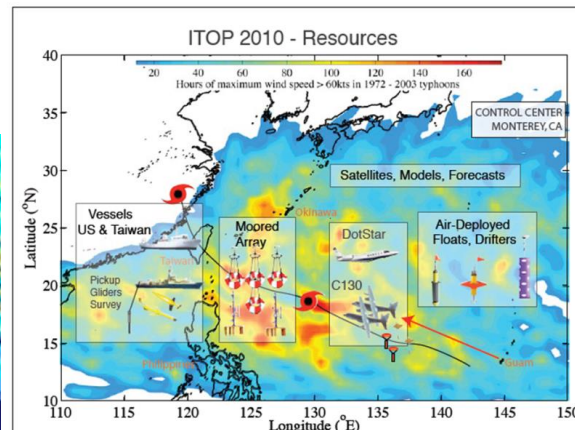
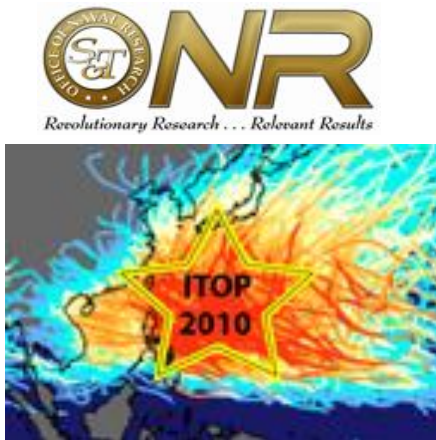
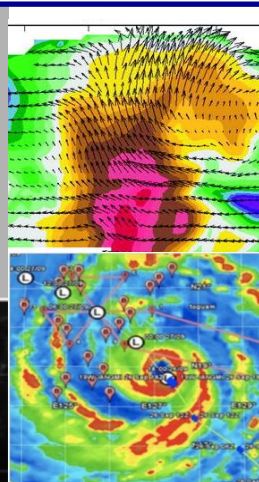
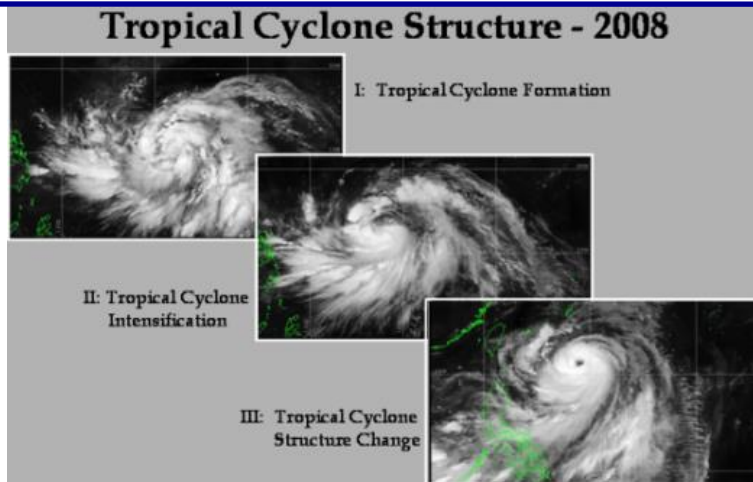




Understanding and Predicting the Impact of Outflow on Tropical Cyclone Intensification and Structure ("TCI-14" & "TCI-15")

**An FY14-18 ONR Departmental Research Initiative
Ronald J. Ferek and CDR Joel Feldmeier, 322MM
3 March 2015**

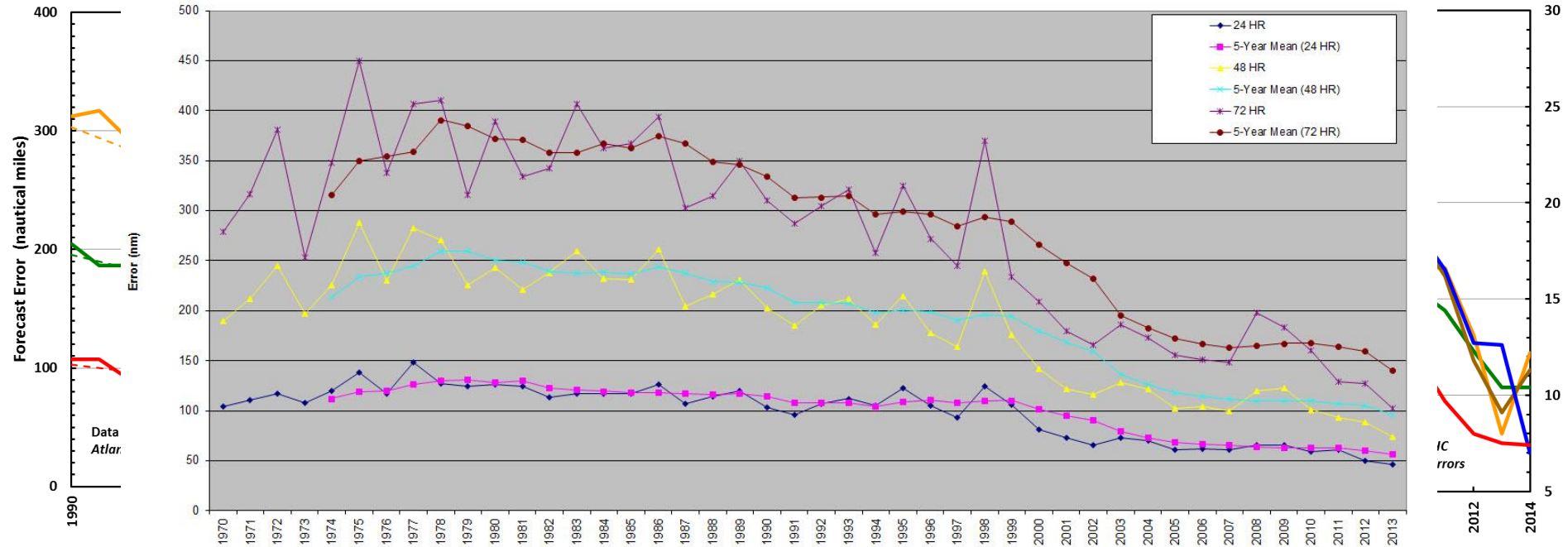
Recent ONR TC Field Campaigns



- Late 80's-early 90's: Tropical Cyclone Motion (TCM) Initiative
- Early 2000's: CBLAST (surface processes)
- 2008: Tropical Cyclone Structure Experiment (TCS-08) (storm-scale processes)
- 2010: ONR Impact of Typhoons on the Ocean in the Pacific (ITOP)

Motivation

WPAC 24,48,72-Hour Mean Error (nm)



- Since 2003 in WPAC, there has been little improvement in TC track prediction
- Since 1990 in WPAC, there has been very little improvement in TC intensity prediction
- 2009 New USPACOM “Goals for Tropical Cyclone Forecasting”
 - 50% reduction in errors
- 2012 ONR held a TC science workshop to identify next set of basic research questions
 - Problem: Upper-level outflow associated with tropical cyclones may be the key link between the environment and TC intensification
 - *processes remain largely unexplored*

Hurricane Structure and Recent Research Programs

Unexplored: *Outflow structure, intensity, and variability, and relationships with hurricane intensity and structure*

ONR TCS-08
NSF TPARC
NOAA IFEX
NASA GRIP
NSF PREDICT

ONR CBLAST
ONR TCS-08
ONR ITOP

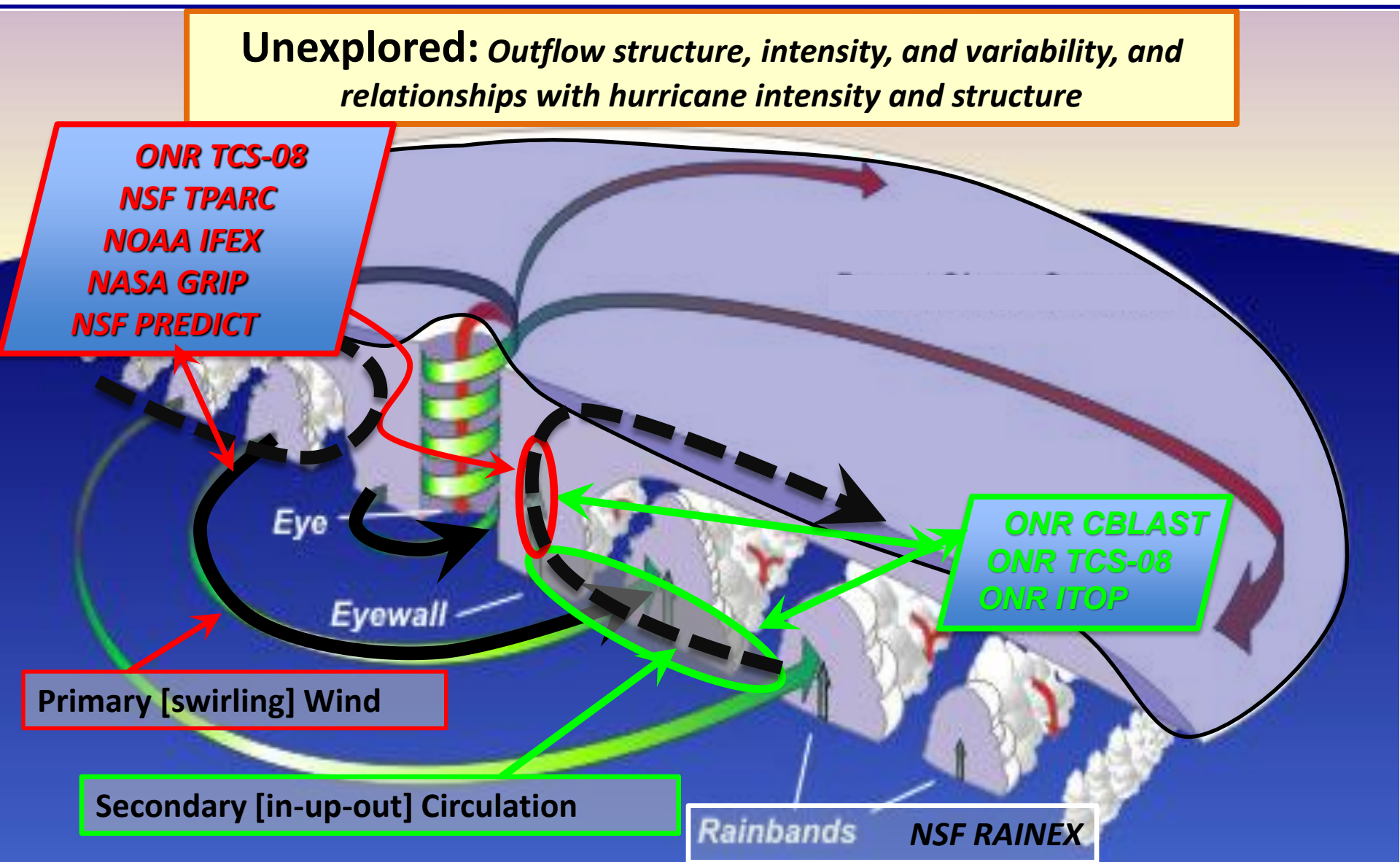
Primary [swirling] Wind

Secondary [in-up-out] Circulation

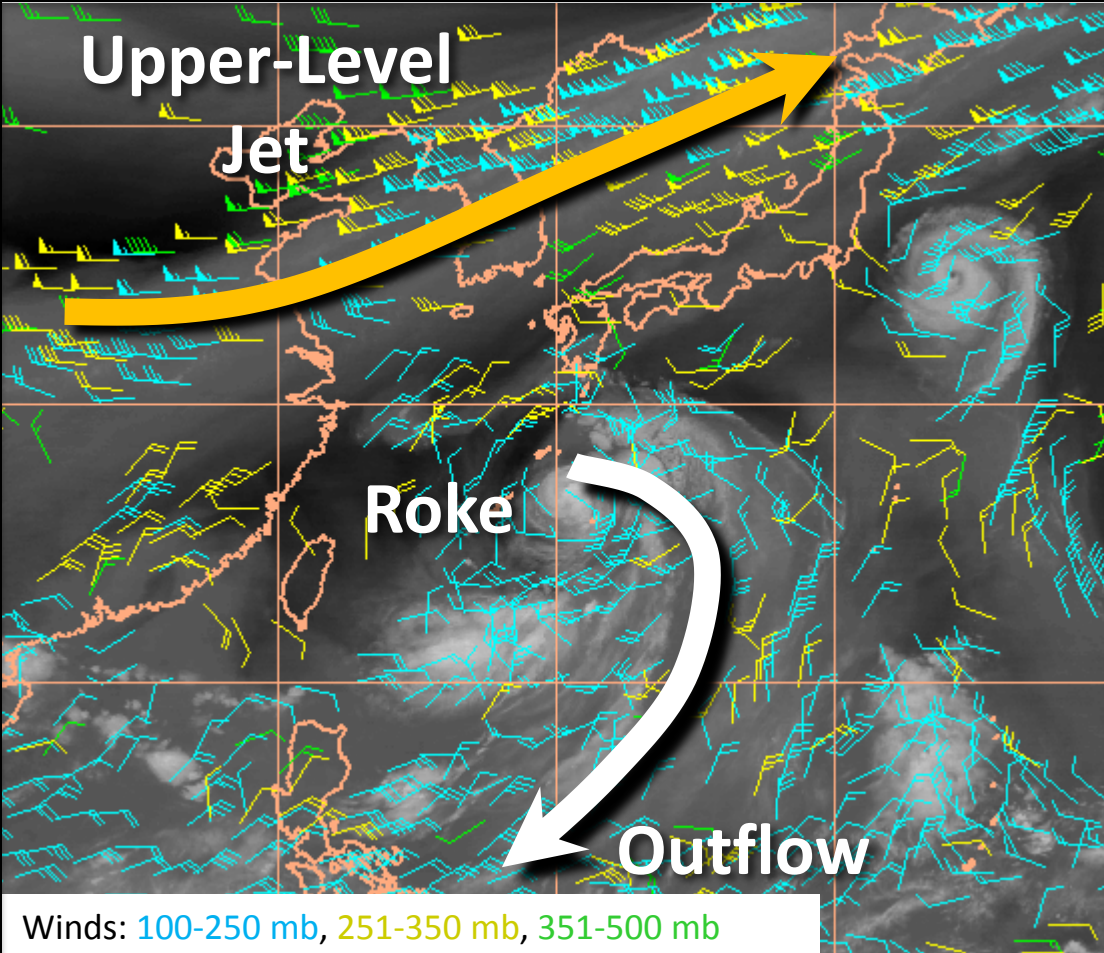
Rainbands **NSF RAINEX**

Eye

Eyewall



Upper-Level Jet

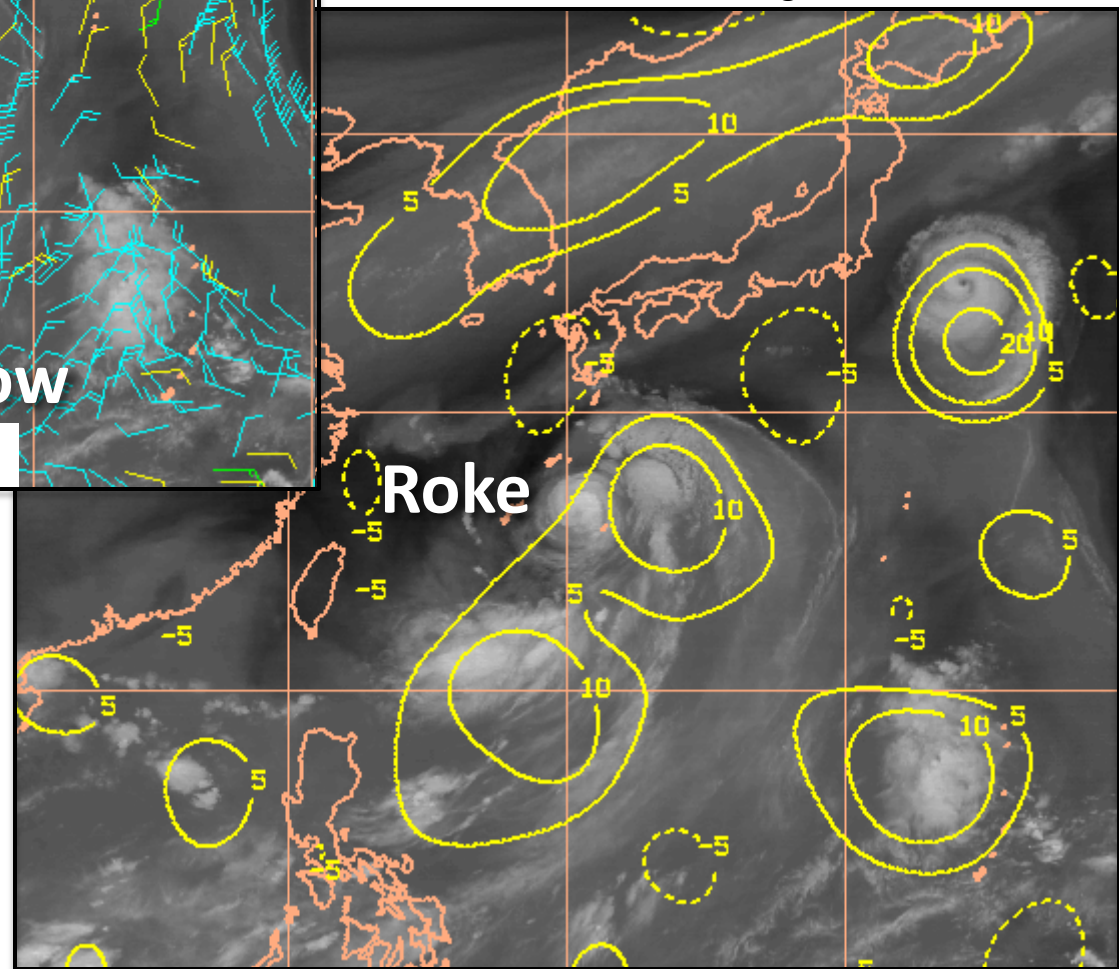


Outflow & Intensification Typhoon Roke

Pre-Rapid Intensification
00 UTC 19 Sep 2011

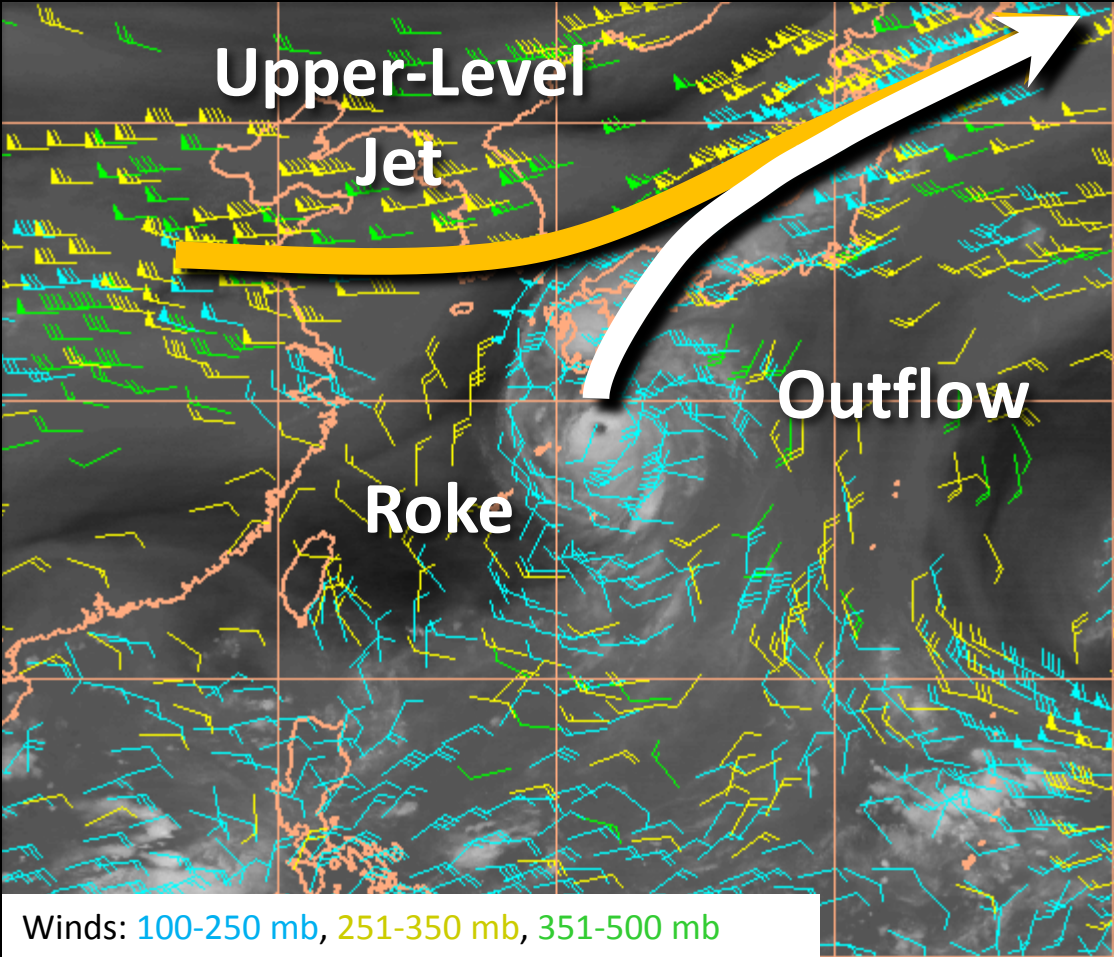
Intensity = 65 kt

150-300 mb Divergence



Winds: 100-250 mb, 251-350 mb, 351-500 mb

- Outflow directed equatorward
- **No interaction** between outflow and approaching upper-level jet
- Weak upper-level divergence
- Weak typhoon

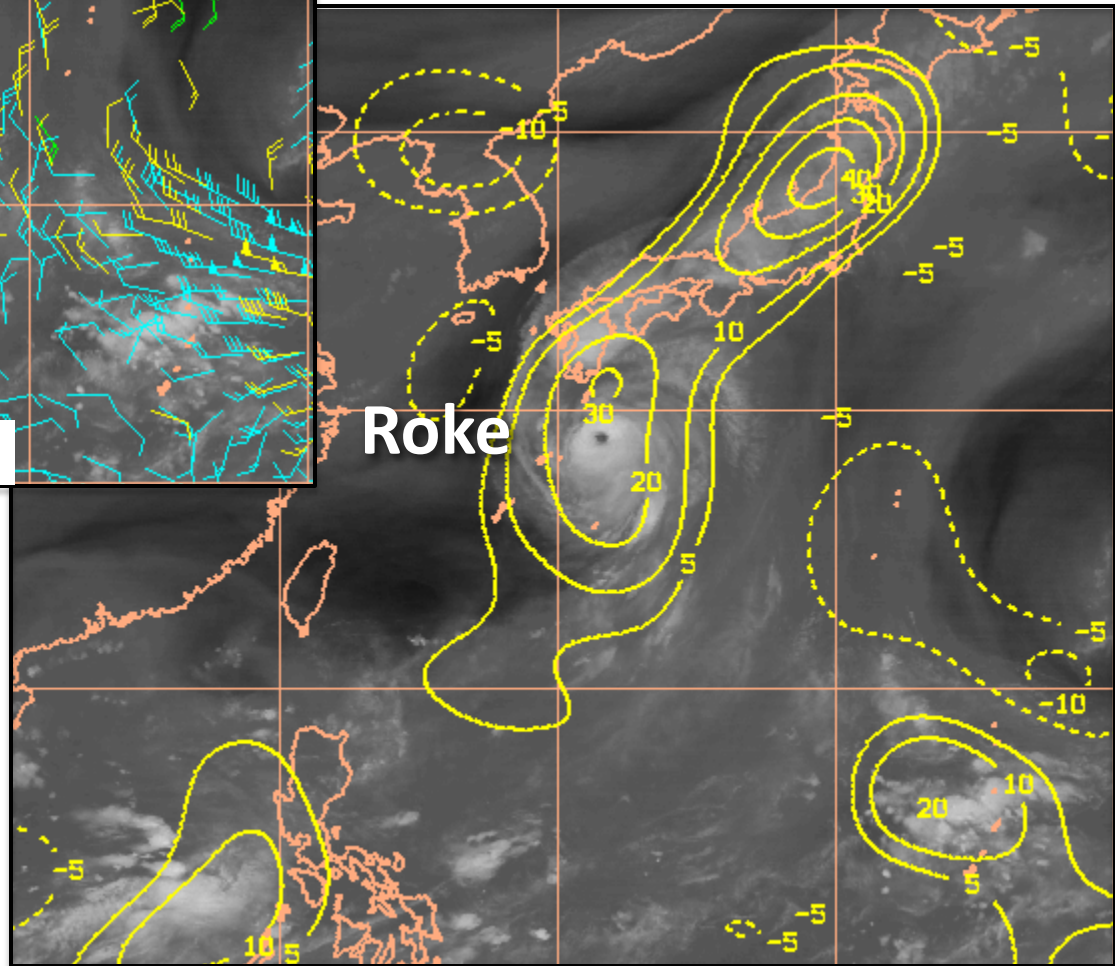


Outflow & Intensification Typhoon Roke

Rapid Intensification
00 UTC 20 Sep 2011 (+24h)

Intensity = **115 kt**

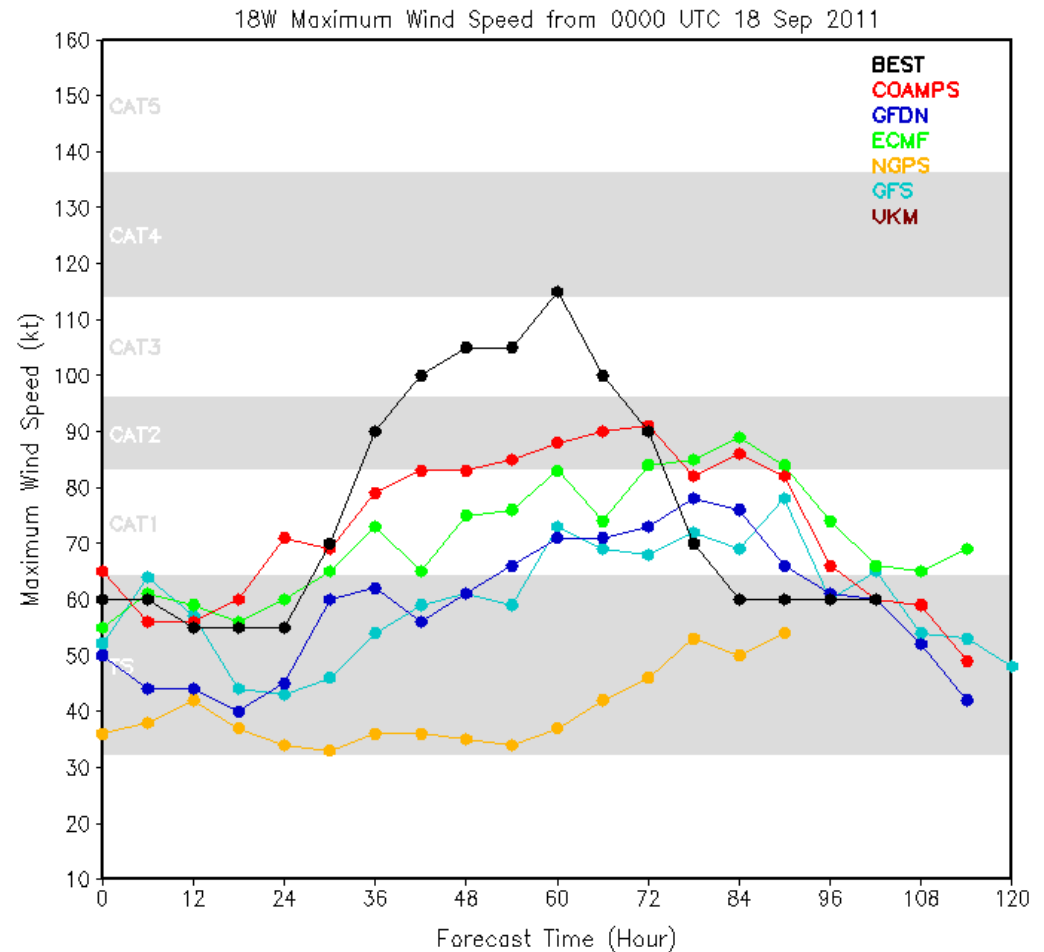
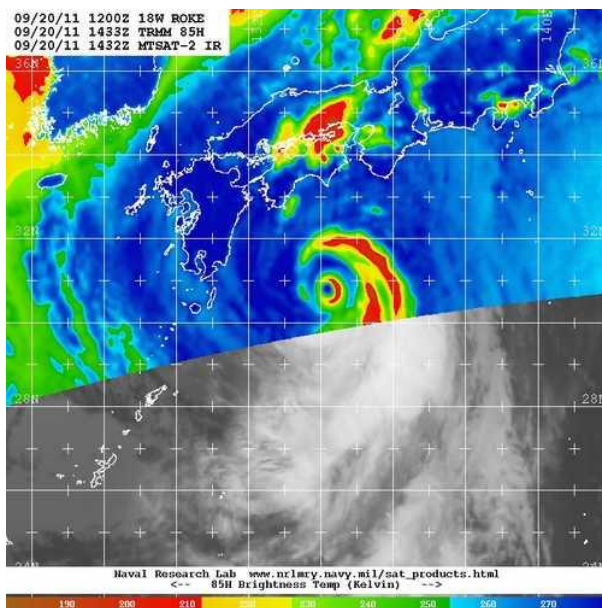
150-300 mb Divergence



- Outflow shifts poleward
- *Outflow couples with midlatitude jet*
- Upper-level divergence triples
- Roke underwent Rapid Intensification, increased intensity by 50 kts in 24 hours

Model Performance during Typhoon Roke (18W)

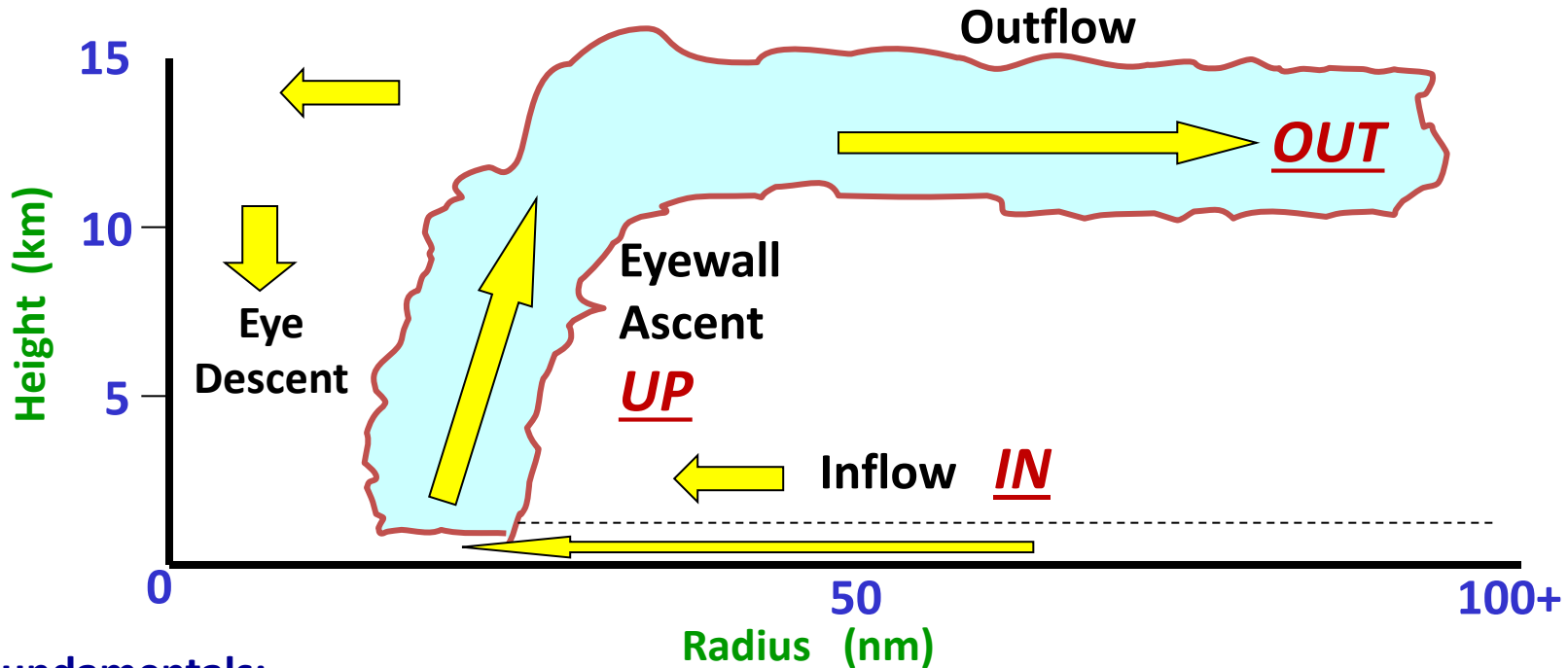
Difficulty Forecasting Rapid Intensification (From J. Doyle, NRL)



- After TY Roke remained weak (and moved slowly) for days, it underwent rapid intensification (RI).
- Models (including COAMPS-TC) failed to capture this RI.

Hurricane Outflow Theory

Secondary Circulation



Fundamentals:

- Secondary circulation impacts the primary circulation (and therefore TC intensity) through variations in gradient wind balance.
- Key factors that determine radial inflow:
 - *Surface and boundary layer characteristics*
 - *Conservation of angular momentum, mass and kinetic energy*
- Changes in one branch of the circulation will impact the other branches through continuity (must *balance*)

Key Science Issues and Approach

Understand the coupling between all the branches of the secondary circulation (and the relationship of this coupling to intensity changes)

- Upper-level outflow changes **lead to** increased convection and intensification (*Active Outflow*)
- Upper-level outflow changes **result from** increased convection (*Passive Outflow*)
- What are the relative roles of the TC vortex and the environment?

Observe the Evolution of outflow in relation to the environment

- Interaction between the outflow and the upper level environment (morphology, vertical structure, phasing, depth and strength of the outflow)
- Evolution of outflow channels and associated rapid intensification or weakening
- Are turbulent-scale mixing and shear instability processes important?
- Diagnose the dynamical balance within the outflow jet

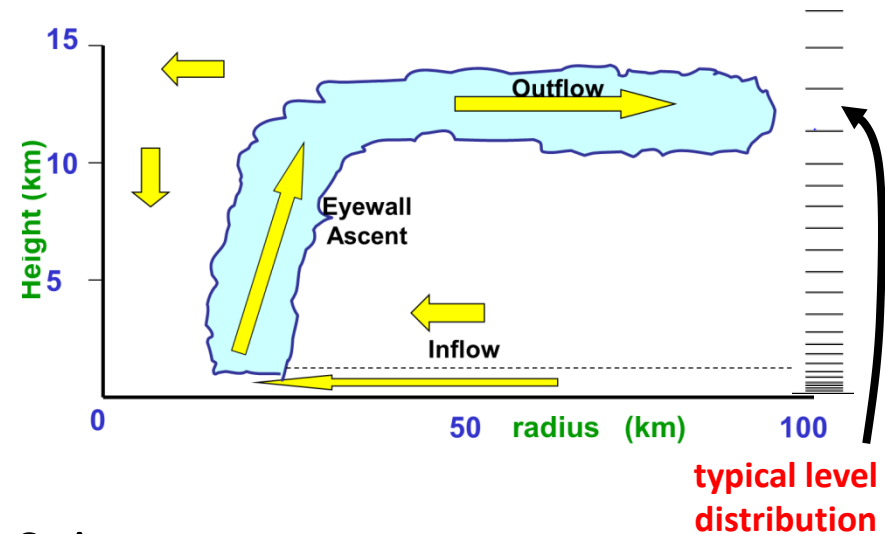
Employ state-of-the-art Numerical Modeling

- Quantify the impact of observations on TC intensity, outflow etc.
- Diagnose the initial state sensitivity using adjoints and ensembles.
- Quantify the predictability of outflow jets and TC intensity change.

Hurricane Outflow Modeling Challenges

1) Vertical Resolution

- There is **large sensitivity** of the **intensity and structure** to vertical resolution, particularly in the outflow layer (Zhang and Wang 2003)
- Typical vertical layer distribution will **poorly resolve** outflow layer

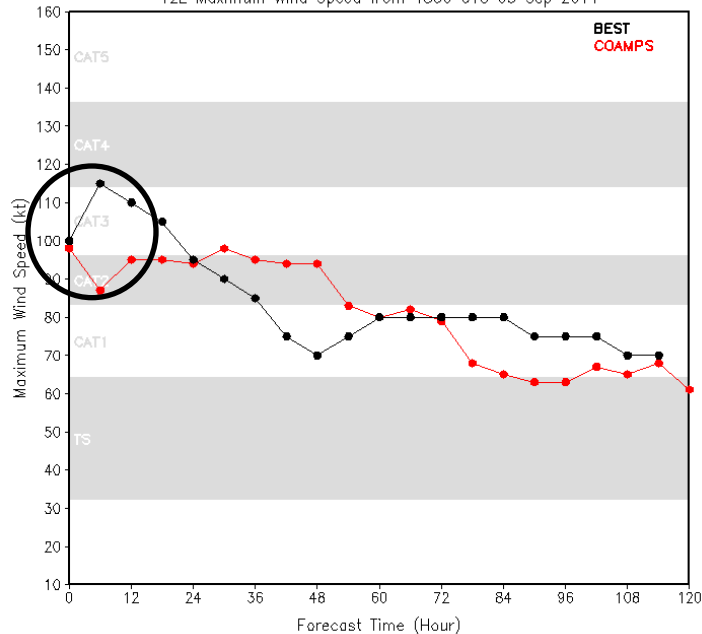


typical level distribution

2) Model Spinup

- Nearly all dynamical models show a spin-up or spin-down of the initial vortex.
- The initial imbalance is likely due to a **poor specification of the secondary circulation, particularly the outflow.**
- The outflow is notoriously difficult for models to represent in the initial conditions (and hence never bogused)

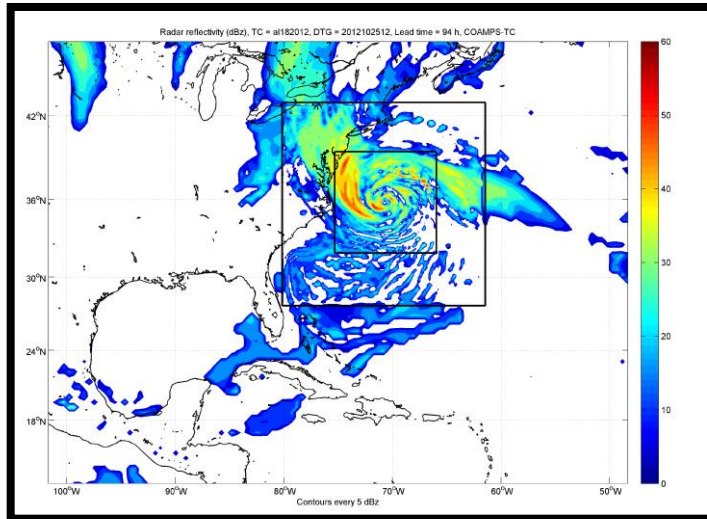
12L Maximum Wind Speed from 1800 UTC 05 Sep 2011



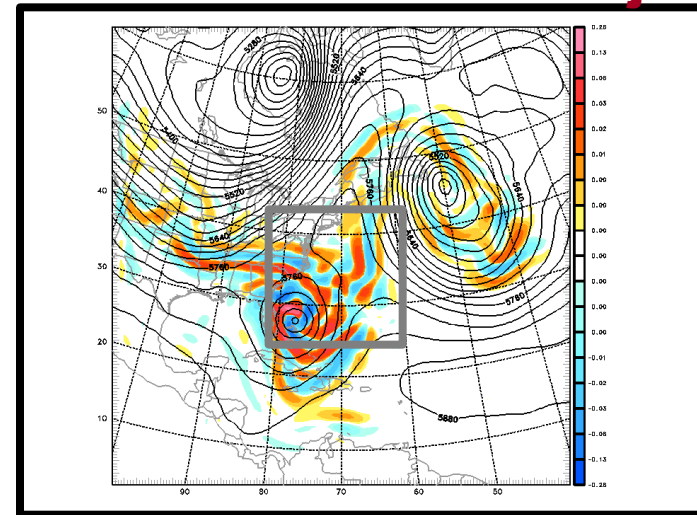
NRL TC Data Assimilation and Modeling Tools

(see J. Doyle, J. Moskitas and S. Chen talks in Session 5b this afternoon)

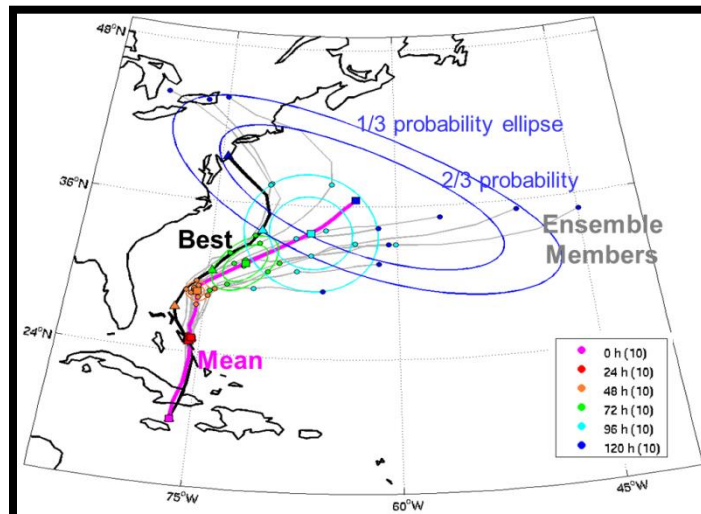
COAMPS-TC



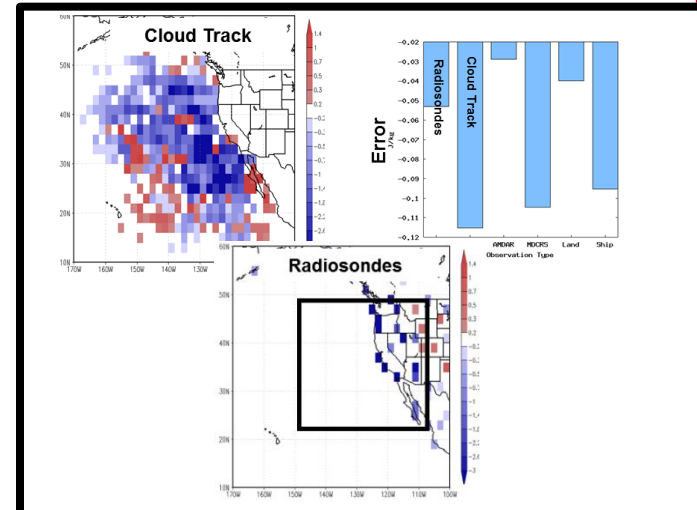
COAMPS-TC Nested Adjoint



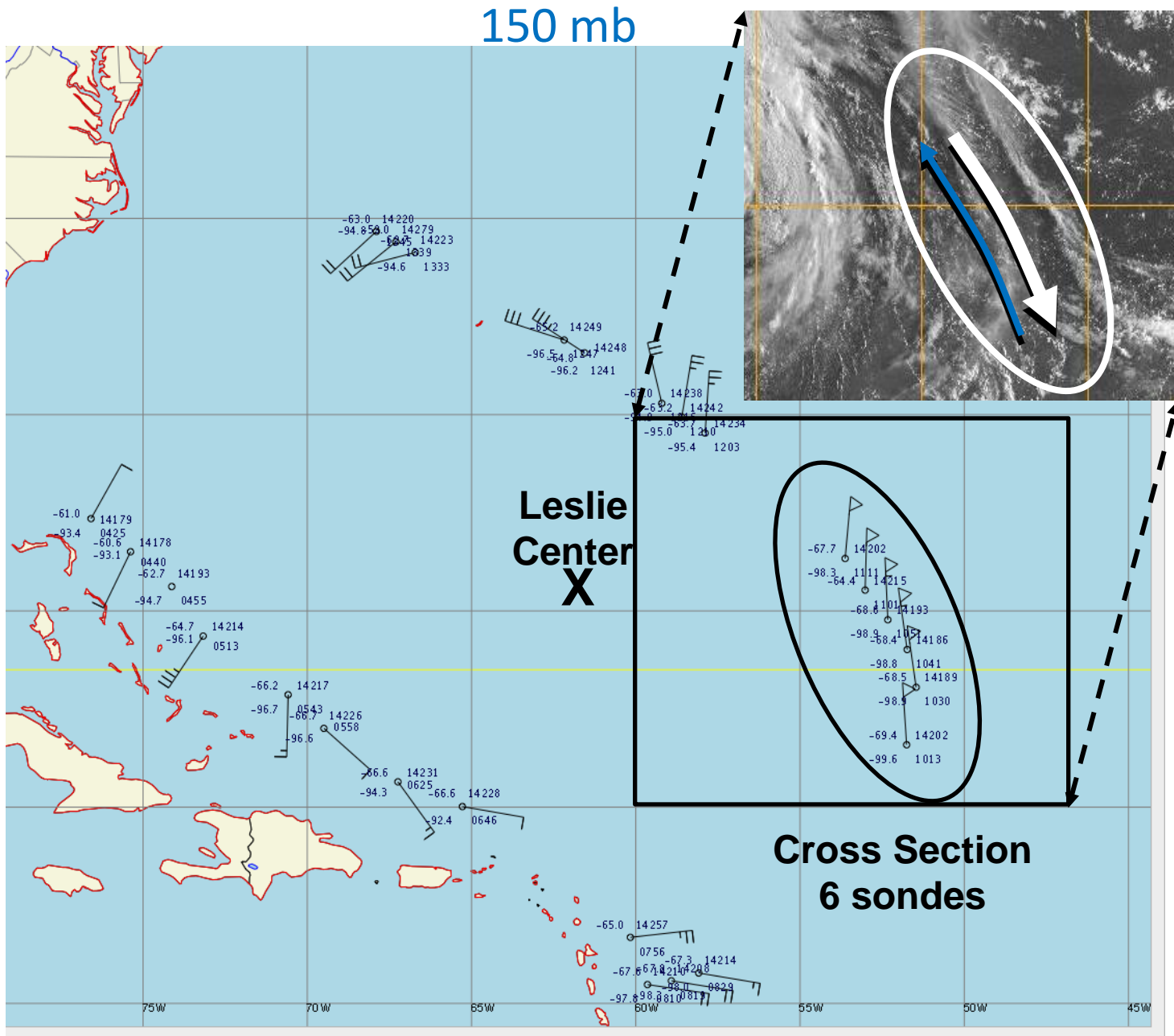
COAMPS-TC EnKF



COAMPS-TC Observation Impact

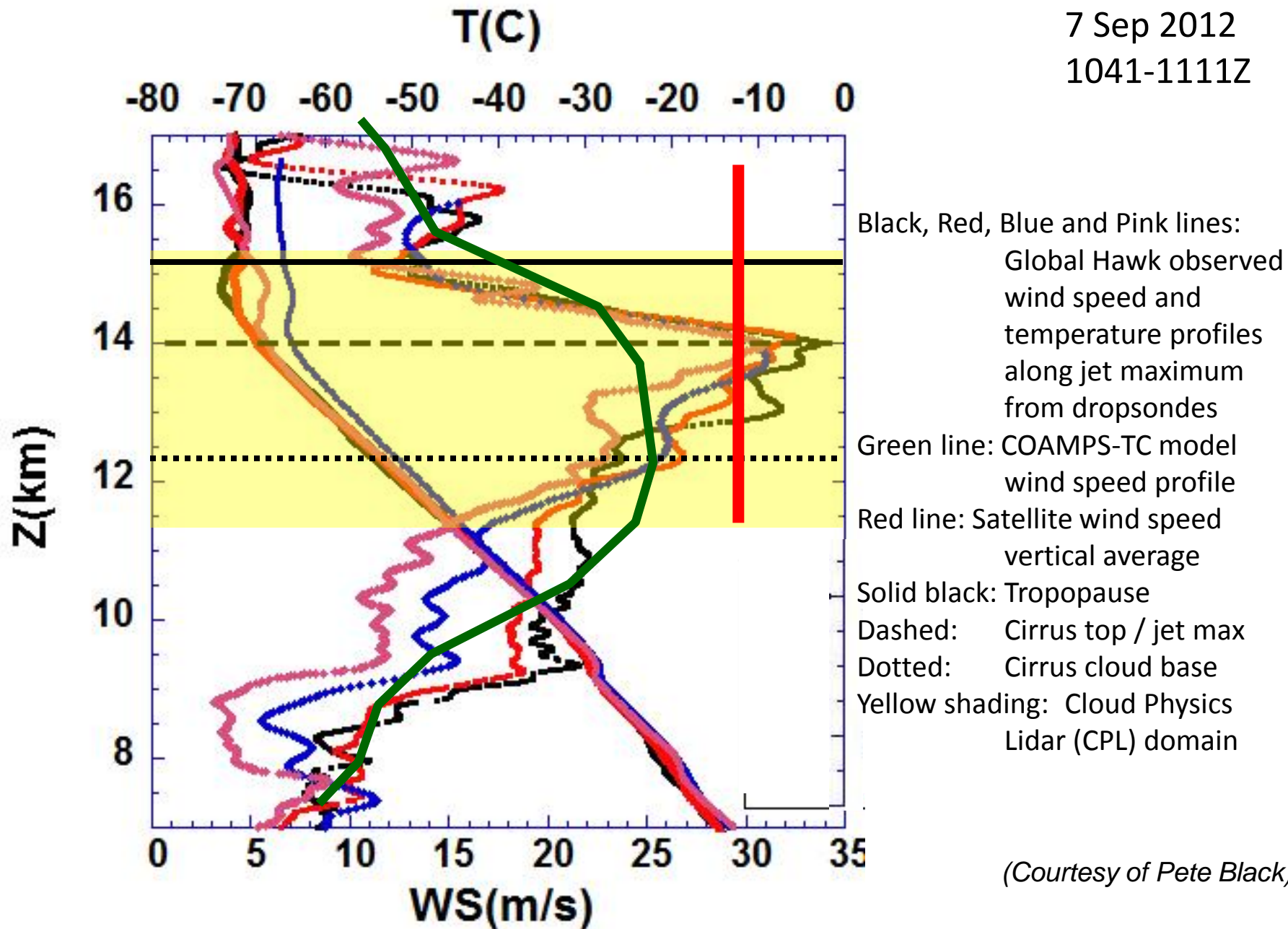


HS3 Observations of Leslie's Outflow



HS3 Observations of Leslie's Outflow

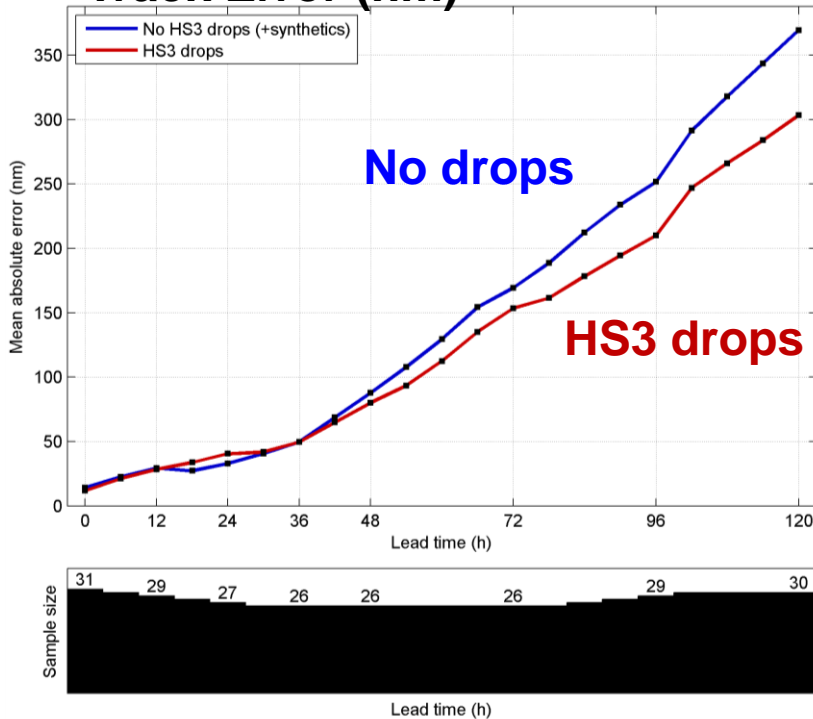
7 Sep 2012
1041-1111Z



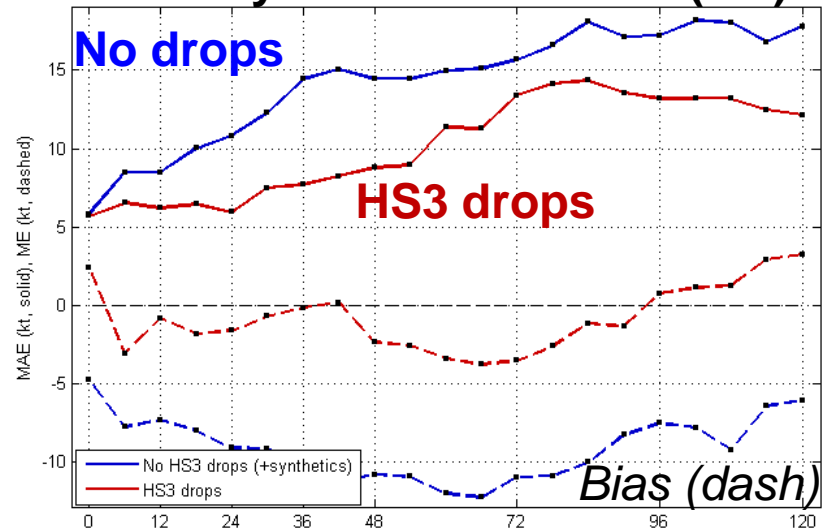
(Courtesy of Pete Black)

Impact of HS3 Dropsondes for Nadine

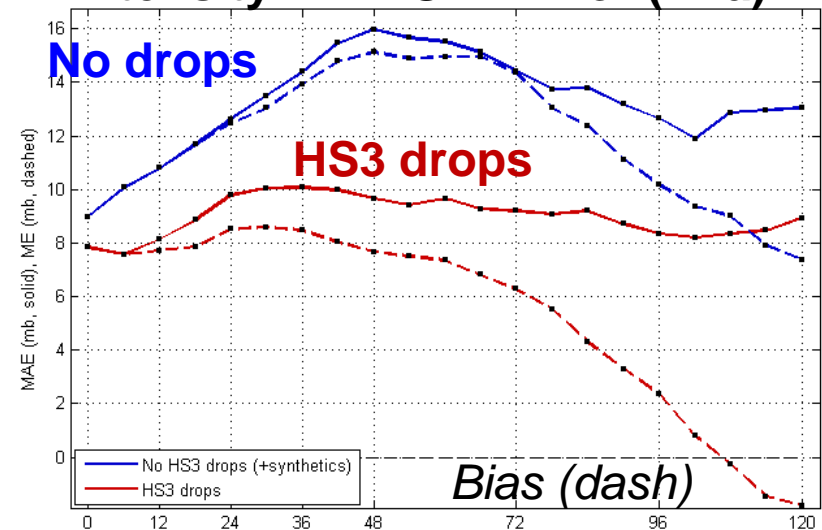
Track Error (nm)



Intensity: Max. Wind Error (kts)



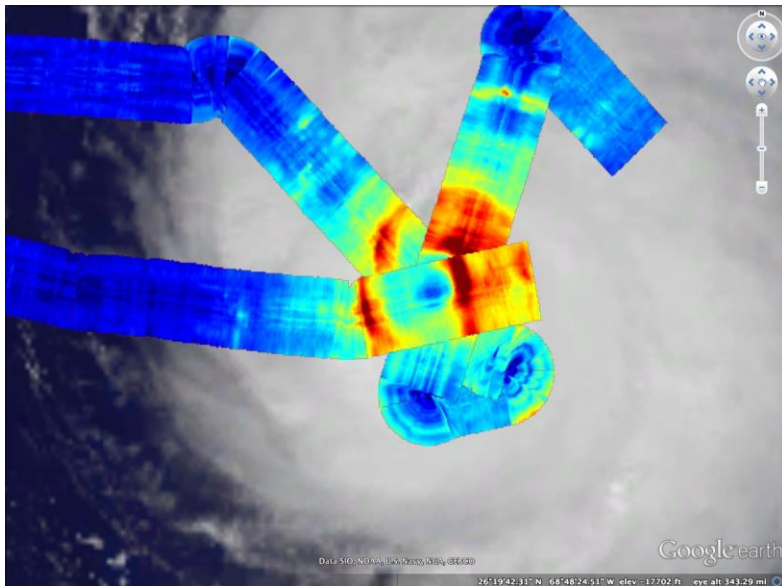
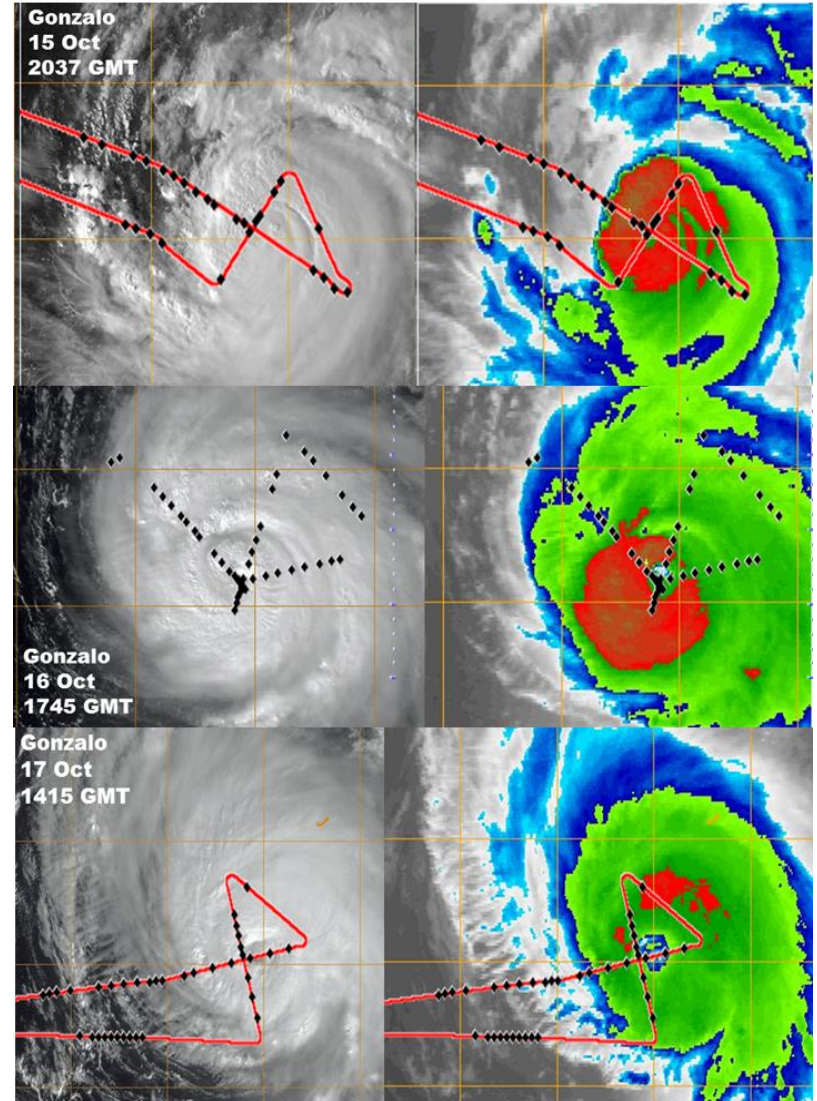
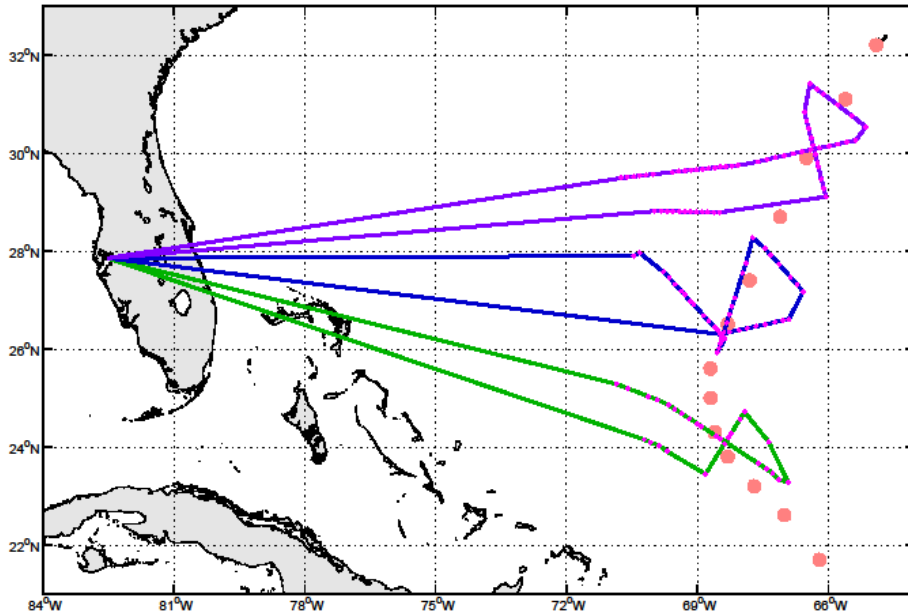
Intensity: Min. SLP Error (hPa)



- Dropsonde impact experiments performed for 19-28 Sep. (3 flights)
 - Blue, with HS3 drops
 - Red, No drops with synthetics
- COAMPS-TC Intensity and Track skill are improved greatly through assimilation of HS3 Drops

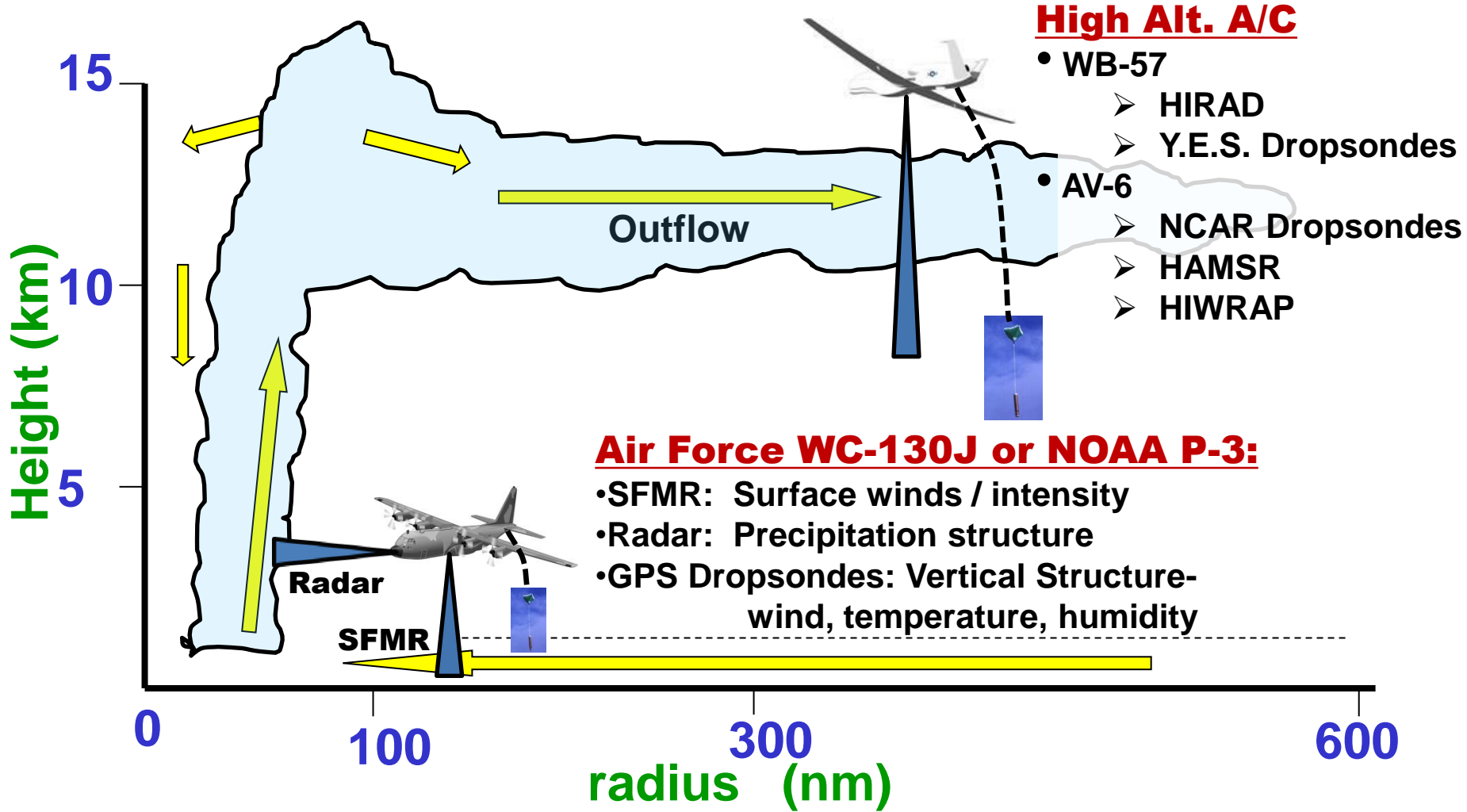
(Doyle et al. 2013)

TCI-14 Pilot Project: Hurricane Gonzalo; HDSS, HIRAD, HIWRAP



HIRAD image courtesy Dan Cecil (Dan and Pete Black spoke earlier about HIRAD and HDSS)

Observational Strategy (collab. with SHOUT and HRD)



Strategy: WC-130J or P-3 to monitor the TC intensity and structure
Global Hawk or WB-57 to observe the outflow and environment



Summary

- We hypothesize that hurricane outflow is the key to unraveling the complex nature of hurricane intensity and structure
- Upper-level outflow is the only TC component that has not been systematically observed or studied
- We now have the observing capability to:
 - investigate all branches of the secondary circulation at the same time
 - evaluate model deficiencies
 - improve understanding of the dynamic processes and represent them in models
 - verify and validate model improvements
- Leverage the opportunity to deploy the NASA Global Hawk and WB-57 and the Hurricane Hunter A/C to observe hurricane intensity, structure and outflow interaction
- Employ new HDSS (high definition dropsonde system) to obtain detailed observations
- **Expected Payoff:** This effort will have two primary benefits:
 1. First ever comprehensive observations of the upper-level outflow structure will provide a unique dataset that will be critical to improving our scientific understanding of the outflow evolution as well as the associated interactions with TC intensification and structure change.
 2. Improved understanding of the relationship between upper-level outflow and the TC vortex, along with new techniques to assimilate field campaign observations using emerging tropical cyclone modeling systems will lead to *much improved TC intensity and structure predictions* (particularly for rapid intensification and rapid weakening)

Science Team & Proposed Topics

- Kerry Emanuel, MIT
 - Pat Harr, NPS
 - Russ Elsberry, UCCS
 - Sharan Majumdar, UMiami
 - John Molinari, SUNYA
 - Michael Bell, UH
 - Jim Doyle, NRL
 - Pete Black, NRL
 - Chris Velden, UWisc
 - Da-Lin Zhang, UMD
 - Xuguang Wang, UOk
 - Zhaoxia Pu, UUtah
 - Greg Tripoli, UWisc
 - Jason Dunnion, UMiami
 - Beth Sanabia, USNA

 - *Collaborative efforts:*
 - Alex Reinecke, NRL
 - Lee Harrison, SUNYA
 - Mark Beaubien, Y.E.S.
 - Dan Cecil, NASA Marshall
- Hurricane Outflow Criticality
 - TC Intensity and Structure Changes due to Upper-Level Outflow and Environmental Interactions
 - Environmental sensitivity of tropical cyclone outflow
 - Outflow layer dynamics and thermodynamics
 - Thermodynamic Constraints on TC Intensity and Structure
 - Impact of Outflow on TC Intensification and Structure: An Observational and Numerical Modeling Perspective
 - Coupling of TC Outflow Vents with the Environment
 - Impact of Upper-Level Processes on TC Intensity and Structure
 - Ensemble-based DA and multi-model ensemble simulation
 - Impacts of Outflow on TC Formation, RI and Structure Changes
 - An observational and numerical investigation of energy exchange between a TC and its environment at the outflow level
 - From Ocean to Outflow: Understanding TC Circulations and Intensification

 - Improved TC Prediction Through Unmanned Obs. Systems
 - High Definition Dropsonde System
 - High Definition Dropsonde System
 - HIRAD

