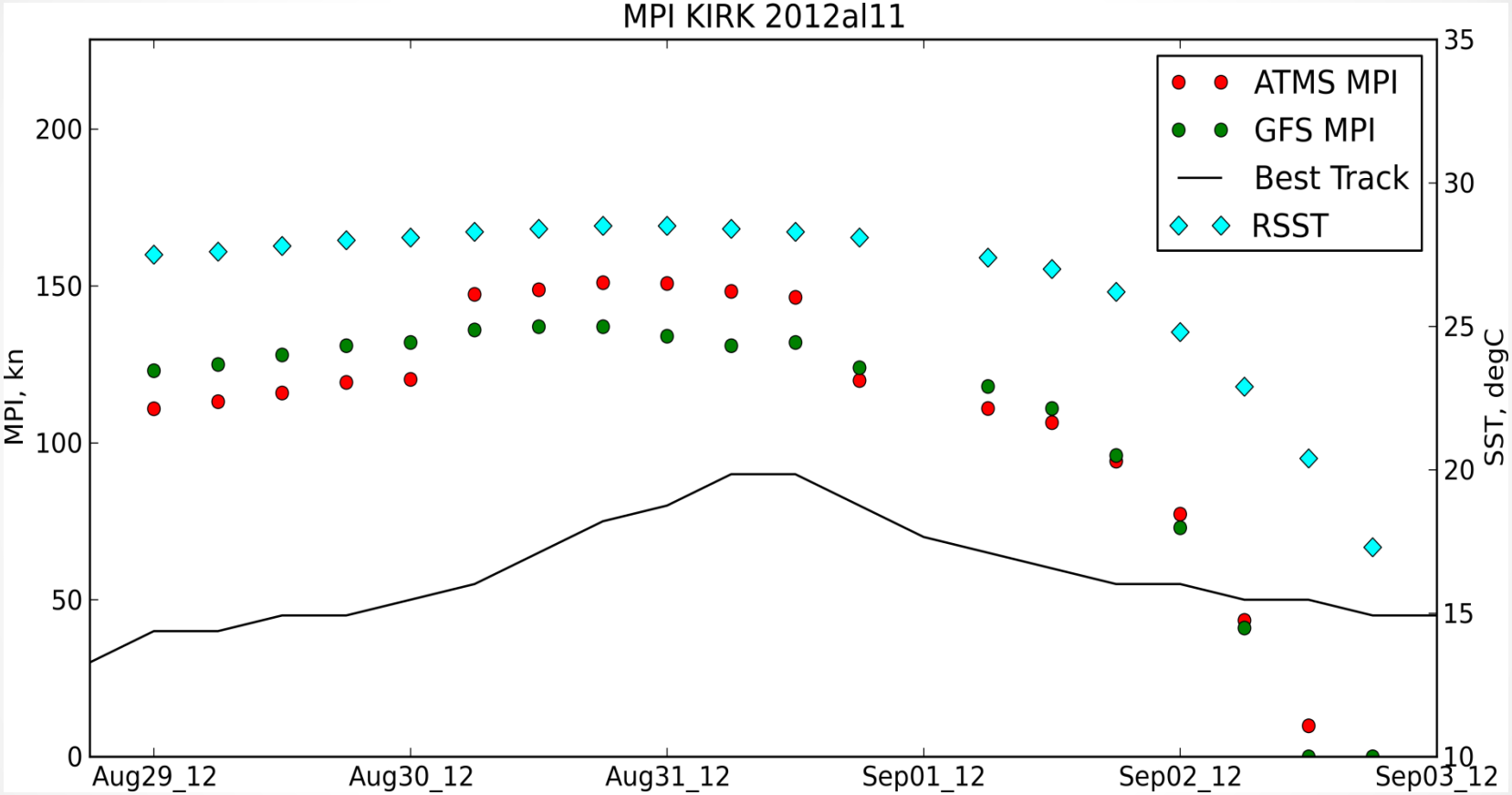
ATMS Sounding and Weighting Functions





- T,q profiles calculated by azimuthally averaging T,q at 500 800km
- Both T and T_d profiles are very smooth (overlapping Wt Functions)

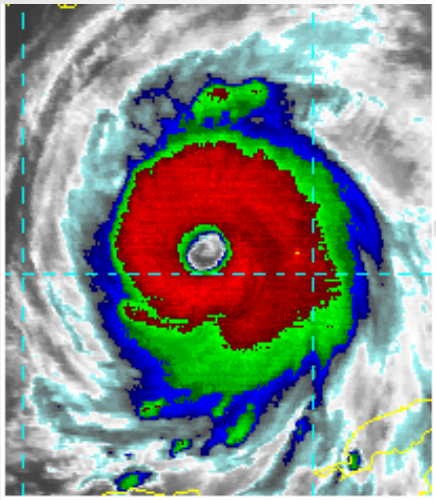
MPI estimates: Operational vs ATMS



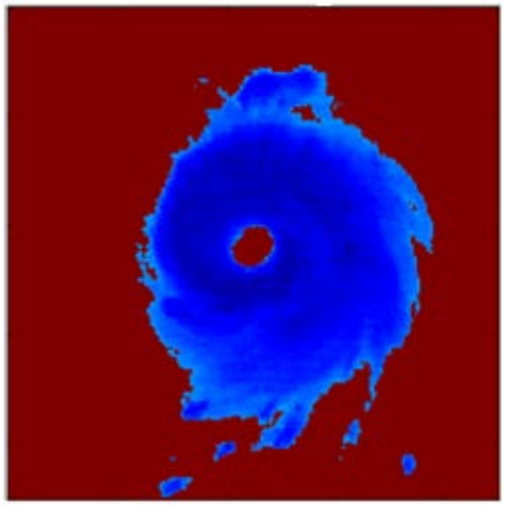
- $\mathrm{MPI}_{Op} > \mathrm{MPI}_{ATMS}$ for weaker storms
- $\mathrm{MPI}_{Op} < \mathrm{MPI}_{ATMS}$ for stronger storms

CHT For Eye Detection:

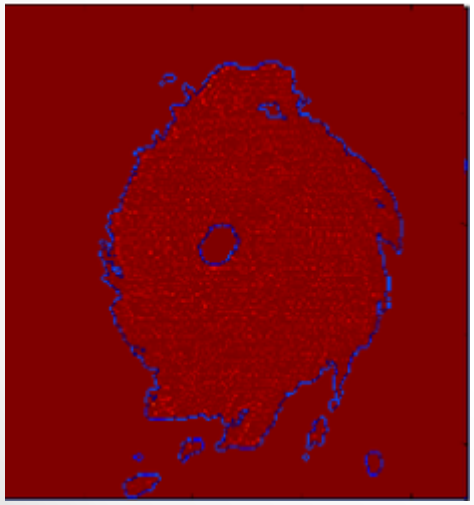
Hurricane Katrina



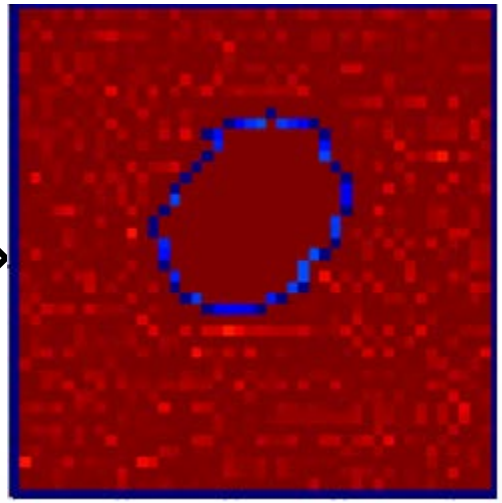
(a)



(b)

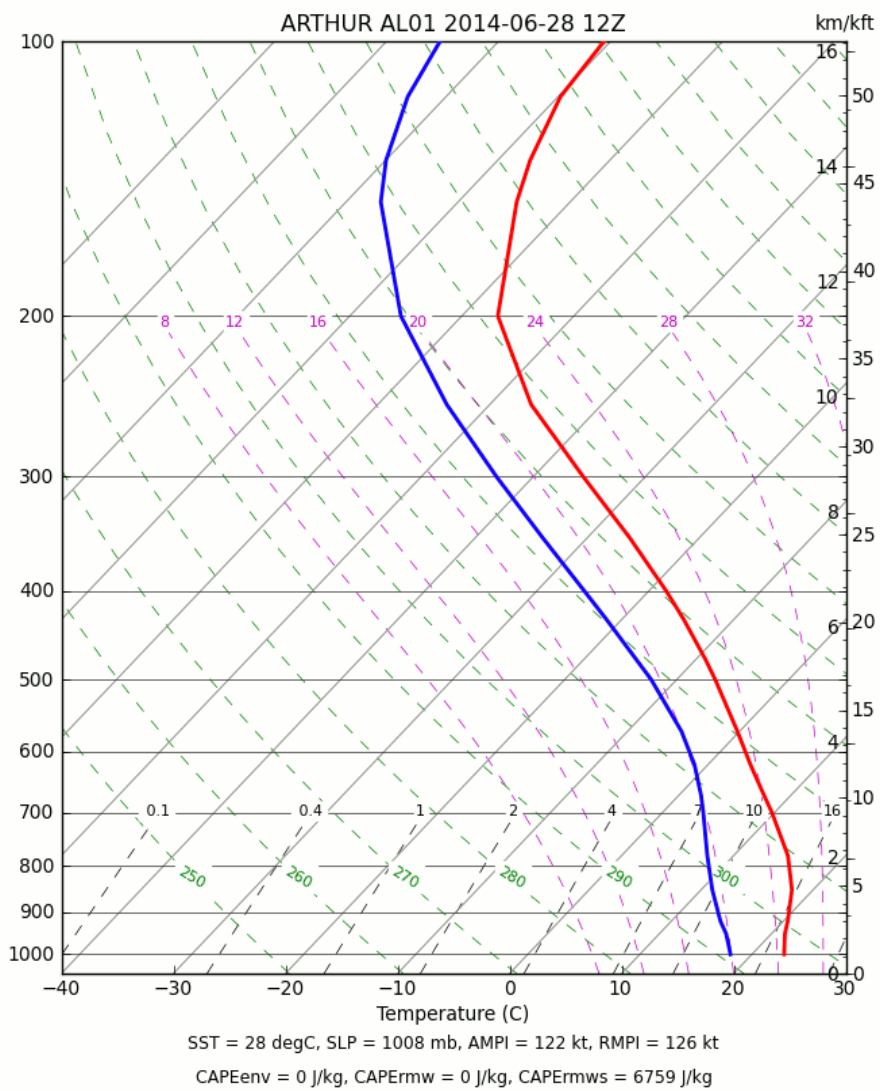


(c)



a. Threshold IR image to isolate clouds
b. Use Laplacian to detect edge pixels
c. If #(edge pixels) near estimated storm center > threshold, → eye is present → reduce image to smaller area

New Real-Time ATMS-MPI Product



Algorithm Inputs:

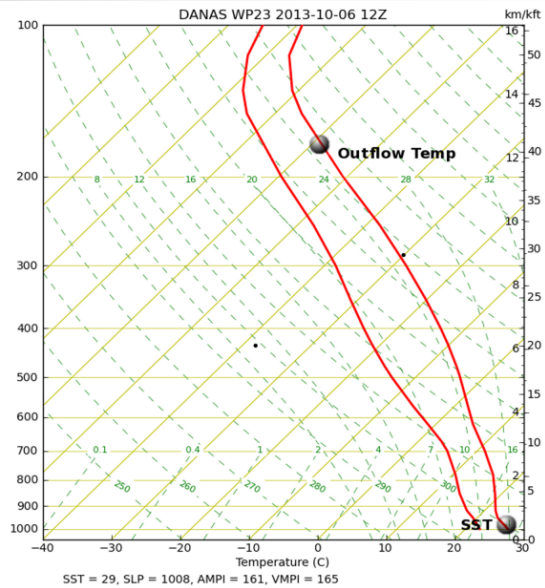
- **SST** – at the storm center
- **T, q profiles and SLP** – azimuthally averaged 200-800 km from the storm center

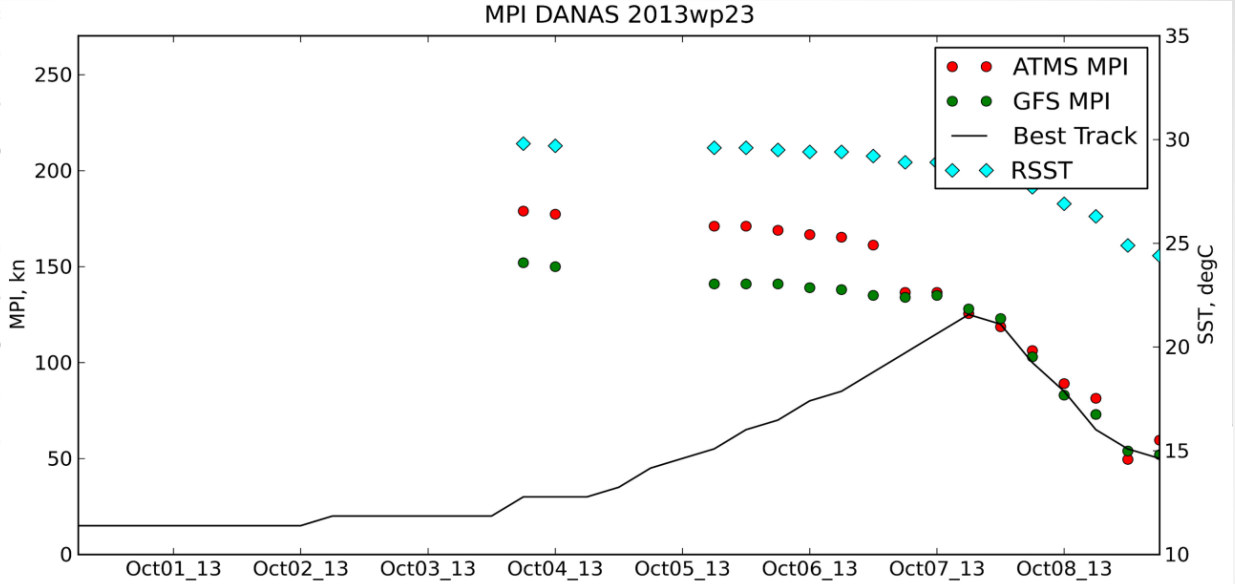
Calculated quantities:

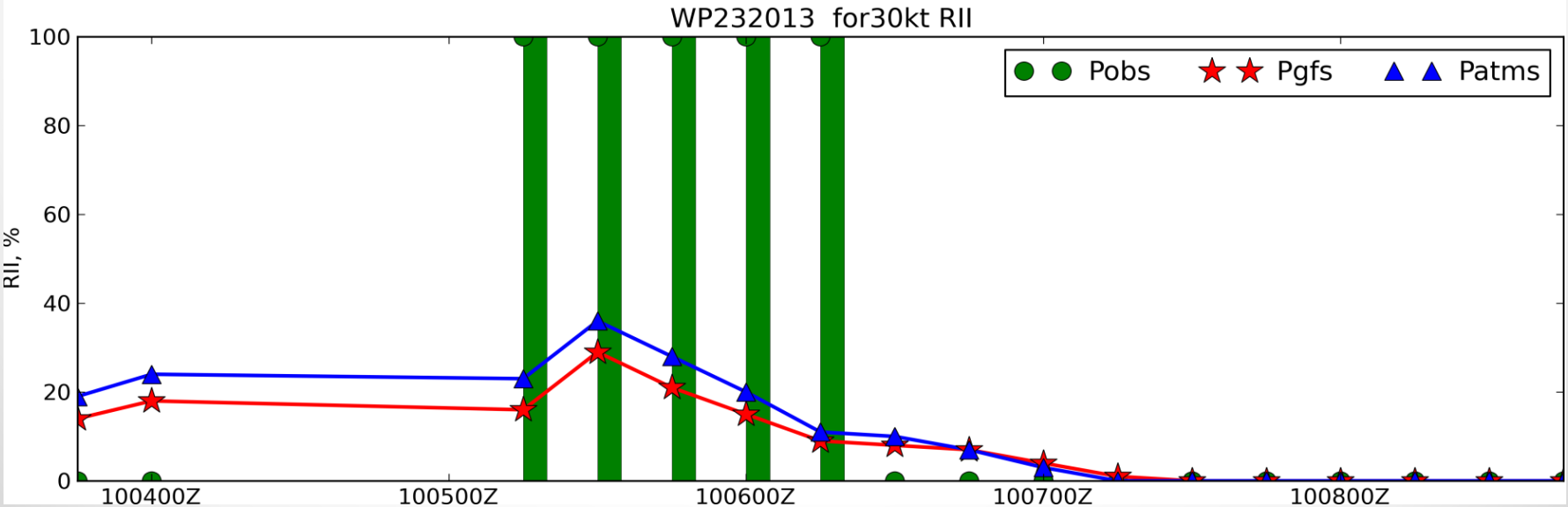
- **AMPI** – MPI calculated from **ATMS T, q profiles and SLP,** and Reynolds SST, using **Bister and Emanuel (1998)** algorithm
- **RMPI** – MPI calculated from Reynolds **SST** only, using **DeMaria and Kaplan (1994)** statistical algorithm
- **CAPEenv** – environmental CAPE
- **CAPErmw** – CAPE of boundary layer air
- **CAPErmws** – CAPE of air saturated at SST and lifted from sea level in reference to the environmental sounding

Available at http://rammb.cira.colostate.edu/products/tc_realtime/index.asp

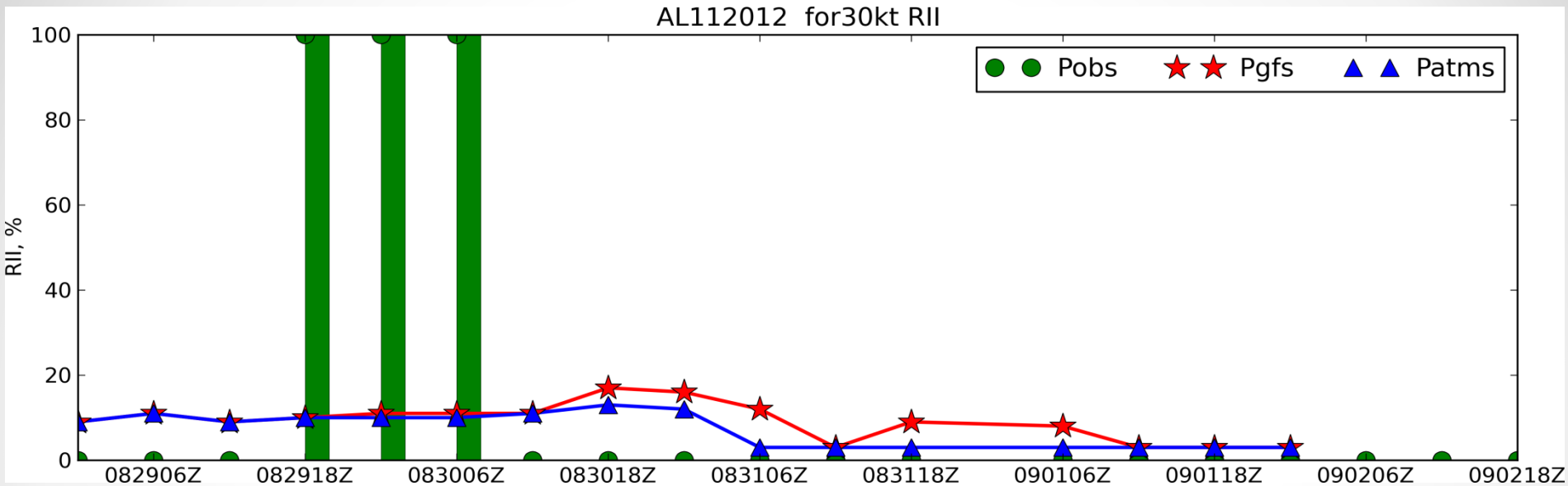
RII with ATMS MPI: WP232013 Danas

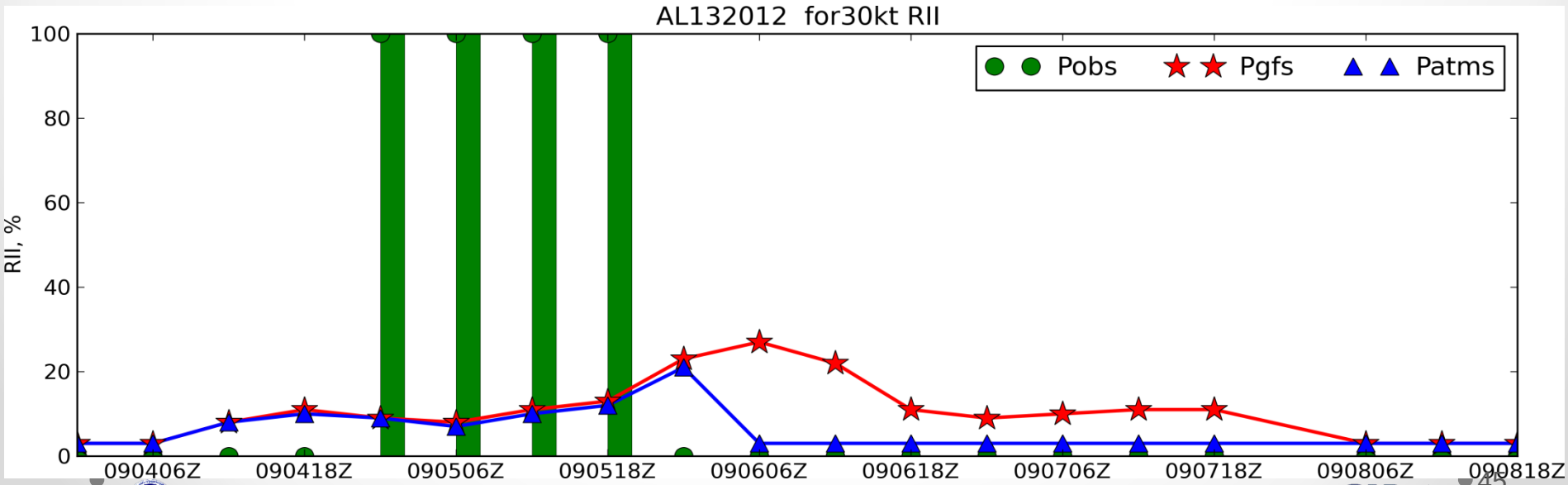






RII sensitivity to MPI



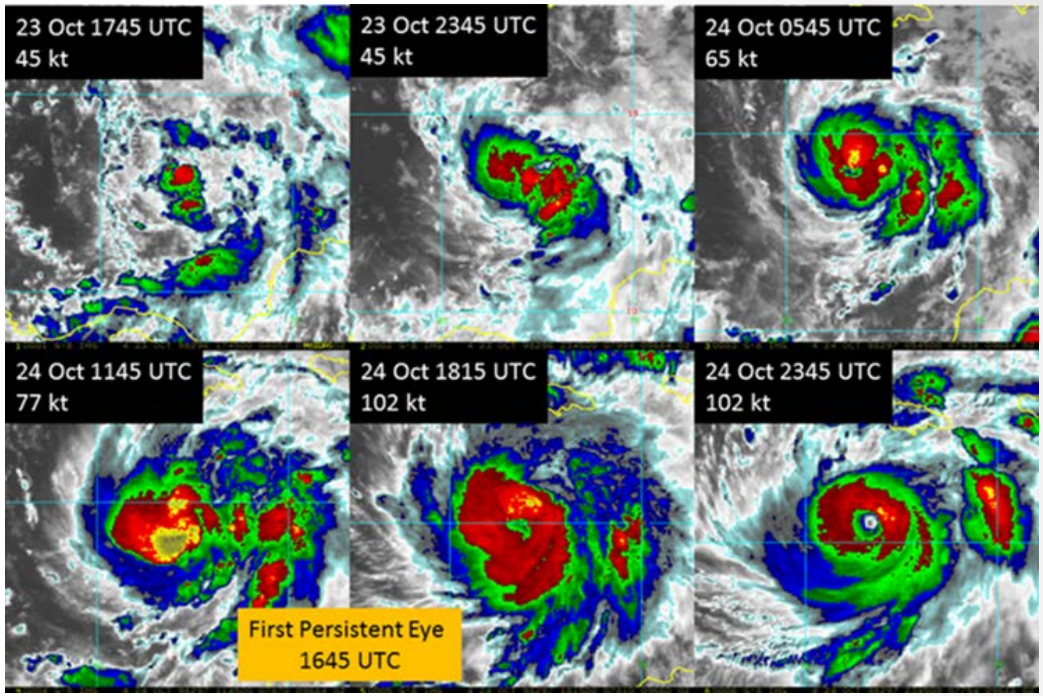


Anticipating Eye Formation

Eye formation is an important stage of TC development often signaling the beginning of more rapid intensification

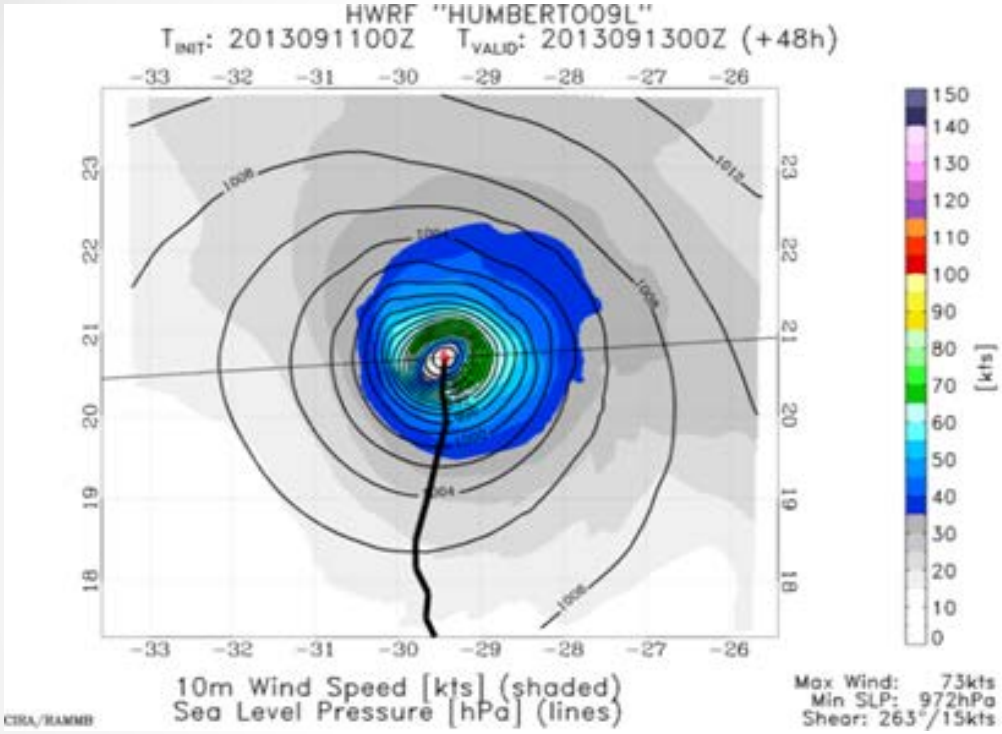
In this work we will

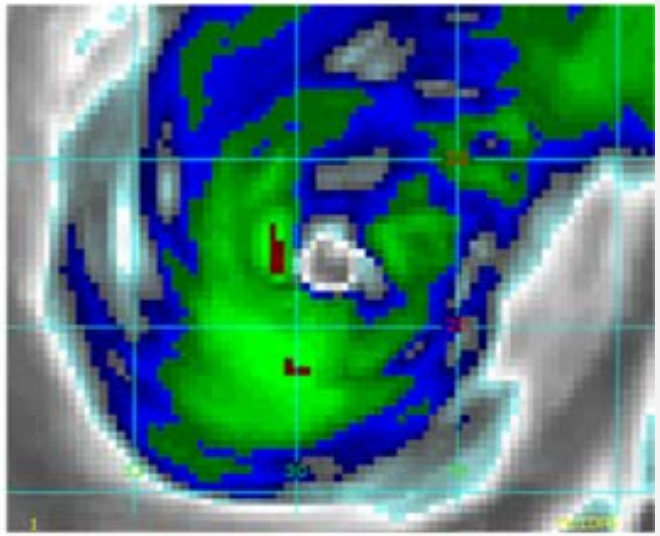
- Identify [**objectively (i.e., CHT)** and subjectively] the first development of the TC eye feature in historical images
- Match eye formation times environmental conditions
- Develop and test deterministic and probabilistic statistical methods to make short-term forecasts of eye formation.



Six-hourly IR images of Hurricane Mitch starting at 18 UTC 23 October. Dvorak-based intensities from SAB are listed in the upper right portion of the images. During this period of time Mitch transformed from a strong tropical storm with no indication of an eye to a major hurricane.

Inference of TC structure from IR imagery





HWRF surface wind field (left) and matching synthetic IR imagery (11 μm) for Hurricane Humberto (2013). Both fields are from the 48h forecast initialized 11 Sept 00UTC and valid at 13 Sept. 00UTC.

Validation

- Verification of dependent sample yields performance comparable to AMSU-based products (below)
  - Due to data acquisition issues, AMSU-based algorithm coefficients used with simple bias correction
  - CAL/VAL project currently underway to redevelop algorithm statistics with MiRS ATMS data, investigate use of moisture soundings
- Projected transition to operations at NESDIS/OSPO/NDE: August 2014
- Text estimates (i.e., fixes) available via ATCF at JTWC, NHC, CPHC

ATMS-based Estimate	N	MAE	Project Goal
Vmax	225	12.9 kt	13.5 kt
Min P	225	8.9 hPa	9 hPa
R34	170	41 nmi	32 nmi
R50	109	19 nmi	18 nmi
R64	67	16 nmi	10 nmi