Overview of the Tropical Cyclone Rapid Intensification (TCRI) Program

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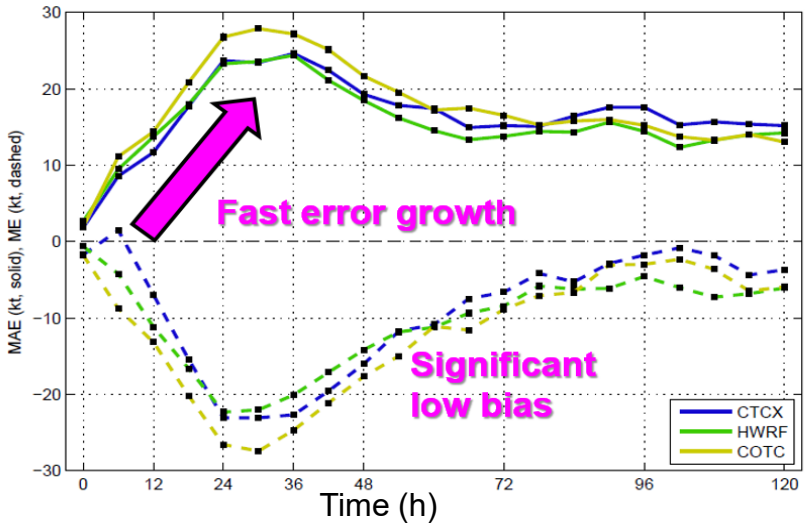
Tropical Cyclone Rapid Intensification Program
ONR Departmental Research Initiative

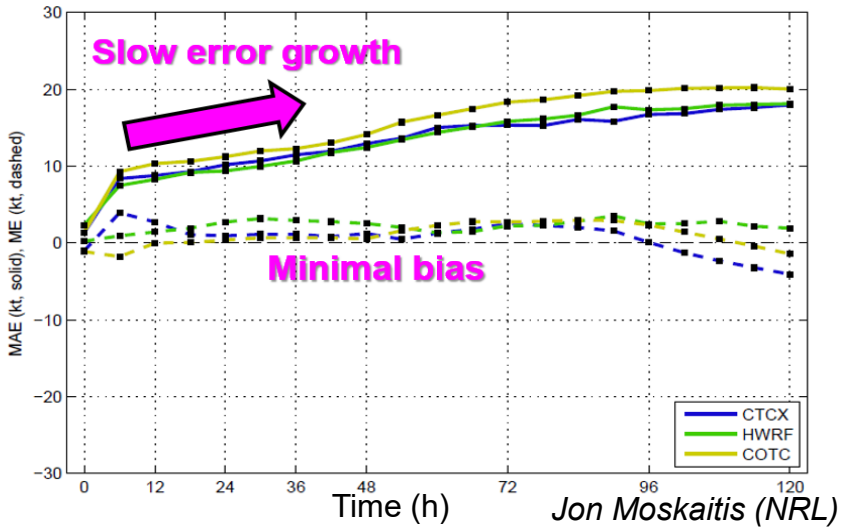
TCRI PIs and Institutions

- *James Doyle (NRL)*
- *Robert Rogers & Jason Dunion (NOAA HRD)*
- *Brian Tang (U. Albany) & George Bryan (NCAR)*
- *David Richter (Notre Dame)*
- *Sharan Majumdar & Dave Nolan (U. Miami)*
- *Dave Raymond & Zeljka Fuchs Stone (New Mex. Tech.)*
- *Michael Bell (CSU)*
- *Steve Guimond (Hampton Univ.)*
- *Ralph Foster (U. Washington)*
- *Chanh Kieu (U. Indiana)*
- *Zhien Wang (Stony Brook Univ.)*
- *Russ Elsberry (UCCS)*
- *Tony Wimmers (U. Wis / SSEC)*

Intensity MAE and ME: Observed RI 0-24 h



Intensity MAE & ME: No observed RI 0-24 h



Jon Moskaitis (NRL)

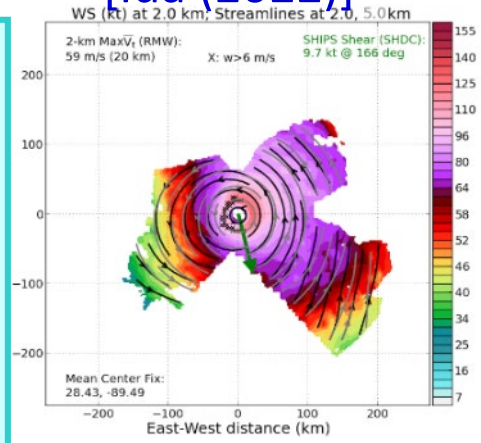
Rapid Intensification is an increase in max. sustained winds of at least 30 kts/24h

- ONR Tropical Cyclone Rapid Intensification (TCRI) Program is focused on identifying key processes and predictability barriers governing the rapid intensification (RI) of TCs including: i) Onset of RI, ii) PBL processes, and iii) cloud microphysics processes
- Make use of high-resolution models, LES, data assimilation systems
- Improve models including Navy's COAMPS-TC and products
- In collaboration with *NOAA IFEX (2020) and APHEX (2021-2023)*

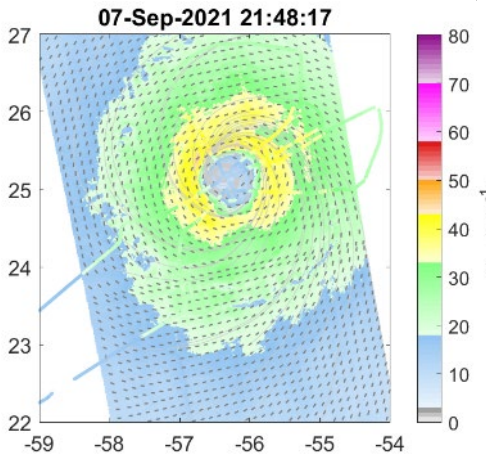
Tropical Cyclone Rapid Intensification Program
Observations Collected

- TCRI P3 flight hours and extra drops on P3 & G-IV
- NOAA APHEX collaboration
- 2020: Sally, Teddy, Delta
  - 159 dropsondes
- 2021: Fred, Grace, Henri, Ida, Larry, Sam
  - 257 dropsondes
- 2022: Earl, Fiona, Ian, Julia, Lisa
  - 266 dropsondes
  - Windborne balloons
- 2023: Franklin, Idalia, Lee, Nigel, Tammy
  - 112 dropsondes

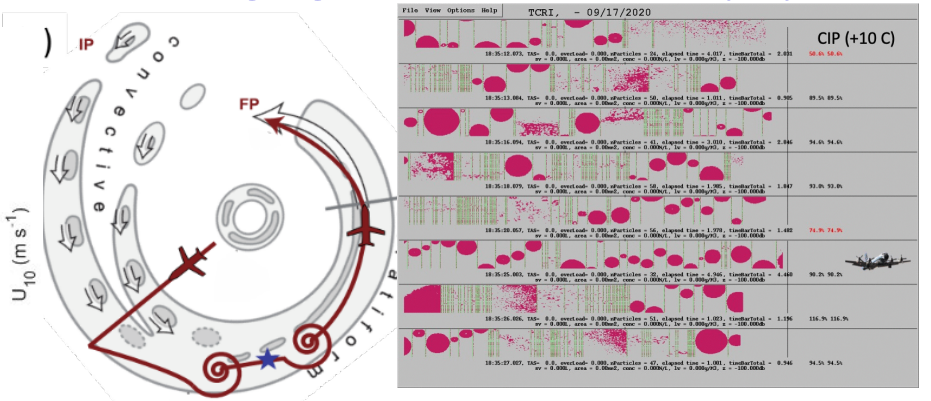
P-3 Tail Doppler Radar [Ida (2022)]



SAR [Larry (2021)]

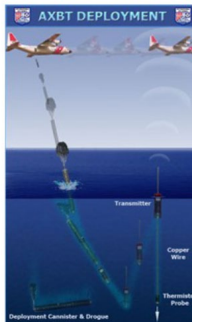


Cloud Imaging Probe (CIP) Microphysics



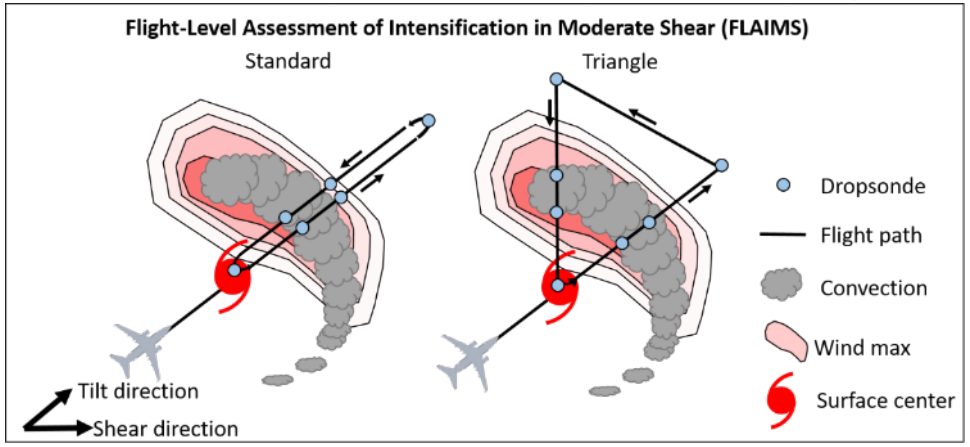
Hydrometeors transition from water to ice as the P-3 flies through and above the freezing level.

Dropsondes and AXBTs



Dropsonde: *Winds, press., height, temp, RH*
AXBT: *Ocean temperature, salinity, depth*

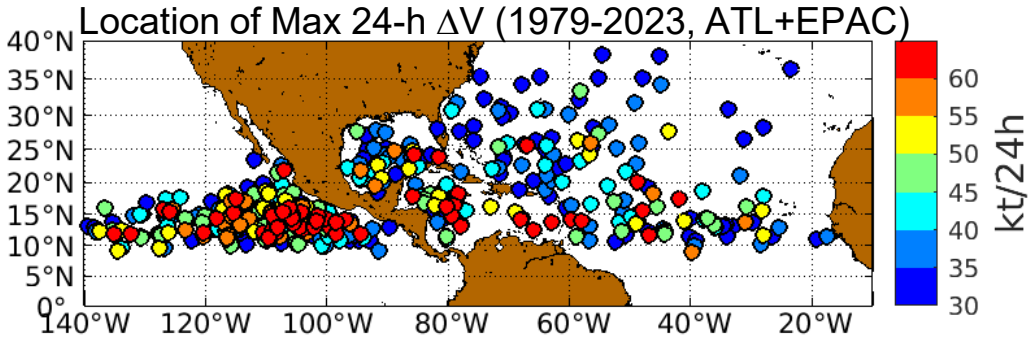
Module for Asymmetrically Intensifying TCs



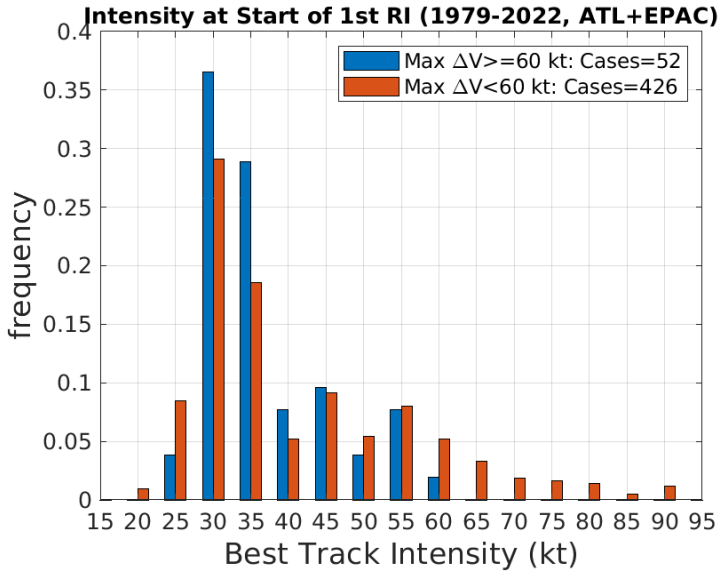
FLAIMS (Flight-Level Assessment for Intensification in Moderate Shear) is designed to repeatedly sample region of maximum winds of an asymmetrically intensifying TC.

RI and Extreme RI Characteristics
TCRI Observing Highlights

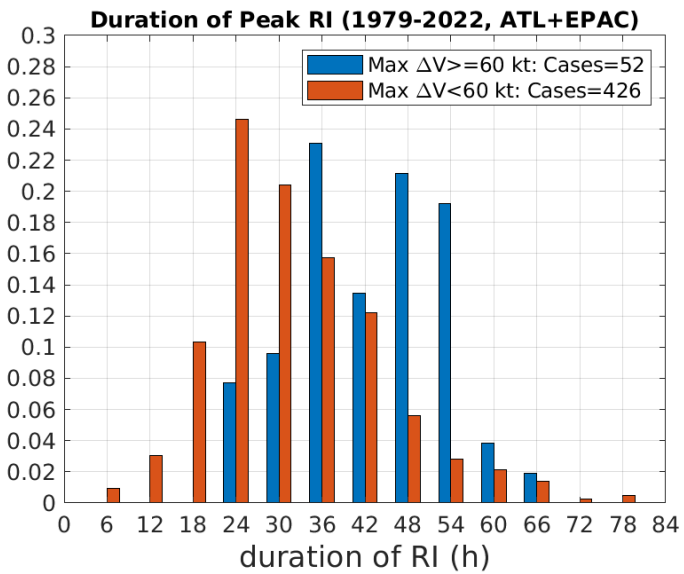
Peak Intensification Rate and Location



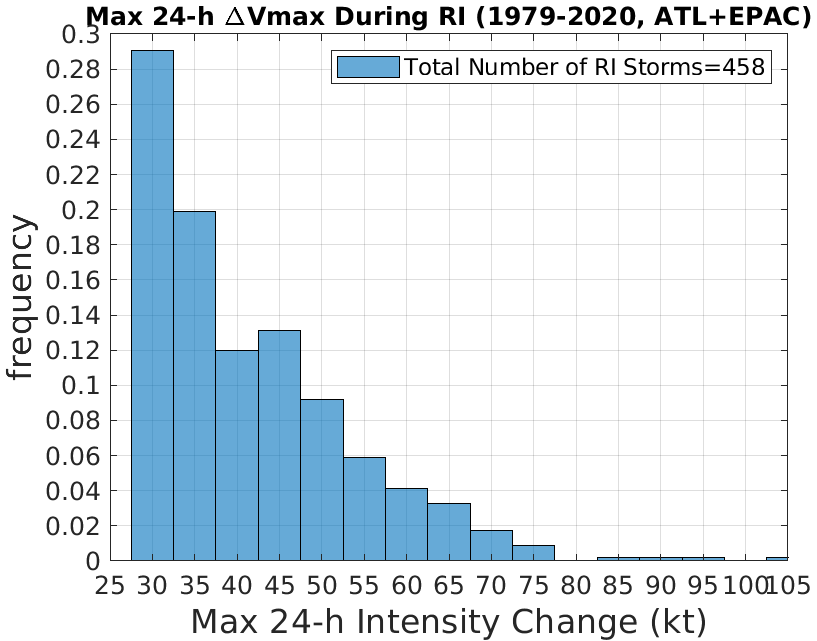
1st RI Onset Intensity



Duration of RI



Frequency of Peak Intensification Rate

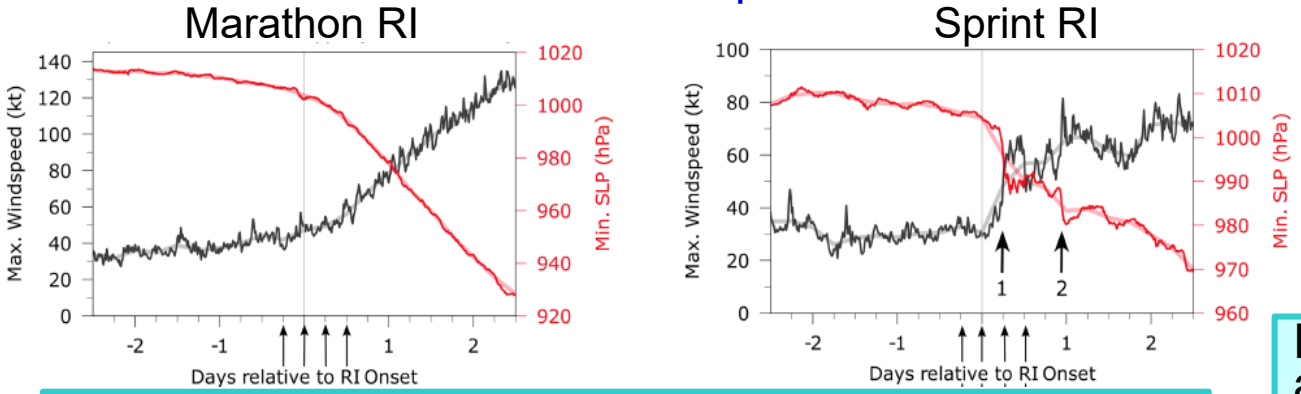


- 11% of RI storms (4% of all storms) have peak intensification rates of at least 60 kt per 24 h, and in the Atlantic basin these are found nearly exclusively in the Main Development Region and the Caribbean.
- **Extreme RI** events at onset are similar to ordinary RI events (at weak intensity, soon after genesis), but **Extreme RI** events last longer and the rate of intensification accelerates when these TCs become hurricanes.

Stern (NRL)

Environmental Influences
Rapid Intensification

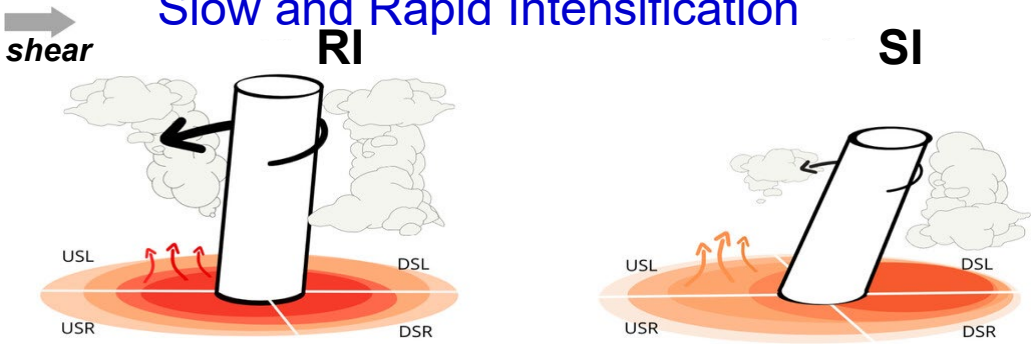
Two Modes of Rapid Intensification



Two modes of RI TCs identified in MPAS simulations

Judt, Rios-Berrios, Bryan (2023; MWR)

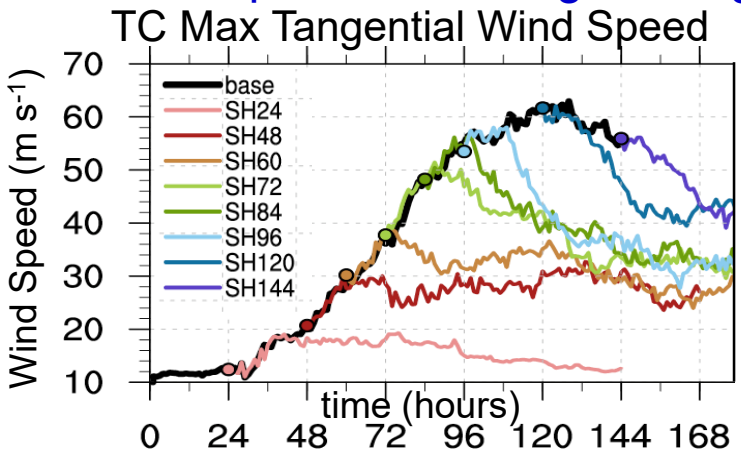
Slow and Rapid Intensification



RI TCs have a stronger, deeper, and more vertically aligned vortex with larger latent heat fluxes, deeper convection that is left of shear and upshear

Richardson, Torn, Tang (2022; MWR)

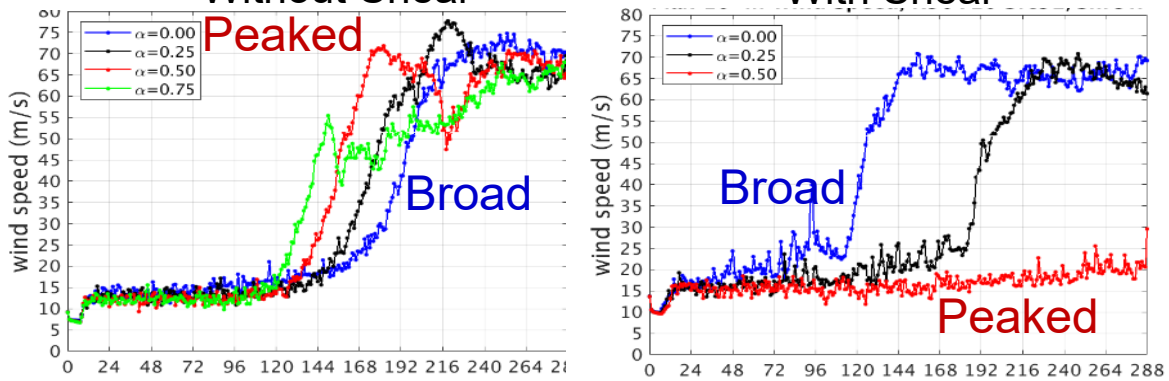
Shear Impact at Differing RI Stages



Vertical shear impact varies at different RI stages

Finocchio and Rios-Berrios (2022; JAS)

Sensitivity of RI Onset to Vertical Shear

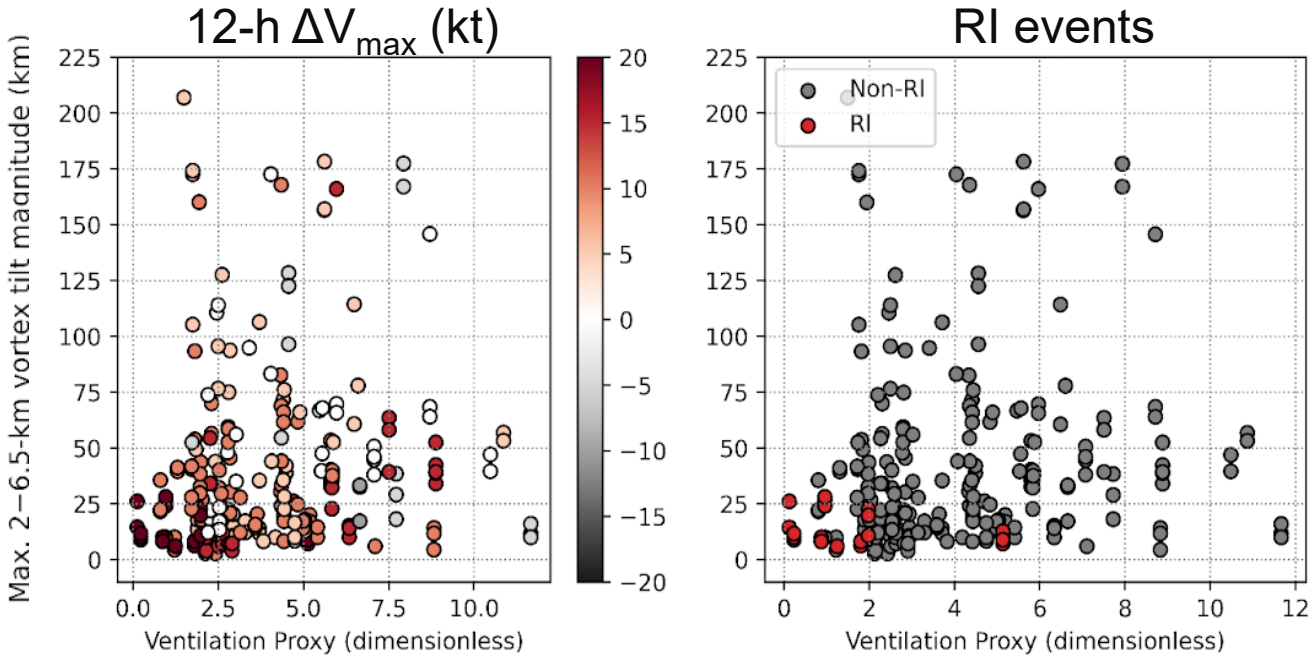


Without shear, RI onset is earlier for more peaked wind profiles; with shear, RI onset is earlier for broader vortices

Stern et al. (in prep 2024)

Vortex-Scale Characteristics at RI Onset
TCRI Research Highlights

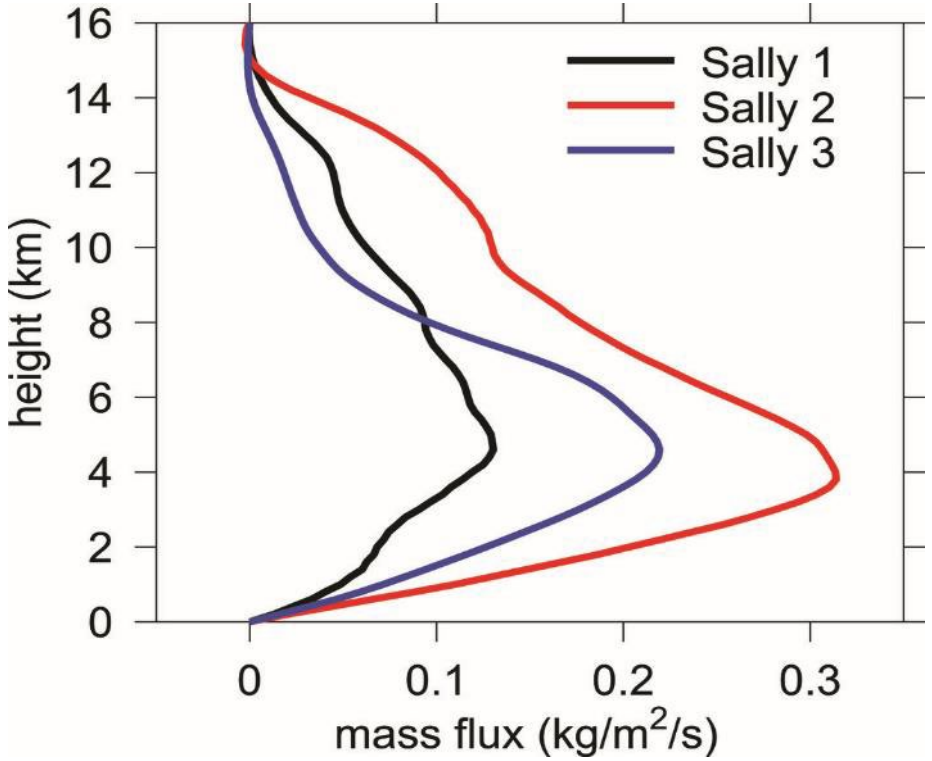
Joint Relationship Between Vortex Tilt, Ventilation, and Intensity Change



- Intensifying TCs concentrated in the low-tilt, low-ventilation region of parameter space
- RI cases mostly occur where tilt < 25 km, ventilation proxy < 2

Fischer et al. (2024; MWR)

Mass Flux for 3 G-IV Flights into Sally (2020)

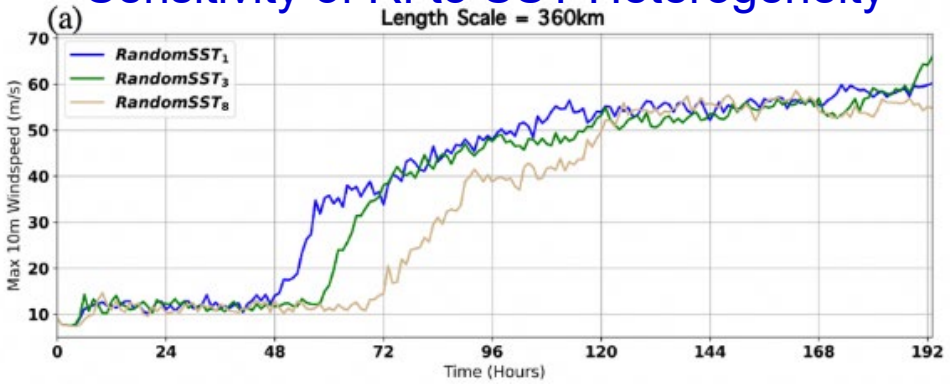


Analysis of Sally (2020) flights indicates that the midlevel vortex favors the formation of strong convection with a bottom-heavy mass flux by decreasing the stability.

Stone et al. (2023; MWR)

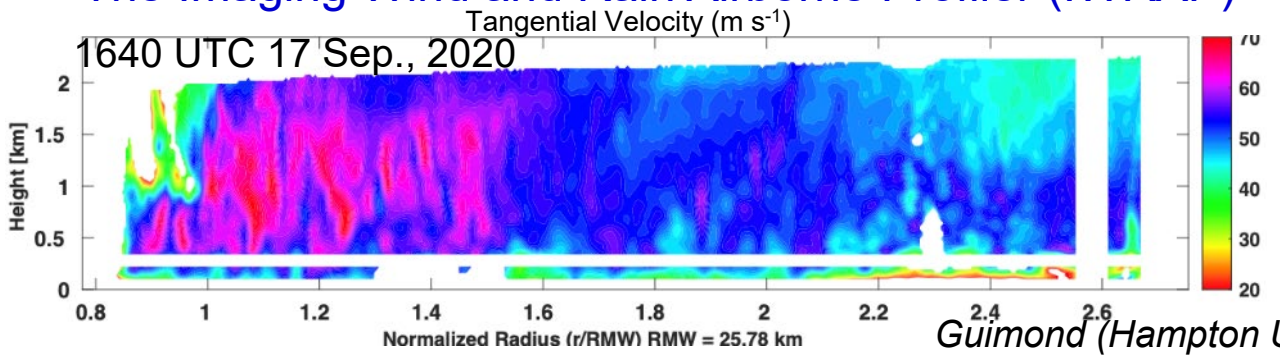
PBL Processes
Rapid Intensification

Sensitivity of RI to SST Heterogeneity



Oguejiofor, Wainwright, Rudzin, Richter (2023; JAS)

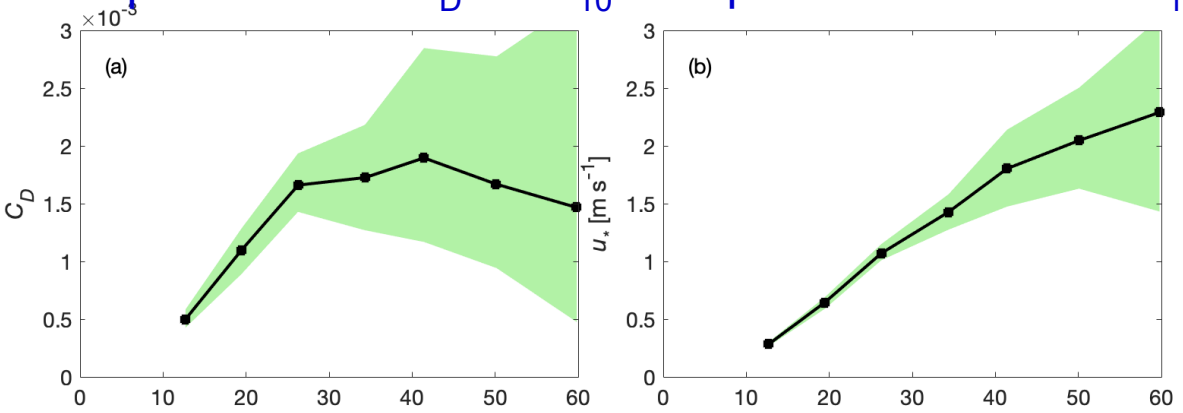
The Imaging Wind and Rain Airborne Profiler (IWRAP)



Guimond (Hampton U.)

IWRAP cross section through boundary layer of Hurricane Teddy (2020)

Dependence of C_D on U_{10} Dependence of U_* on U_{10}



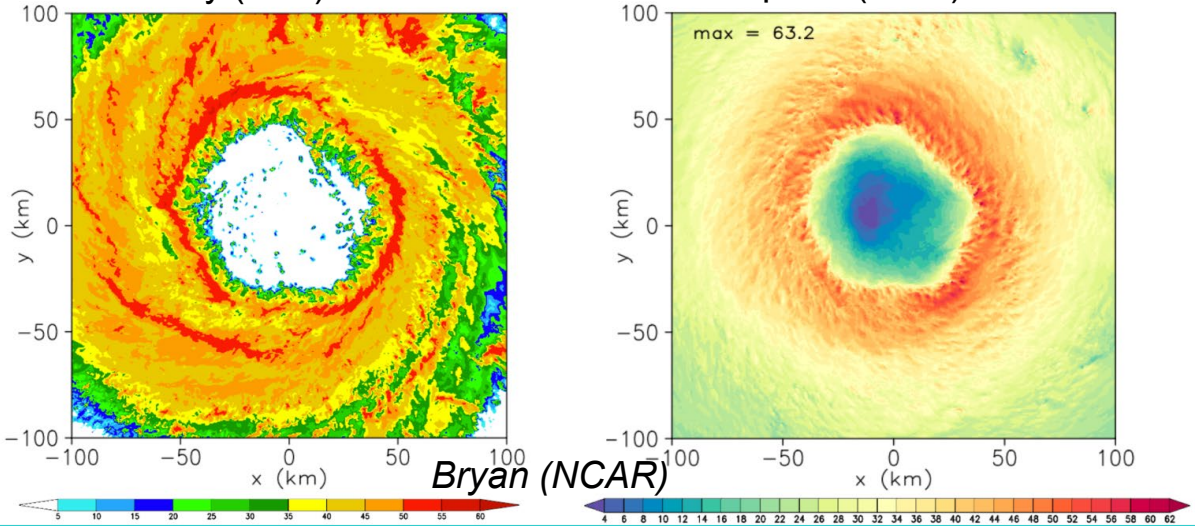
Richter et al. (2021; JAS)

C_D and U* computed from flux-profile method (1997-2018) indicate uncertainty in C_D, U_*, and the C_D "roll off"

LES Fine-Scale Turbulence Structure during RI

Reflectivity (dBZ) at z = 1 km

Wind speed (m s^{-1}) at z = 10 m



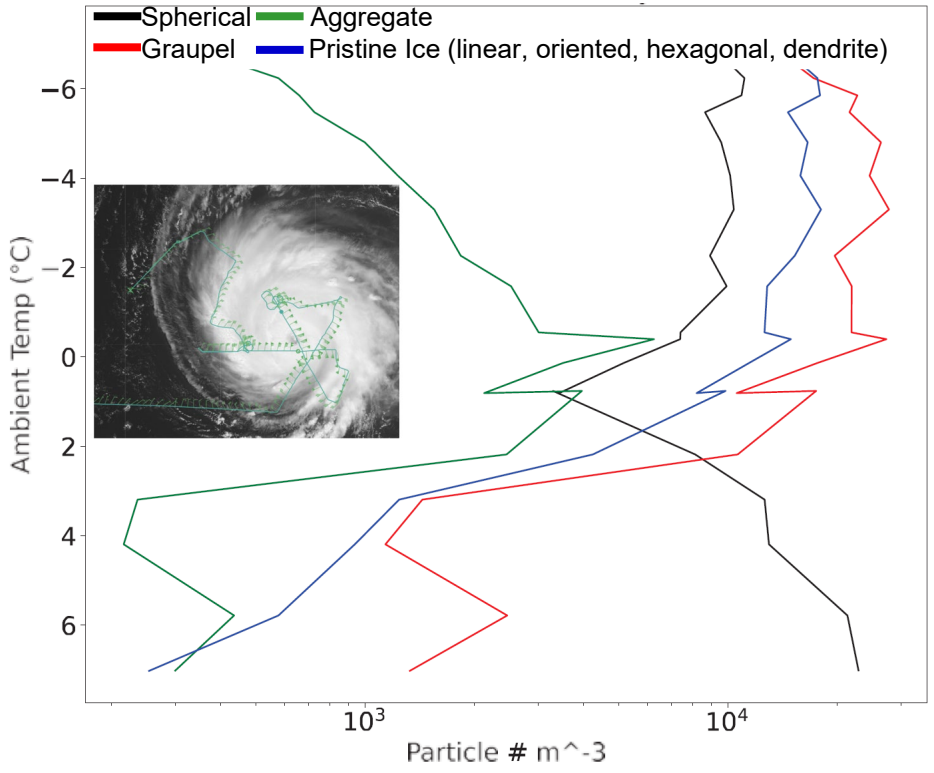
Bryan (NCAR)

RI is sensitive to PBL processes such as SST heterogeneity and surface fluxes including C_D and momentum exchange.

Coherent turbulent structures (IWRAP, SAR, LES) in PBL occur during RI and have implications for RI, structure, & impacts.

Cloud Processes
TCRI Observing Highlights

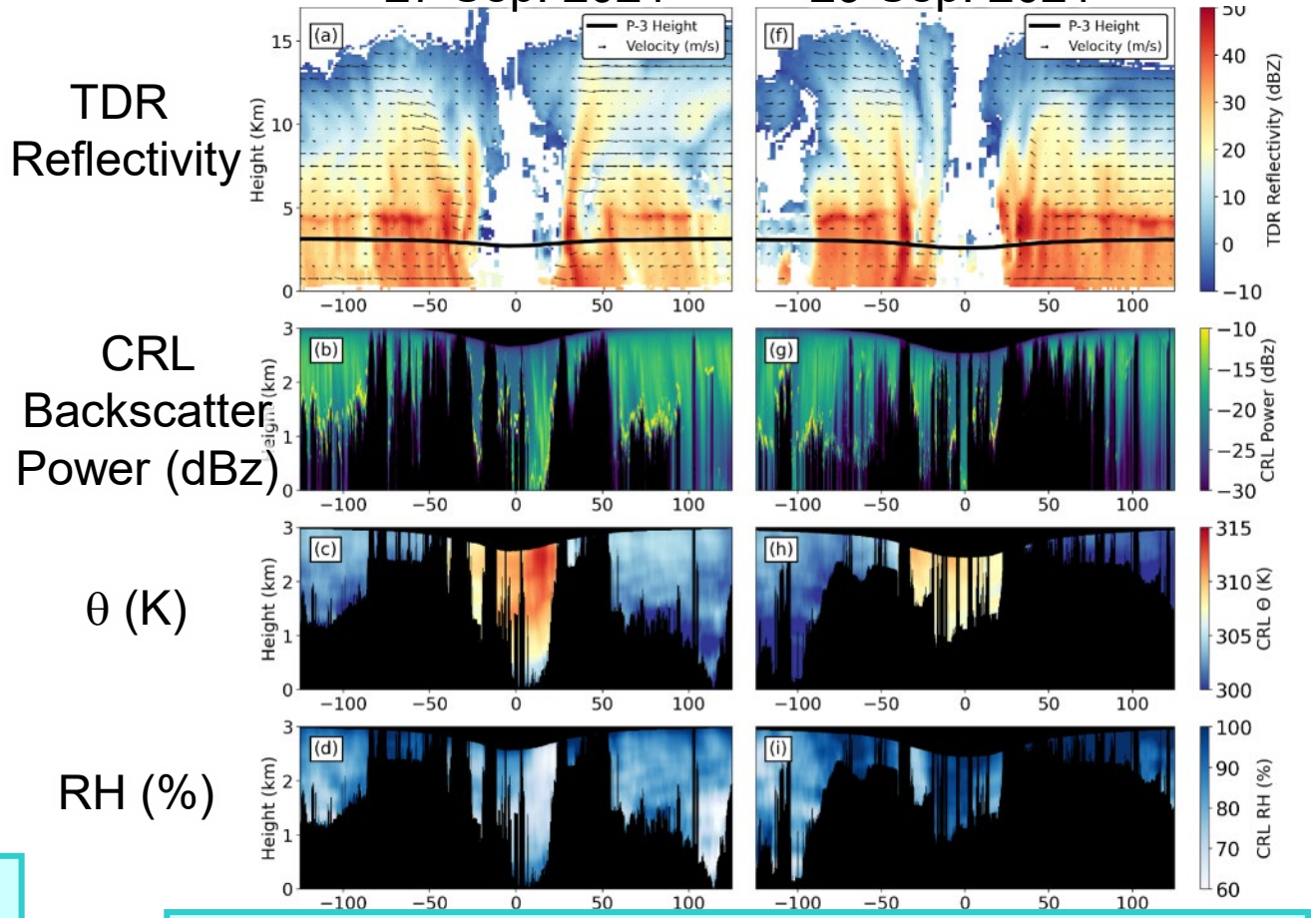
Microphysics Observations
Number Concentration by Habit (Hurricane Sam 2021)



- 33 profiles in TC mixed phase regions collected in TCRI
- Profiles of supercooled liquid droplets, graupel, pristine ice, & aggregates in stratiform region, suggest both local microphysical and advective processes are important

Bell (CSU)

CRL Observations of Hurricane Sam (2021)

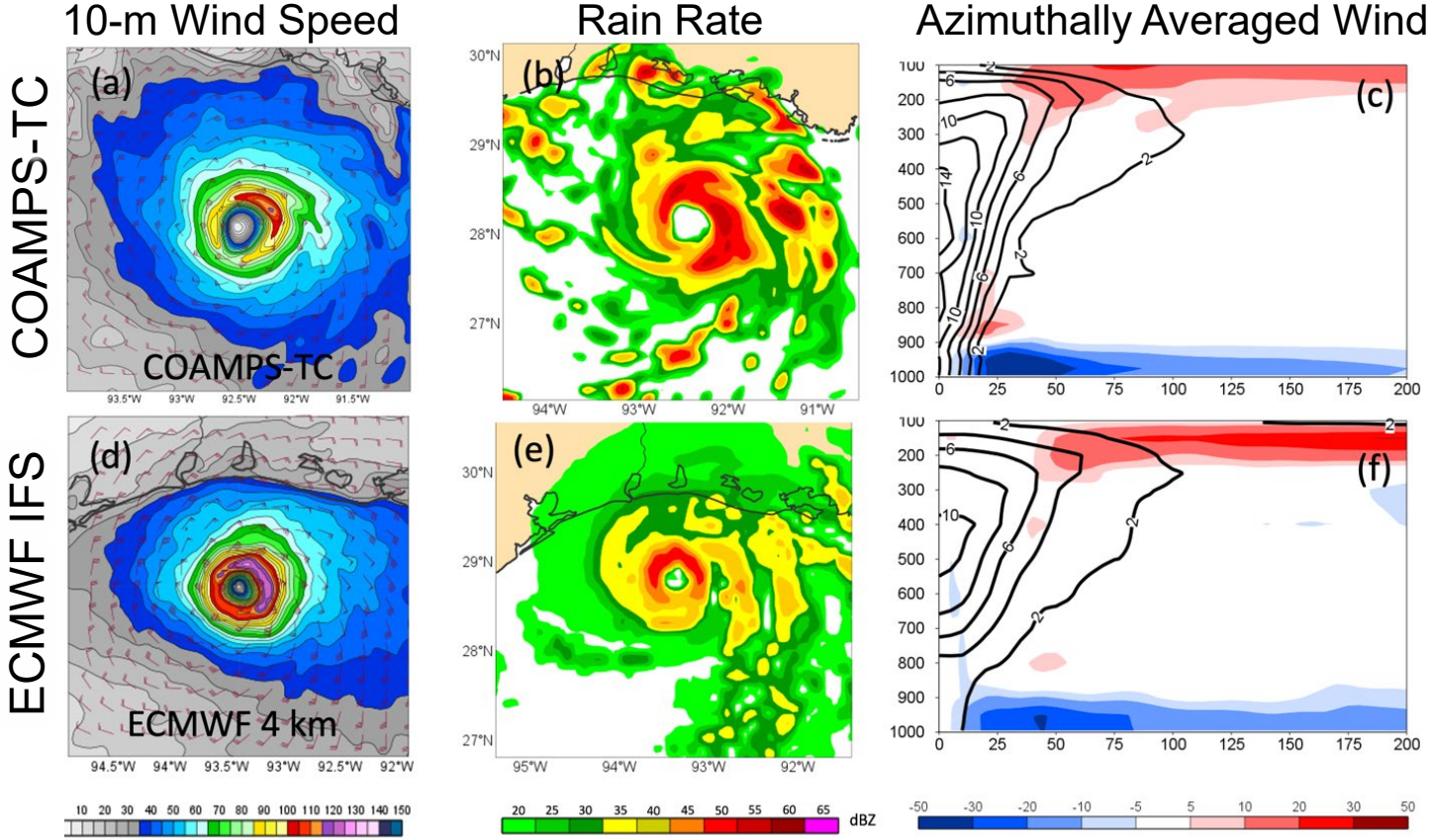


Compact Rotational Raman Lidar (CRL) provided PBL water vapor, temperature, aerosol/cloud measurements that shows evidence of clouds & vertical mixing in the eye

Zhien Wang (Stony Brook Univ.)

Numerical Modeling Highlights
Rapid Intensification

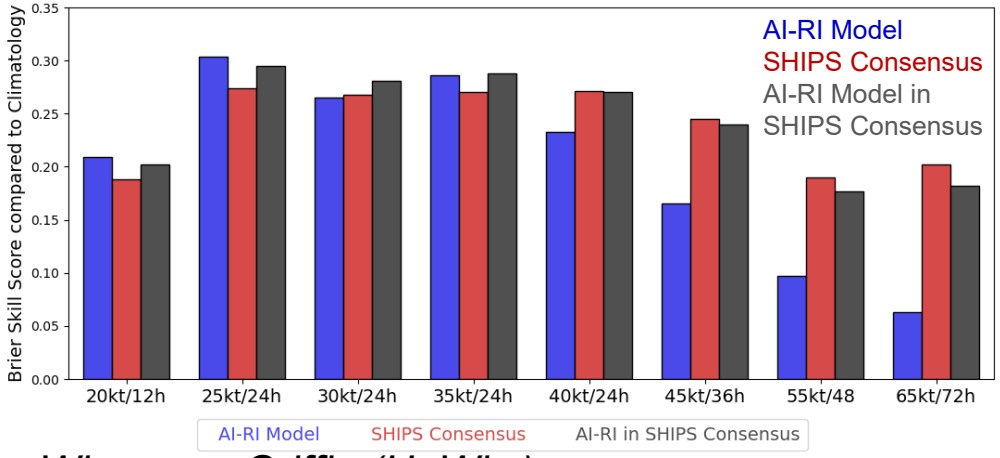
High-Resolution (4-km) Global ECMWF IFS Compared with COAMPS-TC for Hurricane Laura (2020)



Majumdar et al. (2023; MWR)

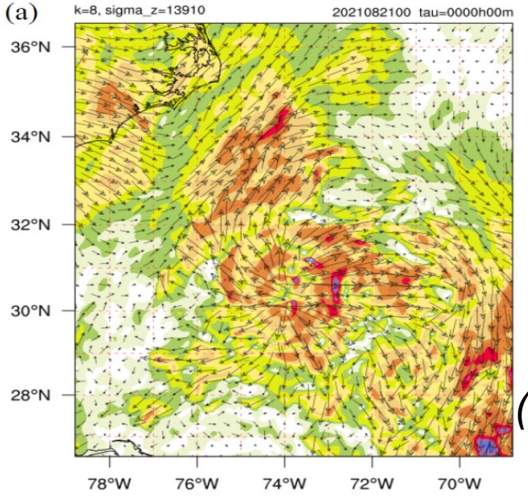
Predicting RI using AI-RI and SHIPS

Brier Skill Score for Atlantic 2019-2020 TC



Wimmers, Griffin (U. Wis.)

4-D Dynamic COAMPS-TC Initialization using GOES-16 AMVs



Elsberry et al. (2024; Atmos.)

- Promising results from global high-resolution models, and AI-RI models
- New methods to initialize high-resolution models using AMVs

ONR Tropical Cyclone Rapid Intensification DRI
Summary

- **Key Findings from the ONR TC Rapid Intensification Program**
  - RI is common and frequently begins at or shortly after genesis. “Extreme RI” events last longer and the intensification rate accelerates when they become hurricanes.
  - Although RI generally begins when vortex tilt decreases below 25 km, RI can occur when TCs are still misaligned. Asymmetric intensification observed during RI of tilted TCs (FLAIMS module in Franklin).
  - Existence of a more robust mid-level vortex can allow misaligned TCs to undergo RI by promoting bottom-heavy mass flux profiles that facilitate rapid vorticity spin-up.
  - Horizontal scale of coherent turbulent structures in the PBL are independent of TC and intensity trend
  - Models such as CTCX can predict RI at horizontal grid spacings of 2-4 km, but these predictions become less reliable for TCs with smaller inner cores.

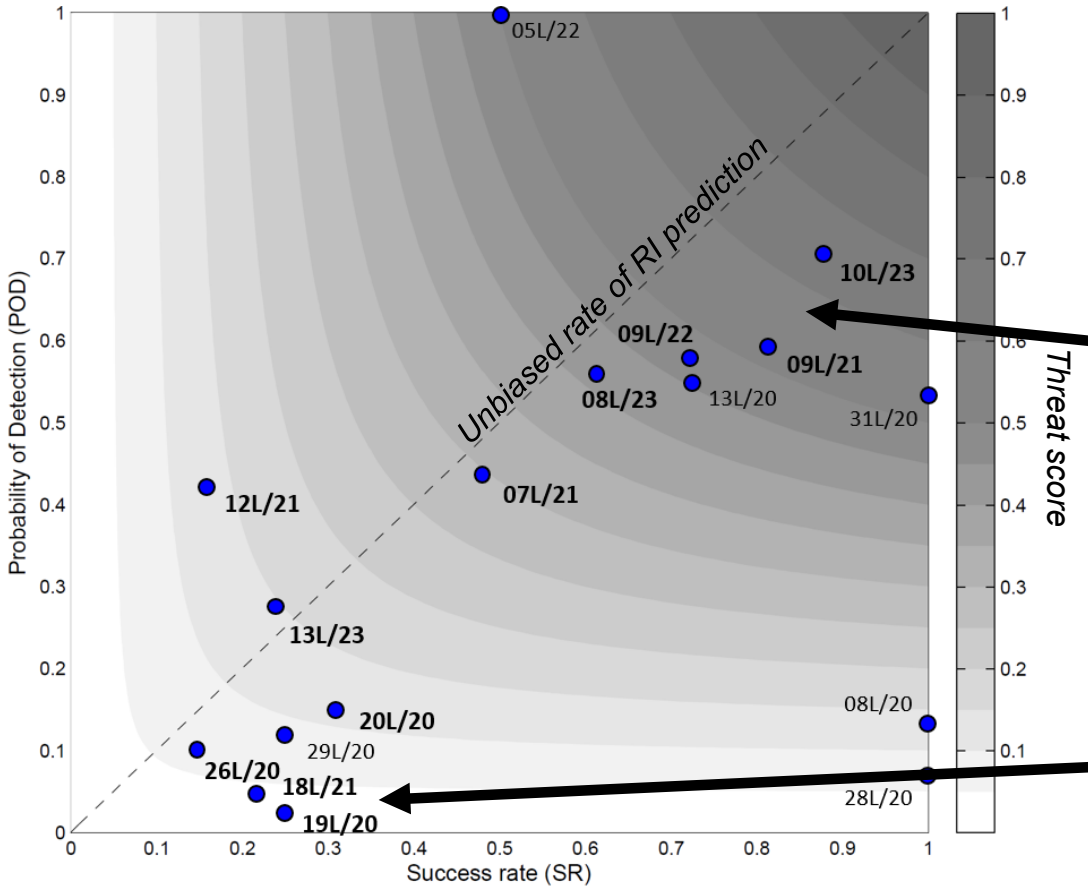
- **ONR MURI “Reexamining Ocean Effects on Atmospheric Wind Drag and Enthalpy Flux” (PI David Richter, U. Notre Dame)**

- **ONR-NRL-NOAA Collaborative Observing Plans (2024)**
  - ONR Moisture and Aerosol Gradients / Physics of Inversion Evolution (MAGPIE) in Barbados focused on the marine atmospheric boundary layer in differing environments including AEWs (NOAA P3)

Tropical Cyclone Rapid Intensification Program

Motivation

2020 - 2023 CTCX Atlantic RI performance



2020 storms

- 19L: Sally*
- 20L: Teddy*
- 26L: Delta*

2021 storms

- 06L: Fred
- 07L: Grace*
- 08L: Henri
- 09L: Ida*
- 12L: Larry*
- 18L: Sam*

2022 storms

- 06L: Earl
- 07L: Fiona
- 09L: Ian*
- 13L: Julia
- 15L: Lisa

2023 storms

- 08L: Franklin*
- 10L: Idalia*
- 13L: Lee*
- 15L: Nigel
- 20L: Tammy

TCRI storms with observed RI (blue), which are shown in* ***bold* *in plot at left*

The best CTCX RI forecasts tend to be for storms with a prolonged period of RI with peak intensity >= Cat4, and a medium-to-large inner core. Ida (09L/21), Ian (09L/22), Idalia (10L/23) are examples.

However, CTCX does not perform well for storms with a very small inner core during RI such as Delta (26L) and Sam (18L).

Jon Moskaitis (NRL)