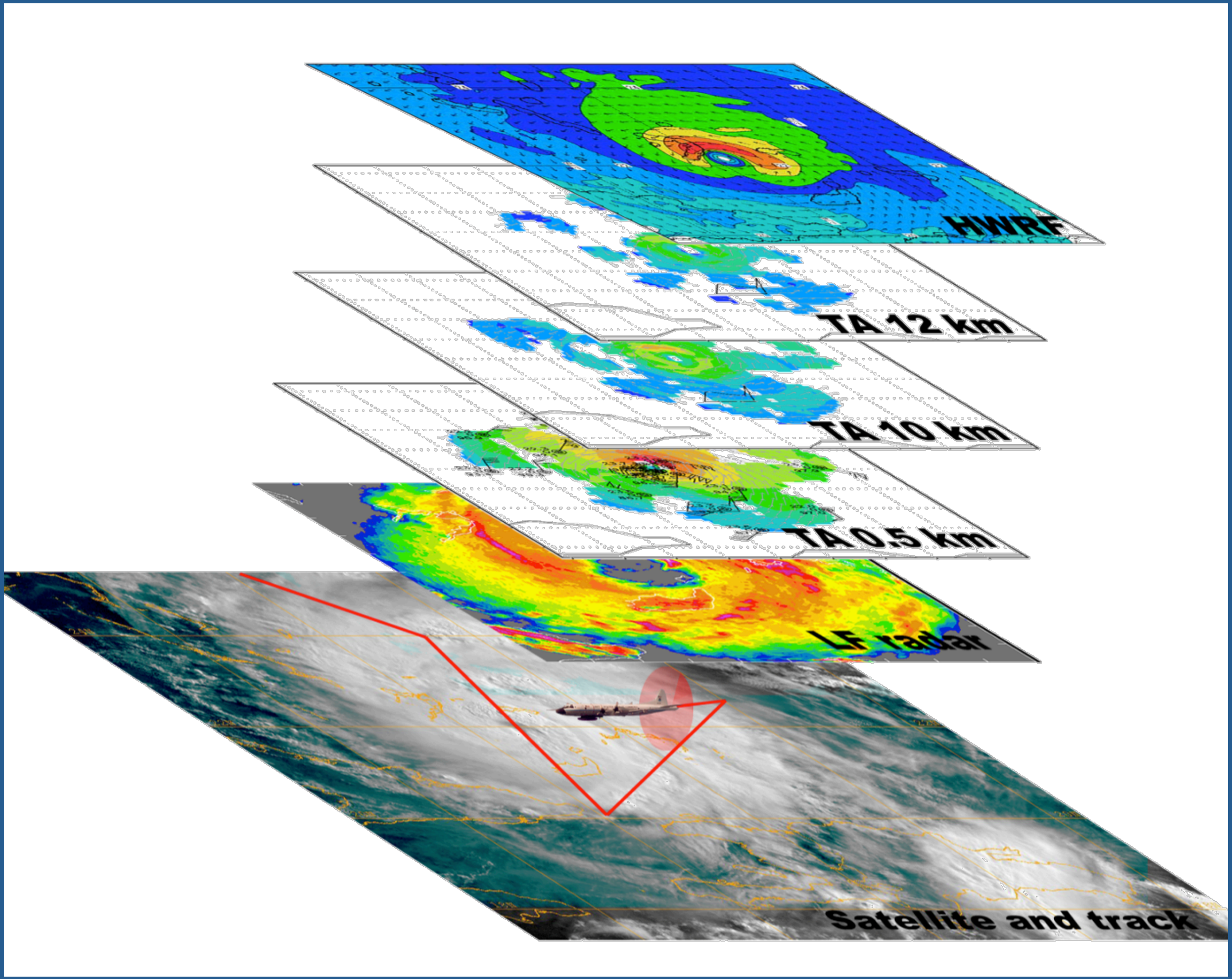
Aircraft Observations of Hurricanes to Improve the Understanding and Prediction of Tropical Cyclones

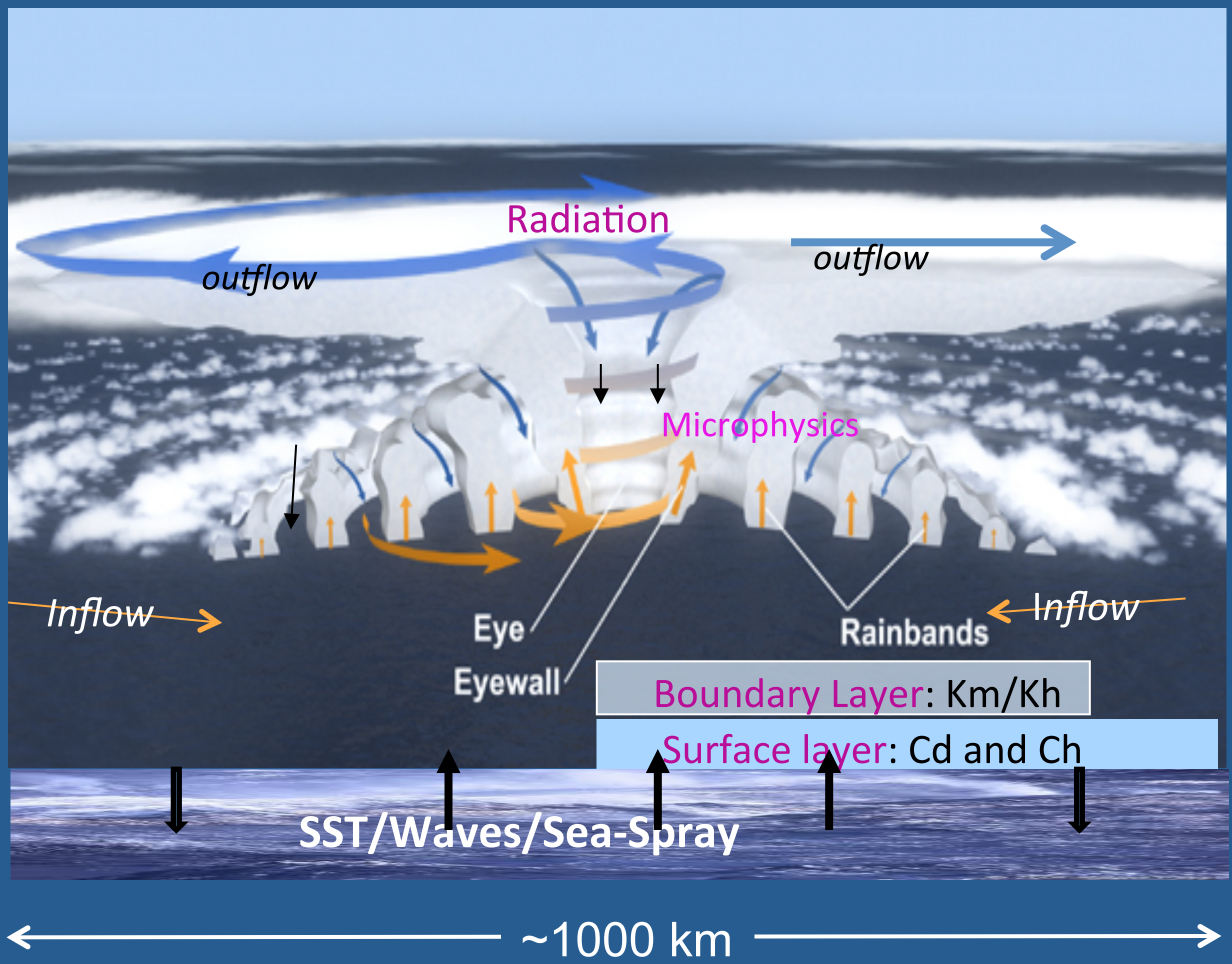


Robert Rogers
NOAA/AOML Hurricane Research Division
Miami, FL

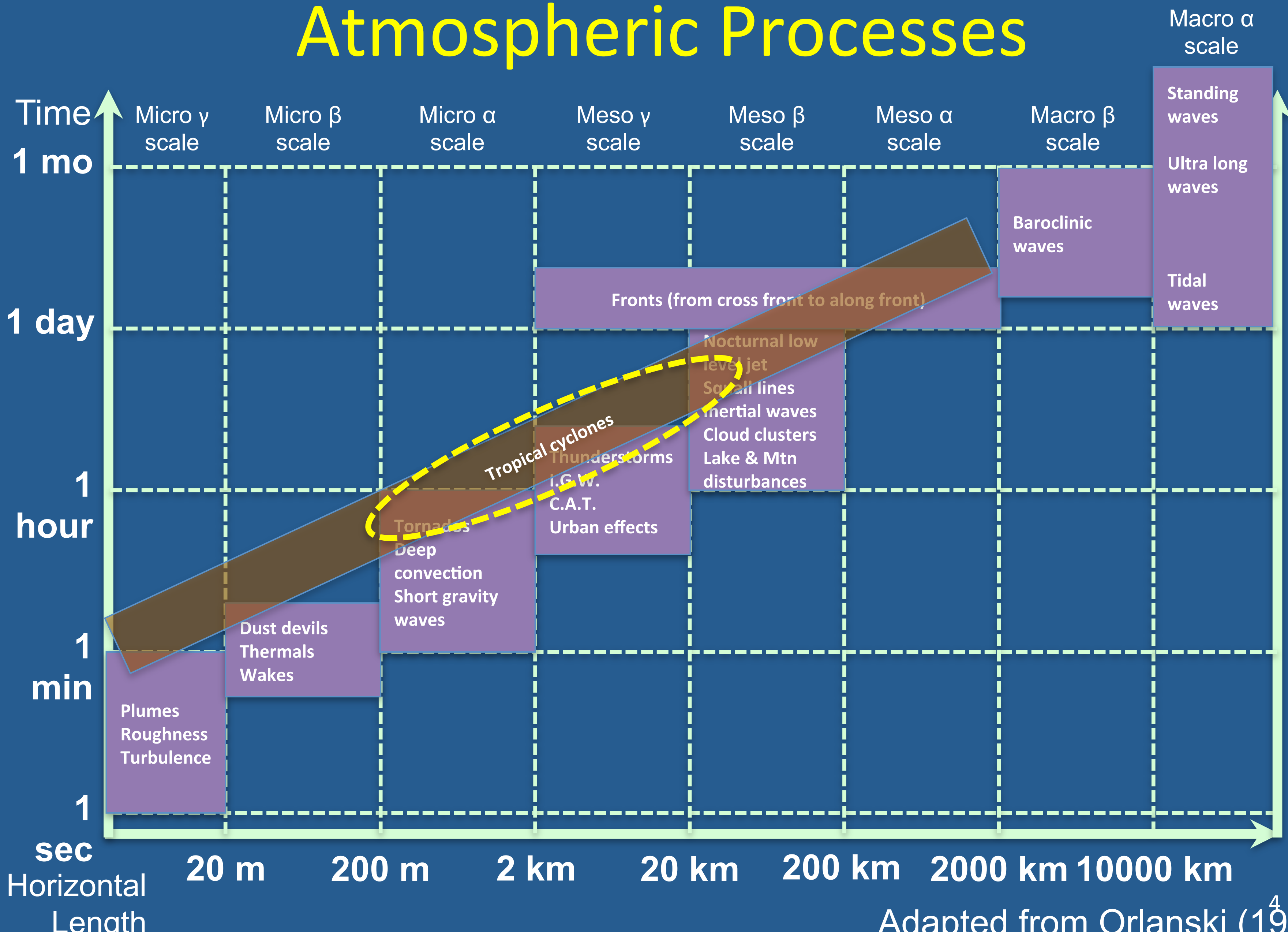
Motivation

- Many important physical processes within TCs occur over a multitude of spatial and temporal scales, from environmental to vortex to convective to turbulent to microphysical
- Observations key component of balanced approach toward advancing understanding and improving forecasts (observations, modeling, theory)
- Three primary platforms for observations – airborne, spaceborne, and land-based

Multiscale processes in hurricanes

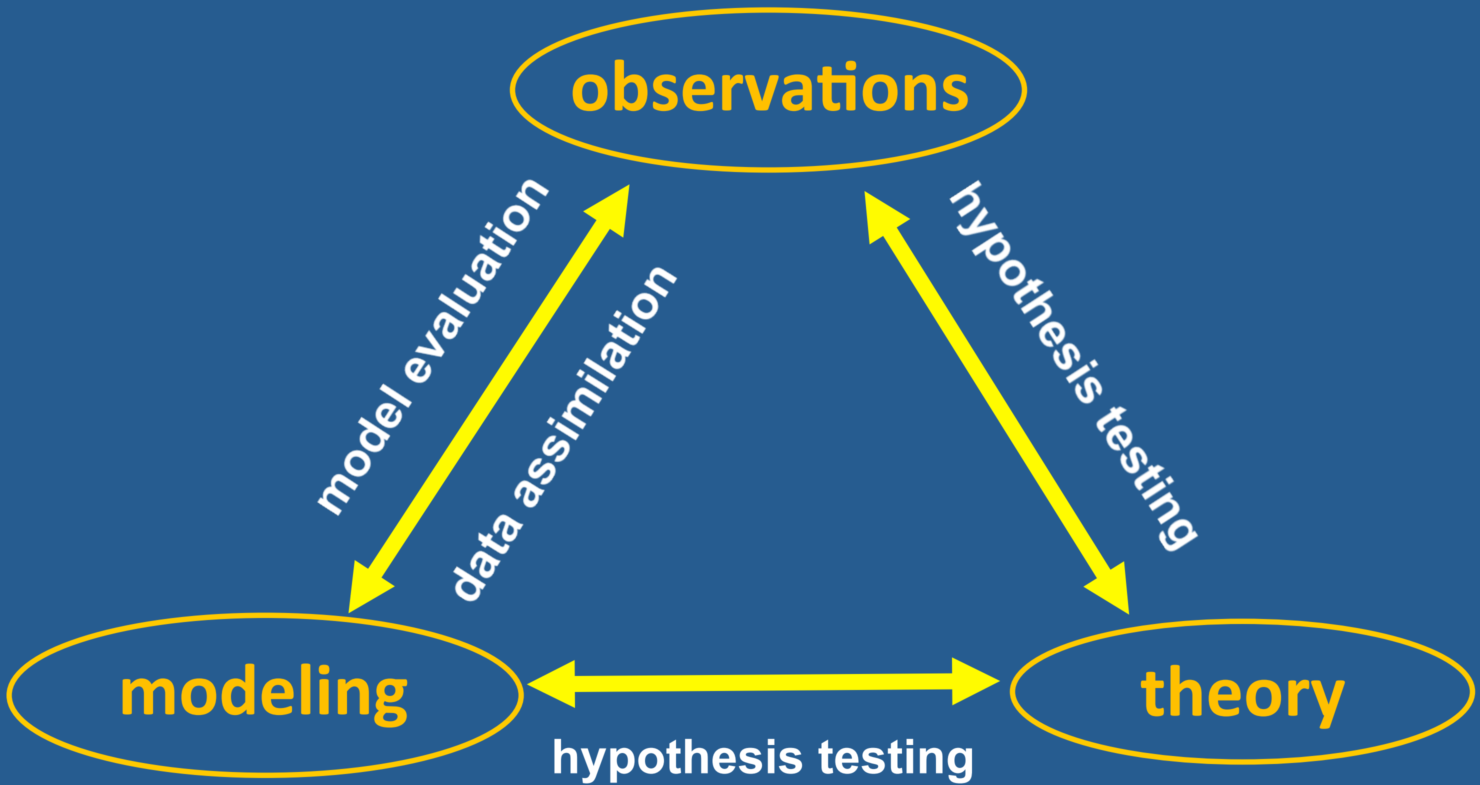


Spatio-Temporal Scales of Atmospheric Processes



Adapted from Orlanski (1975)

Optimal interactions among observations, modeling, and theory



Types of Observations

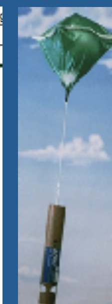
Airborne

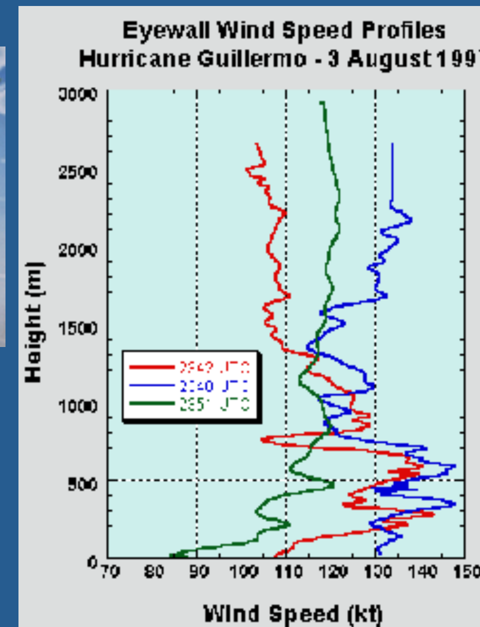
- **In-situ**
  - Wind, press., temp.

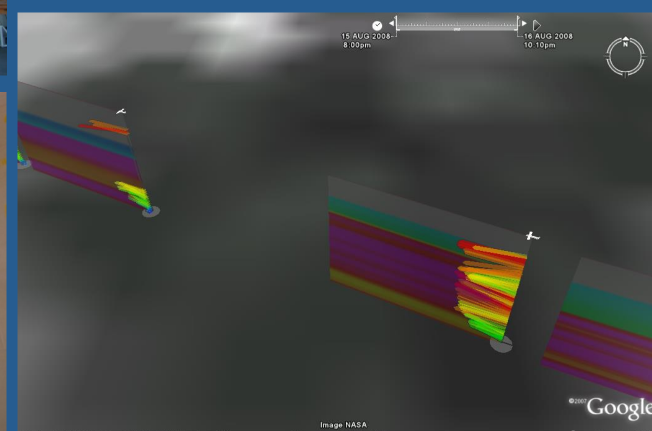
- **Expendables**
  - Dropsondes
  - AXBT, AXCP, buoy

- **Remote Sensors**
  - Doppler Radar
  - SFMR
  - DWL
  - WSRA
  - Scatterometer/ profiler
  - UAS

Coyote UAS



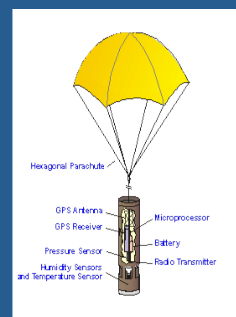


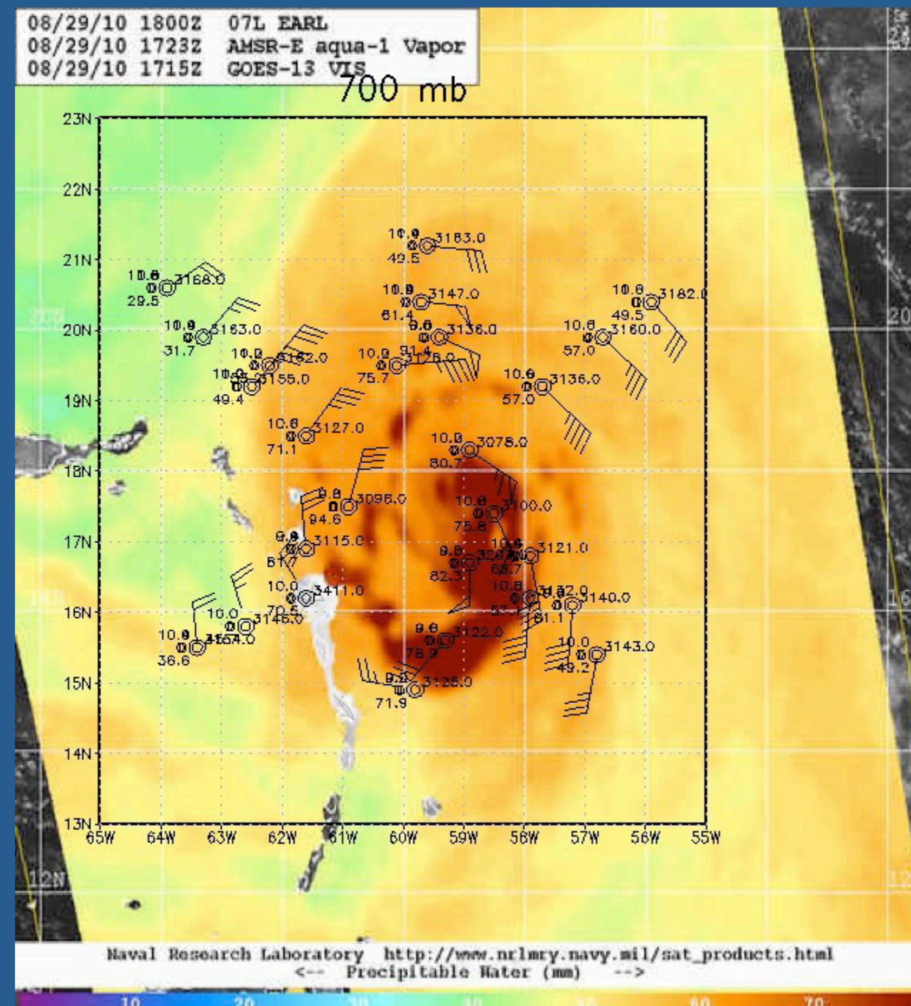


Types of Observations - Airborne

Environmental structure

- Synoptic-surveillance using dropsondes





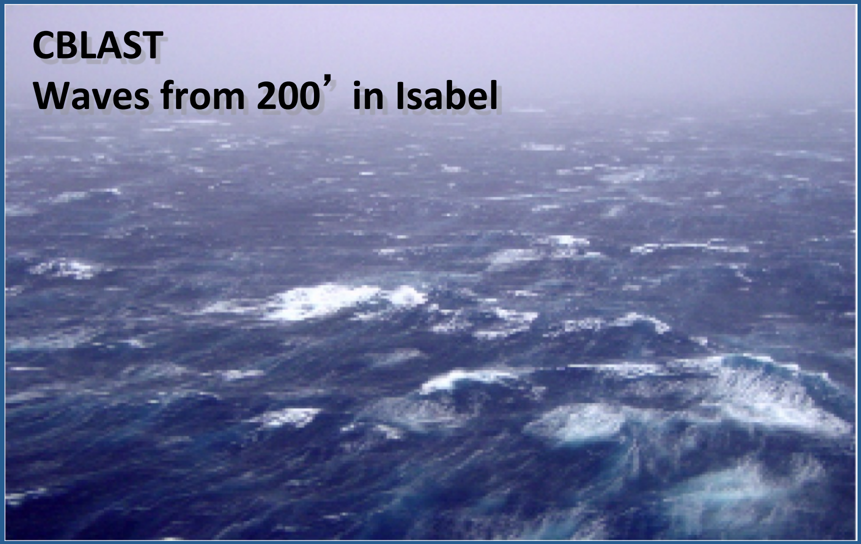
- Analytical & numerical studies.
- Ensemble track forecasting & targeted observations.

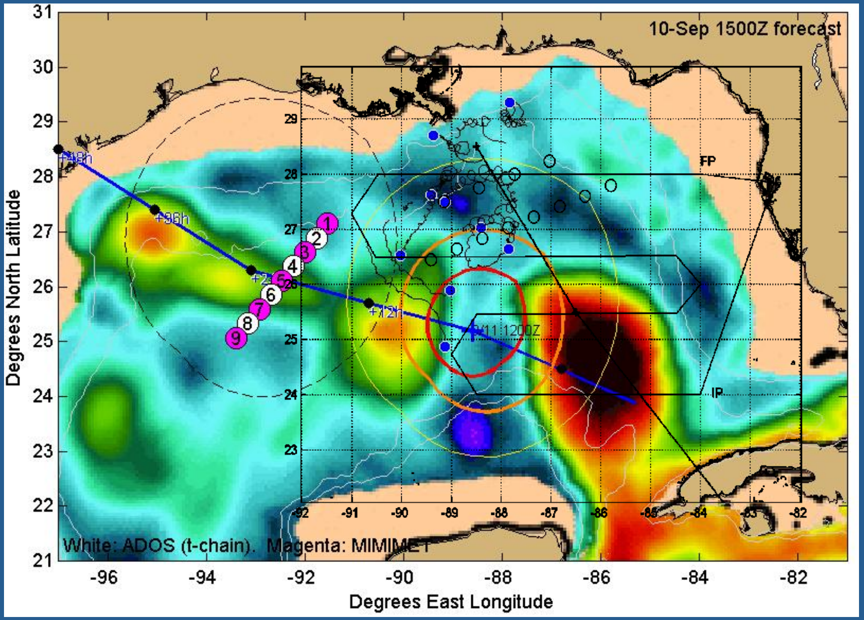
Types of Observations - Airborne

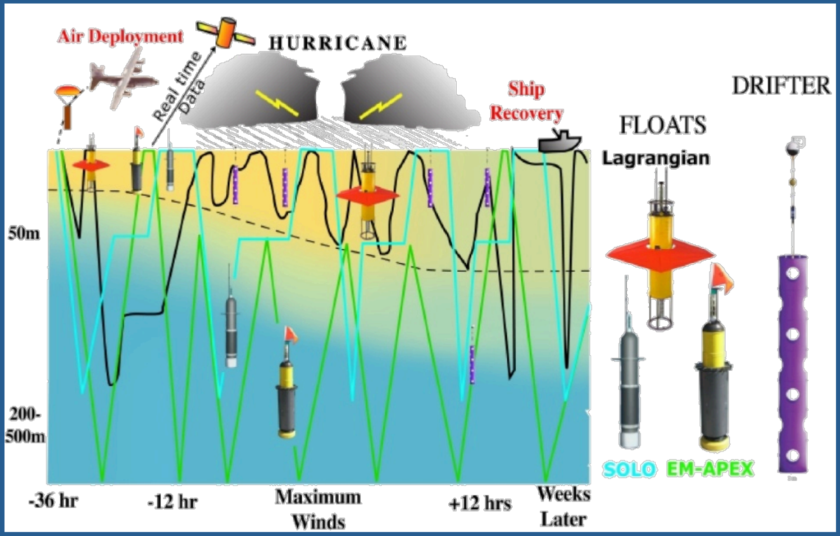
Environmental structure

Targeted upper ocean observations

TC impact on upper ocean effect of Hurricanes Gustav and Ike (2008)



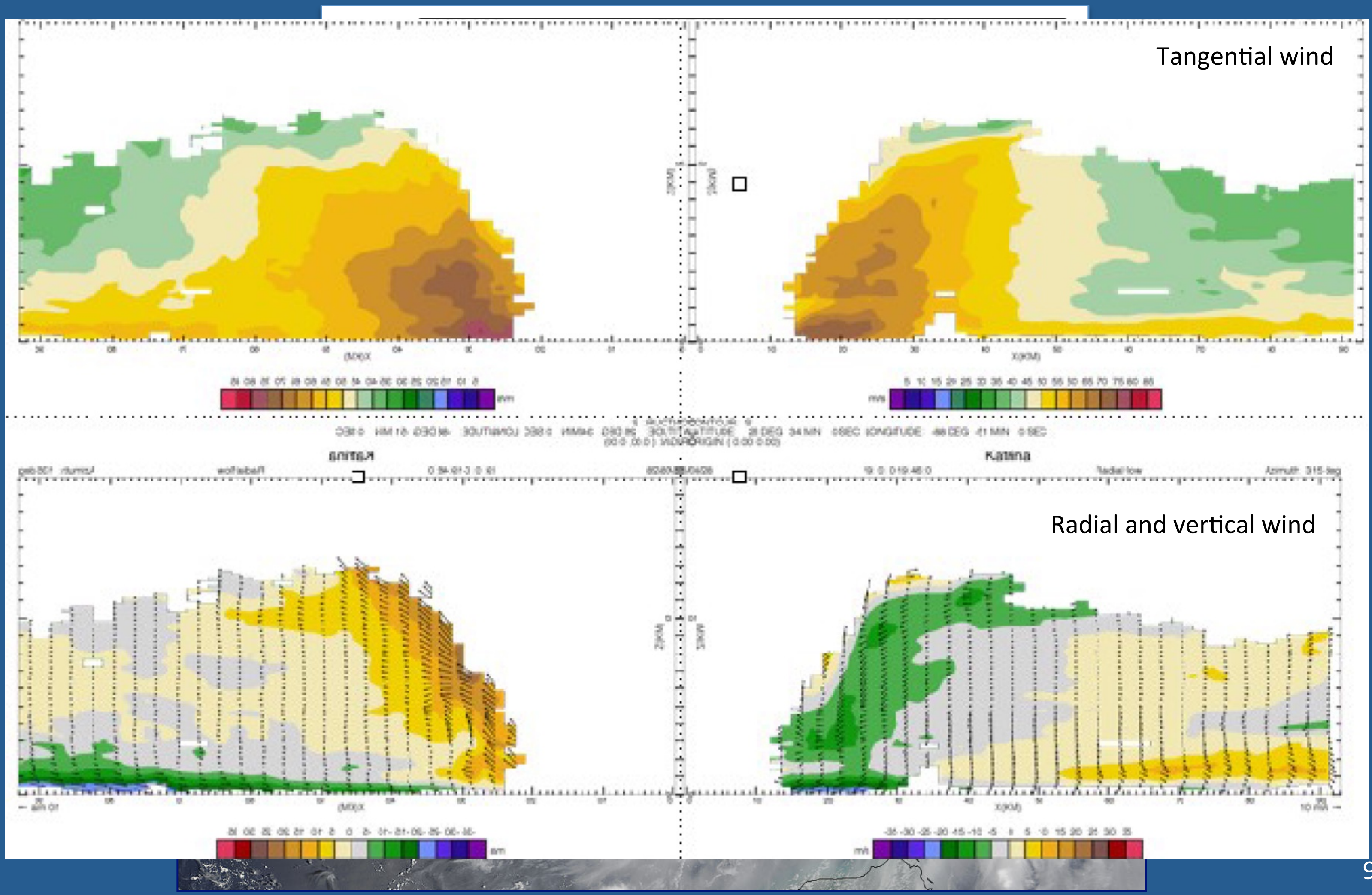




Types of Observations - Airborne

Vortex Structure

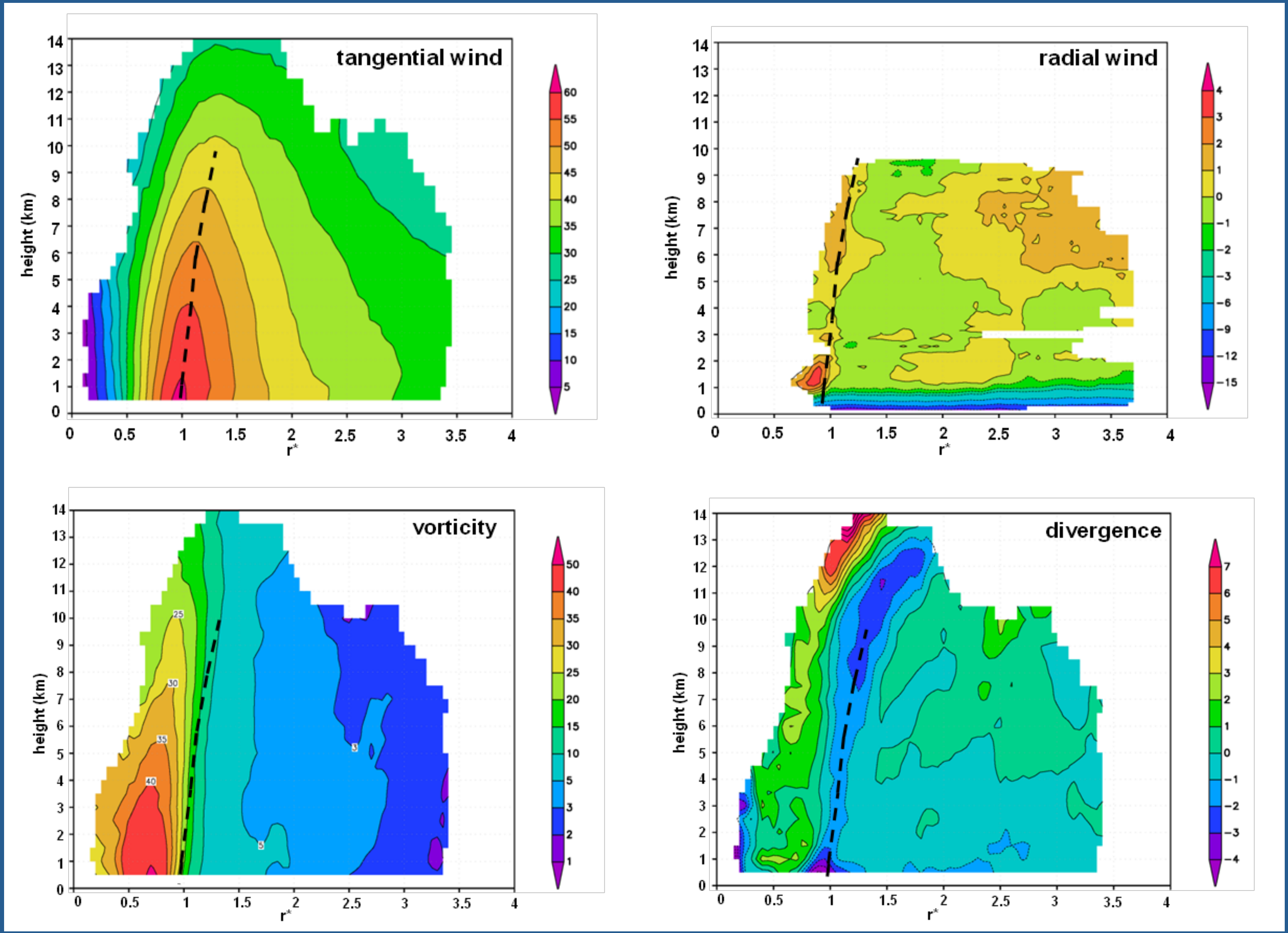
Vortex-scale measurements using Airborne Doppler radar



Types of Observations - Airborne

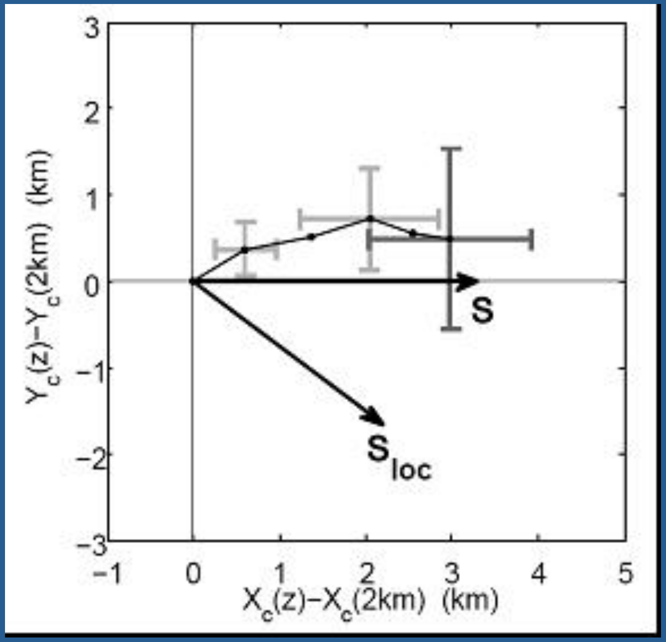
Vortex Structure

Composite axisymmetric vortex structure from mature hurricanes

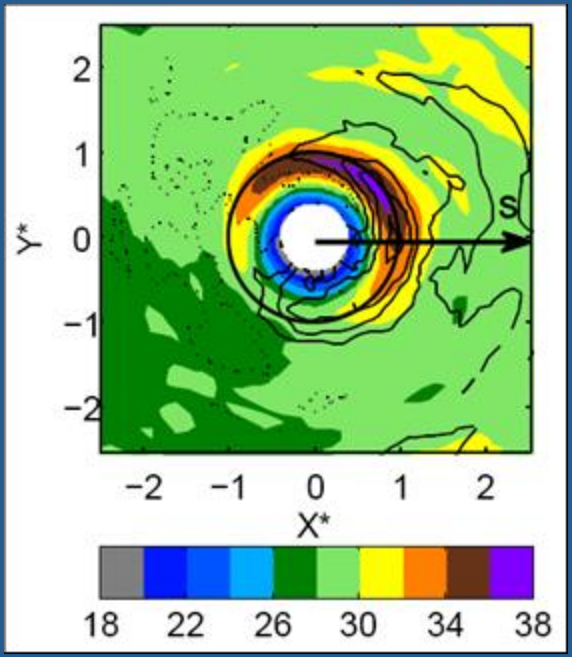


Types of Observations - Airborne
Vortex Structure

Composite asymmetric vortex structure of mature hurricanes in vertical shear



Composite mean 2-7 km vortex tilt

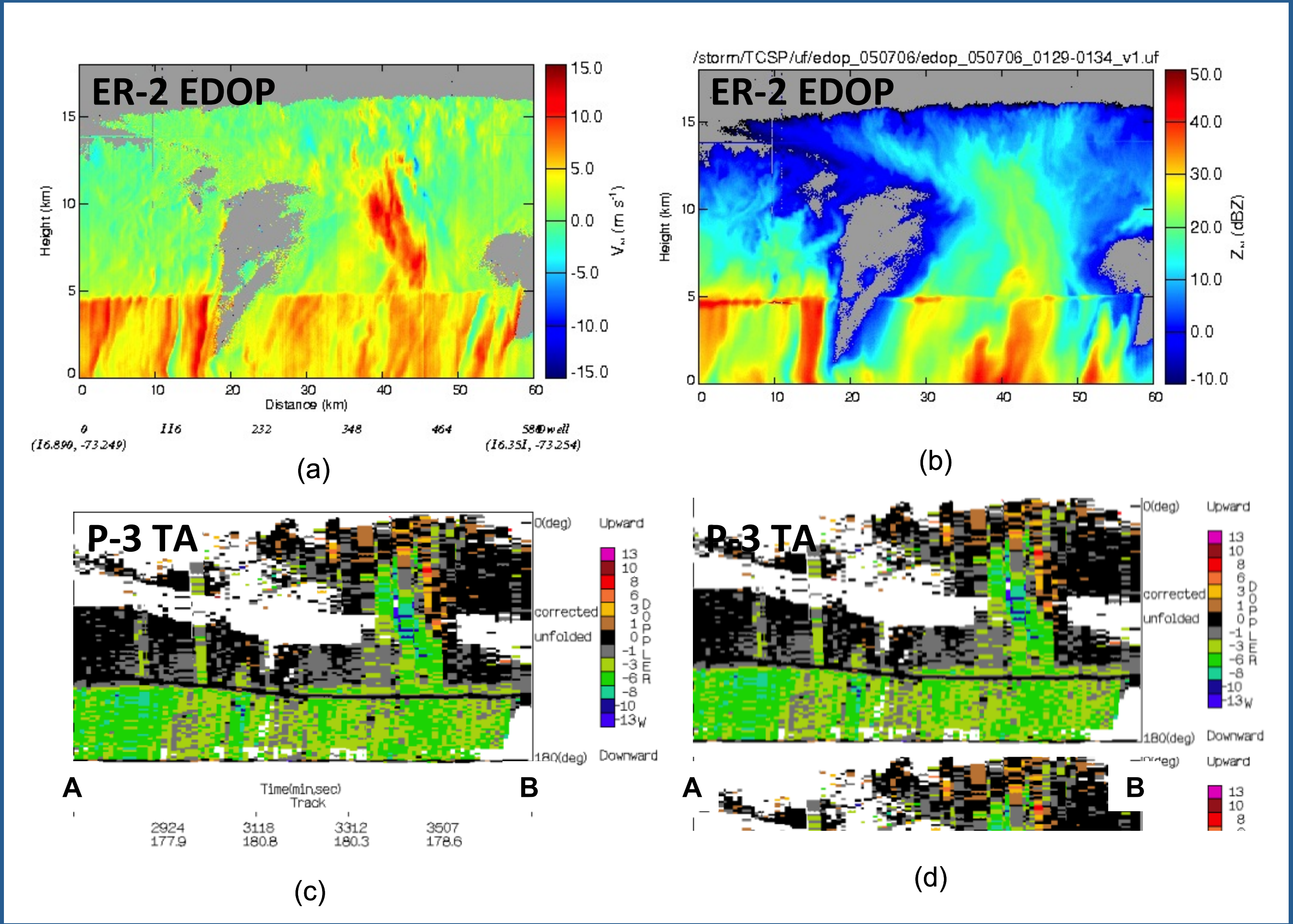


Composite mean 2-km reflectivity (shaded, dBZ) and vertical velocity (contour, m/s)

Types of Observations - Airborne

Convective Structure

Radar measurements in Hurricane Dennis (2005)



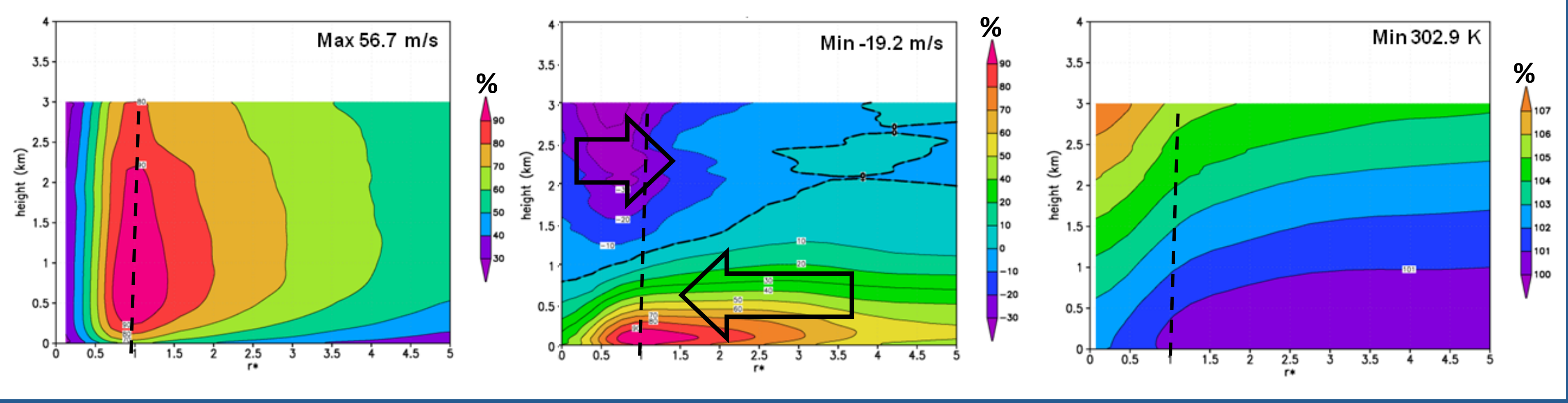
Doppler velocity (m/s) **Reflectivity (dBZ)**

Types of Observations - Airborne

Boundary Layer Structure

Radial variation of mean PBL structures from GPS dropsonde composites

tangential wind | radial wind | virtual potential temperature

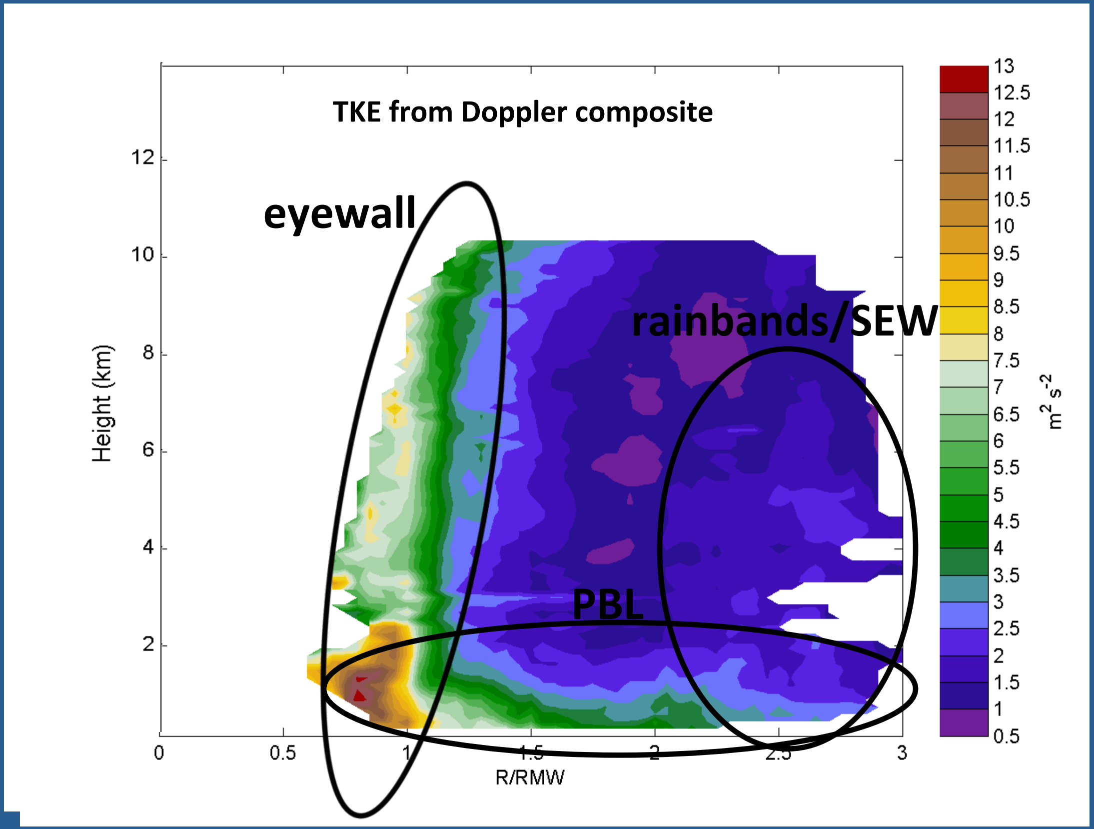


- 794 dropsondes in 13 different storms
- normalized by RMW and peak value within composite

Types of Observations - Airborne

Turbulent Structure

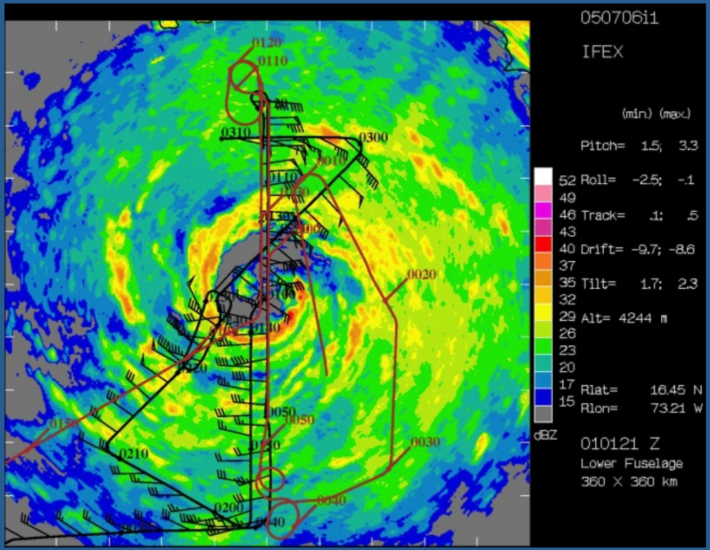
Turbulent kinetic energy inferred from airborne Doppler

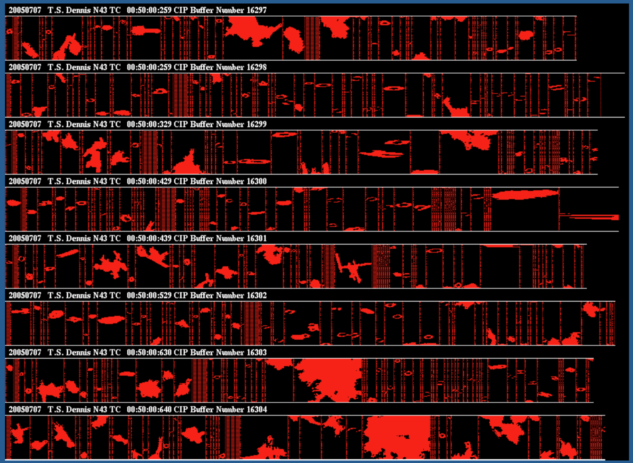


Types of Observations - Airborne

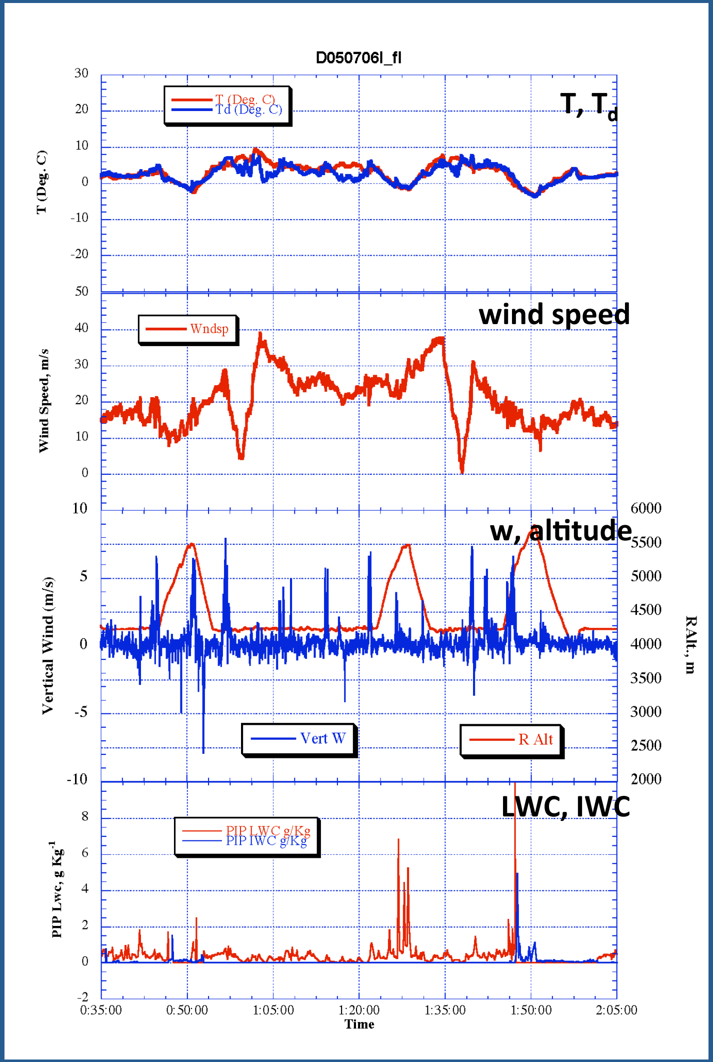
Microphysical Structure

Flight-level parameters during north-south leg on July 6 for Dennis (2005)



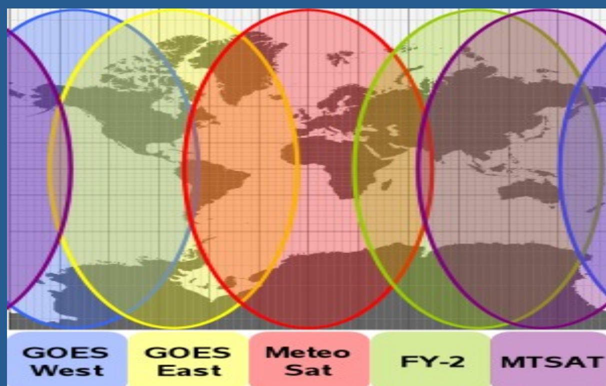


CIP images

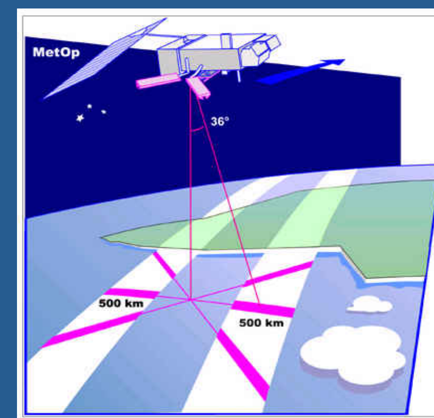


Types of Observations
Spaceborne

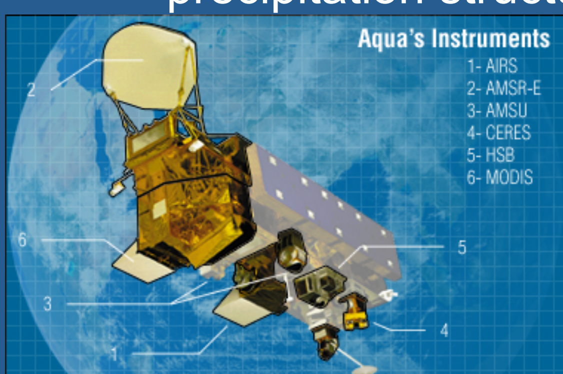
- Geostationary
  - visible, infrared, water vapor channels
  - cloud structure, cloud-drift winds

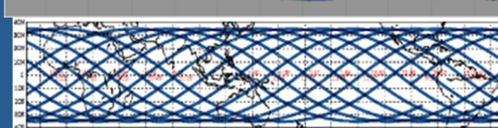


- Polar-orbiting
  - active scatterometer
  - surface wind speed and direction



- Polar-orbiting
  - passive microwave channels
  - precipitation structure, ice scattering

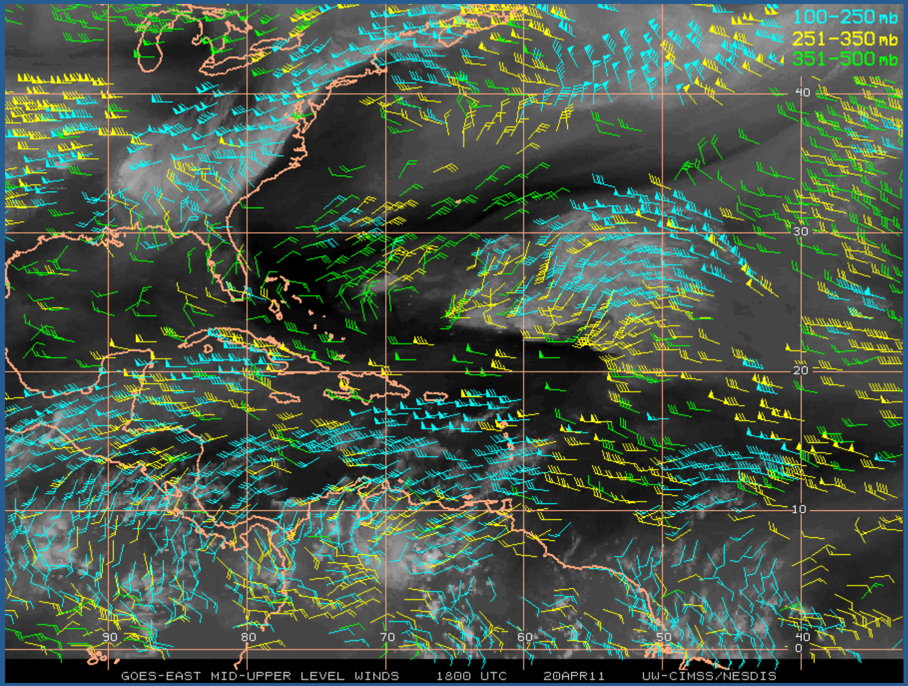


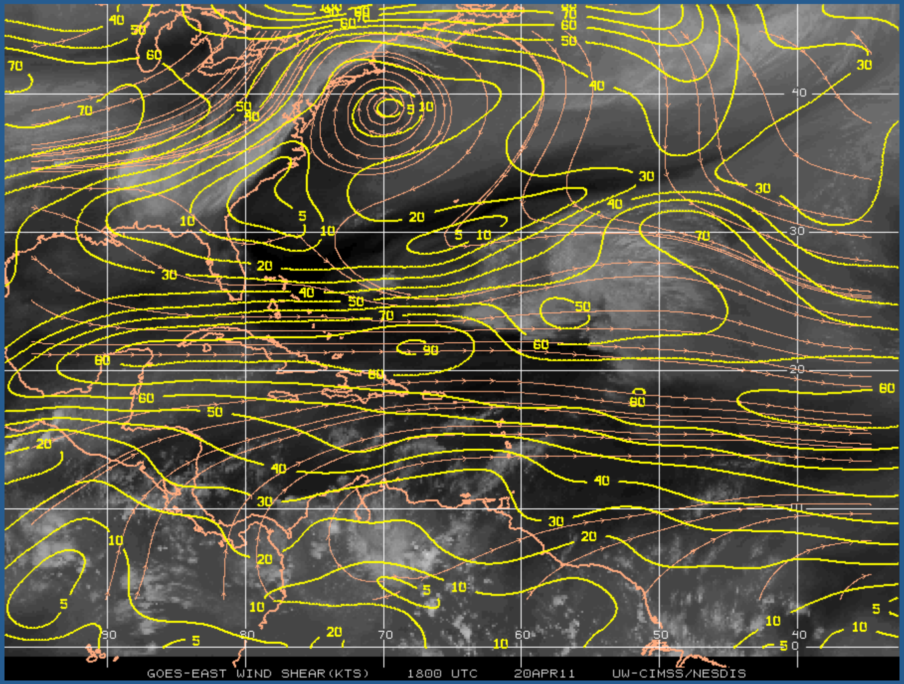


Types of Observations - Spaceborne

Environmental structure

Upper-level winds and vertical shear derived from cloud drift winds

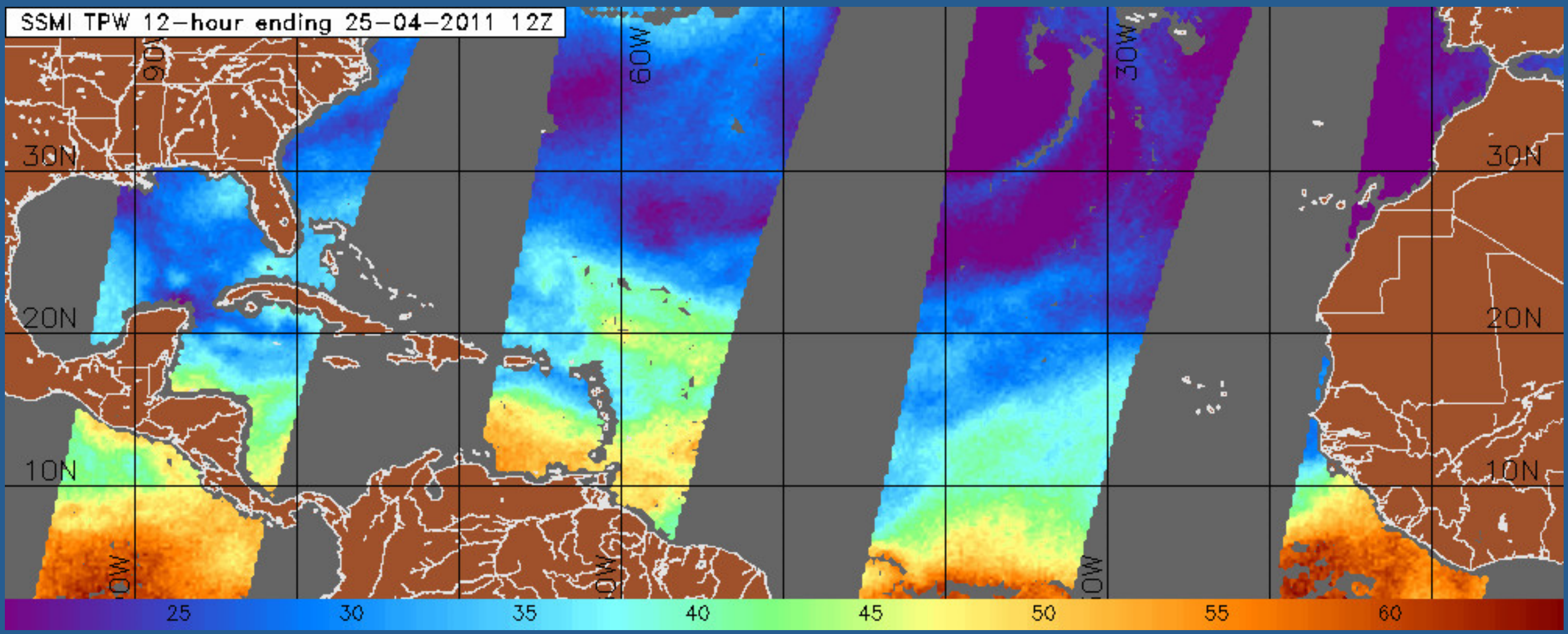




Types of Observations - Spaceborne

Environmental structure

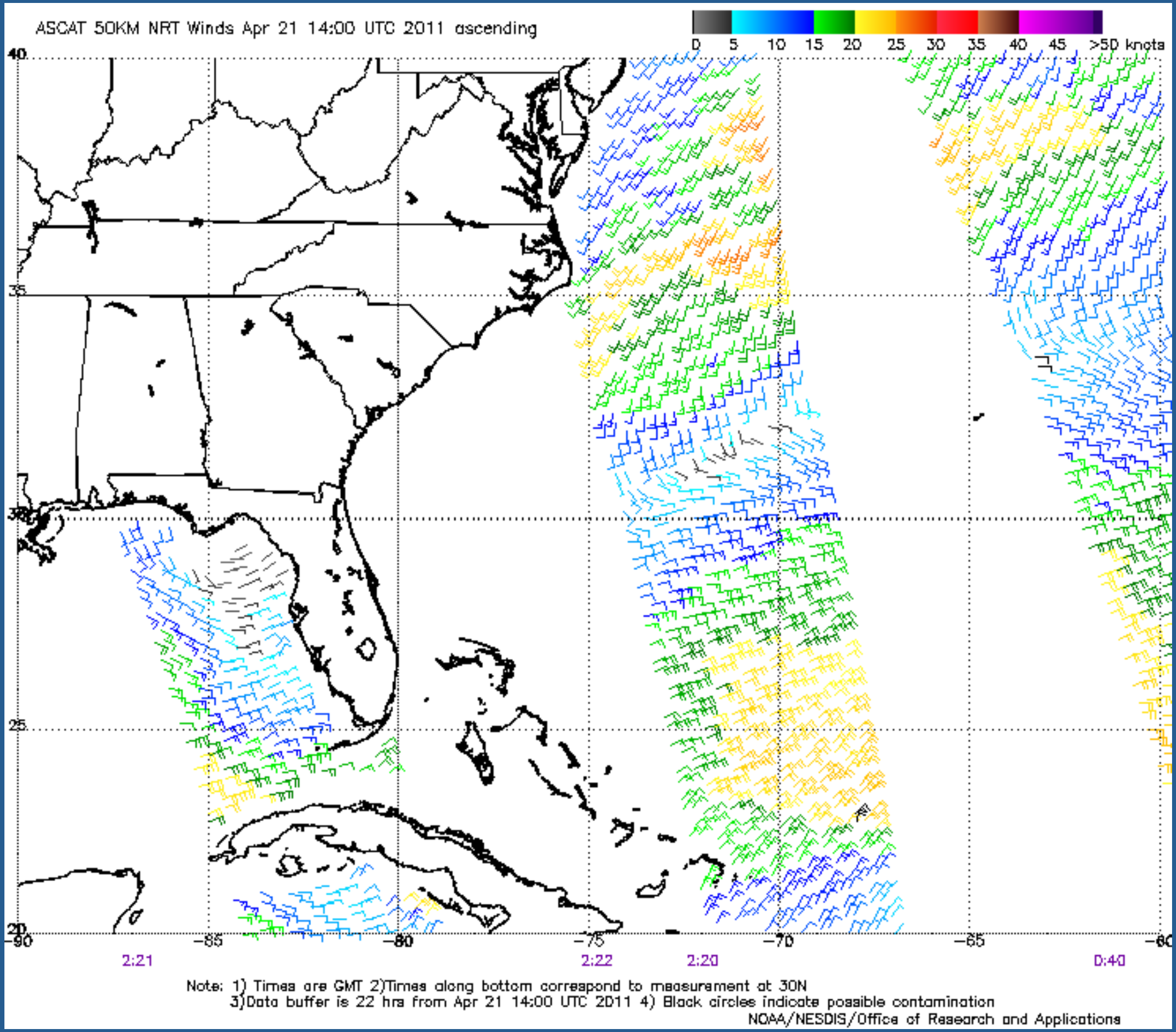
Mosaic of total precipitable water from SSMI polar orbiter



Types of Observations - Spaceborne

Environmental and Vortex structure

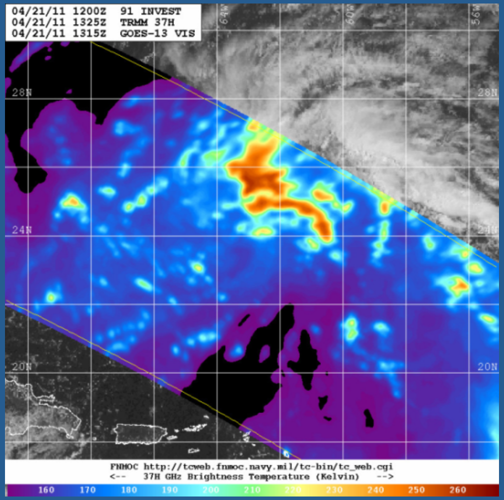
ASCAT surface winds for Invest 91 (2011)

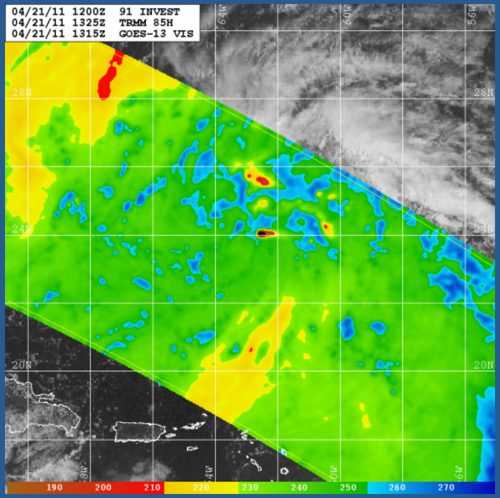


Types of Observations - Spaceborne

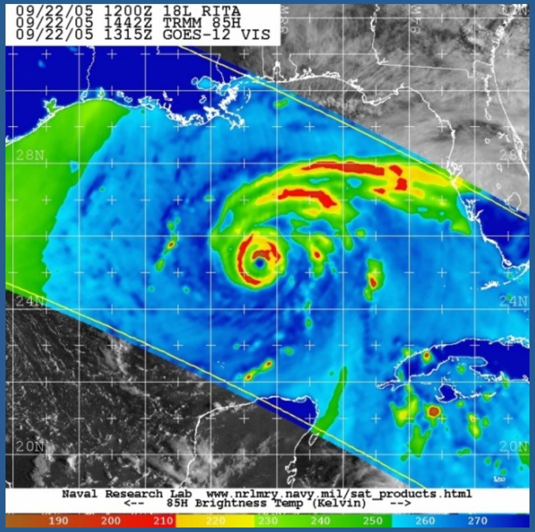
Vortex and convective structure

37 and 85 GHz microwave brightness temperatures for Invest 91 (2011)





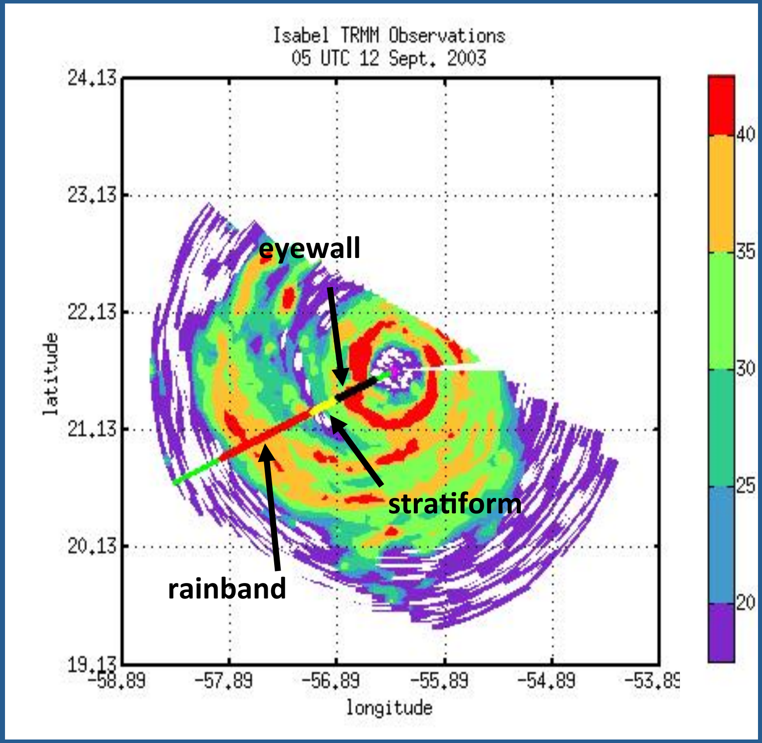
85 GHz microwave brightness temperatures for Rita (2005)

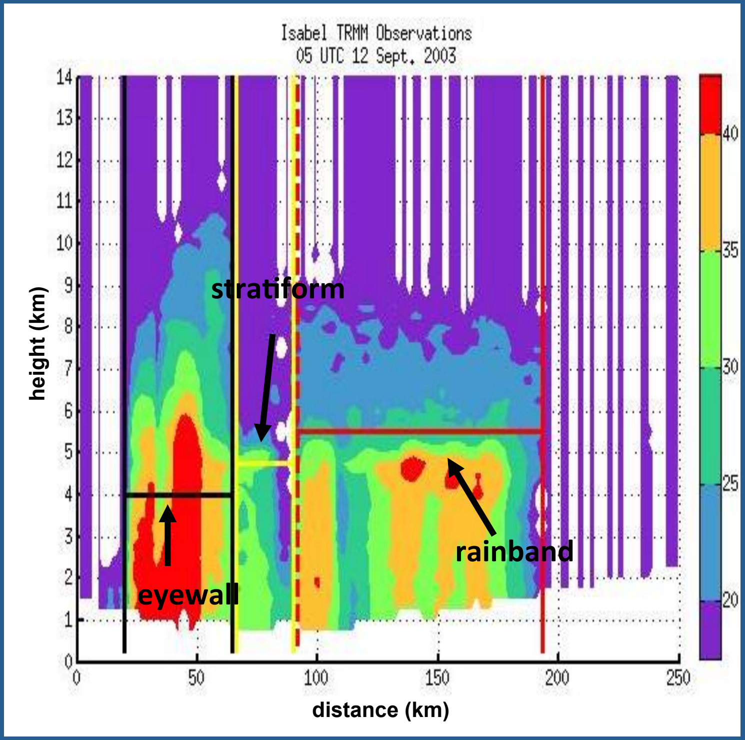


Types of Observations - Spaceborne

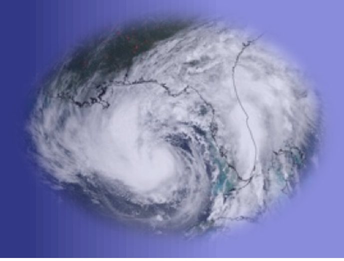
Vortex and convective structure

Eyewall/rainband/stratiform partitioning from TRMM Precipitation Radar

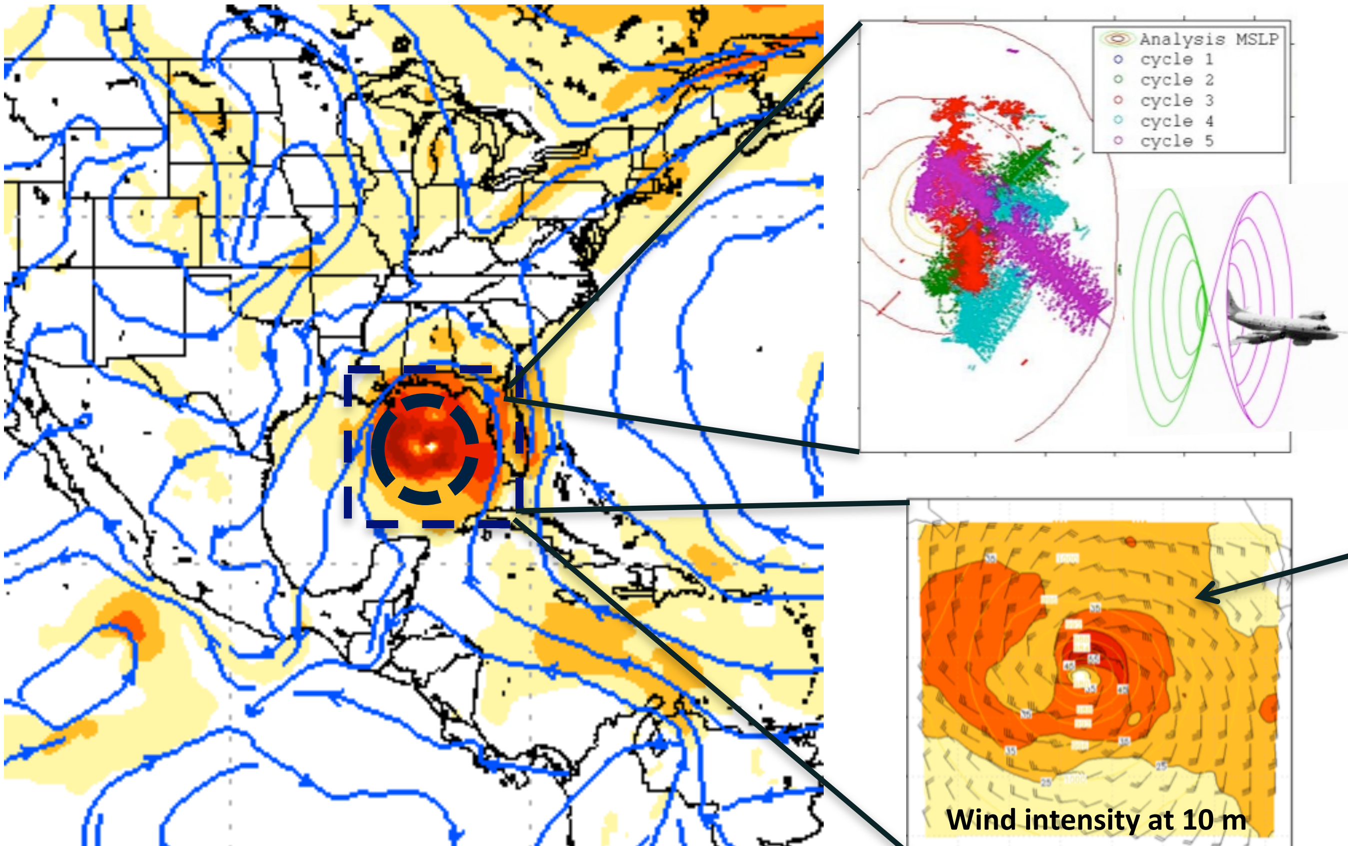




Use of Observations – Data assimilation



Synergy of high resolution forecast and airborne observations



Hurricane Isaac (2012)

P-3 and G-IV QC Doppler observations

↓

Data assimilation

↓

Improving initial condition in storm core region

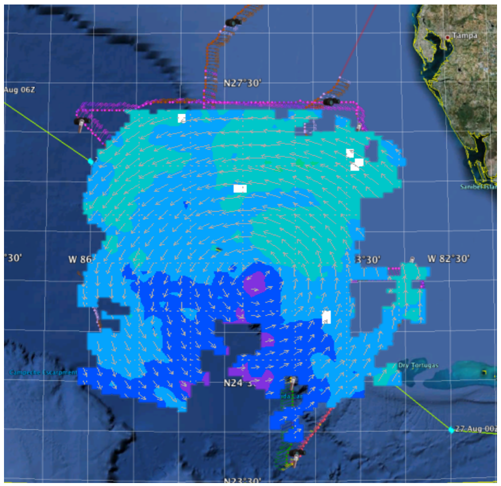
↓

Improving high resolution regional forecast

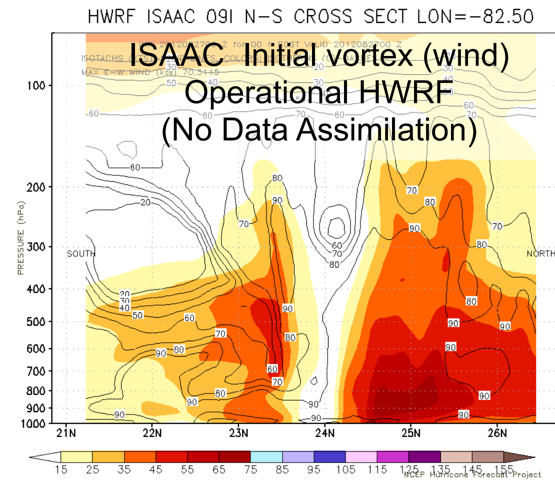
Use of Observations – Data assimilation

Impact Of Aircraft Observations On HWRF Forecast

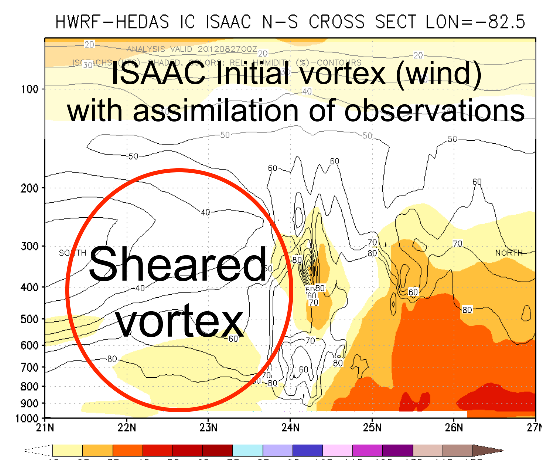
- Improving Storm Structure At Initial Time -



The Hurricane Research Division of AOML developed a state-of the-art inner core data assimilation system for HWRF (HEDAS)
[Runs in real-time under HFIP]



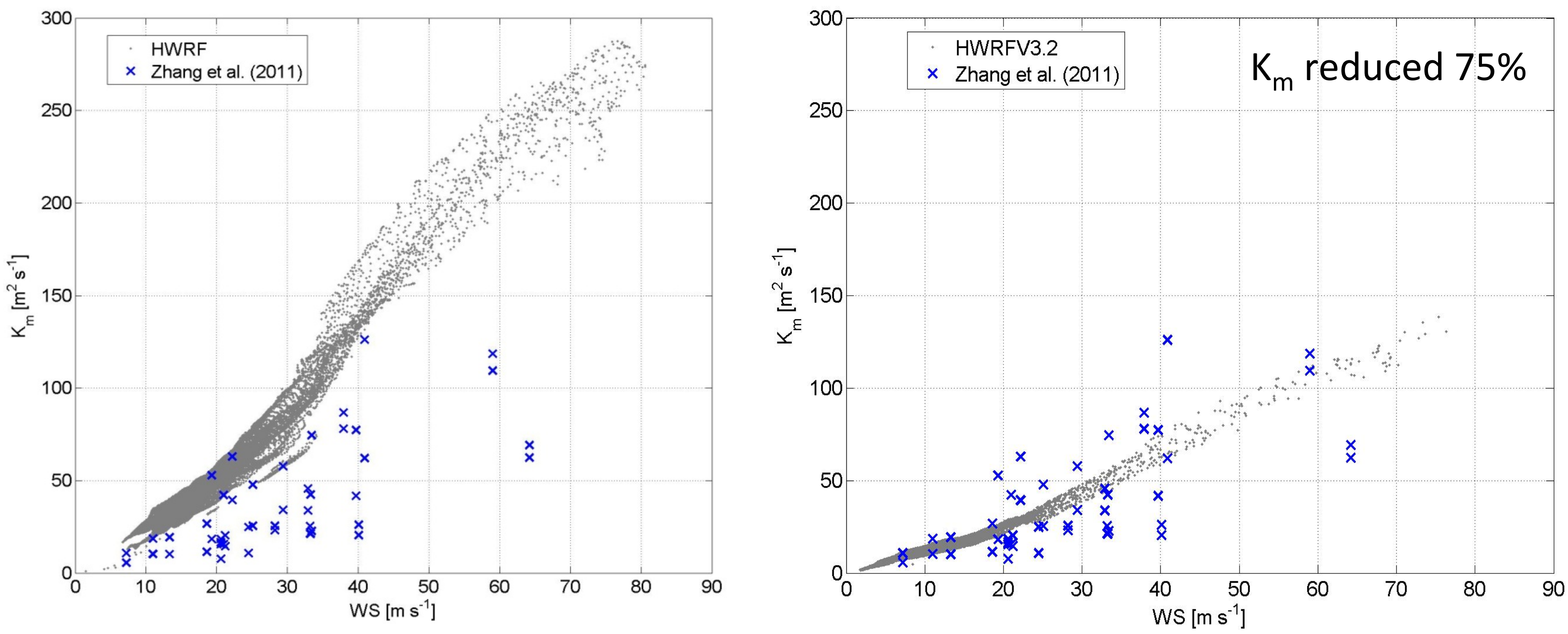
ISAAC (2012): Intensity Errors (kt)				
Forecast Hrs	12	24	36	48
Operational HWRF	13	16	26	26
With P3 Data	8	3	9	20
# Cases	9	7	5	3



Aksoy, A., S. Lorsolo, T. Vukicevic, K. Sellwood, S. Aberson, and F. Zhang, 2012: The HWRF Hurricane Ensemble Data Assimilation System (HEDAS) for high resolution data: The impact of airborne Doppler radar observations in an OSSE. Mon. Wea. Rev (in press).

Use of Observations - Model evaluation

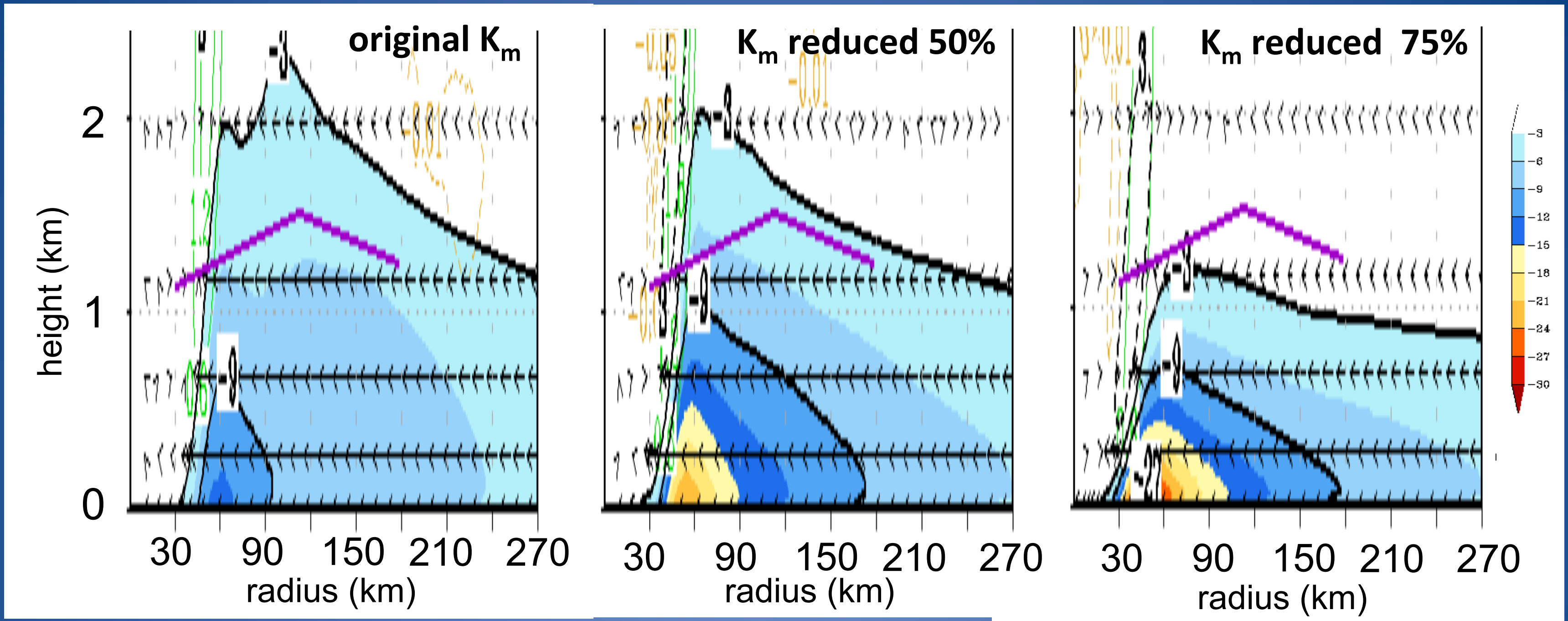
Modification of vertical eddy diffusivity (Km) in the operational HWRF model based on in situ measurements



PBL scheme used in HWRF is too diffusive

Use of Observations - Model evaluation

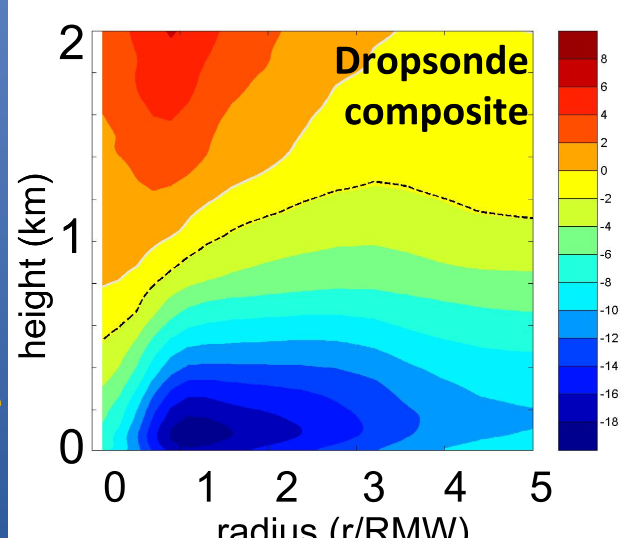
Sensitivity of radial wind (shaded, m s^{-1}) to vertical eddy diffusivity



Gopal et al. 2012

- Peak radial inflow stronger with more accurate K_m
- Depth of inflow layer more consistent with dropsonde composites using more accurate K_m

Dashed line is inflow layer depth from dropsonde composite

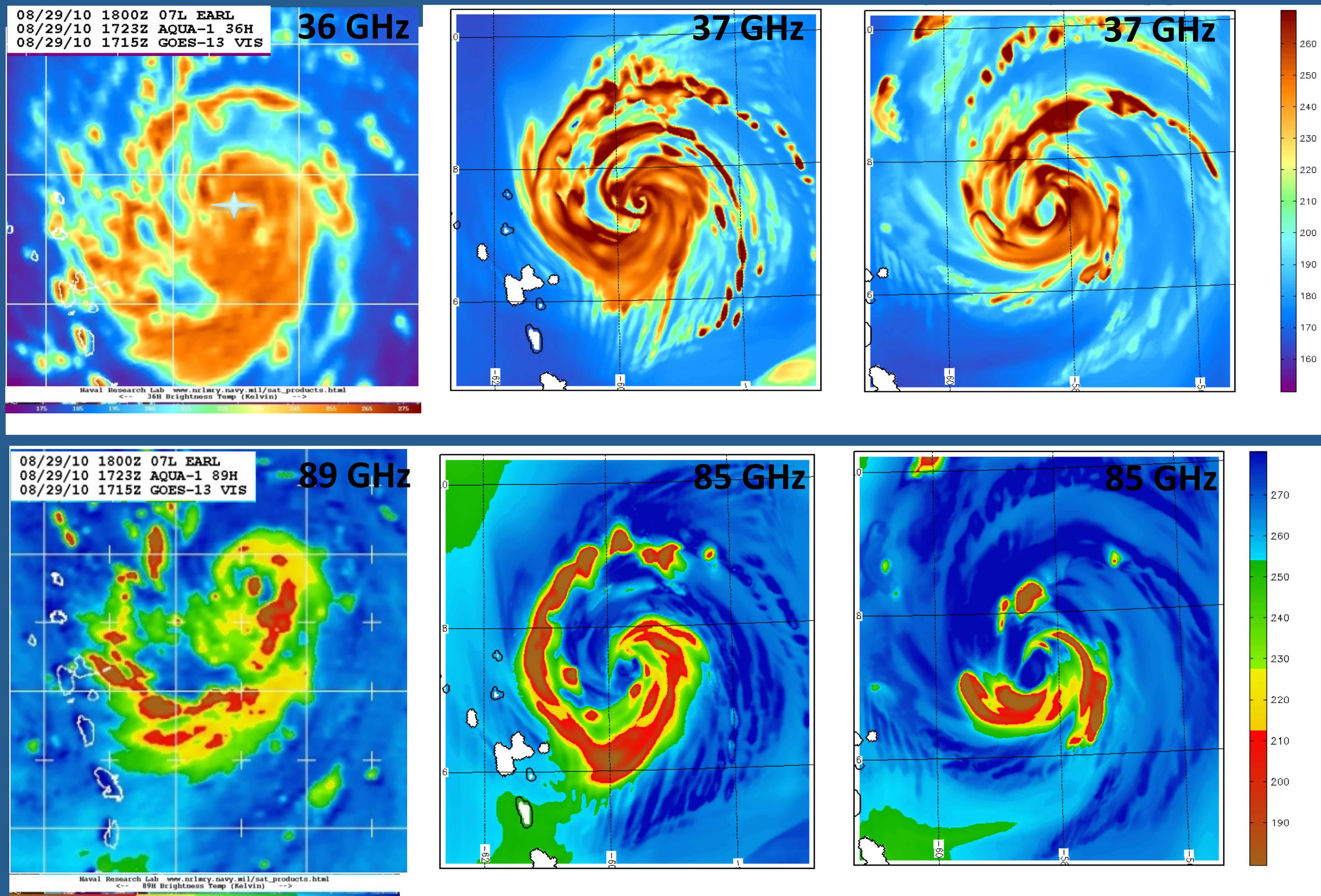


Zhang et al. 2011

Use of Observations - Model evaluation

Comparison of observed and forecast images for Earl (2010) from HEDAS and HWRF ICs

AQUA | HWRFx with HEDAS IC | HWRFx with HWRF IC

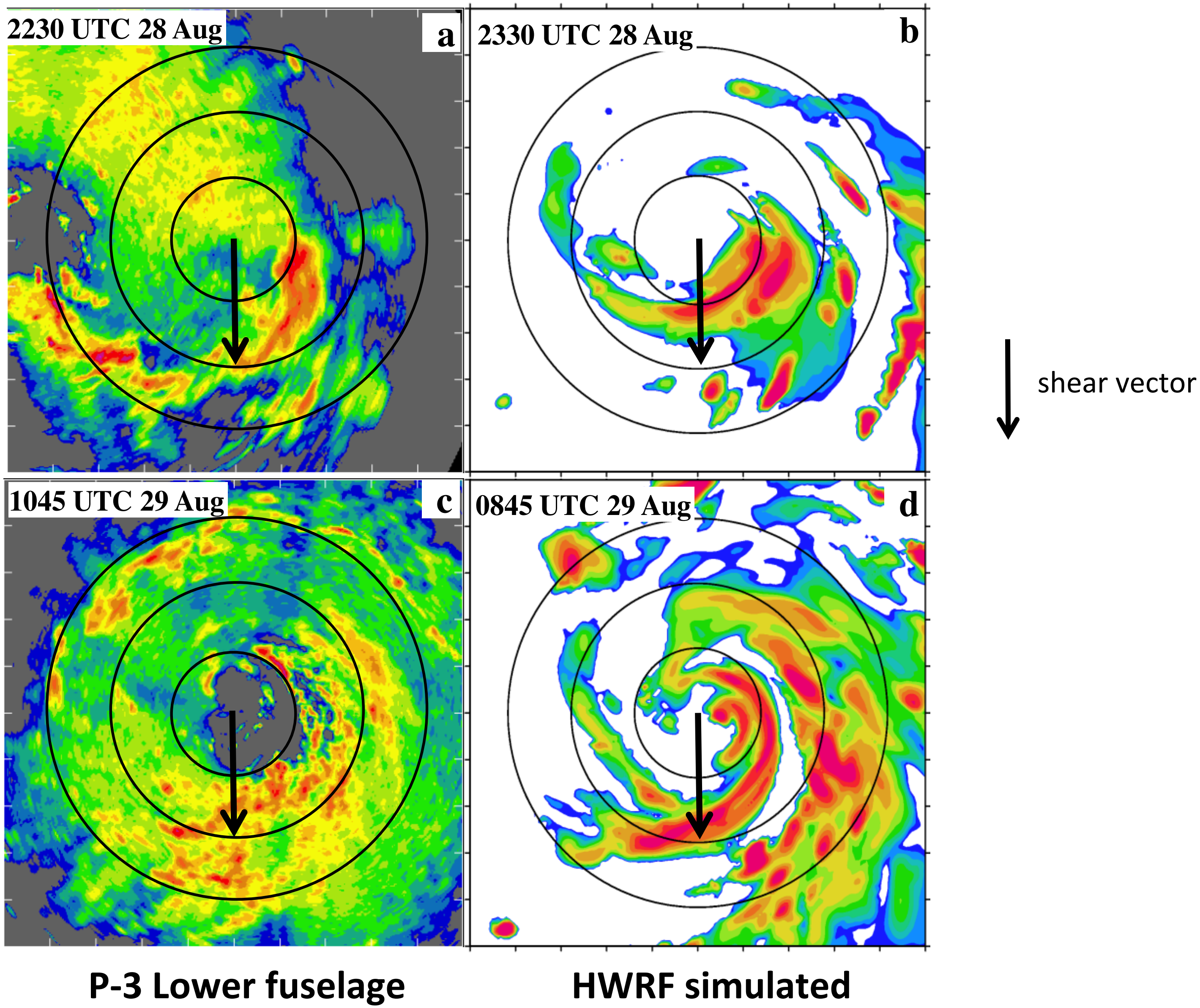


Forecast initial time 12:00Z, 08/29/2010

Use of Observations – Hypothesis testing

What is relationship between vortex tilt and rapid intensification?

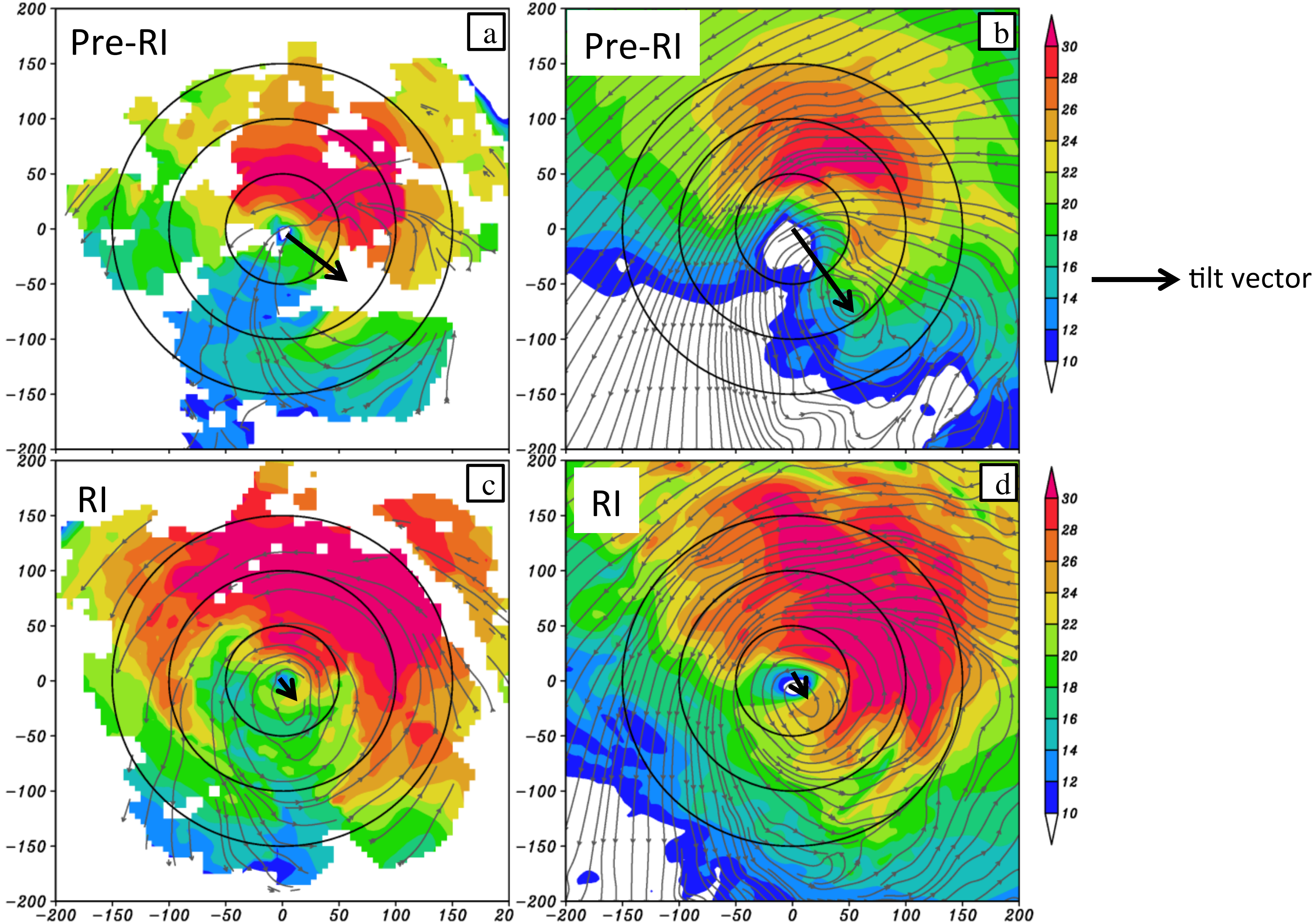
Reflectivity



Use of Observations – Hypothesis testing

What is relationship between vortex tilt and rapid intensification?

2-km wind speed (shaded, m/s) and 8-km streamlines

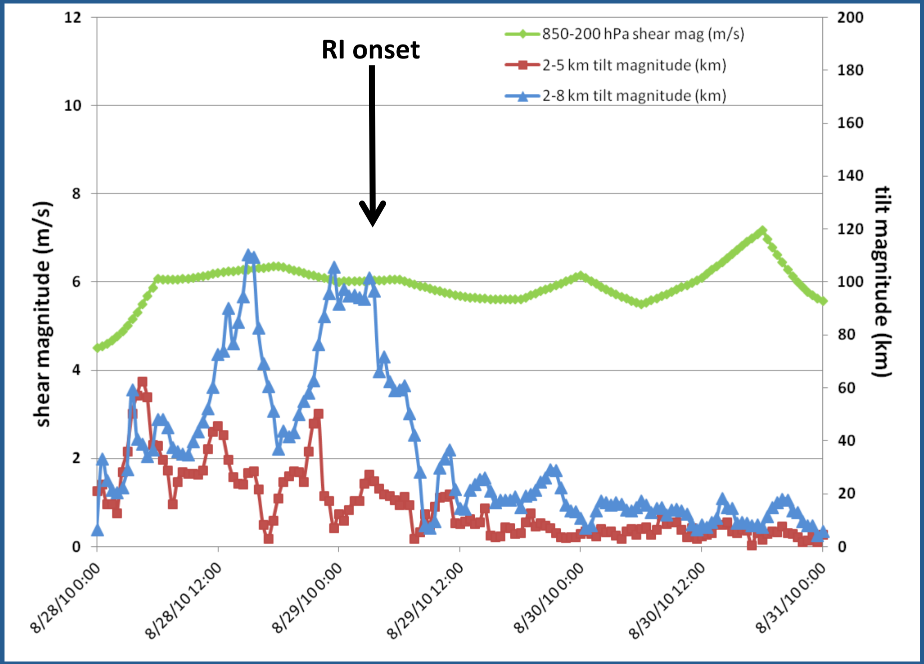


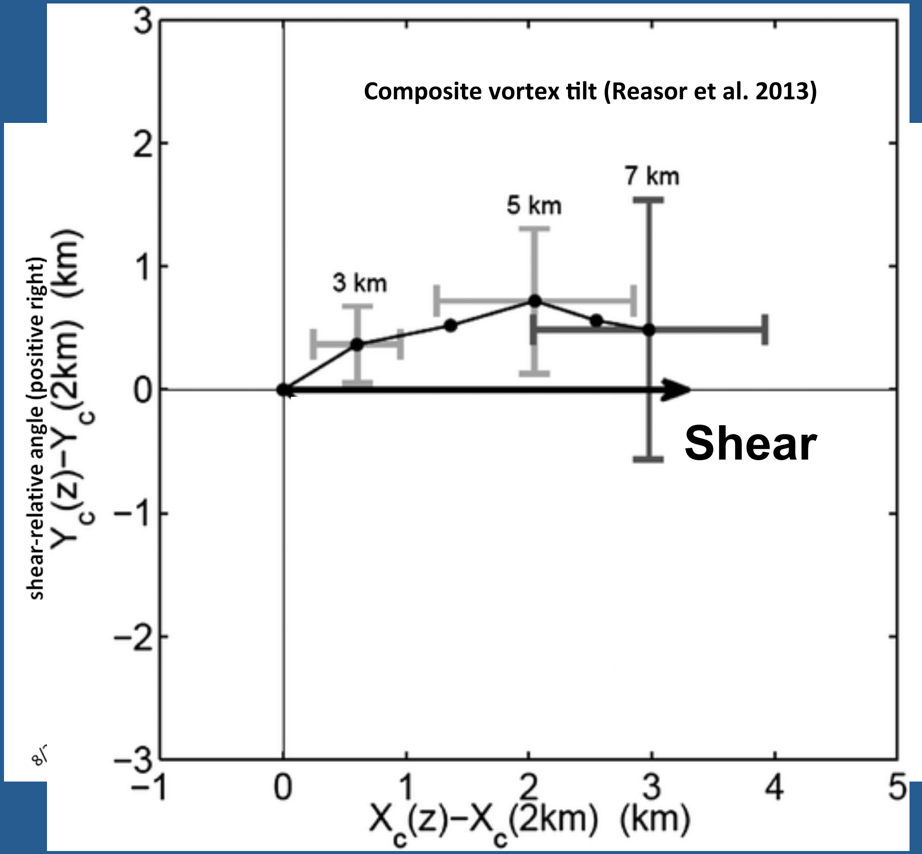
P-3 tail Doppler HWRF simulated

Use of Observations – Hypothesis testing

What is relationship between vortex tilt and rapid intensification?

Time series of SHIPS-derived 850-200 hPa shear (m/s), 2-5 km and 2-8 km tilt magnitude (km)





- large displacement prior to RI onset, continued large displacement at RI onset
- bulk of displacement above 5 km altitude
- vortex becomes nearly aligned several hours after RI onset
- vortex tilts 45-90 degrees left of shear vector prior to RI, oscillates around shear vector after
- vortex alignment is an effect, and not a cause, of RI

Summary

- Wealth of observations across multiple scales collected over many years, continue to be collected in real time
- New tools being developed to analyze observations
  - TKE fields
  - Composites of Doppler and dropsonde measurements
- These observations serve a variety of purposes
  - Model evaluation
  - Data assimilation
  - Hypothesis testing
- Partnerships among government, academic institutions needed to help digest and analyze observational data
  - Testbeds (e.g., JHT, DTC, JCSDA)
  - Hurricane Forecast Improvement Project (HFIP)

Extra slides

Observational databases used in composites

Doppler database

40 radar analyses in 8 different storms

Storm name	Date (mm/dd/yyyy)	Number of analyses	best track intensity (kt)	t+24 h intensity change (kt)
Guillermo	8/2/1997	4	105	25
Fabian	9/3/2003	3	110	0
Isabel	9/12/2003	2	140	0
Isabel	9/13/2003	1	140	0
Isabel	9/14/2003	4	140	-25
Frances	8/30/2004	3	110	15
Frances	8/31/2004	2	125	-5
Frances	9/1/2004	3	120	-5
Ivan	9/7/2004	4	105	15
Katrina	8/28/2005	1	150	-70
Katrina	8/29/2005	3	110	-80
Rita	9/21/2005	3	145	-20
Rita	9/22/2005	3	125	-15
Paloma	11/8/2008	4	125	-100

Rogers et al., MWR, 2011
(in review)

GPS dropsonde database

794 dropsondes in 13 different storms

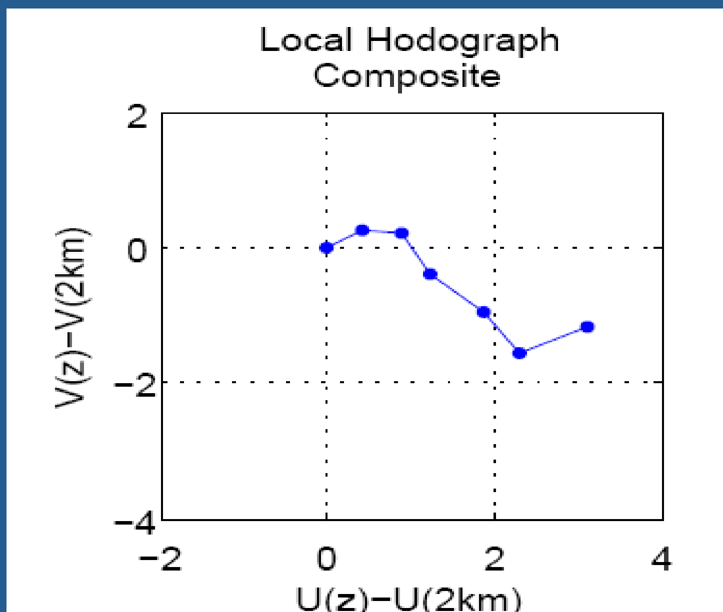
Storm name	Year	Storm Intensity range (kt)	Number of sondes
Erika	1997	83 – 110	40
Bonnie	1998	68 - 93	76
Georges	1998	66 - 78	39
Mitch	1999	145 - 155	28
Bret	1999	75 - 90	33
Dennis	1999	65 - 70	7
Floyd	1999	80 - 110	40
Fabian	2003	68 - 120	131
Isabel	2003	85 - 140	162
Frances	2004	68 - 83	62
Ivan	2004	65 - 135	123
Dennis	2005	65 - 70	7
Katrina	2005	68 - 100	46

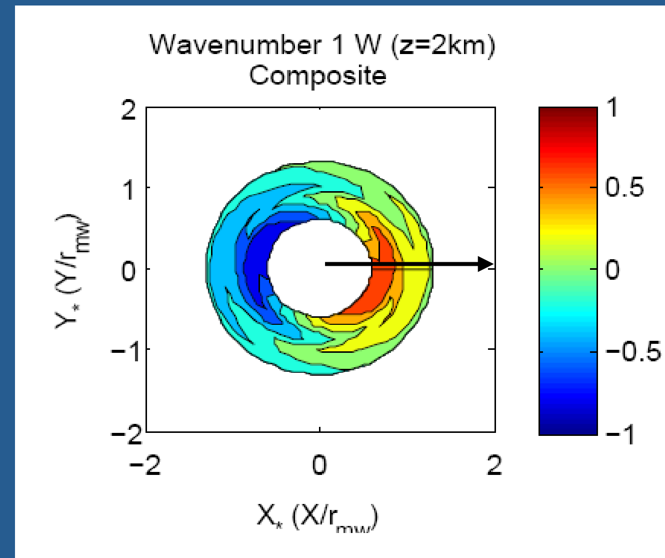
Zhang et al., MWR, 2011
(in press)

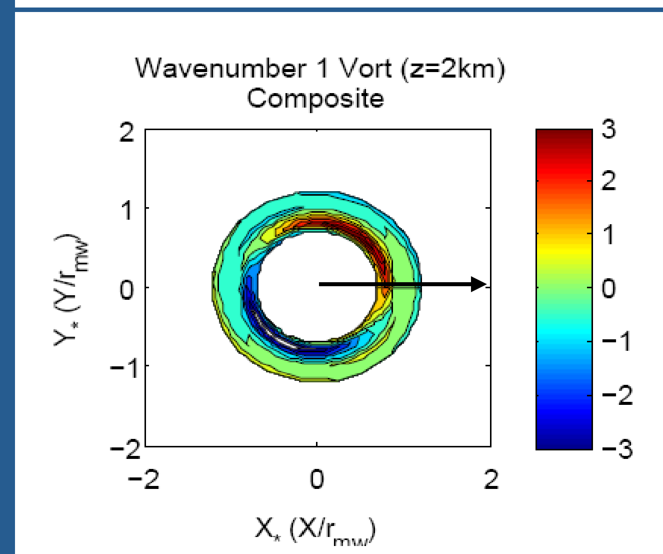
Types of Observations - Airborne

Vortex Structure

Composite asymmetric vortex structure from mature hurricanes







***Shear rotated to be pointing east**

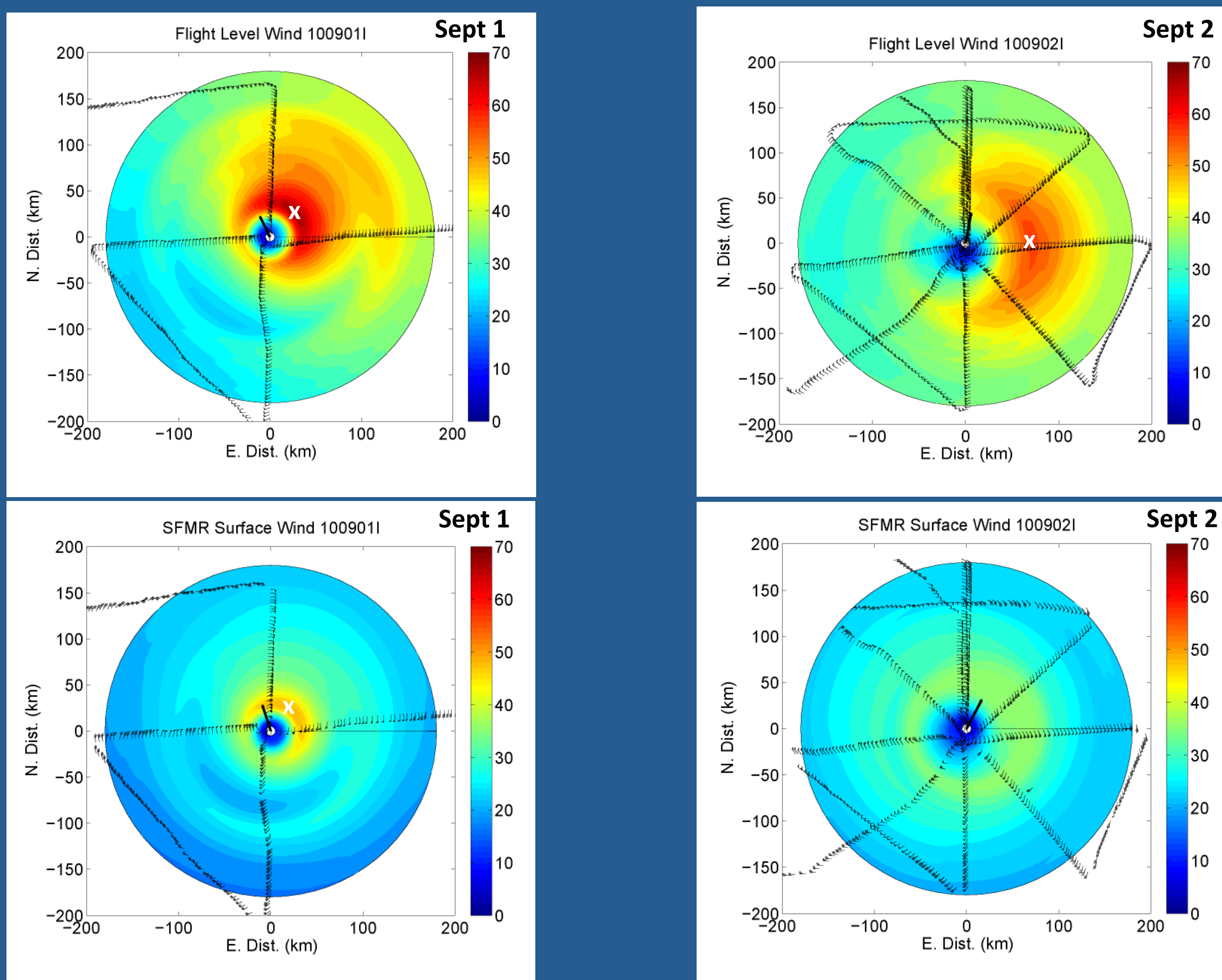
Types of Observations - Airborne

Vortex Structure

Surface and flight-level wind speed (shaded, m/s) during steady-state phase of Earl (2010)

flight-level (~ 3.5 km)

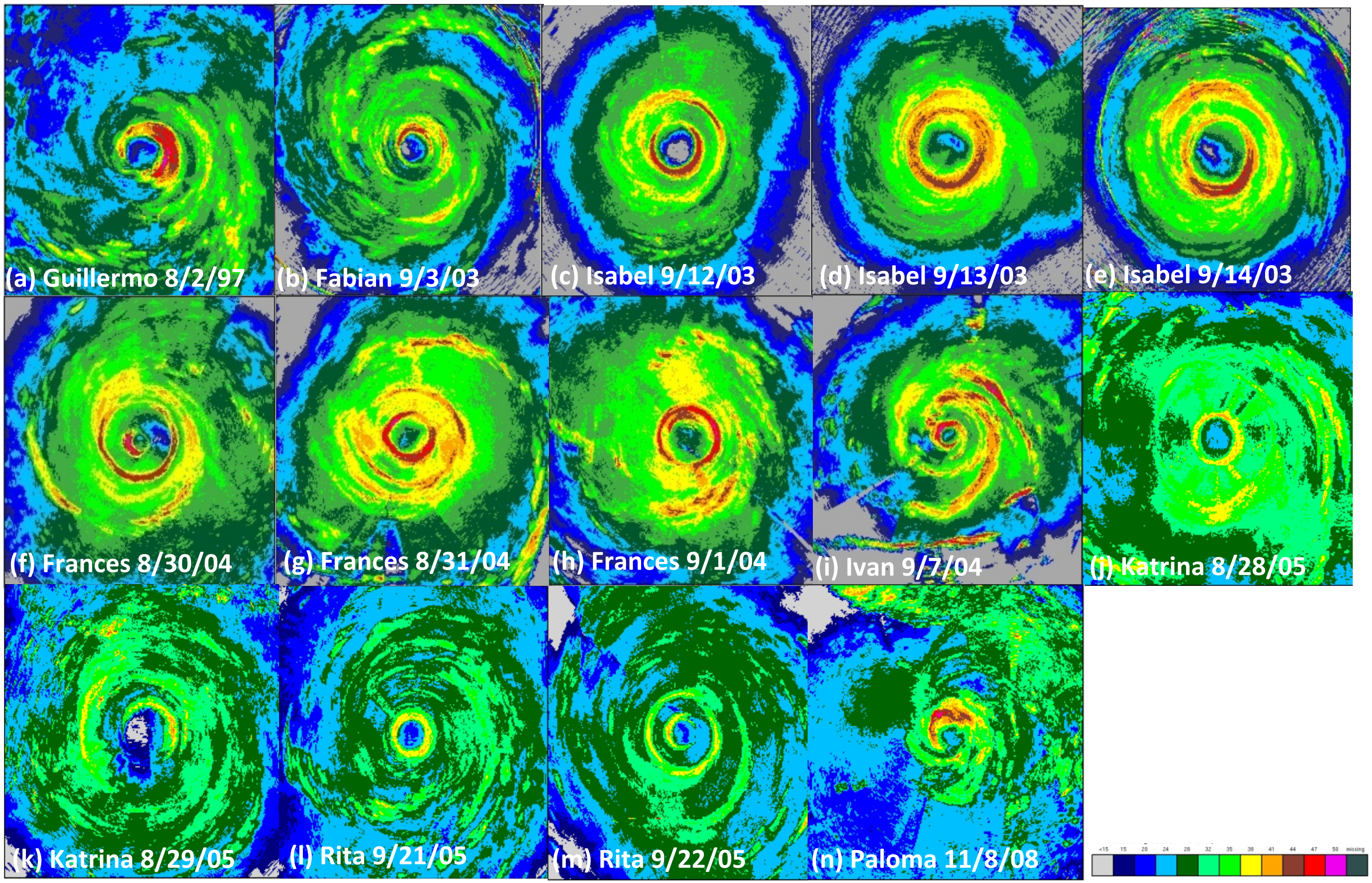
surface



Types of Observations - Airborne

Vortex Structure

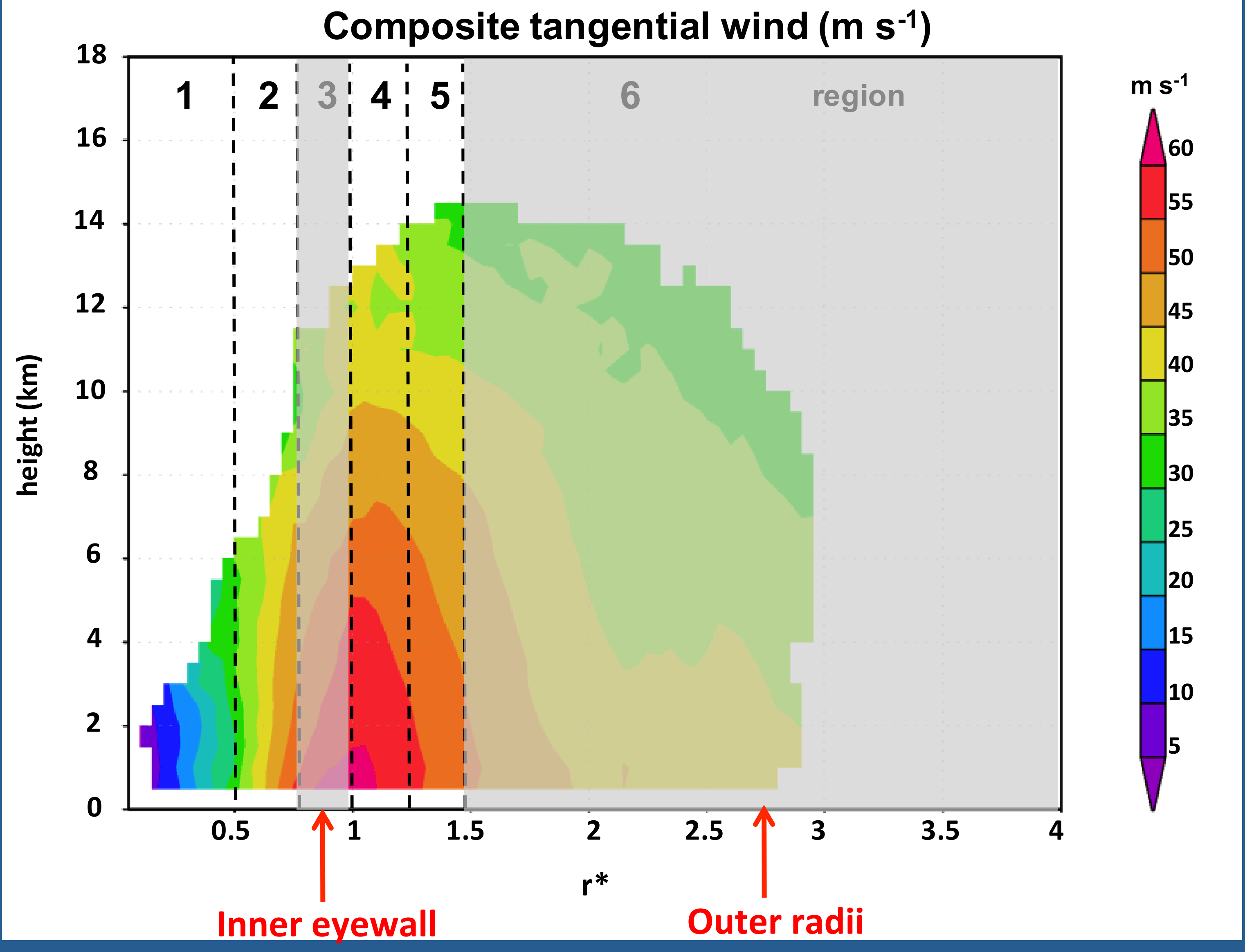
Lower fuselage images from storms used in airborne Doppler composite



Types of Observations - Airborne

Convective Structure

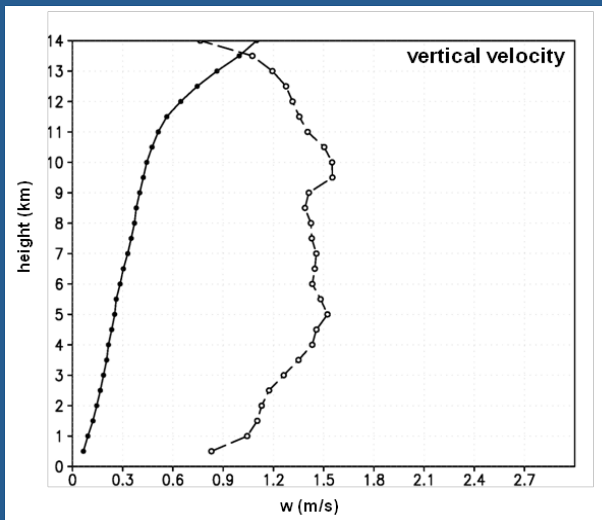
Partitioning into location relative to RMW

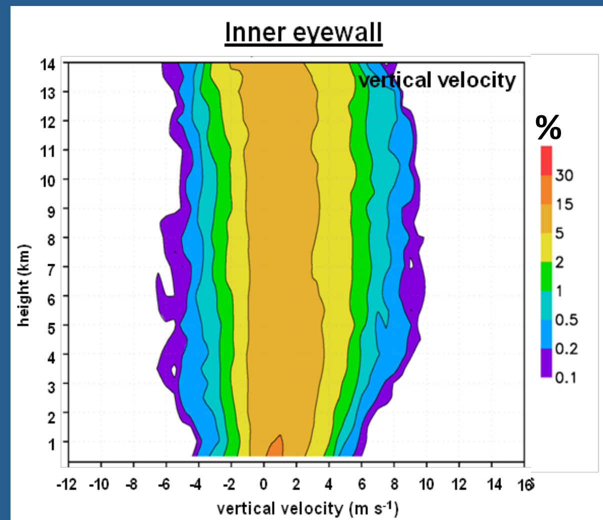


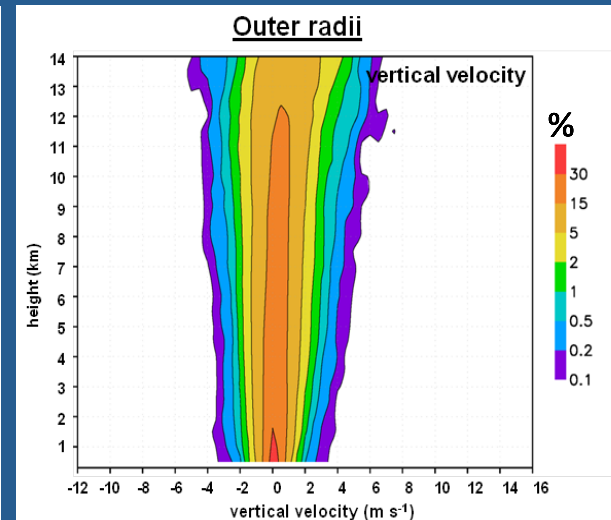
Types of Observations - Airborne

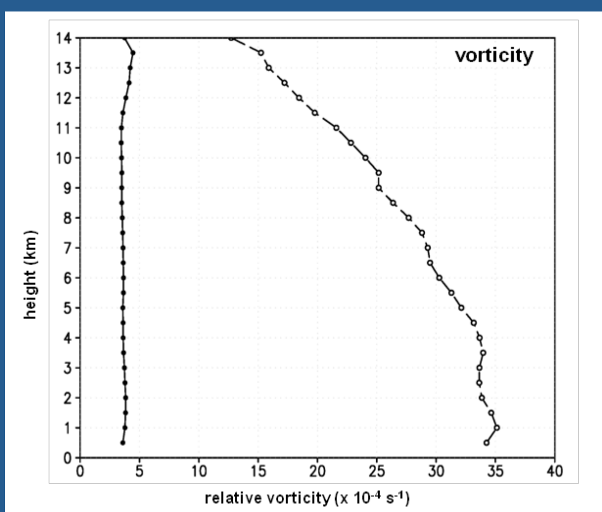
Convective Structure

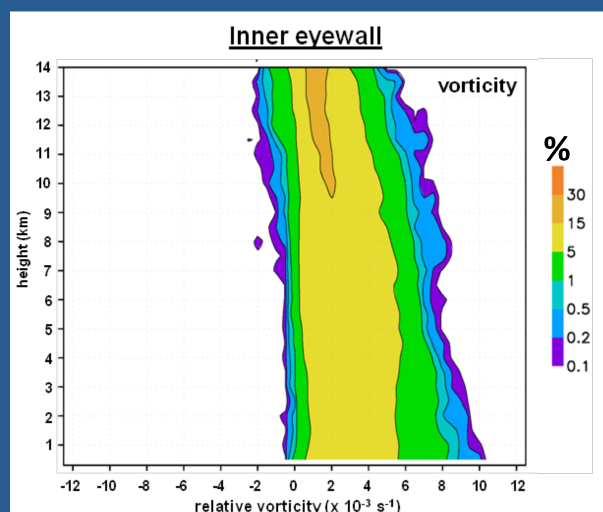
Statistical characteristics (means, CFADs) of convective-scale features

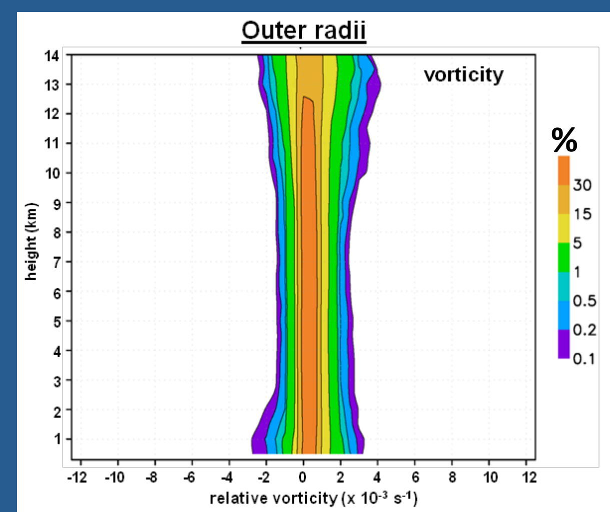






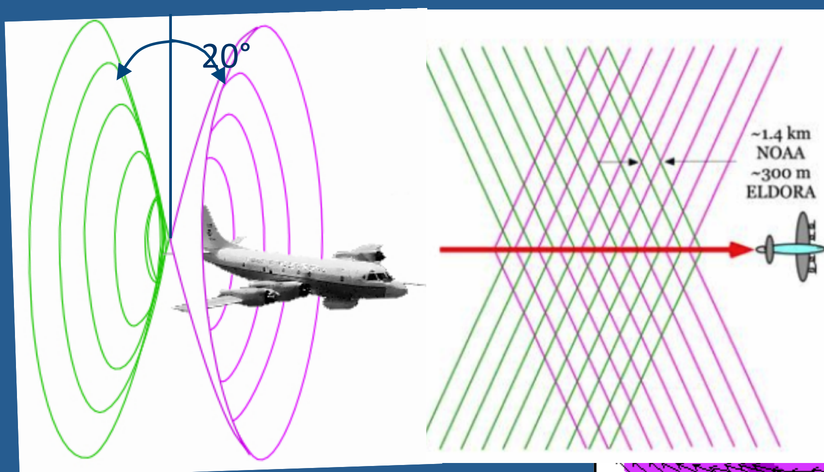


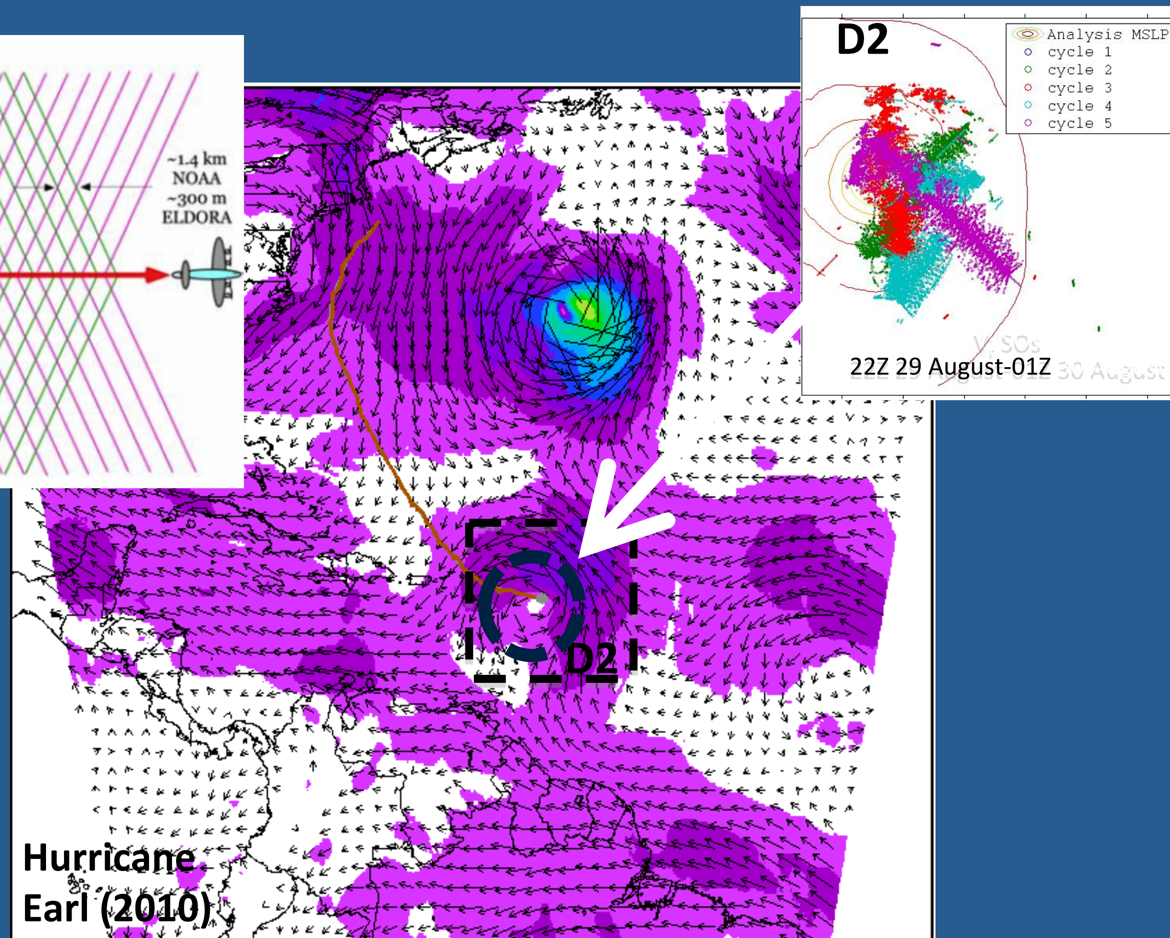




Use of Observations – Data assimilation

EnKF data assimilation of inner core observations



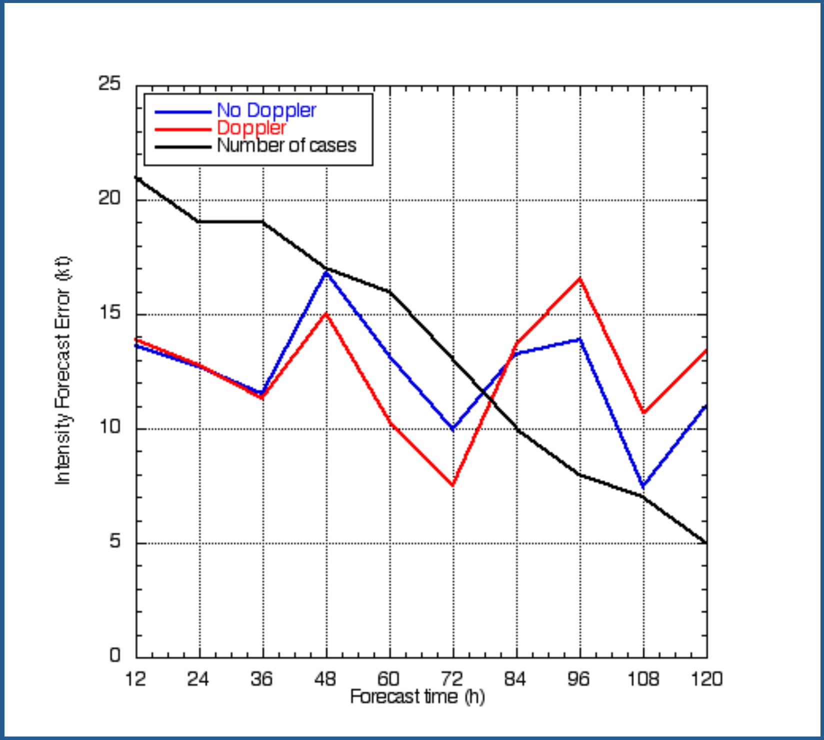


Real-time SOs transmitted during P-3 mission and assimilated into HWRFx using HEDAS

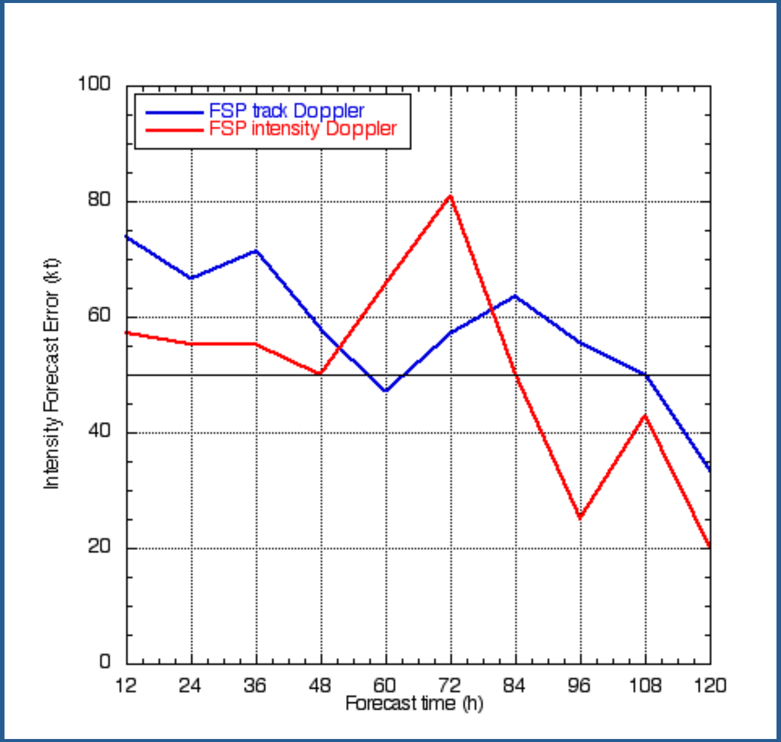
Use of Observations – Data assimilation

Assessing impact of assimilating inner-core observations into HWRF using HEDAS

Intensity error

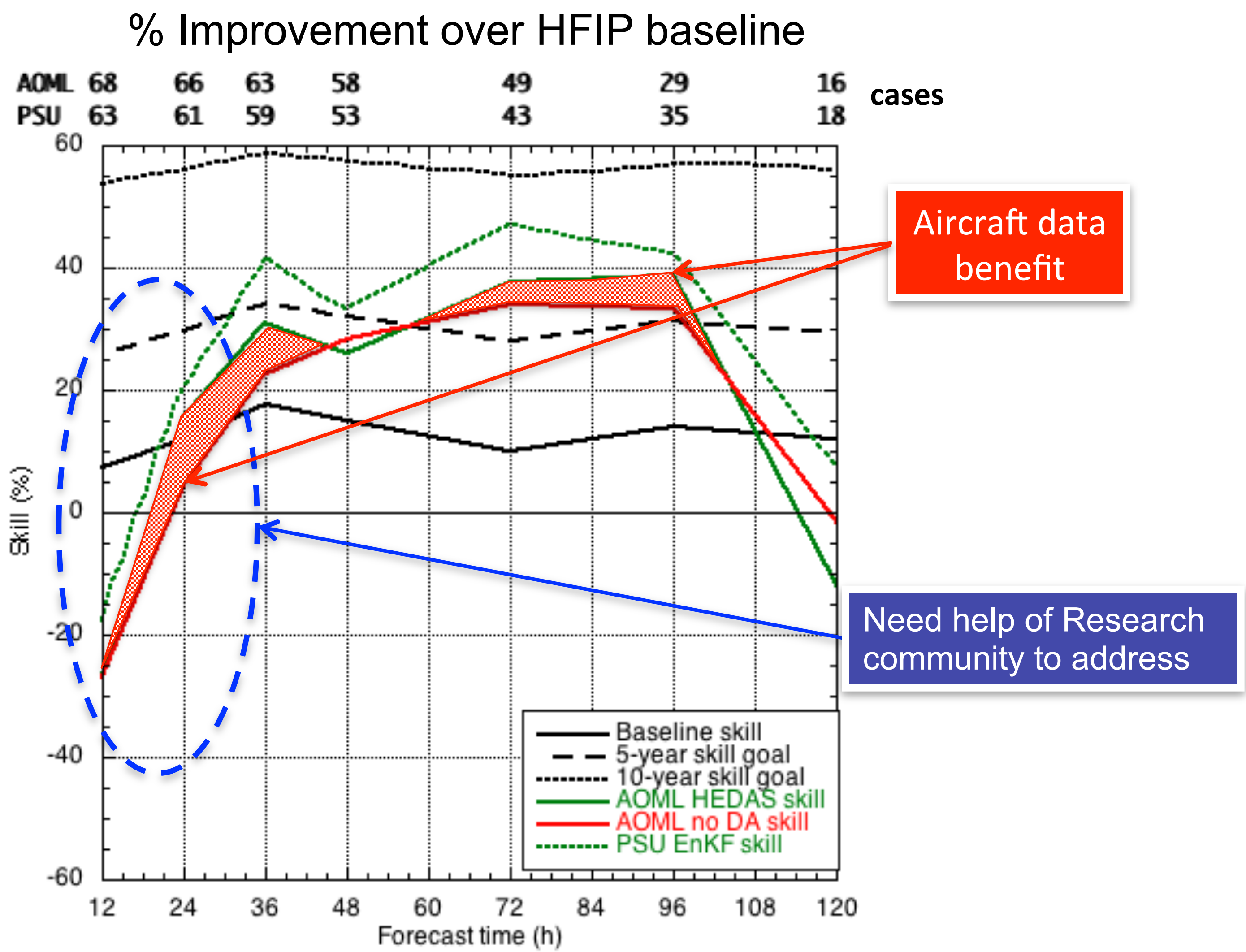


Frequency of superior performance for intensity forecast



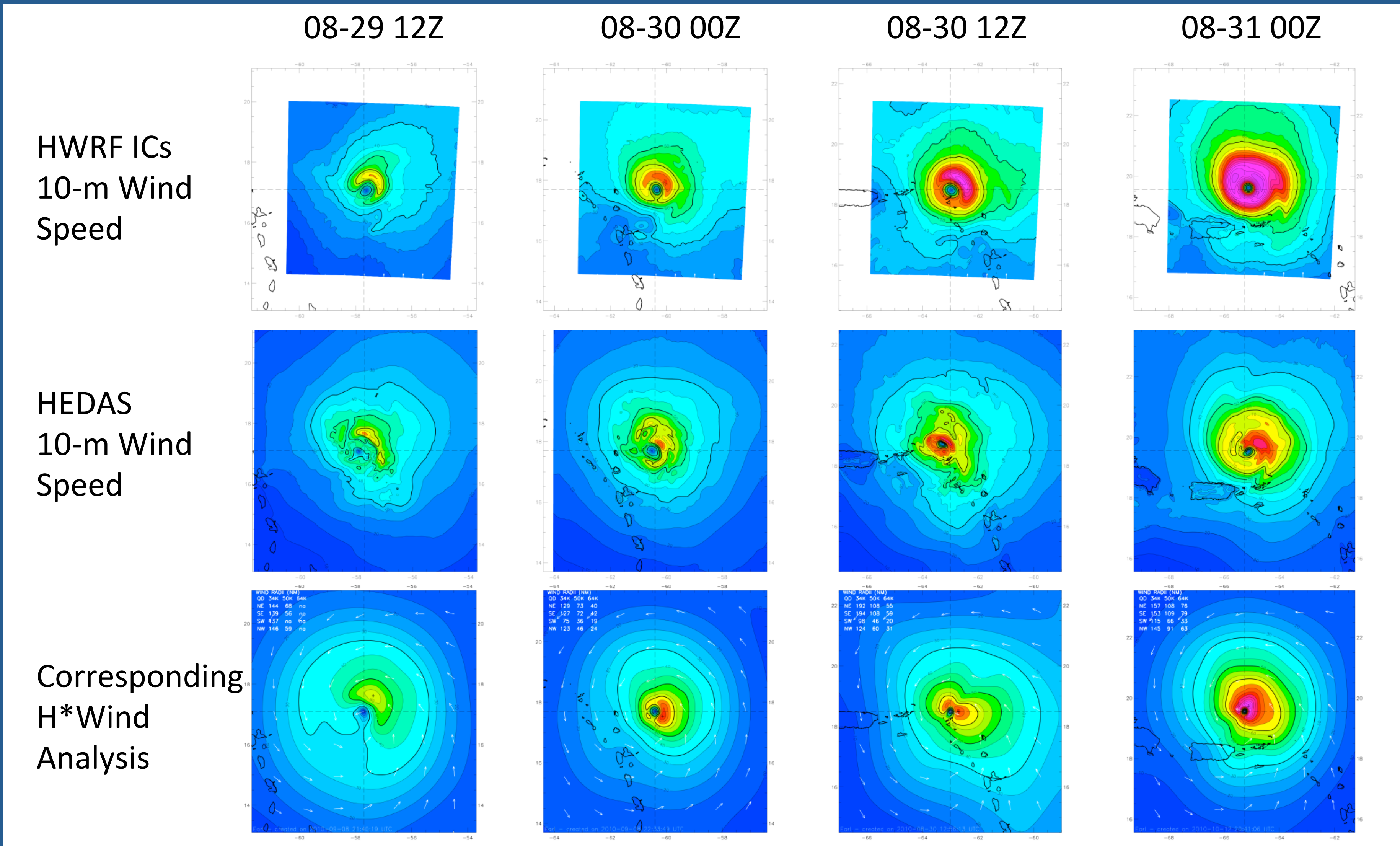
Use of Observations – Data assimilation

All cases with Doppler data 2008-2011



Use of Observations – Data assimilation

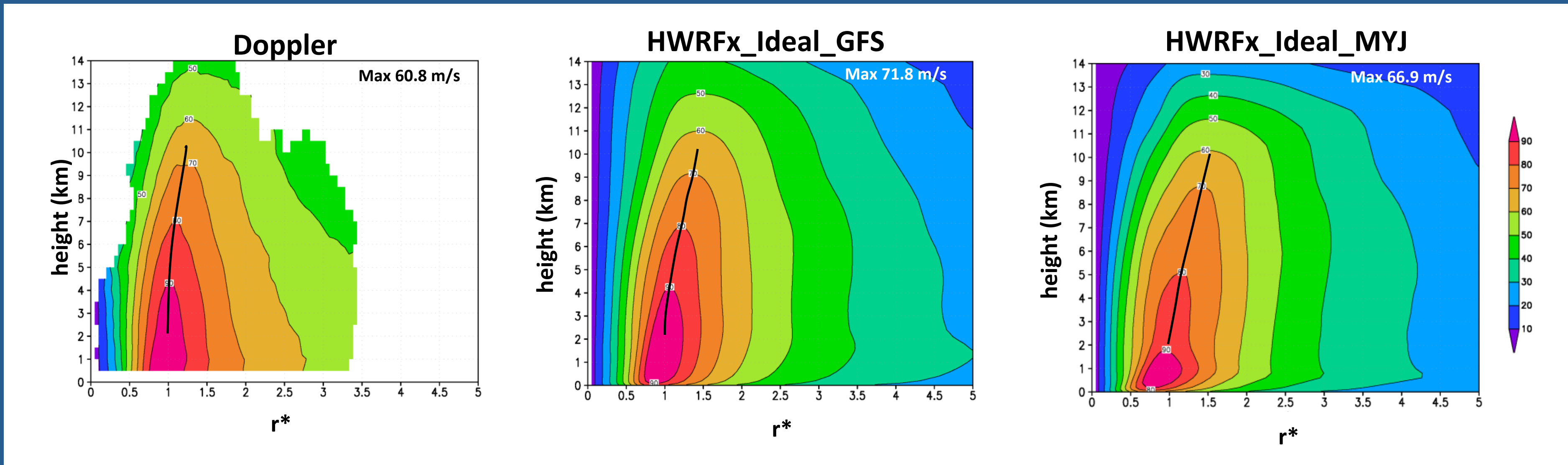
Assessing impact of assimilating inner-core observations into HWRF using HEDAS



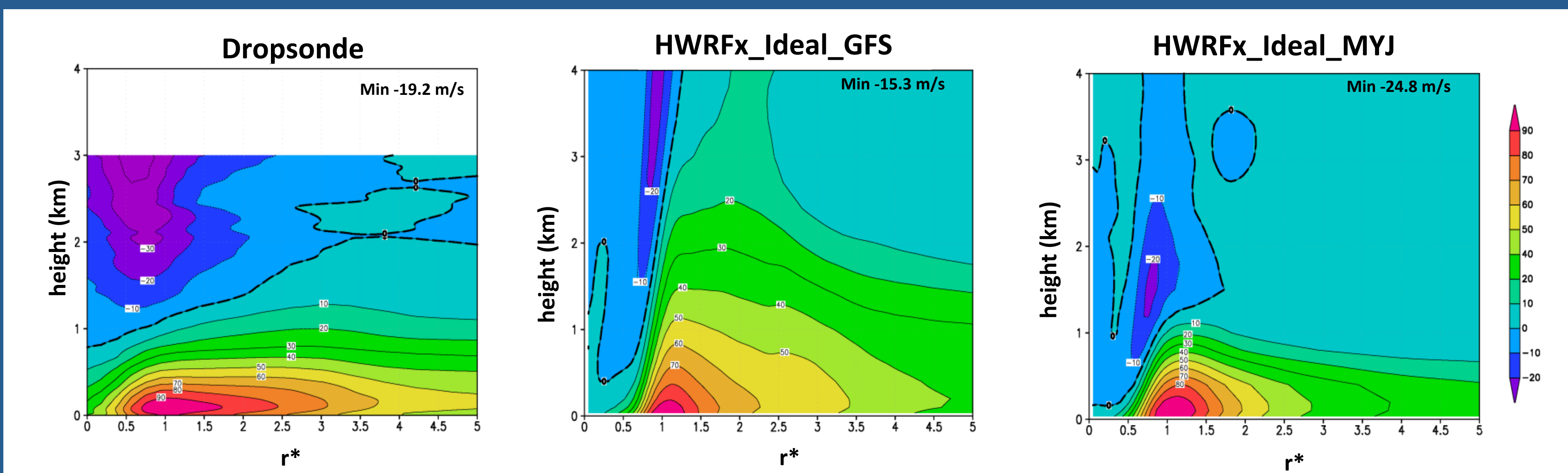
Use of Observations - Model evaluation

Evaluating impact of different PBL parameterizations on HWRF simulations of TC structure

Normalized tangential wind



Normalized radial wind in PBL



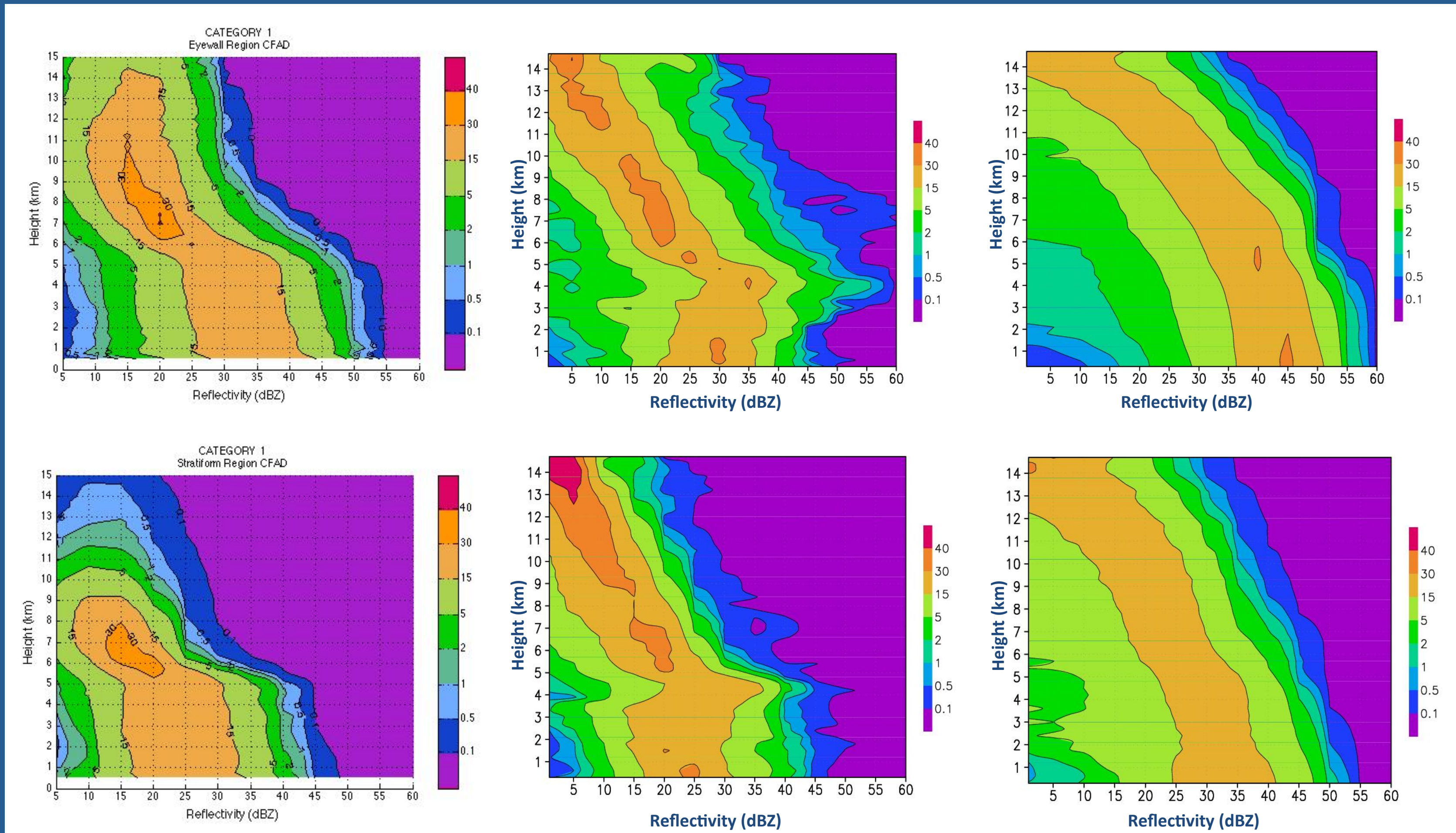
Use of Observations - Model evaluation

CFADs of reflectivity from TRMM, airborne radars and high-resolution models

TRMM PR | Airborne radar | MM5

eyewall

stratiform



118 TRMM PR swaths
64 TCs

233 aircraft radial legs
9 TCs

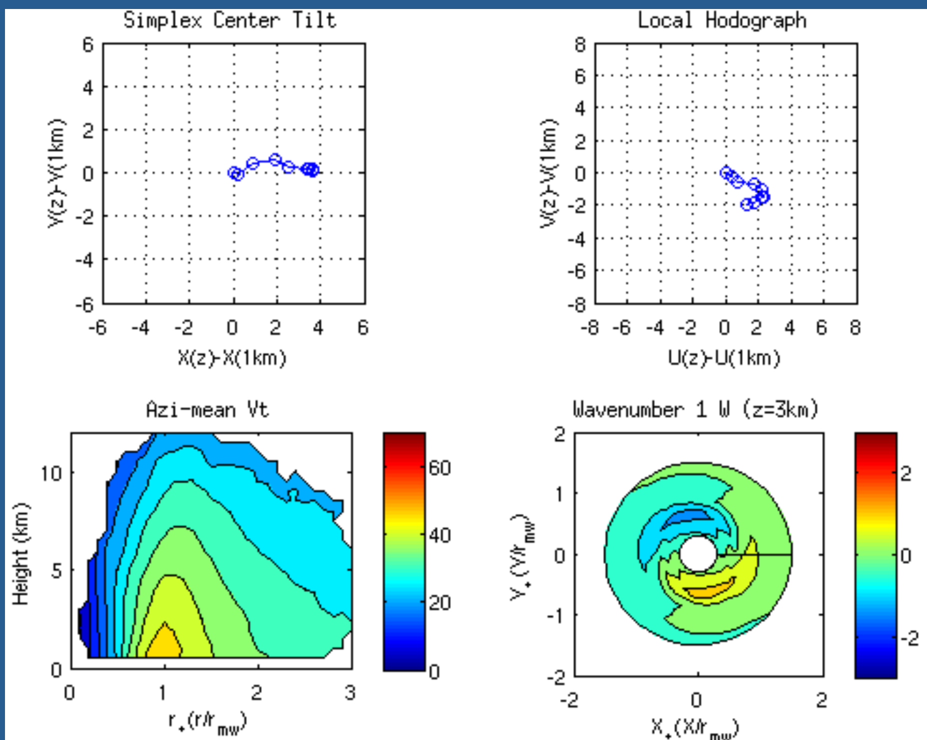
96 output times Δx 1.67 km
2 TCs

Use of Observations – Hypothesis testing

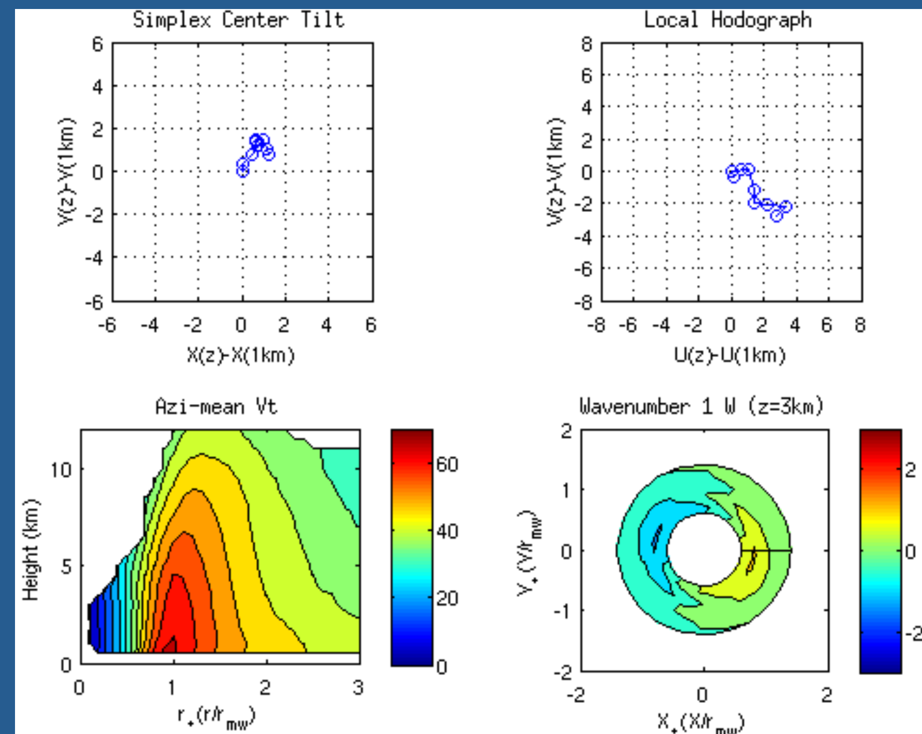
Asymmetric vortex structure in vertical shear as a function of vortex strength

- Using Doppler composite dataset

Weak vortex



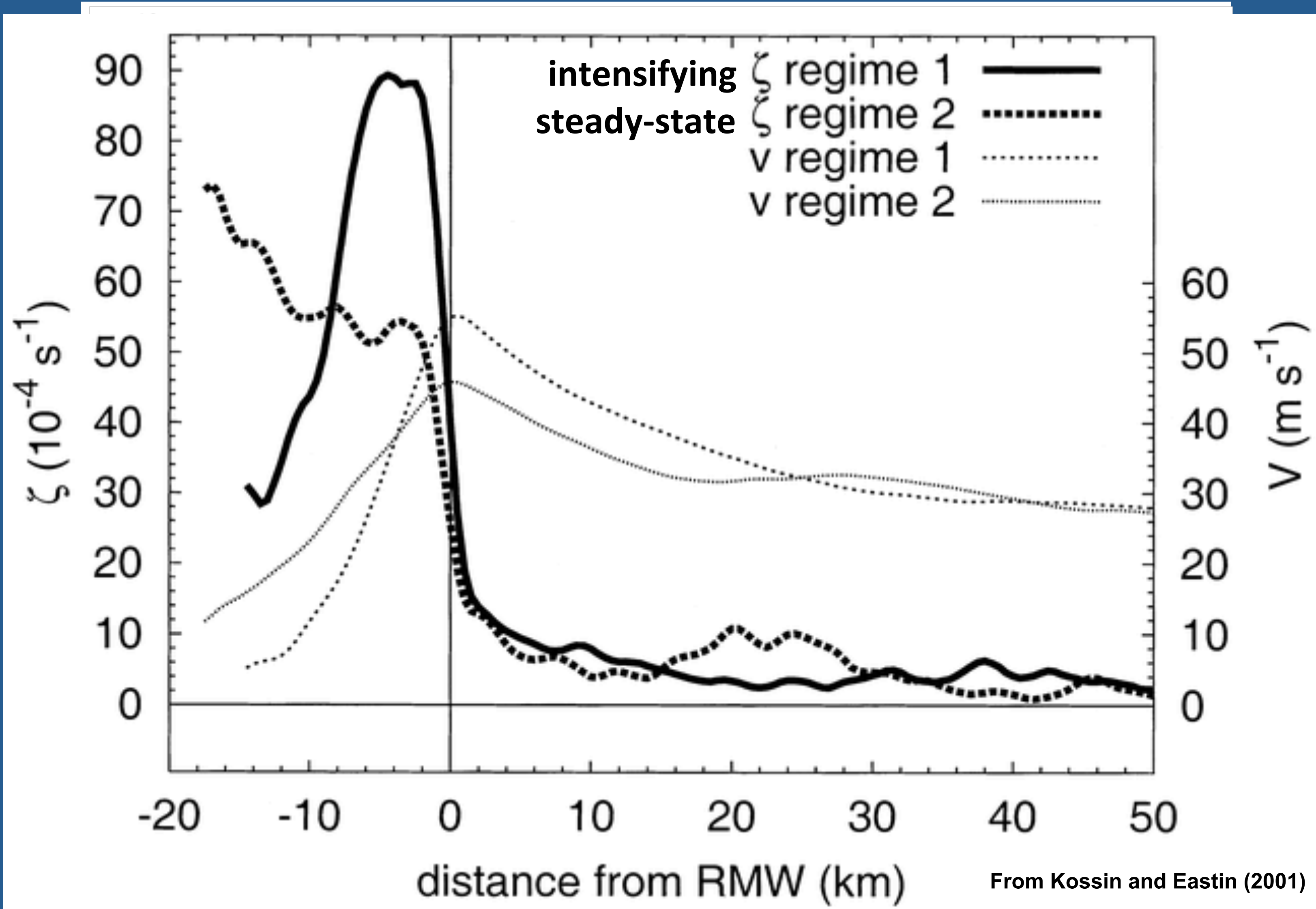
Strong vortex



Use of Observations – Hypothesis testing

Symmetric vortex structure for rapidly-intensifying vs. steady state TCs

- Using Doppler composite dataset



From Kossin and Eastin (2001)