Office of Naval Research

Tropical cyclone research and development supporting 2020-22 operations

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ONR Marine Meteorology Team (322MM)

TCORF - 3 March 2021

Outline

- **Tropical Cyclone Rapid Intensification (TCRI) Program:**
  - An ONR Departmental Research Initiative (DRI) is a competitive, focused 3-5 year effort to advance basic scientific understanding on an environmental topic
  - Develop conceptual framework of physical hierarchy of processes contributing to RI, with a focus on microphysics and boundary layer
  - Modeling strategy: coordinated COAMPS-TC research and analysis with LES simulation to study physics and parameterization capabilities
  - Observational strategy: partner with planned field efforts (NOAA IFEX, potentially NSF PRECIP, NASA, and others) to augment with additional cases and data
- **Navy Modeling (covered by Jim Doyle/Jon Moskaitis brief)**
- **Teaser on Future Projects**

- **Some COVID impacts**
  - Joint 2020 West Pacific typhoon field campaign postponed/cancelled
  - Some delays by performers, mainly related to student hiring and spin-up
  - Delays in collaborative meetings, workshops, and strategies

TCRI Overview and Motivation

9th International TC Working Group Meeting 3-7 Dec 2018:

Recommendation #1: "We recommend that future research focus on:

a) **studying RI** as an event

b) improving understanding of the **conditions and precursors to RI**

c) reconciling seemingly conflicting findings on the **conditions and processes in which inner-core convection** may lead to RI…."

- Over 10 years of ONR investment has contributed to historic improvement in TC intensity prediction, mainly through targeted field campaign efforts and the subsequent development of skillful mesoscale modeling
- Despite steady progress, mesoscale models still perform worse than statistical models in cases of Rapid Intensification (RI)
  - This accounts for the largest fraction of the total intensity errors
- **Hypotheses**:
  - RI can be triggered with the ideal combination of favorable environmental conditions, ocean forcing, internal dynamical/physical state and interaction between scales
  - RI can be solved through basic research combining targeted observing strategies with advanced modeling to better understand missing or incorrect physical processes in mesoscale models

TCRI Technical Approach

- **Fieldwork**
  - Coordinate with NOAA for annual Atlantic hurricane season research
    - Have ONR PIs collaborate and expand logistical and scientific potential
  - Join with NSF PRECIP campaign and foster international joint program with Taiwan, Japan, and Korea to provide high targeted observations of typhoon precipitation and structure changes
  - Coordinate with European Space Agency for special satellite collects
  - Apply aircraft remote sensing to better understand vertical profiles of moisture and wind
  - Add additional dropsondes, flight hours, instruments to better target physical processes
  - Open to other possibilities in future years (NASA campaigns, NCAR G-V, etc)

- **Modeling**
  - Leverage ongoing NRL projects to improve global and mesoscale modeling capabilities
    - Focus COAMPS-TC research runs on physics changes, ensemble runs, and LES comparisons
  - Partner with top atmospheric large eddy simulation (LES) experts to understand turbulent fluxes and how they change through the TC intensification process

- **Theoretical**
  - Develop new parameterizations and bulk formula
    - RI assumption: in the absence of negative inhibiting factors, TCs will likely RI.
  - Determine if governing physics for RI happen as a monotonic progression, or step-function

Funded Participants

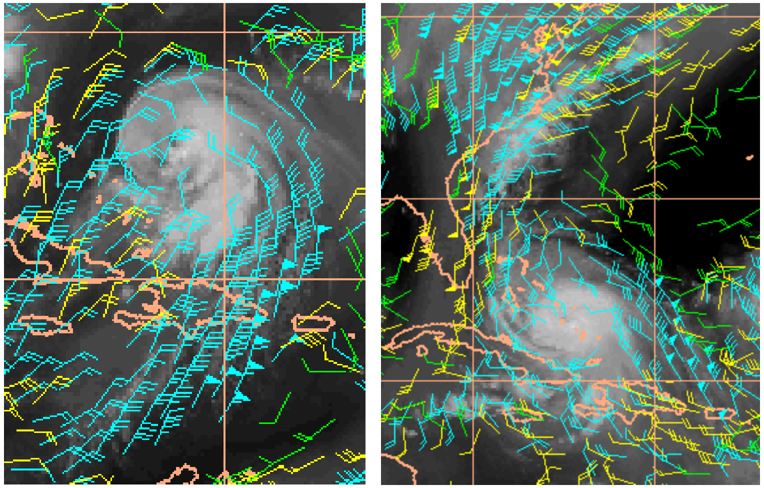
PIs	Institution	Project Title
Michael Bell	CSU	Heating, Cooling, and Rapid Intensity Change in Tropical Cyclones
Jim Doyle	NRL	Dynamics and Predictability of Tropical Cyclone Rapid Intensification
Jason Dunion, Rob Rogers, Jon Zawislak, Joe Cione	UM/CIMAS NOAA/AOML	Investigating interactions between the tropical cyclone inner core and near environment and their impacts on intensity change
Ralph Foster	APL-UW	High-Resolution Hurricane Boundary Layer Structure From Sentinel-1A,B Satellite Synthetic Aperture Radar and Aircraft Observations
Sharanya Majumdar David Nolan	UM/RSMAS	Multi-scale interactions and predictability of tropical cyclone intensification
David Raymond Zeljka Fuchs	New Mexico Tech	Convection in Tropical Cyclone Intensification
David Richter	Notre Dame	Boundary layer structure and large eddy simulation of intensifying tropical cyclones
Brian Tang, George Bryan Jun Zhang	U. Albany, NCAR, UM/CIMAS	Boundary-Layer Processes Associated with Rapid Intensification in Tropical Cyclones
Anthony Wimmers Chris Velden	U. Wisconsin Madison	A Deep Learning Approach to Examining and Predicting Tropical Cyclone Rapid Intensification
Chun-Chieh Wu	NTU	Rapid Intensification in Tropical Cyclones: Dynamics, Thermodynamics and Predictability
Russ Elsberry Joel Feldmeier	UC-CS NPS	ADVANCES IN UNDERSTANDING, ANALYSES, AND PREDICTIONS OF TROPICAL CYCLONE RAPID INTENSIFICATION FROM NEWGENERATION GEOSTATIONARY METEOROLOGICAL SATELLITE DATABASES
Chanh Kieu Louis Fan	Indiana U.	On the Dynamics and Predictability of Tropical Cyclone Rapid Intensification

Environmental Sensitivity of Tropical Cyclone Outflow

Sharanya J. Majumdar, University of Miami

Science Objectives

- **To understand the role of outflow in the processes and predictability of tropical cyclone structure and intensity change**
  - What physical role can outflow play, if any, in secondary eyewall formation?
  - How are the outflow and rainband physically connected?
  - How is outflow captured in satellite data?
  - Does the spread in ensemble predictions capture relationships between outflow and intensity change?



2-day change in outflow of Hurricane Joaquin (2015)

Technical Approach

- Idealized, high-resolution modeling of a tropical cyclone in a controlled environment:
  - In the presence of an upper-level jet
  - In the presence of strong wind shear
- Comparison of satellite-derived Atmospheric Motion Vector (AMV) data versus aircraft data during TCI-15 field campaign
- Examination of ensemble predictions

Accomplishments

- New insights into role of outflow as an "agent" of intensity change:
  - Secondary eyewall formation
  - Rainband development
  - Re-intensification in strong shear
- 1 completed Ph.D. dissertation (Yi Dai)
- 3 peer-reviewed journal articles to date

Dynamics and Predictability of Tropical Cyclone Rapid Intensification

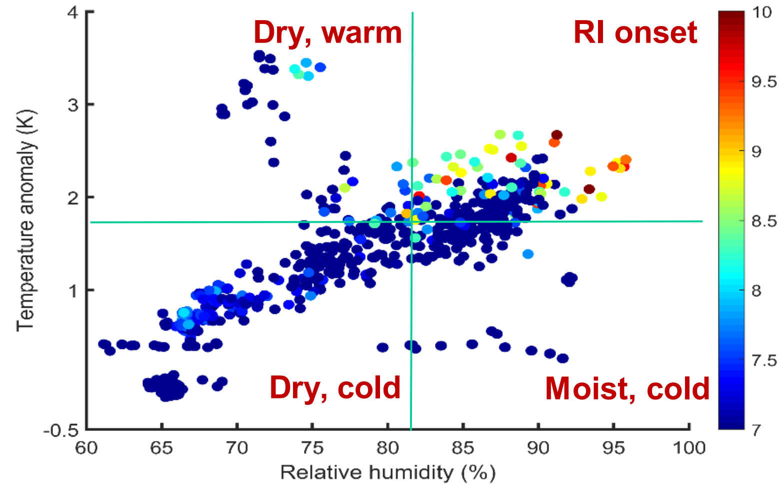
Chanh Kieu and Louis Fan, Indiana University, Bloomington

Science Objectives

i. Determine the key environmental conditions that control the rate of tropical cyclone (TC) rapid intensification (RI) and the timing of RI onset;

ii. Quantify the uncertainty and predictability limit of RI, particularly the maximum potential RI rate in different ocean basins;

iii. Provide new understanding into the relative importance of model physical schemes, stochastic forcing, and feedback mechanisms underlying RI;



COAMPS-TC displays a very consistent structure of a high mean relative humidity (> 80%) and warm core (>1.7 K) at the RI onset in the phase diagram.

Technical Approach

i. Numerical simulations of TC development under different environment conditions;

ii. Diagnostic analyses of TC structure and corresponding ambient environment for real RI events to help verify model simulations and results;

iii. Construct fidelity-reduced theoretical models that could capture distribution of the onset moment of TC rapid intensification under different stochastic forcing representations.

Accomplishments

i. Exploring different versions of stochastic fidelity-reduced models that could capture the distribution of the onset of TC rapid intensification;

ii. Finished preliminary experiments with the COAMPS-TC model to examine RI under idealized conditions;

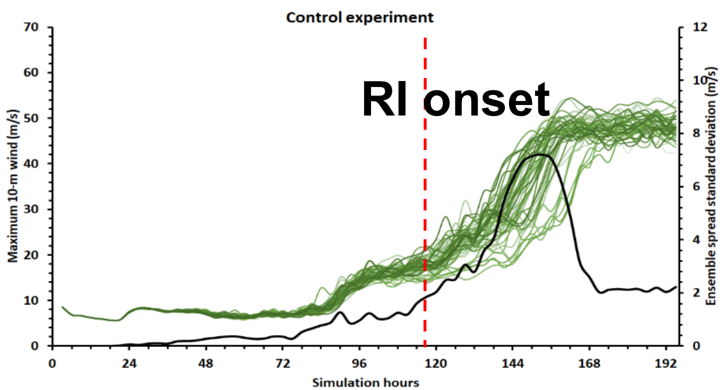
iii. Collected reanalysis data for a total of 23 TCs in the North Atlantic, Eastern Pacific, and Northwestern Pacific basins during 2018-2019 that display RI for model verification;

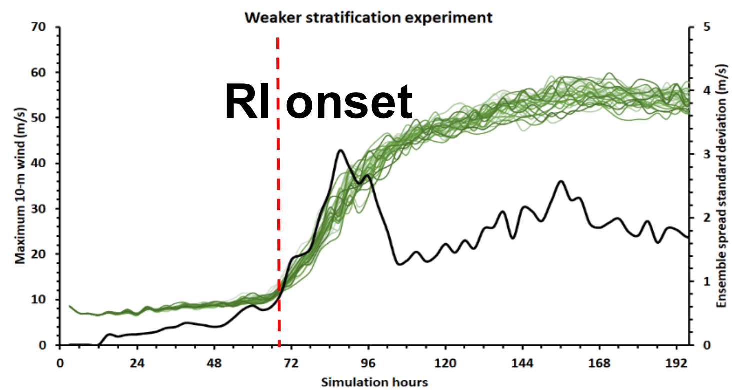
Dynamics and Predictability of Tropical Cyclone Rapid Intensification

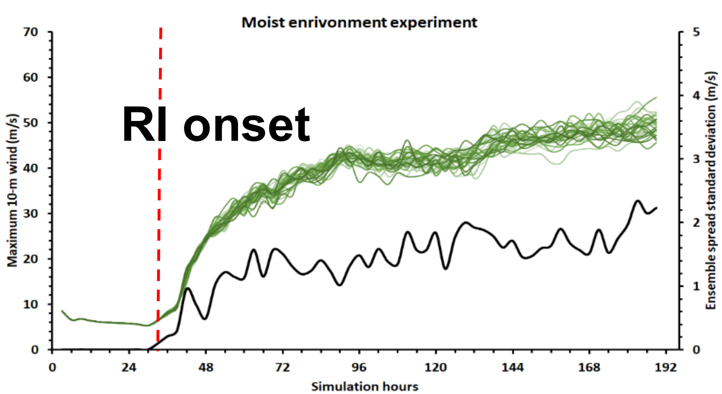
Chanh Kieu and Louis Fan, Indiana University, Bloomington

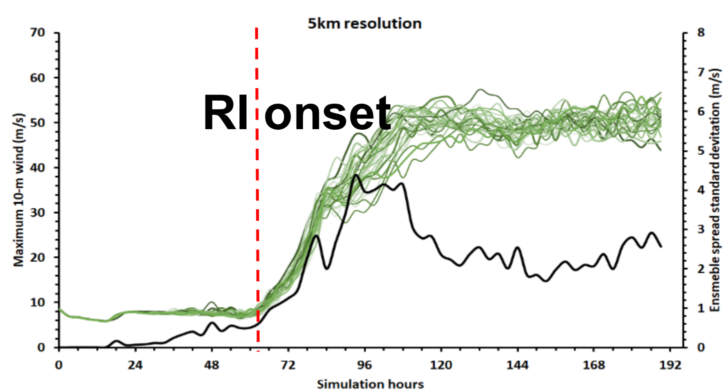
Highlights

- Consistent development of the model vortex in all idealized experiments with three stages 1) pre-conditioning, 2) RI, and 3) quasi-stationary;
- RI onset depends largely on the initial environment but not on the perturbations;
- Maximum RI rate is similar in all experiments;







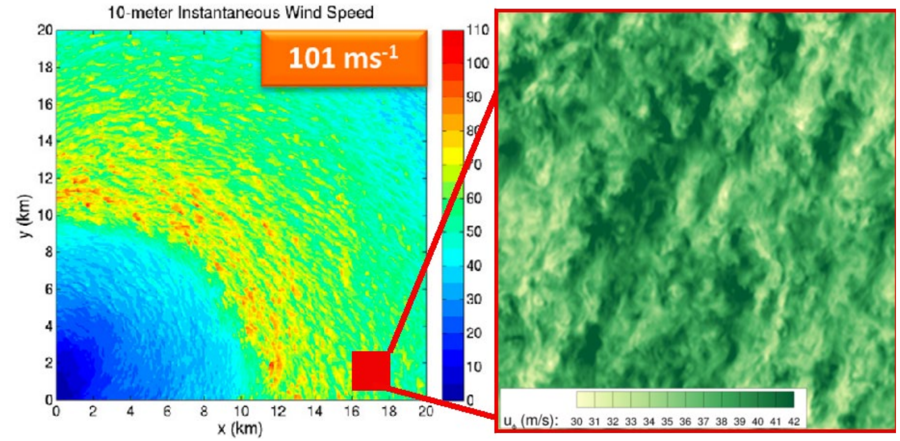


Boundary layer structure and LES of RI

David Richter, U. of Notre Dame

Science Objectives

- Determine the influence and signature of multiple boundary layer processes during RI
  - Waves/swell
  - Microphysics, including both spray and clouds
  - Turbulence
- Assess methods of estimating air-sea fluxes from observations, particularly during RI



From Stern & Bryan 2018

LES resolved to 1m

Technical Approach

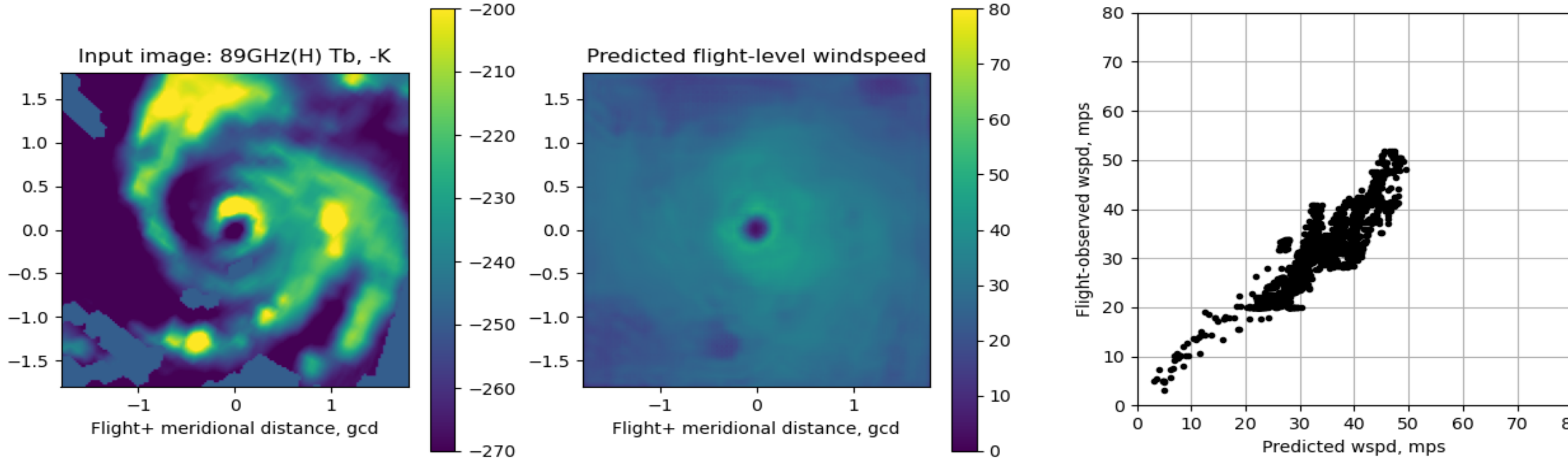
- Using high-resolution large eddy simulation (LES), configured to tropical cyclones
- State-of-the-art Lagrangian cloud modeling for seamless spray/CCN/cloud microphysics and coupling in boundary layer
- Phase-resolved wave/swell
- Theoretical development of simple flux-profile relationships for estimating air-sea fluxes from dropsonde and other measurements

Accomplishments

- Project began Dec. 2019, and is still in preliminary stages
- Multiple configurations of LES are being prepared and tested
- Analysis of “virtual sondes” indicates that flux estimates from dropsondes are sensitive to storm-relative location
  - Developed a database of existing sonde data and analysis in progress
  - Flux coefficients may be underestimated at high winds

A Deep Learning Approach to Predicting 2-Dimensional TC Rapid Intensification

Anthony Wimmers, Chris Velden, Derrick Herndon, Sarah Griffin
UW-Madison, CIMSS



Technical Approach

- Data preparation: We are partitioning flight transect data from the UCAR “Flight+” repository and experimenting with ways to process this into high-accuracy, high-volume 2D wind fields to use as truth data.
- These will then train an image-to-image deep learning model to estimate surface (or flight level) inner-core wind fields entirely from the structural information of microwave conical scanner satellite imagery

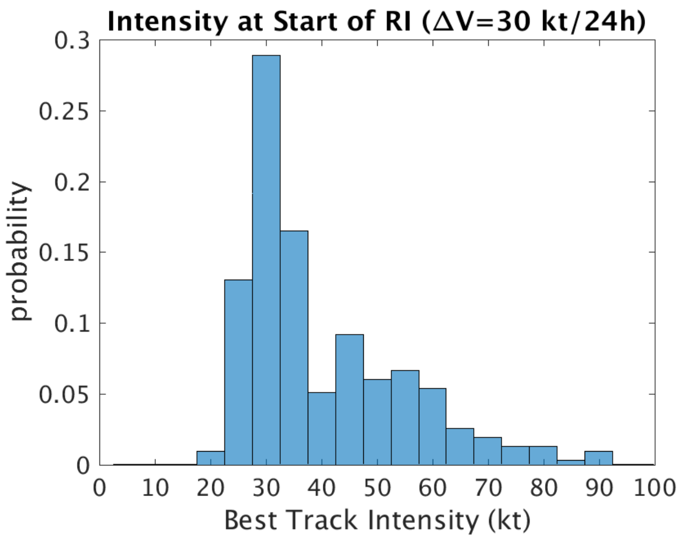
Accomplishments

- Rather than treat rapid intensification as the change in a single scalar property of a tropical cyclone, we demonstrate the ability of deep learning to produce an empirical model that incorporates 2-dimensional inputs and state variables and captures their evolution with time
- Prototype (images above) shows wind speeds predicted from microwave imagery produce reasonable structures when compared to aircraft measurements

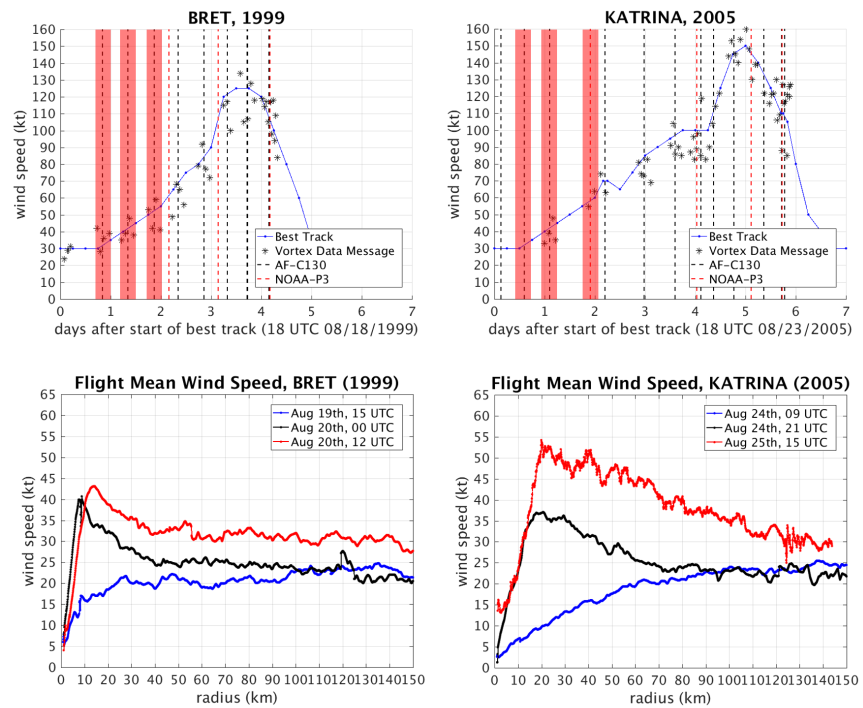
Initial Structure Modulates Intensification Rates

Dan Stern, UCAR/NRL

Distribution of Intensity at RI Onset Time



Observed Wind Profiles

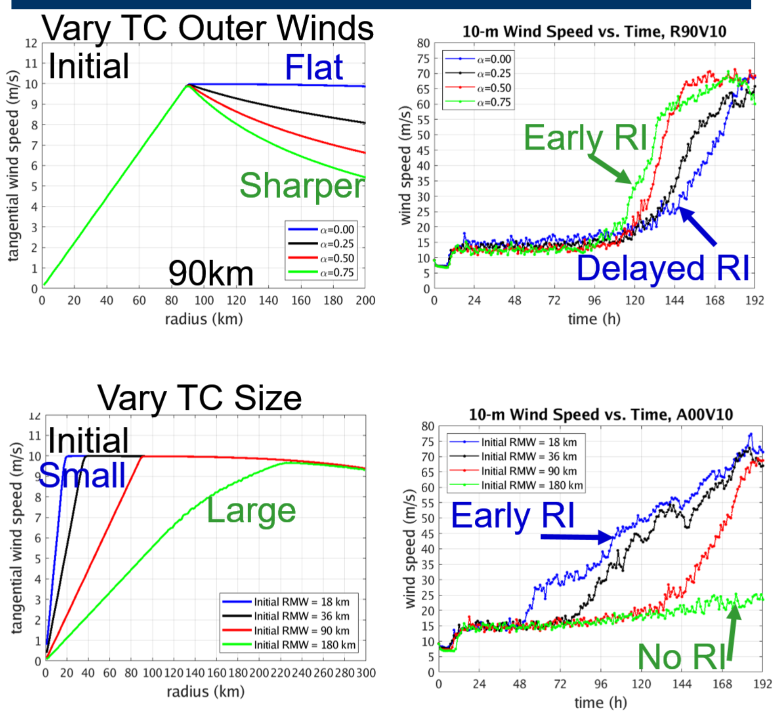


- Onset of RI most often occurs at very weak (25-35 kt) intensities.
- Prior to RI, wind profiles tend to be flat, with no well-defined maximum.
- A wind maximum forms near the time of RI onset.

Constraining TC Size on Intensification

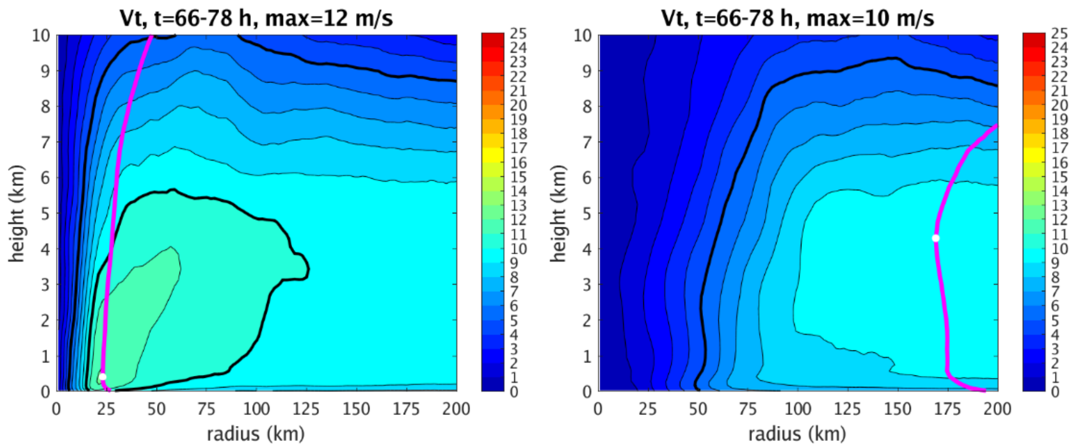
Dan Stern, UCAR/NRL

Idealized Simulations



Small TC (36 km)

Large TC (90 km)



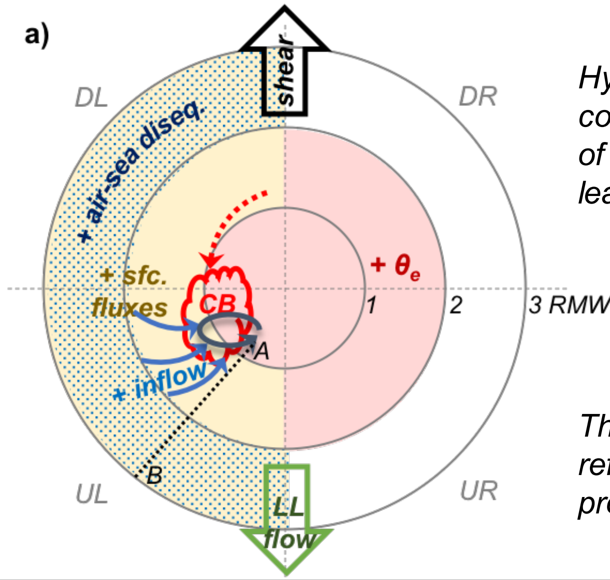
- RI occurs later for broader (more realistic) profiles.
- RI occurs earlier for a smaller initial TC, even without an initial well-defined maximum.
- The formation of a sharply defined low-level wind maximum is a key characteristic of the onset of RI.

Boundary-Layer Processes Associated with Rapid Intensification in Tropical Cyclones

Dr. Brian Tang, University at Albany

Science Objectives

- Understand multiscale processes and interactions occurring ahead of and at the onset of RI
  - Environmental factors
  - Mesoscale processes
  - Boundary-layer (turbulent) structures



Hypothesized conceptual picture of select processes leading to RI.

This picture will be refined as the project continues.

Technical Approach

- Analog technique to compare RI and slowly intensifying (SI) TCs
- Convection-allowing ensemble simulations using COAMPS-TC and CM1
- Large-eddy simulations using CM1
- Comparison of simulation data with observational data

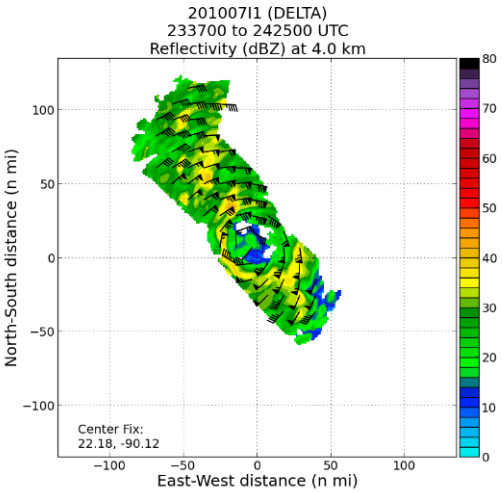
Accomplishments

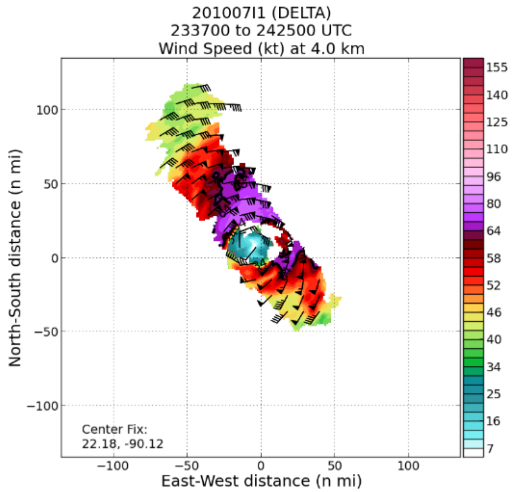
- Identified important differences between RI and SI TCs. Before RI, RI TCs have:
  - Greater left-of-shear and upshear surface heat fluxes and mid-tropospheric moisture
  - Greater horizontal moisture flux convergence
  - More vertically aligned and deeper vortex
  - More persistent, deep convection that propagates upshear

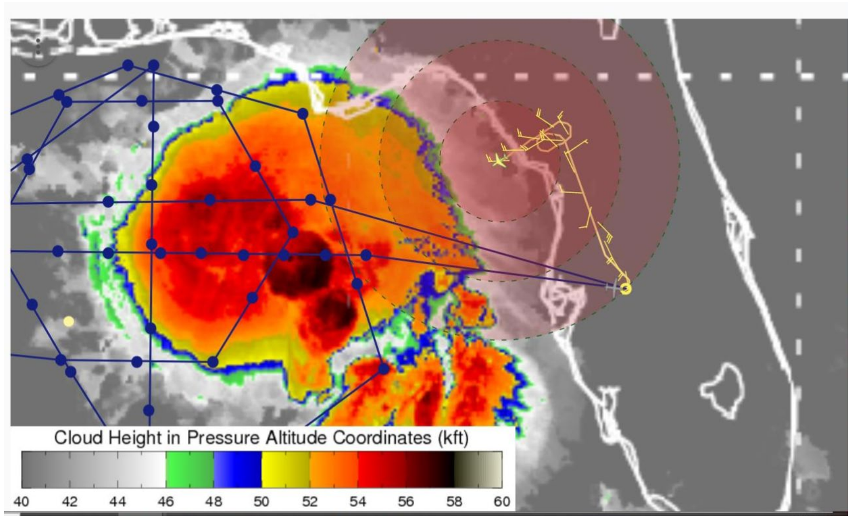
TCRI 2020 Experiment

Jim Doyle (TCRI Chief Scientist), NRL

- Conducted in close collaboration with NOAA IFEX
- 3 P-3 Flights and collaborative G-IV flights during Sally, Teddy, Delta
- Added flight modules for several other storms
- Deployed 159 additional dropsondes for TCRI
- Several flights (including Sally) captured the period prior to and during RI



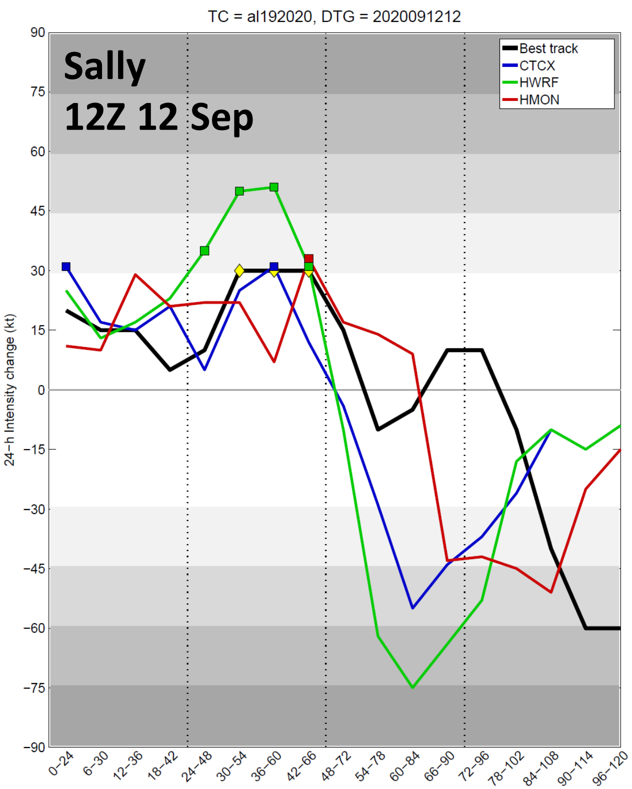




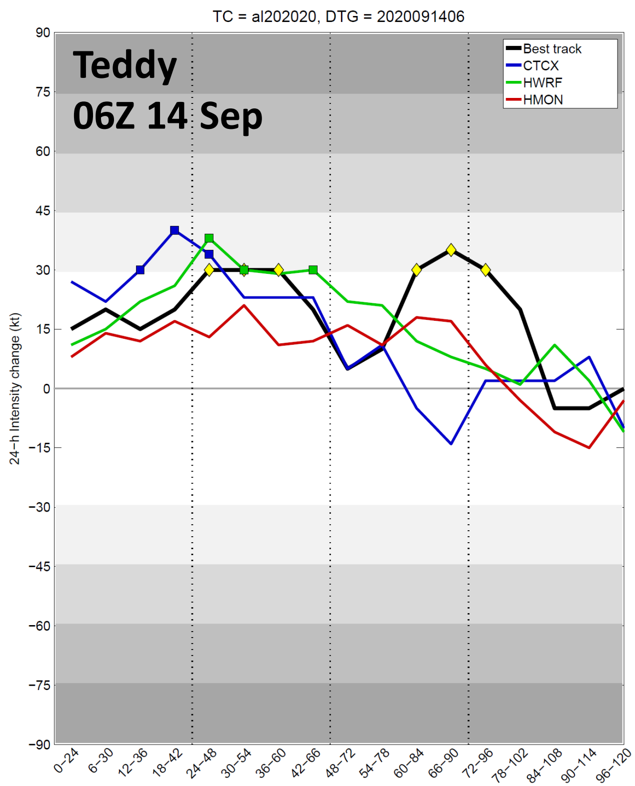
TCRI 2020 Experiment

Jim Doyle and Jon Moskaitis, NRL

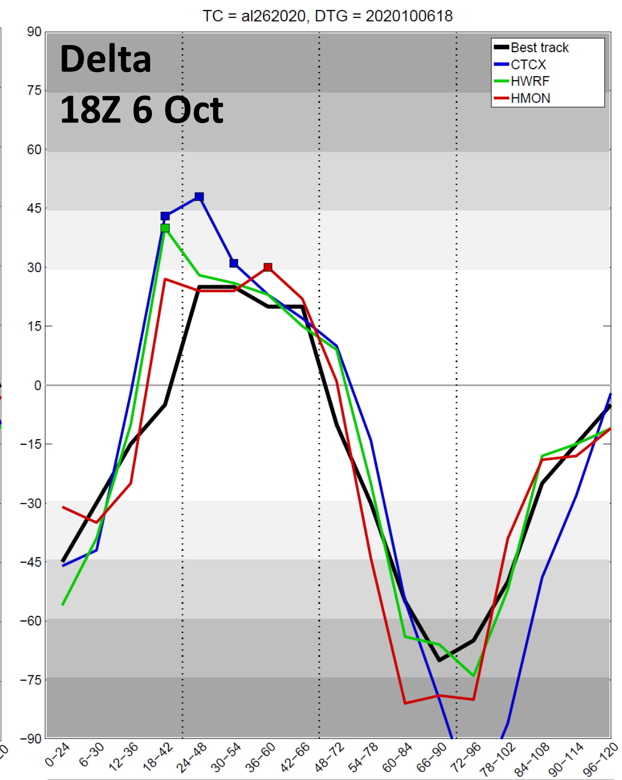
TCRI 2020 Cases: 24-h Intensity Change



Models correctly hinted at Sally RI possibility prior to landfall



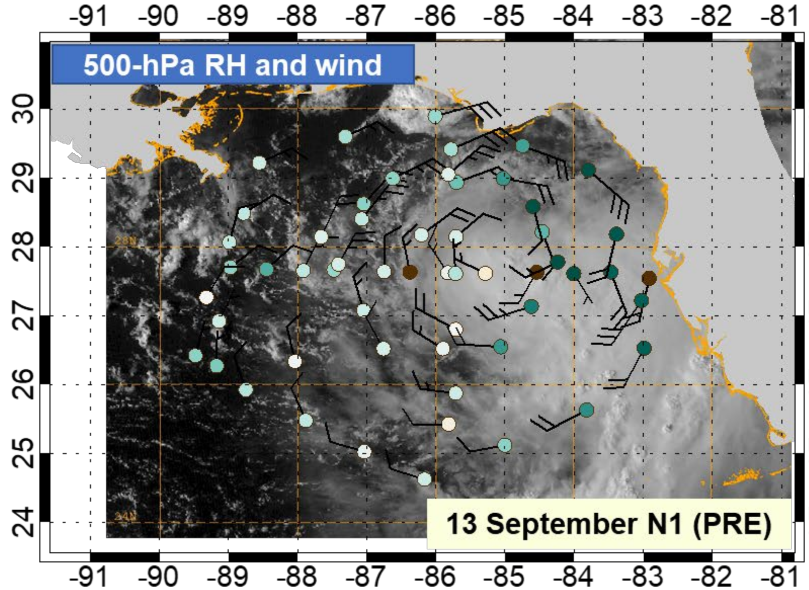
Models missed 2nd RI of Teddy (some success with initial RI)

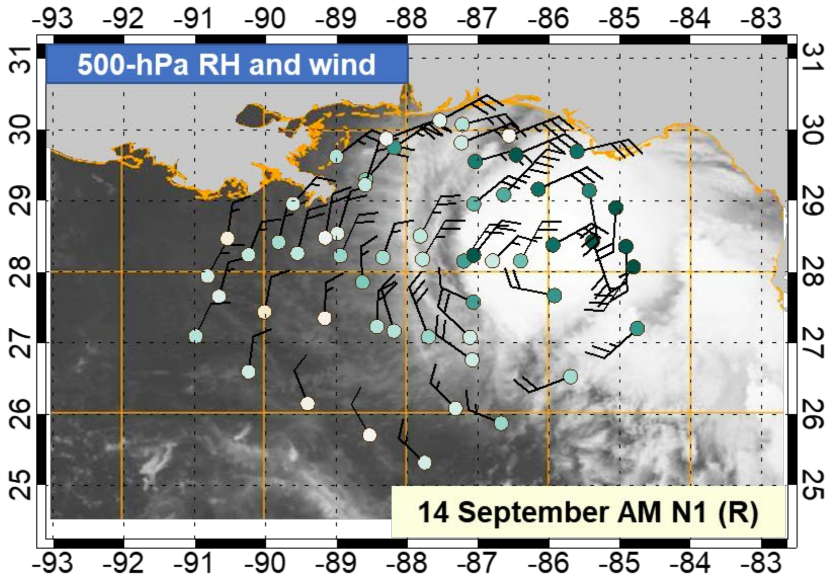


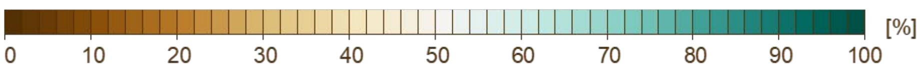
Models captured re-intensification of Delta (short term forecasts)

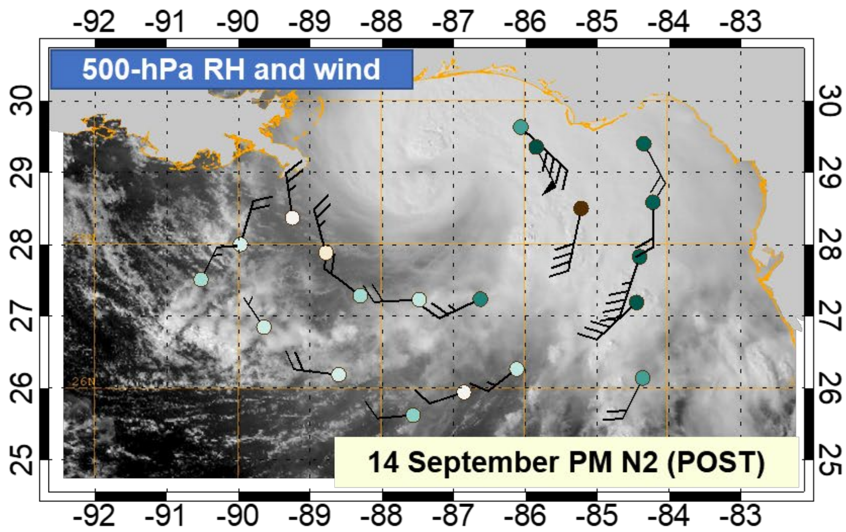
High-density Dropsonde Sampling in Sally

Jon Zawislak, UM/CIMAS, NOAA/AOML/HRD









SEQUENCE OF HRD / ONR-TCRI G-IV MISSIONS INTO SALLY

1800Z 13 September – 0000Z 14 September (**PRE**-reformation)

0630Z 14 September – 1300Z 14 September (**R**eformation)

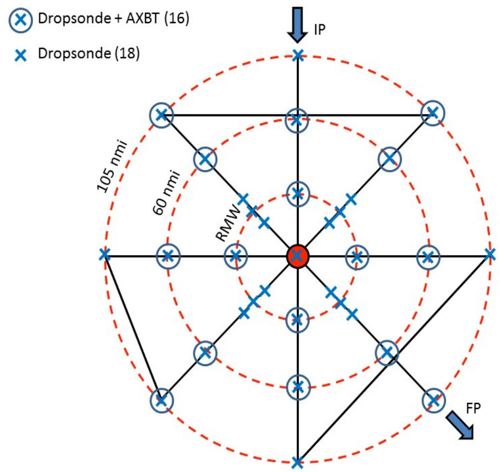
1800Z 14 September – 2100Z 14 September (**POST**-reformation)

Boundary Layer and Gravity Wave Modules

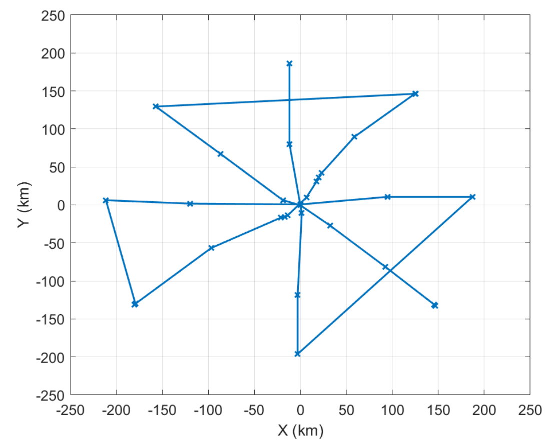
Jun Zhang, UM/CIMAS, NOAA/AOML/HRD

Boundary Layer Module

Goal: Collect observations targeted at better understanding details of the boundary layer structure and evolution that are tied to tropical cyclone (TC) intensity change.

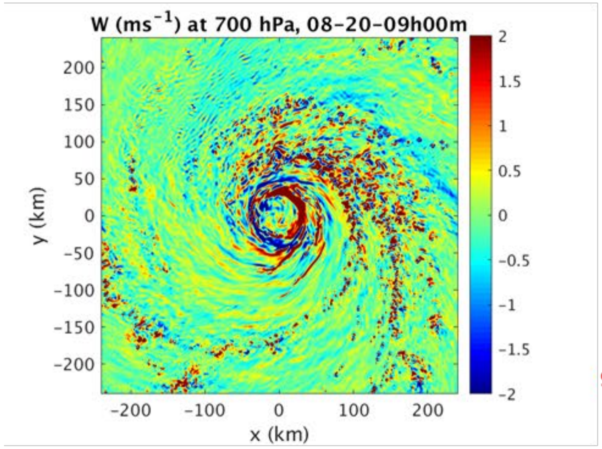


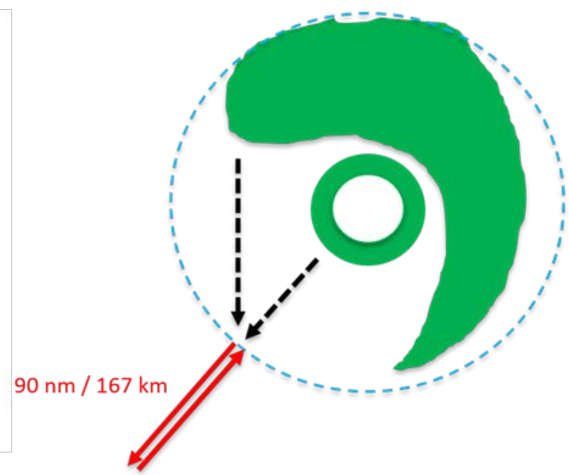
P3 mission in Hurricane Delta – 20201008I1



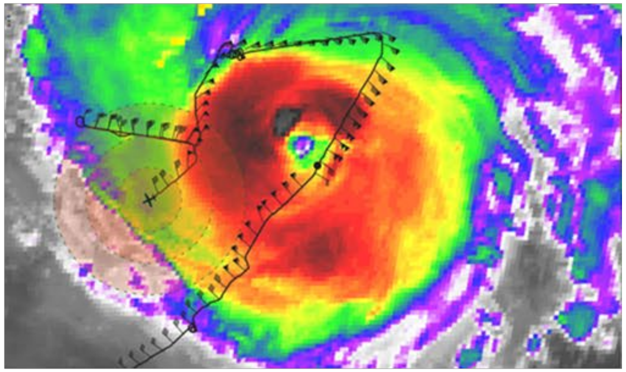
Gravity Wave Module

Goal: Collect observations for improving understanding of the characteristics of gravity waves in hurricanes by directly observing both the phase speed and wavelength of the outward moving gravity waves. Quantify how the characteristics of these waves are related to hurricane intensity.





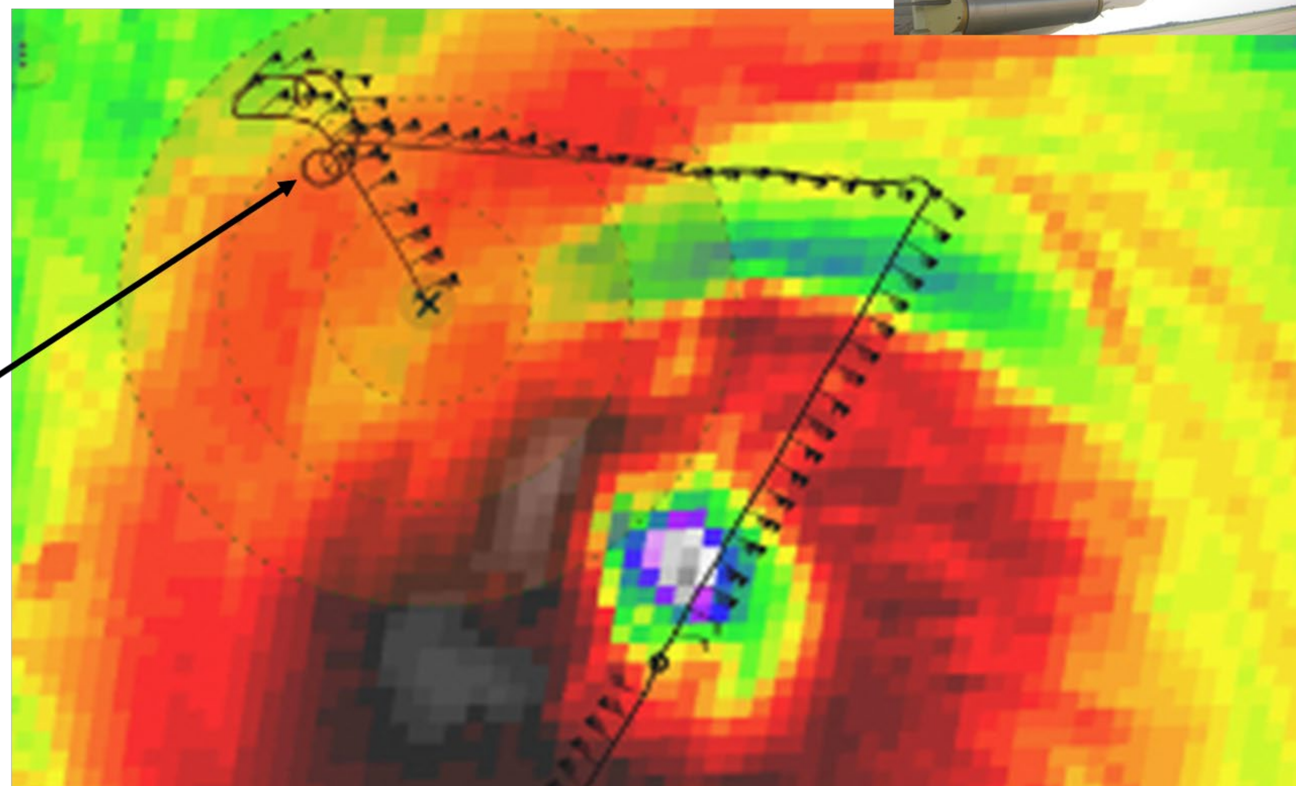
Hurricane Teddy



Hurricane Microphysical Spirals

Michael M. Bell and Alex DesRosiers, CSU

- Precipitation Imaging Probe (PIP) : Size range: 100 μm – 6.2 mm (100 μm resolution)
- Cloud Imaging Probe (CIP) : Size range: 25 μm – 1.55 mm (25-μm resolution)



Spiral up from 1835 – 1851 EST (2335 – 2351 UTC)
~2.5 km to ~6 km
In stratiform sector of connecting portion of principal rainband

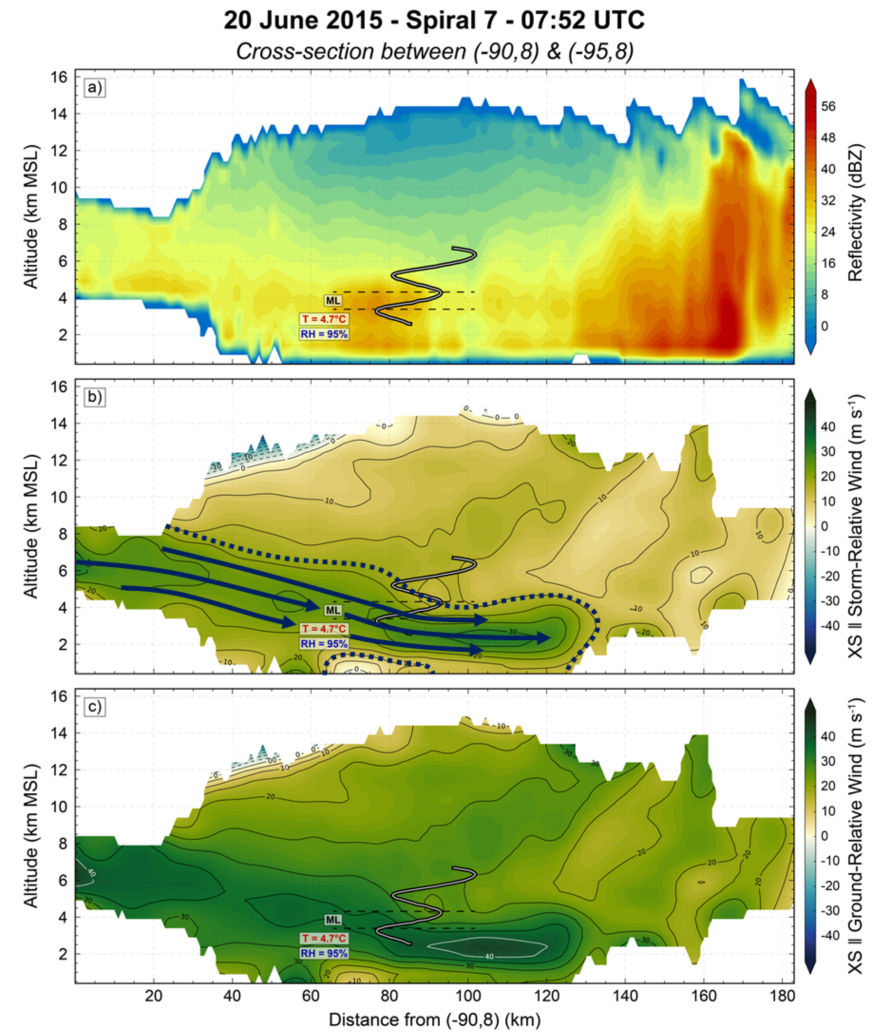
Possibly near eventual secondary eyewall formation, but more analysis is needed

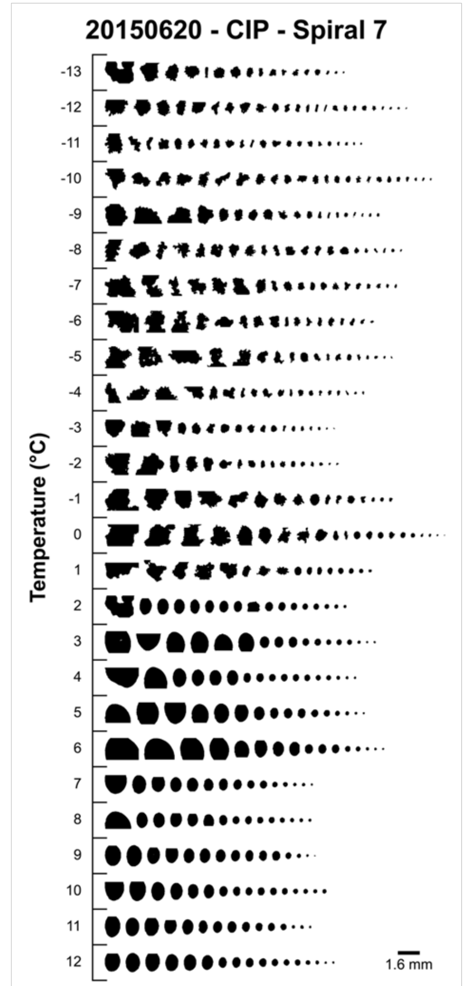
Hurricane Microphysical Spirals

Michael M. Bell and Alex DesRosiers, CSU

Why do spirals?

Results from MCS measurements during PECAN

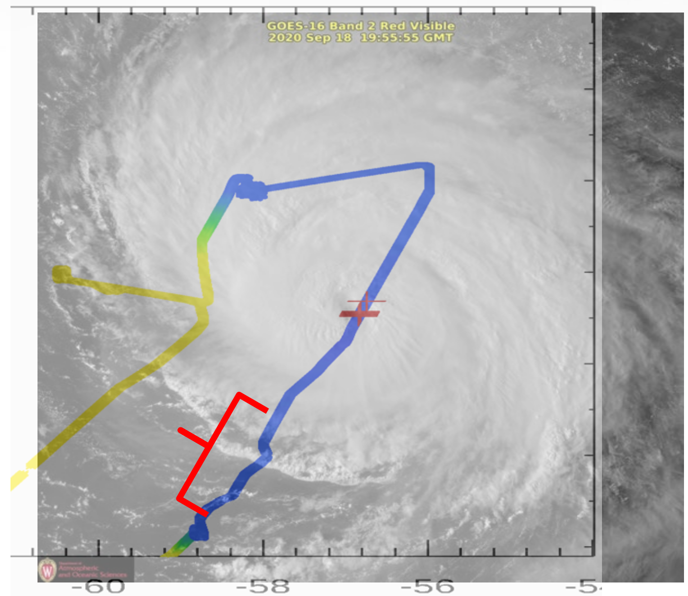




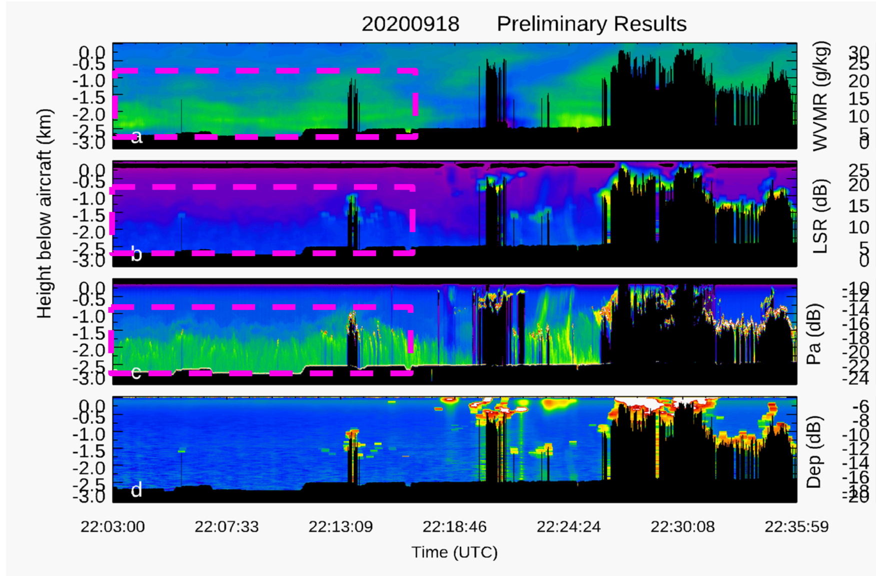
Slide courtesy Dan Stechman (OU)

TCRI Summary and Plans

- TCRI will build on key findings from previous ONR field campaigns at the air-sea interface (CBLAST), at the tropopause (TCI-15), and through the atmospheric column (TCS-08, ITOP) by focusing on:
  - ✓ Onset of RI
  - ✓ Boundary layer and microphysics processes
  - ✓ Sheared storms that undergo RI
- Unprecedented opportunities during the next few seasons by expanding NOAA partnership
  - ✓ Continue to have TCRI PIs work closely with HRD and NOAA IFEX
  - ✓ Add 4 additional P-3 Flights and possible collaborative G-IV flights
  - ✓ Option for additional flight modules
  - ✓ Additional microphysics legs if possible
  - ✓ Should have additional 300+ dropsondes available for the P-3 and G-IV
  - ✓ <u>Support Raman Lidar observing (right)</u>



The mixing layer is about 1 km deep.



Some Future Efforts Beyond TCRI

- NOPP Program (Reggie Beach): Predicting Hurricane Coastal Impacts
  - ✓ https://www.nopp.org/2020/predicting-hurricane-coastal-impacts-fy21-24/
  - ✓ Awards will be going out soon. Project to last through 2024.
  - ✓ Plan to drop buoys along the coast from C-130, P3 and USCG helo flights.
- Continued efforts on Geolocated Information Processing System (GeoIPS)
  - ✓ Updating NRL's TC satellite webpage using an open source python software package
  - ✓ Now available on github: https://github.com/USNavalResearchLaboratory/geoips2
  - ✓ Aim to streamline satellite data processing and algorithms with UW/CIMSS and CSU/CIRA
  - ✓ Have researchers share same software suite as operational production, facilitating faster transition from research to operation.
  - ✓ Lead: Mindy Surratt (Melinda.Surratt@nrlmry.navy.mil)
- Continued support and improvement of the Automated Tropical Cyclone Forecasting system (ATCF)
  - ✓ Transitioning new data and algorithms, including through partnerships with CSU/CIRA, NESDIS/STAR, RSS, UW/CIMSS, and others
  - ✓ Exploring methods to improve software flexibility and continue NOAA collaboration
  - ✓ Lead: Buck Sampson (Buck.Sampson@nrlmry.navy.mil)