Svetla M. Hristova-Veleva[1], P. P. Li[1], B. Knosp[1], N. Niamsuwan[1], T.-P. Shen[1], F. J. Turk[1], Q. Vu[1], B. Lambrigtsen[1], F. Marks[2], R. Rogers[2], S. Gopalakrishnan[2], V. Tallapragada[3], S. Trahan[3], M. Boothe[4], M. Montgomery[4] D. Jones[5], R. Ameller[5]

[1] – Jet Propulsion Laboratory, California Institute of Technology
[2] – HRD/AOML/NOAA, Miami, FL
[3] – EMC/NCEP/NOAA, College Park, MD
[4] - NPS, Monterey, CA
[5] – StormCenter Communications, Inc.

Fusion of Hurricane Models and Observations: Addressing the Needs of Operations and Research

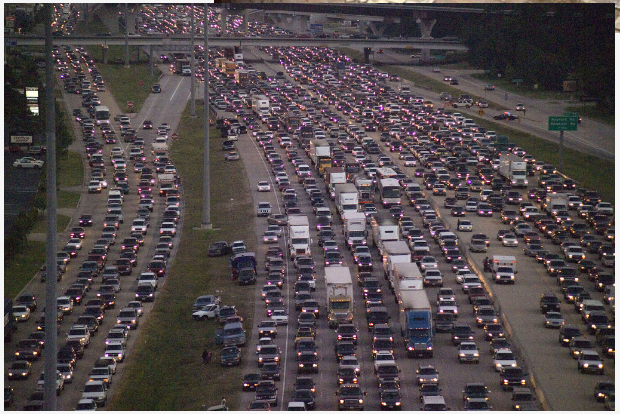
ESTF16
Annapolis, MD
June 26, 2016

Hurricanes are among the most destructive natural phenomena with huge societal and economic impact.

After **Katrina:**
Venice, Louisiana - 8/30/2005

After **Ike:**
Galveston, Texas -9/13/2008

Houston, Texas, 2005 – unnecessary evacuation of 2 million ahead of hurricane **Rita's** landfall



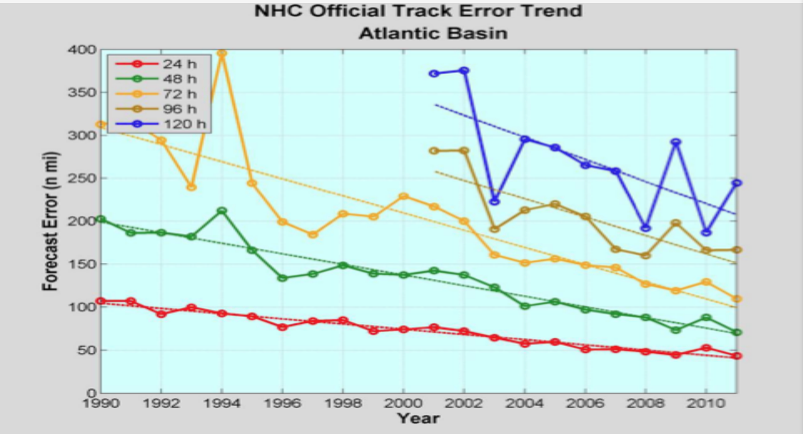
Each year they threaten the US coast, cause damages worth billions and take life.

- Some **130,000 died** when a cyclone struck Myanmar along the Andaman Sea in 2008.
- The deadliest U.S. hurricane was the 1900 Galveston storm, which **killed 8,000 to12,000** people and destroyed the city. Katrina (2005) **killed some 1,200 people**, and left hundreds of thousands homeless.
- Sandy is being blamed for about **$62 billion** in damage and other losses in the U.S. — a number that could increase.
- It is the second-costliest storm in U.S. history after 2005's Hurricane Katrina, which caused **$128 billion** in damage in inflation-adjusted dollars.

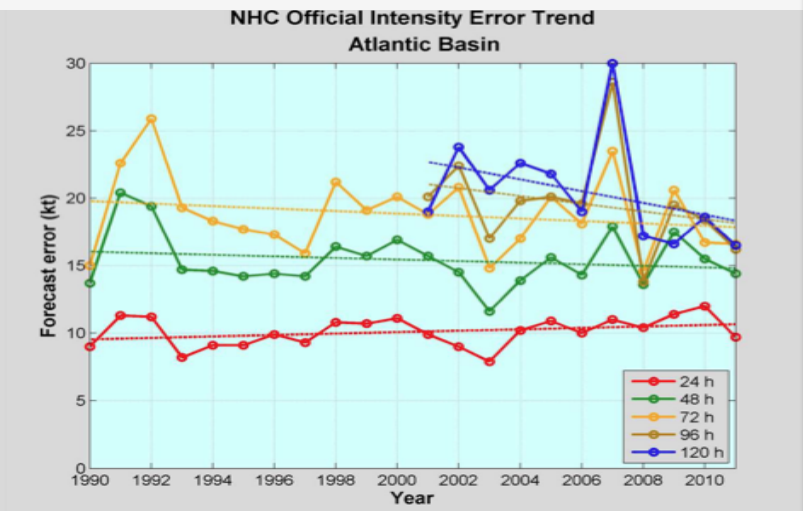
Widespread power outages and subway shutdowns may wind up making **Superstorm Sandy** the second most expensive storm in U.S.

Current state-of-the-art hurricane prediction

- **25% reduction in 48 hour track error over the past 6 years**



- **Intensity forecasts have not improved.**



Graphs: Hurricane Research Division

- **But WHY ???**
  - What are the sources of the intensity errors?
  - Do the models properly reflect the physical processes and their interactions?
    - Is the representation of the precipitation structure correct?
    - Is the storm scale and asymmetry reflected properly
    - Is the environment captured correctly
    - Is the interaction between the storm and its environment represented accurately
- Recognizing an urgent need for more accurate hurricane forecasts, NOAA recently established the multi-agency 10-year Hurricane Forecast Improvement Project (HFIP).

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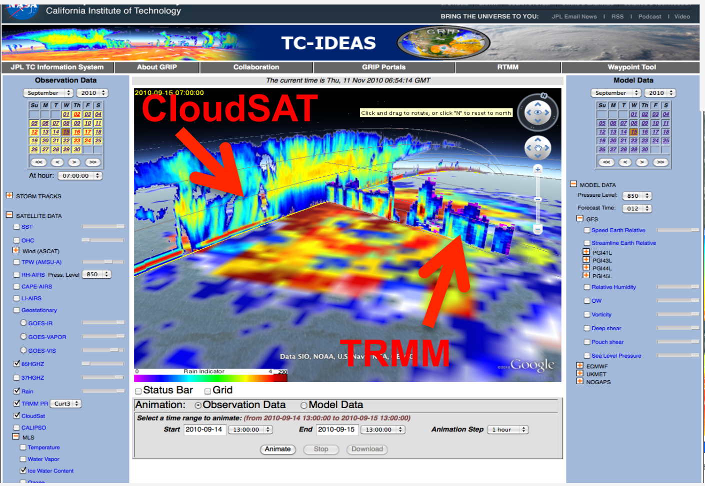
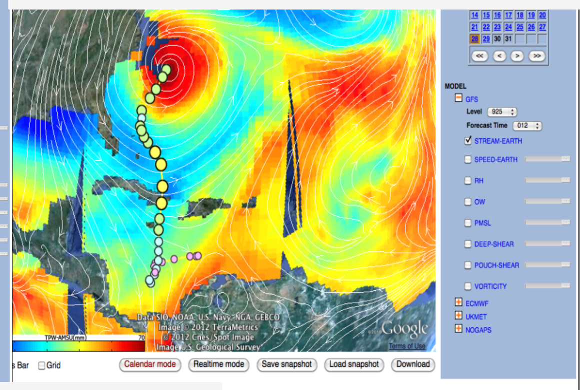
Motivation for our project -
The critical pathways to hurricane forecast improvement

- **Is the representation of the precipitation structure correct?**



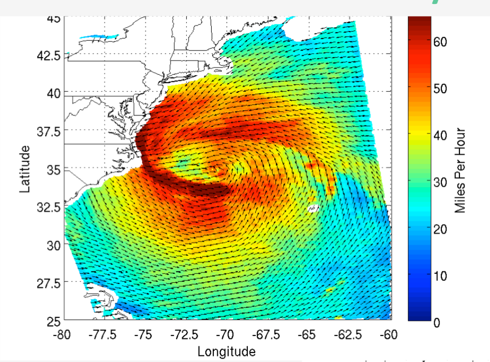
- **Is the environment captured correctly?**
- **Is the interaction between the storm and its environment realistic?**



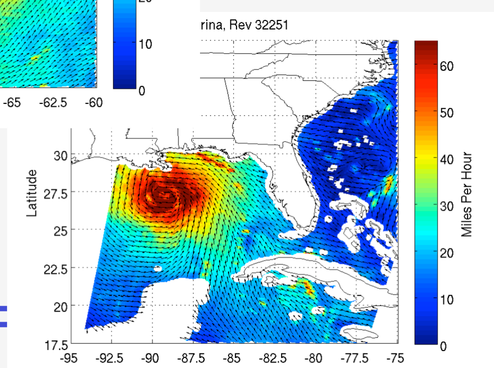
To improve Hurricane Intensity forecasts, **we need to understand how well the models reflect the physical processes and their interactions.**

Satellite observations can help in 3 important ways!

- **Is the storm scale and asymmetry reflected properly?**



Hurricane Sandy As seen by the ISRO's OSCAT



Hurricane Katrina As seen by the NASA's QuikSCAT

1. **Understanding the physical processes**
2. **Validation and improvement of hurricane models through the use of satellite data**
3. **Development and implementation of advanced techniques for assimilation of satellite observations inside the hurricane core.**

- **Despite the significant amount of satellite data today, they are still underutilized in hurricane research and operations, *due to complexity and volume.***

The JPL TCIS – Tropical Cyclone Information System

http://tropicalcyclone.jpl.nasa.gov

To facilitate hurricane research, we are developing the JPL Tropical Cyclone Information System (JPL TCIS) of multi-instrument observations and some model data pertaining to:

i) the thermodynamic and microphysical structure of the storms;

ii) the air-sea interaction processes;

iii) the larger-scale environment.

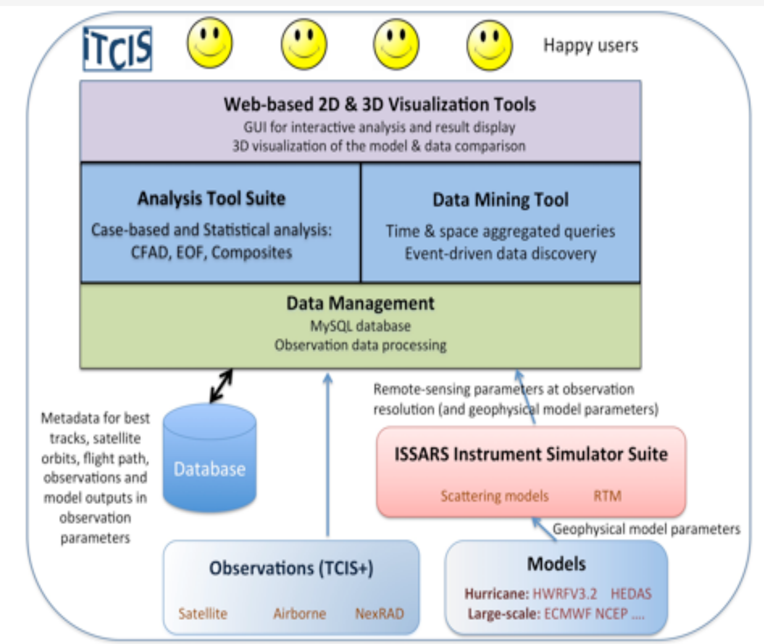
This system is being developed under NASA support:

- ESTO/AIST funding currently
- the Hurricane Science Research Program (HSRP) in the past.

The project is developed in close collaboration with our colleagues from NOAA/EMC and NOAA/AOML/HRD to bring the operational and research versions of HWRF forecasts into the satellite database and to develop a set of on-line analysis tools.

Objectives for the project

- **The main objective of this 3-year effort is to develop the technology to provide the fusion of observations (satellite, airborne and surface) and operational model simulations to help improve the understanding and forecasting of the hurricane processes.** We will develop three critical components that will allow the merger of observations with model forecasts:



1) **Develop visualization to enable analysis** (e.g., data immersion approaches to enable real-time interaction with the models, and visualization of highly complex systems)**.**
2) **the coupling of the instrument simulator with operational hurricane forecast models and incorporation of simulated satellite observables into the existing database of satellite and air-borne observations.**
3) Developing **tools to manage the validation and assessment of model-data intercomparisons** to more easily evaluate the performance of different models

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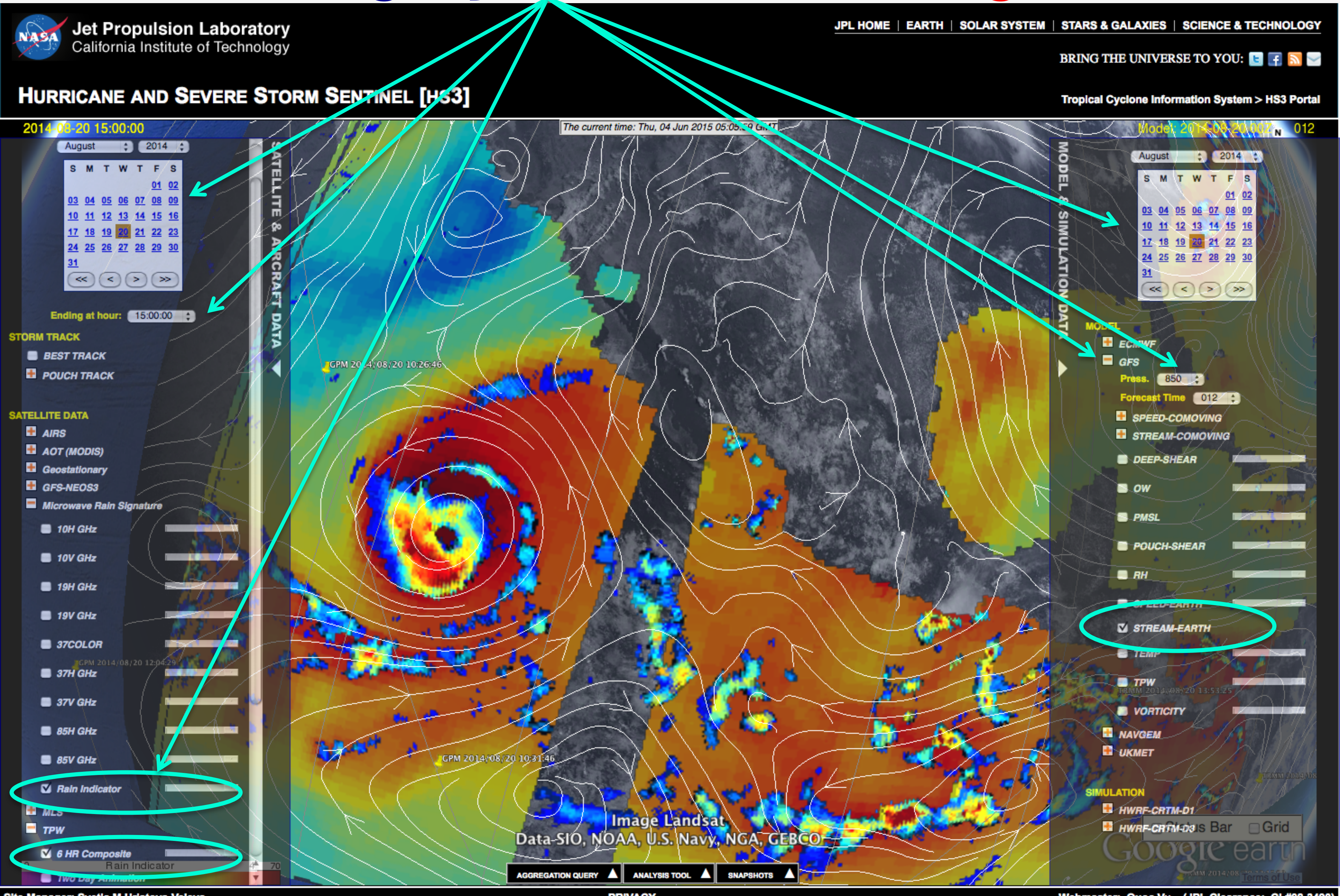
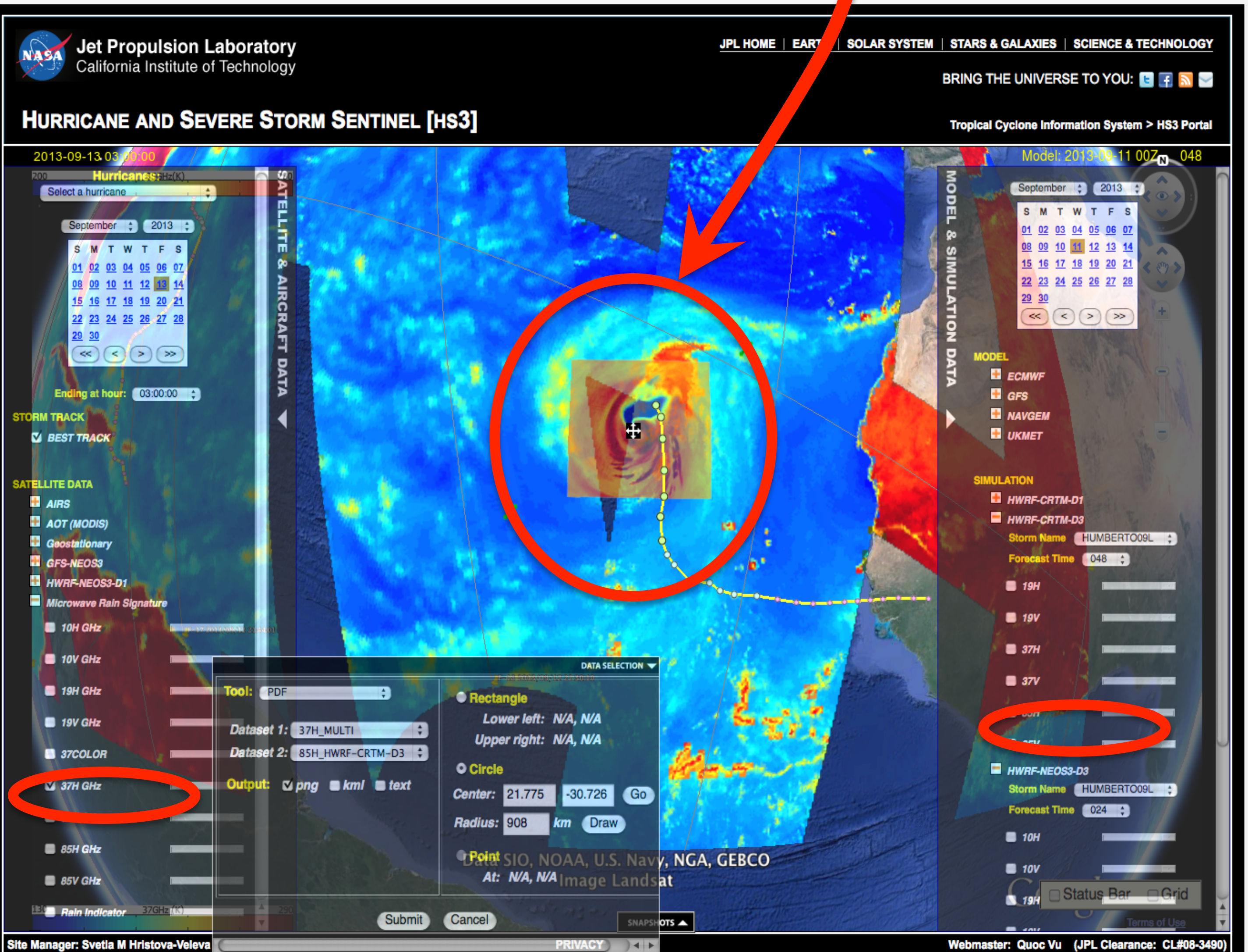
Driving by desire: Interrogate!



Driving by desire: Evaluate!

- Interactively select region
- Gather data from observed and synthetic brightness temperature



- **PERFORM:**
  - Statistical evaluation
    - EOFs, Joint PDFs
    - Azimuthal averages
  - Storm Structure
    - Storm Size/ Asymmetry
    - Wave-number analysis
    - Storm Center - ARCHER
    - Convective/ Stratiform
  - Visualization of analysis

Goals for our latest efforts

- This is a follow-up on an AIST-11 funded proposal. The objective of the AIST-11 task was to develop the technology to provide the fusion of observations (satellite, airborne, and surface) and operational model simulations to help improve the understanding and forecasting of hurricane processes

- This latest work is an augmentation. It has two goals aimed at transitioning to an operational environment:
  1. to upgrade the technology of the developed system in order to facilitate its adoption and usefulness

  2. to actively introduce our system to the operational and research communities and to respond to their feedback with the aim to promote the use of our system and to lay the framework for its adoption.

Goals

- Goal 1: to upgrade the technology of the developed system in order to facilitate its adoption
  - Selection and implementation of an alternative to Google Earth visualization
  - Automation of the portal configuration and the collection of observations.
  - Development of web services
- Goal 2: to actively introduce TCIS to the operational and research communities with the aim to promote its use and to lay the framework for its adoption
  - Collaborate with StormCenter to build the GeoCollaborate capability around TCIS
  - Operate the portal and engage HRD/NHC
  - Participate in the ESIP independent evaluation

Upgrading the technology

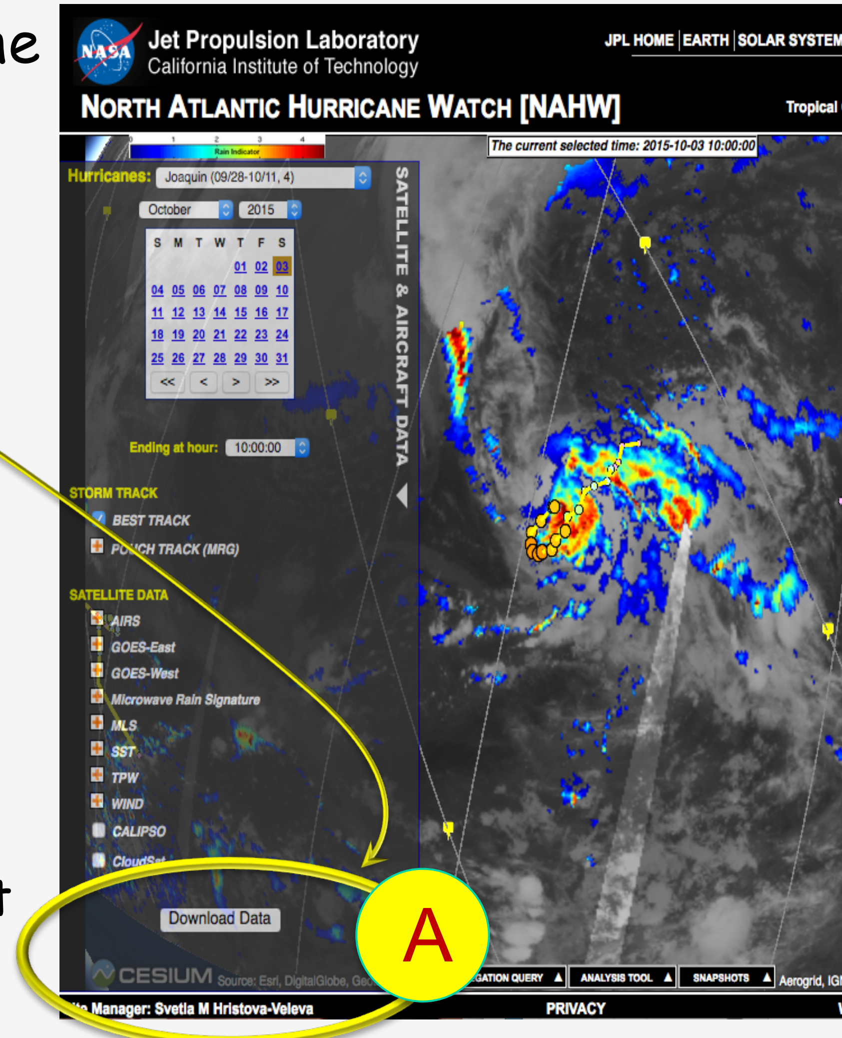
Web Services

Motivation: "How could I download the data that I view on the portal?"

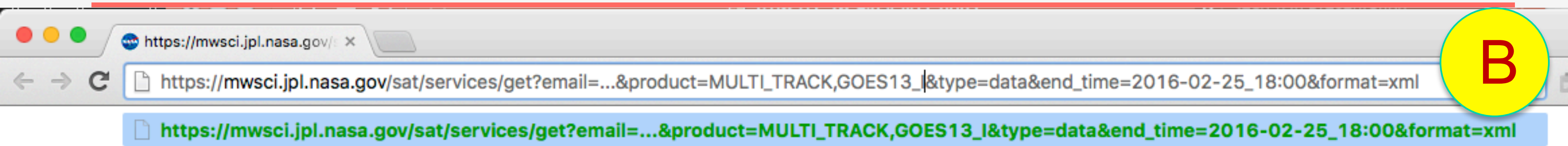
Options:

A. Download button
- Provides links to the files
- Returns a list of URLs of the datasets
  - wget -i {file with dataset URLs}
  - Properties:
    - » Immediate response
    - » No staging area required on the server

B. URL request
- Implemented simple services to allow product listing and product retrieval.
- Search by product and time constraint
- Return raw data (for offline processing) or image

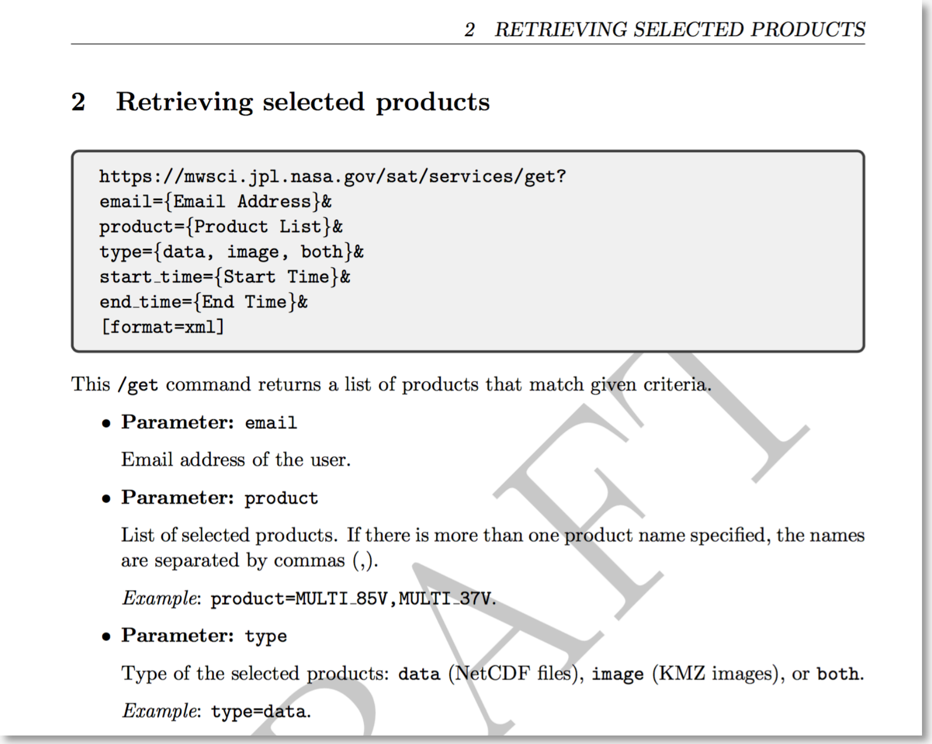


Upgrading the technology



2. Web Services

- Benefits
  - The web services would not only benefit the individual users but will help in exporting the TCIS products to other portals facilitating collaboration with different programs (e.g. SERVIR) and institutions
  - Replace the current image retrieval process with web service
    - Paving a way for decoupling data server from the web server (distributed data source)



2 RETRIEVING SELECTED PRODUCTS

2 Retrieving selected products

```
https://mwsci.jpl.nasa.gov/sat/services/get?
email={Email Address}&
product={Product List}&
type={data, image, both}&
start_time={Start Time}&
end_time={End Time}&
[format=xml]
```

This /get command returns a list of products that match given criteria.

- **Parameter:** email

  Email address of the user.
- **Parameter:** product

  List of selected products. If there is more than one product name specified, the names are separated by commas (,).

  Example: product=MULTI_85V,MULTI_37V.
- **Parameter:** type

  Type of the selected products: data (NetCDF files), image (KMZ images), or both.

  Example: type=data.

DRAFT

Goal 2: Engaging the community

1. Participate in the ESIP independent evaluation
2. Collaborations with StomCenter
3. Operate the portal during 2015 and engage HRD/NHC
   - HRD/NHC visits and telecons
   - Wave Number Analysis investigations and engaging NHC/HRD and some researchers

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ESIP evaluation of TRL

What

- The AIST program uses Technology Readiness Level (TRL) to assess the maturity of its funded projects.
- AIST concluded that independent assessment of TRL within the ESIP Testbed could mitigate several issues with the current technology development process
- ESIP is well-situated to perform independent technology evaluations

The key objectives of ESIP's evaluation of AIST projects were:

- Independent TRL verification.
  - Ensure that technology is usable by someone other than developer.
  - Identify components which need maturation in order to be usable by others.
- Showcase technologies to potential adopters.
  - Identify more technology infusion opportunities.
  - Get more people thinking about who else (individuals, agencies, missions) might use it.
  - Encourage projects to examine technologies for possible use.
    - ! Examine it without making an investment.

Goal 2: Engaging the community

1. Participated in the ESIP independent evaluation of TRL

The evaluation summary:

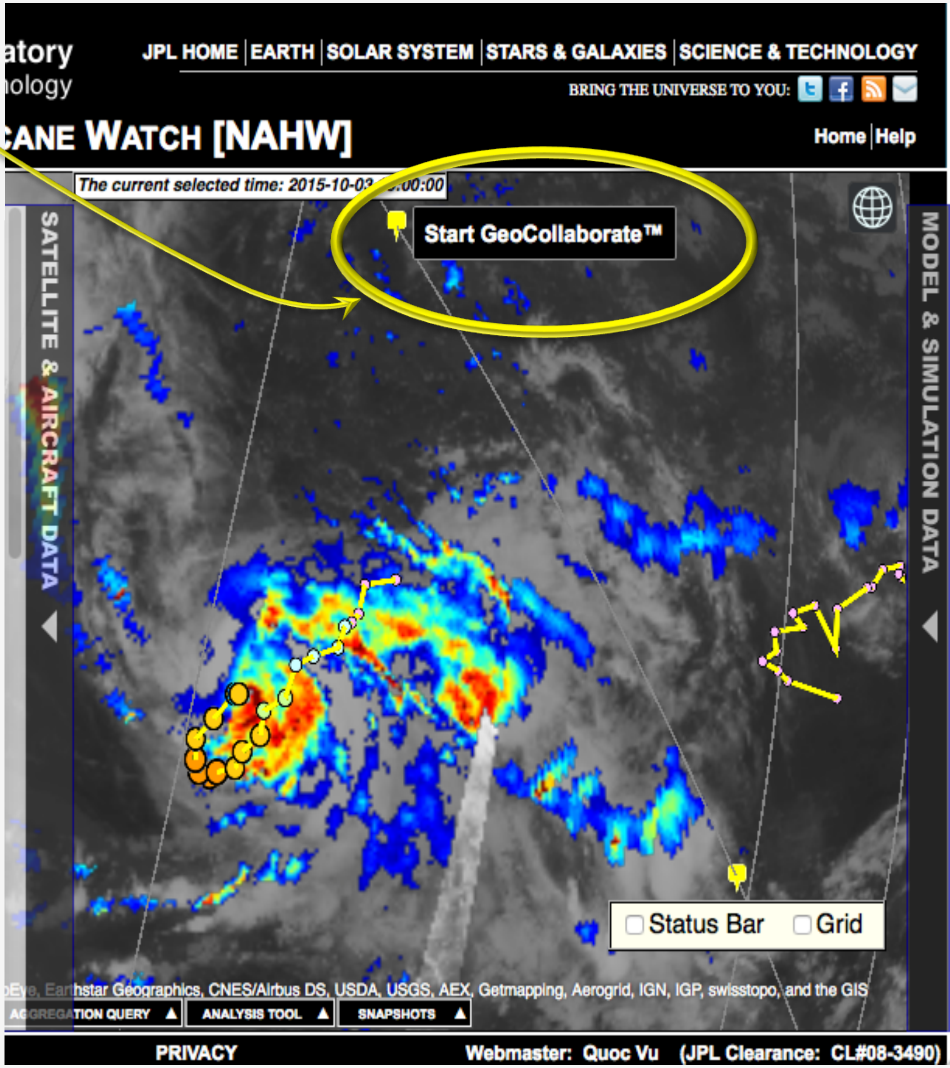
- The Tropical Cyclone Information System (TCIS) developed at NASA JPL **is a valuable tool for the tropical cyclone community**.
- The available **TCIS products are generally recognized as important** for describing a tropical cyclone (TC) structure and its surrounding environment.
- **The analysis tools the TCIS team has developed, particularly the implementation of the ARCHER algorithm and a Wave Number Analysis, are appropriate for popular research topics in the TC community**.
- The TCIS and the incorporated analysis tools are **generally easy to use**, though the ARCHER and Aggregation tools were less successful.
- Overall, **the capabilities currently available in the TCIS for synthesizing satellite observations with similarly simulated model observables can contribute towards the community's broad goal of better understanding and forecasting hurricane processes**

Goal 2: Engaging the community

2. Collaborate with StormCenter to build the GeoCollaborate capability around the NAHW

- The latest version of GeoCollaborate is capable of capturing all necessary features of our portal.

- More importantly, through our joined efforts, the key online analysis tools have also been made available through GeoCollaborate.



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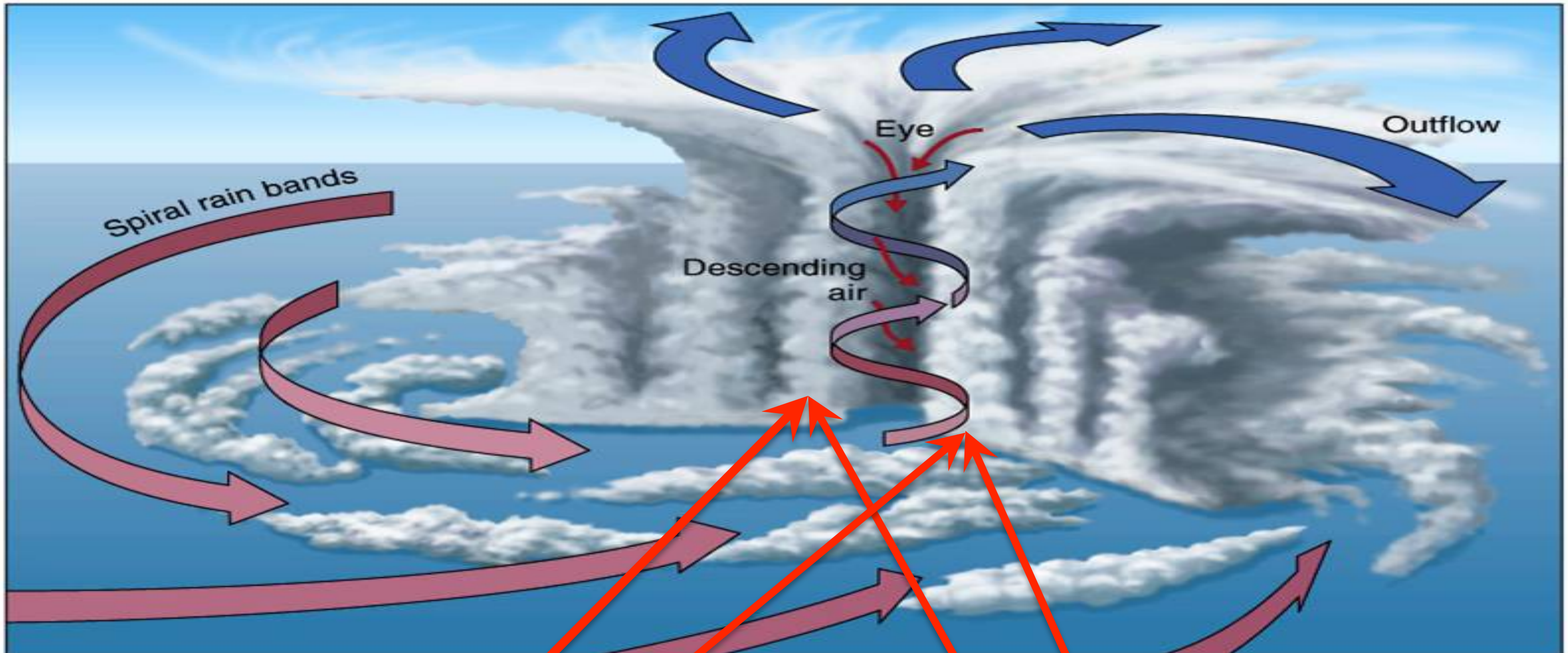
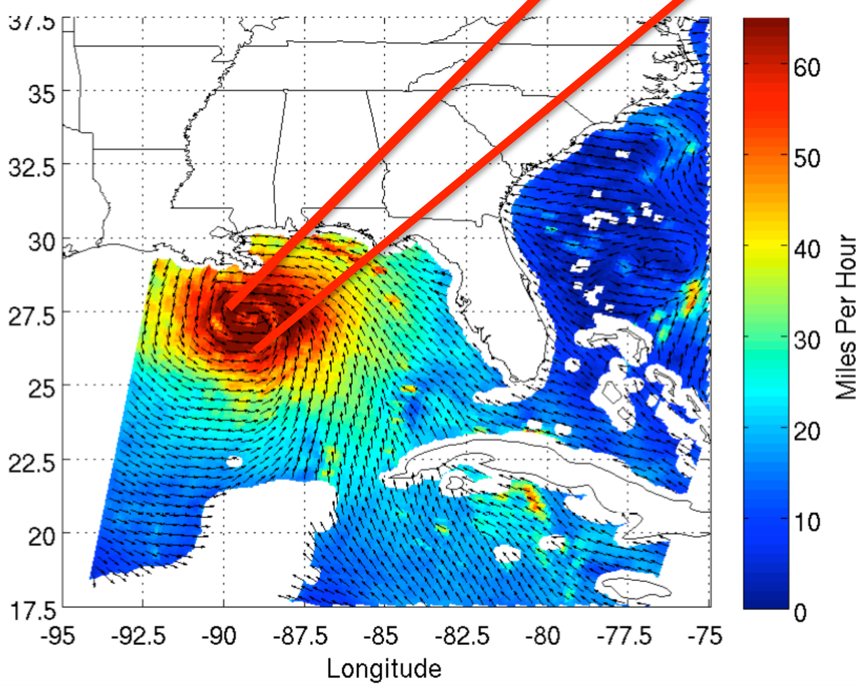
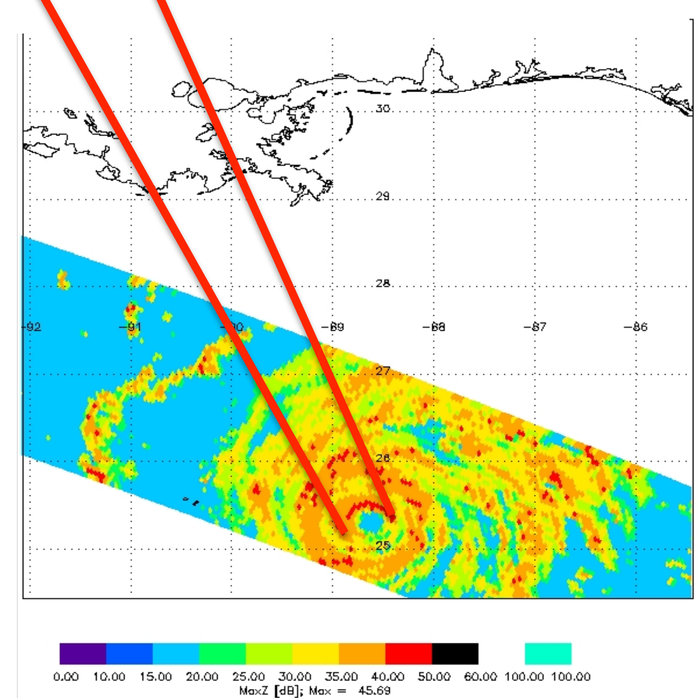
Studying hurricanes



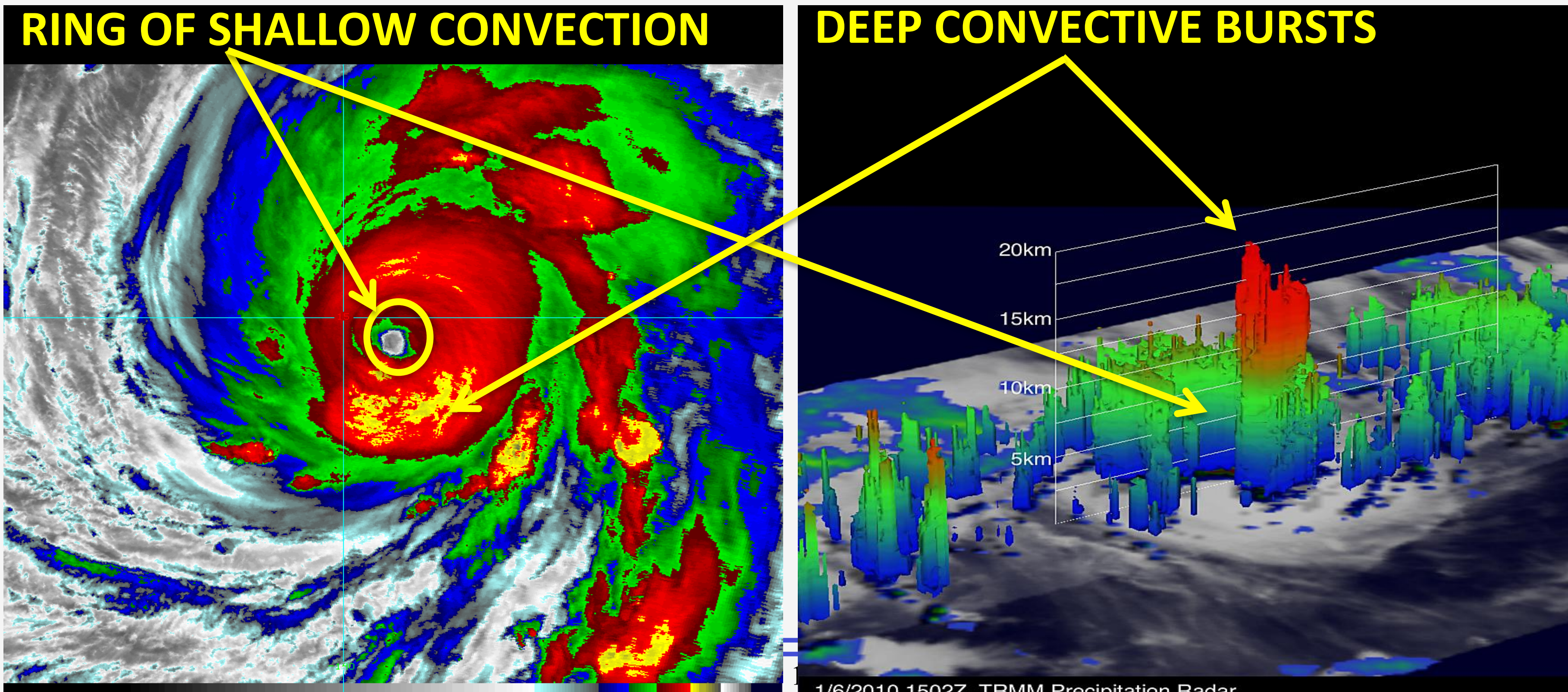
Katrina (2005) as seen from QuikSCAT



TRMM - max reflectivity



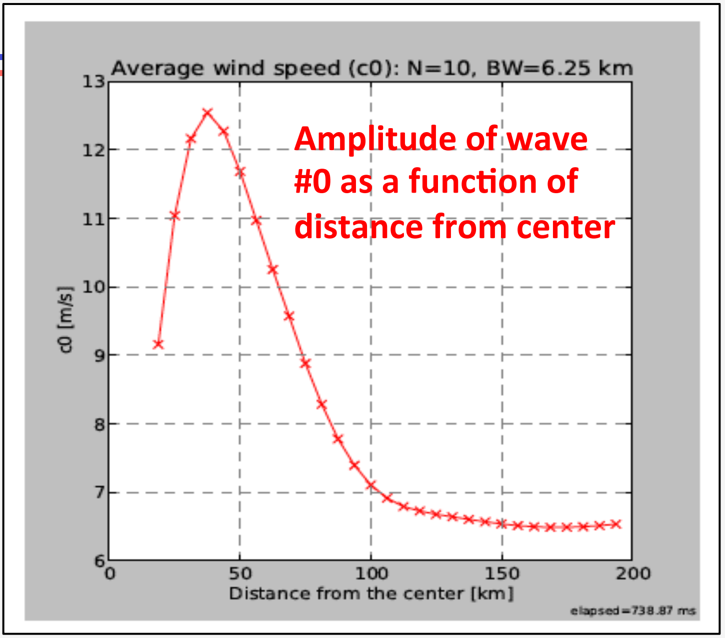
- Recent studies have linked RI to intermittent occurrence of deep, strong convective bursts within the inner core, occupying as little as 5–10% of the area of the hurricane eyewall.
- However, an alternative hypothesis is that RI follows abundant and well organized but weaker convection in the inner-core region. A continuous azimuthally symmetric eye wall (i.e., a ring) of precipitation then indicates the imminent onset of RI. This occurs when the ring is closed and dominated by shallow precipitation extending from near the freezing level to the surface. In this scenario, individual deep and strong convective bursts may still be embedded in the outer edge of the ring but play only a secondary role in RI.
- We use observations from scatterometers and radiometers to investigate whether storm asymmetry decreases in association with increase in storm intensity.

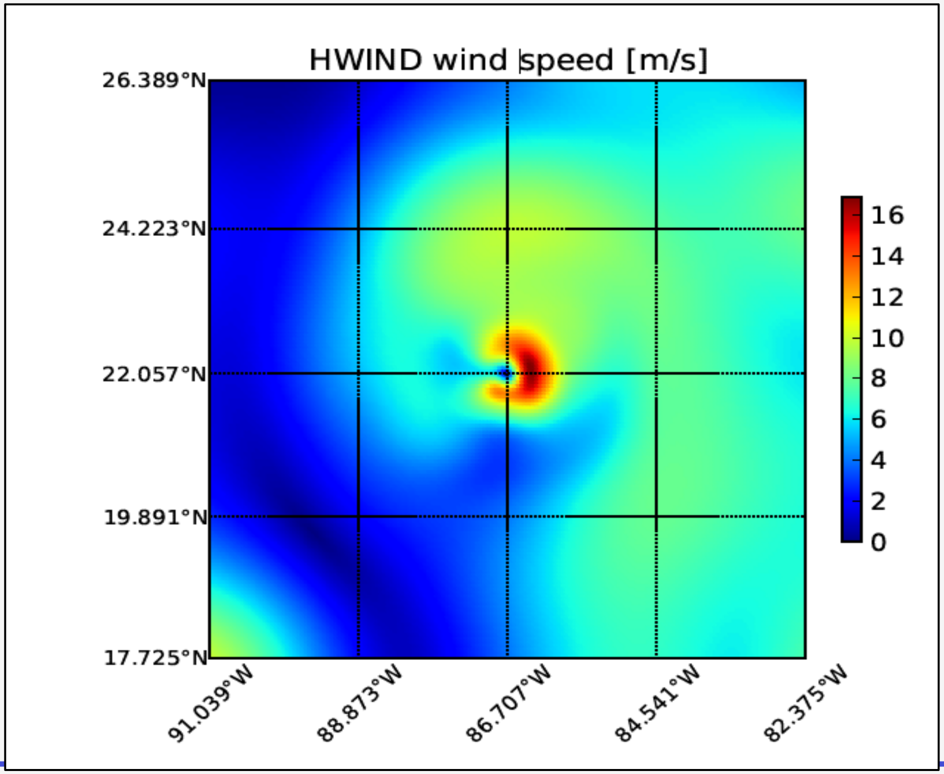


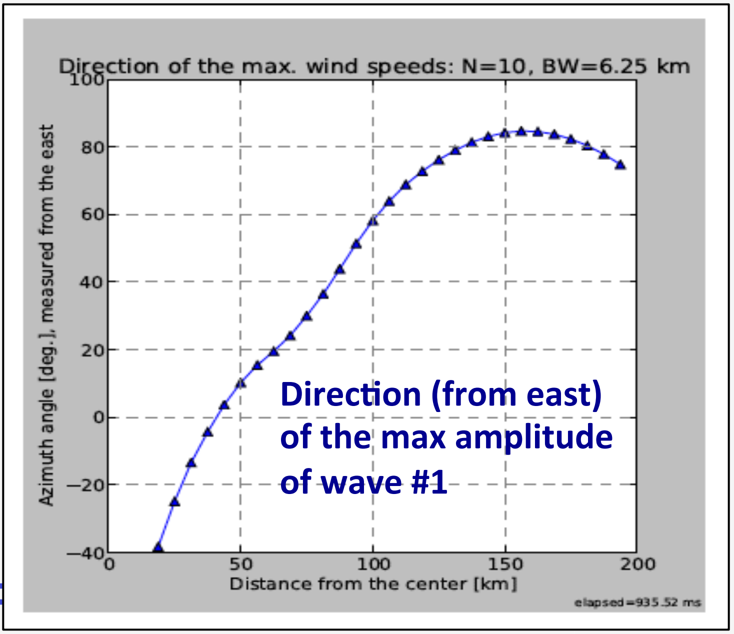
Storm structure Tool: Storm Size and Asymmetry

The Wave Number Analysis Tool

- **First adopted and used by NOAA/AOML/HRD**
  - **Vukicevic, T., E. Uhlhorn, P. Reasor and B. Klotz, 2013: "A novel multi-scale intensity metric for evaluation of tropical cyclone intensity forecasts", Journal of the Atmospheric Sciences 2013 ;doi:** http://dx.doi.org/10.1175/JAS-D-13-0153.1
- **Tool Developed for the JPL TCIS by**
  - Z. Haddad, N. Niamsuwan, T.-S. Shen







Possible predictors for the Rapid Intensification and evolution of hurricanes from satellite observations of precipitation and surface winds

Questions regarding hurricane evolution:

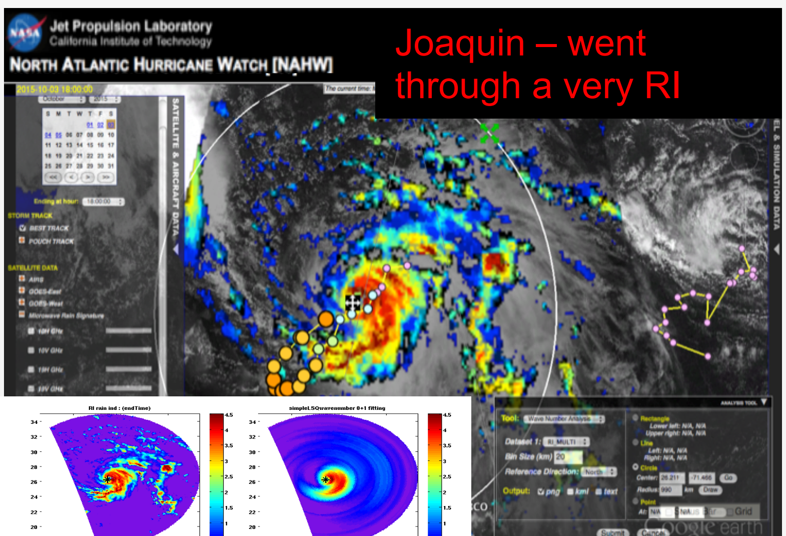
What is the **role of the azimuthally symmetric, weak convection?**

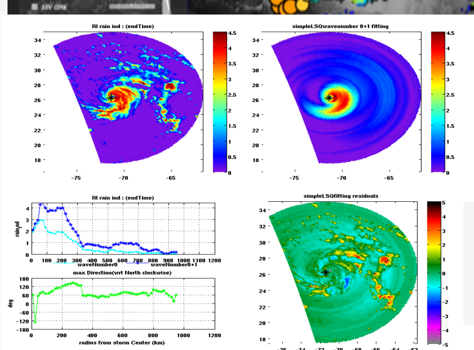
What is the **role of the isolated, intense convection?**

What is the **importance of the radial distribution of convection?**

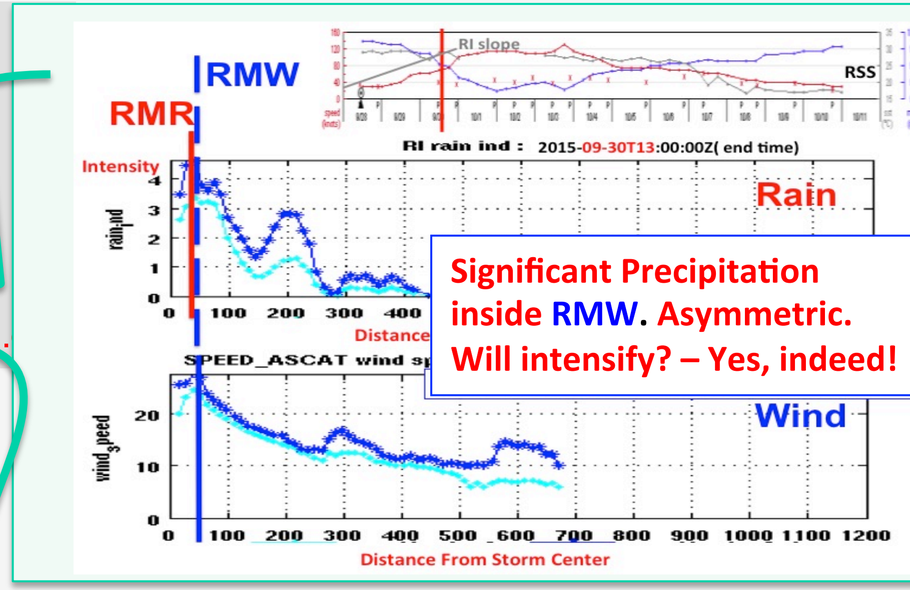
Can we use satellite observations to understand these roles? – It seems so …

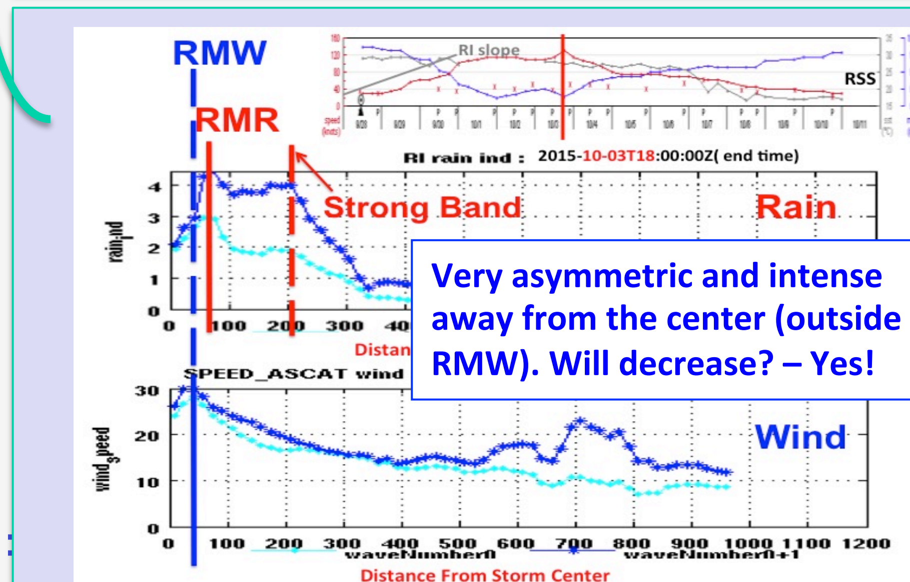
The JPL Tropical Cyclone Information System and The North Atlantic Hurricane Watch





Wave Number Analysis (online)

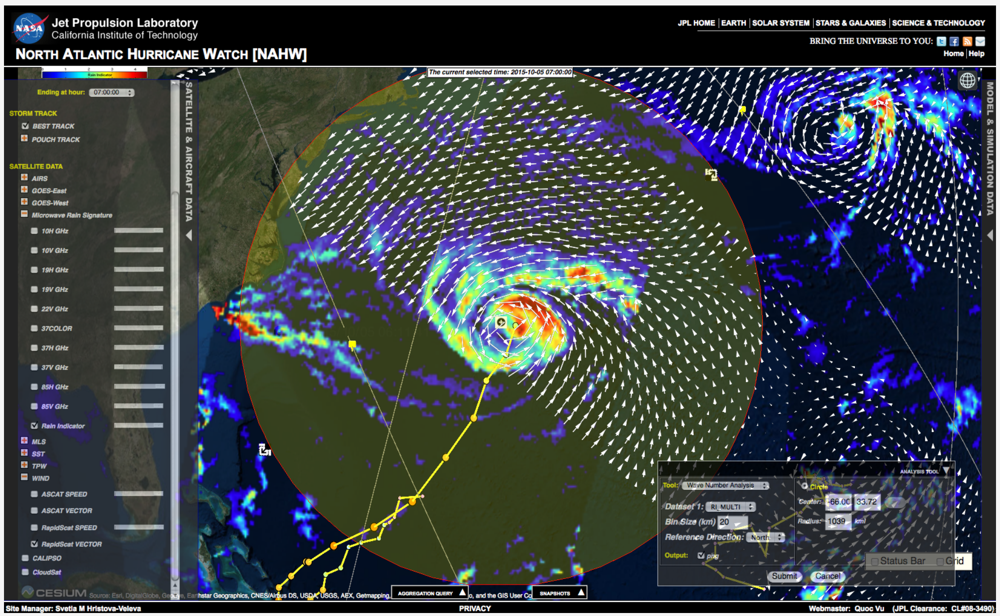




Technology Highlight:

Tropical Cyclone Information System (TCIS) Demonstrated During Hurricane Joaquin

In October 2015, products from the AIST-funded TCIS were presented to personnel at NOAA's National Hurricane Center and the Hurricane Research Division (HRD) for use in analyzing Hurricane Joaquin. The output from a TCIS on-line analysis tool, developed in collaboration with HRD, suggested the potential for rapid intensification (RI) several hours before it happened.



Recent enhancements to TCIS support interactive region selection, model and data acquisition, statistical comparison, and visualization and analysis. The figure reveals the structure of Hurricane Joaquin as depicted by near-coincident observations of the surface wind (from RapidScat) and rain fields (from passive microwave observations). Wave Number Analysis of similar observations at an earlier time suggested the potential for RI several hours before it happened.

TCIS is a tool that provides scientists the ability to overlay user-selected observational data on top of a variety of user-selected model predictions, and to perform some online analysis on models and observations to improve forecasts

NOAA's initial reaction was that TCIS analysis could provide valuable new information for understanding and forecasting hurricane rapid intensity changes, and NOAA researchers also commented positively on the value of TCIS's user interface, analytic tools, and data access.

PI: Svetla Hristova-Veleva, JPL

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Summary

- To achieve the HFIP goals of improving the forecast accuracy of hurricane intensity, track and impact at landfall we first **need to understand whether the models properly reflect the physical processes and their interactions**.
- To address the need for improving the model physics, the 2013 annual HFIP meeting suggested that **all available observations (satellite, airborne, in-situ) should be used systematically and extensively to evaluate the model performance.**
- Furthermore, the participants highlighted **the need for developing new metrics and tools for evaluating the:**
  - **storm structure**
  - **the interaction between different physical processes** (multiparameter observations) **and**
  - **the evaluation of the multi-scale interactions** (feedback between the storm and its environment).
- **Such studies require the use of large amounts of satellite data, coming from diverse instruments in order to create robust statistics.** Due to the complexity of the remote sensing data and the volume of the respective model forecast this in-depth evaluation is usually limited to a number of case studies.
- **With the goal to facilitate model evaluation that goes beyond the comparison of "Best Track" metrics, we are working on providing fusion of models and observations by bringing them together into a common system and developing online analysis and visualization tools.**

What is unique about our efforts

- **Large number of Observations, COMBINED with Models**
  - New source for all radar and passive microwave data –PPS – with consistent format and inter-calibration, lower latency and higher reliability
- **Interactive visualization and interrogation**
  - Search by Date; Search by Hurricane; "Storm Track", Forecasts Tracks
  - Overlays, Transparency
- **Synthetic data from two instrument simulators**
  - Simulation of Satellite-like observations
    - Operational – Using CRTM and HWRF; in NRT
    - Research - Orbit-sampling; Antenna-averaging; Instrument specific viewing geometry; Synthetic data from the large-scale models
- **On-line Analysis tools**
  - Environment
    - the "Slicer"; Thermodynamics from AIRS –Skew-T plots, at pressure levels
  - Storm structure – Vitals and Vertical structure
    - Storm Center Finding (ARCHER); Wave Number Analysis, Joint PDFs; PCA/EOFs
- **Integration with the 12+ year climatology**

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Thank you !

BACKUP

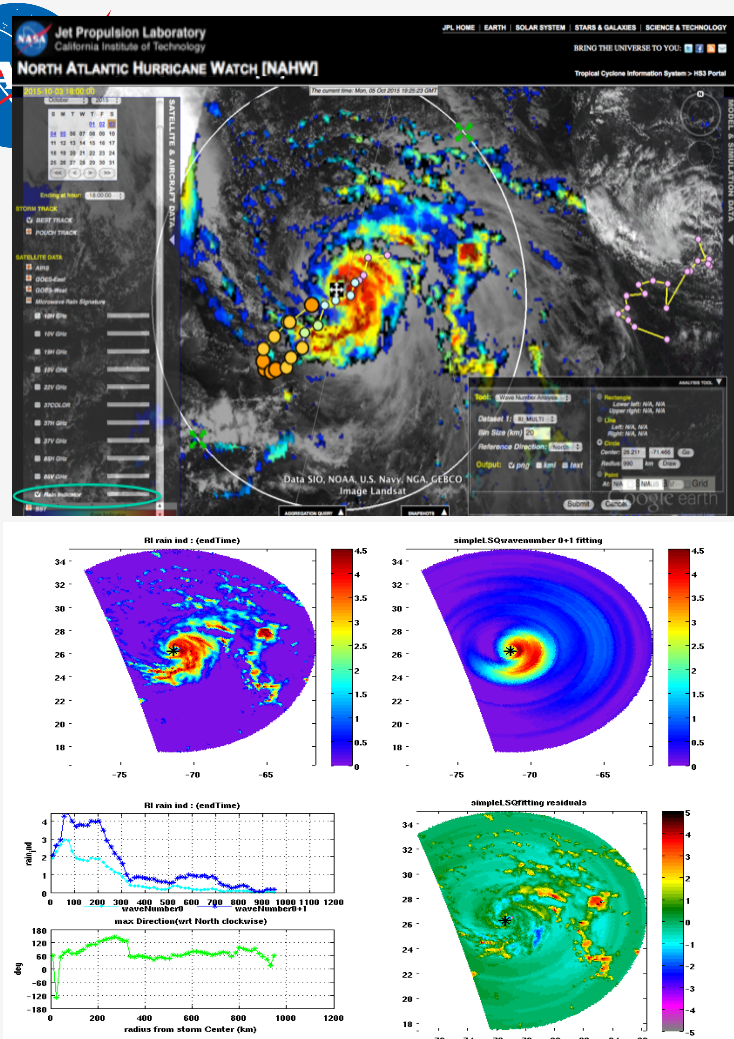


Figure 1. Top panel shows the NAHW portal and how the WNA tool can be initiated . The bottom panel illustrates the results from the WNA of the storm's precipitation structure (as depicted by the Rain Index on 10/03/2015). The four panels show (in clockwise direction from top-left): the full field; the representation as depicted by wave numbers 0+1; the residual; the radial distribution of: wave number 0 (cyan) and the amplitude of wave numbers 0+1 (blue) in the top line plots; the radial distribution of the direction in the peak of wave number 1 (green). The distance between the two curves in the top line plot signifies the degree of storm asymmetry: the larger the distance, the more energy there is in wave number 1, the more

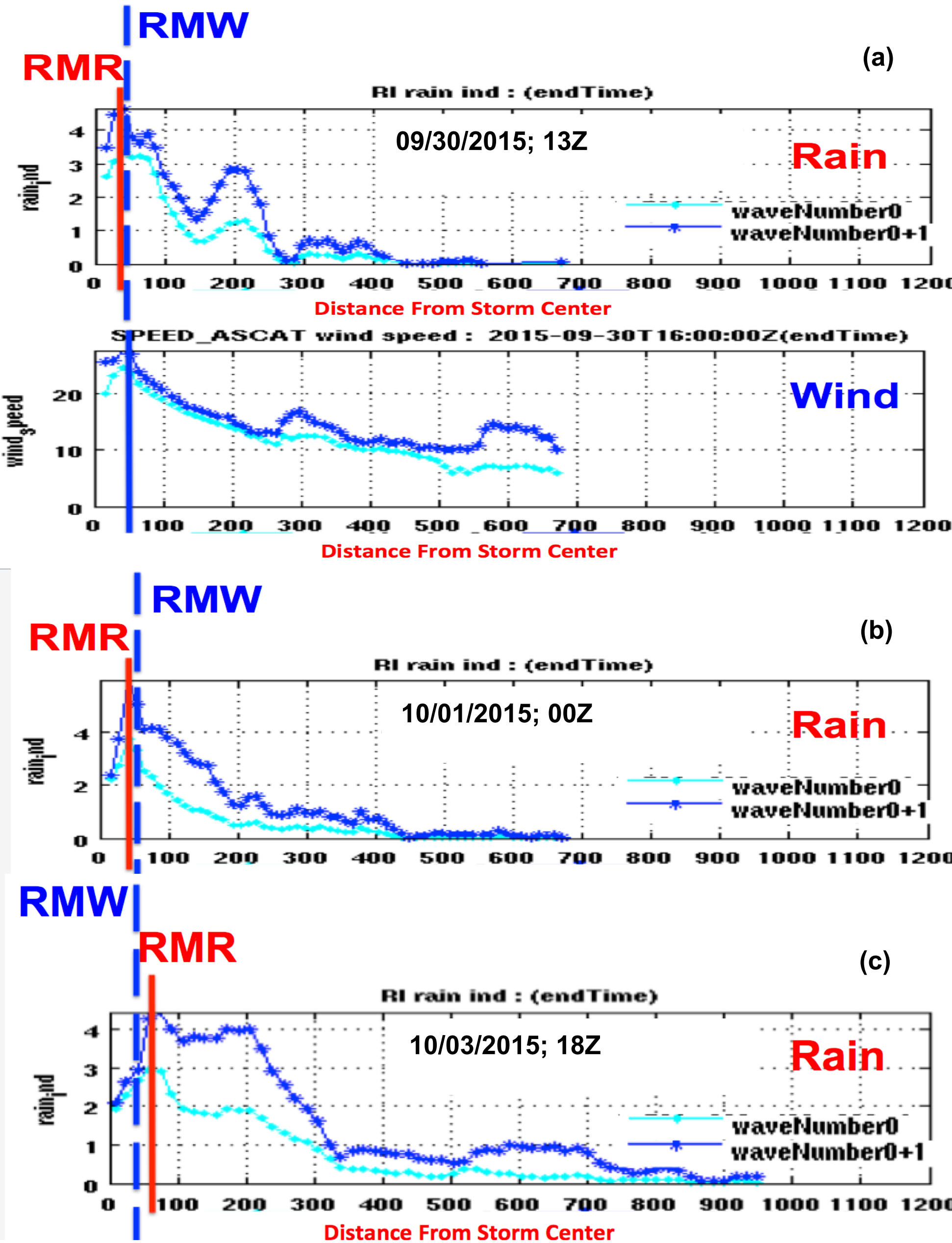


Figure 2. Radial distribution of the satellite-derived wind and rain fields at three different observation times. A very important aspect of the hurricane Rapid Intensification process is regarding the location of the convective activity (Radius of Maximum Rain – RMR)

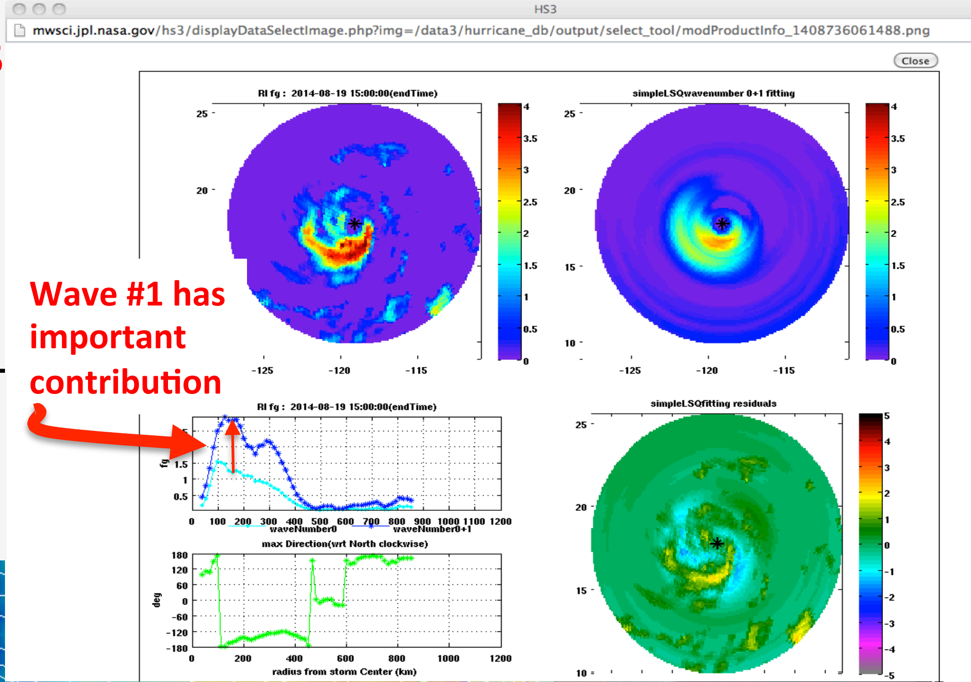
Storm structure Tool: Observations

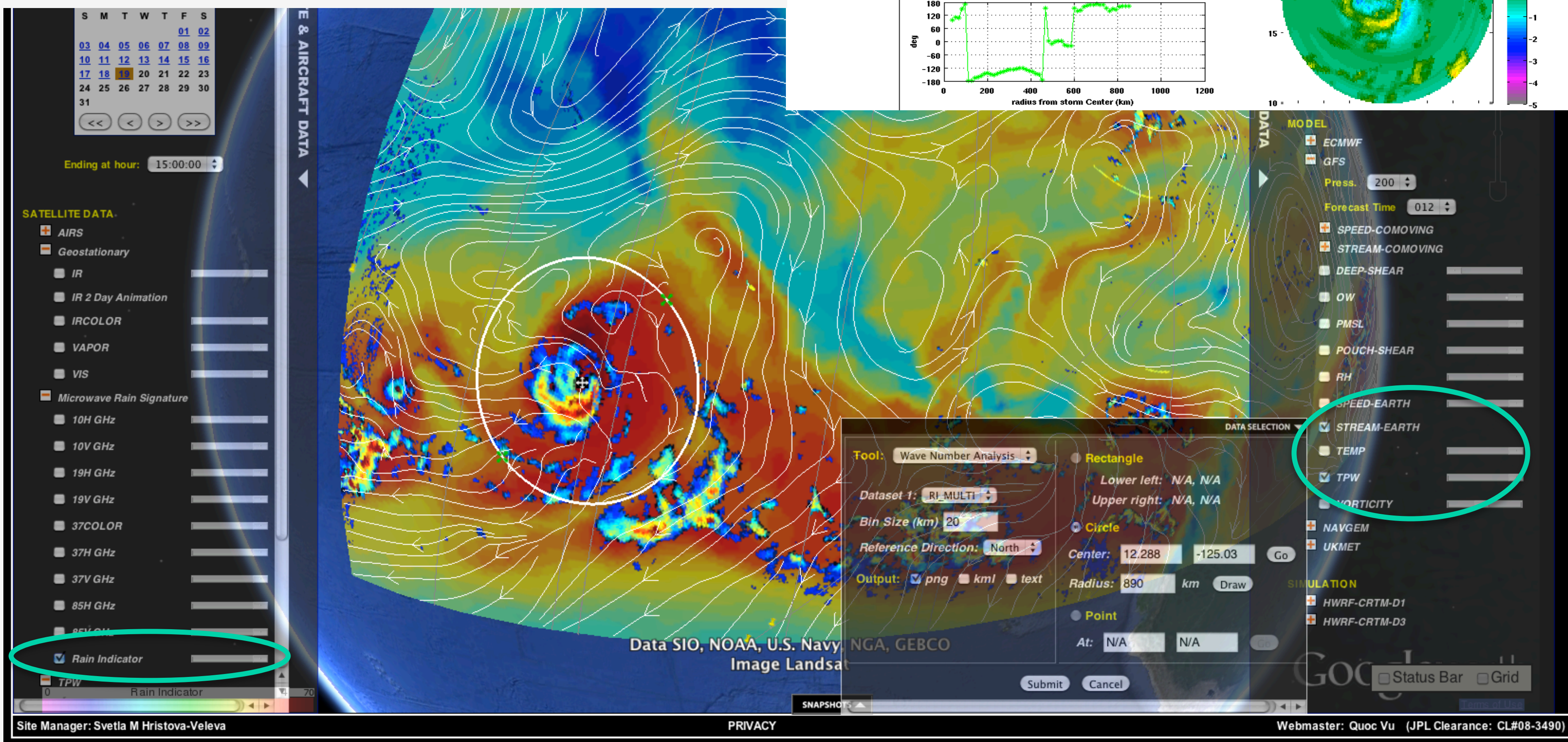
Storm Size and Asymmetry: The Evolution

The Wave Number Analysis Tool using the Rain Index

EP hurricane Lowell -08/19/2014: 15Z

Vukicevic, T., E. Uhlhorn, P. Reasor and B. Klotz, 2013: "A novel multi-scale intensity metric for evaluation of tropical cyclone intensity forecasts", Journal of the Atmospheric Sciences 2013 ;doi: http://dx.doi.org/10.1175/JAS-D-13-0153.1





Storm structure Tool: Observations

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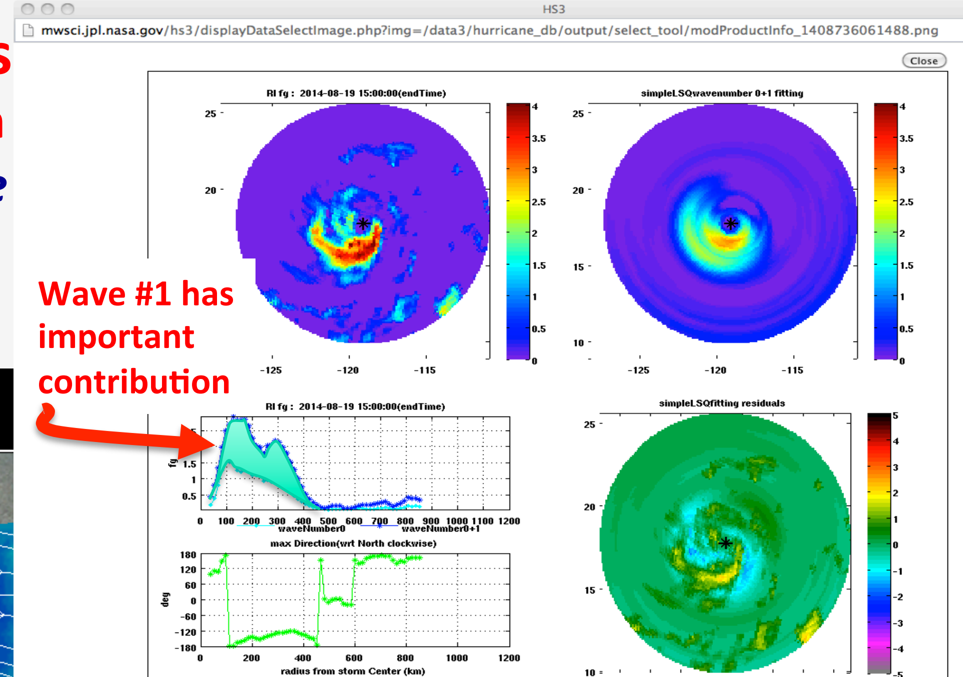
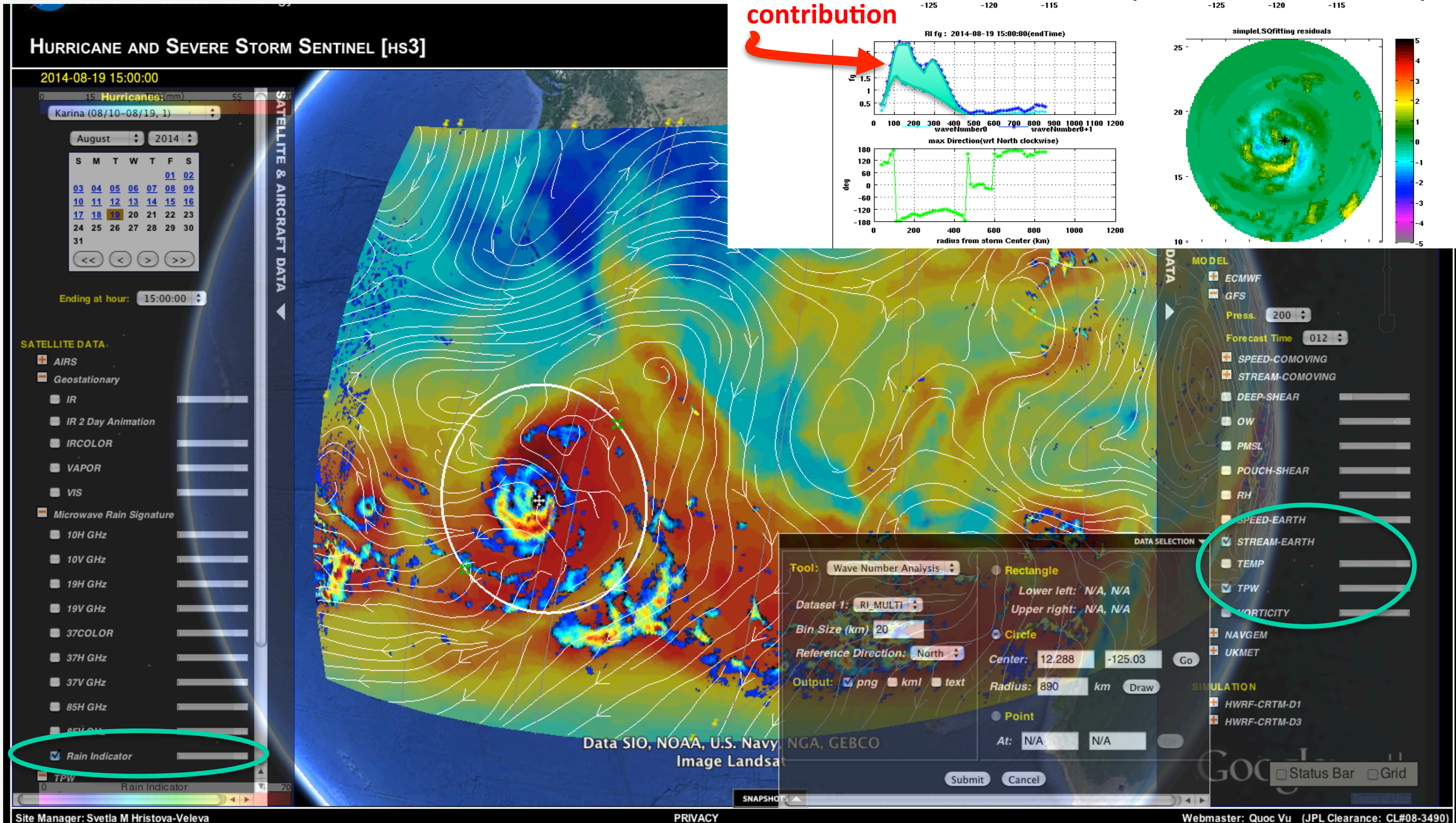
EP hurricane Lowell -08/19/2014: 15Z



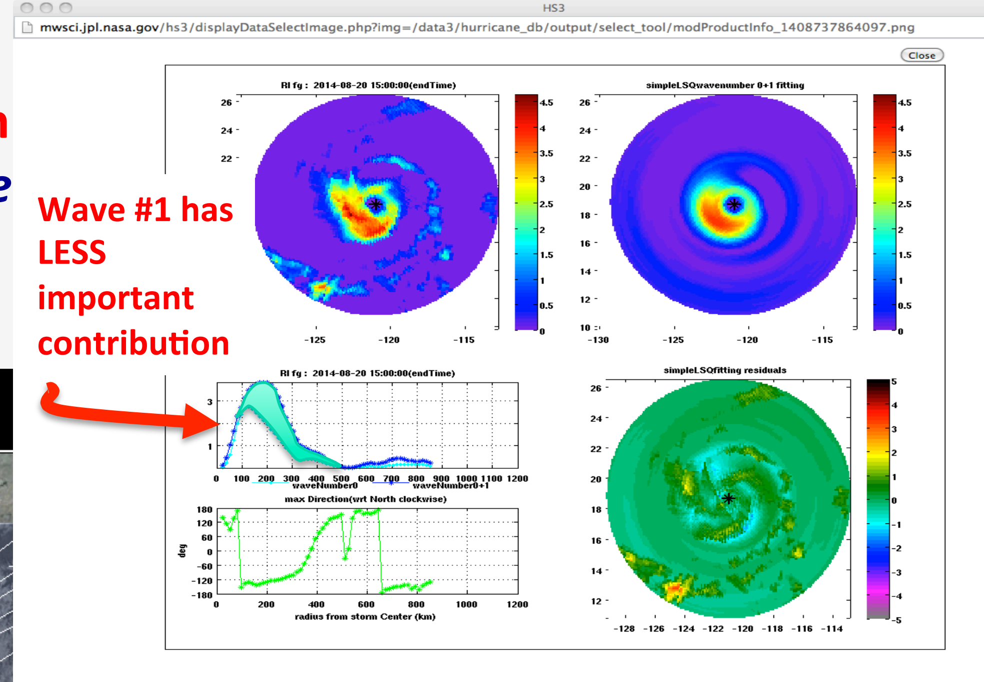


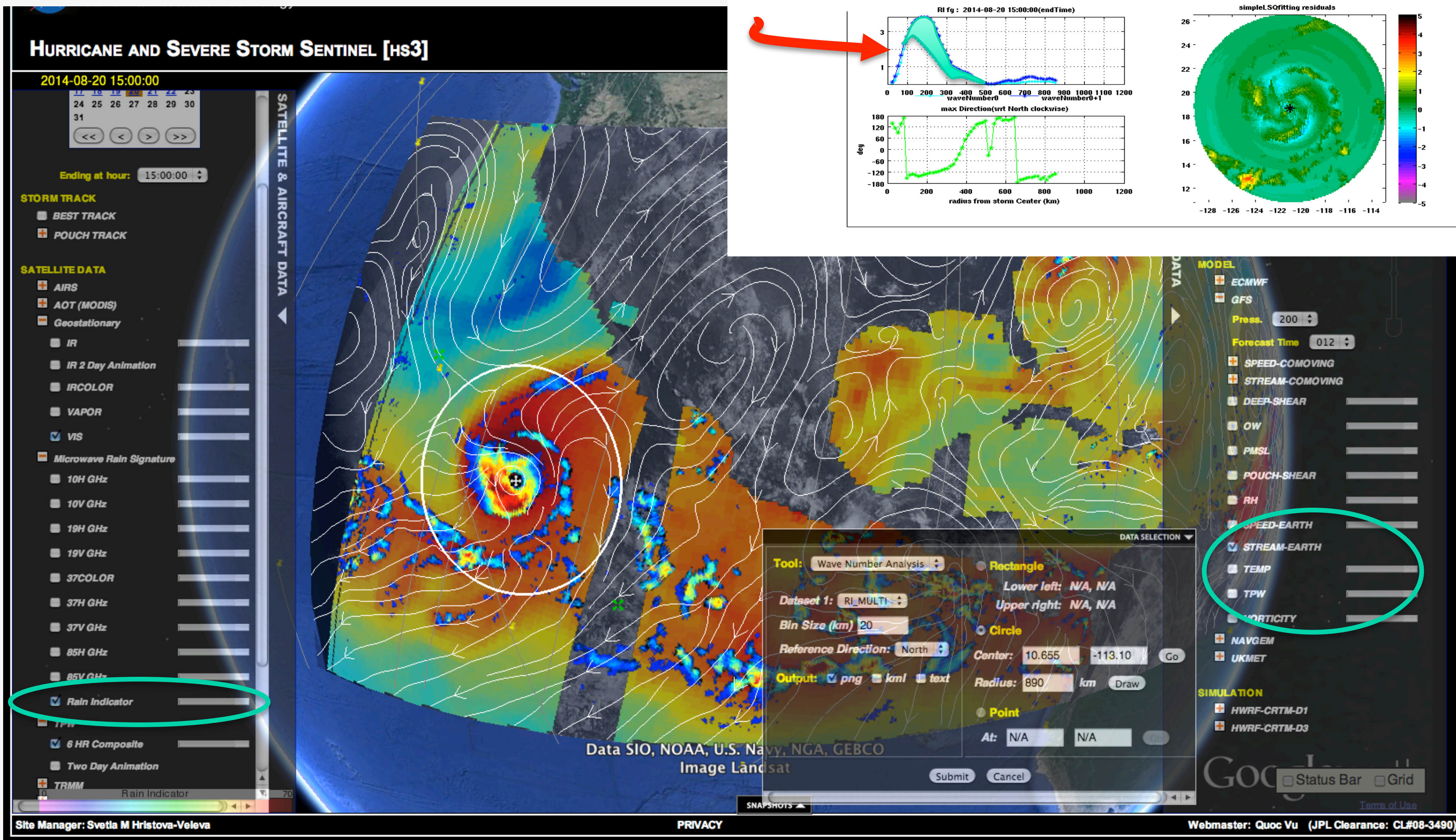
Storm structure Tool:

Storm Size and Asymmetry: The Evolution

The Wave Number Analysis Tool using the Rain Index

EP hurricane Lowell -08/20/2014: 15Z



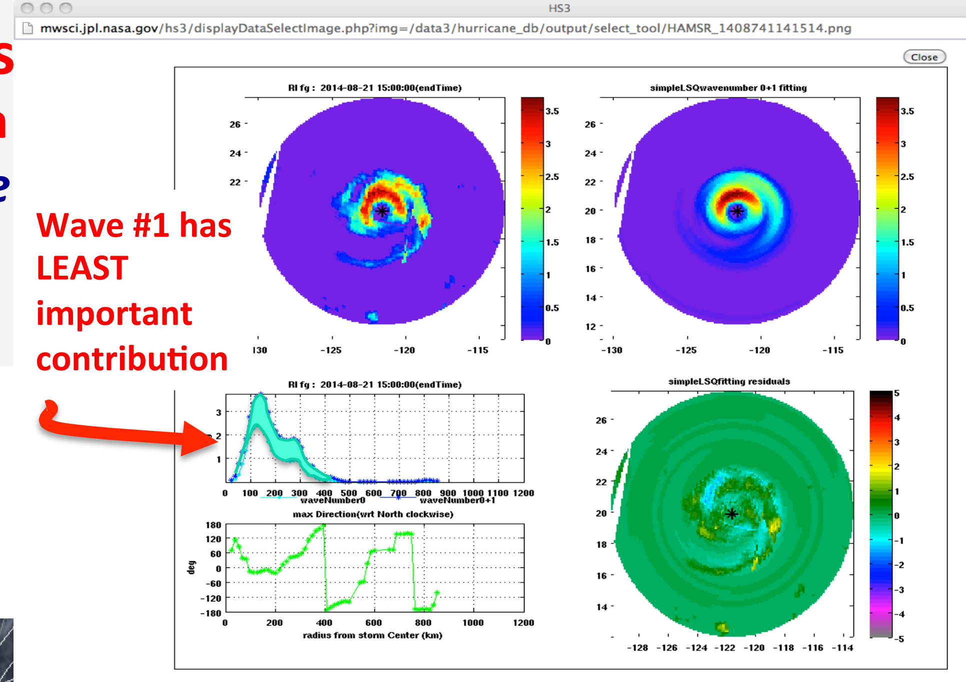


Storm structure Tool: Observations

Storm Size and Asymmetry: The Evolution

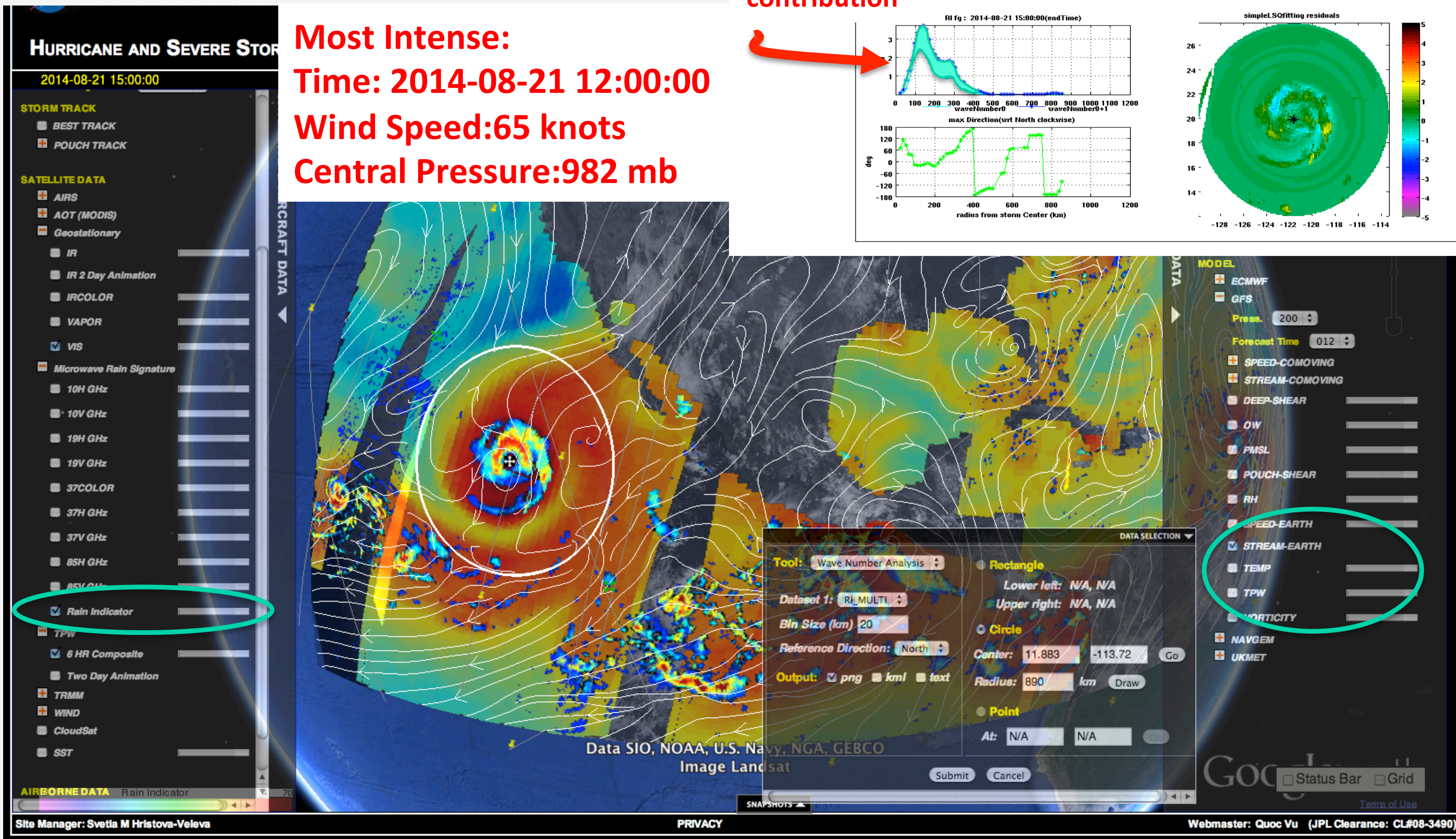
The Wave Number Analysis Tool using the Rain Index

EP hurricane Lowell -08/21/2014: 15Z



Wave #1 has LEAST important contribution

Most Intense:
Time: 2014-08-21 12:00:00
Wind Speed:65 knots
Central Pressure:982 mb

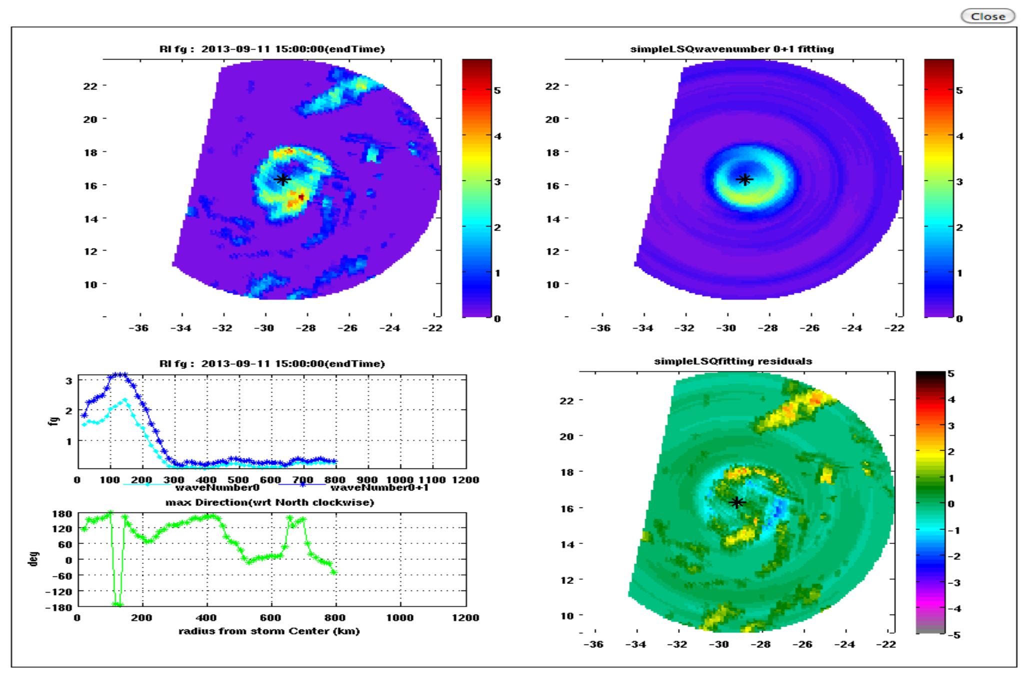


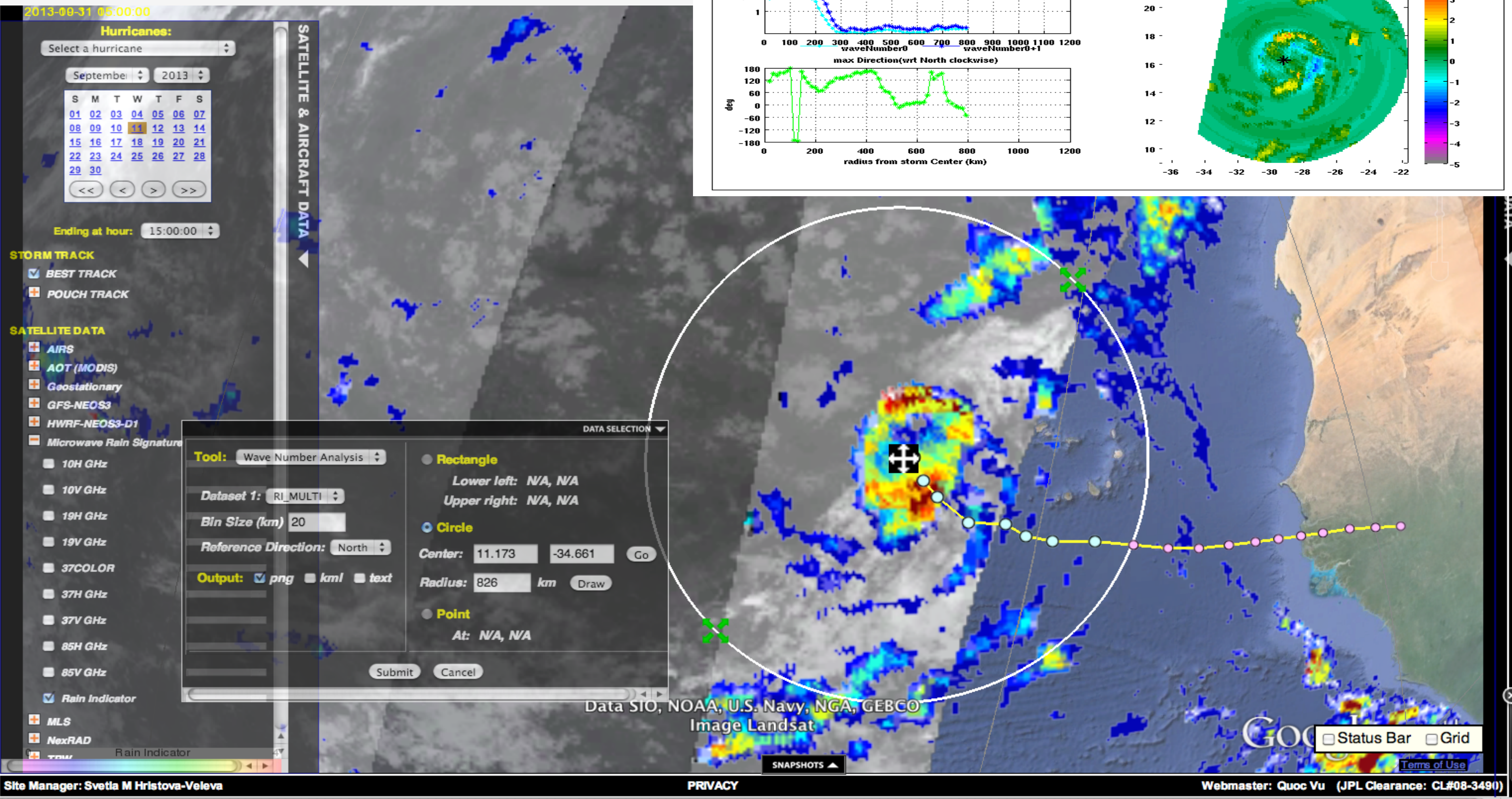
Storm structure Tool:

Observations: Rain

Storm Size and Asymmetry: *The Wave Number Analysis Tool using the Rain Index*

Hurricane Humberto -09/11/2013: 15Z



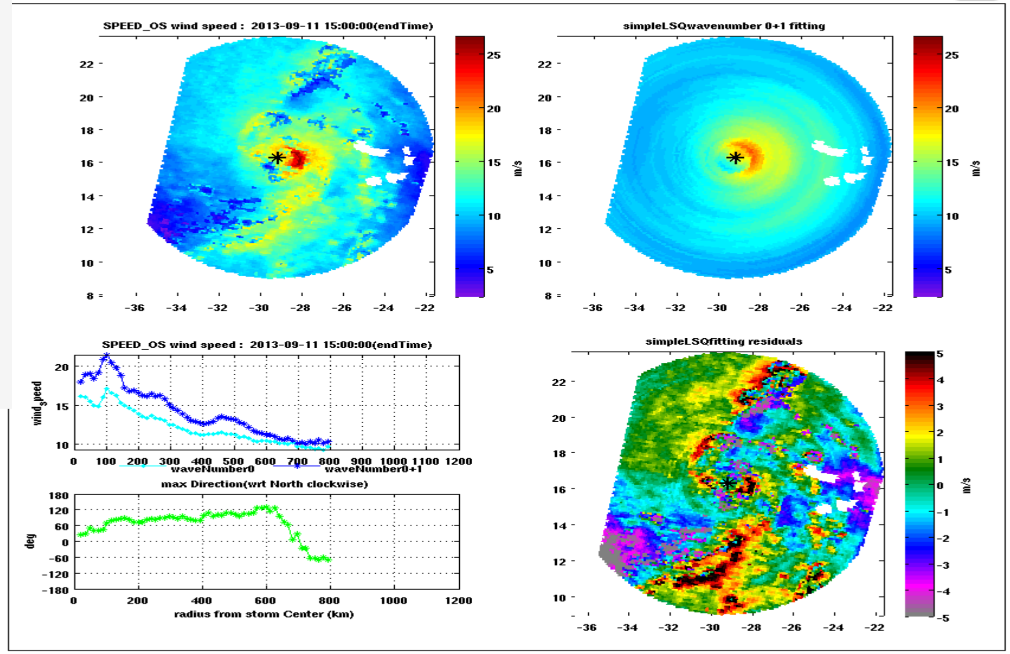


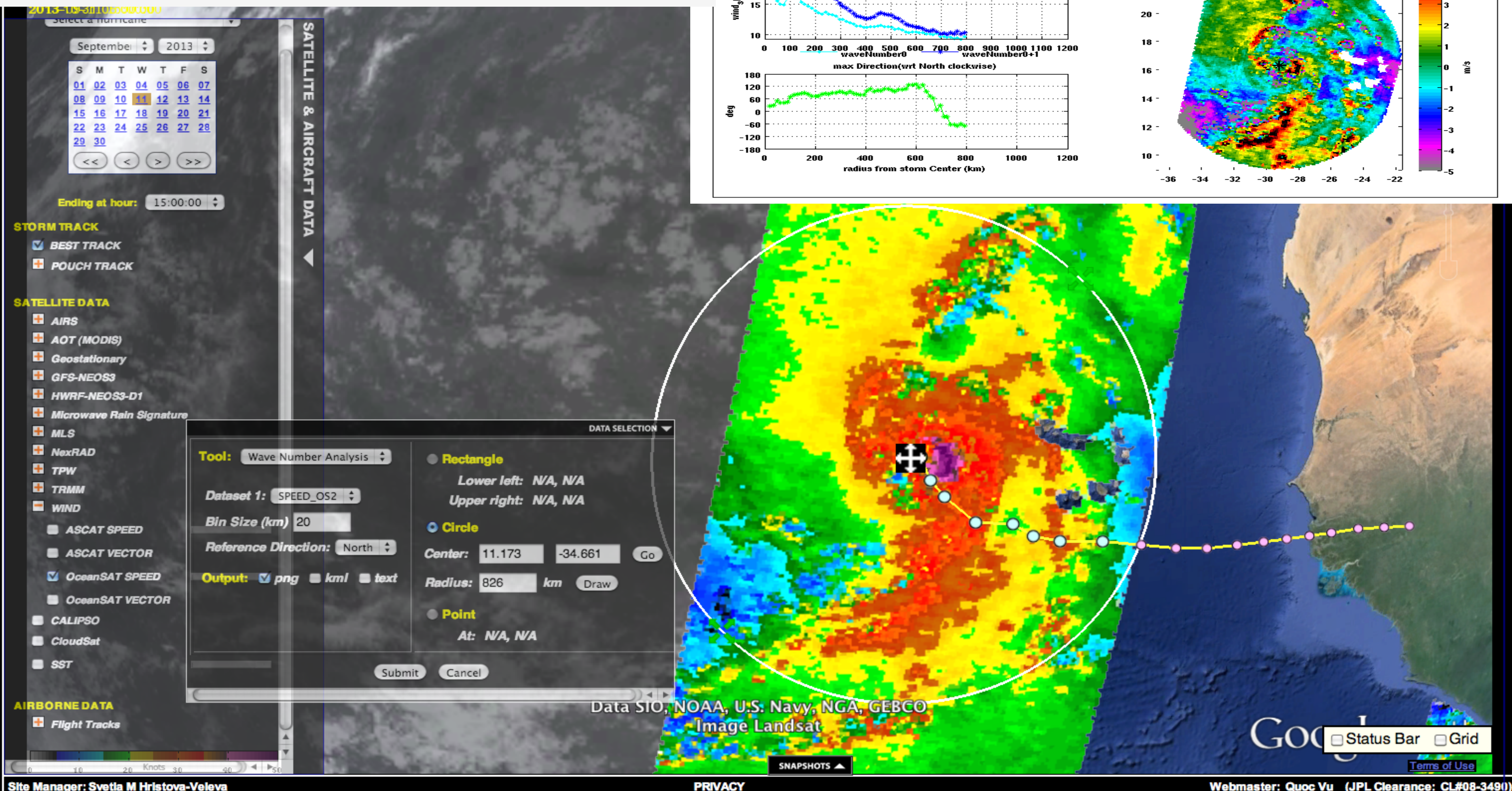
Storm structure Tool:

Observations: Wind from OSCAT

Storm Size and Asymmetry: *The Wave Number Analysis Tool using the Rain Index*

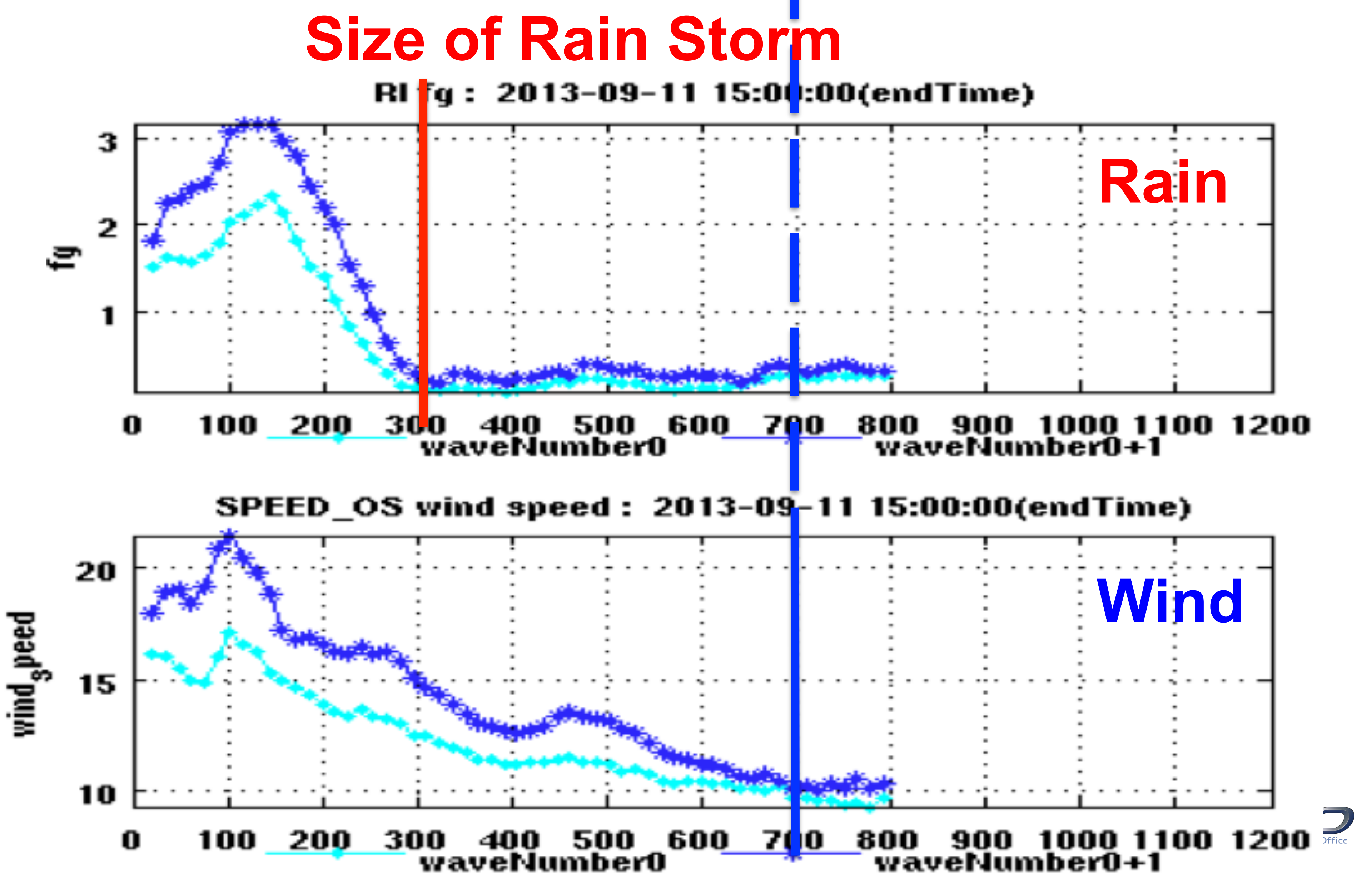
Hurricane Humberto -09/11/2013: 15Z



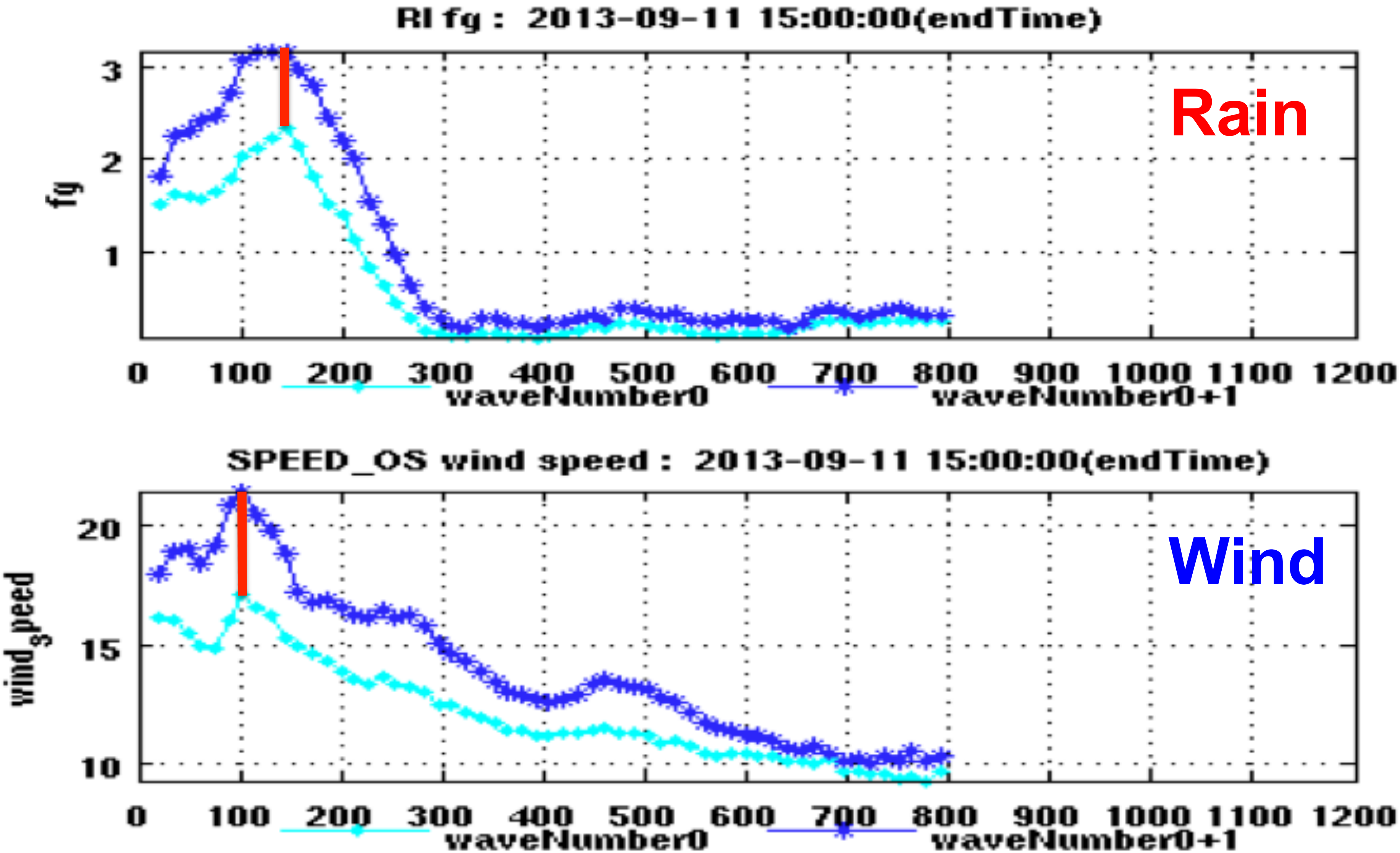


Size of precipitation is much smaller than the size of the wind field

Size of Wind Storm



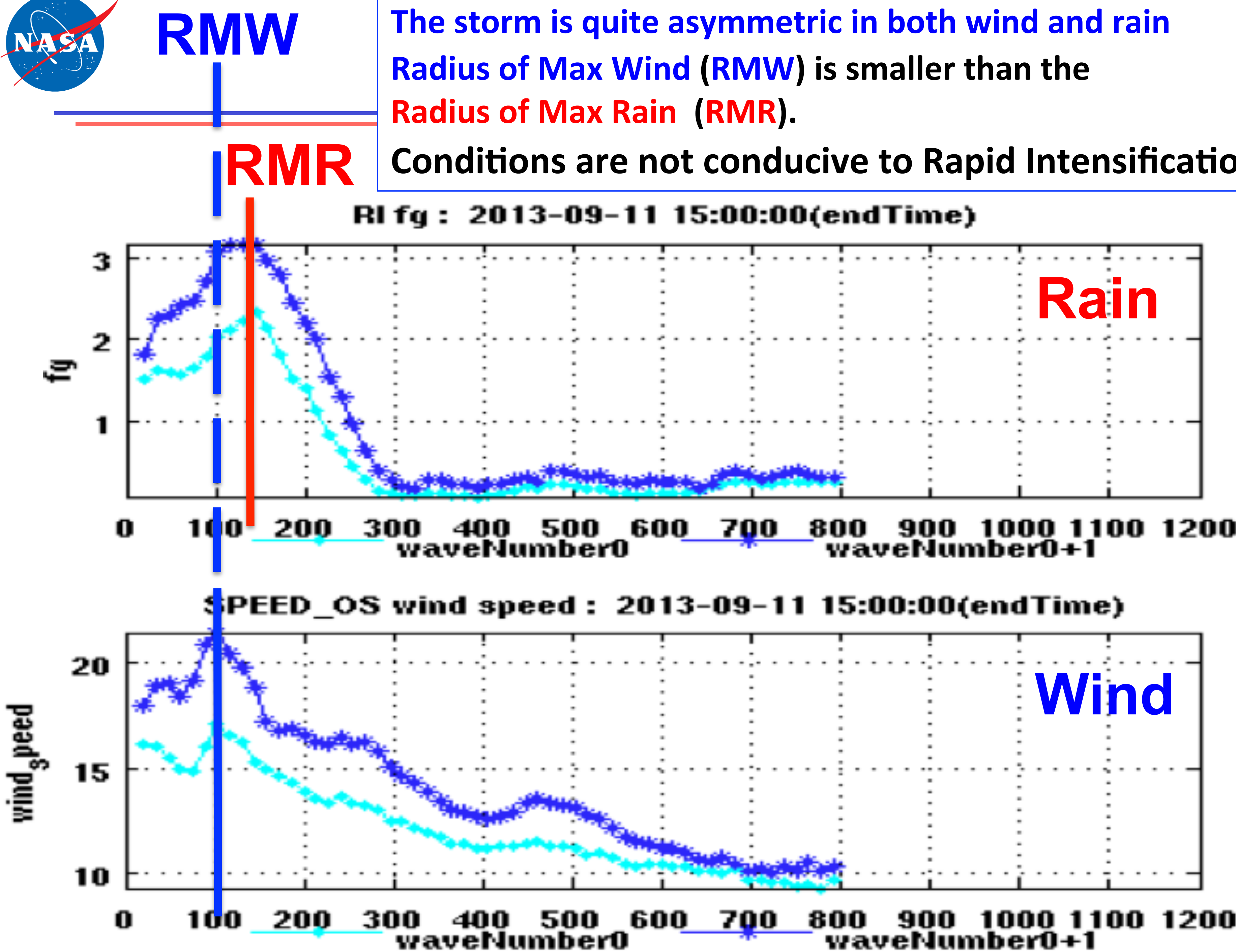
The storm is quite asymmetric in both wind and rain



The storm is quite asymmetric in both wind and rain

Radius of Max Wind (RMW) is smaller than the Radius of Max Rain (RMR).

Conditions are not conducive to Rapid Intensification.



The storm is quite asymmetric in both wind and rain

Radius of Max Wind (RMW) is smaller than the Radius of Max Rain (RMR).

Conditions are not conducive to Rapid Intensification.

Indeed, the storm remained very steady for 36 hours, before staring to weaken on 09/13/2013 at 06Z