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

Airborne Observations in Tropical Cyclones

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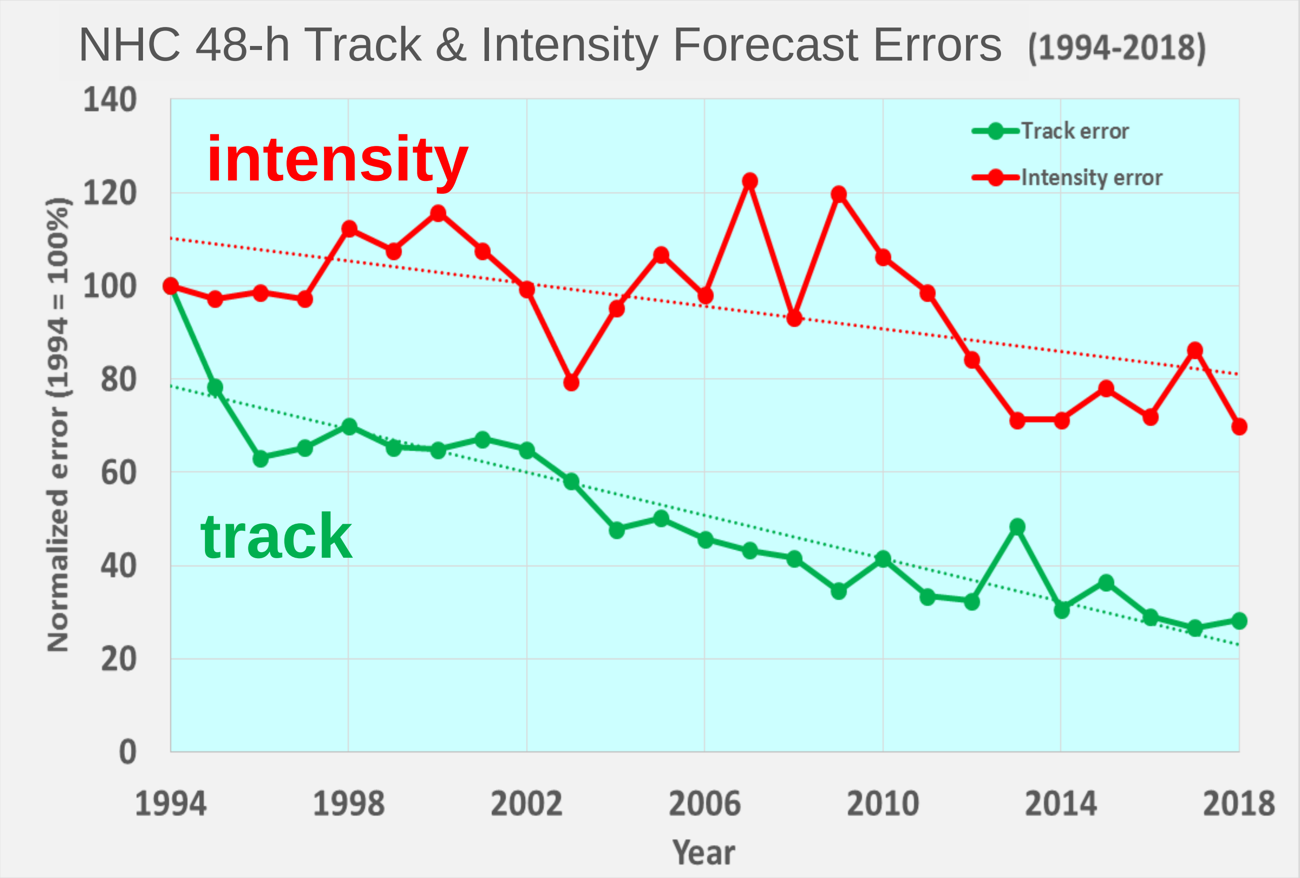
The Challenge: Hurricane Intensity Forecasting



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

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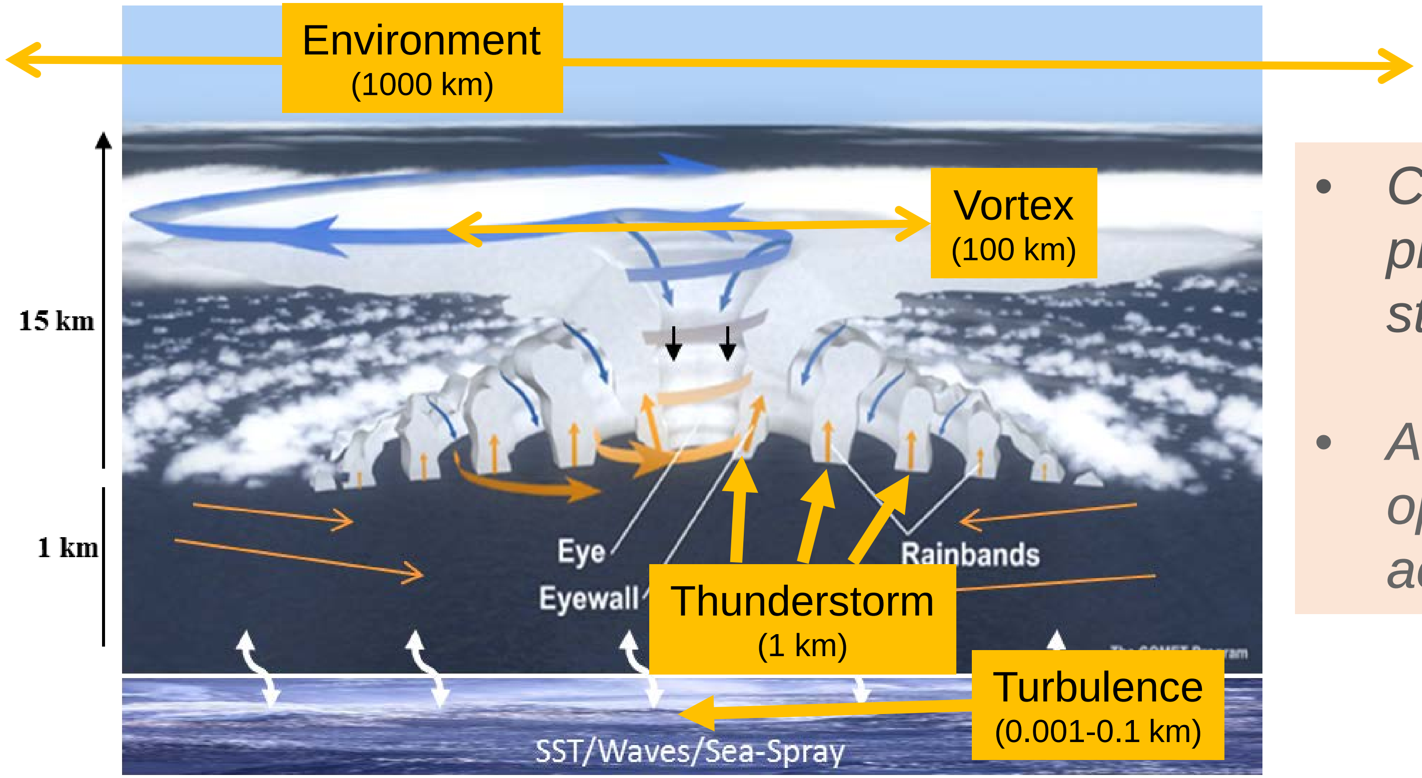
The challenge: Hurricane Intensity Forecasting

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*

Why are observations important?

- 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)
- Provide real-time information on TCs, assess performance of models, and provide a check on theories
- Three primary platform types: airborne, spaceborne, and land-based
- Focus here on airborne

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

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

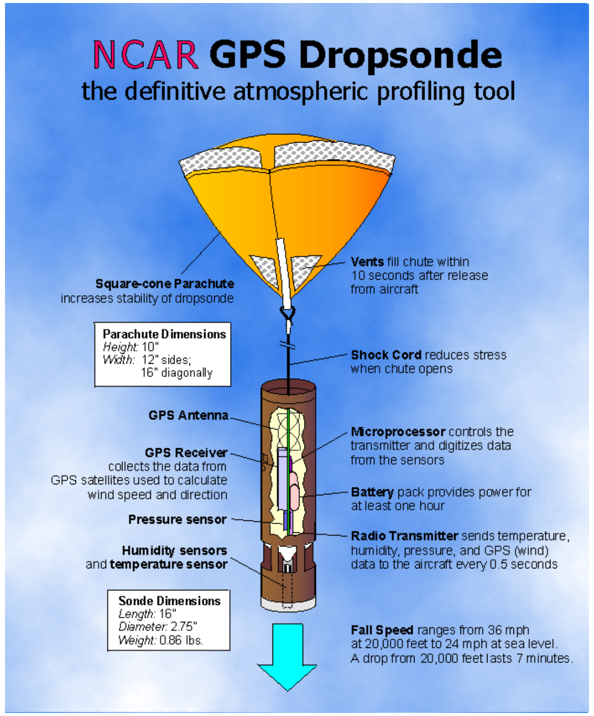
"Gonzo" Built in 1994 at Gulfstream Aerospace Corporation, Savannah, Georgia

Tools for observing hurricanes - instruments

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

Tools for observing hurricanes - instruments

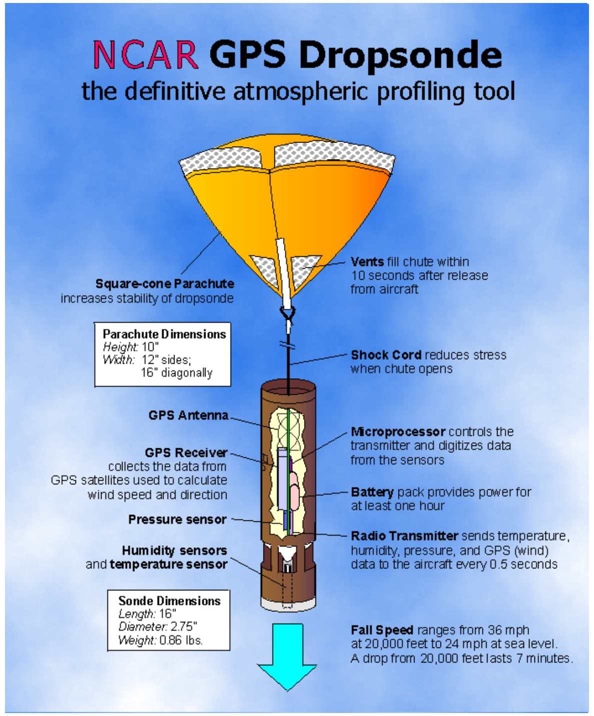
- **In-situ**
  - Wind
  - Pressure
  - Temperature
  - Moisture
- **Expendables**
  - Dropsondes
  - Aircraft-launched ocean probes



GPS Dropsonde

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

Tools for observing hurricanes - instruments

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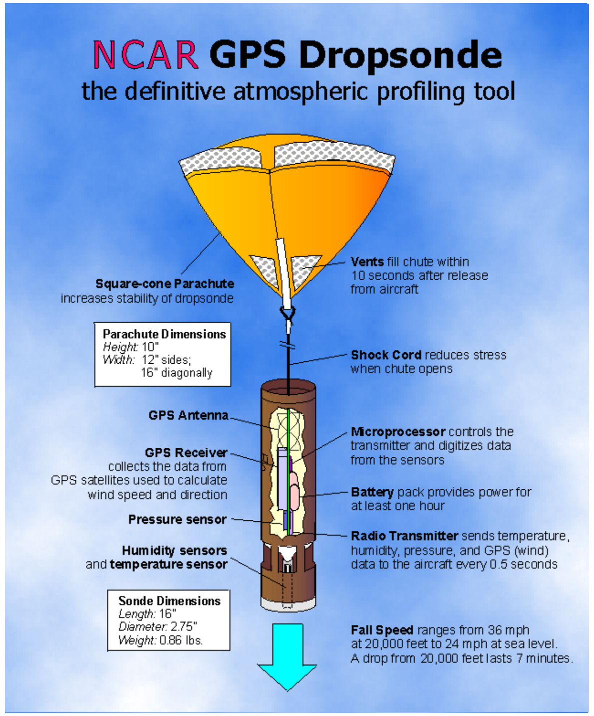
- **Expendables**
  - Dropsondes
  - Aircraft-launched ocean probes
- **Remote Sensors**
  - Tail Doppler Radar(TDR)
  - Stepped Frequency Microwave Radiometer (SFMR)
  - Scanning Radar Altimeter (SRA)
  - Doppler Wind Lidar
- **Uncrewed**
  - Uncrewed Aerial Systems (UASs) (e.g., Coyote)
  - Autonomous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



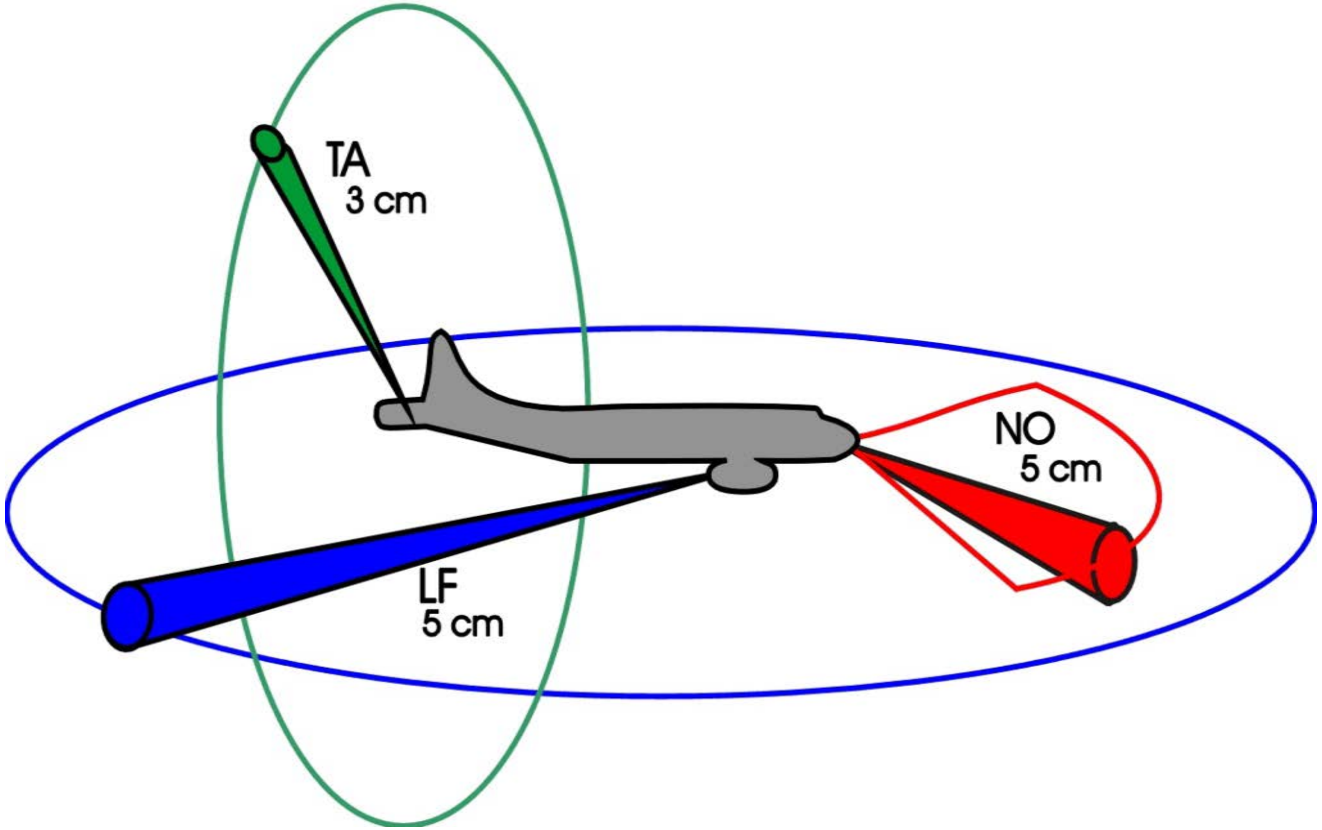
GPS Dropsonde

Tail Doppler Radar

Doppler Wind Lidar

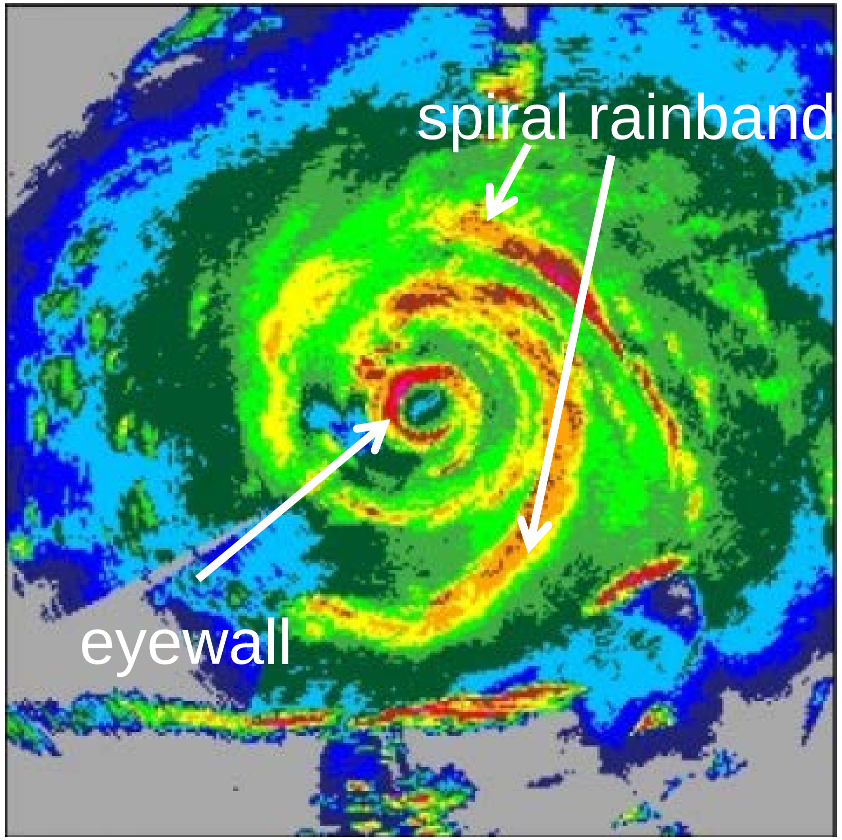
Tools for observing hurricanes - instruments

Airborne Radars on P-3



Tools for observing hurricanes - instruments

Lower Fuselage (LF) Radar

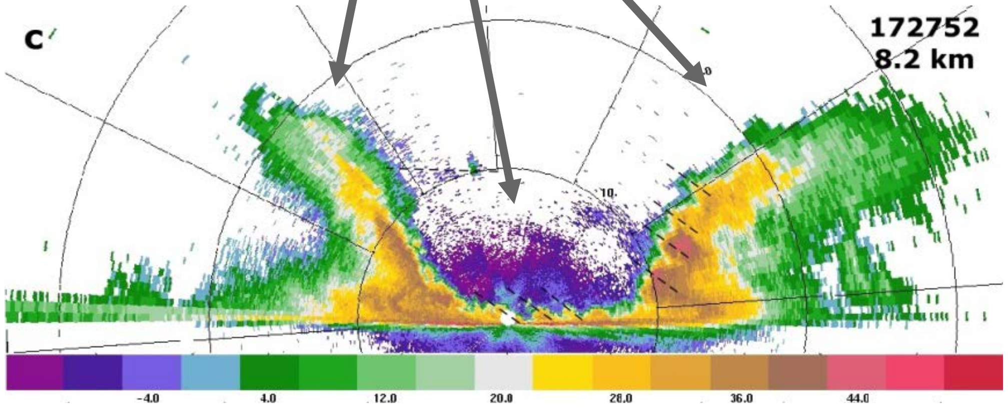


Tools for observing hurricanes - instruments

Tail Doppler Radar

eyewall

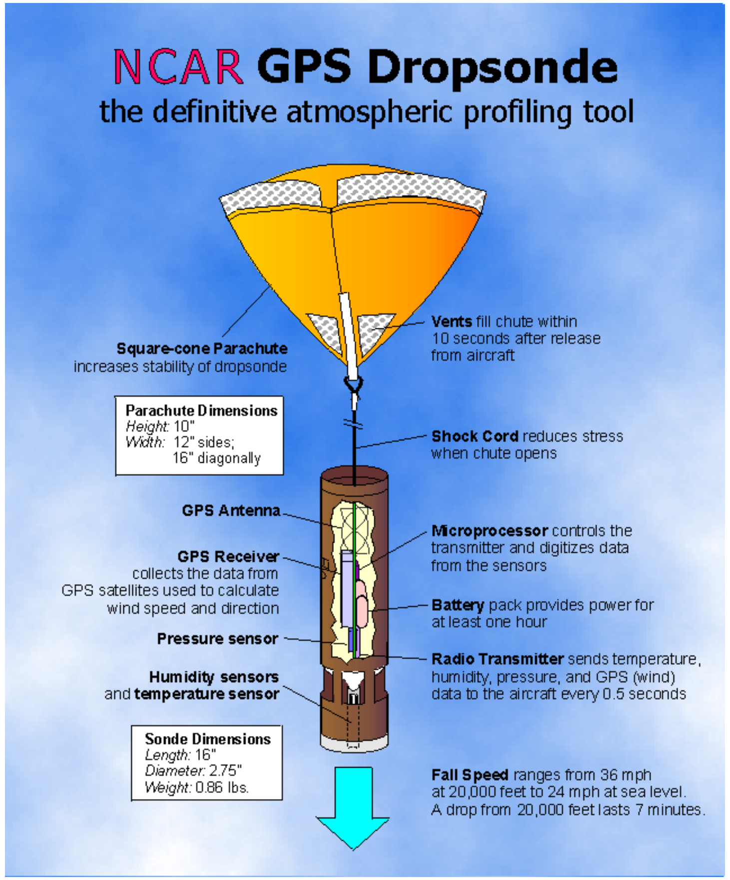
eye

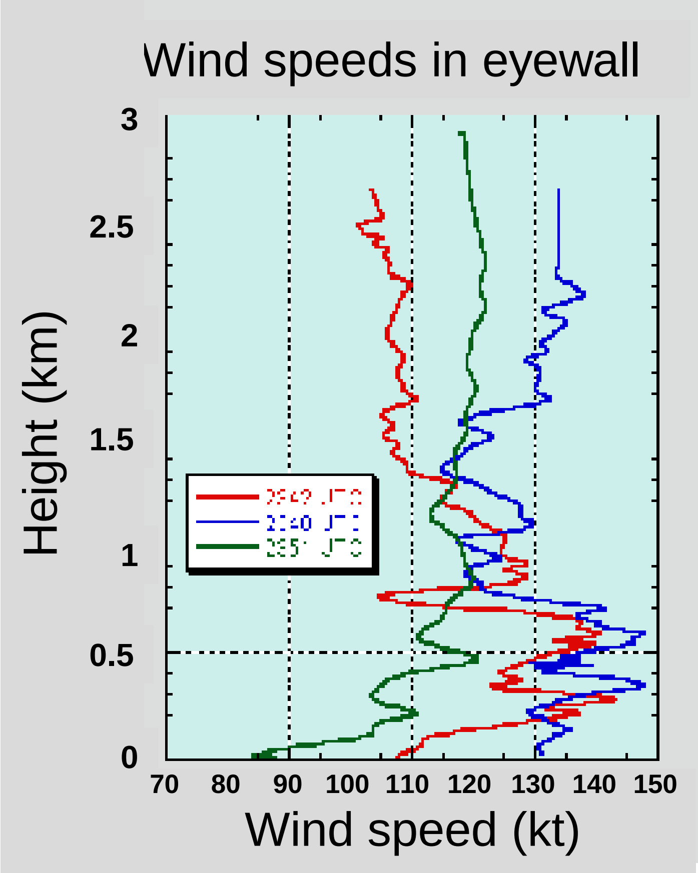


Vertical slice shows eyewall, eye structure

Tools for observing hurricanes - instruments

GPS dropsonde

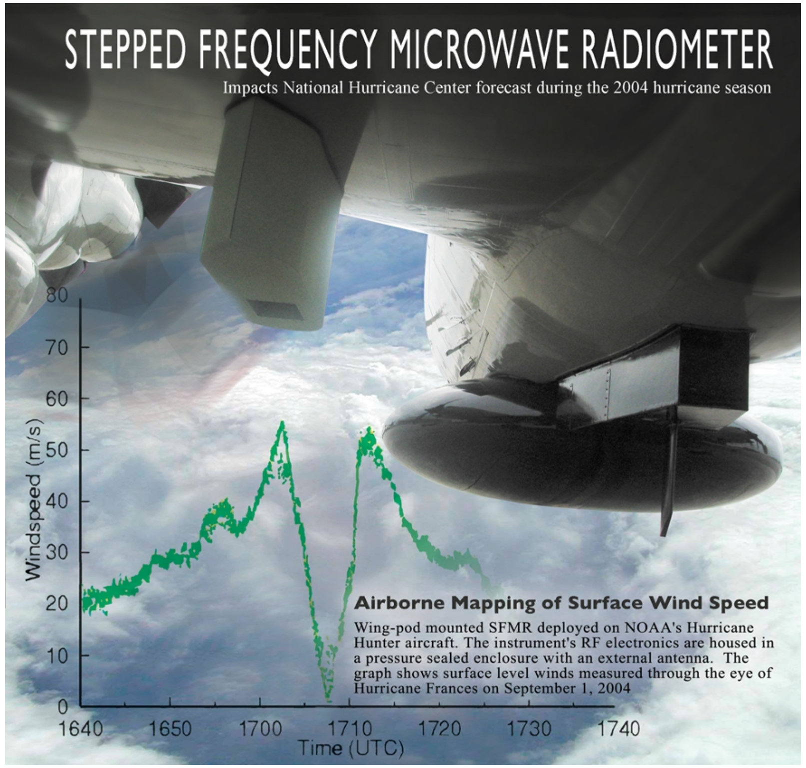


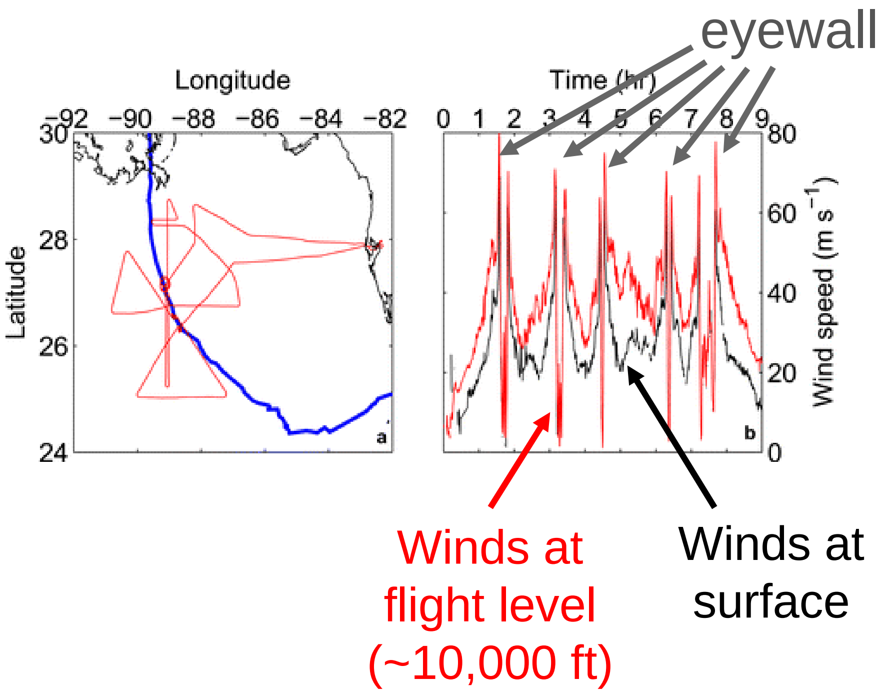


Cat-5 wind speeds in lowest 1500 ft

Tools for observing hurricanes - instruments

Stepped Frequency Microwave Radiometer (SFMR)



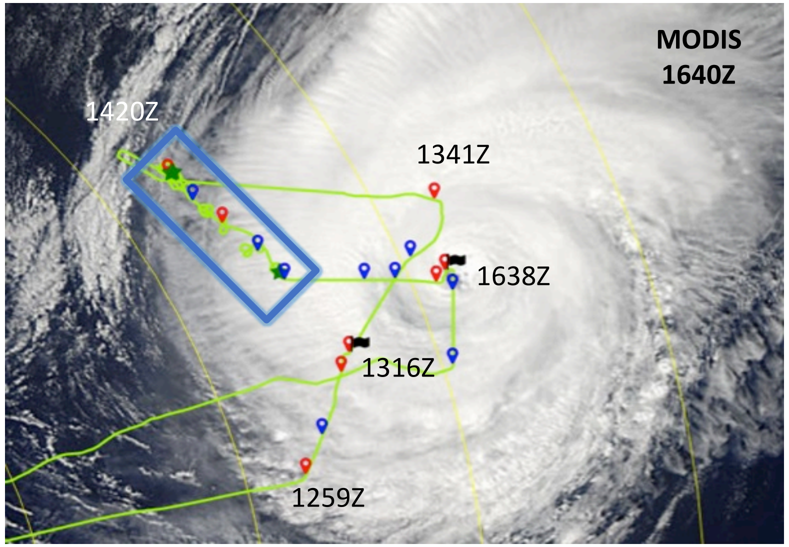


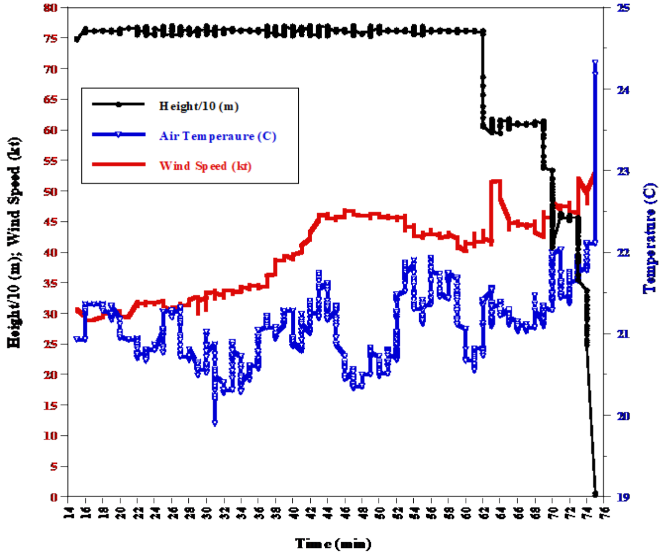
Winds at surface usually a little weaker than winds at flight level

New Airborne Platforms

Small uncrewed aerial systems (sUAS)

Coyote measurements in Hurricane Edouard (2014)





- released from P-3 like a dropsonde, can be controlled for ~2 h
- new versions have 3-4 h duration, range of ~200 nm
- can get measurements down to surface, where manned aircraft can not reach

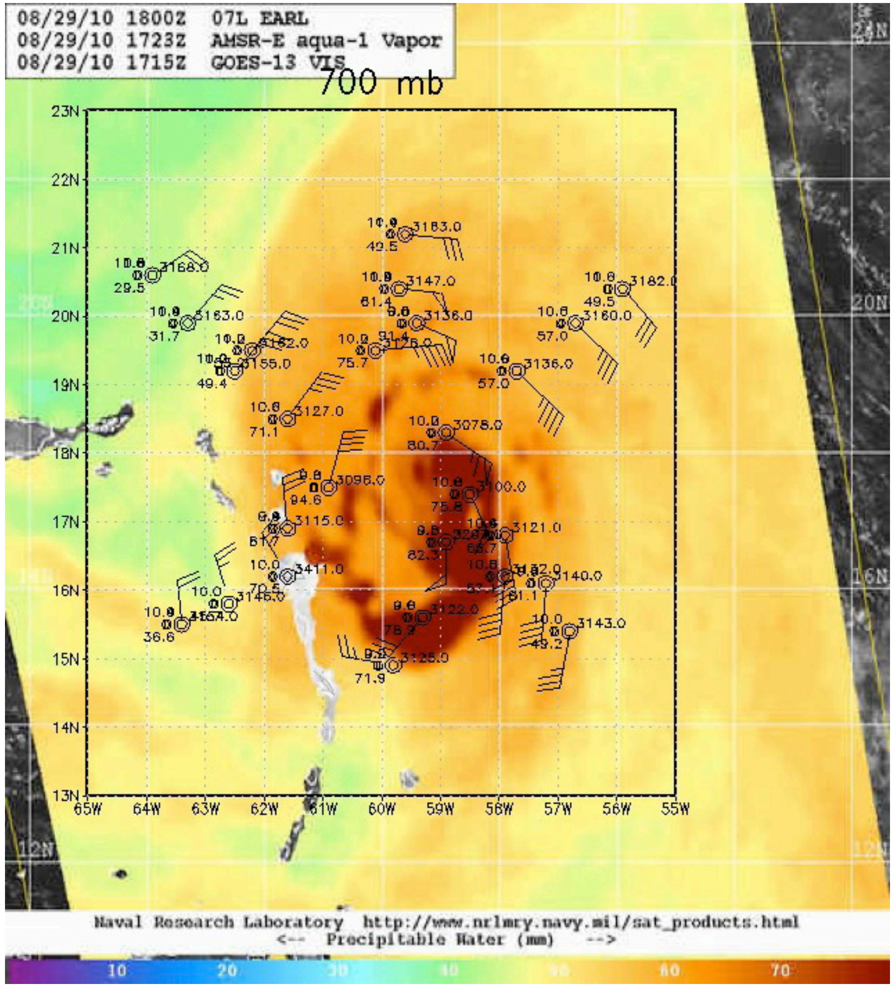
New Airborne Platforms

Depiction of sUAS launch

Scales sampled by Airborne Observations

Environmental structure

- Synoptic-surveillance using dropsondes

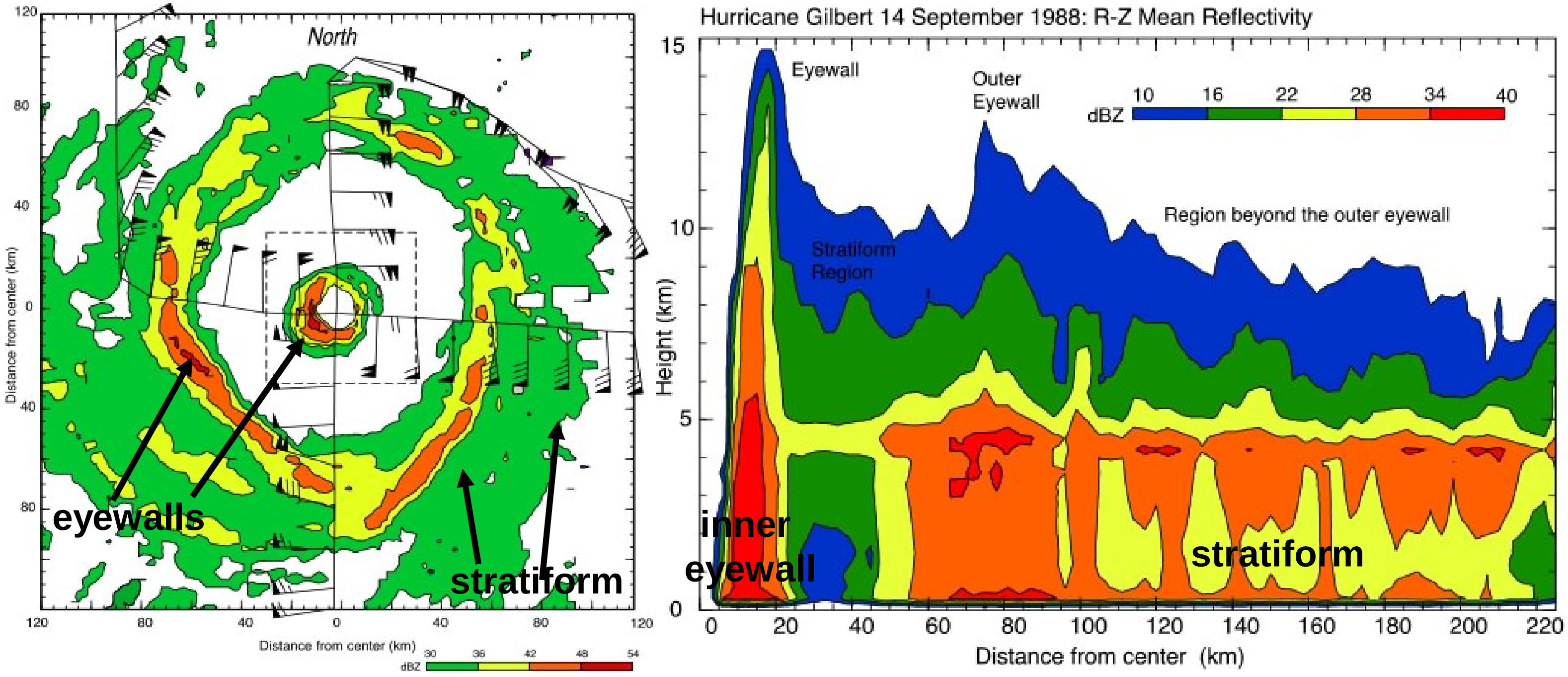


- Steering flow
- Variation in moisture content of environment around hurricane

Scales sampled by Airborne Observations

Vortex Structure

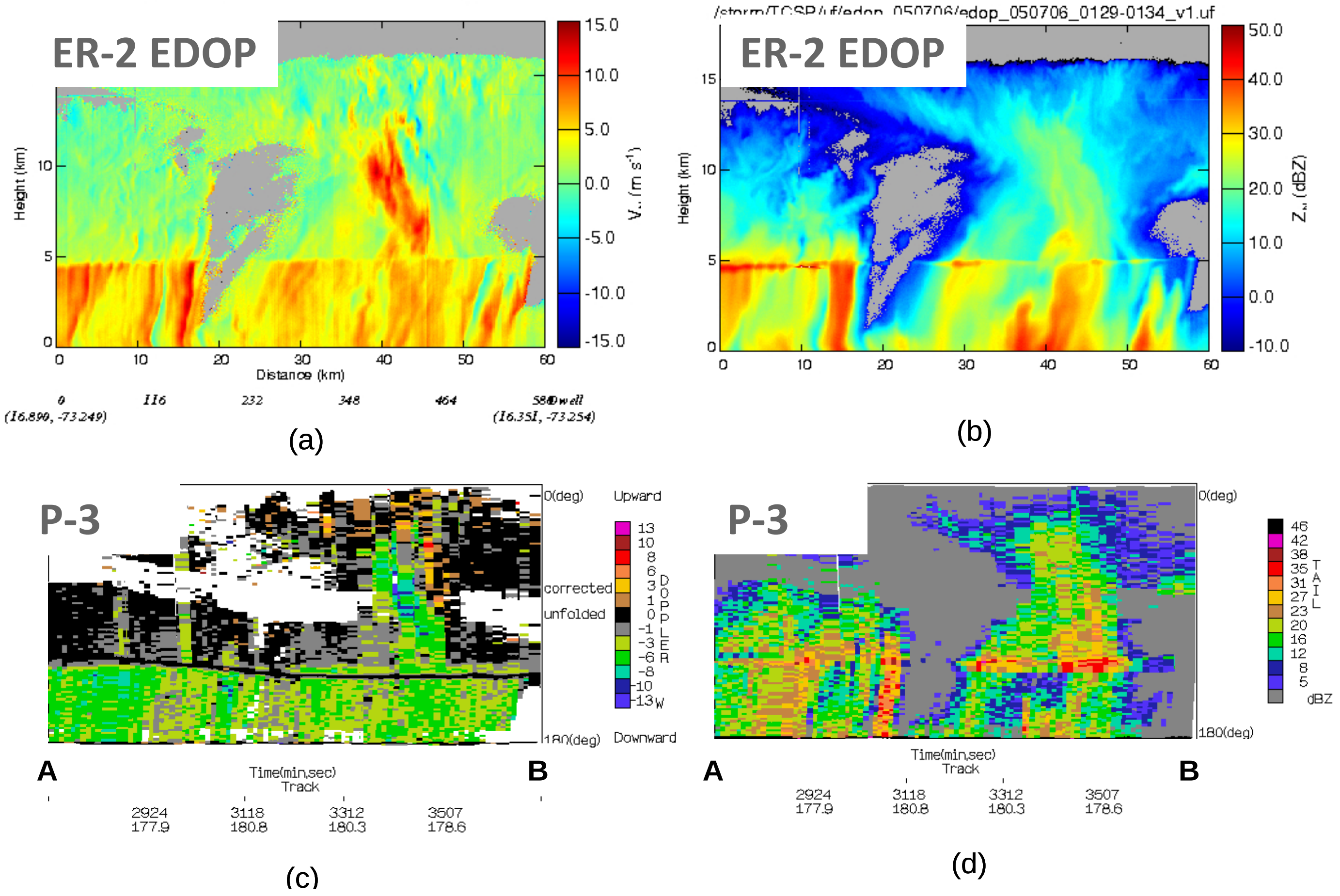
<u>Double eyewalls seen from airborne radar</u>



- Highest rain rates normally in eyewall, mostly convective, cover small area
- Lighter rain rates in stratiform areas outside eyewall, cover larger area

Scales sampled by Airborne Observations

Convective Structure



Vertical velocity (m/s)

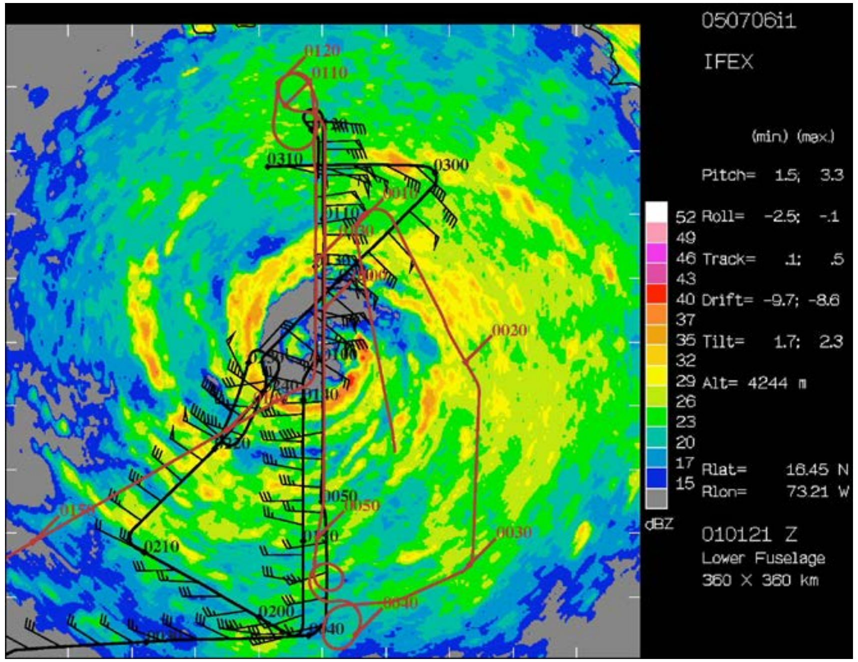
Reflectivity (dBZ)

- Strong convection seen from radar

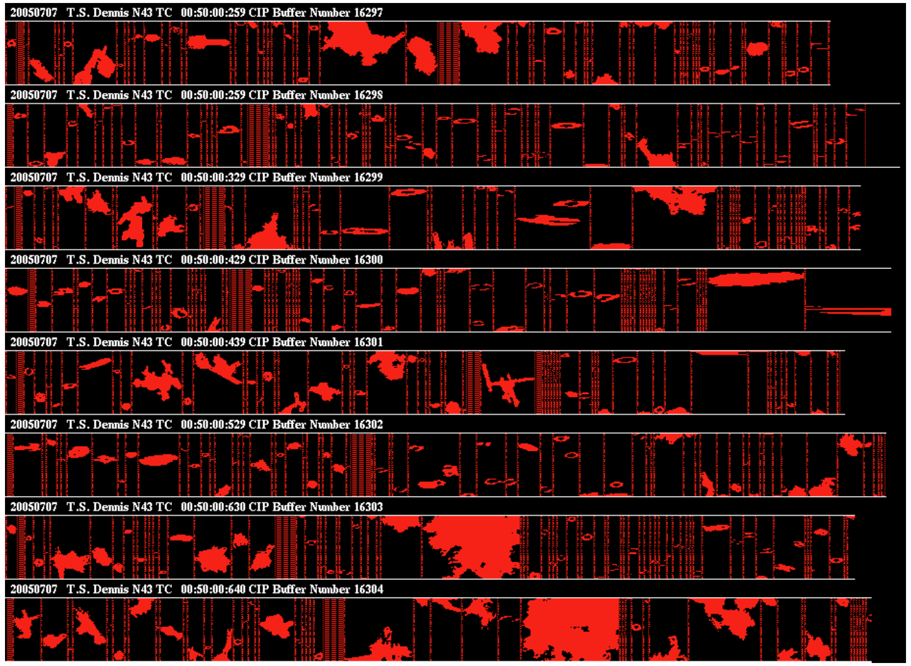
Scales sampled by Airborne Observations

Microphysical Structure

Flight track and LF image



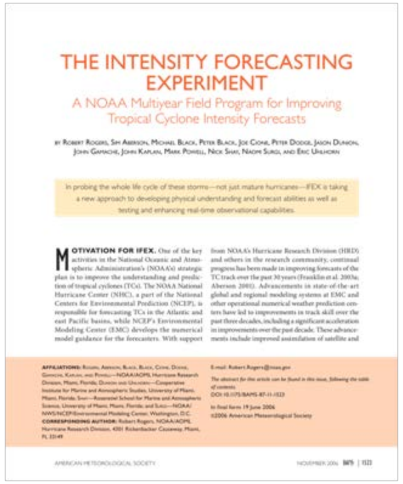
Cloud physics particle images



- snowflakes, graupel pellets, ice crystals seen in probe imagery

2. Use of observations to improve hurricane forecasts

Intensity Forecasting Experiment (IFEX)



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

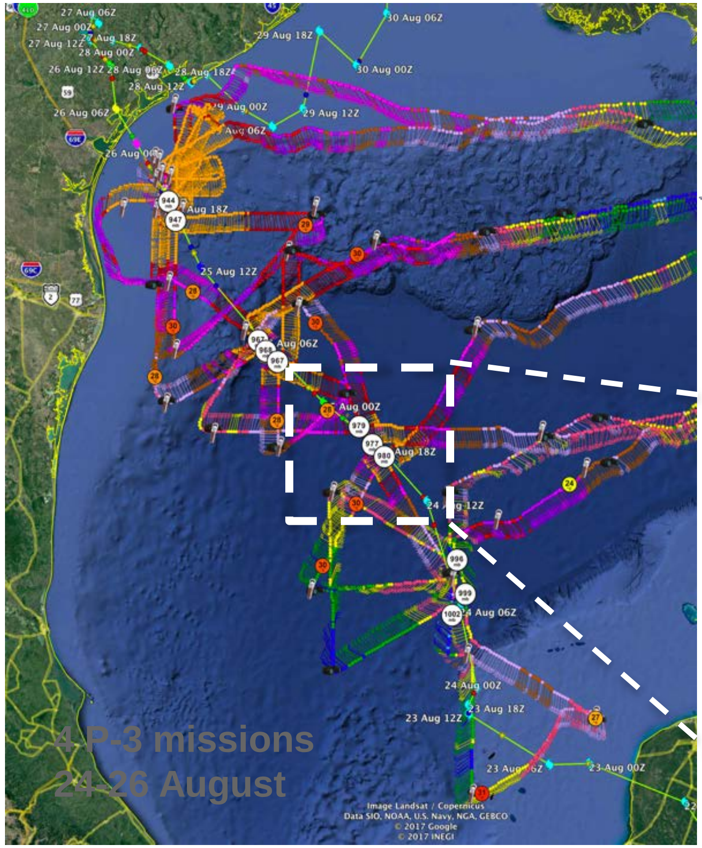
A Progress Report

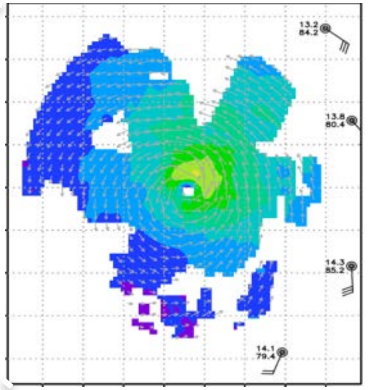
Rogers et al., BAMS, 2013

IFEX intended to improve prediction of TC intensity change by addressing <u>three goals</u>:

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

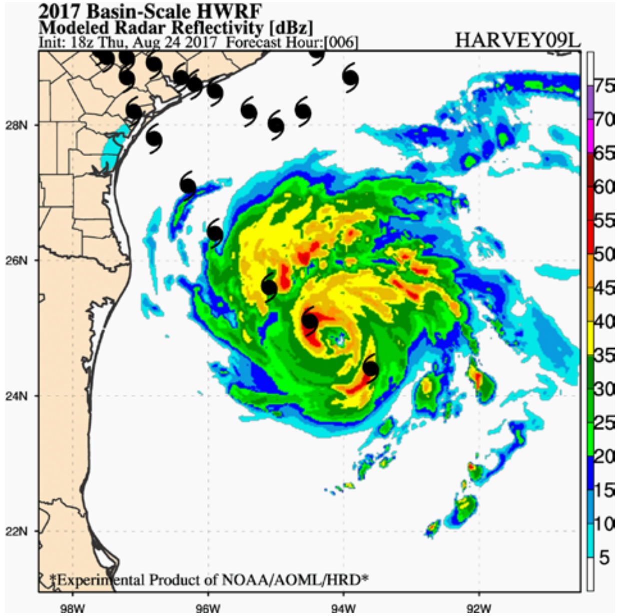
IFEX FORECASTS: Assimilation of data into numerical models





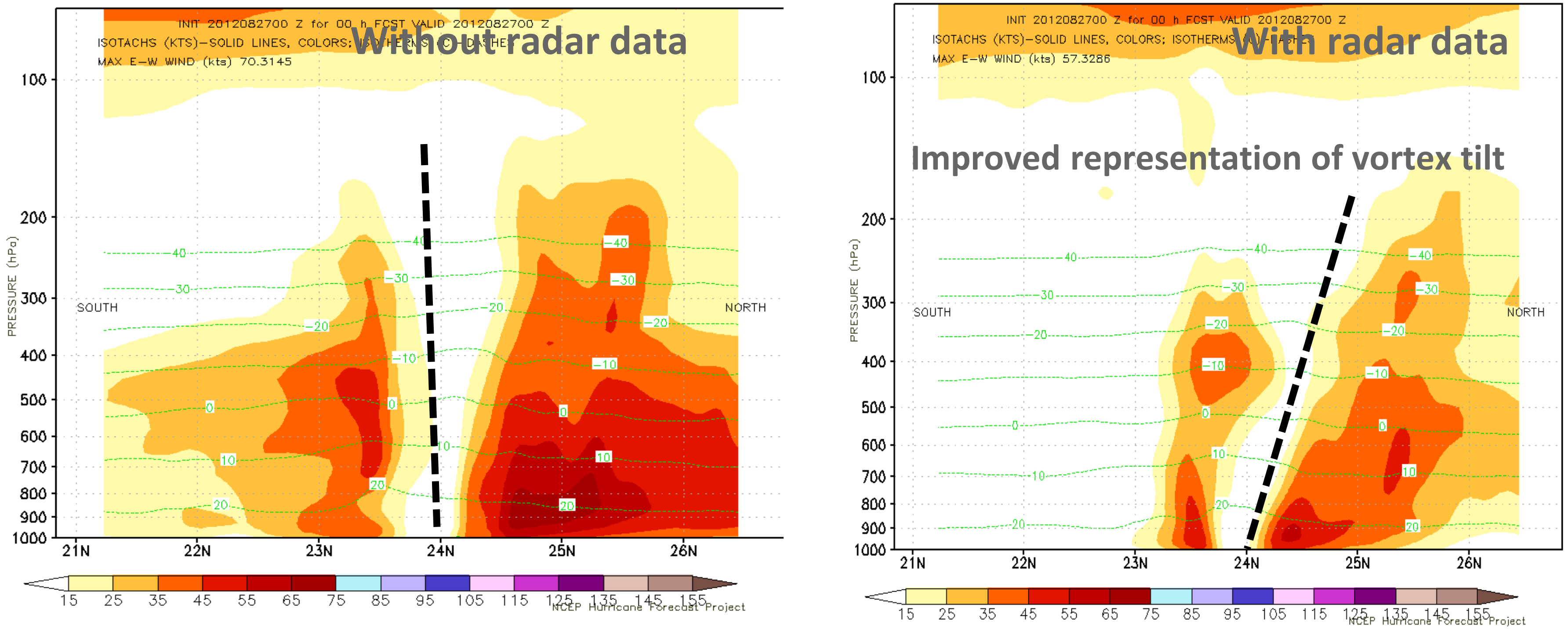
Hurricane Harvey (2017)

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



IFEX FORECASTS: Assimilation of data into numerical models

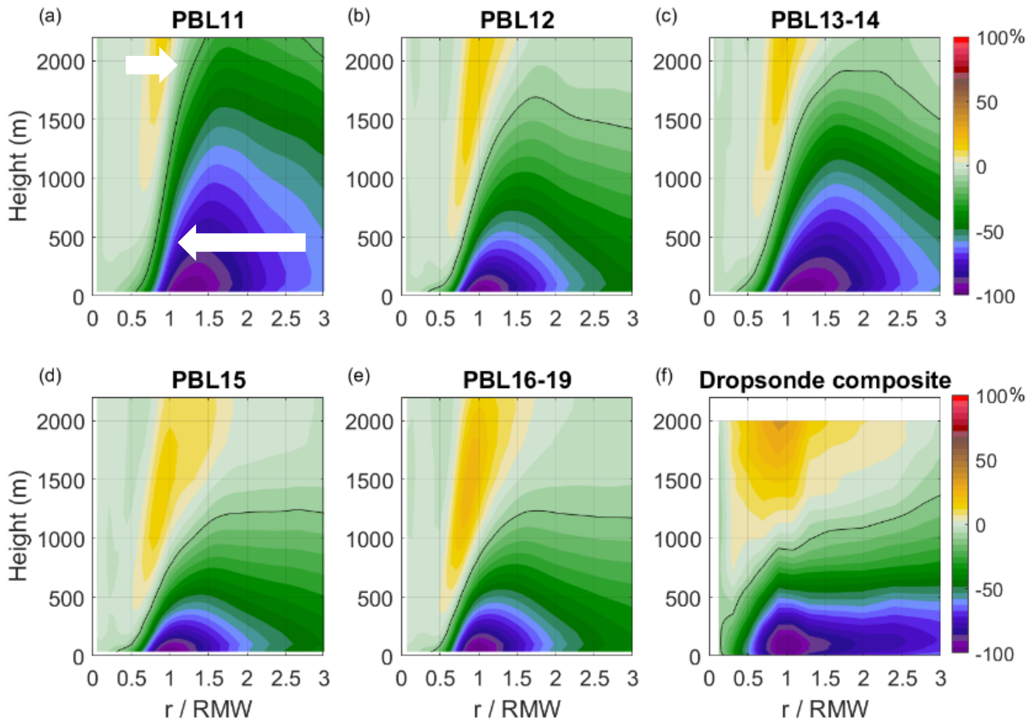
Vertical cross section of wind speed in Isaac (2012) at start of model forecast



IFEX FORECASTS: Model evaluation

Sensitivity of radial wind to mixing processes in low levels

Radial inflow for different HWRF model configurations from 2011-2019

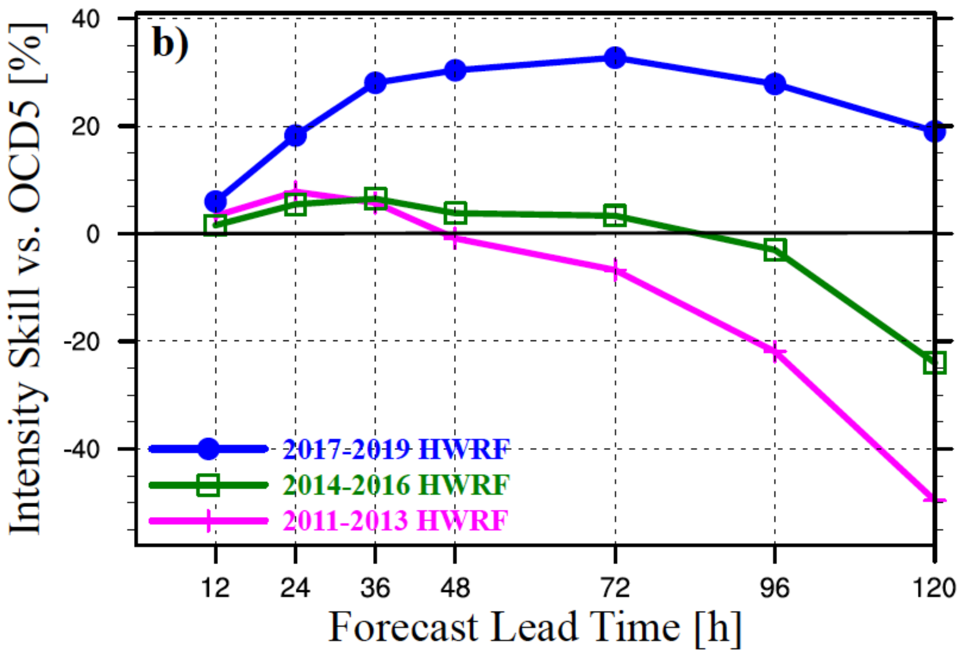


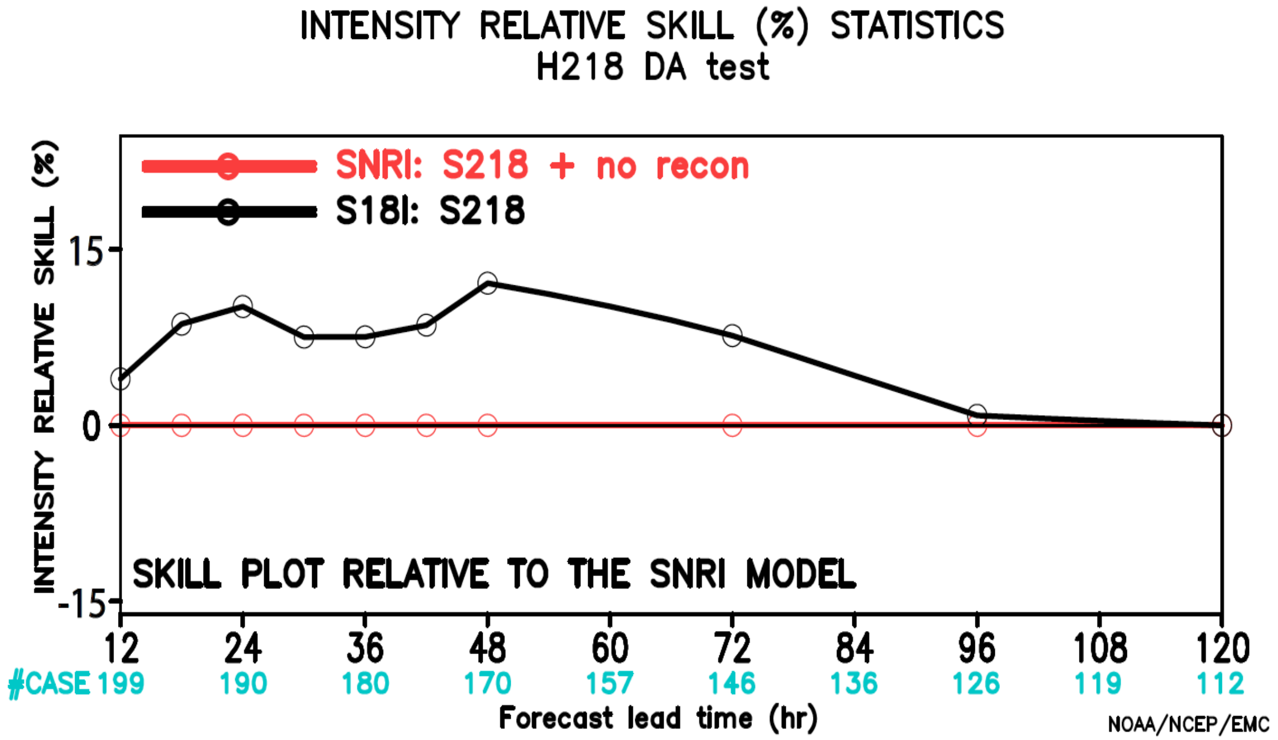
Zhang et al. 2020

- 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

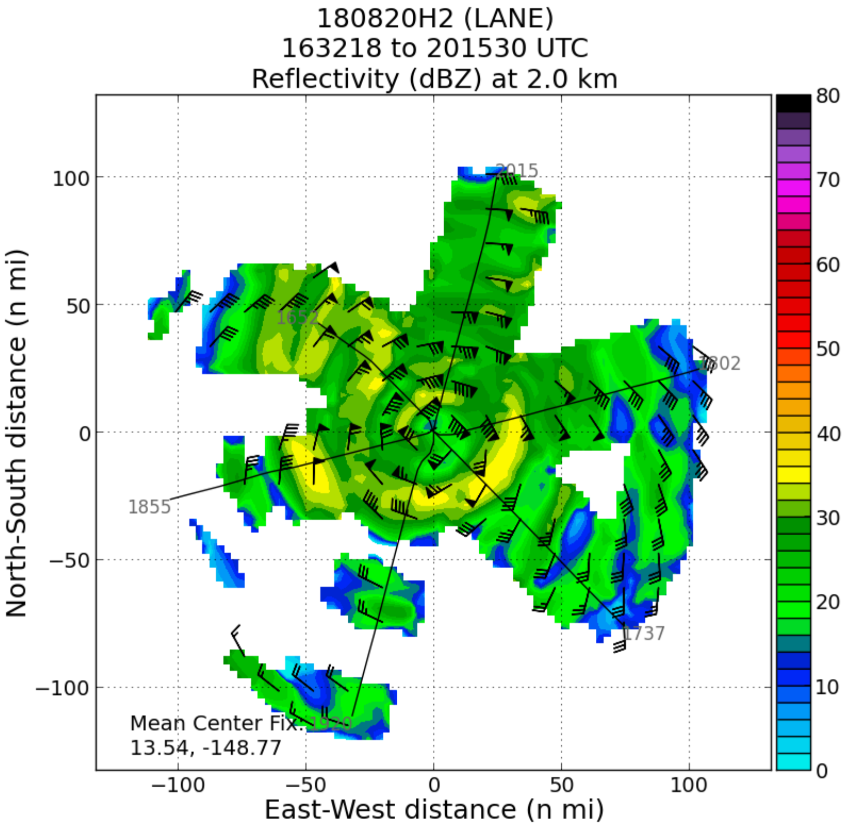


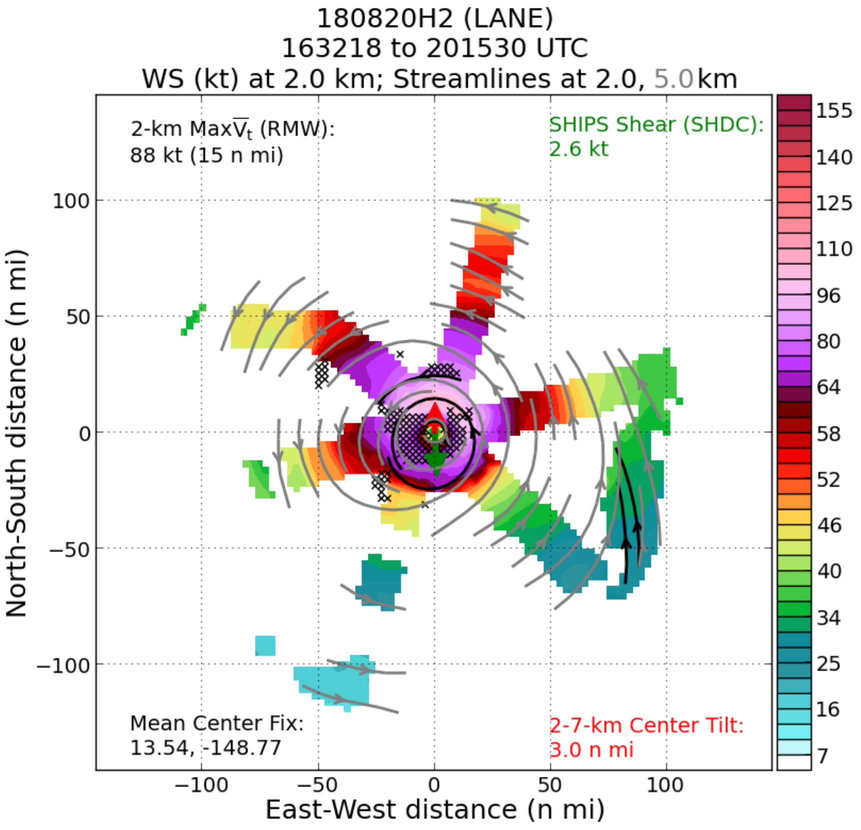


- HWRF intensity forecast improved steadily from 2011-2019
- Use of aircraft reconnaissance improves HWRF intensity forecast by ~15% at 48 h

IFEX NOWCASTS: Improved representation of TC structure

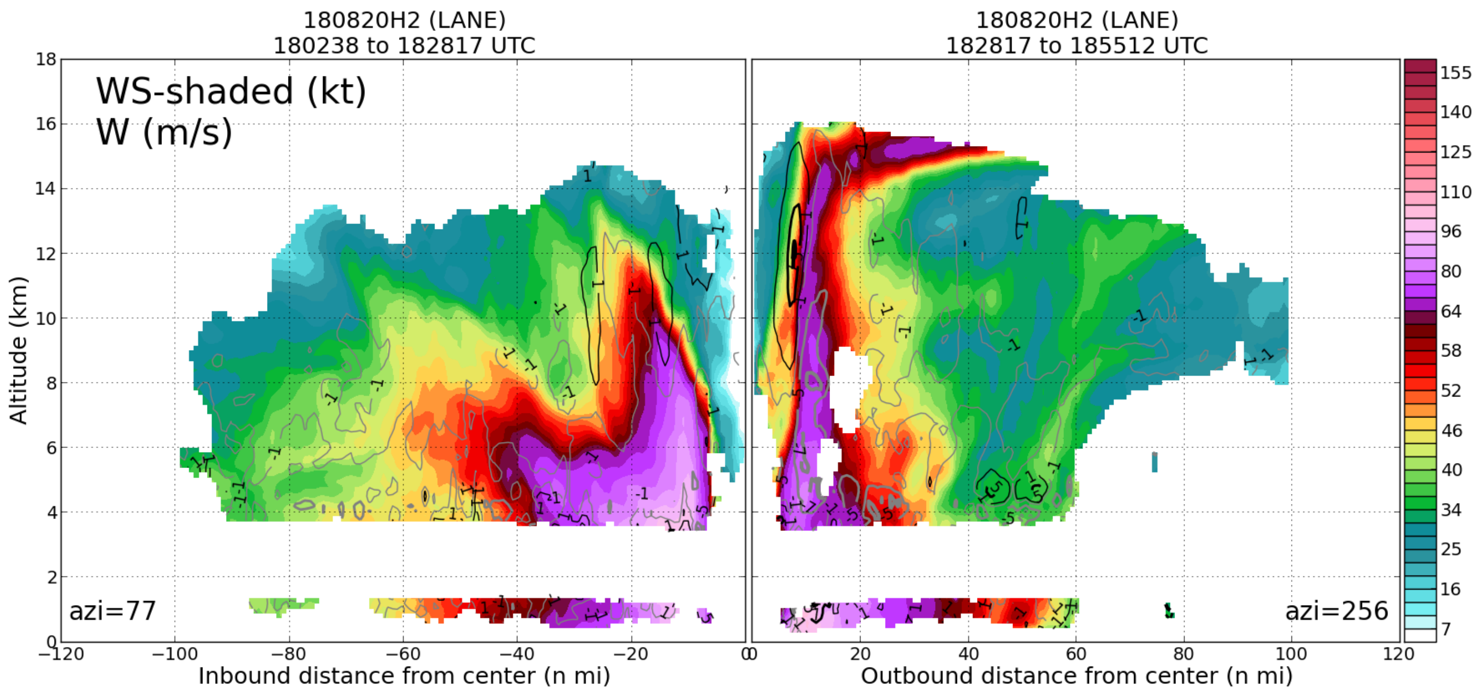
Real-time display of reflectivity and winds in Hurricane Lane





IFEX NOWCASTS: Improved representation of TC structure

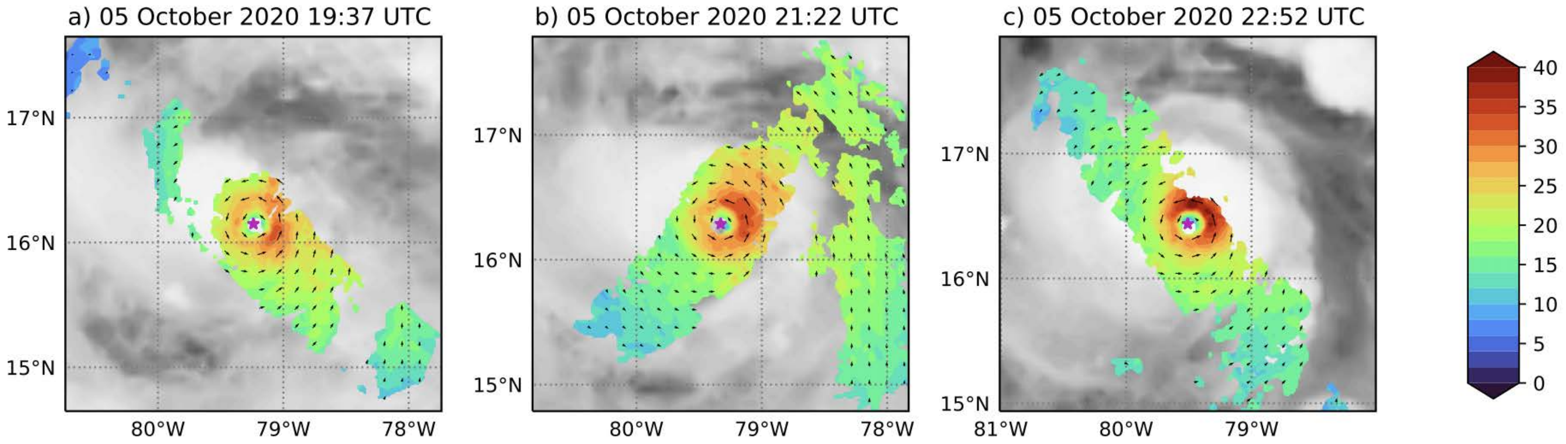
Real-time vertical cross section of wind speeds in Hurricane Lane



IFEX NOWCASTS: Improved representation of TC structure

Real-time incorporation of aircraft data into operational visualization tools

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



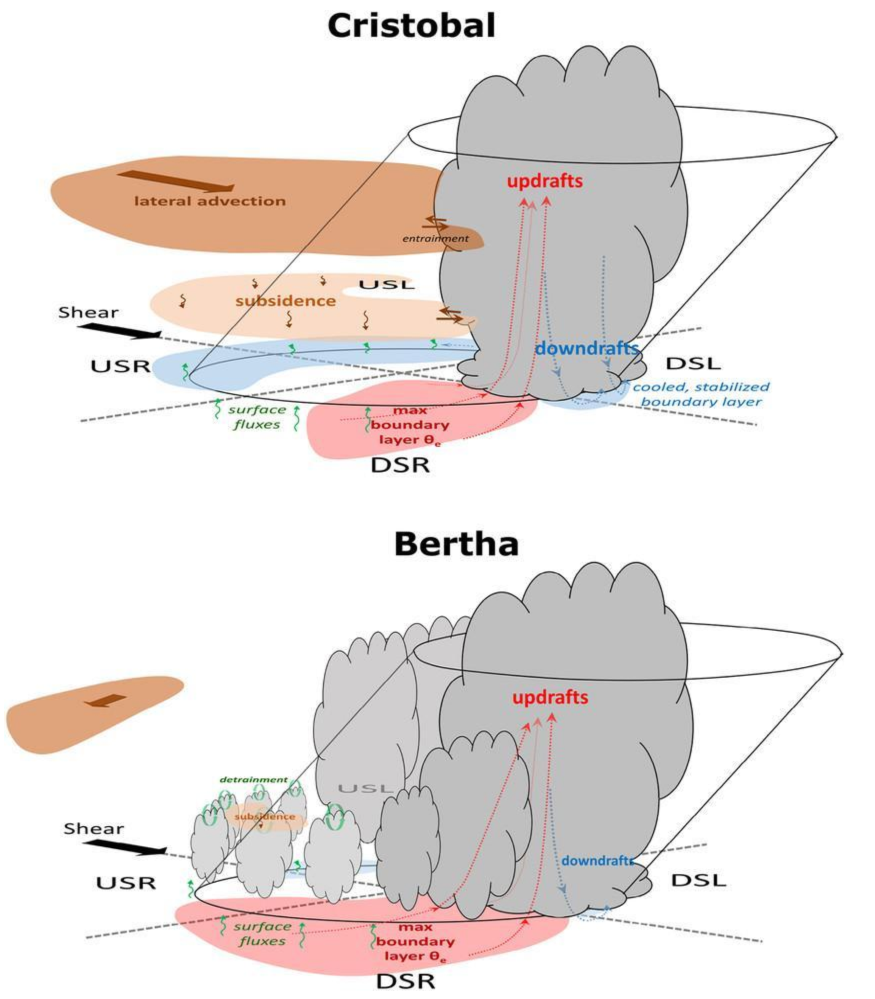
Sequence of passes in Delta (2020) while rapidly intensifying

IFEX RESEARCH: Improved understanding of intensity change

- Characterizing TC Inner-core Structure and Intensity Change
    - composite TDR analysis for intensifying vs. non-intensifying TCs (Rogers et al. 2013)
    - composites of flight-level data (Martinez et al. 2017)
    - shear-relative TC asymmetry (Reasor et al. 2013)
    - analyses of Hurricane Patricia (Rogers et al. 2017; Martinez et al. 2019)

IFEX RESEARCH: Improved understanding of intensity change

- Characterizing TC Inner-core Structure and Intensity Change
- TC Intensity Change in Vertical Wind Shear
  - Shear-relative evolution during RI of Edouard (2014) (Zawislak et al. 2016; Rogers et al. 2016)
  - Composited TDR data showing that convective bursts in the USL quadrant in intensifying v. non-intensifying (Wadler et al. 2018a)
  - Shear-relative distributions of RH, theta-e, stability in PBL (Nguyen et al. 2017) and mid-troposphere (Zawislak et al. 2016)
  - Multi-scale interactions between convection, moistening, mass flux, and the vortex during Hermine RI (Rogers et al. 2020)



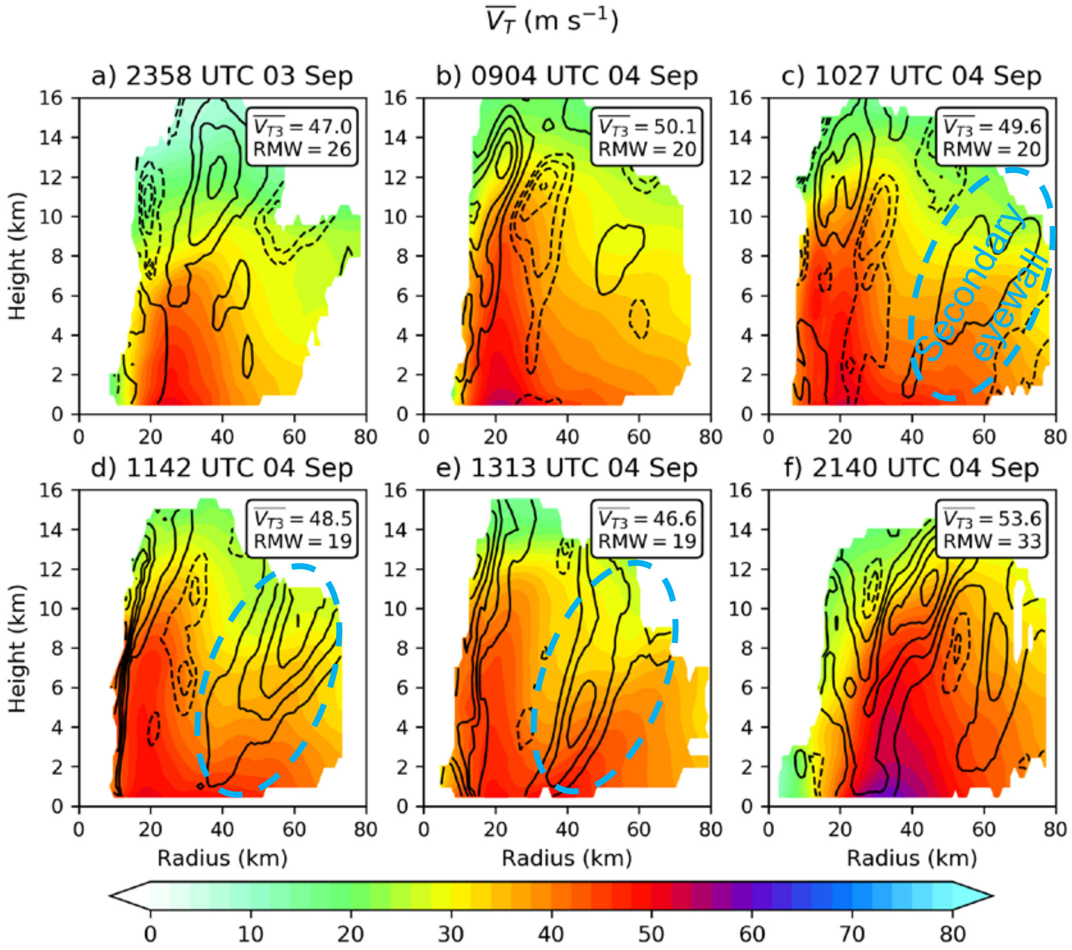
Nguyen et al. 2017

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
  - shear-relative low-level entropy distribution and importance of PBL recovery of downdraft cooled air for RI (Zhang et al. 2013; Zhang et al. 2017a; Wadler et al. 2020)
  - difference in upshear fluxes between intensifying and non-intensifying TCs (Cione et al. 2013; Jaimes et al. 2015; Zhang et al. 2017a; Wadler et al. 2018b; Nguyen et al. 2019; Zhang and Rogers 2019)
  - stronger and more symmetric PBL inflow in intensifying TCs v. non-intensifying (Zhang et al. 2017b; Zhang and Rogers 2019)
  - PBL structure of a landfalling storm (Alford et al. 2020)

IFEX RESEARCH: Improved understanding of intensity change

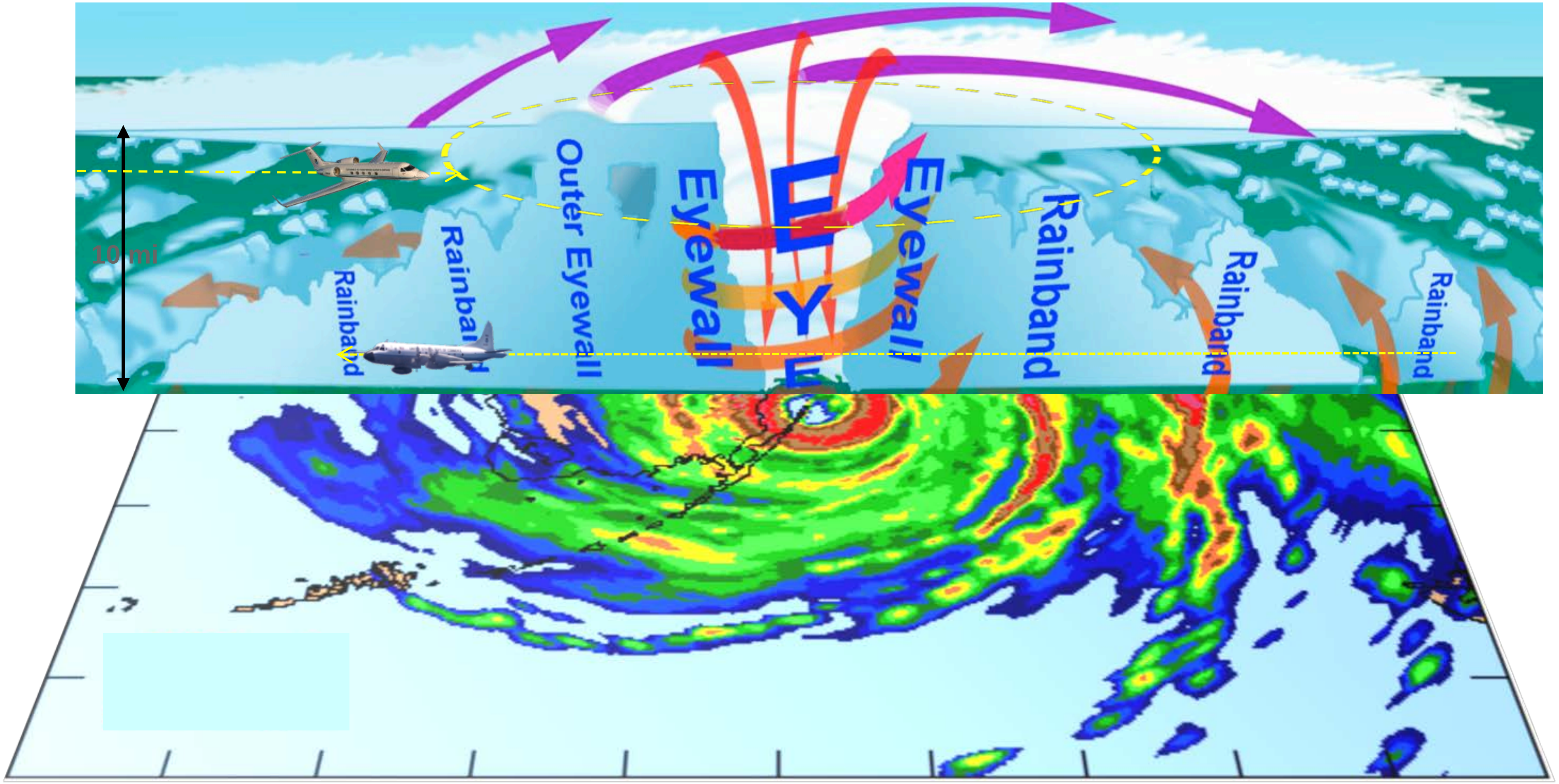
- Characterizing TC Inner-core Structure and Intensity Change
- TC Intensity Change in Vertical Wind Shear
- Boundary Layer Processes and Air-sea Interactions
- Secondary Eyewall Formation and Eyewall Replacement Cycles
  - SEF: mesoscale descending inflow jet in the stratiform rain region (Didlake et al. 2018)
  - SEF: axisymmterizing vortex Rossby waves (Dougherty et al. 2018; Guimond et al. 2020)
  - SEF: contributions from both (Fischer et al. 2020)
  - ERC: storms don't necessarily weaken (Dougherty et al. 2020) but can even rapidly intensify (Fischer et al. 2020)
  - ERC: convective asymmetries (Didlake et al. 2017, 2018)



Fischer et al. 2020

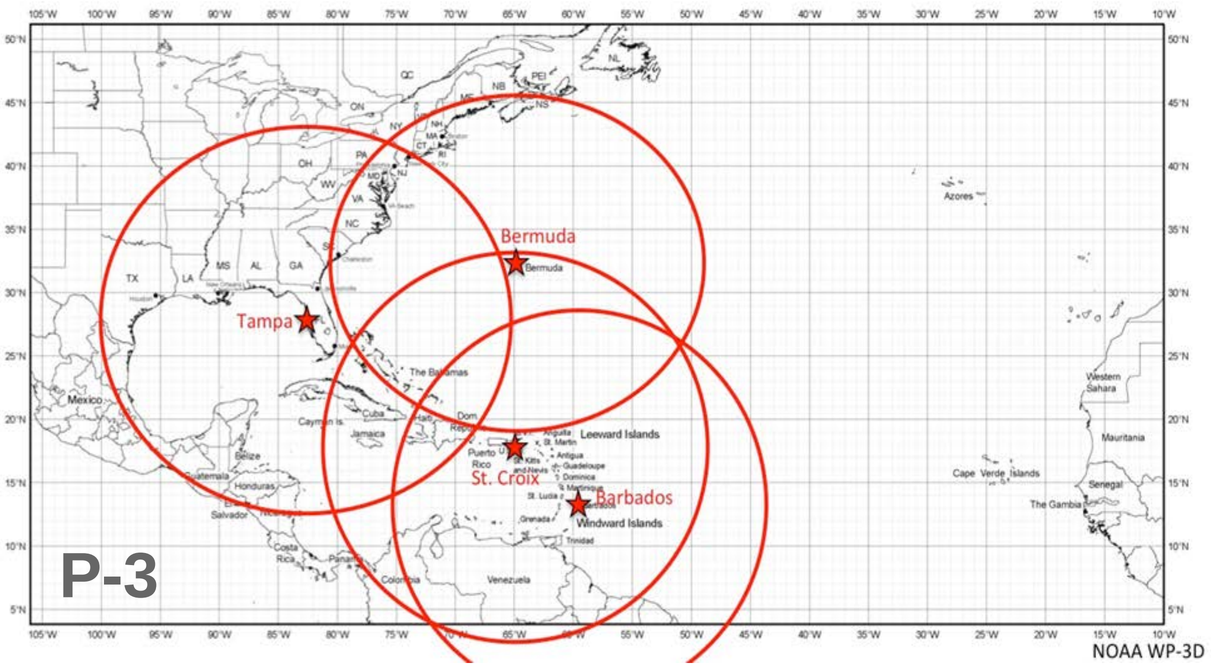
3. Flight profiles

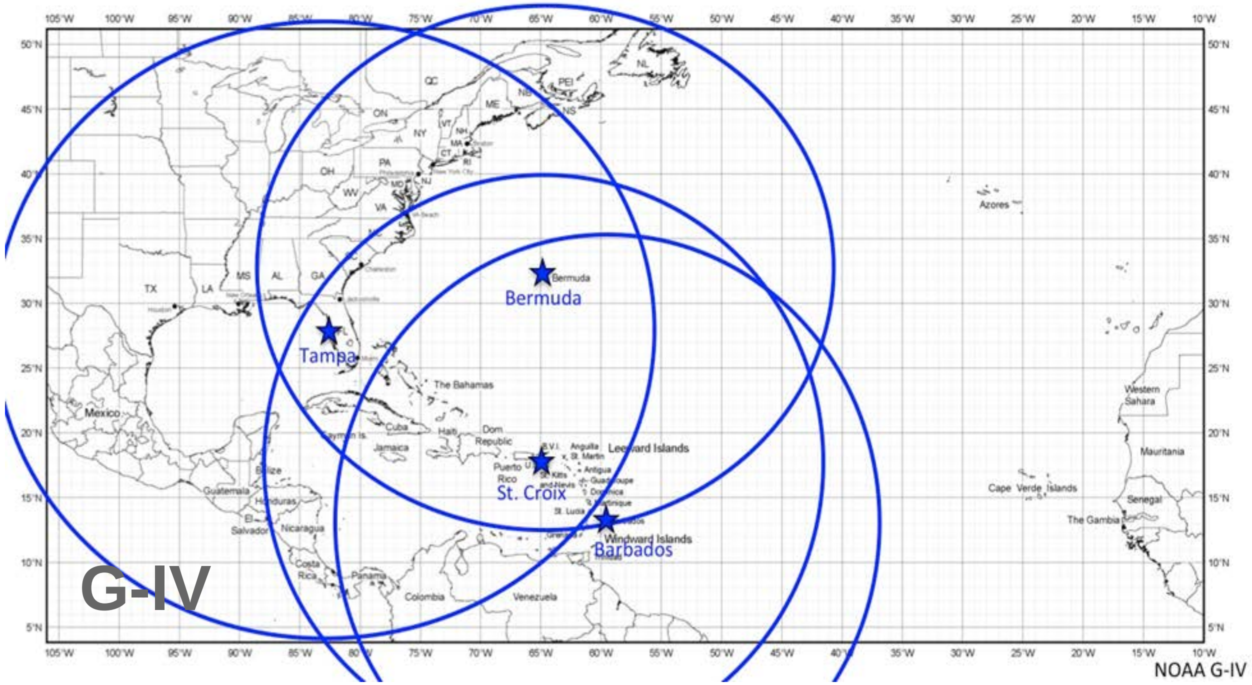
Aircraft sampling of TCs



P-3 and G-IV Atlantic bases of operations

Assuming 2 hours of on-station time





Typical flight patterns

P-3

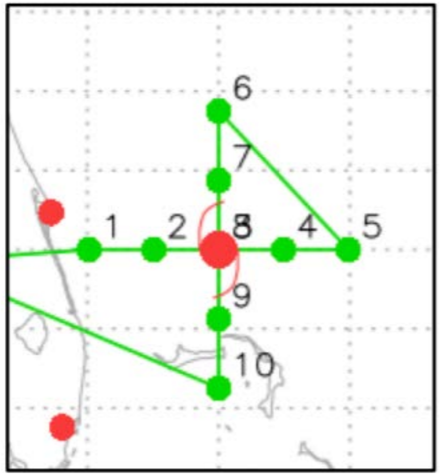
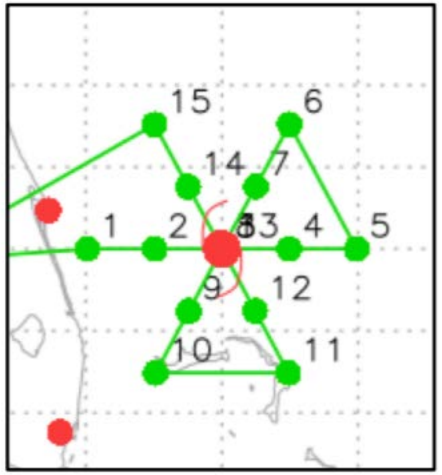
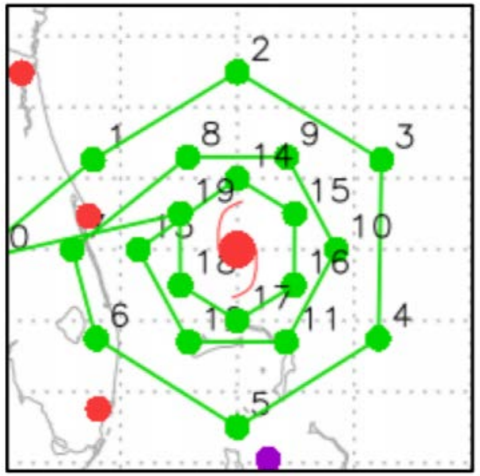


Figure-4

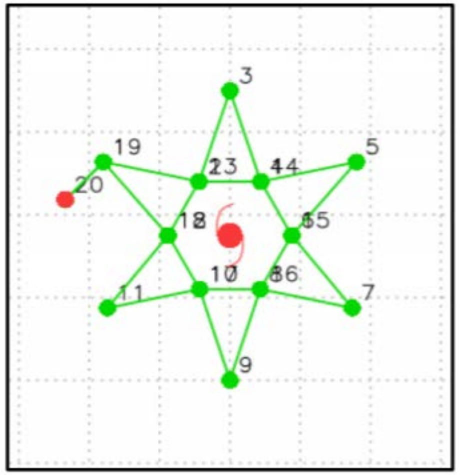


Butterfly

G-IV



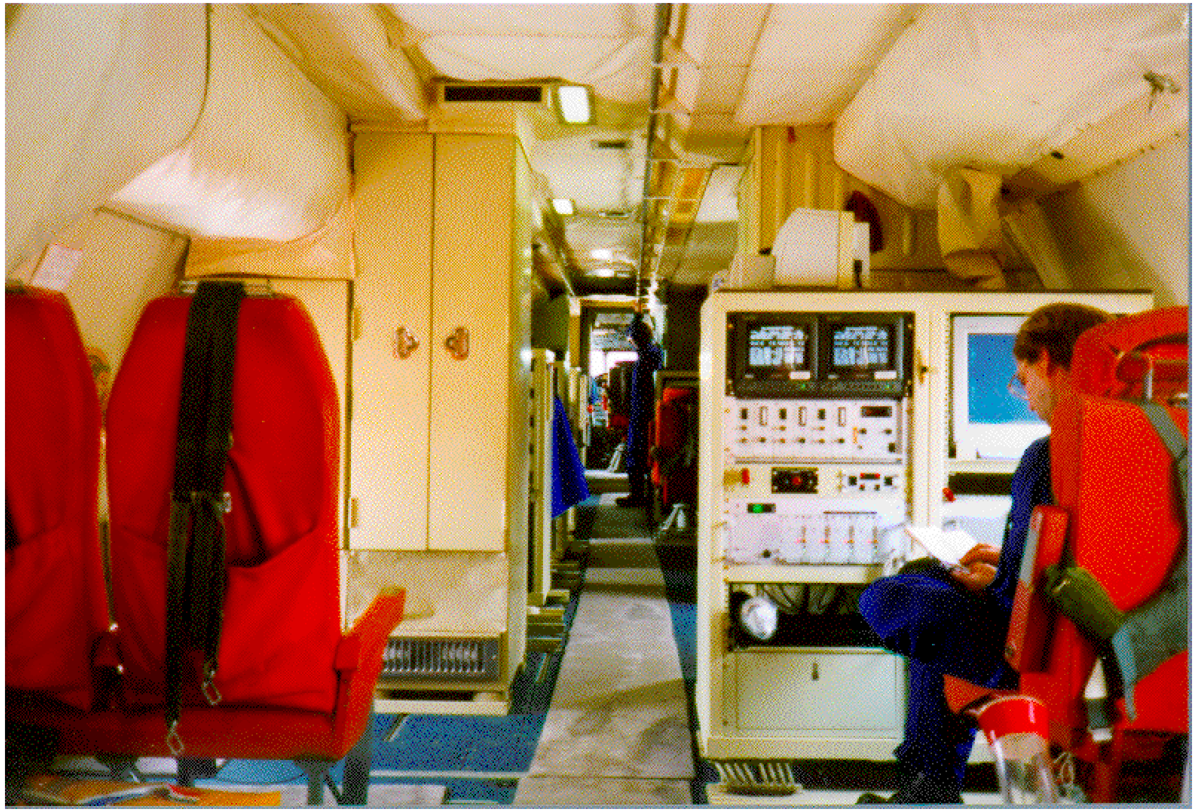
Circumnavigation



Star

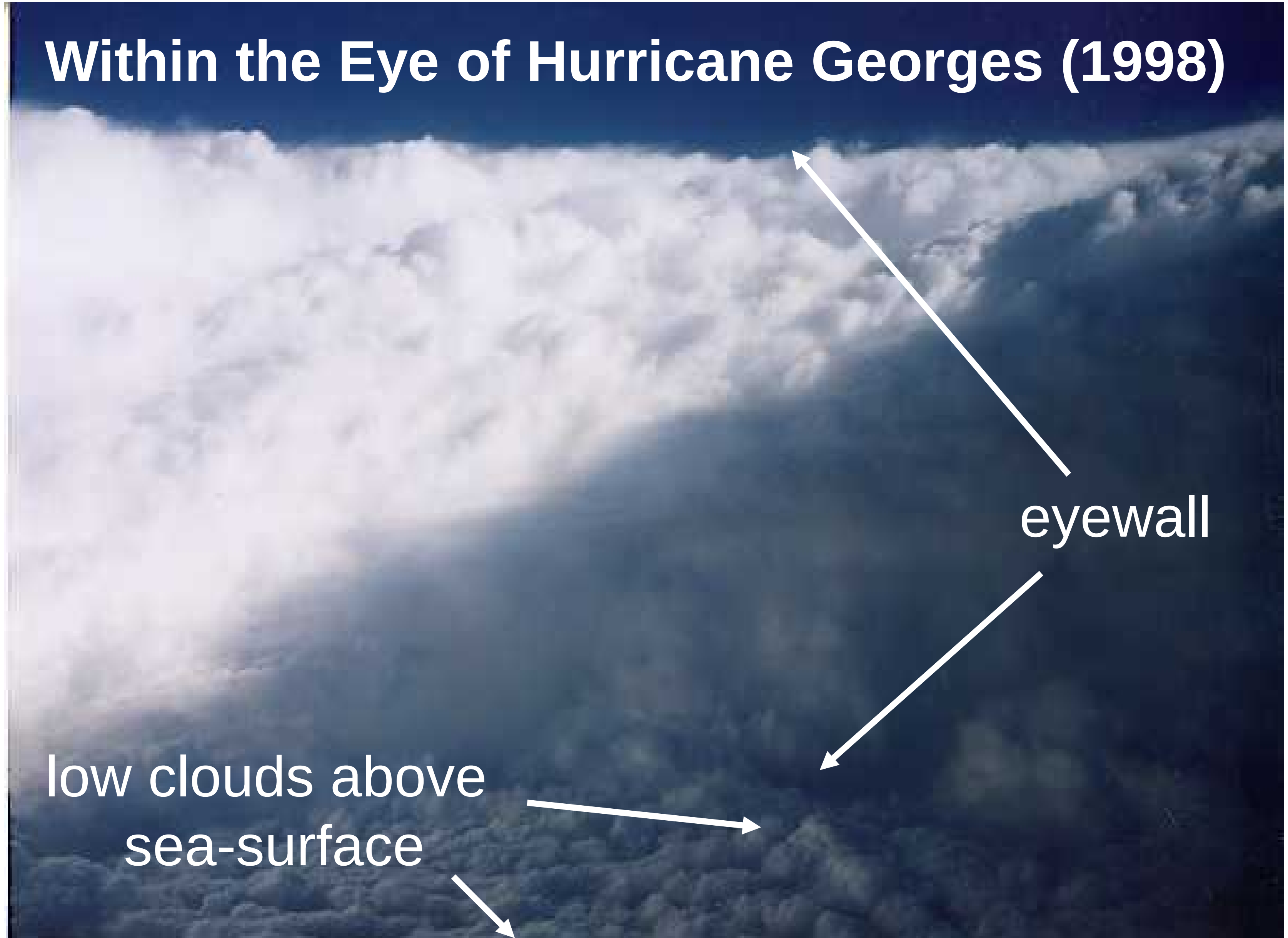
4. Views from the aircraft

Inside the P-3 Aircraft



Inside the G-IV Aircraft

Dropsonde release on P-3


Within the Eye of Hurricane Georges (1998)
eyewall
low clouds above
sea-surface

Low-level flight

Stadium effect

5. Toward the future

- Over the past several years there have been *multiple billion dollar TC-related disasters* (NOAA/NCEI)
- 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) are responsible for most deaths (Rappaport 2000)
- **Emphasizes the importance of hazards**
- Almost every one of these storms had *at least one RI period*

Storm (Year)	Landfall Location	Rainfall [in]	Surge Inundation [ft]	Wind [kt]	US Tornadoes
Matthew (2016) [1]	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) [2]	Barbados	Unknown	Unknown	40	52
	St. Vincent	Unknown	Unknown	40	
	Texas[#]	**60.58**	10	**115**	
Irma (2017) [3]	Barbuda	Unknown	8	***155***	25
	St. Martin	Unknown	Unknown	***155***	
	British V. I.	Unknown	Unknown	***155***	
	Bahamas	Unknown	Unknown	**135**	
	Cuba	**23.90**	10	***145***	
	Florida Keys	6–10	8	**115**	
	Marco Island, FL	**21.66**	10	**100**	
Maria (2017) [4]	Dominica	**22.80**	Unknown	***145***	3*
	Puerto Rico	**37.90**	9	**135**	
Florence (2018) [5]	North Carolina	**35.93**	11	80	44
Michael (2018) [6]	Florida	11.45	14	***140***	16
Dorian (2019) [7]	Barbados	Unknown	Unknown	45	21
	St. Lucia	Unknown	Unknown	45	
	St. Croix	Unknown	Unknown	65	
	St. Thomas	Unknown	Unknown	70	
	Bahamas[^]	**22.84**	20[+]	***160***	
	North Carolina	15.21	7	85	

Zawislak et al. 2021

5. Toward the future

- 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***

THANK YOU

QUESTIONS?

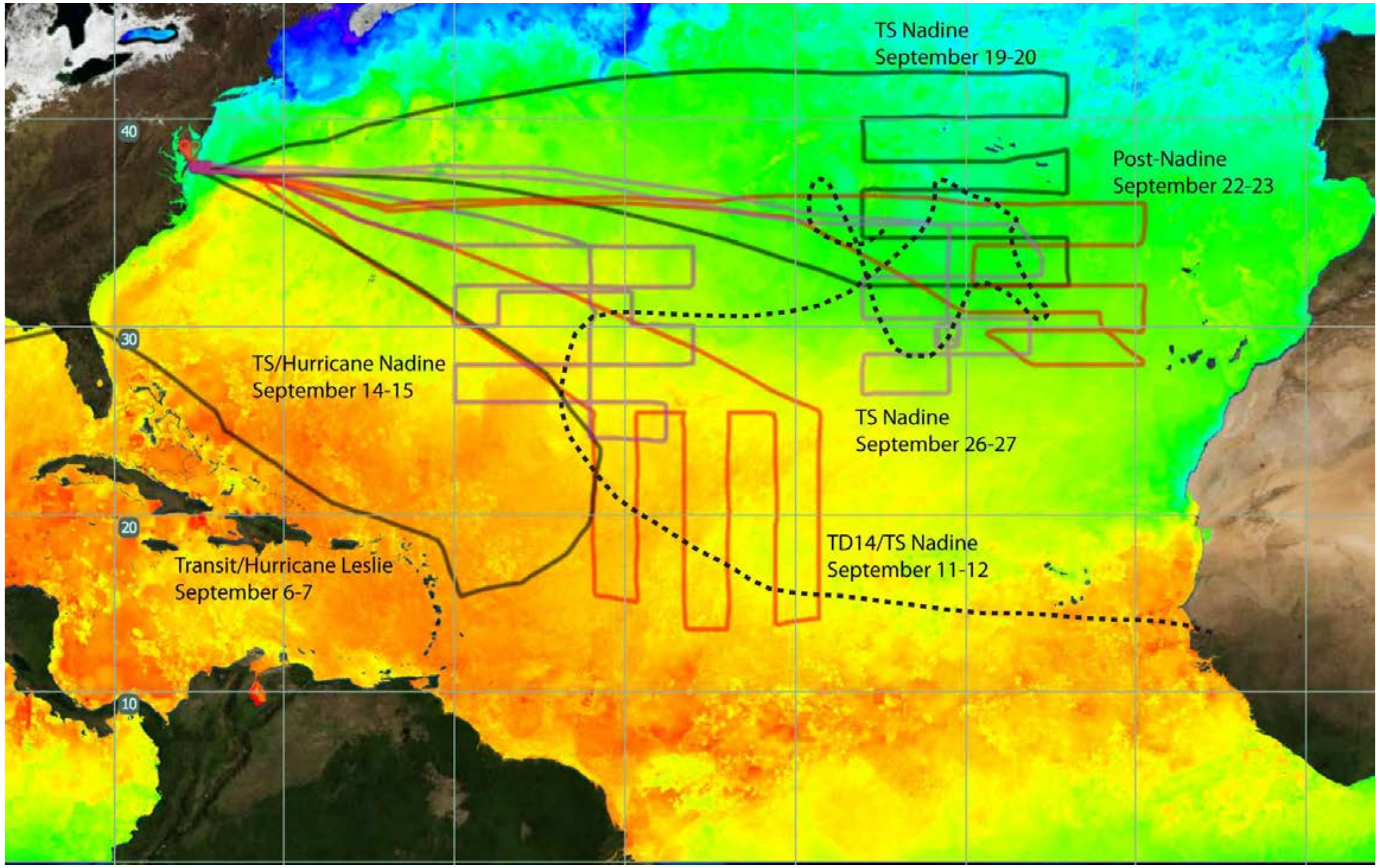
New Airborne Platforms

Global Hawk Aircraft (Uncrewed Aerial System)

- can stay airborne for >24 h, compared with 8 h for P-3 and G-IV

New Airborne Platforms

Long range of Global Hawk



(Hurricane and Severe Storm Sentinel, HS3, from 2012)