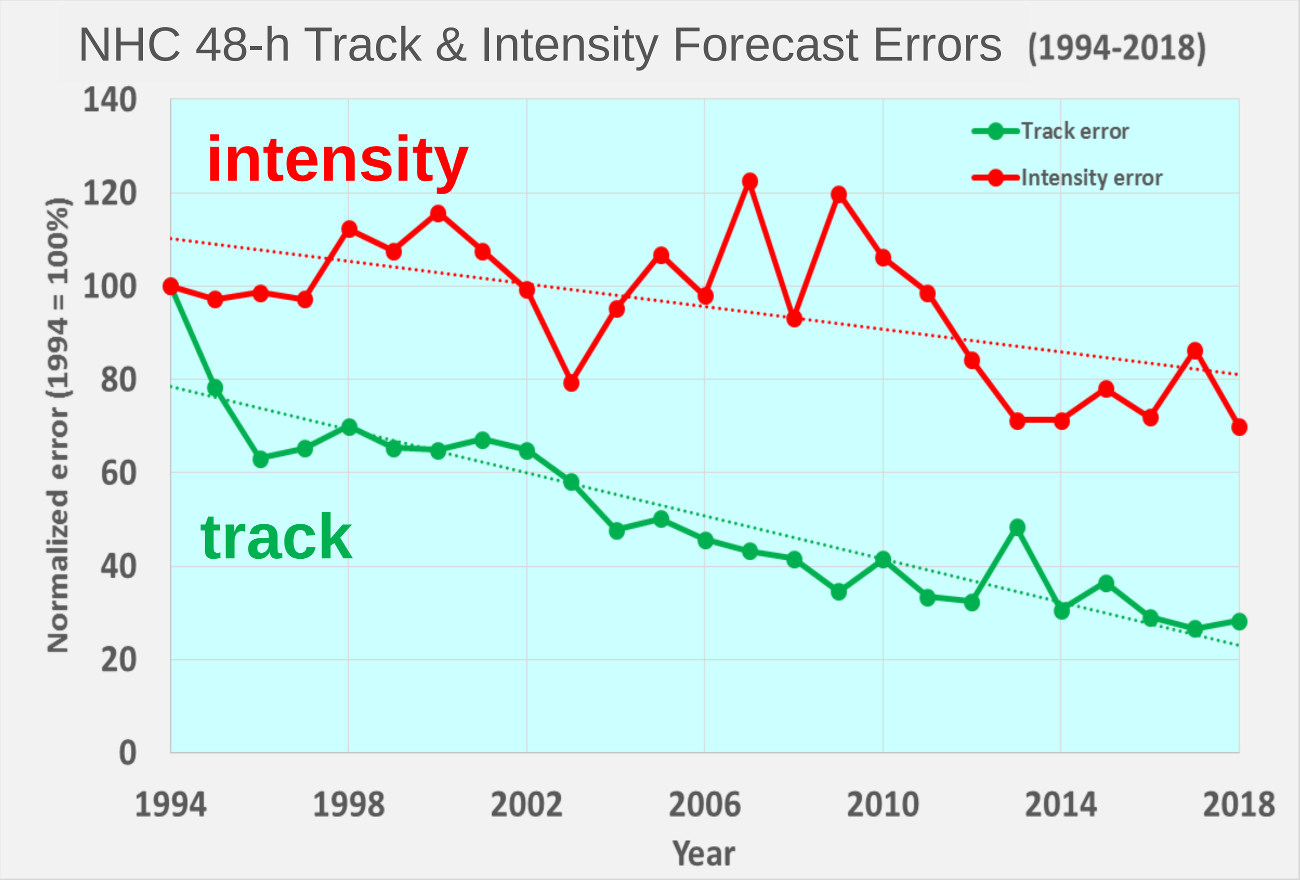
NOAA's Atlantic Oceanographic
and Meteorological Laboratory
U.S. Department of Commerce

Aircraft Observations in Tropical Cyclones

Robert Rogers
NOAA/AOML Hurricane Research Division

The Challenge: Hurricane Intensity Forecasting



Between 1994 and 2018

Track forecast errors reduced by

70%

Intensity forecast errors reduced by

30%

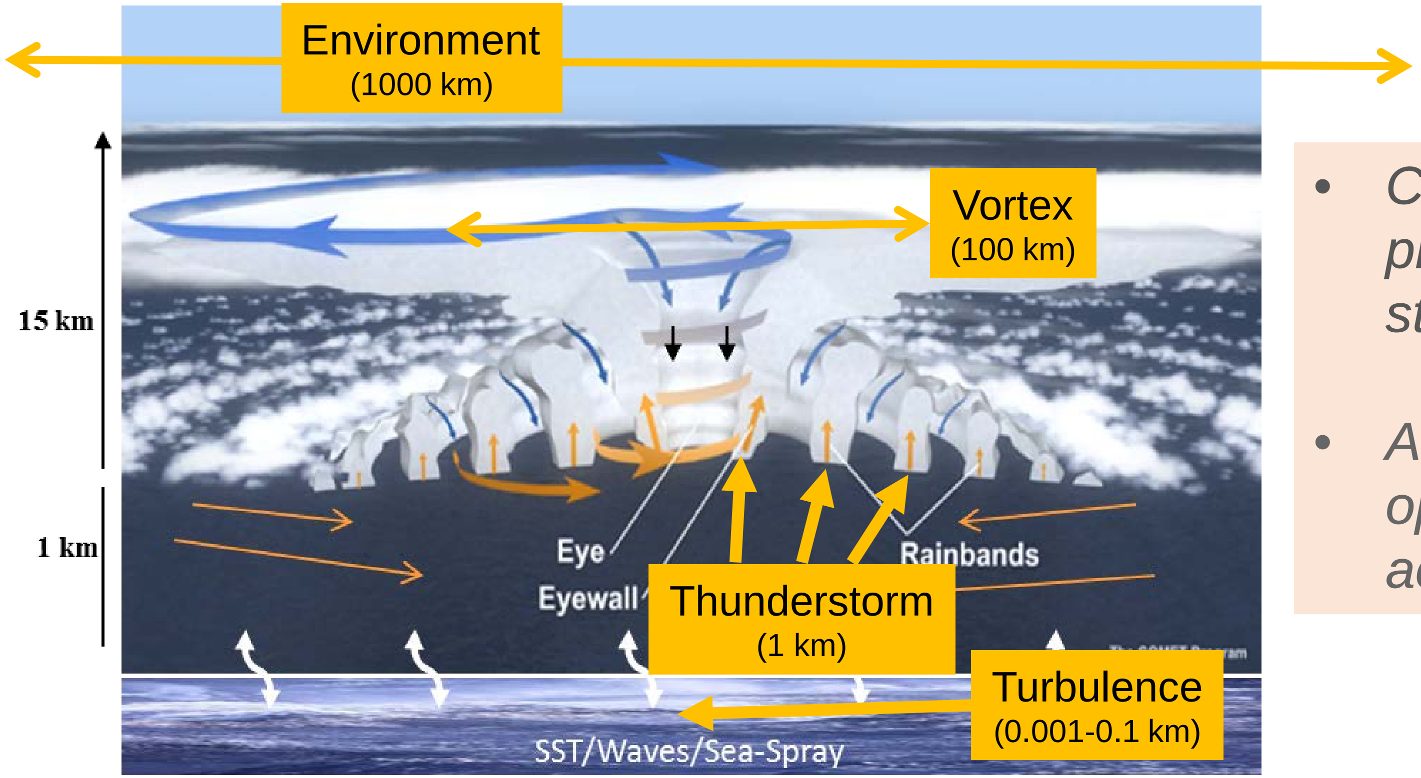
For hurricanes undergoing rapid intensification

3 x

Greater intensity error than non-rapidly intensifying

The Challenge: Hurricane Intensity Forecasting

Multiscale nature of processes are major reason for this difficulty



- *Characterizing and understanding these processes and their interactions are key steps in forecast improvement*
- *Airborne observations provide a unique opportunity to study these processes across scales*

Outline

1. Tools for observing hurricanes
2. Use of observations to improve hurricane forecasts
3. Flight profiles
4. Views from the aircraft
5. Toward the future
6. Quiz

1. Tools for observing hurricanes - platforms

NOAA fleet

"Kermit" Built in 1975 at Lockheed-Martin, Marietta, Georgia

"Miss Piggy" Built in 1976 at Lockheed-Martin, Marietta, Georgia

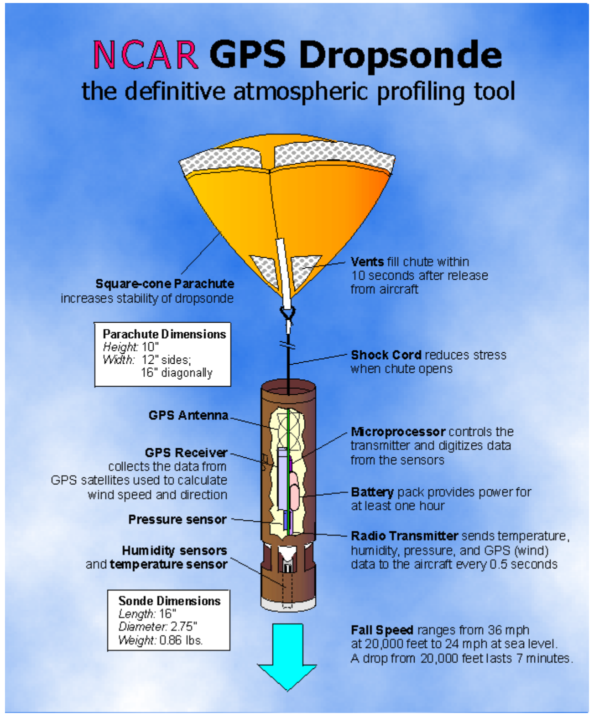
"Gonzo" Built in 1994 at Gulfstream Aerospace Corporation, Savannah, Georgia

1.Tools for observing hurricanes - instruments

- **In-situ**
  - Wind
  - Pressure
  - Temperature
  - Moisture

1.Tools for observing hurricanes - instruments

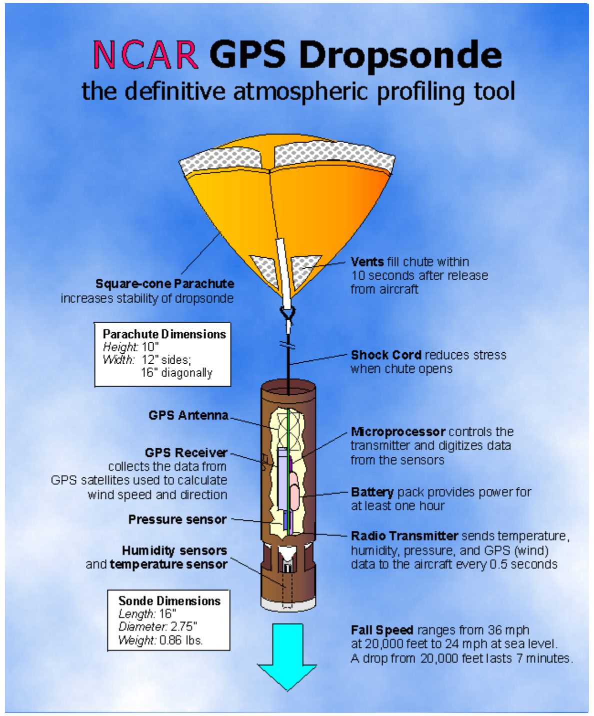
- **In-situ**
  - Wind
  - Pressure
  - Temperature
  - Moisture
- **Expendables**
  - Dropsondes
  - Aircraft-launched ocean probes



GPS Dropsonde

1.Tools for observing hurricanes - instruments

- **In-situ**
  - Wind
  - Pressure
  - Temperature
  - Moisture
- **Expendables**
  - Dropsondes
  - Aircraft-launched ocean probes
- **Remote Sensors**
  - Tail Doppler Radar(TDR)
  - Stepped Frequency Microwave Radiometer (SFMR)
  - Scanning Radar Altimeter (SRA)
  - Doppler Wind Lidar



GPS Dropsonde

Tail Doppler Radar

Doppler Wind Lidar

1.Tools for observing hurricanes - instruments

- **In-situ**
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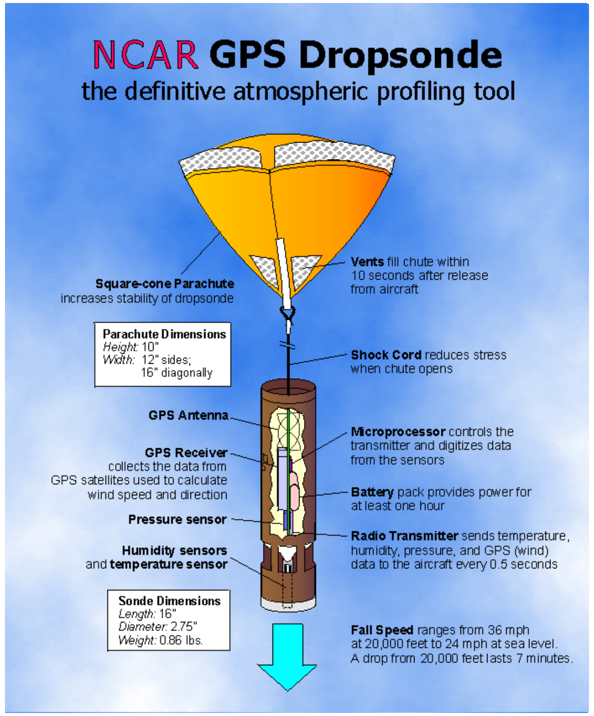
  - Tail Doppler Radar(TDR)
  - Stepped Frequency Microwave Radiometer (SFMR)
  - Scanning Radar Altimeter (SRA)
  - Doppler Wind Lidar
- **Uncrewed**
  - Uncrewed Aerial Systems (UASs) (e.g., Coyote)
  - Autonomous Underwater Vehicles (AUVs) (e.g., Ocean Glider)



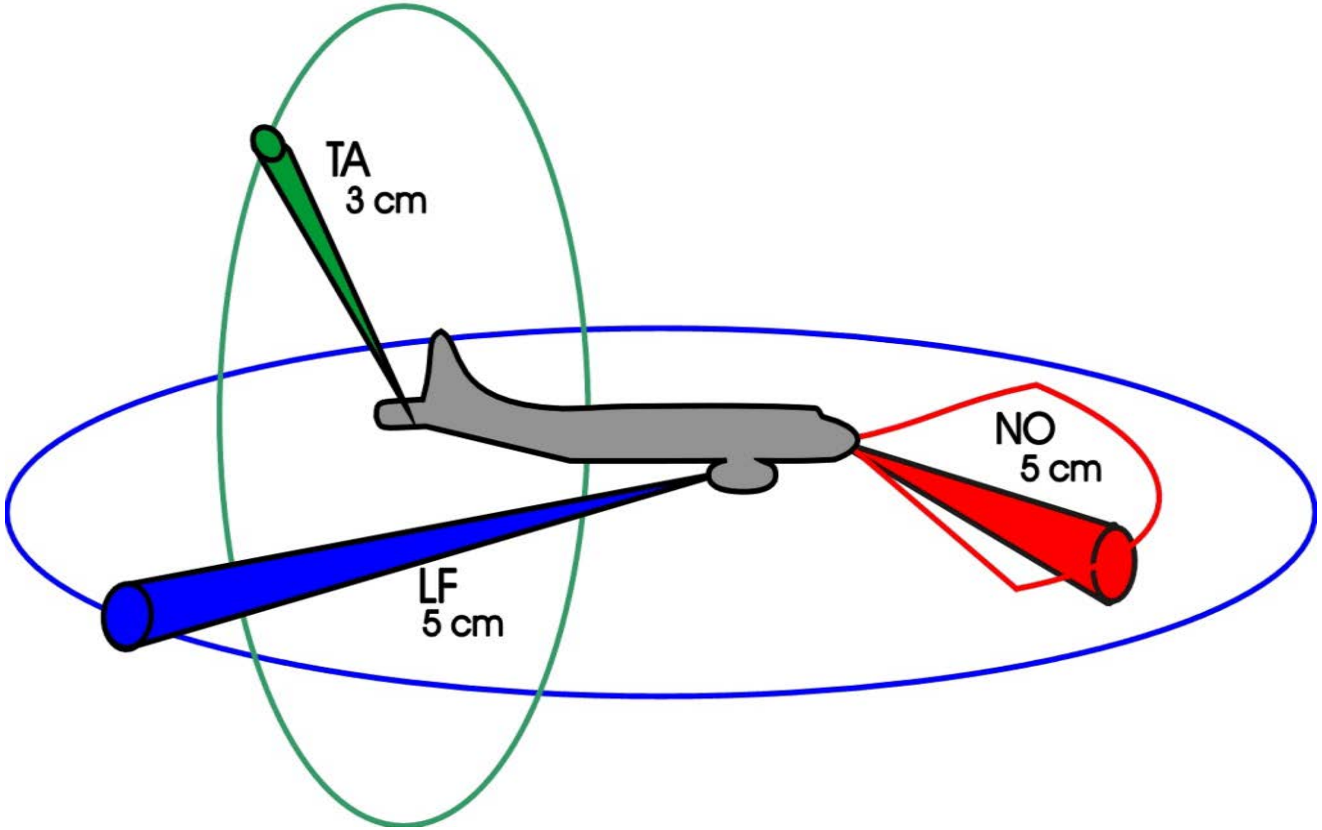
GPS Dropsonde

Tail Doppler Radar

Doppler Wind Lidar

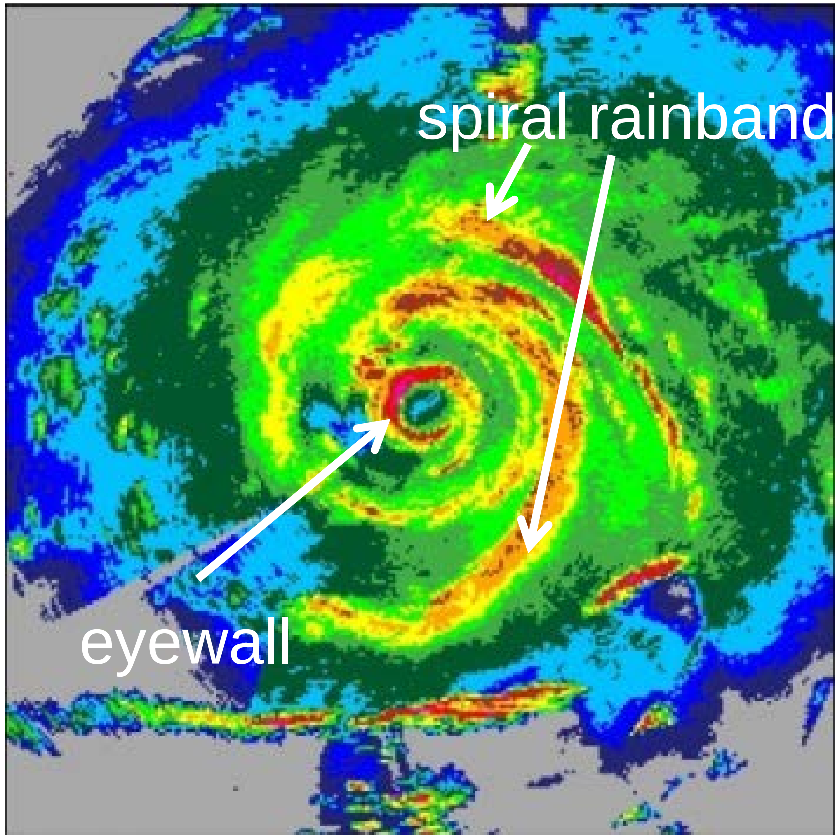
1.Tools for observing hurricanes - instruments

Airborne Radars on P-3



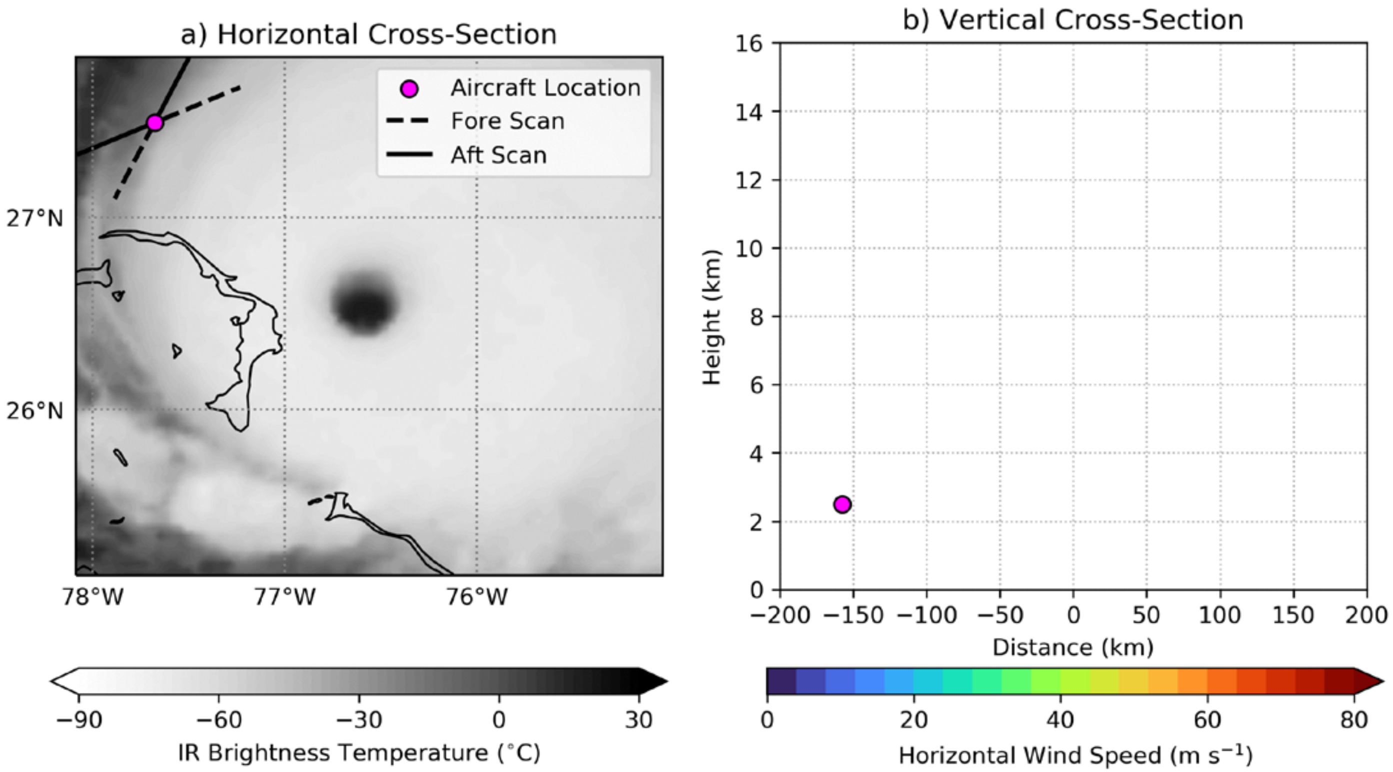
1.Tools for observing hurricanes - instruments

Lower Fuselage (LF) Radar



1.Tools for observing hurricanes - instruments

Tail Doppler Radar (TDR)

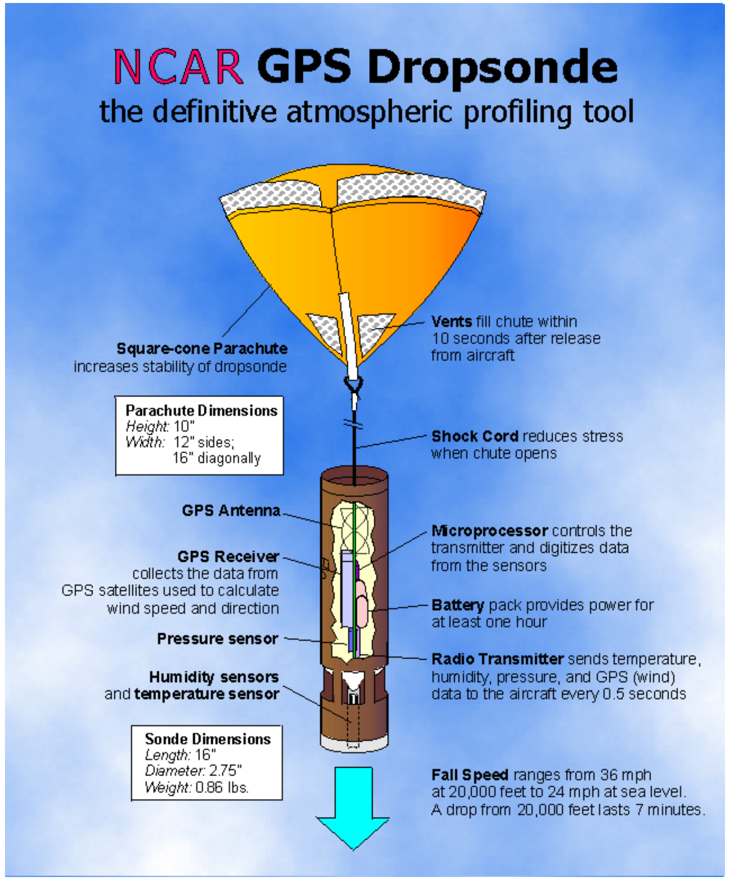


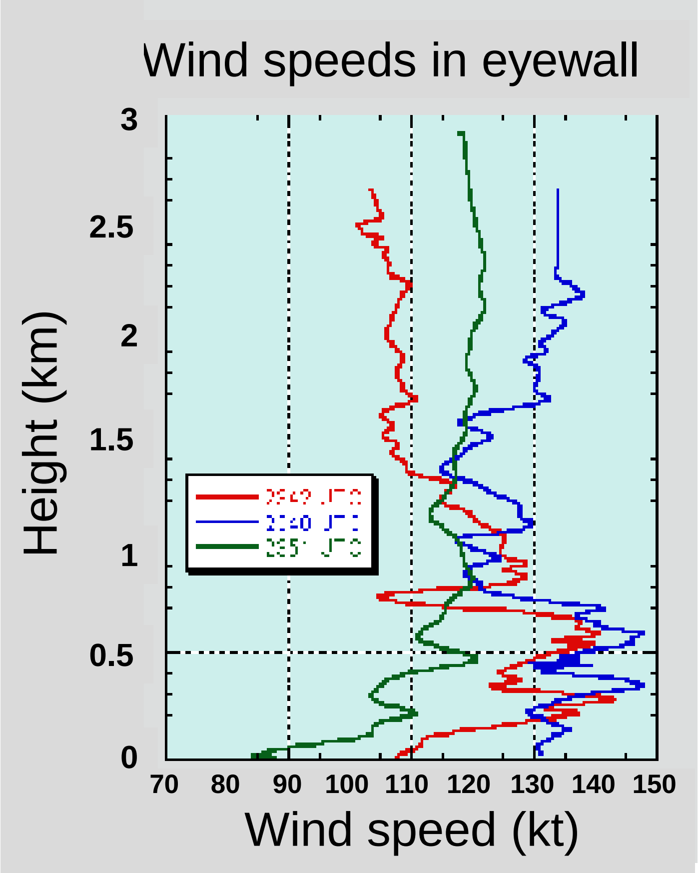
Vertical slice shows eyewall, eye structure

- Measurements of reflectivity and three-dimensional winds in inner core, from 0.5 km to ~18 km altitude

1.Tools for observing hurricanes - instruments

GPS dropsonde

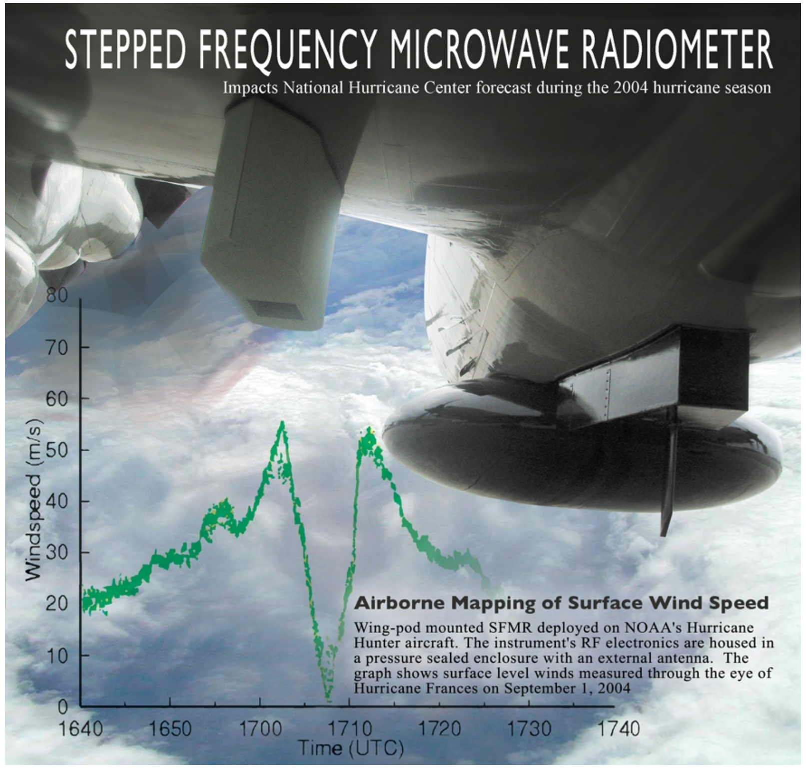


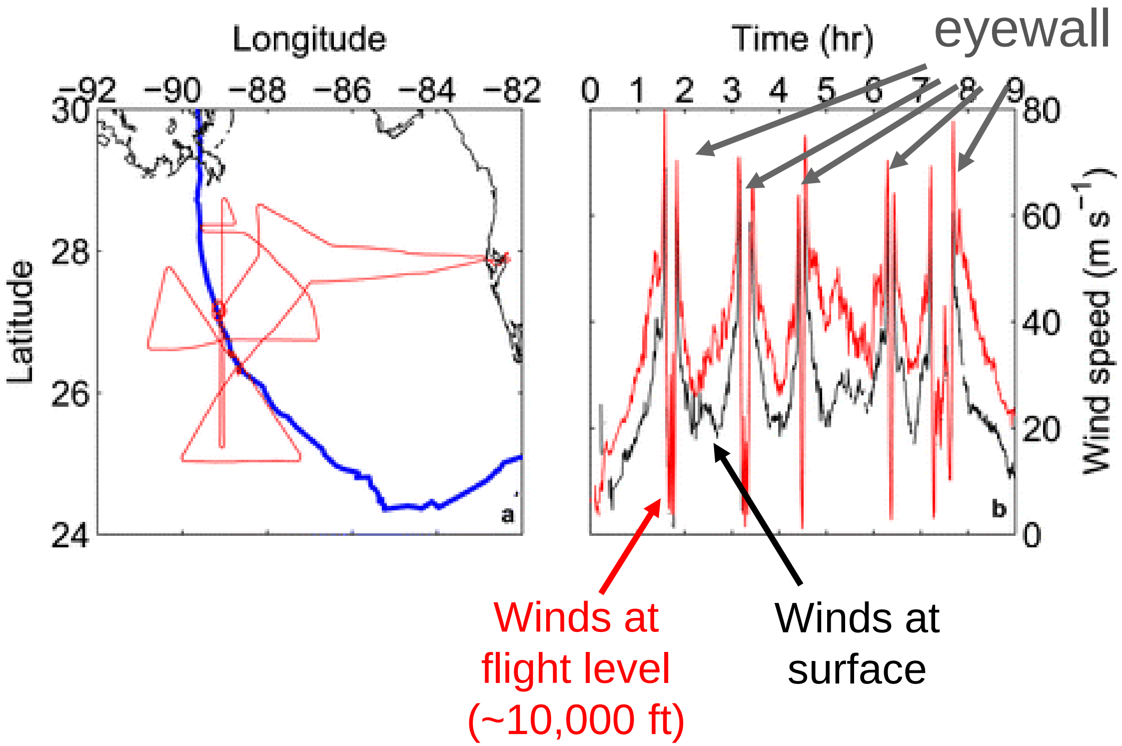


- Profiles of wind speed and direction, temperature, moisture, pressure
- Uses GPS for accurate wind speed and direction
- High-frequency 4 Hz sampling
- Cat-5 wind speeds in lowest 1500 ft

1.Tools for observing hurricanes - instruments

Stepped Frequency Microwave Radiometer (SFMR)



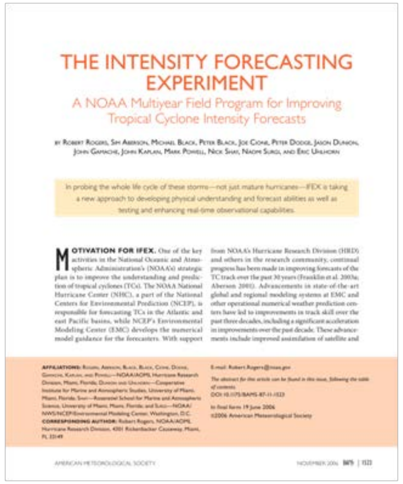


Winds at surface usually a little weaker than winds at flight level

- Uses brightness at ocean surface to retrieve surface wind speed underneath aircraft
- Helpful in assessing storm intensity, compare with flight-level reductions

2. Use of observations to improve hurricane forecasts

Intensity Forecasting Experiment (IFEX): 2005-2021


THE INTENSITY FORECASTING EXPERIMENT

A NOAA Multiyear Field Program for Improving Tropical Cyclone Intensity Forecasts

Rogers et al., BAMS, 2006


NOAA'S HURRICANE INTENSITY FORECASTING EXPERIMENT

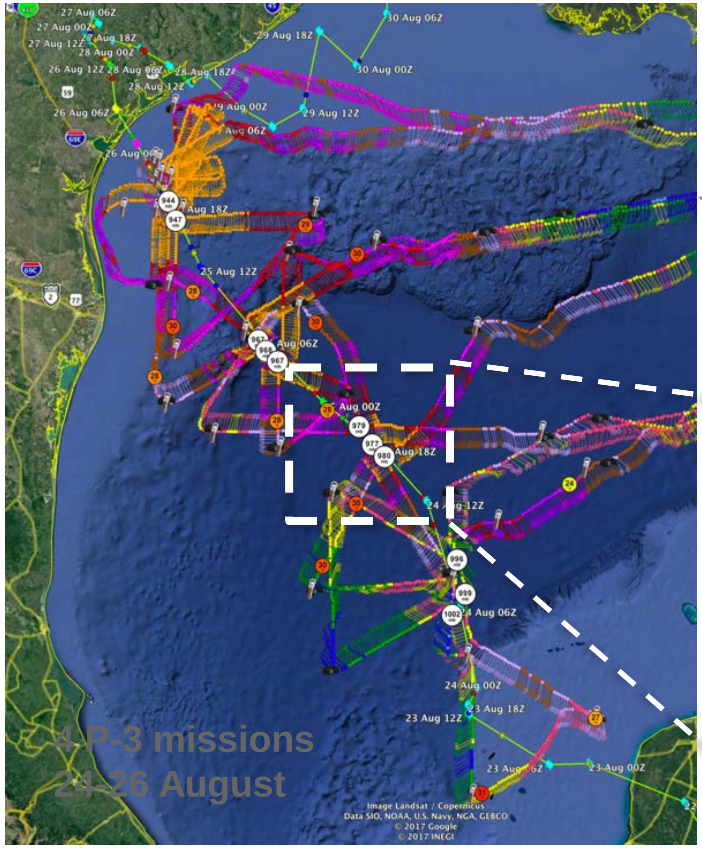
A Progress Report

Rogers et al., BAMS, 2013

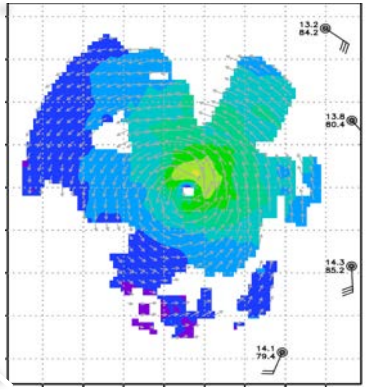
IFEX intended to improve prediction of TC intensity change by addressing three goals:

1) **FORECASTS**: Collecting observations that span TC life cycle across scales for model initialization, evaluation
2) **NOWCASTS**: Developing and refining measurement technologies that provide improved real-time monitoring of TC intensity, structure, and environment
3) **RESEARCH**: Improving understanding of physical processes important in intensity change for a TC at all stages of its life cycle

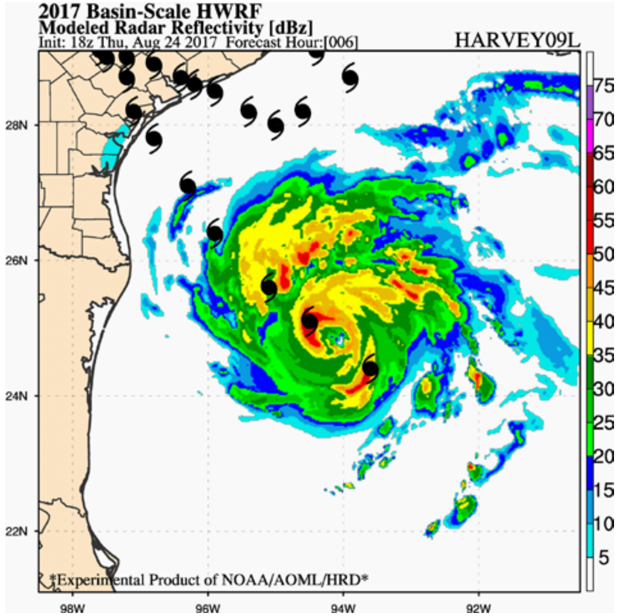
IFEX FORECASTS: Assimilation of data into numerical models



Hurricane Harvey (2017)

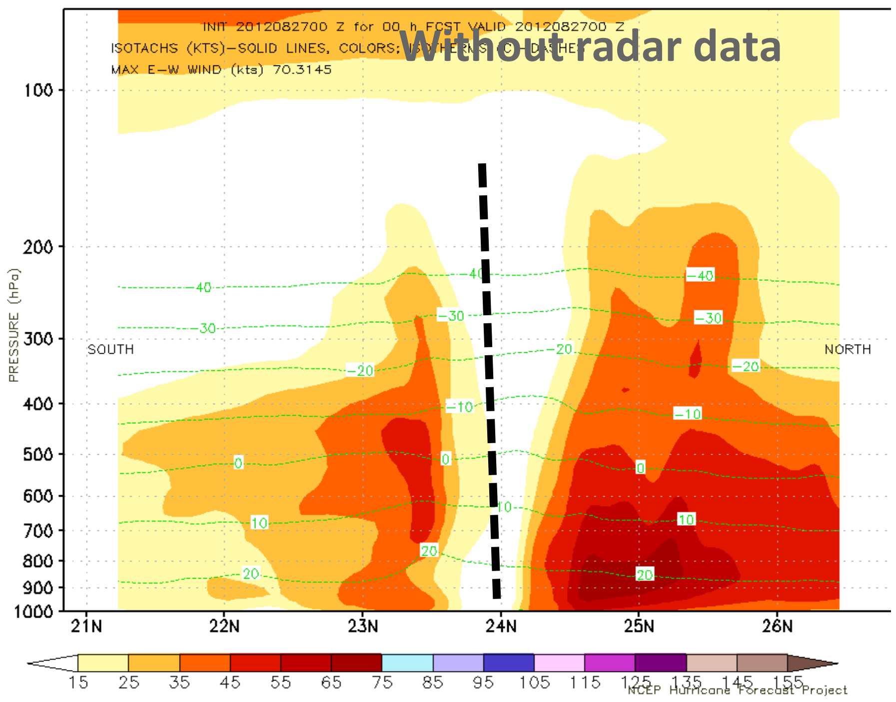


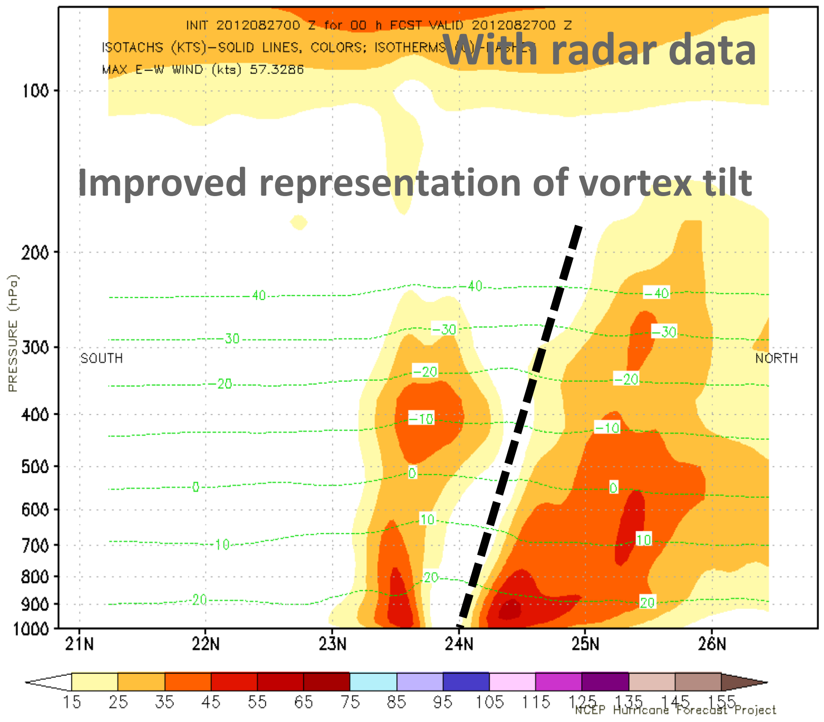
- NOAA P-3 transmitted Tail Doppler radar data in real-time for assimilation into HWRF



IFEX FORECASTS: Assimilation of data into numerical models

Vertical cross section of wind speed in Isaac (2012) at start of model forecast

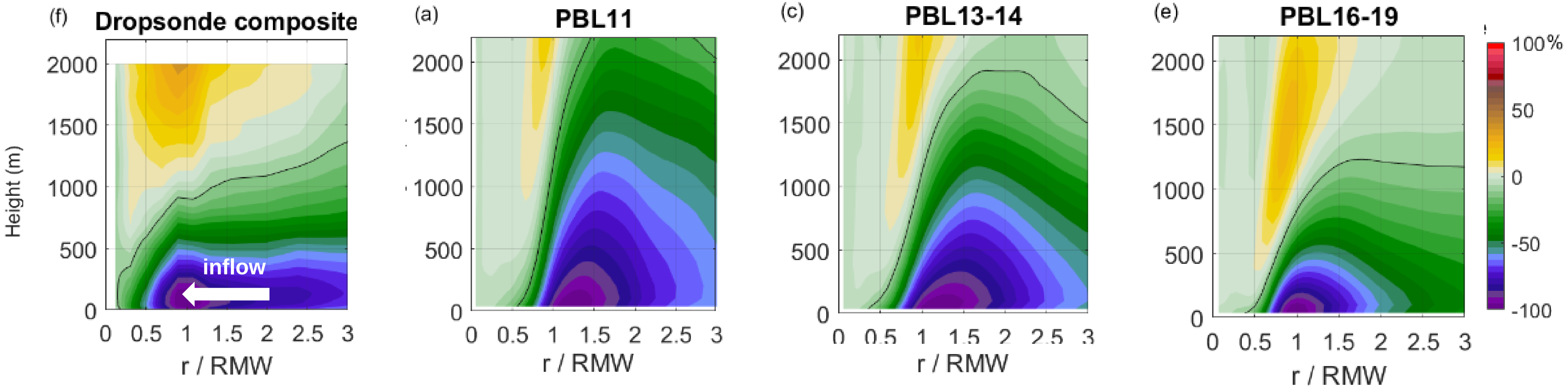




IFEX FORECASTS: Model evaluation

Sensitivity of radial wind to mixing processes in low levels

Radial inflow for different HWRF mixing formulations from 2011-2019

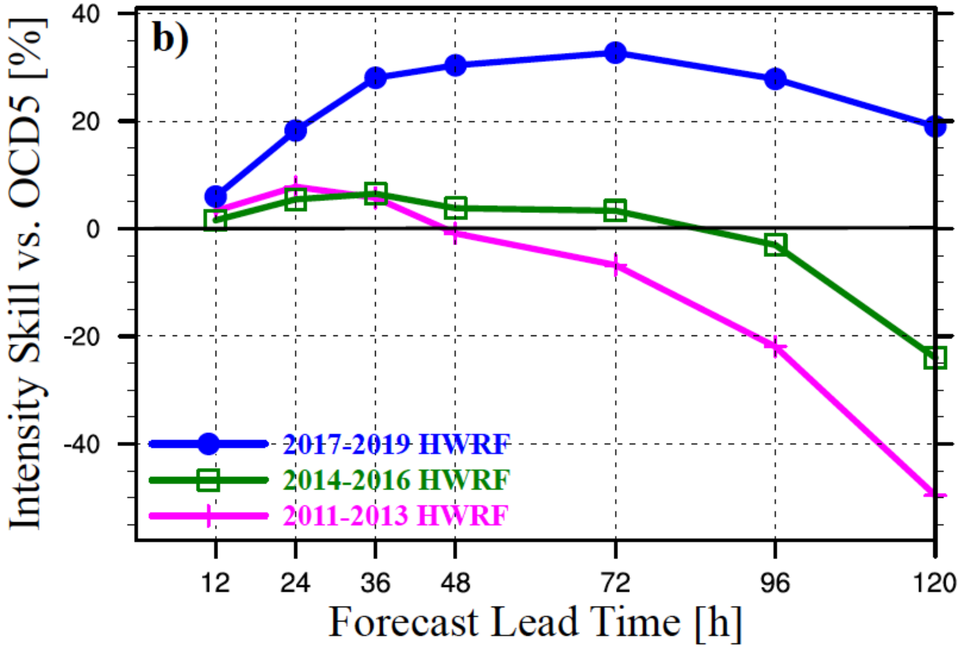


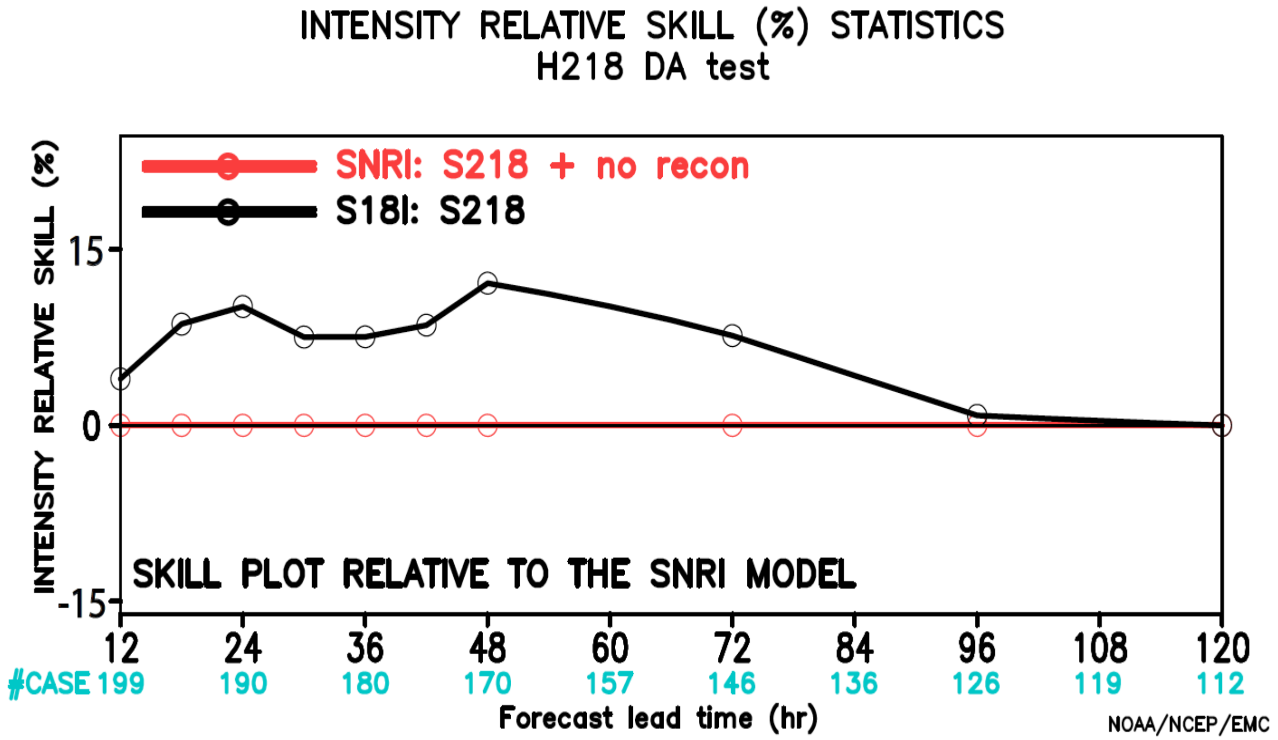
Zhang et al. 2020

- PBL structure (depth of inflow layer, outflow channel) more consistent with dropsonde composites using mixing based on observations (more recent versions of model)

IFEX FORECASTS: Improvements to numerical model forecasts

HWRF Intensity forecast skill

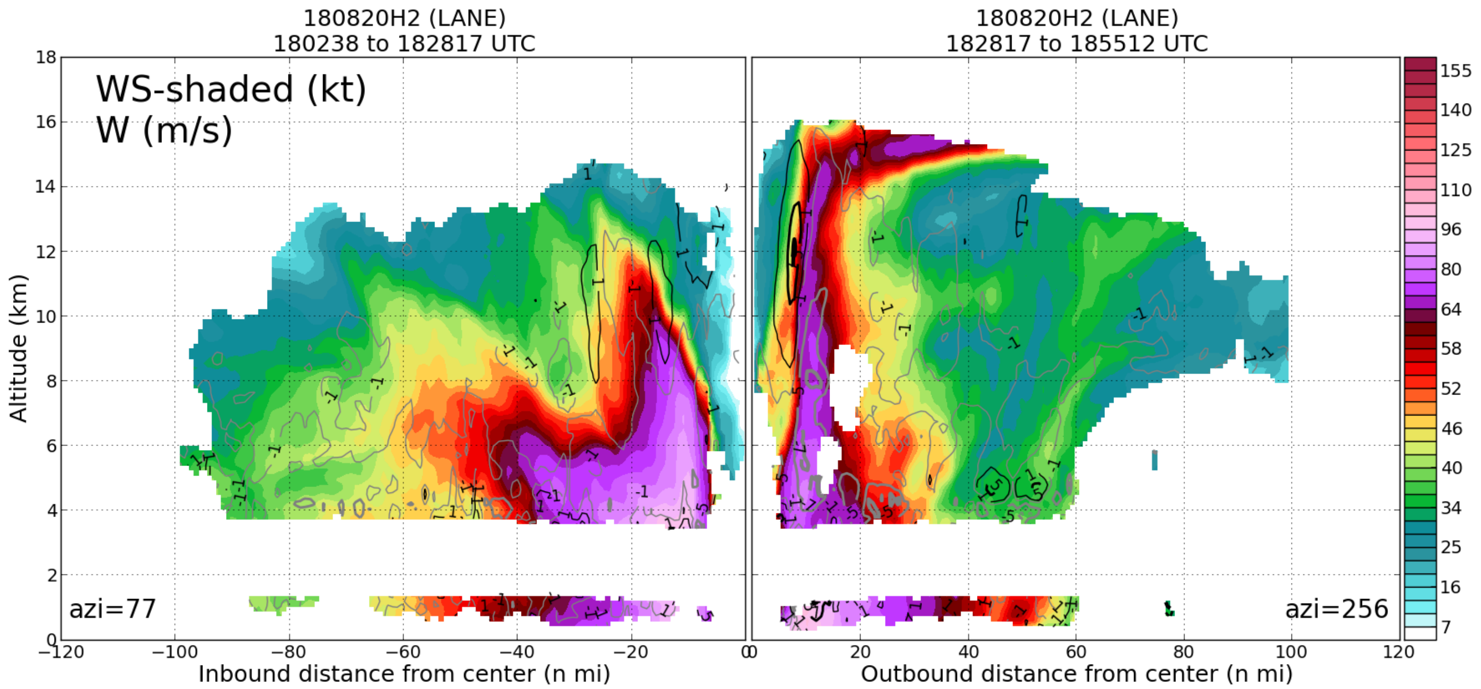




- HWRF intensity forecast improved steadily from 2011-2019
- Use of aircraft reconnaissance improves HWRF intensity forecast by ~15% at 48 h

IFEX NOWCASTS: Improved representation of TC structure

Real-time vertical cross section of wind speeds in Hurricane Lane

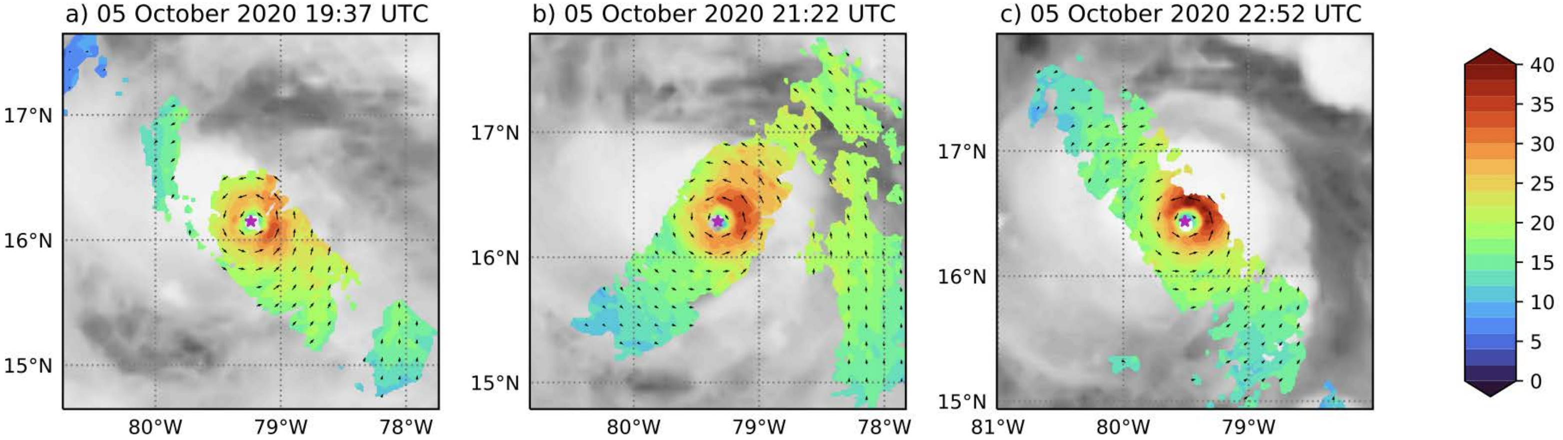


- Noteworthy across-storm asymmetries in strength, radial, and vertical structure of winds evident

IFEX NOWCASTS: Improved representation of TC structure

Real-time incorporation of aircraft data into operational visualization tools

The "first look" of TDR and lightning data in AWIPS-II during Hurricane Lane (2018) flights

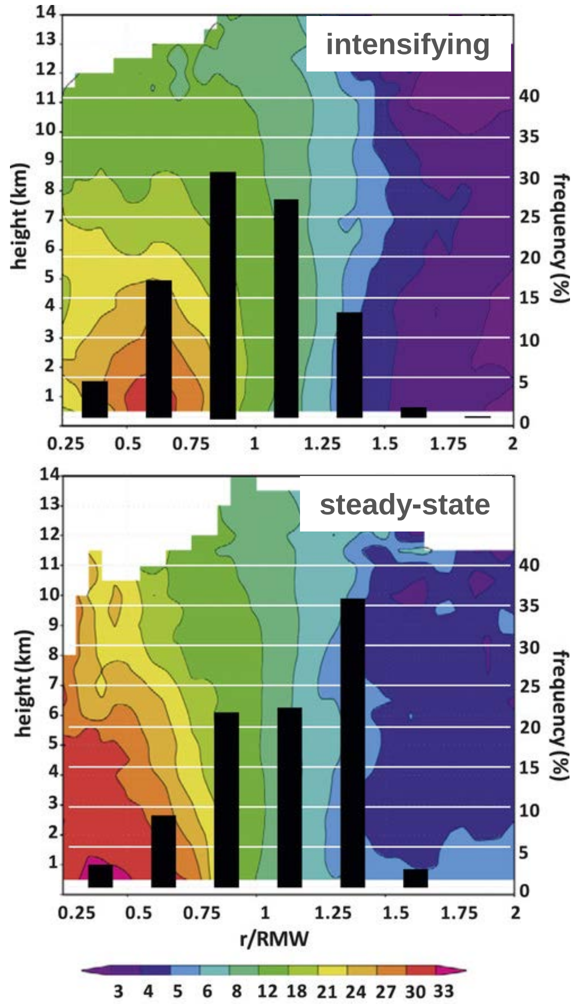


Sequence of passes in Delta (2020) while rapidly intensifying

IFEX RESEARCH: Improved understanding of intensity change

- Characterizing TC Inner-core Structure and Intensity Change

Azimuthally-averaged vorticity (shaded, x 10^{-4} s^{-1}) and radial distribution of convective bursts



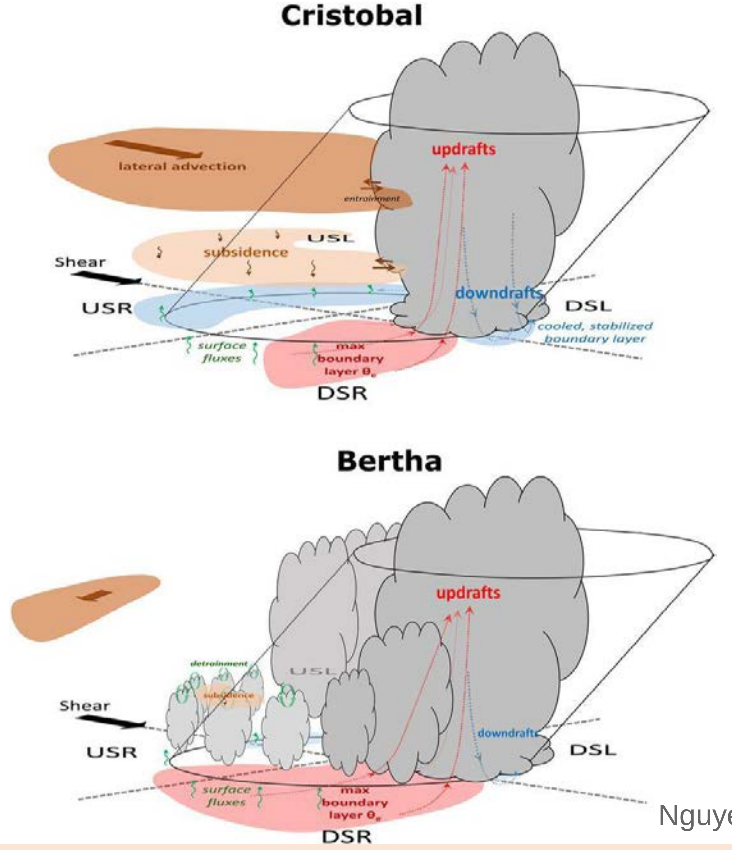
- Peak in distribution of strong convection inside RMW for intensifying TCs, outside for steady-state

Rogers et al. 2013

IFEX RESEARCH: Improved understanding of intensity change

- Characterizing TC Inner-core Structure and Intensity Change
- TC Intensity Change in Vertical Wind Shear

Schematic of intensifying (Bertha) and steady-state (Cristobal) TC structure in shear



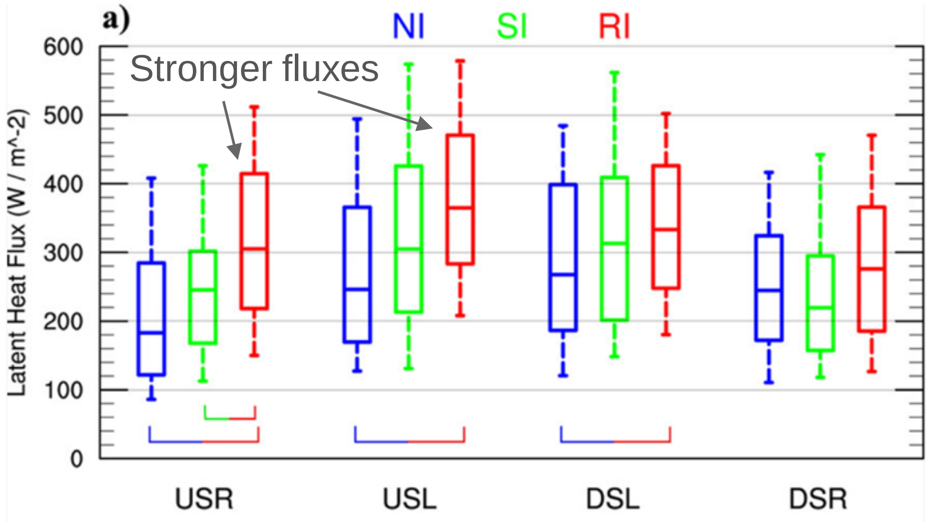
Nguyen et al 2017

- Symmetric distribution of precipitation, more moist boundary layer right of shear for intensifying case

IFEX RESEARCH: Improved understanding of intensity change

- Characterizing TC Inner-core Structure and Intensity Change
- TC Intensity Change in Vertical Wind Shear
- Boundary Layer Processes and Air-sea Interactions

Boxplots of surface latent heat flux in shear-relative quadrants for non-intensifying (blue), slowly intensifying (green) and rapidly intensifying (red) hurricanes from dropsondes.

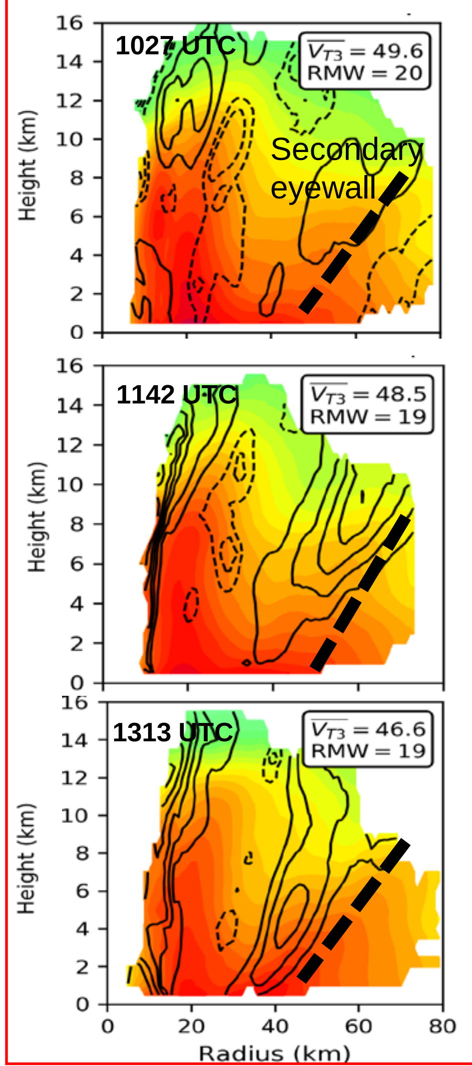


Nguyen et al 2019

- Stronger surface heat fluxes upshear distinguish RI TCs from non-intensifying TCs

IFEX RESEARCH: Improved understanding of intensity change

- Characterizing TC Inner-core Structure and Intensity Change
- TC Intensity Change in Vertical Wind Shear
- Boundary Layer Processes and Air-sea Interactions
- Secondary Eyewall Formation and Eyewall Replacement Cycles



Azimuthally-averaged tangential wind (shaded, m/s) and vertical velocity (contour, m/s) during consecutive center passes in Hurricane Irma (2017)

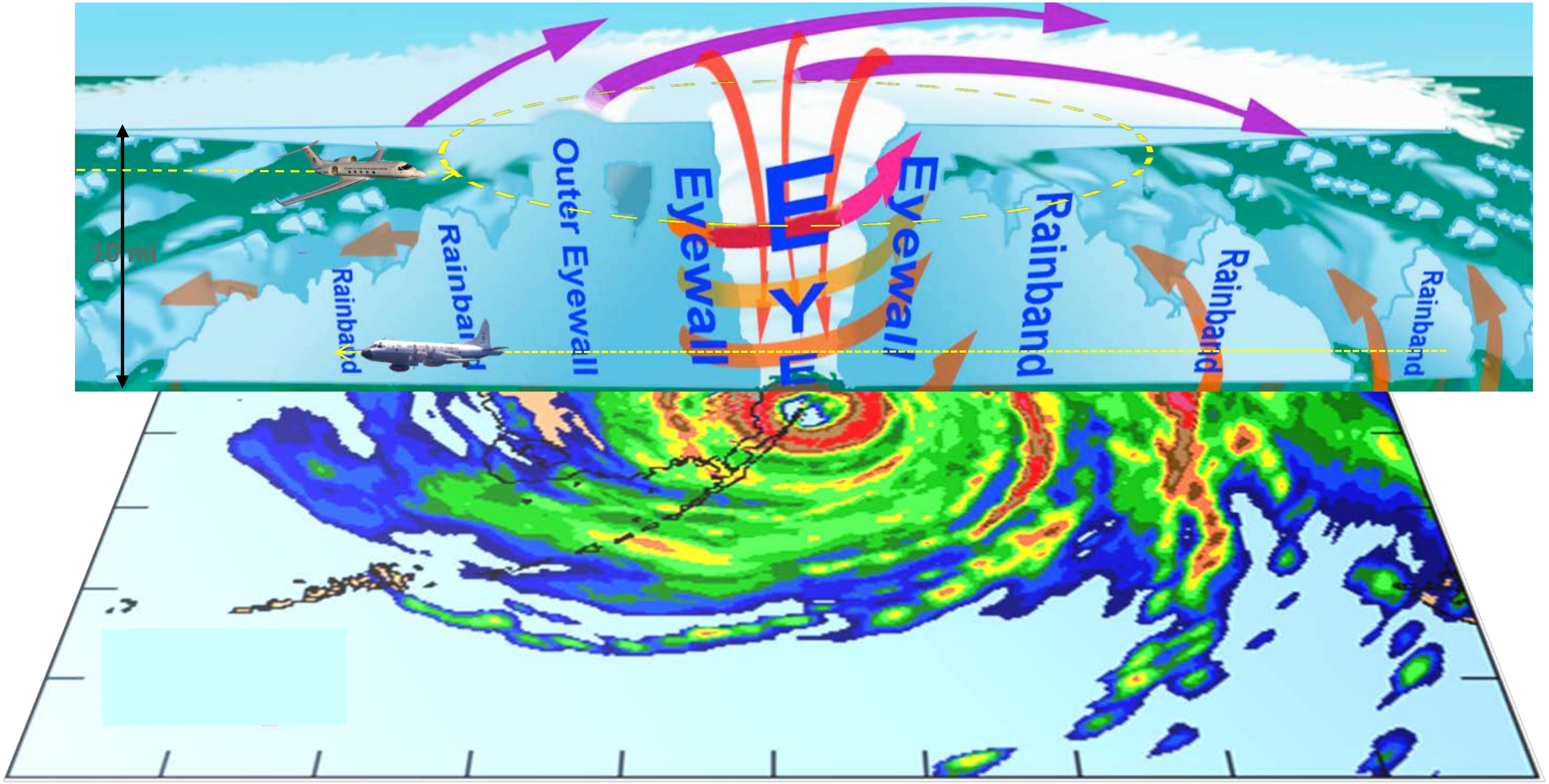
- Clear evidence of secondary eyewall formation over ~3 h period
- Anomaly first appears in midlevels, then surface
- Likely midlevel inflow initiated process

Fischer et al 2020

3. Flight profiles

3. Flight profiles

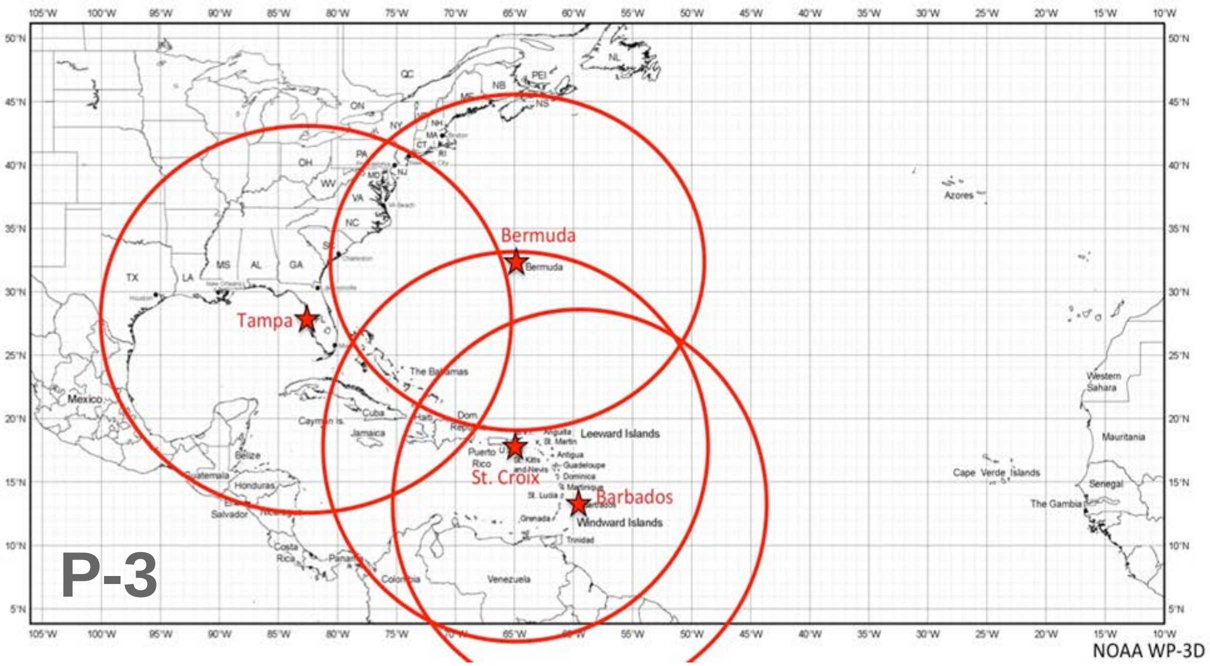
Aircraft sampling of TCs

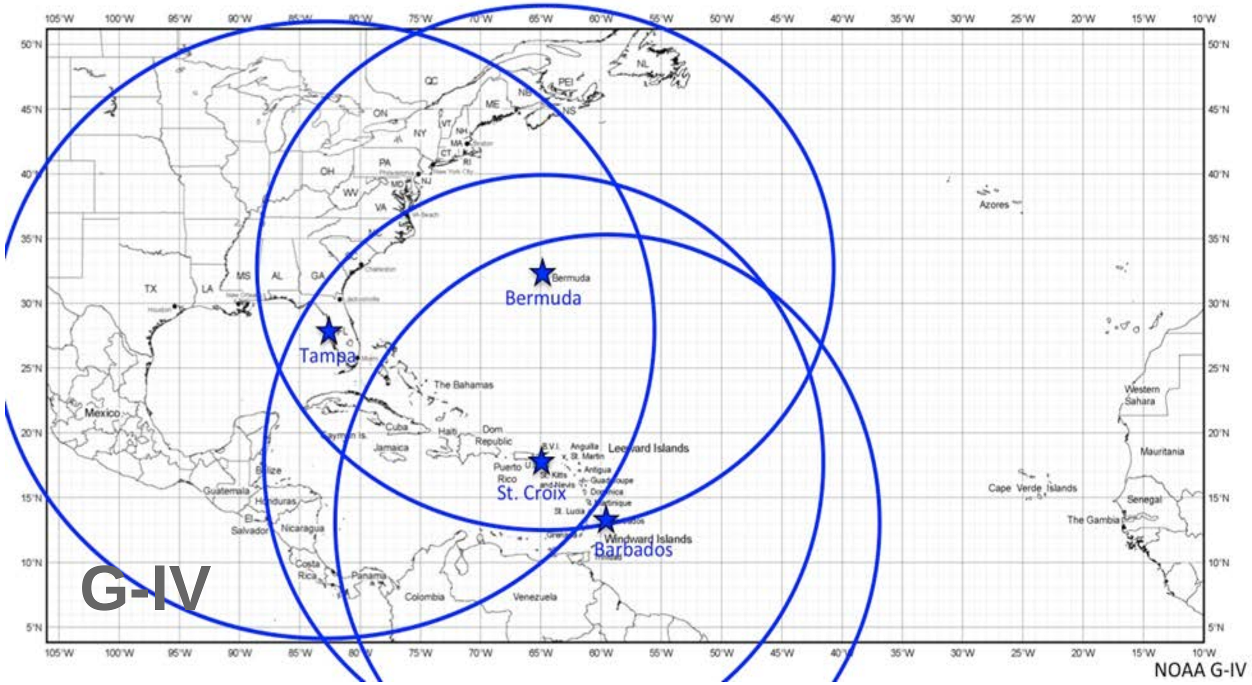


3. Flight profiles

P-3 and G-IV Atlantic bases of operations

Assuming 2 hours of on-station time





3. Flight profiles

Typical flight patterns

P-3

G-IV

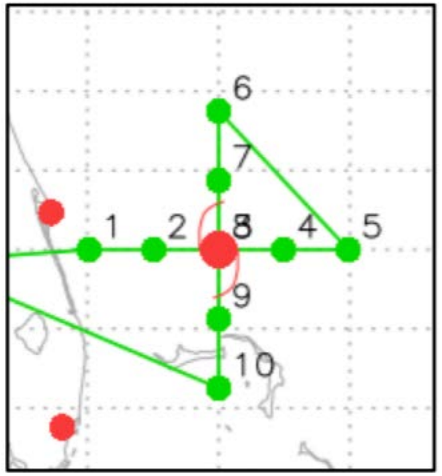
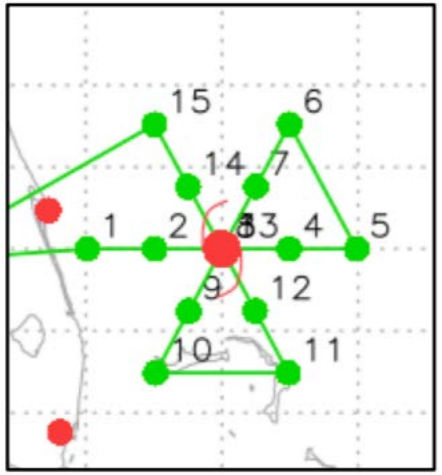
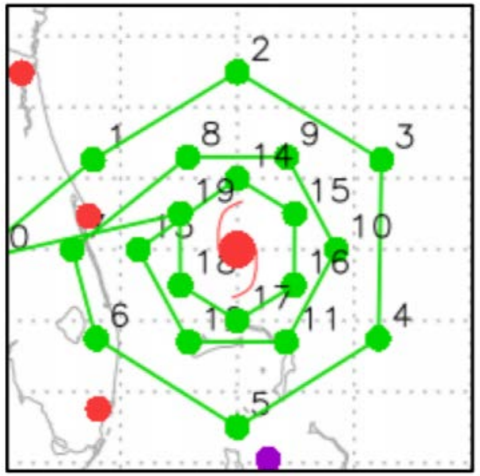


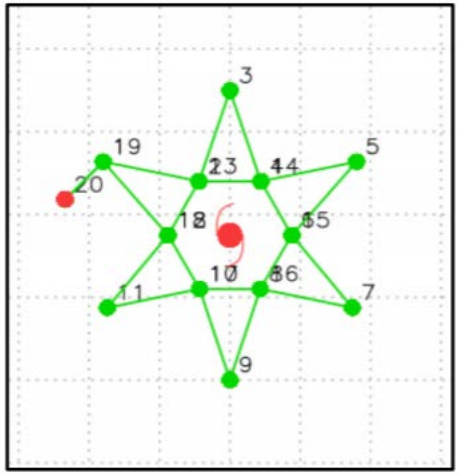
Figure-4



Butterfly



Circumnavigation

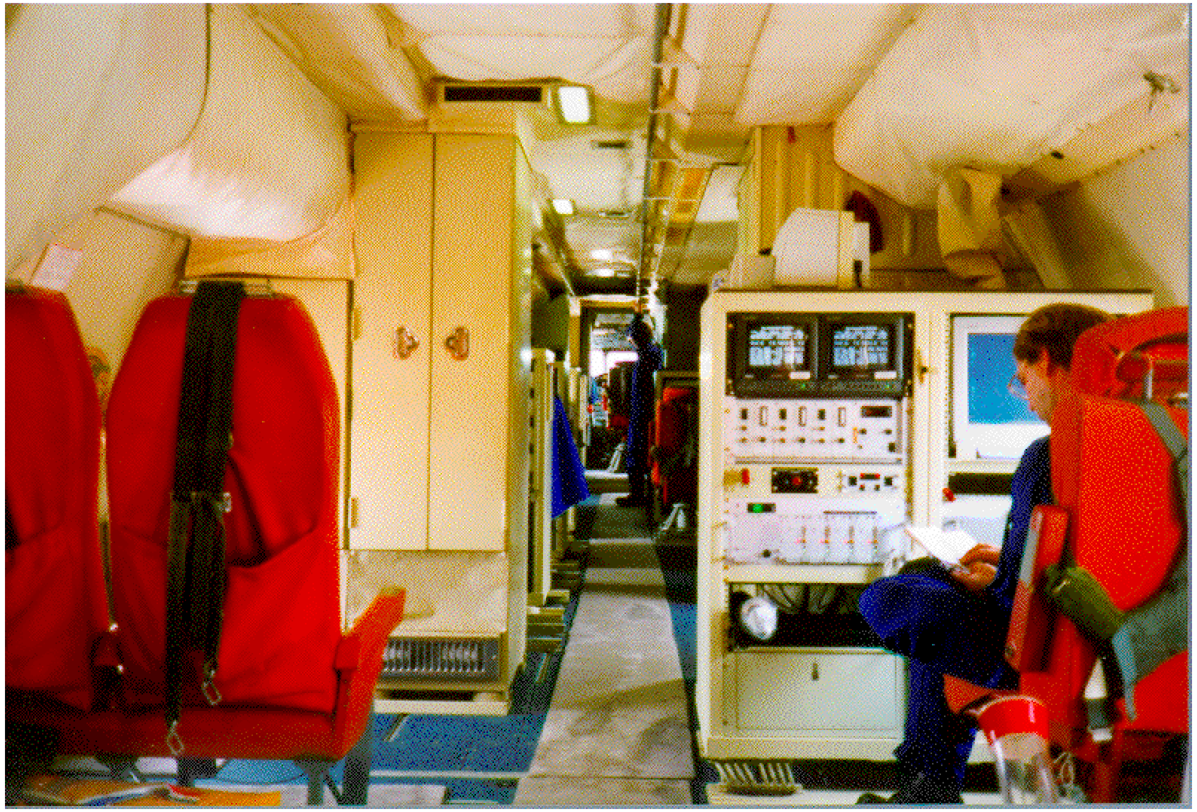


Star

4. Views from the aircraft

4. Views from the aircraft

Inside the P-3 Aircraft

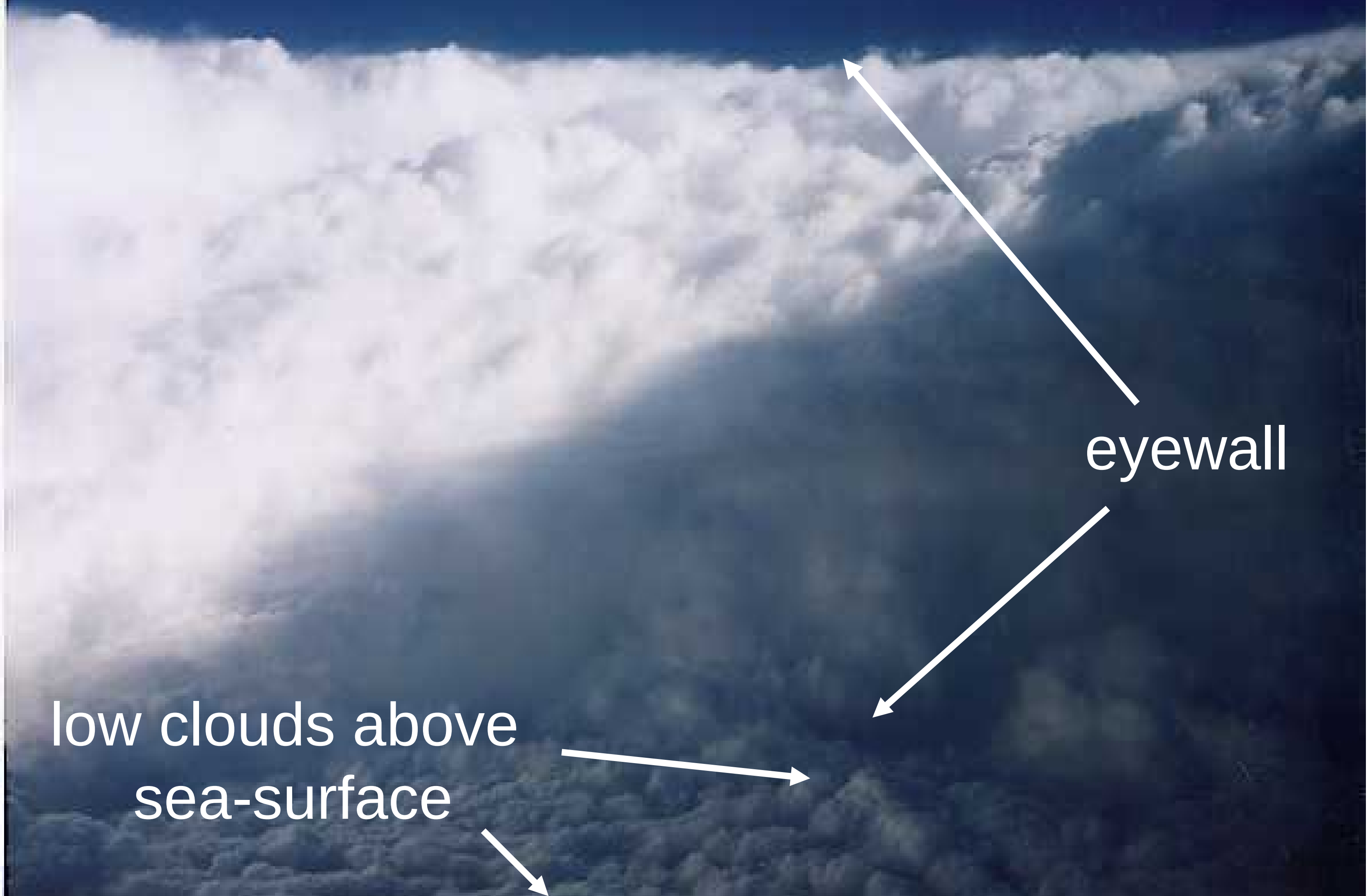


Inside the G-IV Aircraft

4. Views from the aircraft

Dropsonde release on P-3

Within the Eye of Hurricane Georges (1998)



Low-level flight

Stadium effect

5. Toward the future (APHEX)

- Over the past several years there have been *multiple billion dollar TC-related disasters* (NOAA/NCEI)
- Almost every one of these storms had *at least one RI period*
- Storm-surge inundation, extreme rainfall, high surf, and tornadoes are significant contributors to damage, in addition to high winds
- Water (inland flooding from rainfall and surge) is responsible for most deaths (Rappaport 2000)
- **Emphasizes the importance of hazards**

Storm (year)	Landfall location	Rainfall (in.)	Surge inundation (ft)	Wind (kt)	U.S. tornadoes
Matthew (2016; Stewart 2017)	Haiti	**23.80**	Unknown	**130**	2
	Cuba	**26.40**	13	**115**	
	Bahamas	19.70	8	**115**	
	South Carolina	18.95	7.7	75	
Harvey (2017; Blake and Zelinsky 2018)	Barbados	Unknown	Unknown	40	52
	Saint Vincent	Unknown	Unknown	40	
	Texas[a]	**60.58**	10	**115**	
Irma (2017; Cangialosi et al. 2018)	Barbuda	Unknown	8	***155***	25
	Saint Martin	Unknown	Unknown	***155***	
	British Virgin Islands	Unknown	Unknown	***155***	
	Bahamas	Unknown	Unknown	**135**	
	Cuba	**23.90**	10	***145***	
	Florida Keys	6–10	8	**115**	
	Florida	**21.66**	10	**100**	
Maria (2017; Pasch et al. 2019)	Dominica	**22.80**	Unknown	***145***	3[b]
	Puerto Rico	**37.90**	9	**135**	
Florence (2018; Stewart and Berg 2019)	North Carolina	**35.93**	11	80	44
Michael (2018; Beven et al. 2019)	Florida	11.45	14	***140***	16
Dorian (2019; Avila et al. 2020)	Barbados	Unknown	Unknown	45	21
	Saint Lucia	Unknown	Unknown	45	
	Saint Croix	Unknown	Unknown	65	
	Saint Thomas	Unknown	Unknown	70	
	Bahamas[c]	**22.84**	20[d]	***160***	
	North Carolina	15.21	7	85	
Imelda (2019; Latto and Berg 2020)	Texas	**44.29**	2	40	2
Isaias (2020; Latto et al. 2021)	Dominican Republic	8	Unknown	55	39
	Bahamas	Unknown	Unknown	70	
	North Carolina	9.15	6	80	
Laura (2020; Pasch et al. 2021)	Louisiana[e]	11.74	18	**130**	16
Sally (2020; Berg and Reinhart 2021)	Alabama[f]	**29.99**	7	95	16

Zawislak et al. 2022

5. Toward the future (APHEX)

- Focus on "intensity forecasting" at the inception of IFEX now a narrow scope within a broad expanse of forecast challenges and knowledge gaps that must be addressed at all stages of the TC life cycle
- IFEX priorities broadened beyond intensity to include **structure and hazards**, and with the focus of **improving model analyses** with observations

APHEX (Advancing the Prediction of Hurricanes Experiment)

Goal 1: Collect observations that span the TC life cycle in a variety of environments for model initialization and evaluation

Goal 2: Develop and refine measurement strategies and technologies that provide improved real-time ***analysis*** of TC intensity, structure, environment, ***and hazard assessment***

Goal 3: Improve the understanding of physical processes ***that affect TC formation, intensity change, structure, and associated hazards***

5. Toward the future (APHEX)

New Airborne Platforms and Instruments

Small uncrewed aerial systems (sUAS)

- released from P-3 like a dropsonde, can be controlled for ~2 h
- new versions have 3-4 h duration, range of ~200 nm
- APHEX 2023 will see continuation of sUAS missions, tests of new platforms (dropsonde swarm)

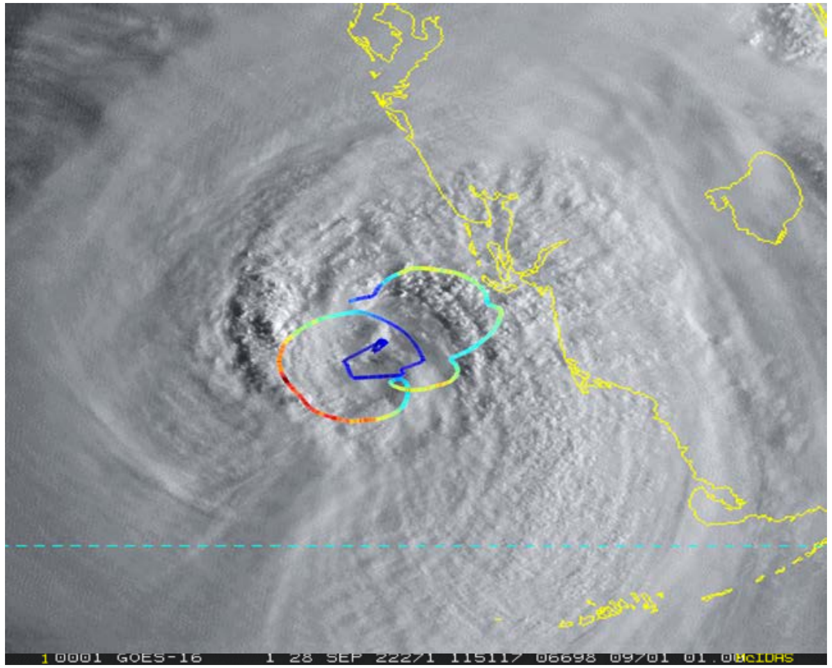
- depiction of sUAS launch

5. Toward the future (APHEX)

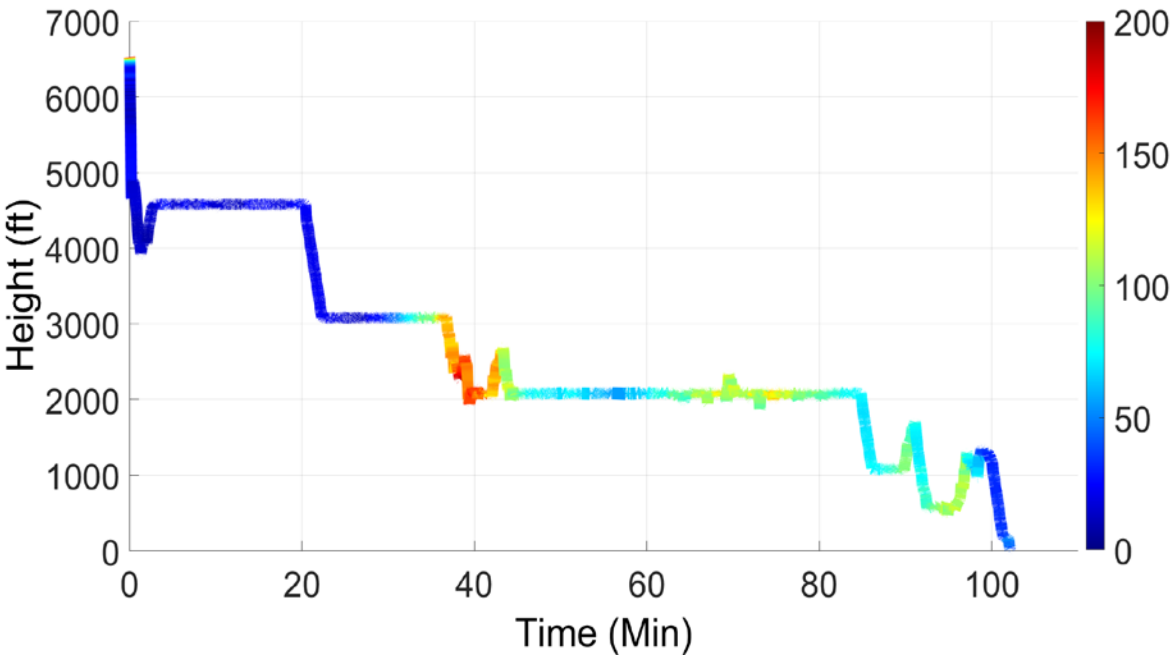
New Airborne Platforms and Instruments

Small uncrewed aerial systems (sUAS)

Altius track and wind speed (shaded, kt)



Altius altitude (ft) and wind speed (shaded, kt)

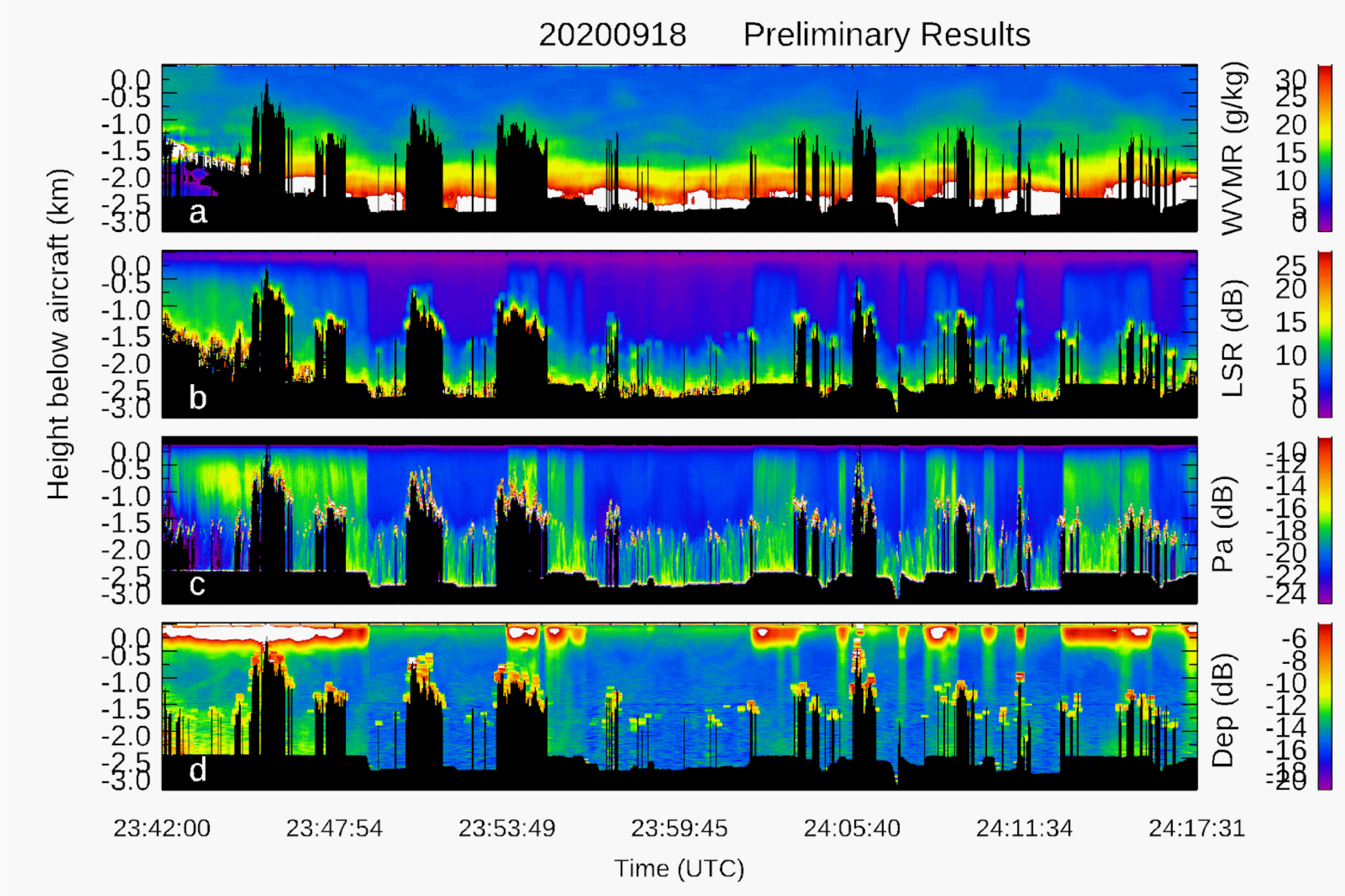


- Altius measurements in Hurricane Ian (2022)
- Can get measurements down to surface, where crewed aircraft can not reach

5. Toward the future (APHEX)

New Airborne Platforms and Instruments

Compact Raman Lidar (CRL)

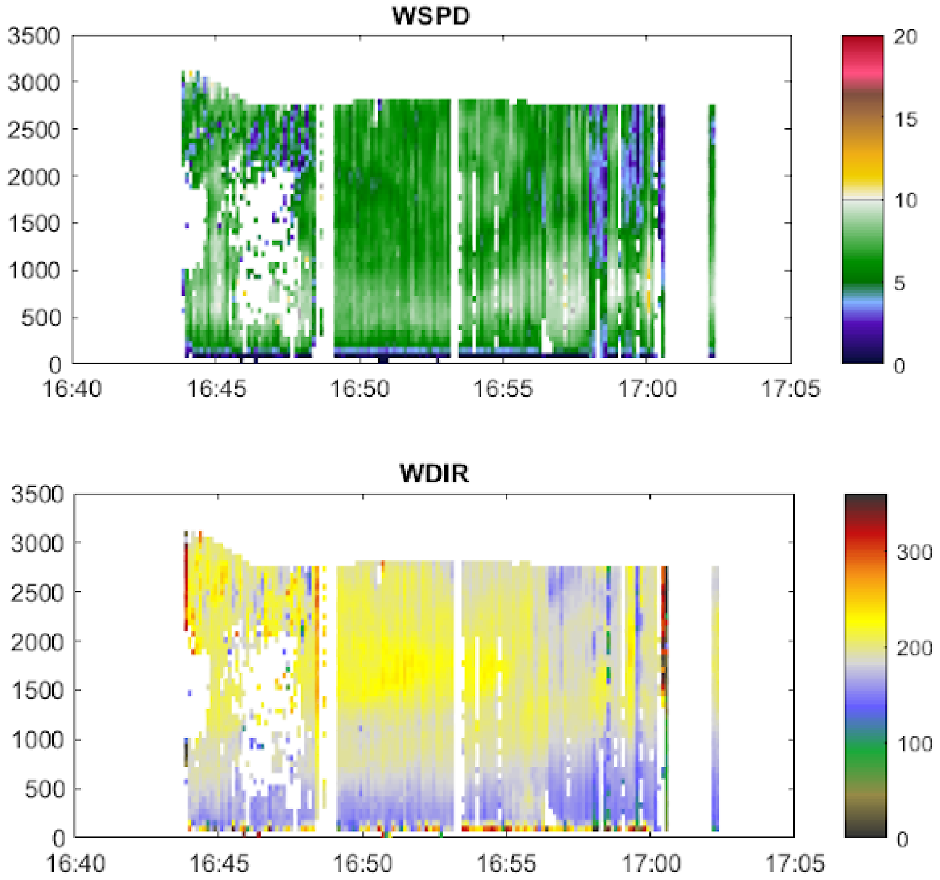


- Lidar retrievals of three-dimensional fields of temperature, water vapor, clouds, and aerosols below flight level
- 45 m vertical, 100-1000 m horizontal resolution
- Provide valuable thermodynamic information in boundary layer

5. Toward the future (APHEX)

New Airborne Platforms and Instruments

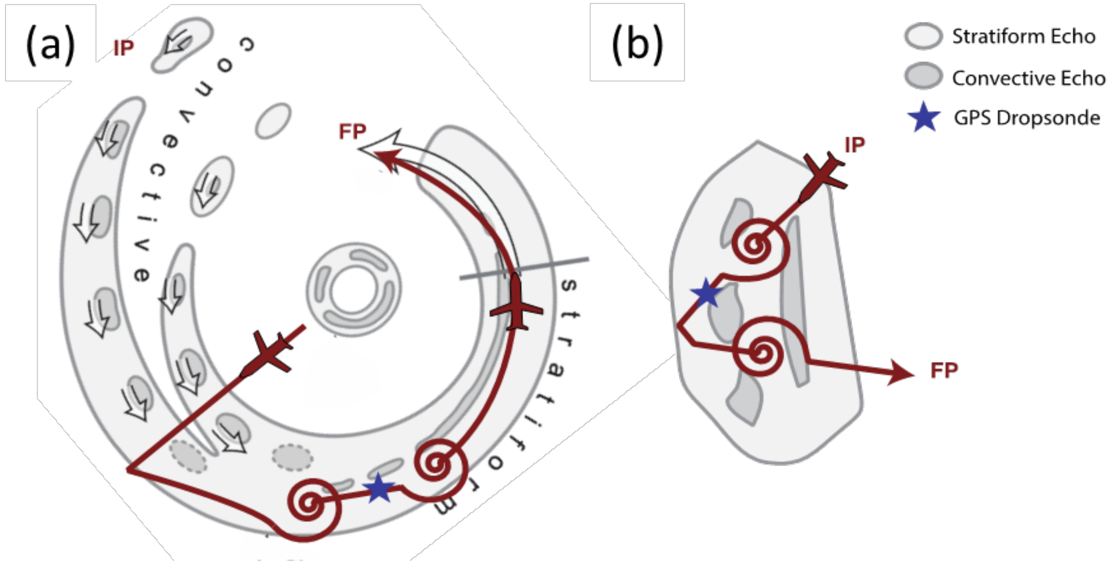
Micro-Pulse Doppler (MicroDop) Lidar

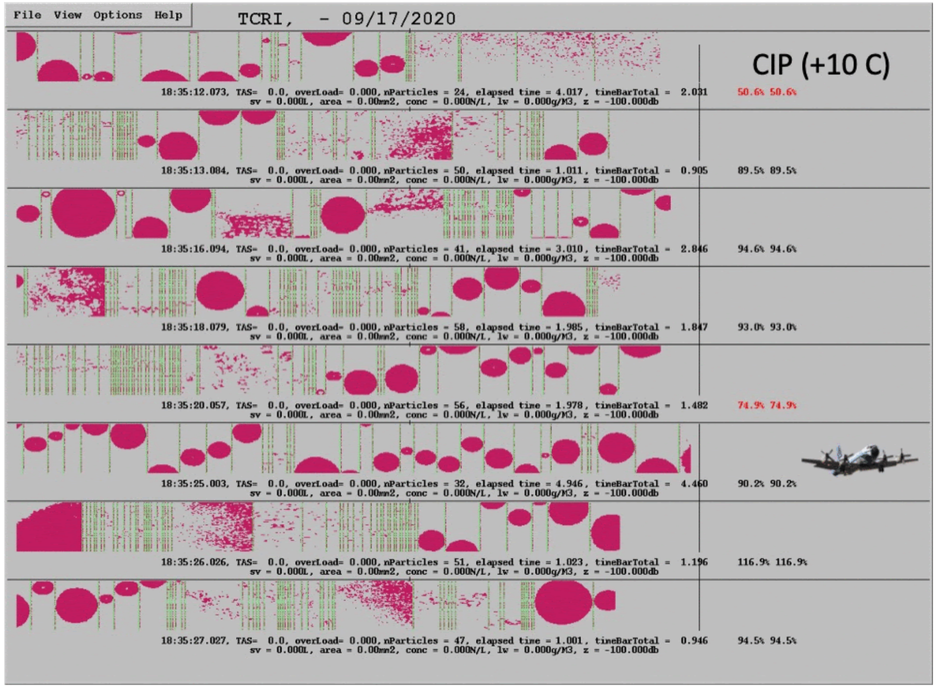


- Lidar retrievals of three-dimensional fields of winds and aerosol backscatter below flight level
- Complements tail Doppler radar by providing winds in absence of precipitation scatterers

5. Toward the future (APHEX)

New airborne sampling strategies





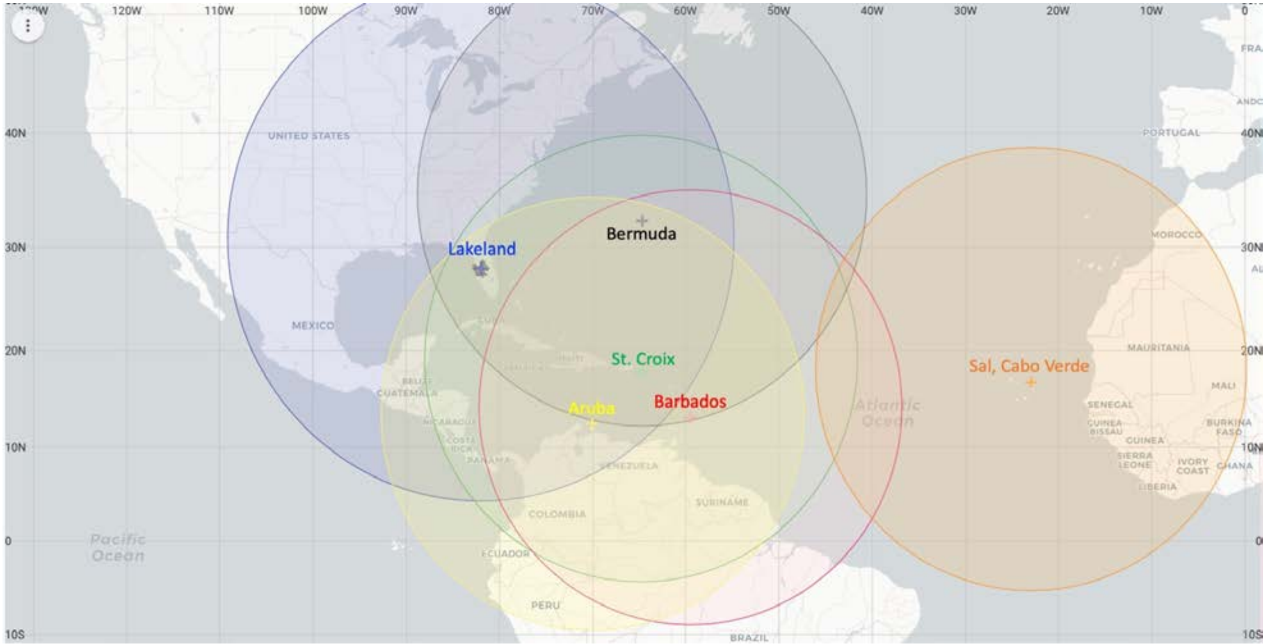
- P-3 Stratiform Spiral module: a spiral ascent and descent across the freezing level in the stratiform portion of a primary rainband is shown in (a)
- Microphysics measurements can help with rainfall, possibly intensity forecasts from numerical models

- Hurricane Teddy Cloud Imaging Probe (CIP) measurements of rain droplets, ice crystals, and snow. Hydrometeors transition from water to ice as the P-3 flies through and above the freezing level.

5. Toward the future (APHEX)

A global approach

ITOFS-East



- G-IV operating out of Cabo Verde sampled environment of pre-genesis disturbances emerging off Africa in August 2022

6. Quiz

What is the difference in intensity forecast error for TCs undergoing RI compared with TCs not undergoing RI?

a) Half the forecast error for RI TCs
b) About the same forecast error
c) 3x the forecast error for RI TCs
d) 5x the forecast error for RI TCs

6. Quiz

Which airborne instrument provides a measurement of surface wind speed?

a) Tail Doppler Radar (TDR)
b) Compact Raman Lidar (CRL)
c) Lower Fuselage Radar (LF)
d) Stepped-Frequency Microwave Radiometer (SFMR)

6. Quiz

What is the name of the new Hurricane Field Program run by the NOAA/AOML Hurricane Research Division?

a) Intensity Forecasting Experiment (IFEX)
b) Convective Processes Experiment (CPEX)
c) Advancing the Prediction of Hurricanes Experiment (APHEX)
d) Rapid Updates on the Mesoscale Experiment (RUMEX)

NOAA's Atlantic Oceanographic and Meteorological Laboratory
U.S. Department of Commerce

THANK YOU

QUESTIONS?

Why are observations important?

- Provide real-time information on position, intensity, and structure of TCs
- Assess performance of models, and provide a check on theories
- Many important physical processes within hurricanes span scales that cover many orders of magnitude, ranging from thousands of kilometers to millionths of meters
- Observations can span these scales, and are a key component of a balanced approach toward advancing understanding and improving forecasts of hurricanes (observations, modeling, theory)
- Three primary platform types: airborne, spaceborne, and land-based
- Focus here on airborne – in situ sampling of fields that can not be done by other platform types, a form of ground-truthing important for forecasters