Overview and Recent Performance of the Navy's COAMPS-TC

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Outline

- COAMPS-TC Background & History
- Model Development Topics
- v2023 Upgrades: Deterministic and Ensemble
- Recent Performance (Atlantic and EastPac)
- Summary and Future Directions

COAMPS-TC Background & History

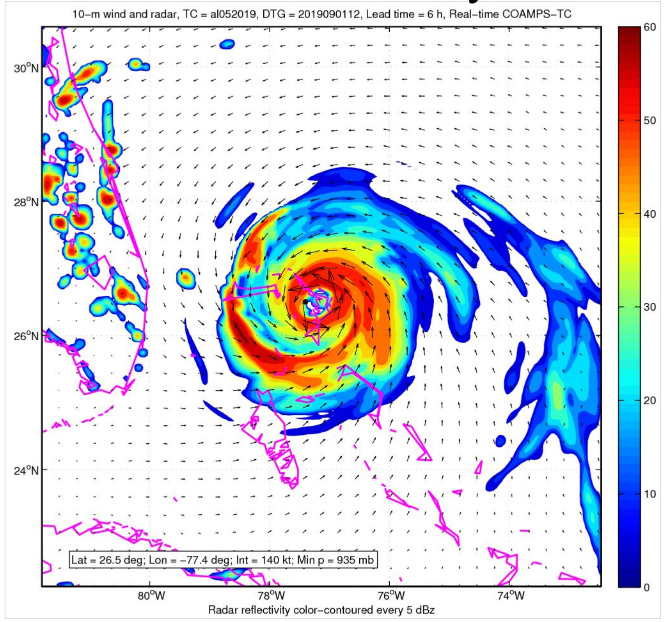
System overview

•COAMPS-TC is a specialized version of the U.S. Navy's mesoscale numerical weather prediction (NWP) model COAMPS, designed to predict (5 day) tropical cyclone (TC) track, intensity and structure (wind radii)

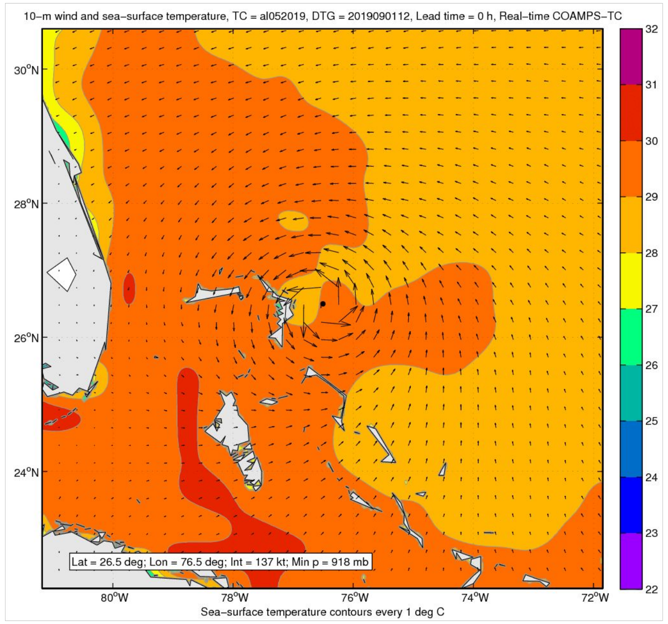
•Features: TC-following nested grid meshes (4 km on inner mesh, 40L)
Specialized TC physics (drag coefficient; boundary layer; microphysics); TC Vortex initialization
Coupled with NRL Coastal Ocean Model, NCOM

•Operational at Navy FNMOC: i) deterministic NAVGEM BCs (**COTC**) and NOAA GFS BCs (**CTCX**)
ii) COAMPS-TC ensemble (11 member, 4 km resolution) based on NOAA GFS

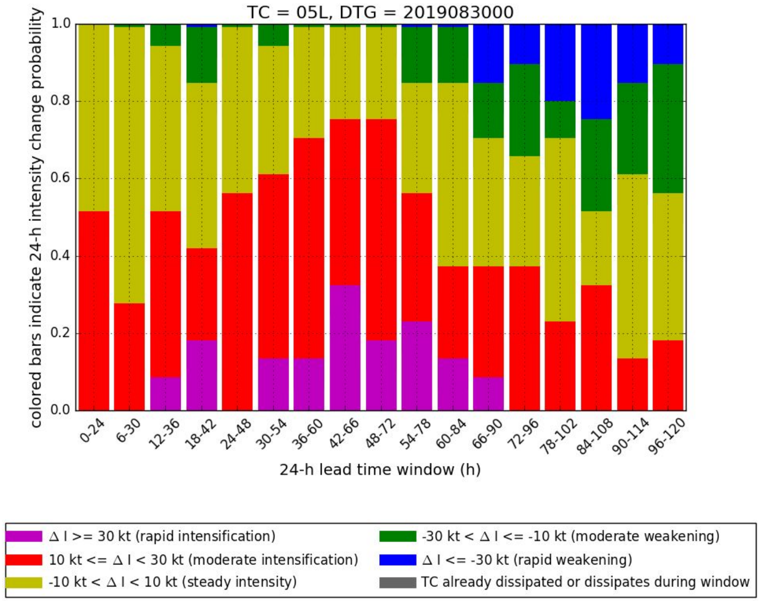
COAMPS-TC Deterministic (4km)
Dorian (05L) (12Z 1 Sep 2019)
Simulated Radar Reflectivity and 10-m Winds



NCOM Ocean (10km)
Dorian (05L) (12Z 1 Sep 2019)
SSTs and 10-m Winds



COAMPS-TC Ensemble (4km)
Dorian (05L) (00Z 30 Aug 2019)
24-h Intensity Change Probability



COAMPS-TC Background & History

Current real-time capabilities

Real-time Operational at FNMOC

- COTC deterministic: All storms worldwide, every 6 h
- CTCX deterministic: WP/IO/SH storms (JTWC AOR), every 6 h
- CTCX ensemble: 11 members, up to two storms every 6 h with JTWC AOR prioritized

Real-time demonstration at NRL*

- CTCX deterministic: All storms worldwide, every 6 h. Run on dedicated nodes at Navy DSRC. AL/CP/EP storm forecasts provided to NHC/CPHC.
- CTCX ensemble: 21 members, 00z and 12z only for select storms depending on available Navy DSRC computational resources (prioritizing WP and AL storms). Not run on dedicated nodes, so latency varies.

COTC: COAMPS-TC with ops NAVGEM initial and lateral boundary condition information

CTCX: COAMPS-TC with ops GFS initial and lateral boundary condition information

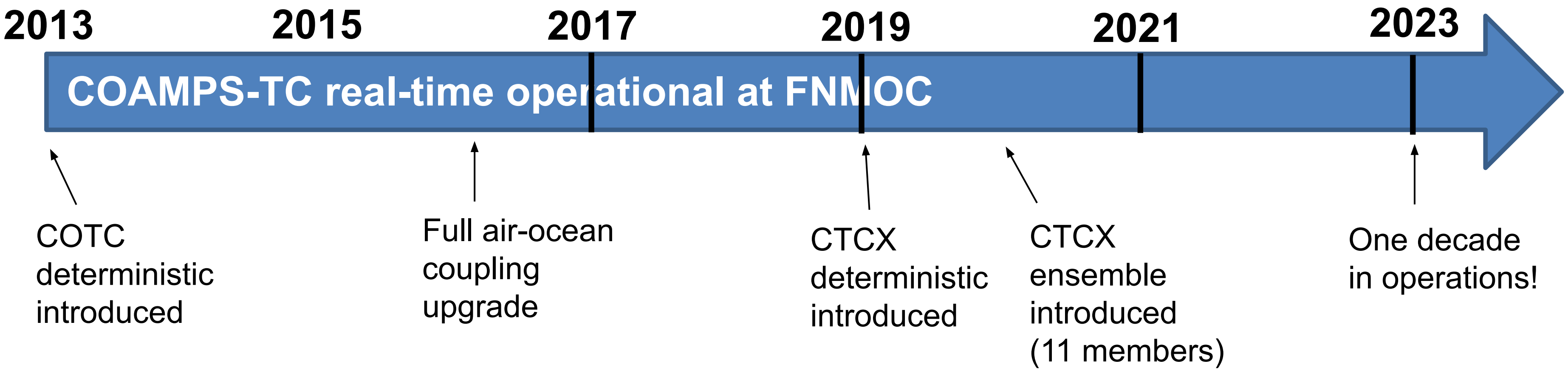
Navy DSRC: Navy DoD Supercomputing Resource Center (Stennis Space Center, MS)

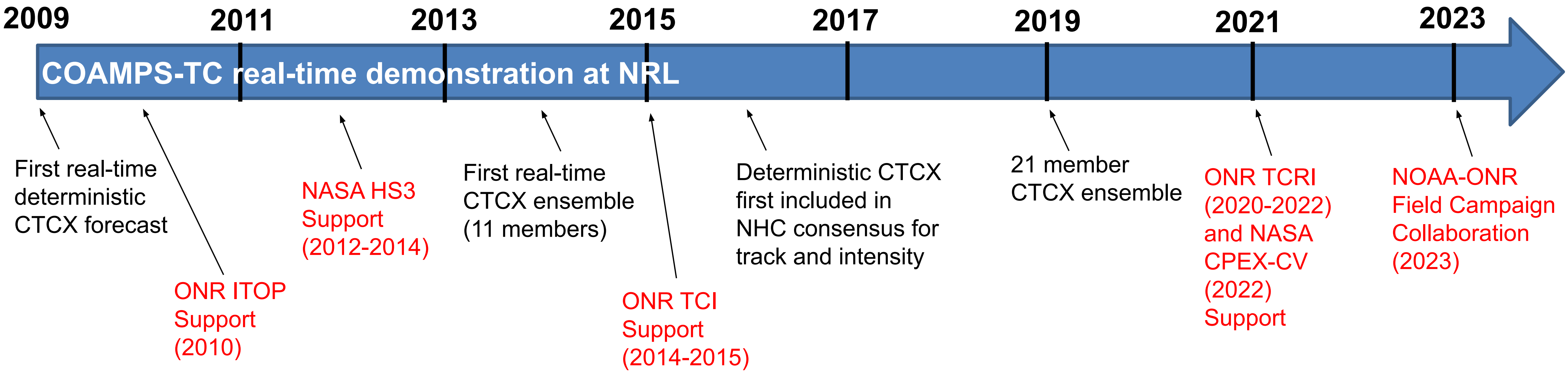
*Forecasts available at https://www.nrlmry.navy.mil/coamps-web/web/tc

COAMPS-TC Background & History

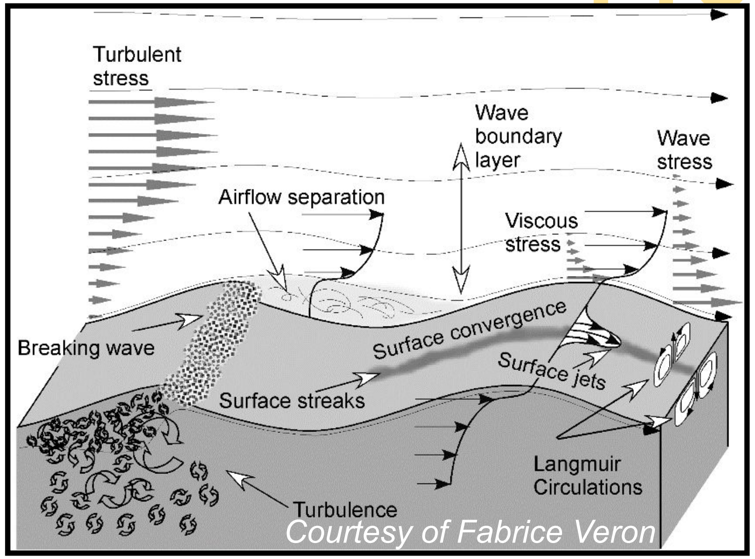
Timeline

COAMPS-TC was first developed ~15 years ago and has been in operational use for a decade (with yearly upgrades)

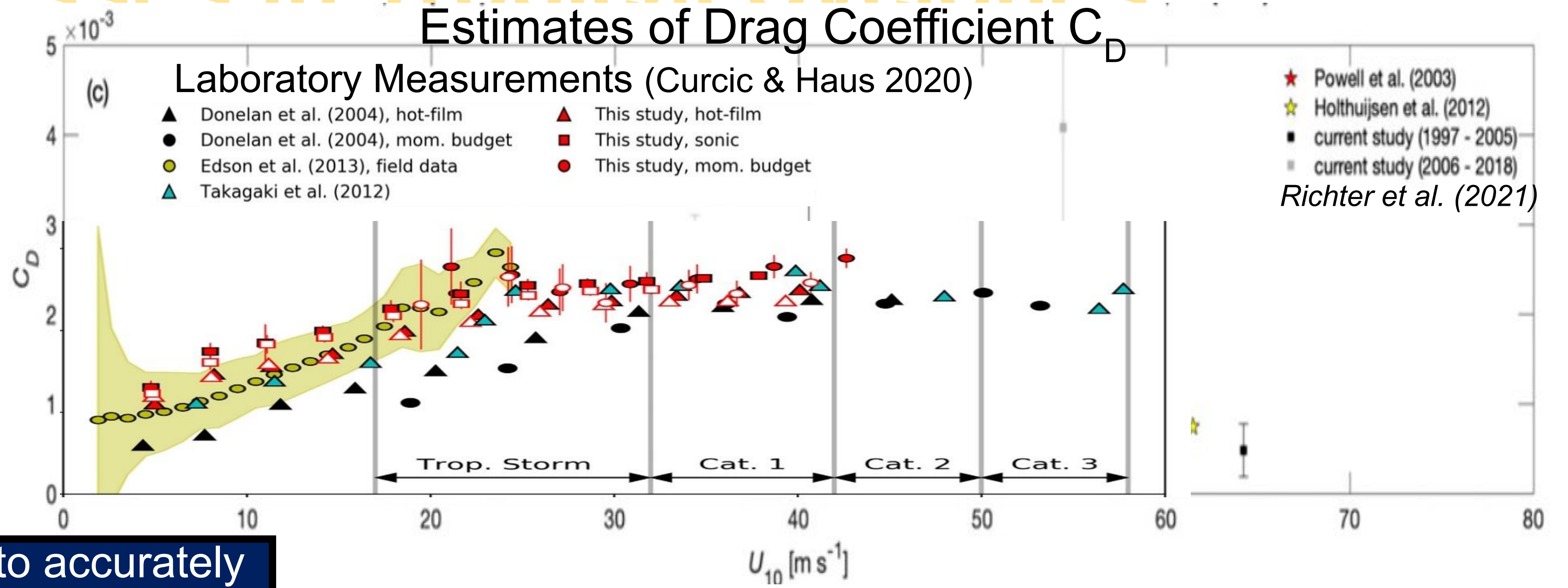




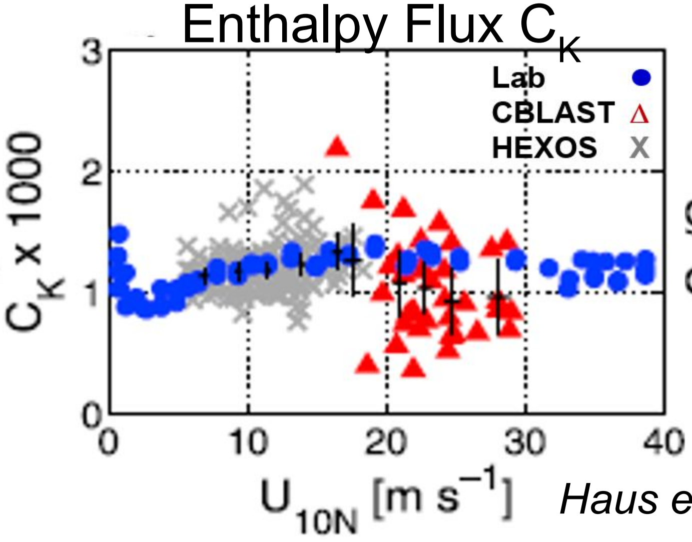
Surface Exchange and Boundary Layer Processes in Tropical Cyclones

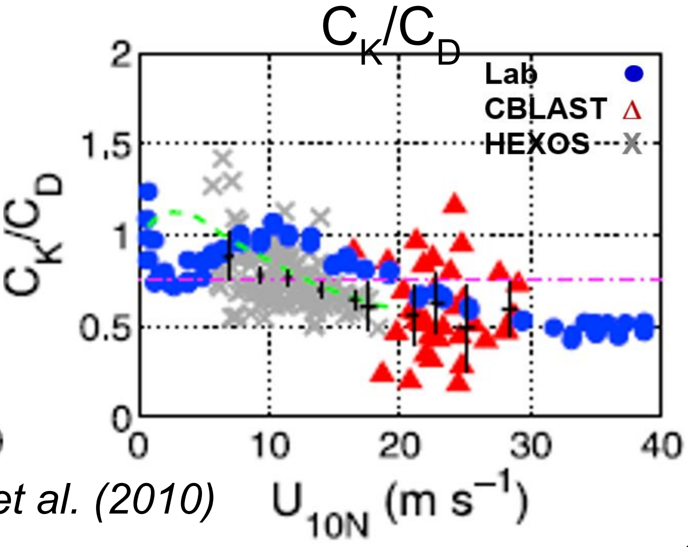


Courtesy of Fabrice Veron



Richter et al. (2021)





Haus et al. (2010)

- Air-sea processes in TCs are crucial to accurately represent (fluxes, ocean mixing, spray) (Shay 2010; Holthuijsen et al., 2012; Bell et al. 2012; Nystrom et al. 2020)
- Estimation of air–sea momentum transfer in high winds use flux-profile method; C_D can be inferred from dropsondes (Powell et al. 2003)
- High-resolution TC models use C_D “rolloff” for U_{10}>30 ms^{-1} (large spread, e.g., Richter et al. 2021)
- Surface exchange coefficients at high winds are very uncertain (laboratory & nature estimates)
- C_K/C_d average is ~0.75 (Emanuel 1995).

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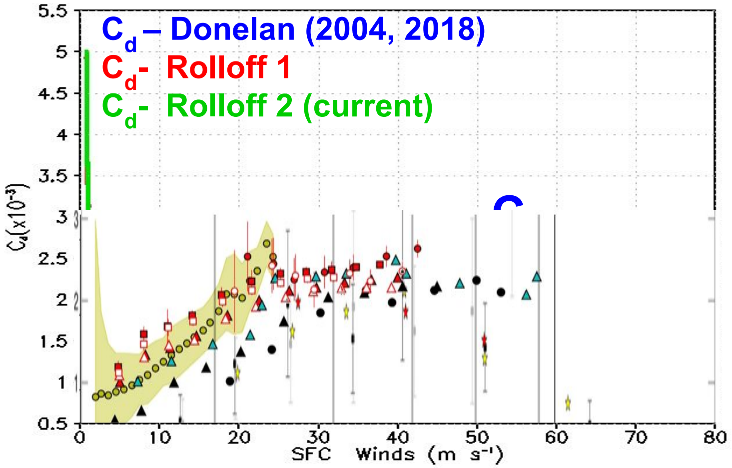
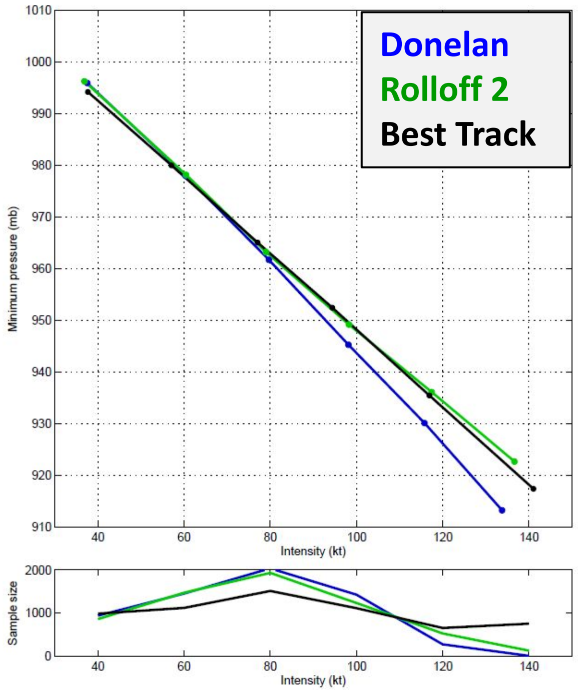
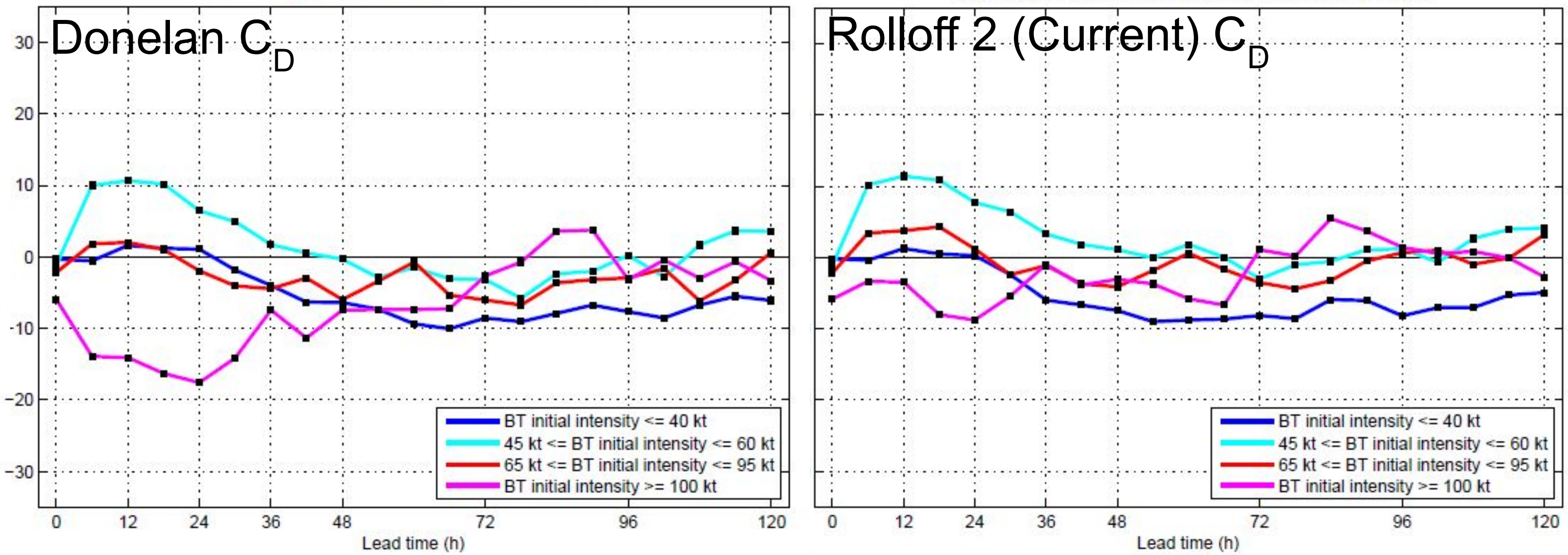
Surface Drag Parameterization

COAMPS-TC C_D Formulation





Mean Intensity Error (kt)



- **Motivation:** Address large intensity bias in strong storms
- **Methods:** Explore the C_D – Wind relationship
- **Key Findings:**
  - Large sensitivity of the forecast intensity to the C_D
  - C_D Cap and Rolloff improves bias for most intense (>100 kt) TCs
  - The pressure-wind relationship is very sensitive to the C_D

Air-Ocean Coupling in Tropical Cyclones

Upper Ocean Processes

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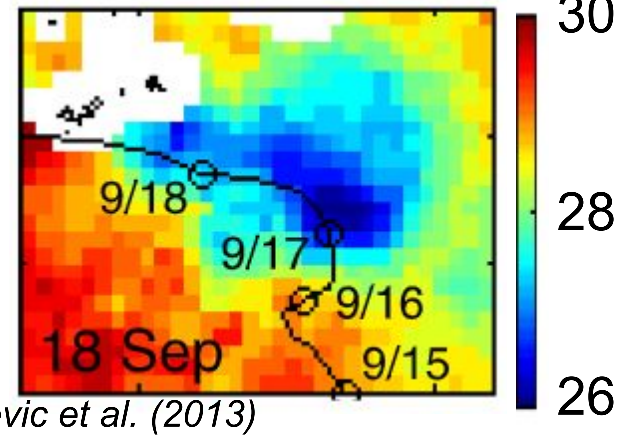
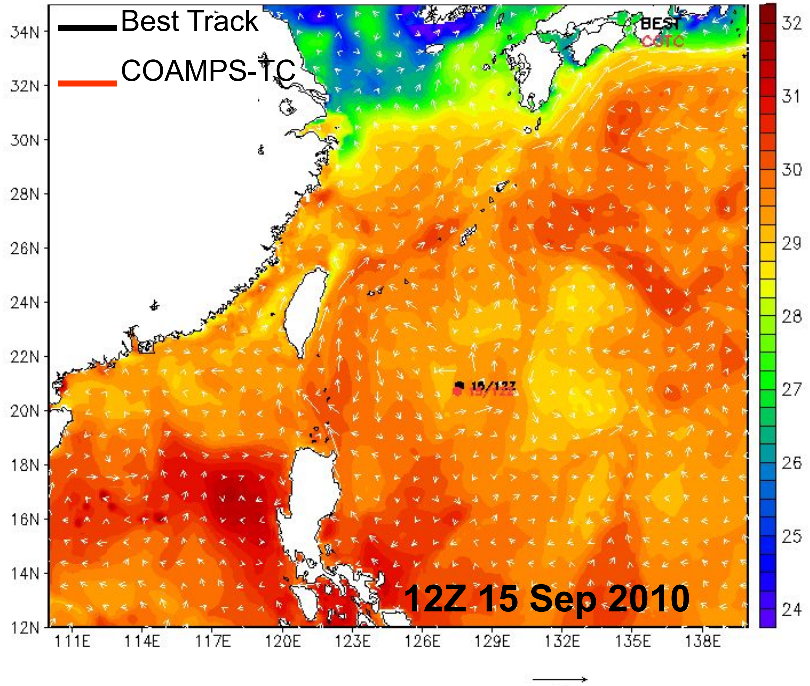
Microwave SST [TY Fanapi (2010)]

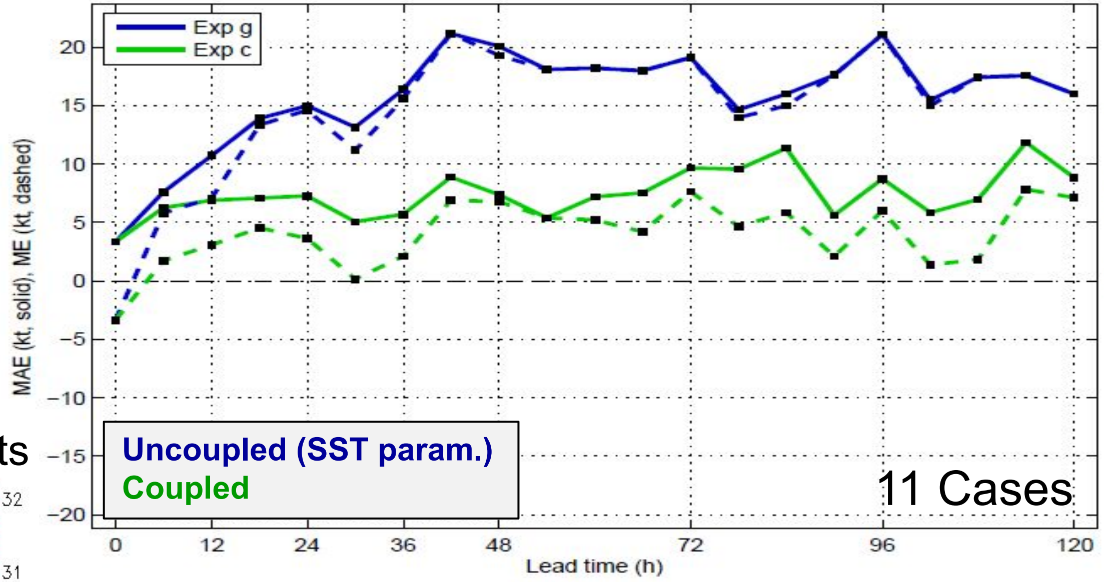


Mrvaljevic et al. (2013)

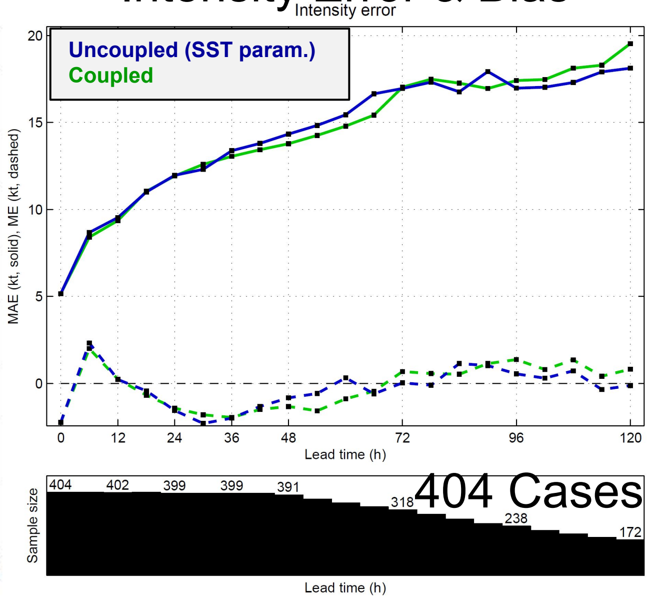
ITOP Typhoon Fanapi: SST (°C), Currents



Hurricane Leslie (2012): Intensity Error & Bias



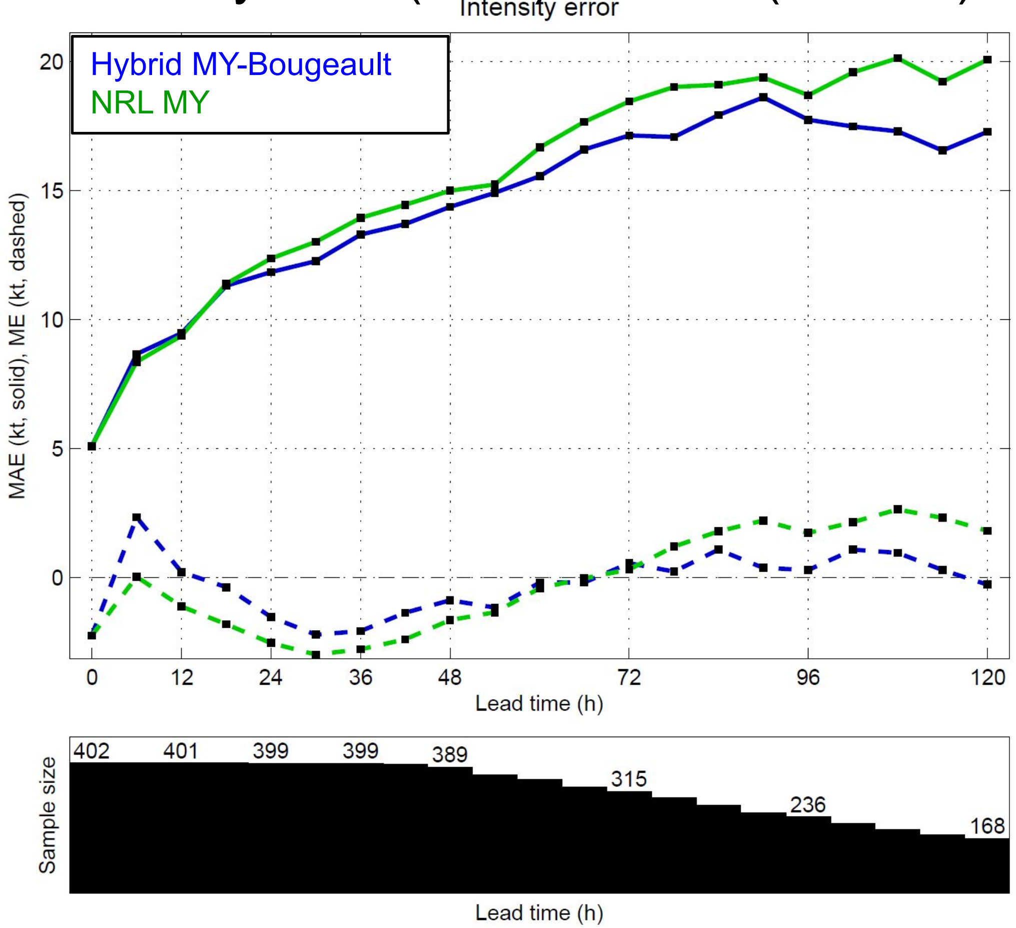
Intensity Error & Bias



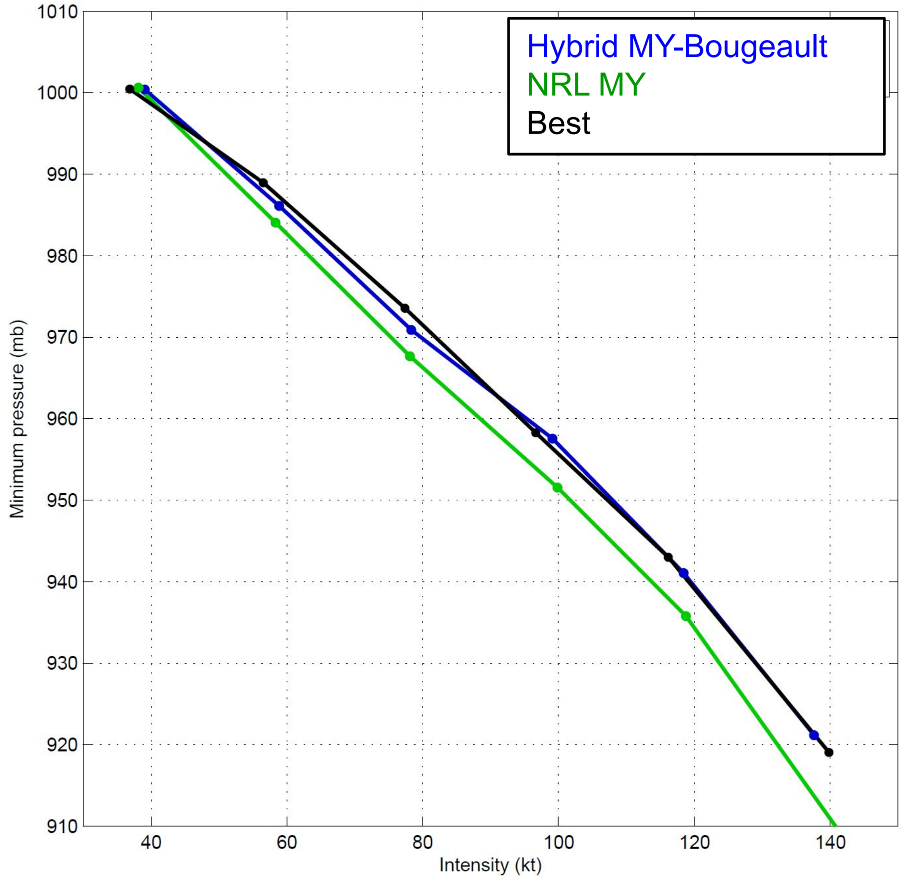
- **Motivation:** Upper-ocean mixing results in SST cooling beneath TC core & in wake (Bender & Ginis, 2000; Cione & Uhlhorn, 2003; Chen et al., 2007)
- **Methods:** Air-sea & air-sea-wave coupling; 1-D simple ocean
- **Key Findings:**
  - Air-sea coupling reduces over intensification biases, particularly for slow moving storms (such as Hurricane Leslie)
  - 1-D simple SST cooling allows for efficient testing

Hurricane Boundary Layer
Sensitivity to PBL Parameterization

Intensity MAE (solid) and ME (dashed)



Pressure-Wind Relationship

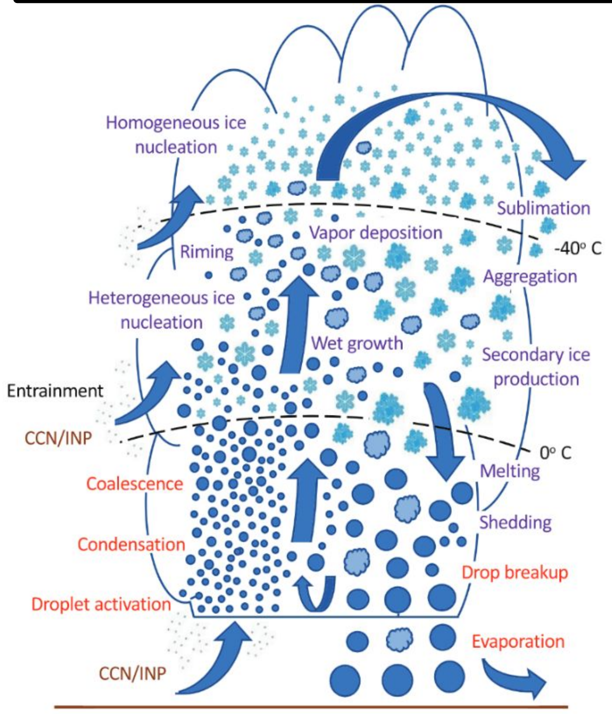


- Using the MY-Bougeault mixing length improves the intensity MAE, ME, and pressure-wind relationship
- The MY mixing length produces more weaker storms and over intensifies stronger storms
- The radius of the 34 kt (and 50 kt, RMW) are slightly degraded by the MY-Bougeault mixing length

Microphysics

Sensitivity to Microphysics Representation

- Motivation: Large uncertainties exist in the representation of cloud microphysics (Morrison et al. 2020). Parameterizations of convection, clouds and interaction with radiation are key for accurate TC forecasts of track, intensity, and structure (Wang 2002; Bu et al. 2014; Jin et al. 2014; Fovell et al. 2010, 2016; Park et al. 2020)
- Methods: Single (NRL) and double moment schemes (Thompson, Morrison) experiments and diagnostics

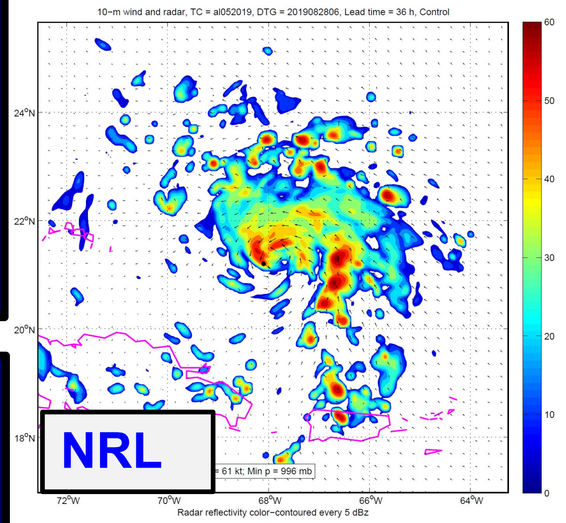


Morrison et al. (2020)

Key Findings:

- Substantial differences in storm structure and hydrometeor distribution, and intensification (including RI) using NRL, Thompson, and Morrison microphysics
- Interactions of clouds, convection and radiation is important for TCs structure and intensity as well

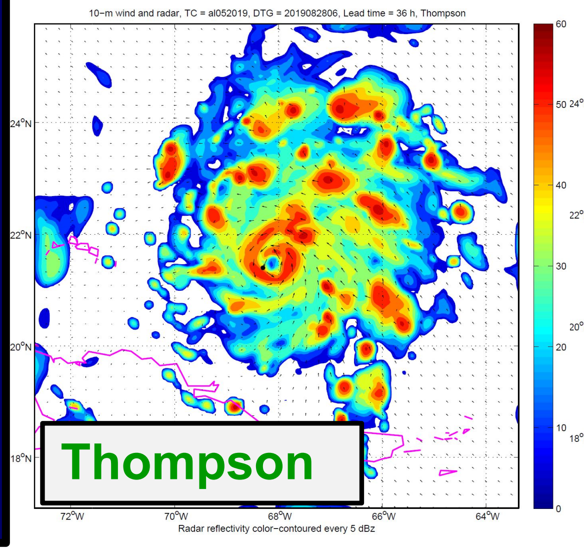
Simulated radar reflectivity, 36 h CTCX forecast for Hurricane Dorian

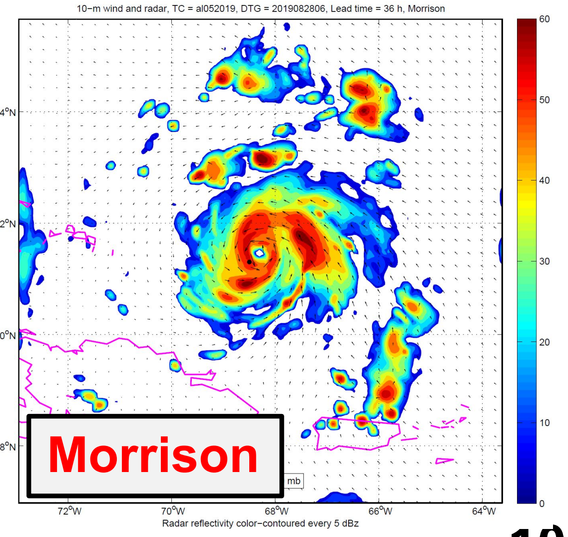


***NRL (Control)**: 6 class microphysics with graupel*

***Thompson**: 6-class microphysics with graupel. Prognostic ice and rain number concentrations.*

***Morrison**: 6-class microphysics with graupel. Prognostic rain, ice, snow, and graupel number concentrations.*





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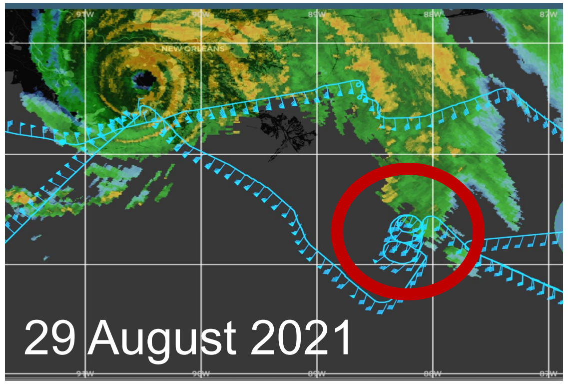
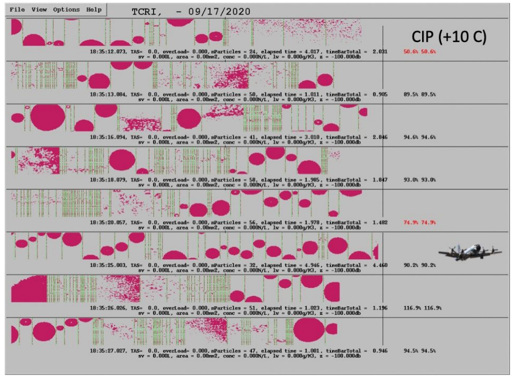
Microphysics Observations in Hurricane Ida

ONR TCRI Microphysics Observations

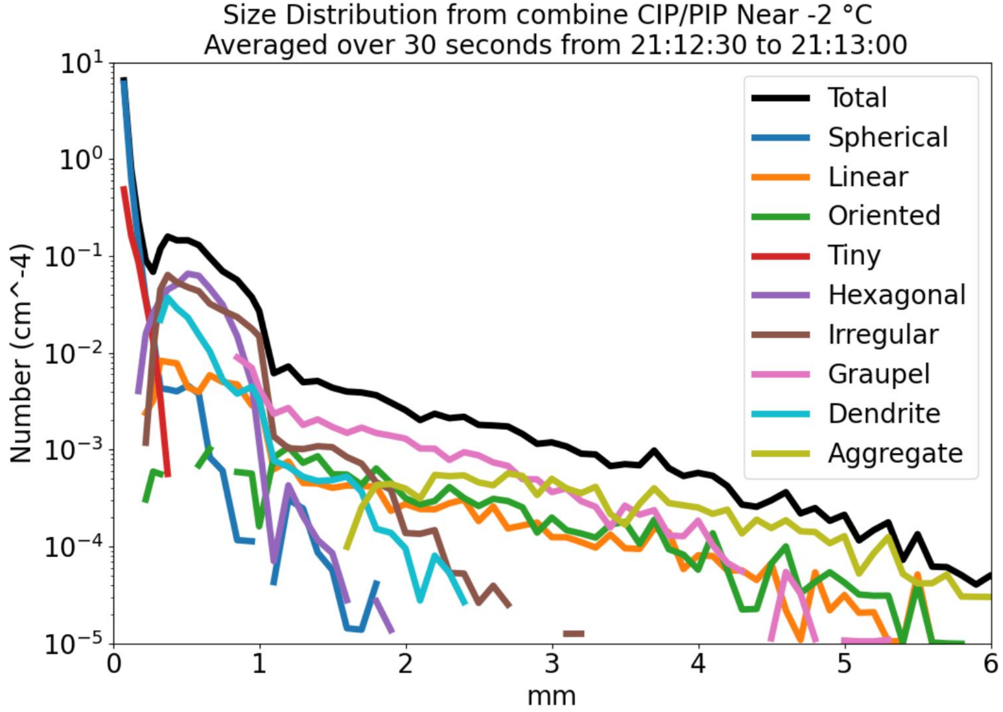
Hurricane Ida P3 track microphysical spiral

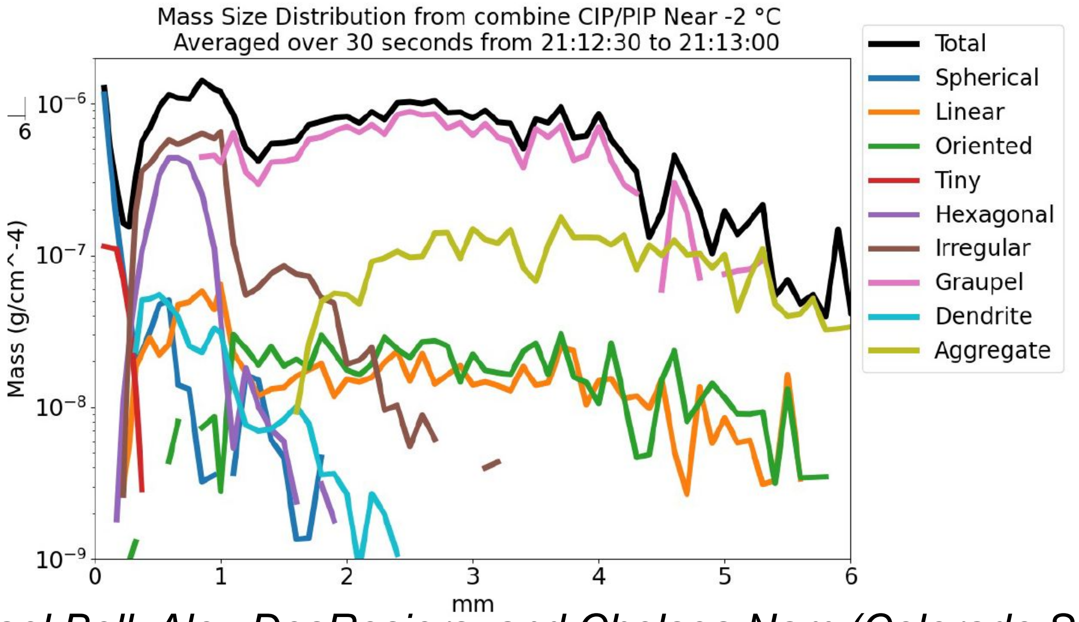


Hydrometeors transition from water to ice



- Motivation: Lack of observations of cloud microphysics in TCs
- Methods: New microphysics obs (NOAA P3s) in ONR TCRI
- Preliminary Findings:
  - Sample size and habit distribution near -2 C
  - Numerous spherical particles below 0.2 mm (supercooled drops?)
  - High concentrations of pristine ice (plates, dendrites) and possible rimed ice (irregular) near 1 mm
  - Graupel and aggregates dominate distribution > 1 mm





Michael Bell, Alex DesRosiers, and Chelsea Nam (Colorado State Univ.)
ONR TCRI Team and NOAA APHEX Team

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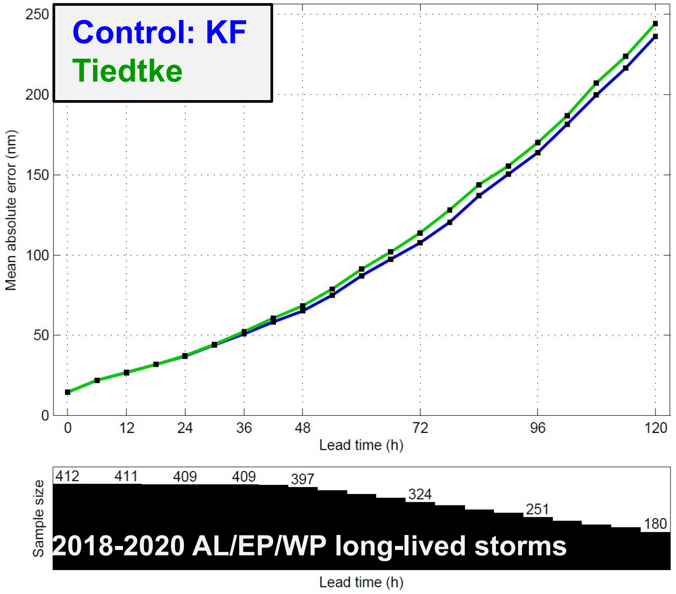
Convection

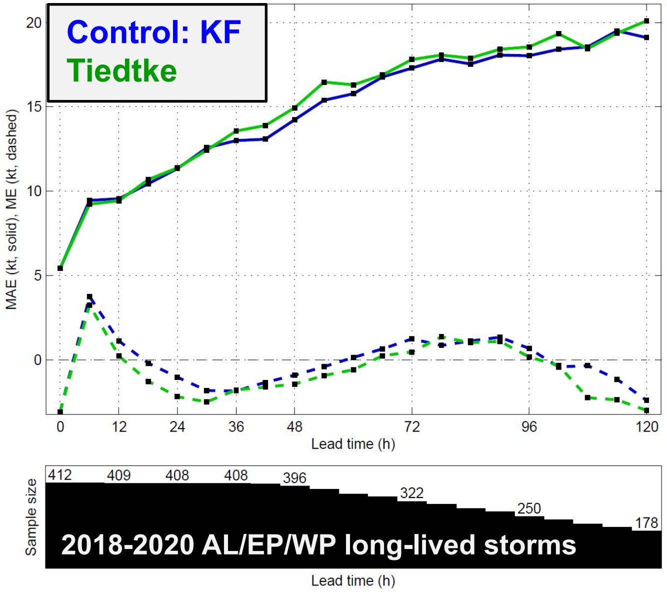
Deep Convection

- Motivation: CTCX track errors lag global models. Track errors have been linked to cumulus parameterization. (Nasrollahi et al. 2012; Sun et al. 2014a,b; Shepherd & Walsh 2017)
- Methods: Testing with Kain Fritsch, Tiedtke (WRF), and SAS (NOAA)
- Key Findings:
    - Some sensitivity to track and intensity, however greater sensitivity to the wind radii, in part due to changes in the middle tropospheric moisture biases.

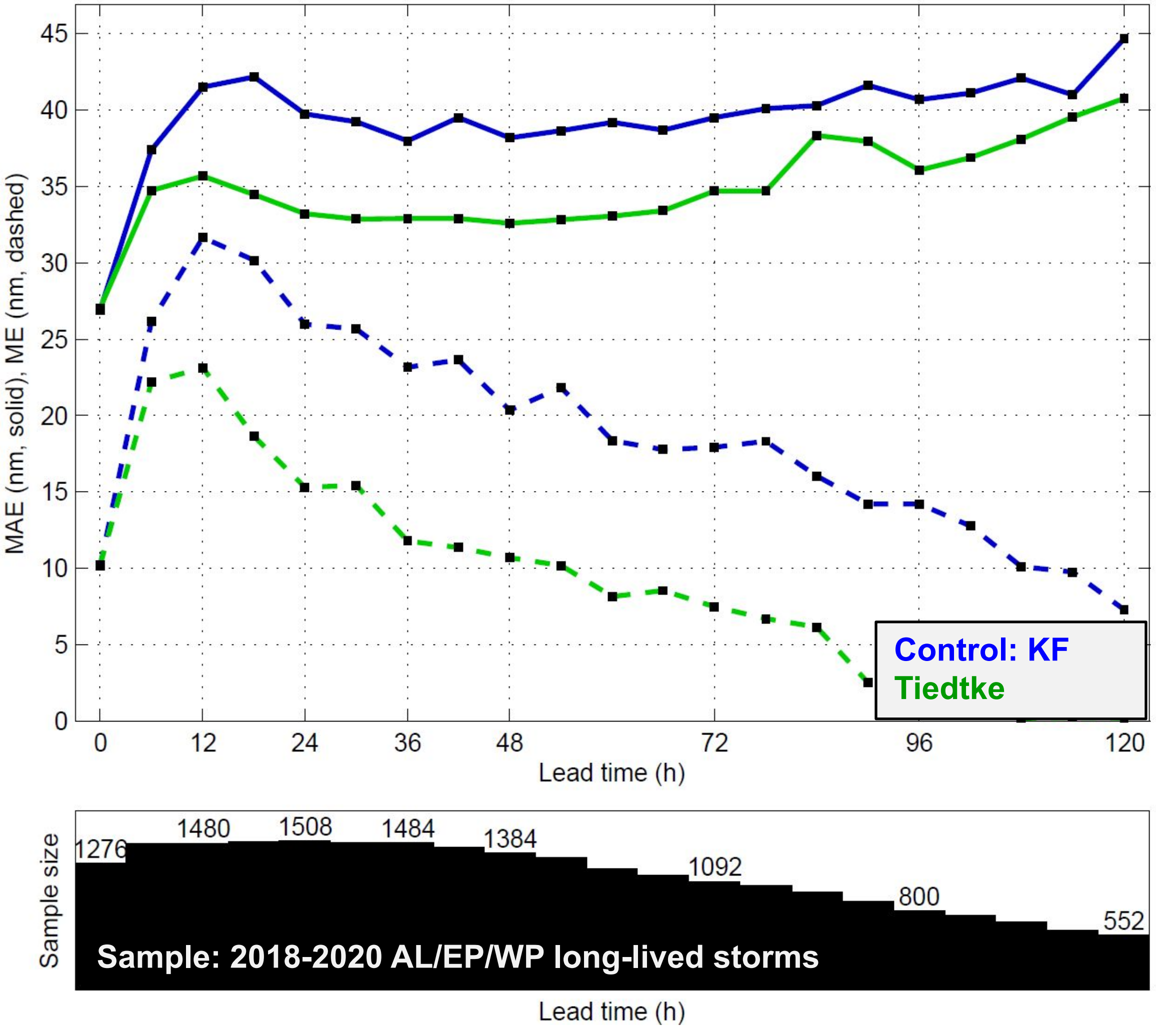
Track Mean Absolute Error (n mi)



Intensity MAE (solid); ME (dashed)



R34 MAE (solid) and ME (dashed)



Tiedtke has a drier middle free troposphere than KF, which helps reduce positive bias in R34

Sensitivity to Resolution

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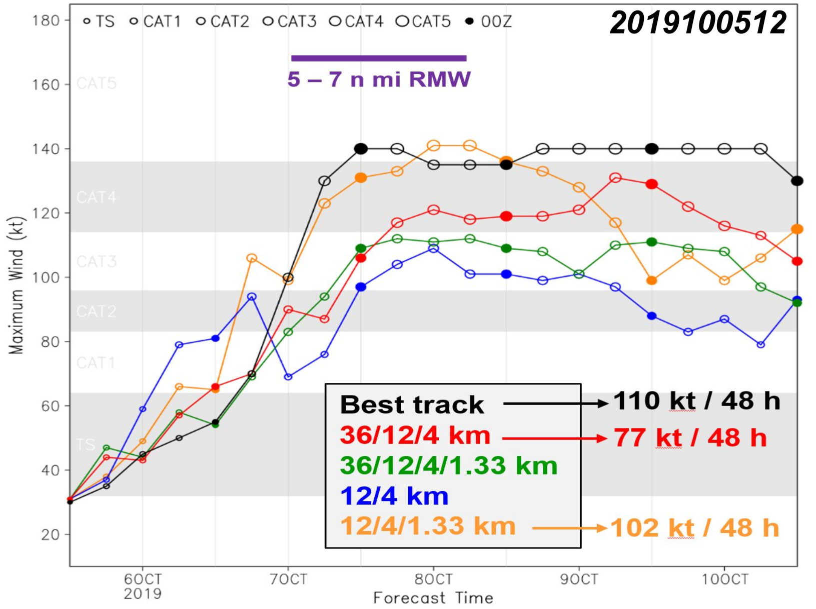
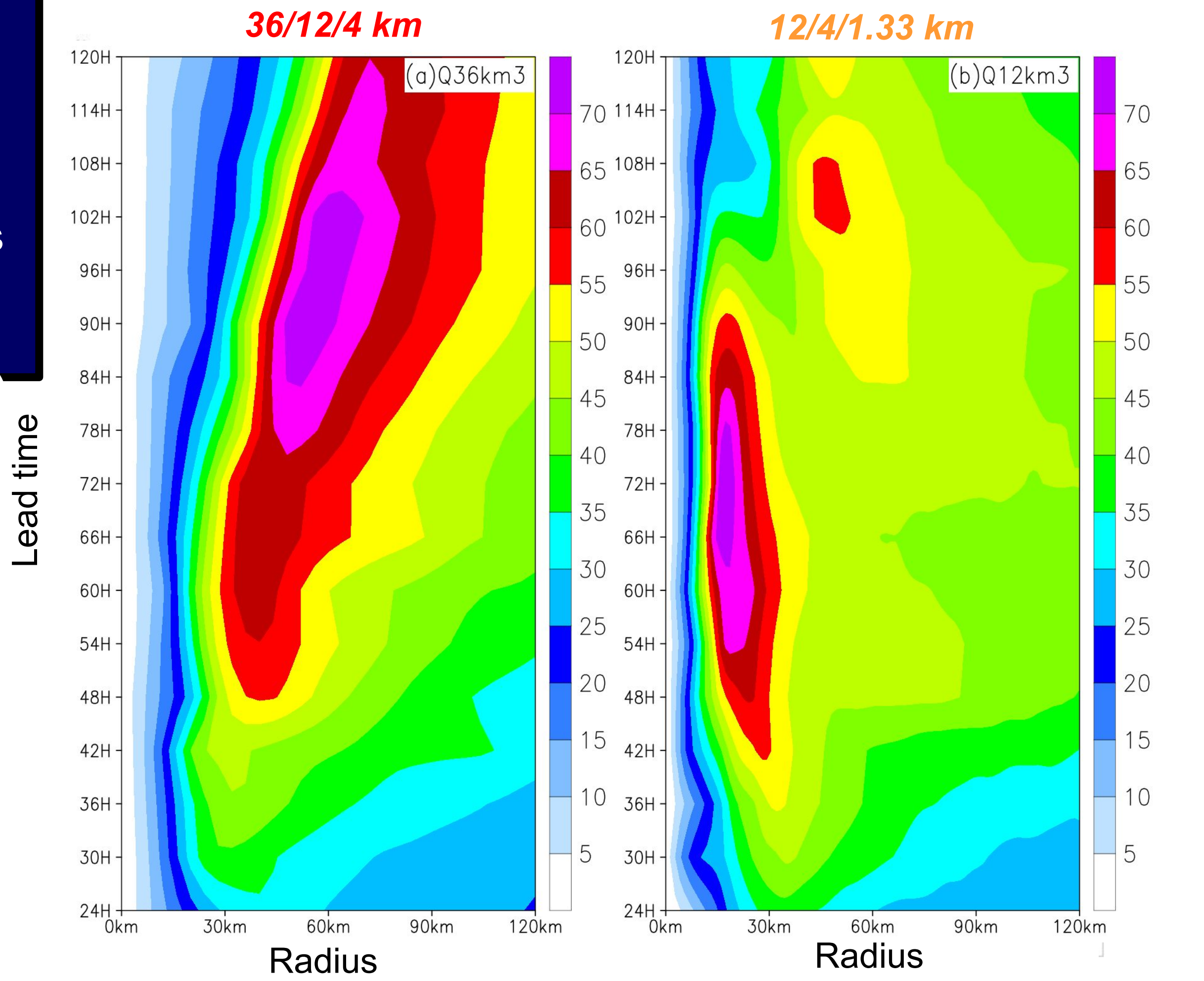
Horizontal Resolution

- Motivation: Numerical prediction of TC intensity & structure require resolving horizontal scales of ≤4 km to capture sharp gradients of momentum & moisture (Alaka et al. 2022). COAMPS-TC does not predict intensification of small core systems well.
- Methods: Higher horizontal/vertical resolution tests; case studies
- Key Findings:
  - Higher horizontal resolution (~1 km) improves structure and intensity of small core systems (necessary but not sufficient)

Intensity experiments: Hagibis (20W)



Azimuthally Averaged Tangential Wind at 1 km



12/4/1.33 km configuration simulates ***extreme rapid intensification*** of >100 kt in 48 h

ECMWF and COAMPS-TC Comparison

Can High-Res Global Models Perform Similarly to a Specialized TC Model?

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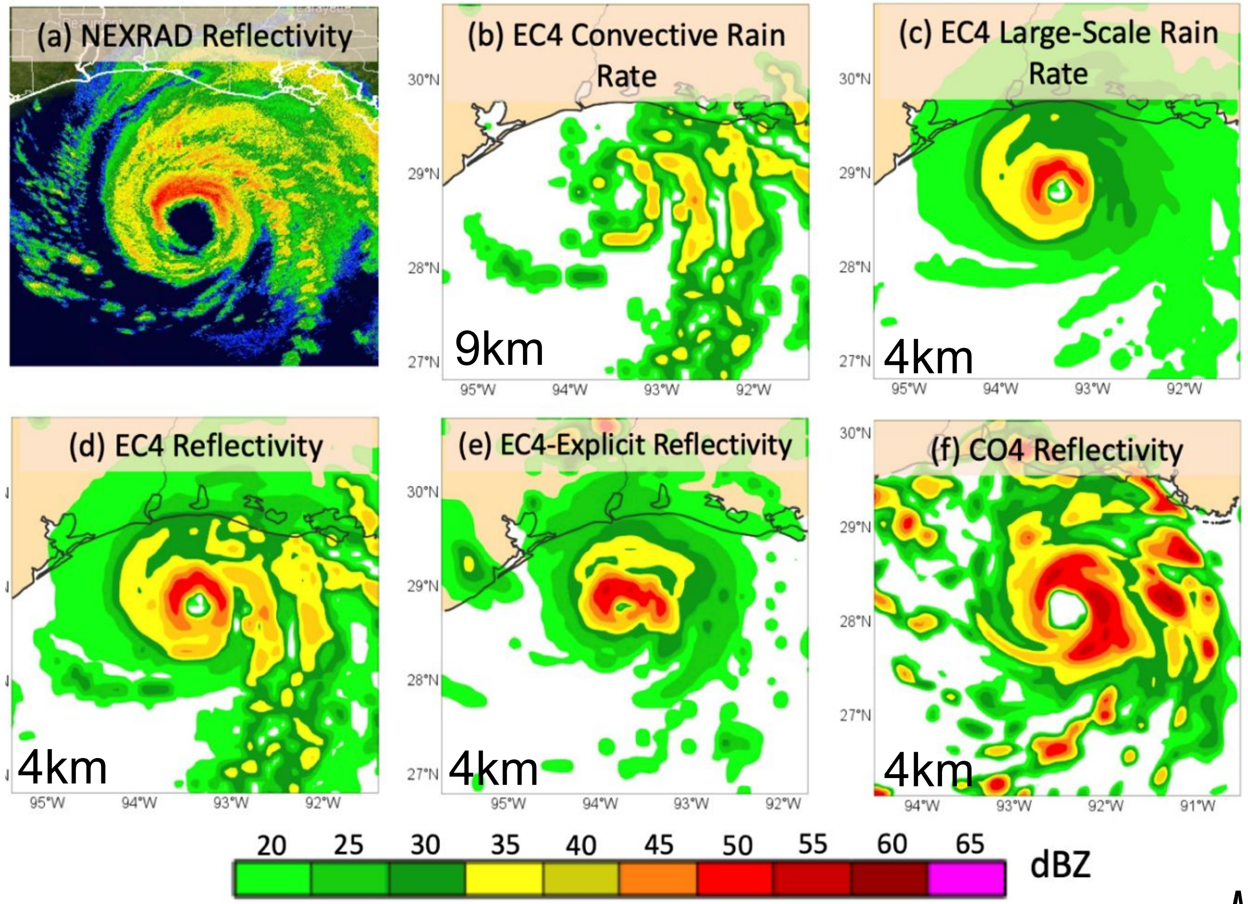
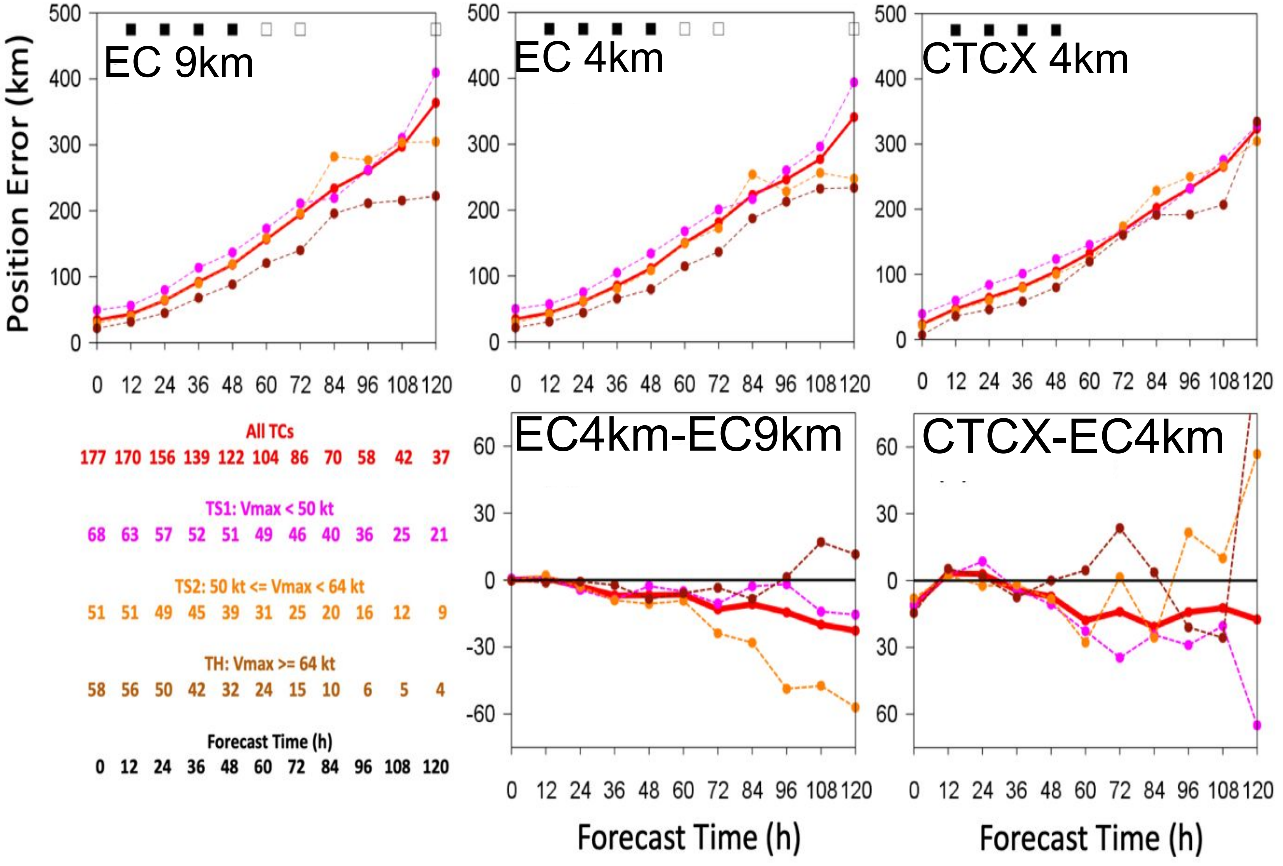
Comparison of ECMWF IFS and COAMPS-TC with Observations for Hurricane Laura



Comparison of ECMWF IFS and COAMPS-TC for 2020 W. Atlantic Basin



Majumdar, Magnusson, Bechtold, Bidlot, Doyle, 2023

- In the relatively near future, global models may be able to replicate the skill of high-res. TC models
- Open questions : required resolution, cumulus parameterization, C_D/C_K, coupling, PBL, dynamics

v2023 Upgrades: Deterministic and Ensemble Overview and Testing Strategy

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New in v2023

- Expanded the inner nest blend zones from 2 to 18 grid points with the lblend_nest = t namelist option (deterministic and ensemble)
- New graphical forecast products (ensemble)
  (1) Minimum SLP candlestick
  (2) Wind radii candlestick
  (3) Wind radii annulus

- v2023 in ops production at FNMOC on 5 July 2023
- v2023 capabilities integrated in the NRL real-time demonstration runs up to 1 year before becoming operational at FNMOC

Retrospective test sample

WestPac

Storm	Cases
wp092019	4
wp102019	6
wp112019	9
wp142019	5
wp152019	4
wp192019	4
wp202019	5
wp212019	3
wp222019	5
wp242019	5
wp262019	3
wp272019	3
wp292019	7
wp012020	3
wp032020	2
wp092020	3
wp102020	4
wp112020	5
wp142020	3
wp152020	2
wp162020	6
wp192020	5
wp212020	3
wp222020	8
wp232020	2
wp252020	3
wp022021	6
wp042021	5
wp062021	5
wp092021	8
wp132021	5
wp142021	4
wp162021	4
wp182021	3
wp192021	9
wp202021	7
wp232021	5
wp252021	4
Total	**177**

Atlantic

Storm	Cases
al052019	11
al082019	5
al092019	4
al102019	6
al122019	3
al132019	7
al082020	3
al092020	4
al132020	7
al172020	7
al182020	6
al192020	4
al202020	7
al262020	3
al272020	4
al292020	10
al052021	6
al062021	4
al072021	5
al082021	6
al092021	3
al102021	3
al122021	8
al172021	3
al182021	6
Total	**135**

EastPac

Storm	Cases
ep022019	1
ep062019	4
ep072019	7
ep112019	4
ep132019	10
ep052020	4
ep082020	7
ep092020	2
ep122020	3
ep142020	3
ep172020	3
ep182020	6
ep192020	3
ep052021	3
ep062021	5
ep082021	5
ep122021	8
ep152021	2
ep162021	2
Total	**82**

Other

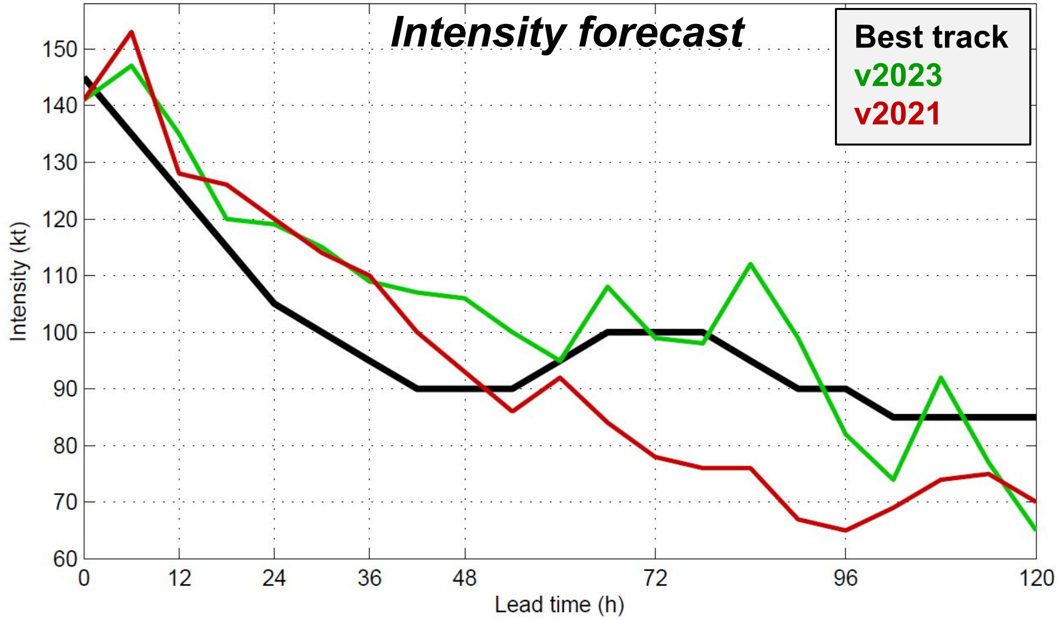
Storm	Cases
cp012019	1
io012019	1
io042019	1
sh222020	1
sh252020	1
Total	**5**

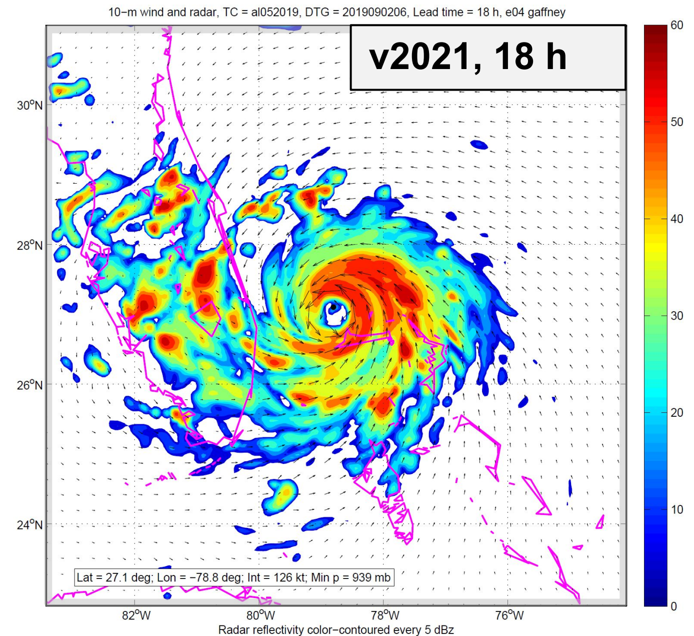
- Full sample is 399 cases from 87 TCs from the prior three years
- For a given storm, forecasts are run every 24 h such that they are quasi-independent

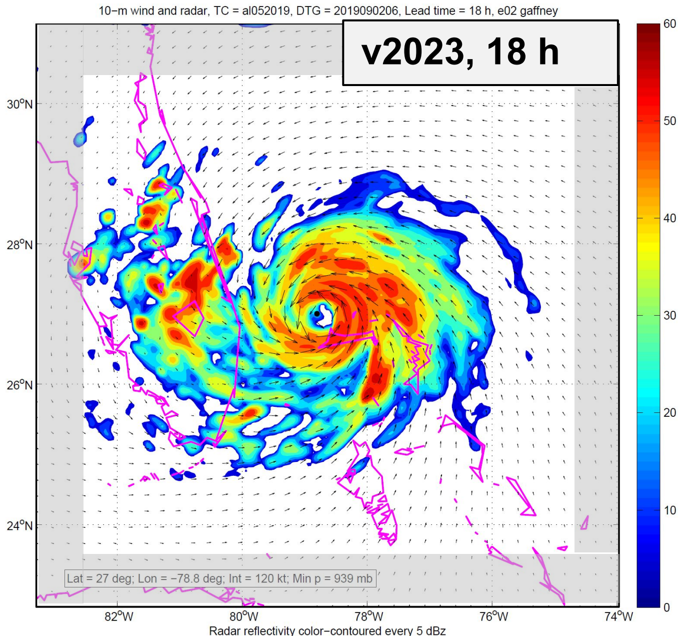
v2023 Upgrades: Deterministic and Ensemble

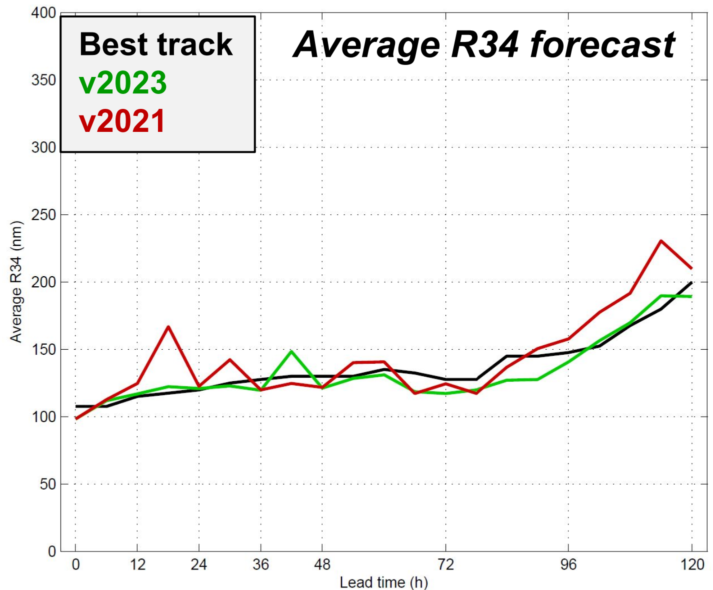
Inner nest blend zone

- Expanded blend zone reduces convection close to grid boundaries by “importing” drier air from grid 2 into grid 3
- In the Dorian example shown here, the v2023 forecast is stronger than v2021 at later leads, although this is not systematic in a large sample of cases
- Wind radii, particularly R34, are slightly reduced in the Dorian example. This impact *is* systematic over many cases.





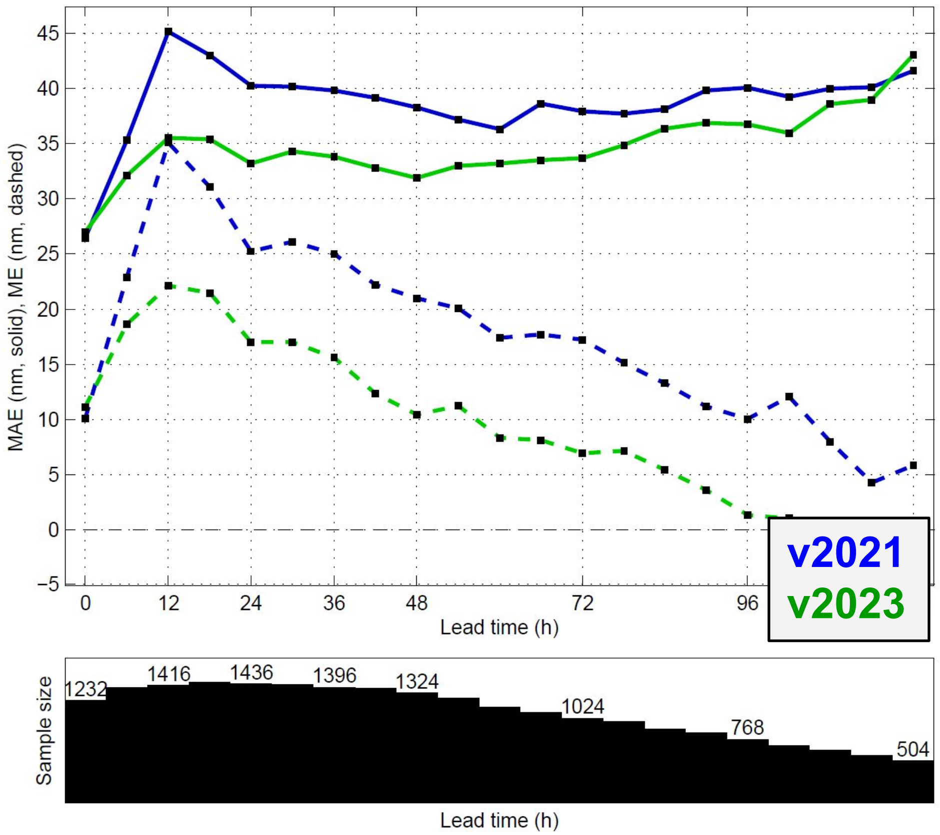




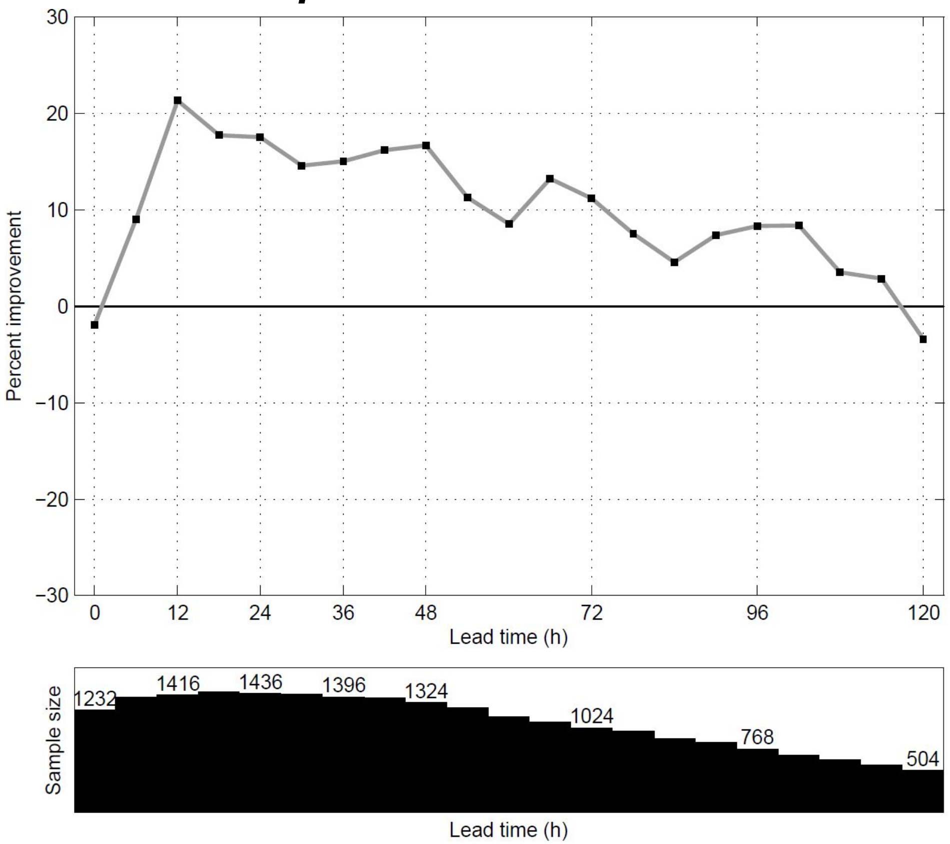
v2023 Upgrades: Deterministic and Ensemble

Inner nest blend zone

R34 MAE (solid) and ME (dashed)



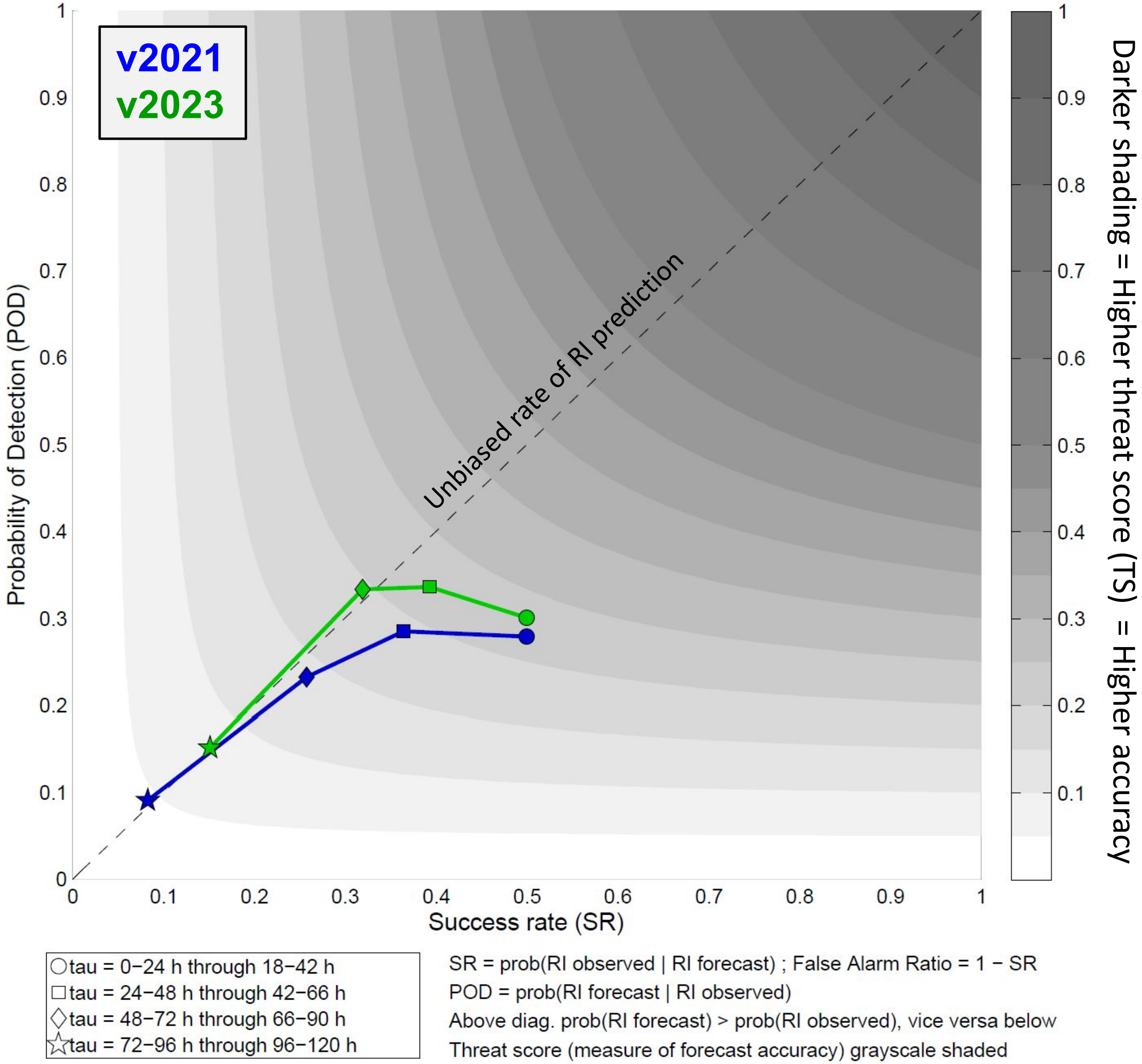
Percent improvement of v2023 w.r.t. v2021



- Summary R34 statistics are greatly improved due to the inner nest blend zone update (i.e. v2023 vs v2021)
- Positive bias is reduced at all lead times and MAE is improved up to 20%

v2023 Upgrades: Deterministic and Ensemble

Inner nest blend zone



- Rapid intensification performance is improved with wider inner nest blend zone, (i.e. v2023 w.r.t v2021) with higher threat scores and RI relative frequency closer to the observed rate
- Wider inner nest blend zone causes smaller TCs with less outer convection, which are more likely to RI

Threat Score

	0 - 24 h	24 - 48 h	48 - 72 h	72 - 96 h
v2021	0.22	0.19	0.14	0.05
v2023	0.23	0.22	0.19	0.08

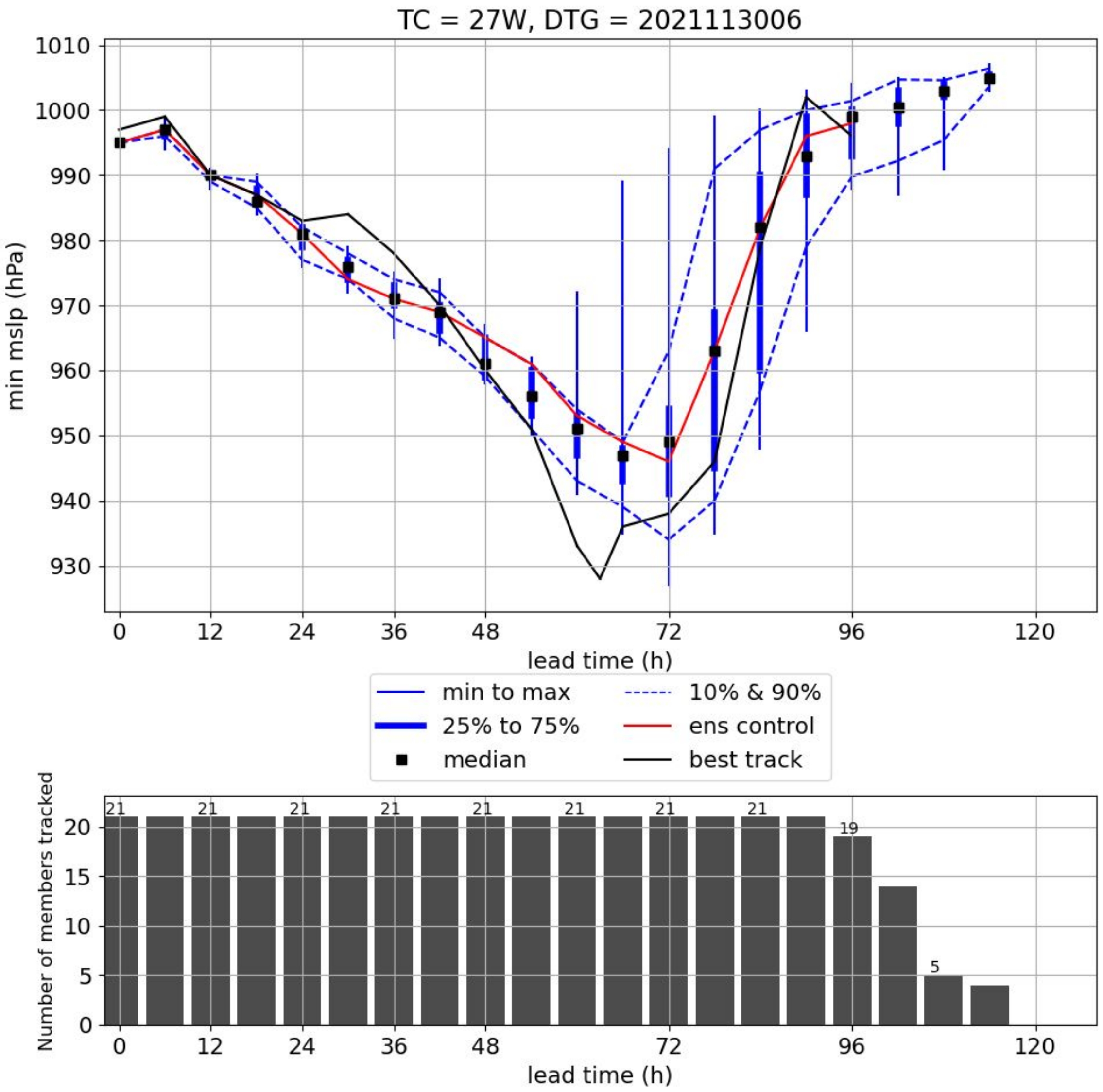
RI relative frequency

	0 - 24 h	24 - 48 h	48 - 72 h	72 - 96 h
Observed	11.7%	9.7%	6.2%	3.4%
v2021	6.5%	7.6%	5.6%	3.7%
v2023	7.1%	8.3%	6.5%	3.4%

v2023 Upgrades: Ensemble

New graphical products

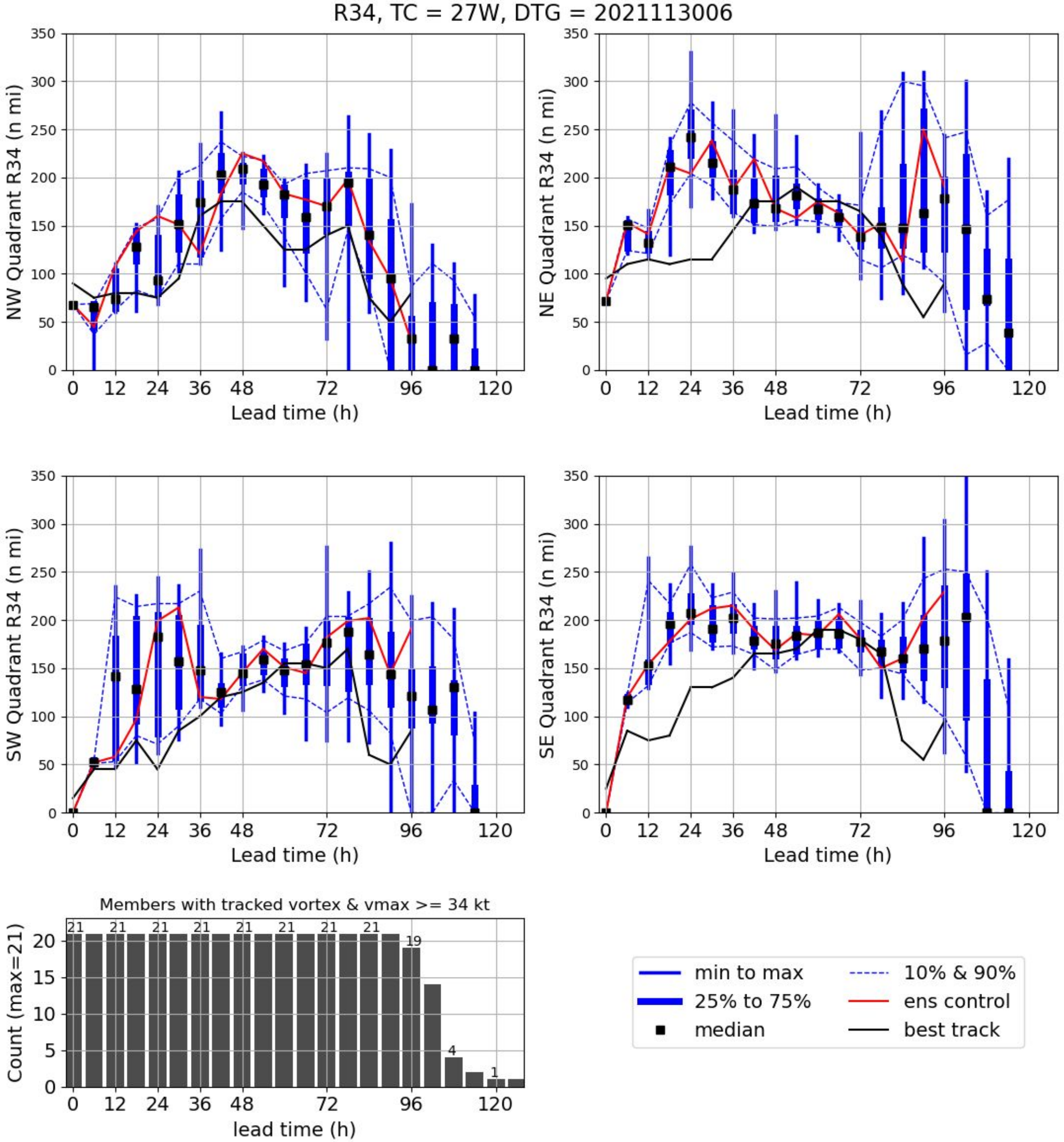
- Minimum SLP candlestick
- R34 candlestick
- R50 candlestick
- R64 candlestick
- R34 annulus
- R50 annulus
- R64 annulus



v2023 Upgrades: Ensemble

New graphical products

- Minimum SLP candlestick
- R34 candlestick
- R50 candlestick
- R64 candlestick
- R34 annulus
- R50 annulus
- R64 annulus



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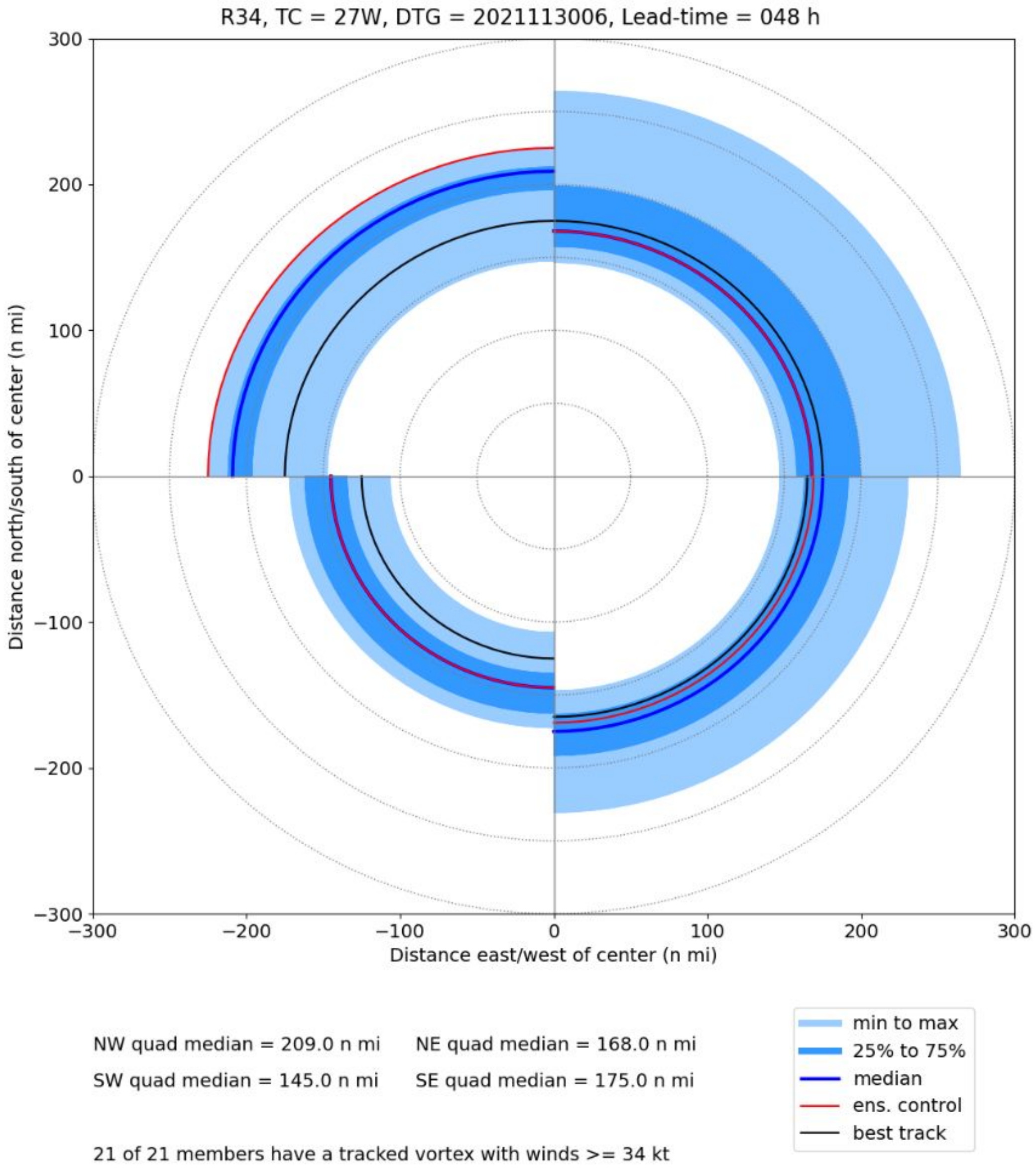

v2023 Upgrades: Ensemble

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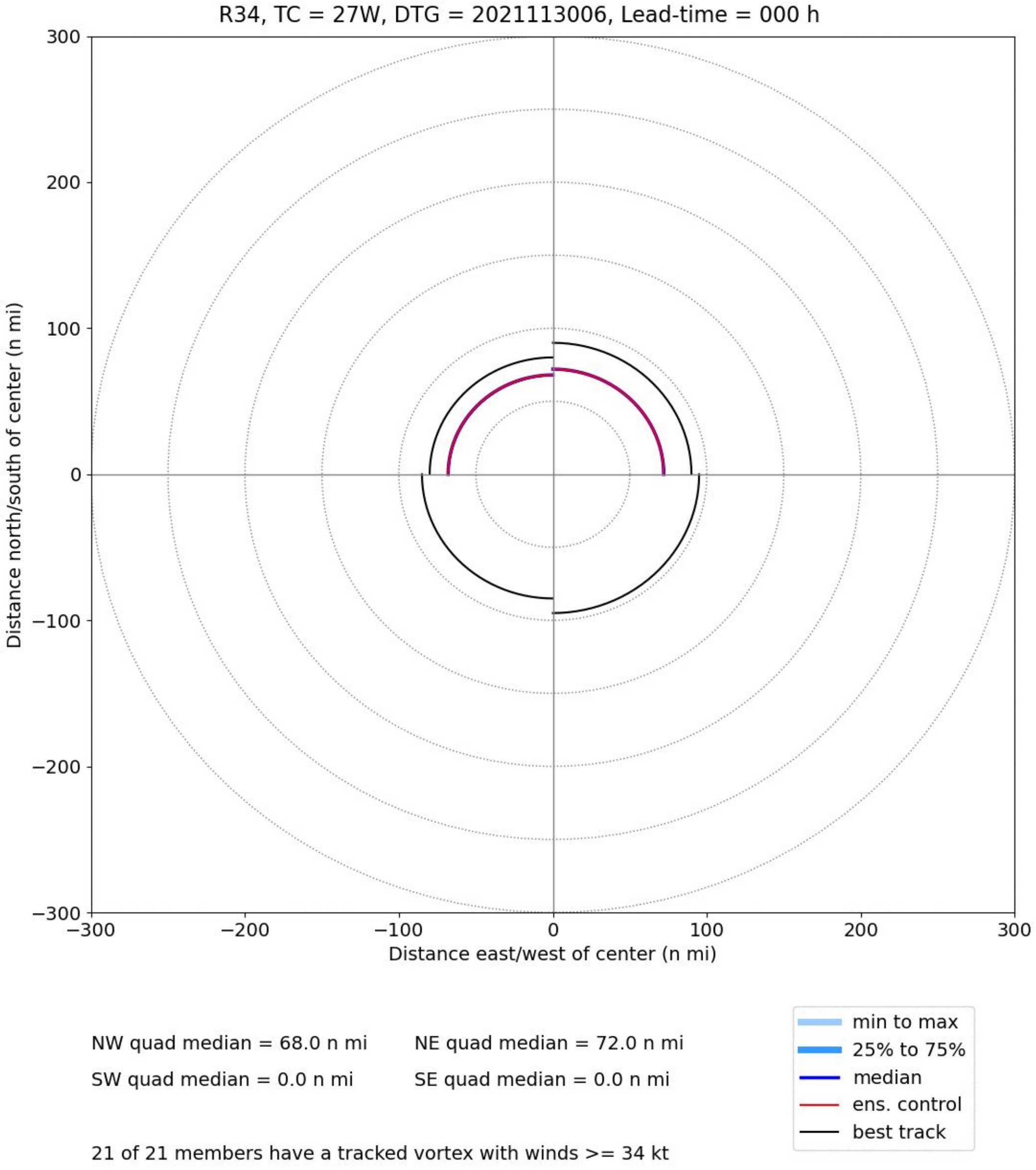
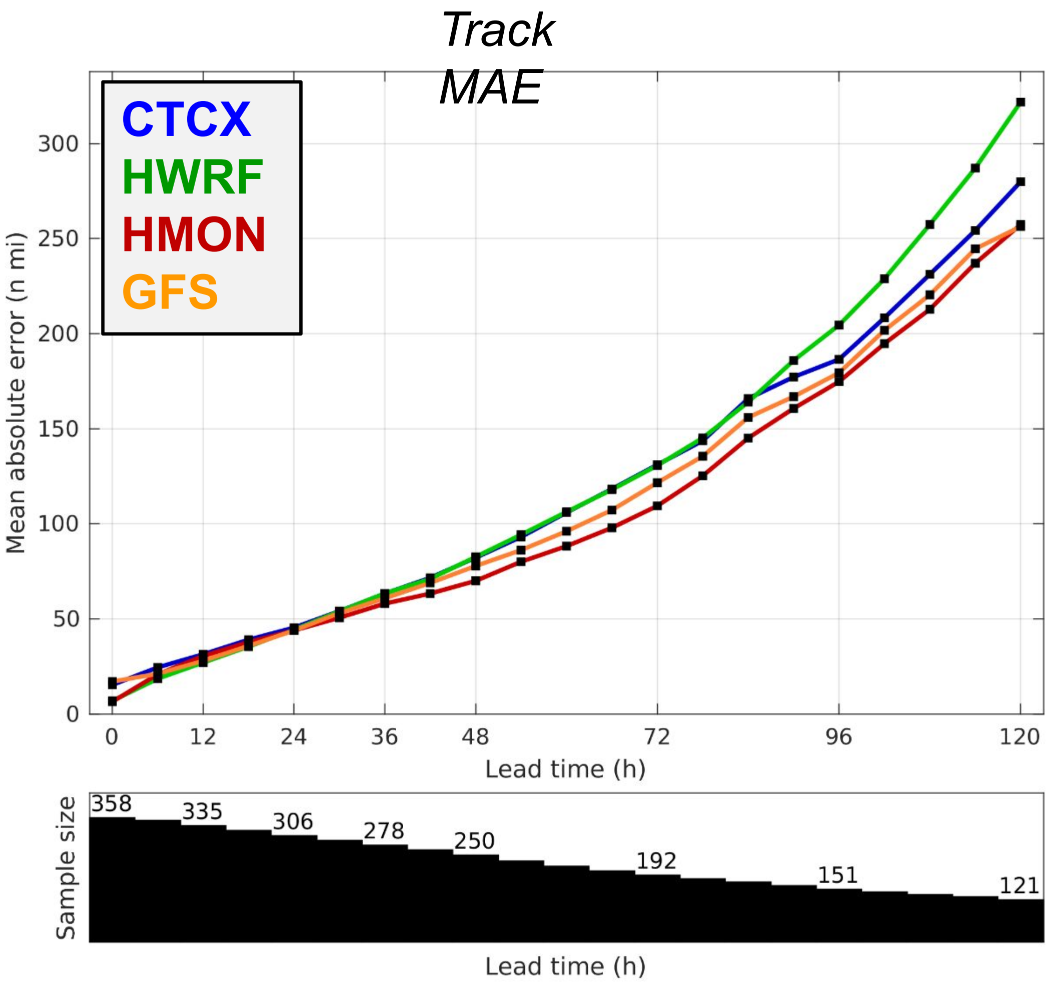
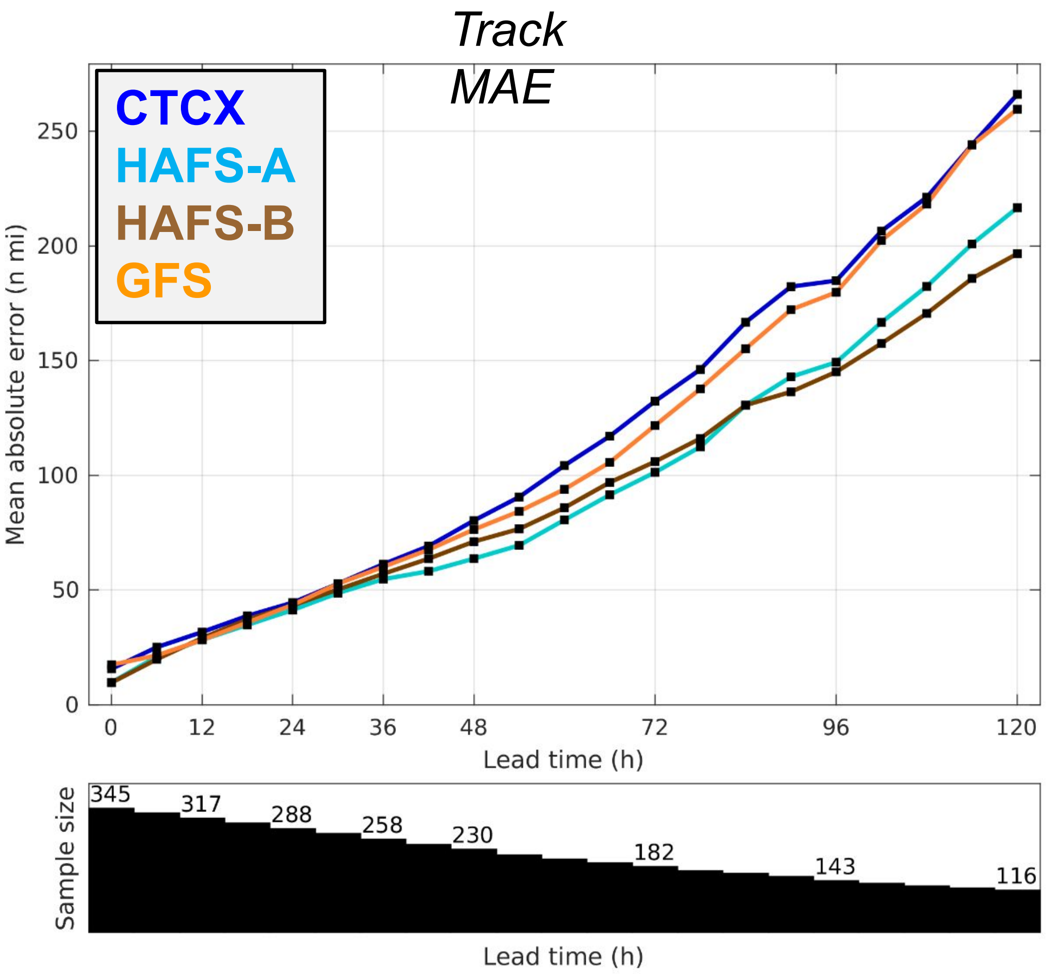


Recent Performance

2023 Atlantic track (02L-18L)



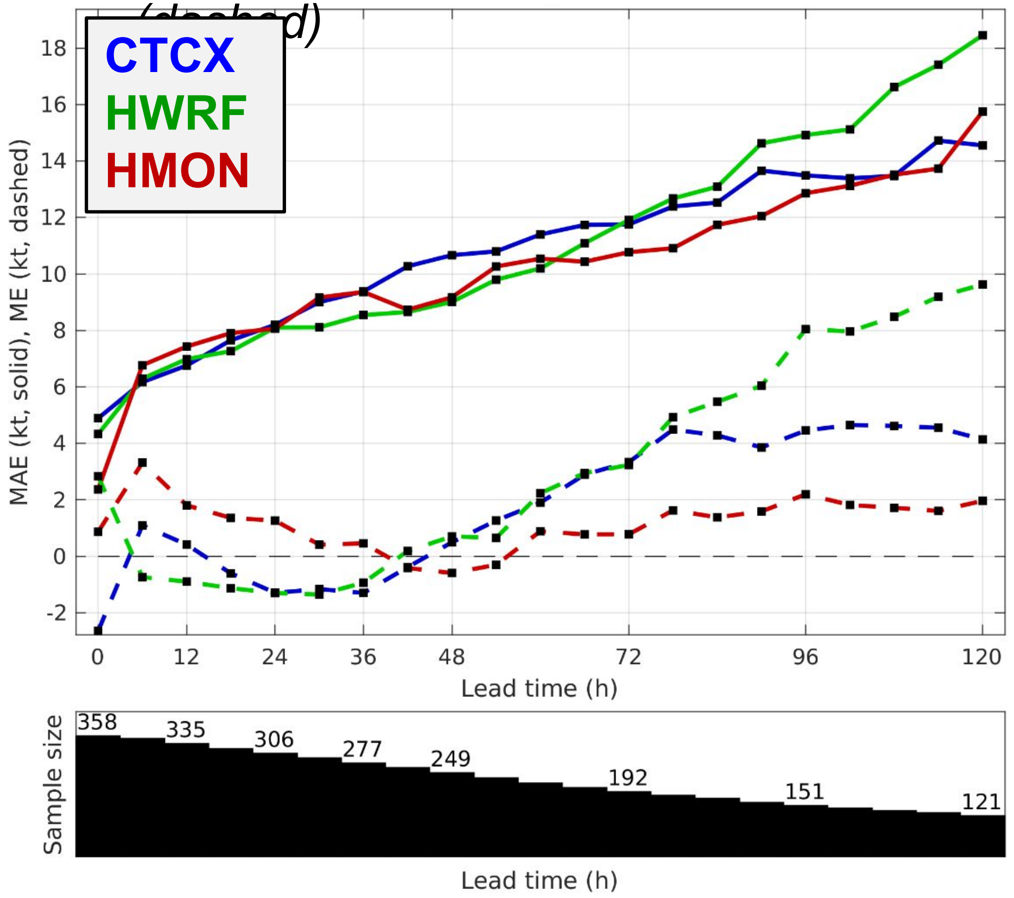


- CTCX track MAE slightly higher than GFS at most lead times
- CTCX better track MAE w.r.t. GFS in 2022 & 2020 Atlantic, worse in 2021 Atlantic

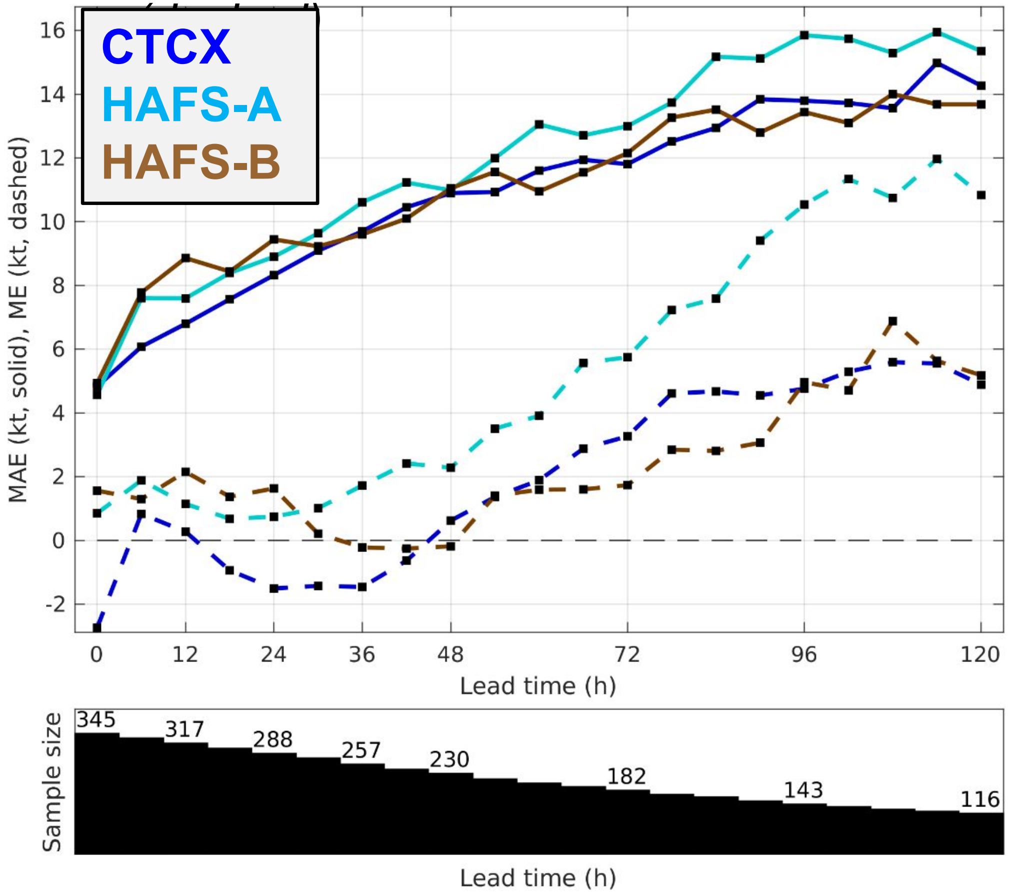
Recent Performance

2023 Atlantic intensity (02L-18L)

Intensity MAE (solid) and ME (dashed)



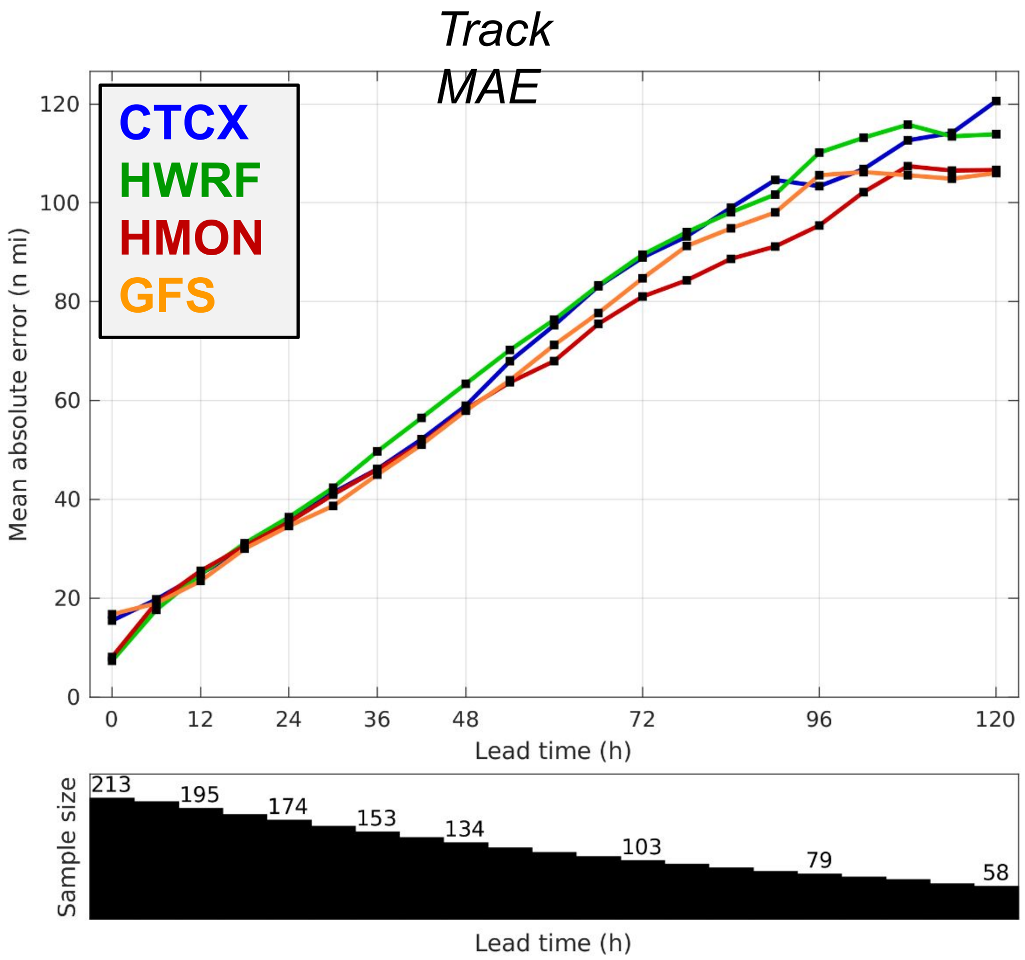
Intensity MAE (solid) and ME (dashed)

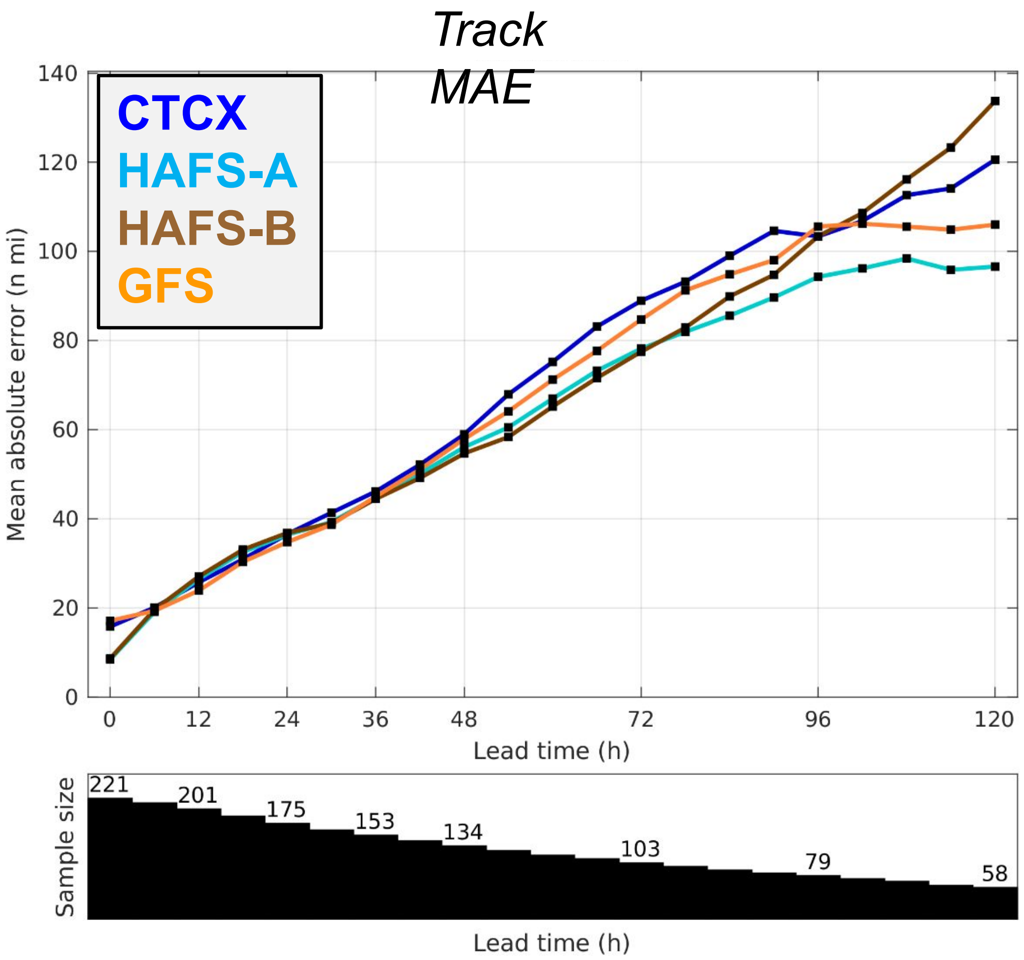


- CTCX intensity MAE broadly similar to the other 4 GFS-based regional TC models
- CTCX biased high at longer leads, similar to the other models

Recent Performance

2023 EastPac track (01E-14E)





- Like the Atlantic, CTCX EastPac track MAE a little higher than GFS
- CTCX better track MAE w.r.t. GFS in 2022 & 2021 EastPac, worse in 2020

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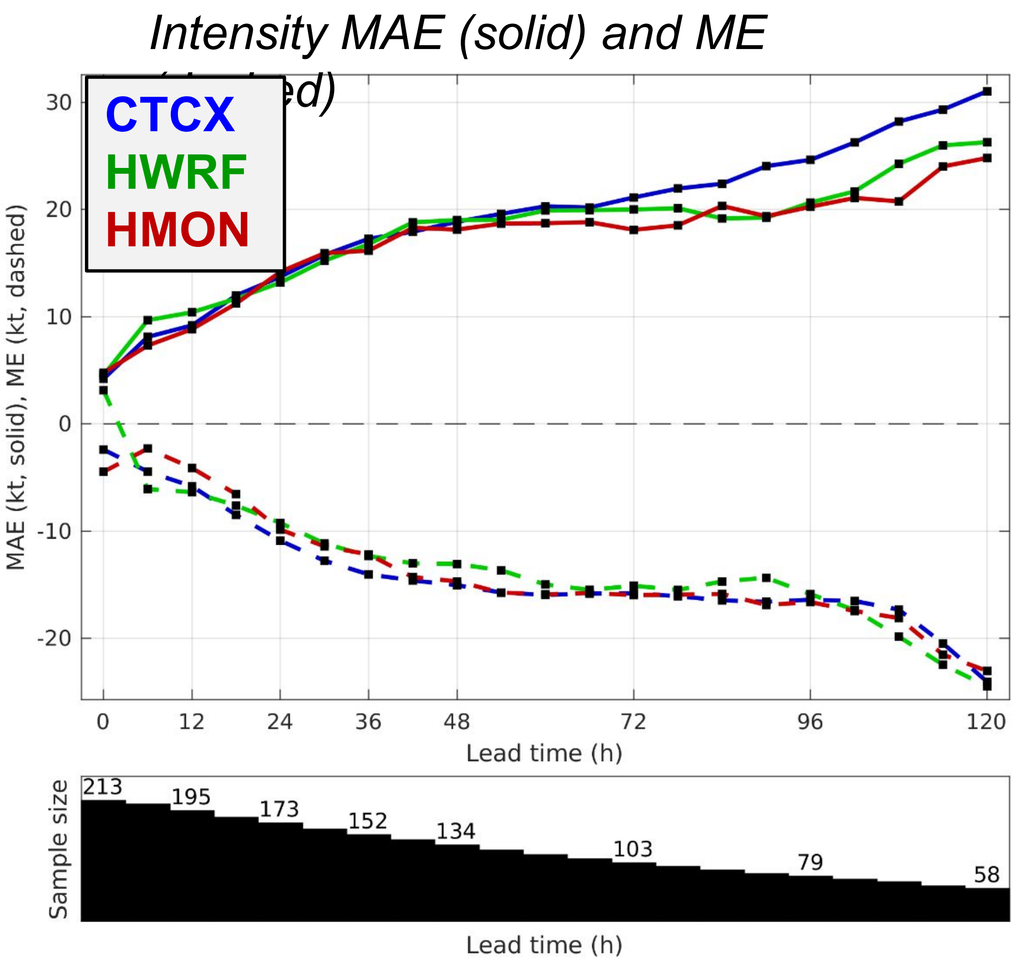
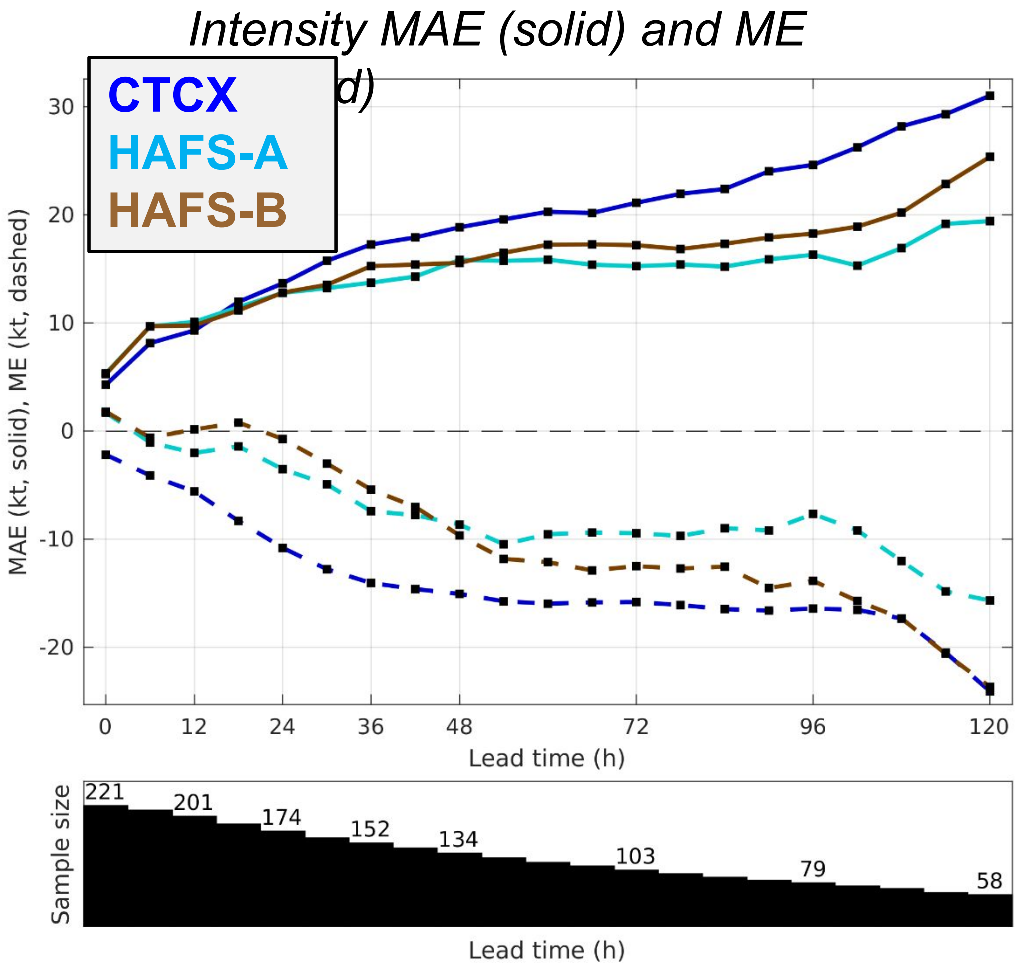
Recent Performance

2023 EastPac intensity (01E-14E)





- Regional models have huge negative bias that you don’t usually see in a season/basin sample
- CTCX intensity MAE relatively high compared to the other models, especially at long leads (Dora)

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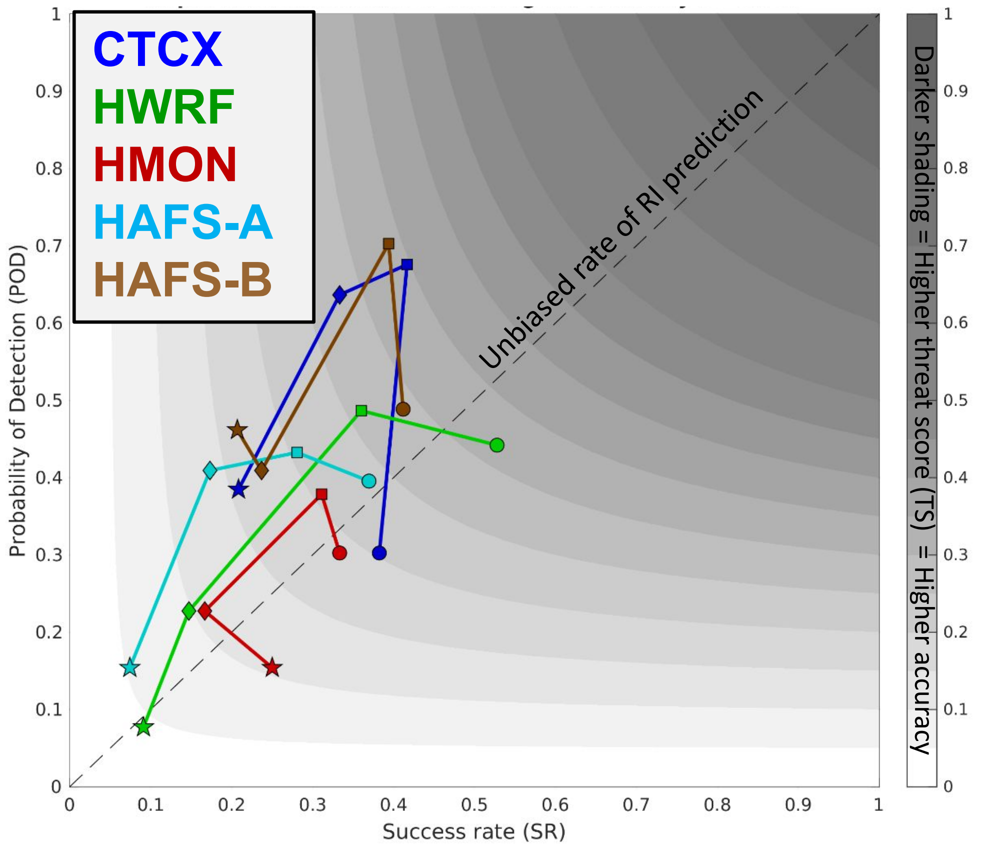
Recent Performance

2023 Rapid Intensification

Atlantic 02L-18L



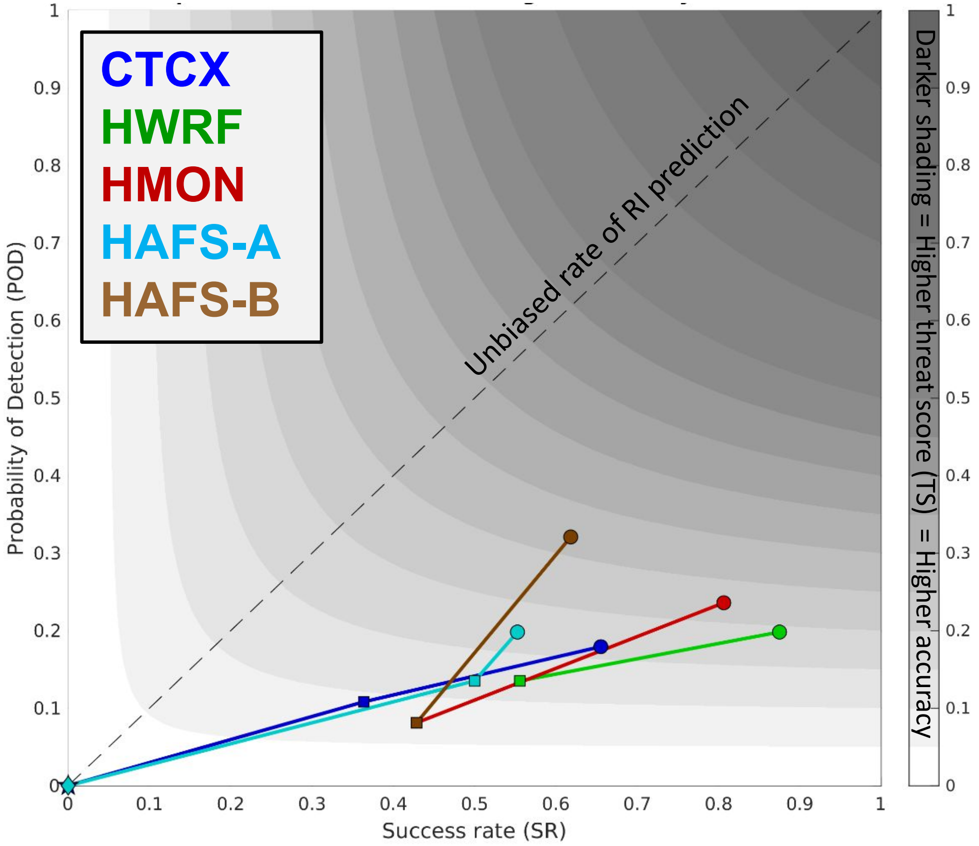
○ tau = 0-24 h through 18-42 h
□ tau = 24-48 h through 42-66 h
◇ tau = 48-72 h through 66-90 h
☆ tau = 72-96 h through 96-120 h

SR = prob(RI observed | RI forecast) ; False Alarm Ratio = 1 - SR
POD = prob(RI forecast | RI observed)
Above diag. prob(RI forecast) > prob(RI observed), vice versa below
Threat score (measure of forecast accuracy) grayscale shaded

Line legend: CTCX, HWRF, HMON, HAFS-A, HAFS-B

	0-24 h	24-48 h	48-72 h	72-96 h
Sample Size	1053	835	665	640
prob(RI observed)	0.041	0.044	0.033	0.020
prob(RI forecast) (CTCX)	0.032	0.072	0.063	0.037
prob(RI forecast) (HWRF)	0.034	0.060	0.051	0.017
prob(RI forecast) (HMON)	0.037	0.054	0.045	0.013
prob(RI forecast) (HAFS-A)	0.044	0.068	0.078	0.042
prob(RI forecast) (HAFS-B)	0.048	0.079	0.057	0.045

EastPac 01E-14E



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Threat score (measure of forecast accuracy) grayscale shaded

Line legend: CTCX, HWRF, HMON, HAFS-A, HAFS-B

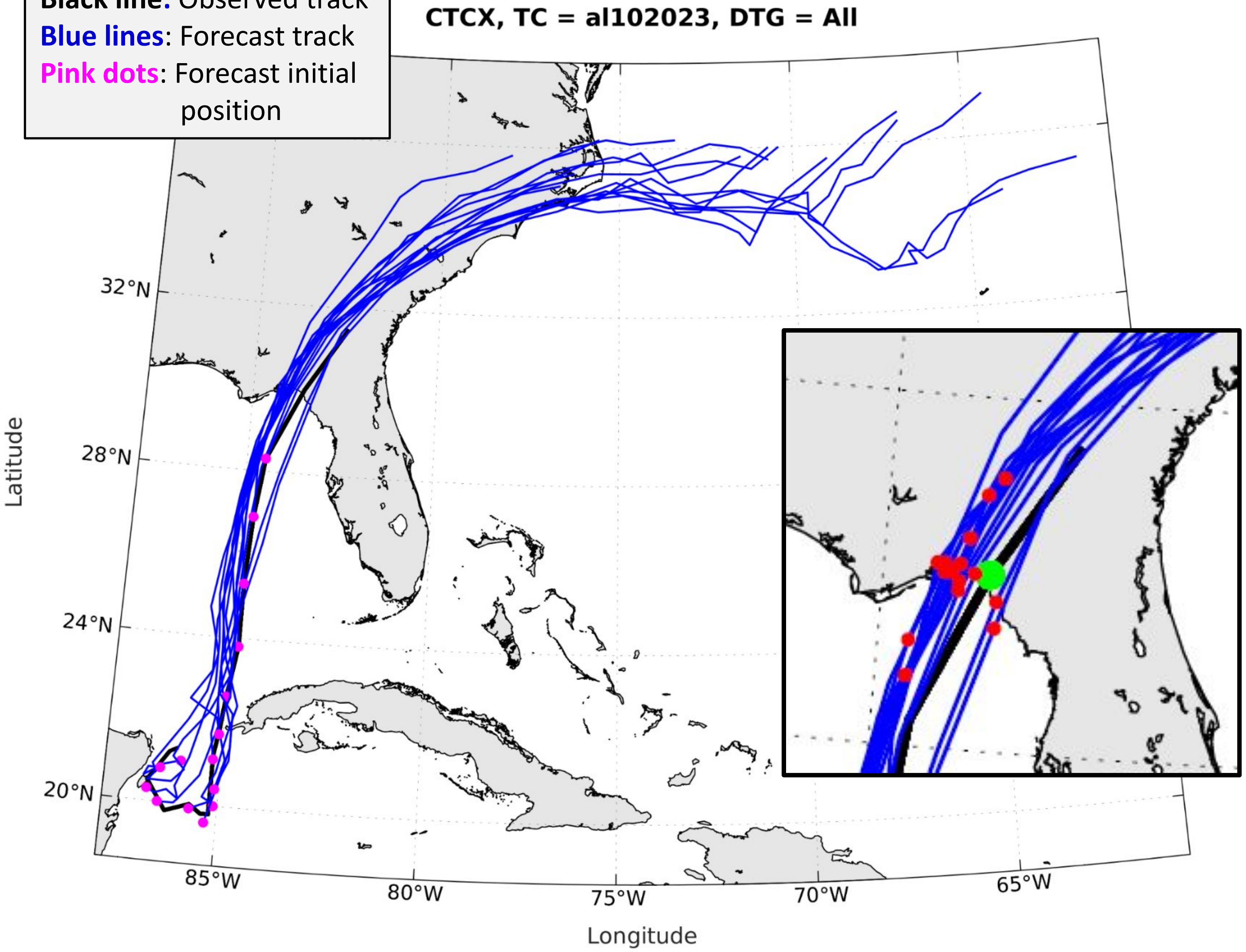
	0-24 h	24-48 h	48-72 h	72-96 h
Sample Size	630	486	373	342
prob(RI observed)	0.168	0.076	0.024	0.029
prob(RI forecast) (CTCX)	0.046	0.023	0.016	0.018
prob(RI forecast) (HWRF)	0.038	0.019	0.000	0.000
prob(RI forecast) (HMON)	0.049	0.014	0.000	0.000
prob(RI forecast) (HAFS-A)	0.060	0.021	0.008	0.000
prob(RI forecast) (HAFS-B)	0.087	0.014	0.000	0.000

- Atlantic: Not much RI observed, models overpredict RI rel. frequency
- EastPac: Lots of RI observed, models underpredict RI rel. frequency
- CTCX accuracy relatively good in Atlantic, relatively poor in EastPac

Recent Performance

Hurricane Idalia

Black line: Observed track
Blue lines: Forecast track
Pink dots: Forecast initial position



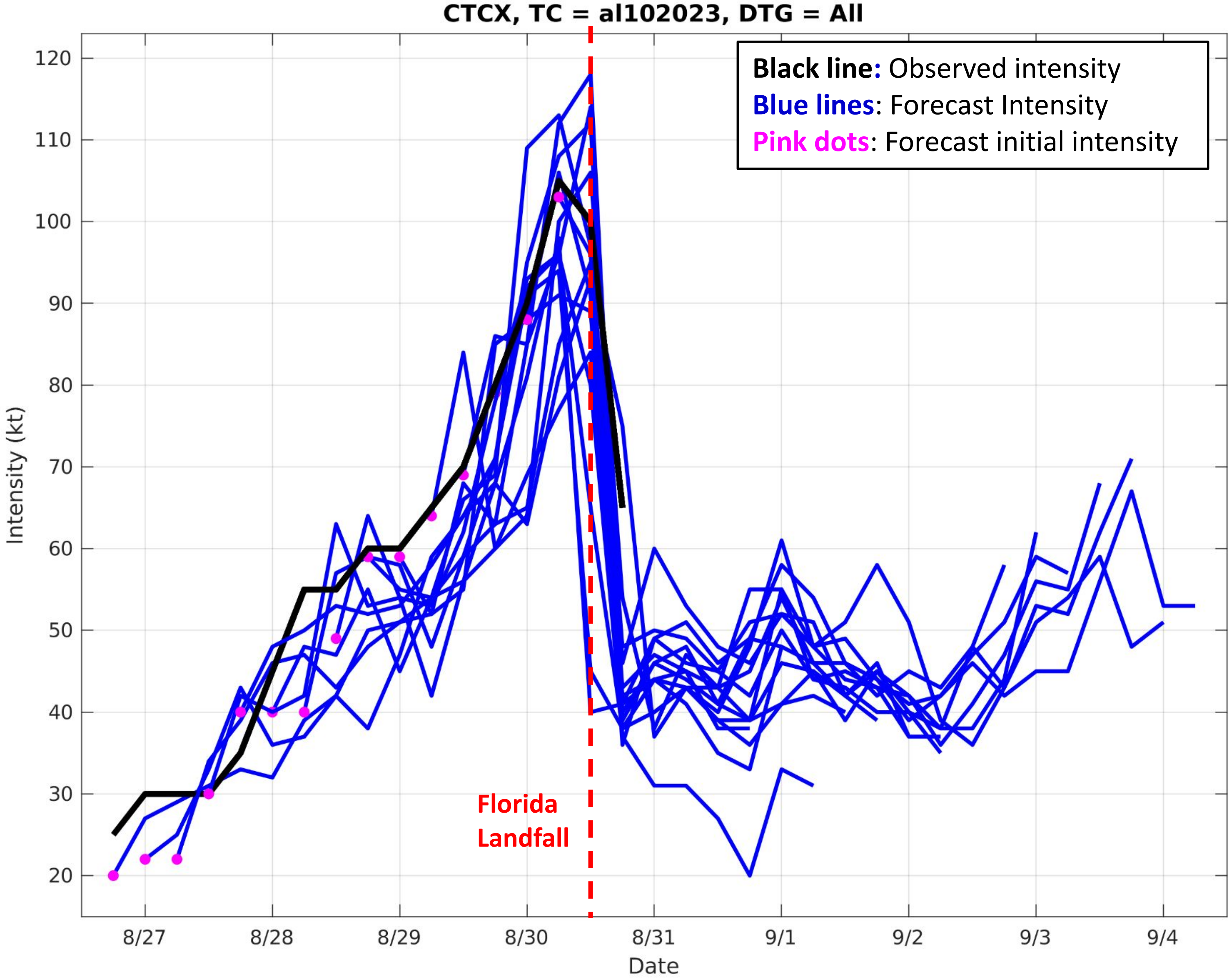
- Plots show all CTCX forecasts of 10L through 2023083006 (last initial time before landfall)
- For landfall forecast: CTCX had minimal cross-track error but a slight bias to the left. Early forecast had some along-track errors but little overall bias

Black line: Observed track
Green dot: Observed TC position at time of landfall

Blue lines: Forecast tracks
Red dots: Forecast TC positions at time of landfall

Recent Performance

Hurricane Idalia



- Excellent rapid intensification forecasts from CTCX, with RI indicated leading up to landfall starting with the first forecast of 10L. Intensity forecasts biased a bit to the low side.

CTCX Forecast

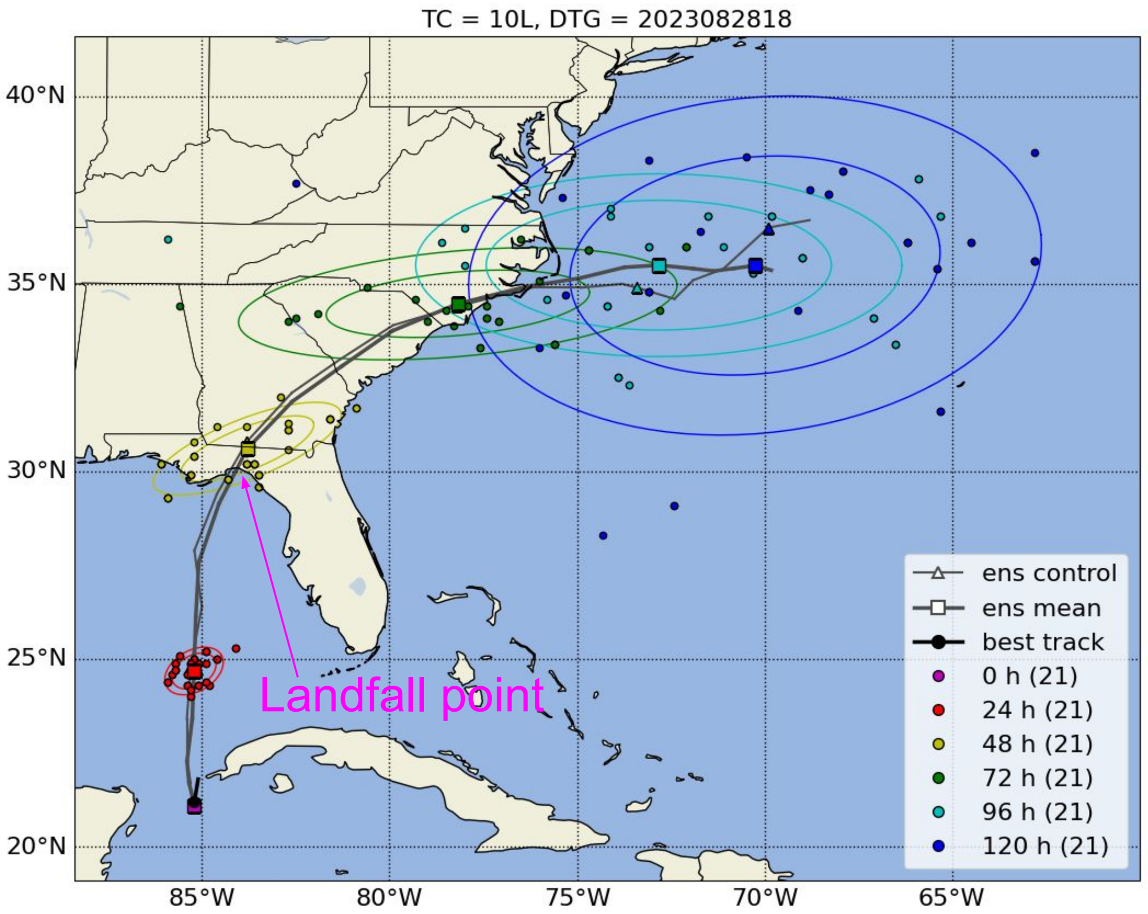
Initial time	Peak Intensity (kt)
2023082618	98
2023082700	94
2023082706	91
2023082712	92
2023082718	112
2023082800	113
2023082806	114
2023082812	93
2023082818	106
2023082900	95
2023082906	84
2023082912	118
2023082918	96
2023083000	106
2023083006	103
Average	**101**
Observed	***105***

TS: 33-63 kt
Cat 1: 64-82 kt
Cat 2: 83-95 kt
Cat 3: 96-112 kt
Cat 4: 113-136 kt
Cat 5: 137+ kt

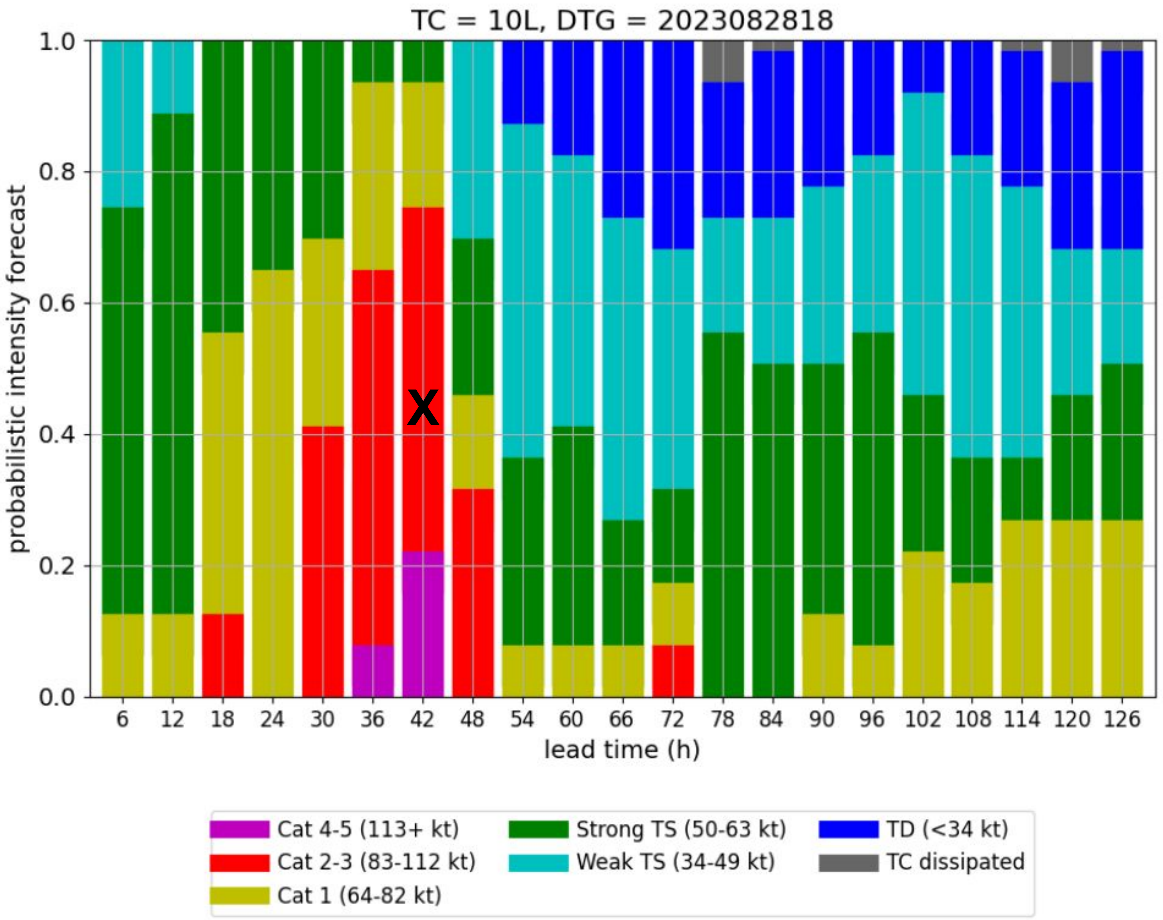
Recent Performance

Hurricane Idalia

Example 21-member NRL real-time demonstration CTCX ensemble forecast for Idalia (2023082818)



Ensemble mean had excellent forecast of landfall position/timing 42 h in advance



Landfall intensity of 110 kt was well within the ensemble envelope of possibilities

Summary and Future Directions

- **COAMPS-TC development provides insights into key systematic errors & how to address them**
  - Intensity systematic errors identified are most sensitive to:
    - C_D, air-sea coupling, boundary layer, microphysics, shallow & deep convection
  - Track systematic errors identified are most sensitive to:
    - Shallow & deep convection, cloud microphysics and radiation, boundary layer
- **Near Future**
  - FY24 focus on transitioning updated CTCX ensemble: Potentially more members, improved initial perturbations, new probabilistic forecast products
- **Long-Term Outlook**
  - Use observations (aircraft, field programs…) and continue to collaborate with HRD/APHEX
  - Focus on TC intensification and structure prediction challenges.
    - Predicting RI: Models now have sufficient skill for RI that some cases are reasonably captured (e.g. Ida, Ian, Idalia), but other TCs that undergo RI remain a challenge (extreme RI, e.g. Lee)
    - Predicting secondary eyewall formation, moderately sheared TCs that intensify, inner core dynamics (roll circulations, TC gusts etc.)
  - Significant Physics and DA challenges remain

Extra Slides

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Hurricane Boundary Layer

Sensitivity to PBL Parameterization

- Motivation: TC intensity and structure are very sensitivity to PBL parameterizations (Kepart 2010; Hazleton 2018; Zhu 2021; Chen 2022)
- Methods: Testing 1.5 Order TKE scheme, 1st order closure (YSU PBL)
- Key Findings:
  - Sensitivity of intensity and structure to mixing length (& S_h, S_m)
    - NRL MY (Blackadar 1962; Mellor & Yamada 1982; Burk & Thompson 1990)
    - Bougeault (Bougeault & Andre 1986; Bougeault & Lacarrère 1989)
    - Hybrid (Mellor-Yamada in PBL and Bougeault above PBL)
  - Poor performance of the 1st order close scheme (YSU) (not shown)

COAMPS-TC 1.5 order closure

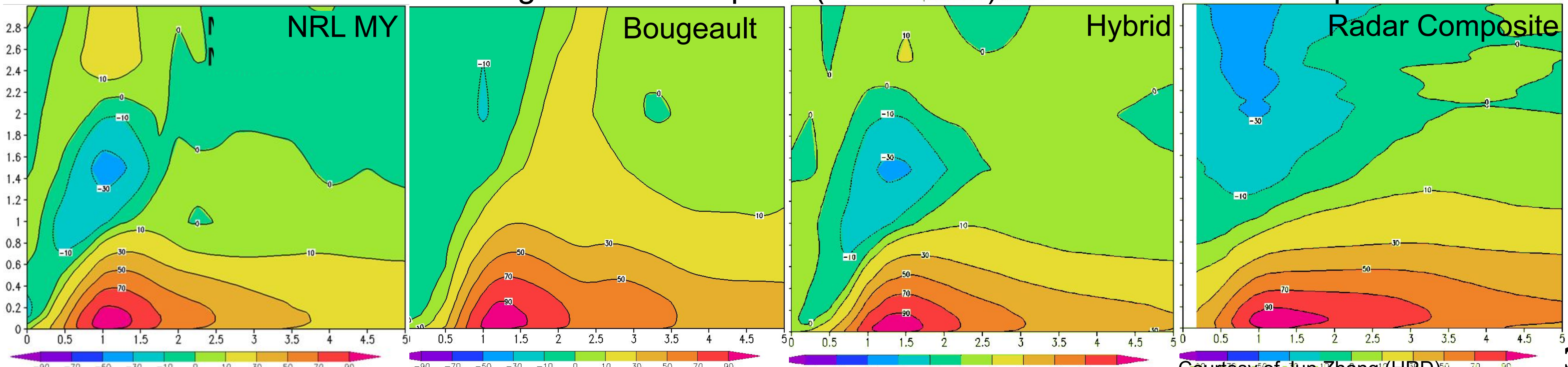
(modified Mellor and Yamada 1982)

$$e = \overline{(u'^2 + v'^2 + w'^2)}/2 \qquad K_{h,m} = S_{h,m}\, l e^{-1/2}$$

$$\frac{D}{Dt}(e) - \frac{\partial}{\partial z}\left(K_e \frac{\partial}{\partial z}(e)\right) = K_M\left(\frac{\partial U}{\partial z}\right)^2 + K_M\left(\frac{\partial V}{\partial z}\right)^2 - \beta g K_H \frac{\partial \theta}{\partial z} - \frac{(2e)^{3/2}}{\Lambda_1} + U\frac{\partial}{\partial x}(e)^* + V\frac{\partial}{\partial y}(e)^*$$

Diffusion, Shear, Buoyancy, Dissipation, Advection

Azimuthal Mean of the Tangential Wind Speed (normalized) for an Idealized TC Experiment



Courtesy of Jun Zhang (HRD)

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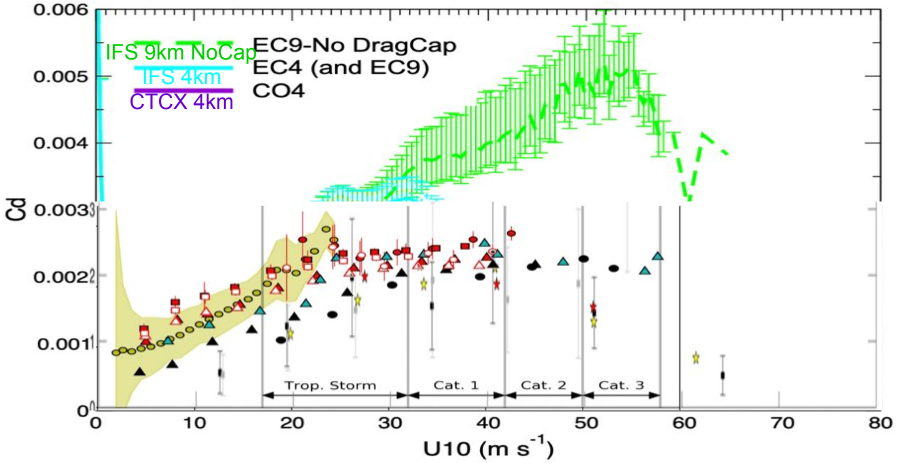
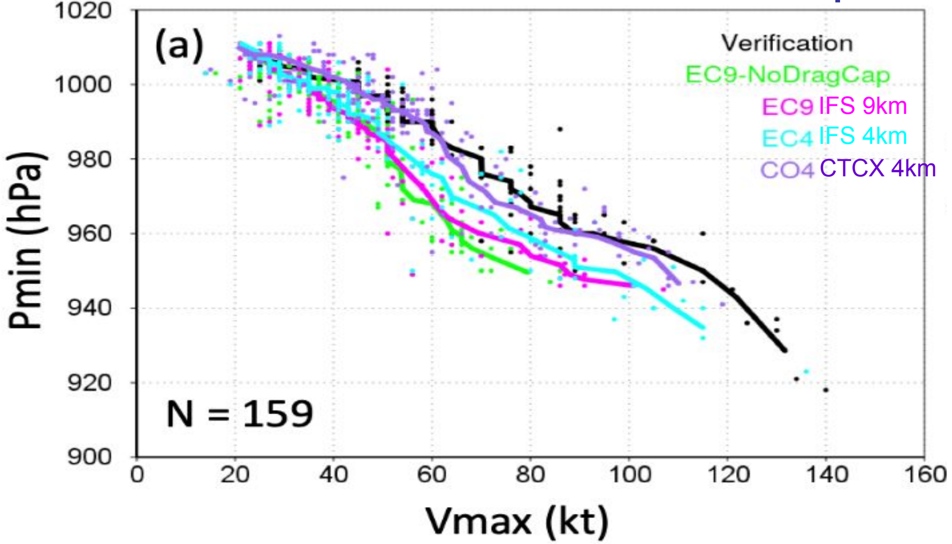
Surface Drag Parameterization
C_D Formulation (ECMWF IFS and COAMPS-TC)

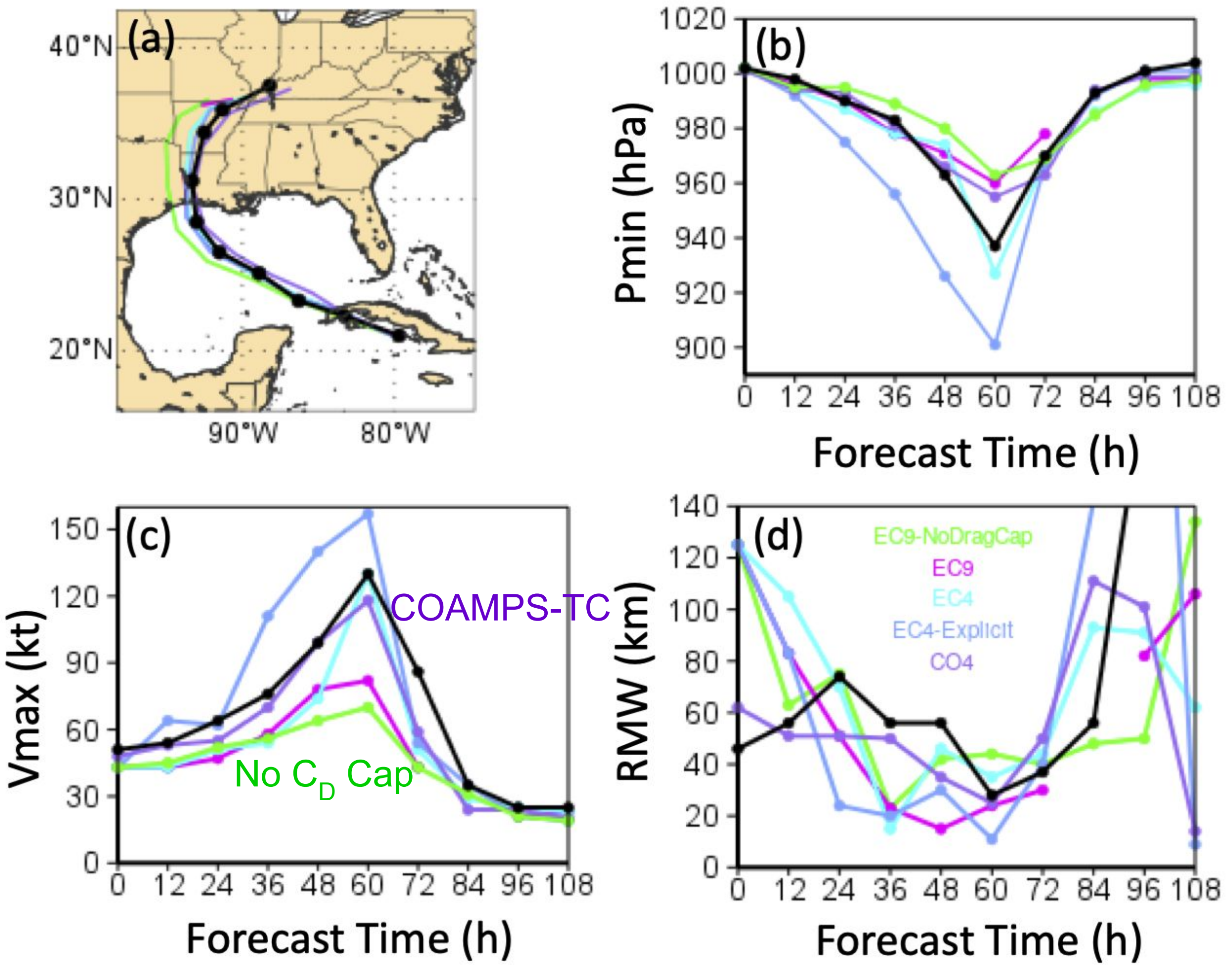
Comparison of ECMWF IFS & COAMPS-TC C_D



Pressure-Wind Relationship



Comparison of COAMPS-TC and Global ECMWF IFS for Hurricane Laura



- ECMWF IFS also shows a similar large sensitivity to the C_D formulation

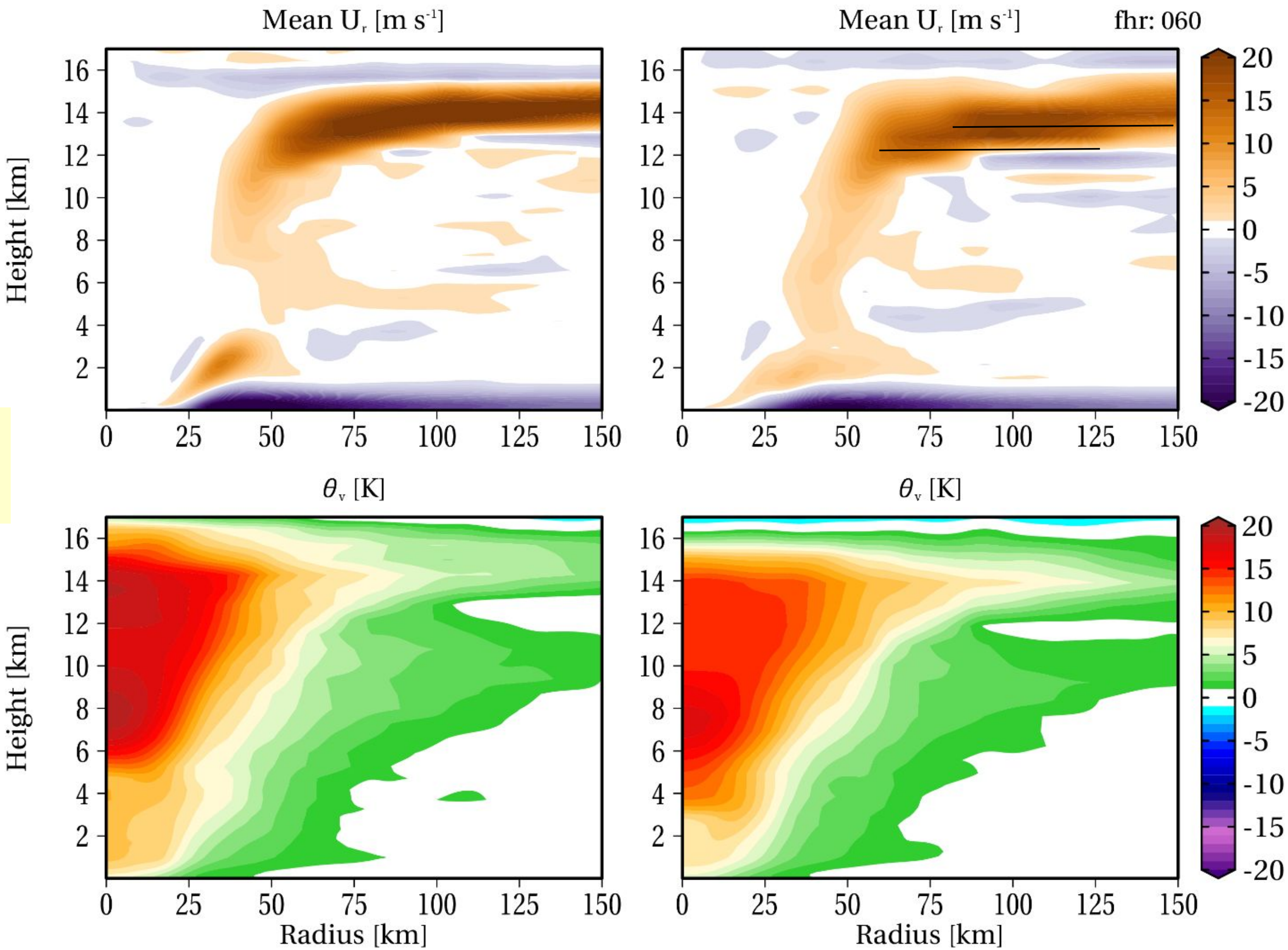
Majumdar, Magnusson, Bechtold, Bidlot, Doyle, 2023 (submitted)

Sensitivity to Resolution

Vertical Resolution

- We have extensively tested 50L and 60L configurations
  - 50L about ~1 kt stronger than 40L Control on average
  - RI relative frequency 6.6% in 40L Control, 7.5% in 50L
- Why are TCs stronger and quicker to intensity in 50L w.r.t. 40L?
  - Stronger radial outflow around 14 km in 50L w.r.t. 40L
  - Thin layer of radial inflow (above outflow layer) better defined in 50L
  - "Double" warm-core extending to higher altitude in 50L

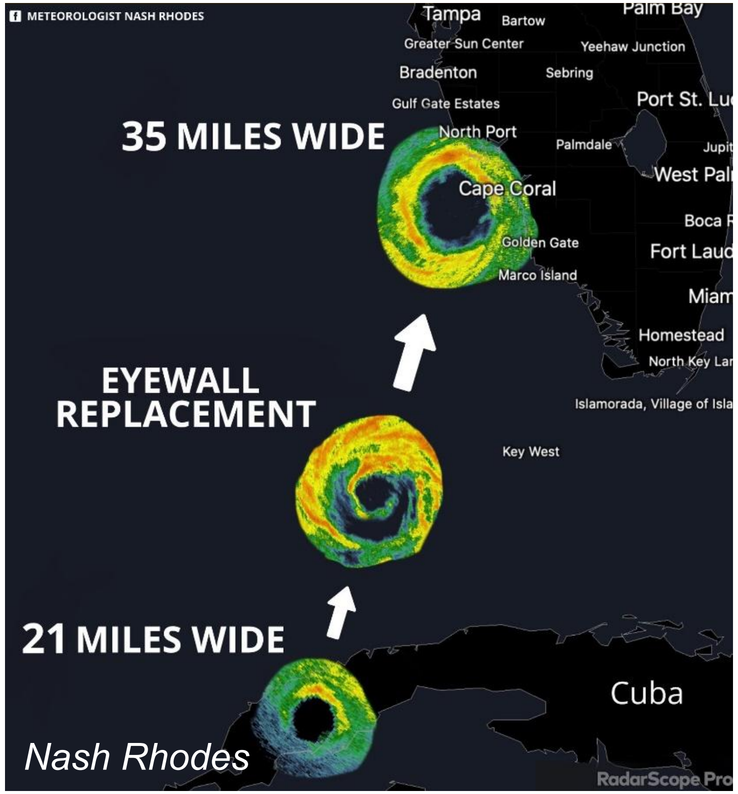
50L, Intensity = 124 kt | ***40L Control, Intensity = 115 kt***



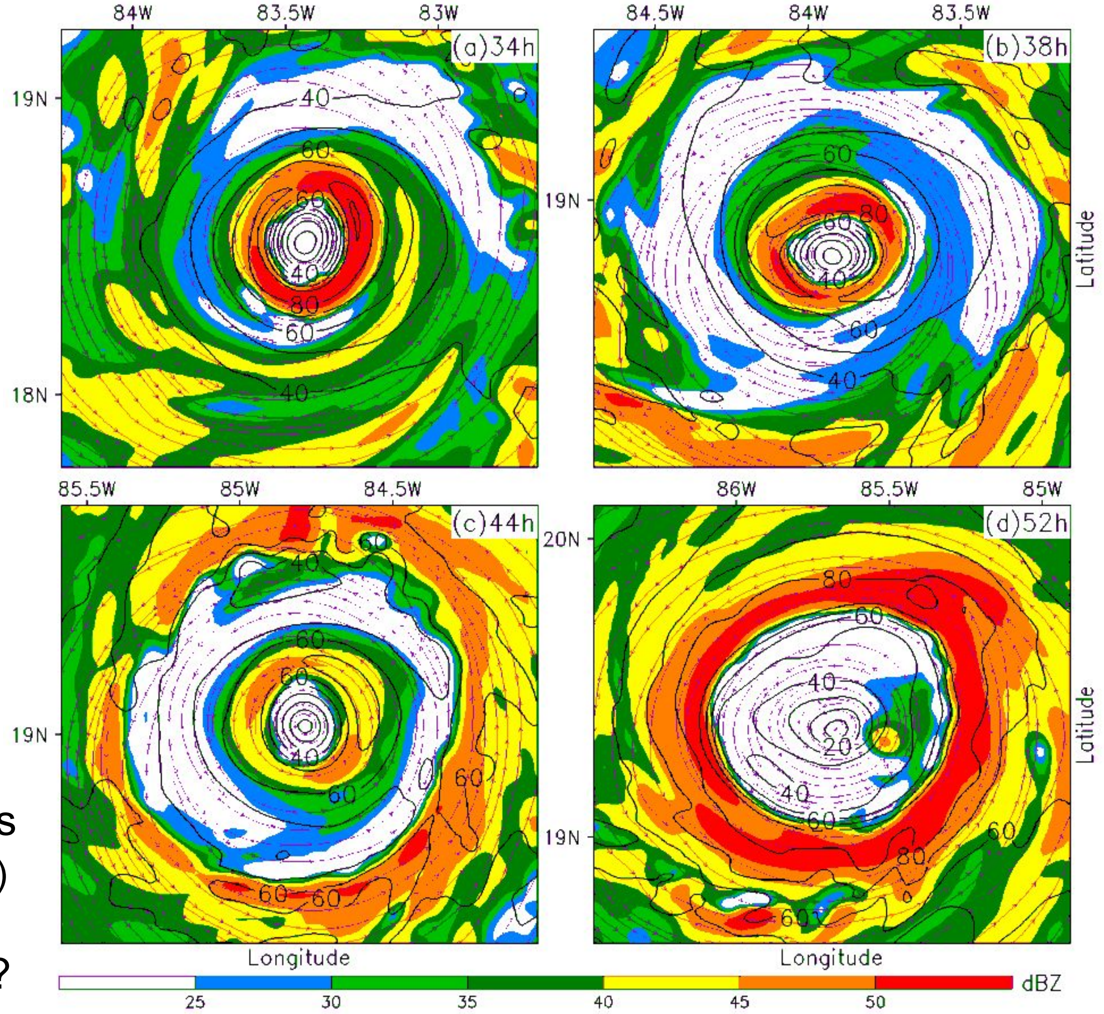
Sensitivity to Resolution

Secondary Eyewall Formation / Eyewall Replacement Cycle

Secondary Eyewall Formation / Eyewall Replacement Cycle in Hurricane Ian



At high resolution (1.67 km), COAMPS-TC can represent a SEF/ERC for Hurricane Wilma

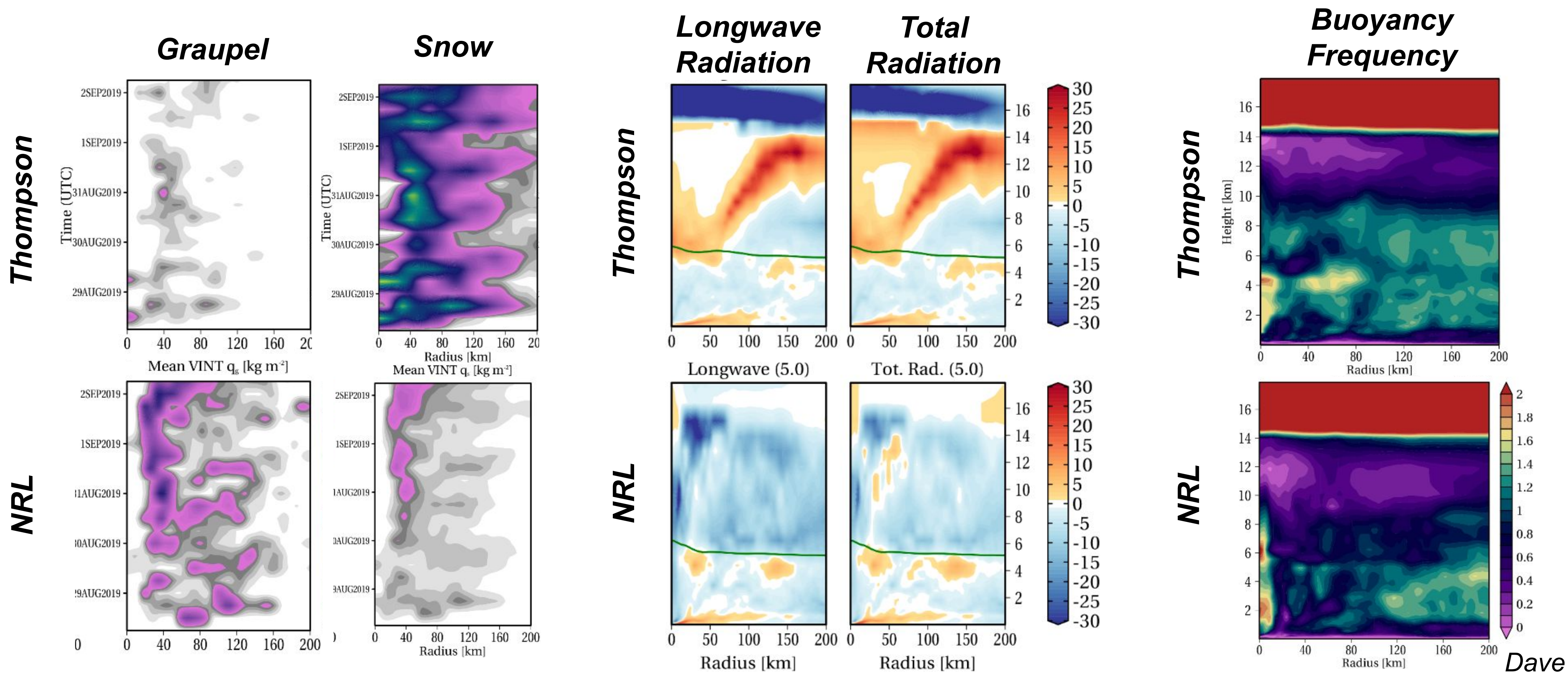


- ERCs form due to the interplay between annular heating and BL inflow
- During SEFs/ERCs, the maximum wind speed of the inner core weakens significantly after formation of the secondary eyewall (Sitkowski et al. 2011)
- Wind field then broadens, which has implications for impacts
- Can operational TC models predict SEFs/ERCs – are these predictable?

Microphysics

Sensitivity to Microphysics Parameterization

Why are tropical cyclones in Thompson systematically weaker than in the Control?



Dave Ryglicki

Thompson has *a lot* more snow than NRL, and less graupel

Thick layer of snow causes net radiative warming in NRL

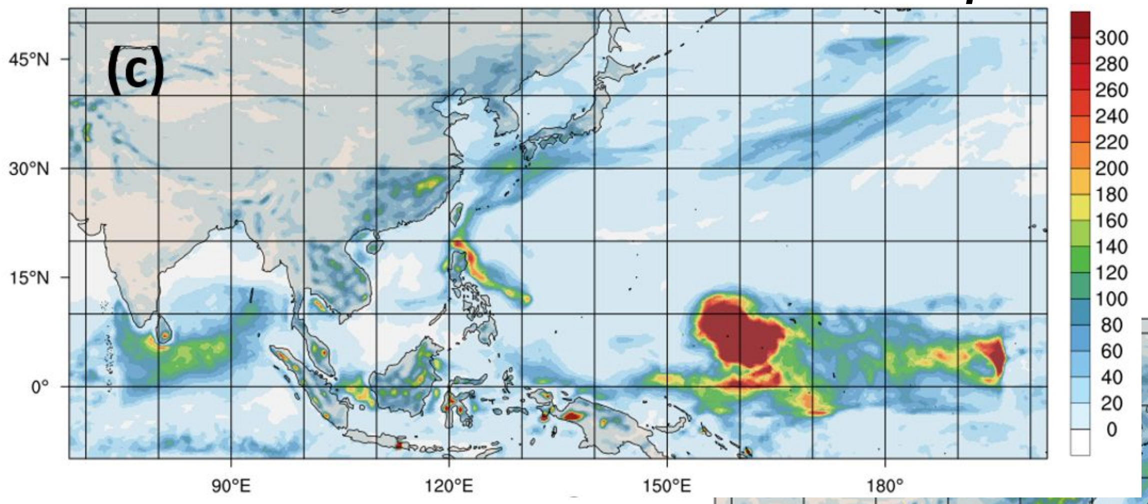
Higher stability in Thompson w.r.t. NRL

Convection

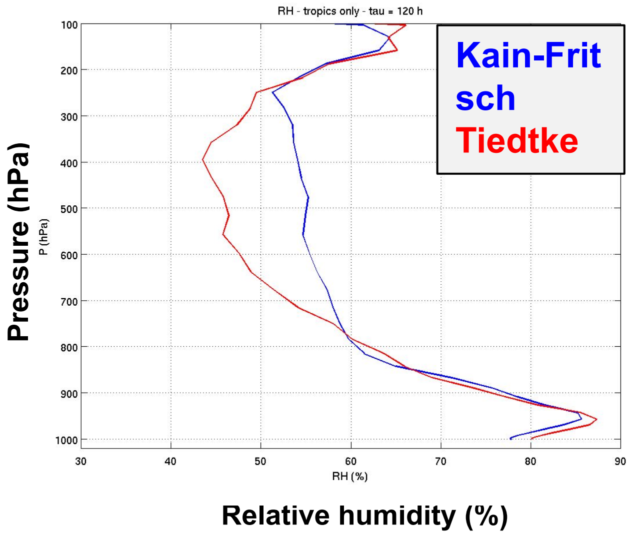
Deep Convection: Kain-Fritsch vs. Tiedtke

Analysis of the Tiedtke cumulus parameterization on the 36 & 12 km grid

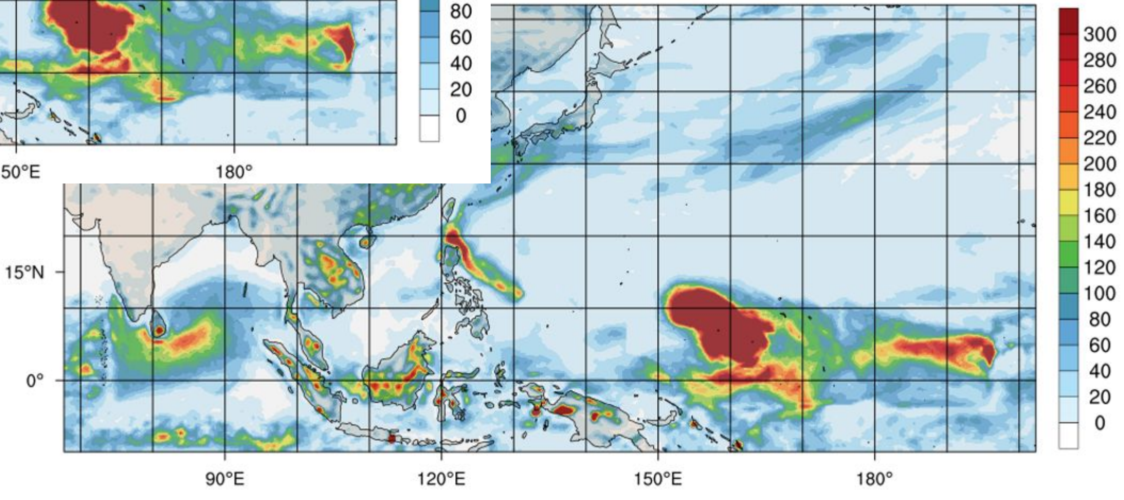
Tiedtke with reduced cw2rw Forecast Precip.



Tiedtke is much drier than KF in the free troposphere



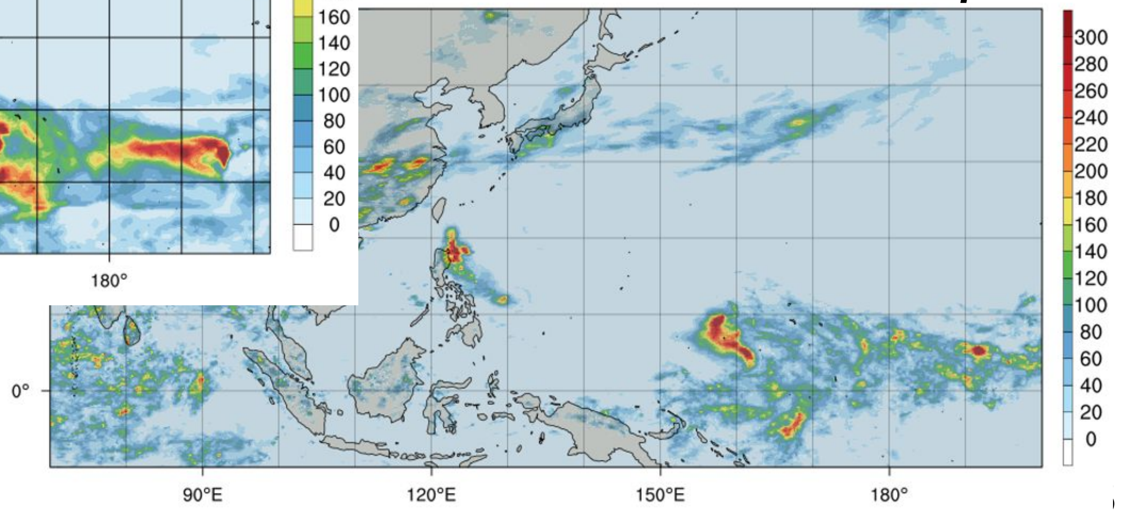
Tiedtke Forecast Precip.



Reducing the cloud water to rain water conversion rate results in improved accumulated precipitation while maintaining most of the free-tropospheric drying

Tiedtke has too much precipitation w.r.t. IMERG

NASA IMERG Observed Precip.



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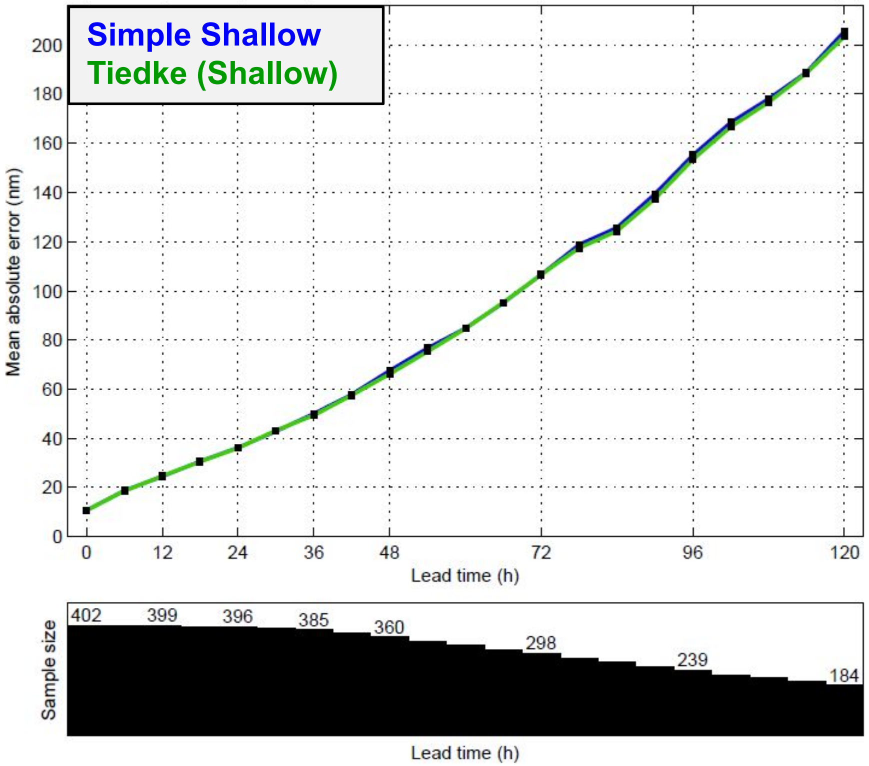
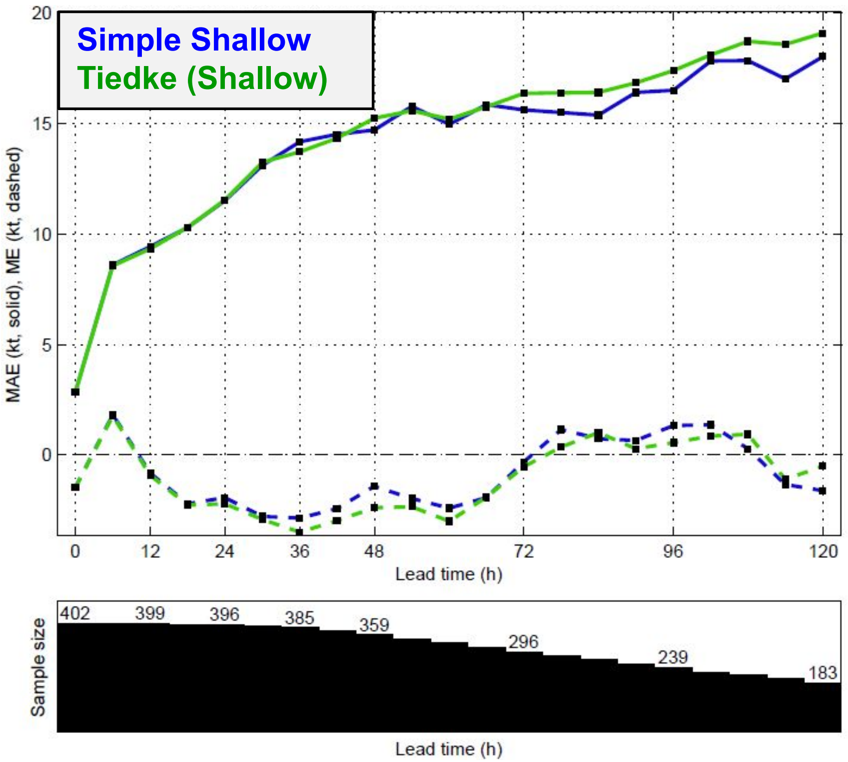
Convection

Shallow Convection

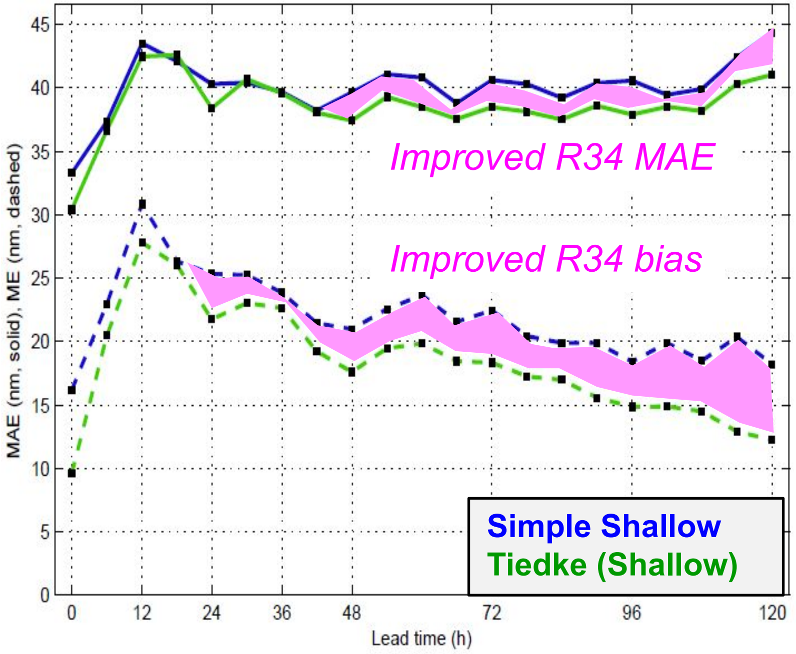
Track MAE



Intensity MAE (solid) and ME (dashed)



R34 MAE (solid) and ME (dashed)



- Motivation: Impact of shallow and congestus convection parameterization on TC track (Han and Pan 2011; Torn and Davis 2012) and intensity and structure (Wang 2014; Parker et al. 2016)
- Methods: Sensitivity tests using a simple shallow convection and the Tiedtke shallow convection
- Key Findings:
  - Tiedtke (mass flux closure) shallow convection on 36km and 12km meshes improved the R34.
  - Tiedtke convection scheme on the fine mesh results in an over-intensification bias

Hurricane Boundary Layer
Dissipative Heating

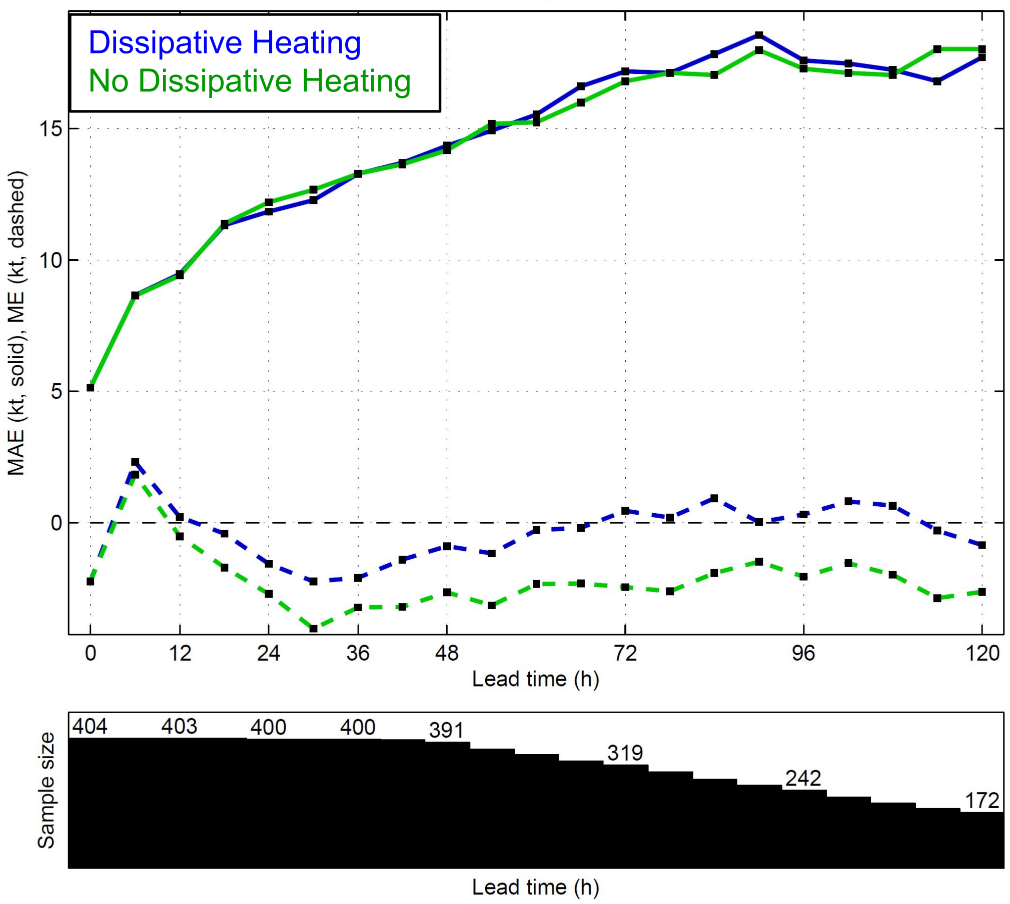
Dissipative Heating Parameterization

$$C_p \frac{\partial T}{\partial t} \approx \varepsilon$$

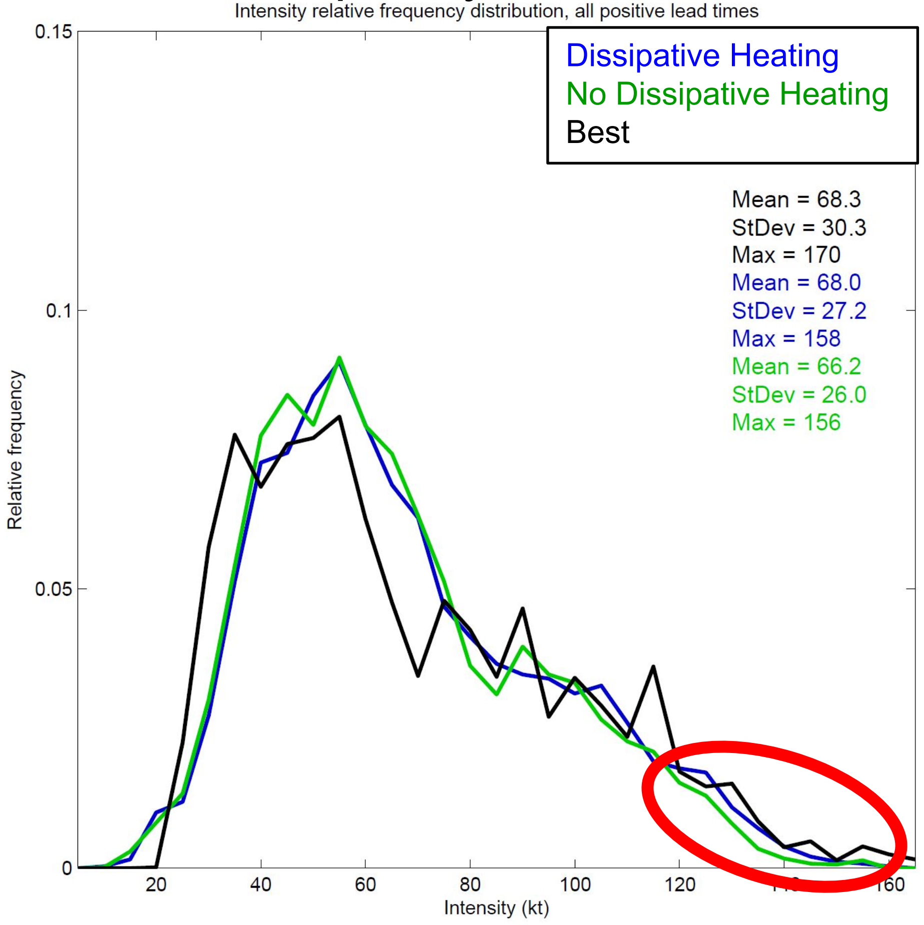
$$\varepsilon = -\tfrac{1}{2}[\partial(u'^2 + \upsilon'^2 + \overline{u'}^2)/\partial t]|_{diss}$$

Following Jin et al. (2007)

Intensity MAE (solid) and ME (dashed)



Frequency Distribution

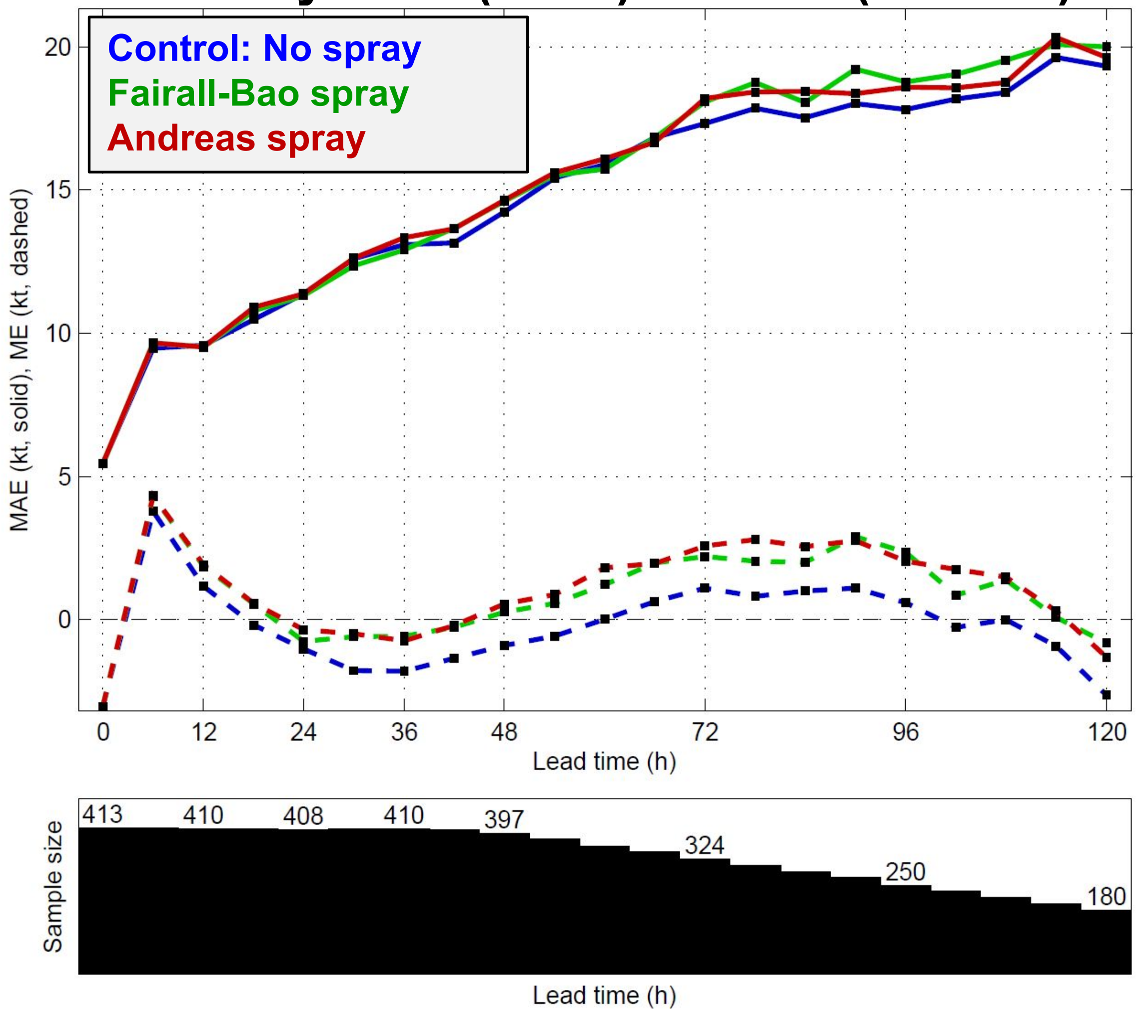


- Dissipative heating improves mean intensity bias by ~2-3 kt, especially for strong TCs
- Intensity relative frequency distribution is improved for strong TCs

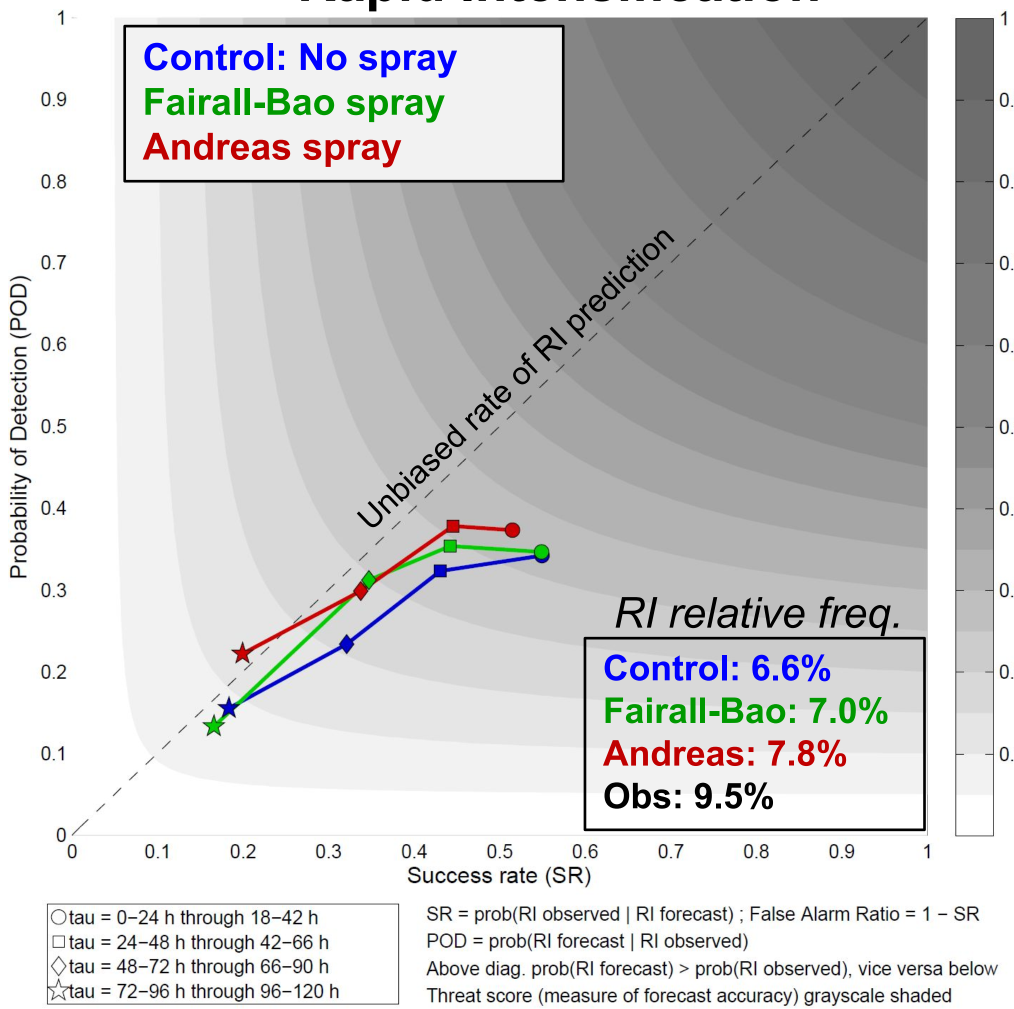
Air-Ocean Coupling in Tropical Cyclones

Sea Spray Processes

Intensity MAE (solid) and ME (dashed)



Rapid Intensification



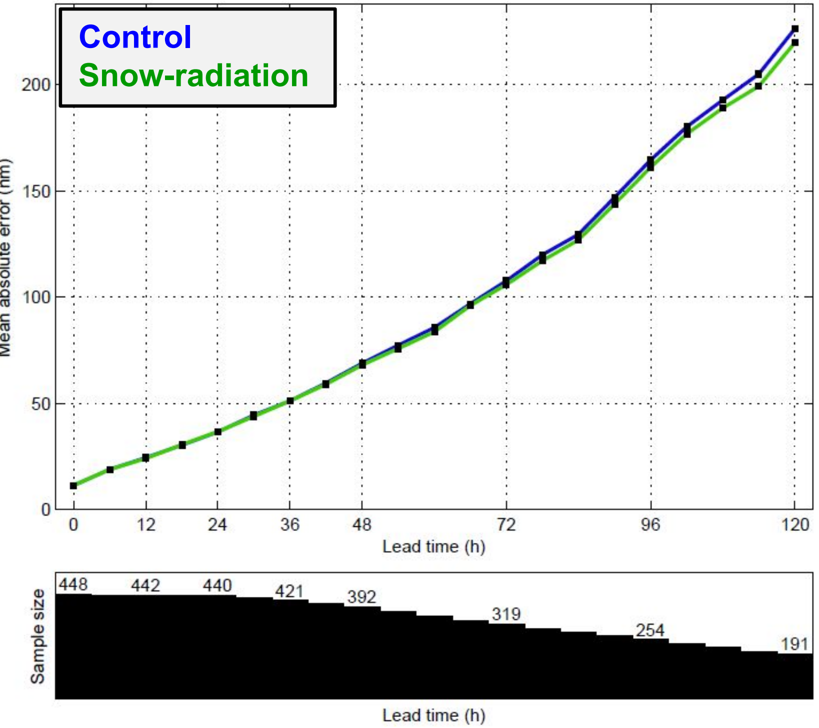
- Sea spray parameterizations (Fairall-Bao and Andreas) show improved RI statistics, however the mean absolute and mean errors are larger than the control

Microphysics

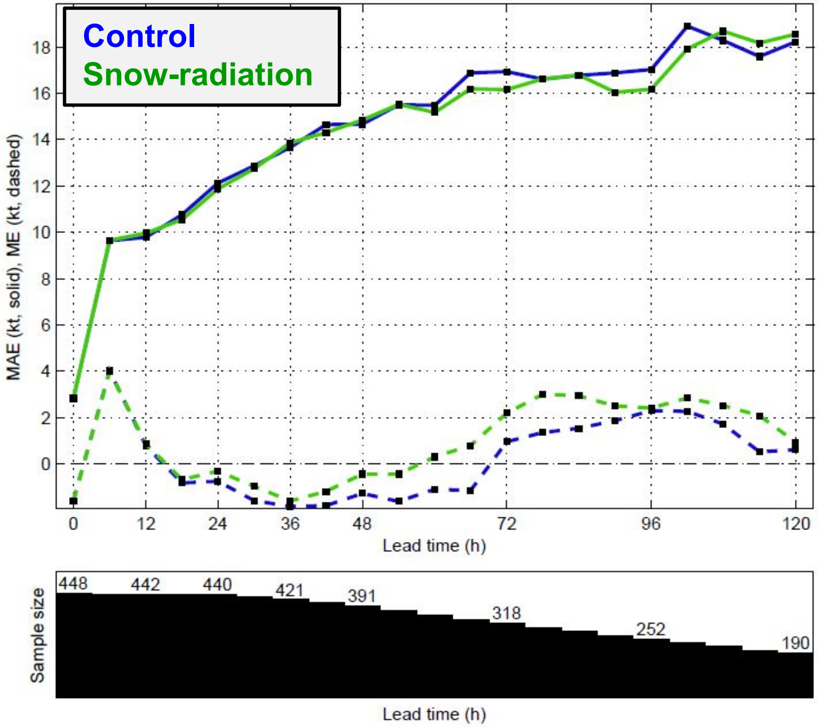
Microphysics and Radiation Interactions

Snow-Radiation Interaction

Track MAE

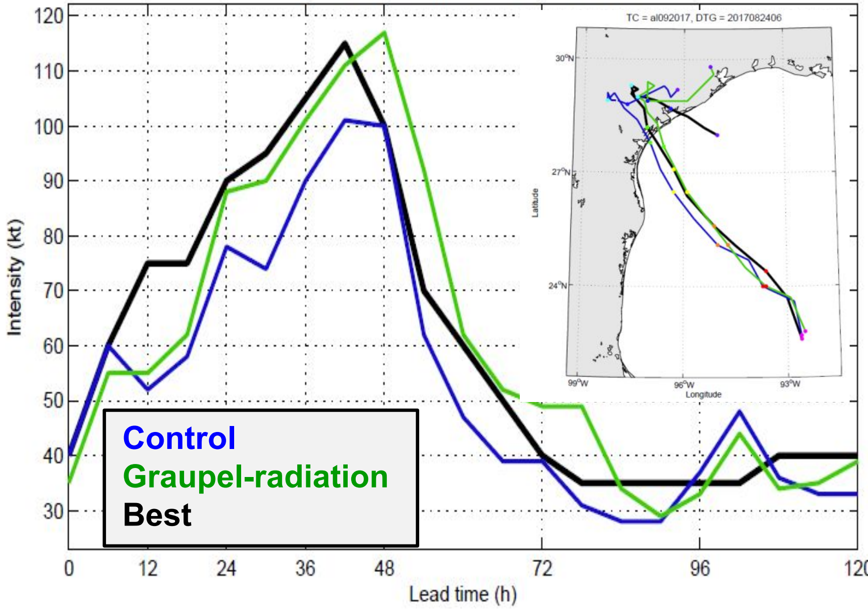


Intensity MAE (solid) and ME (dashed)



Graupel-Radiation Interaction

Hurricane Harvey (2017)



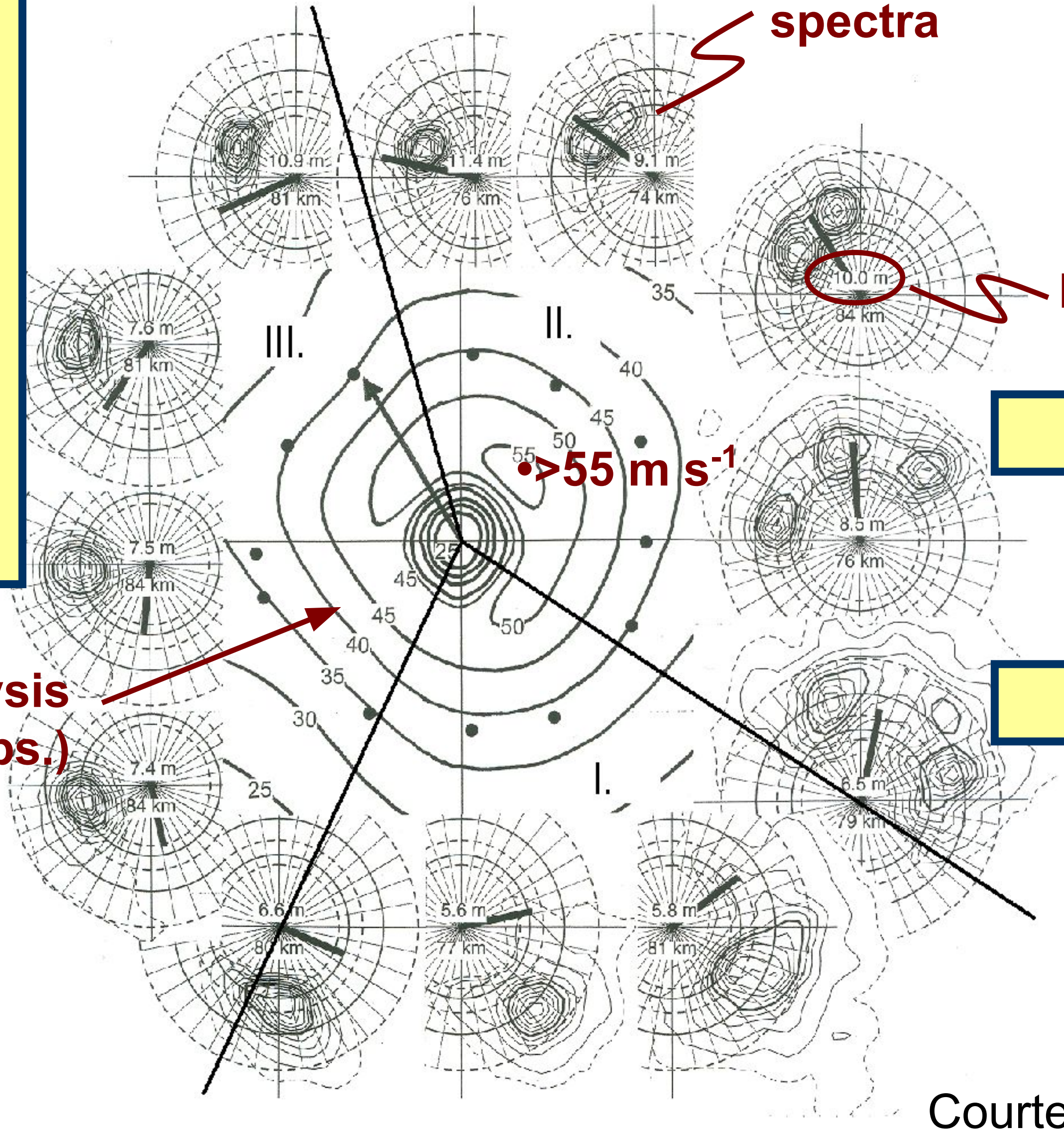
- Inclusion of interactions between snow and radiation show modest improvements in track and intensity errors
- Graupel and radiation interactions show improved intensity errors as well

TC Air-Sea Interaction

Scanning Radar Altimeter in Hurricane Ivan

- Young, steep, and short waves in the right-rear quadrant
- Older, flatter, and longer waves in the right-front and left-front quadrants.
- To the left rear and left front of the eye, the wind and waves are at right angles to each other.

Directional wave spectra



Hs

Tri-modal

Bi-modal

HWIND wind analysis (includes SFMR obs.)

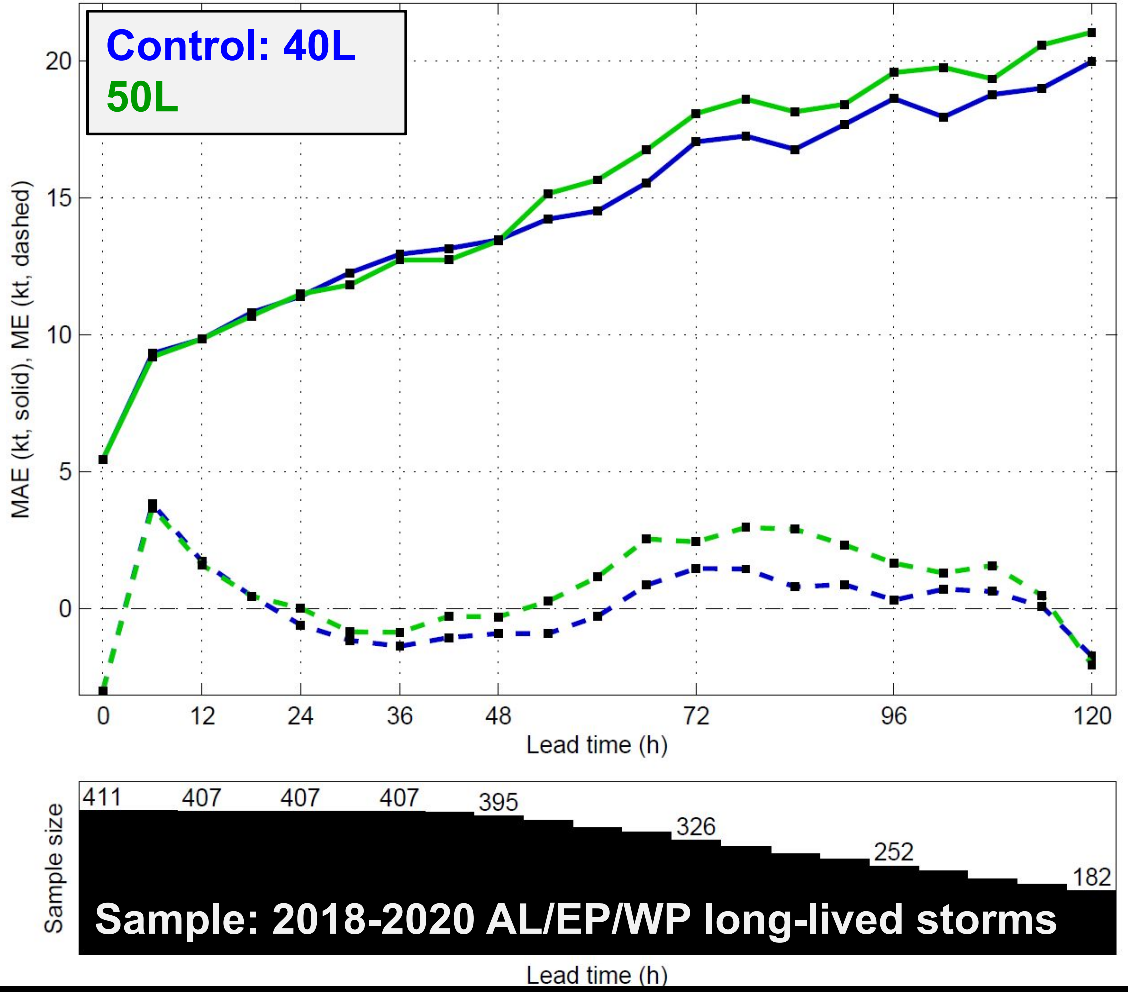
Black et al. (2007)

Courtesy: Ed Walsh

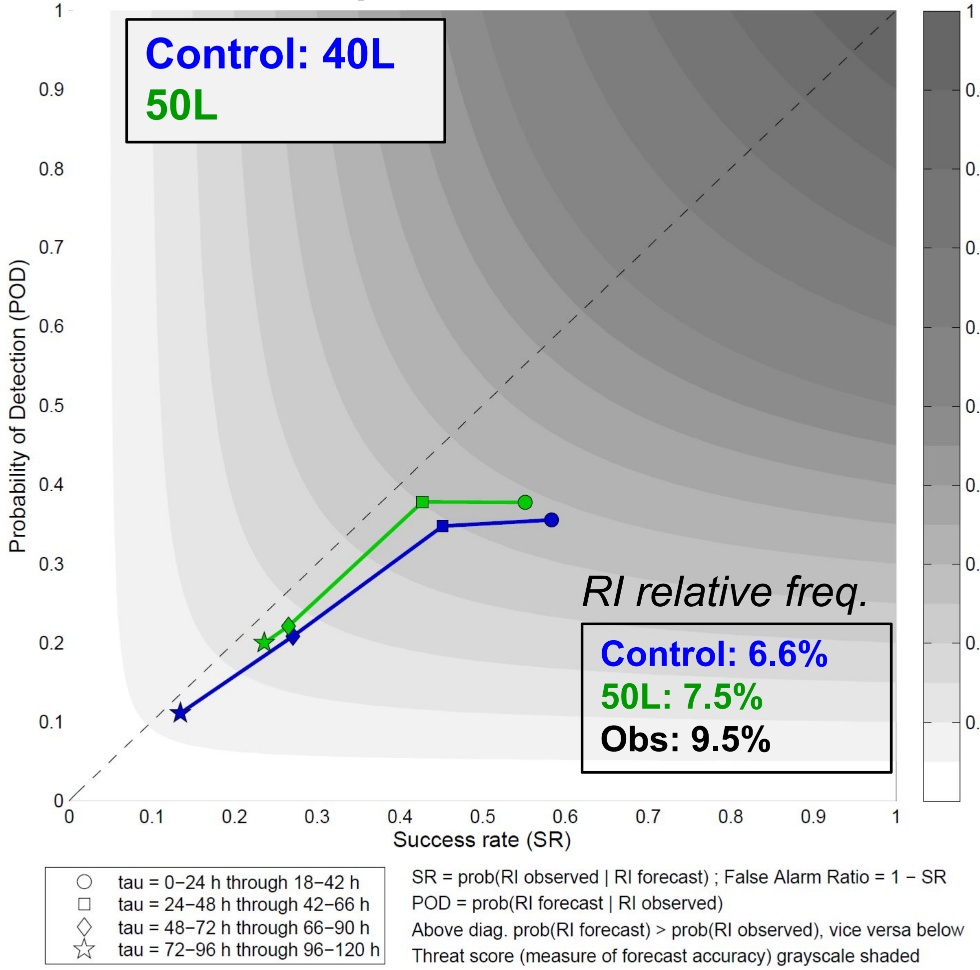
Sensitivity to Resolution

Vertical Resolution

Intensity MAE (solid) and ME (dashed)



Rapid Intensification



- 50L configuration with additional levels in mid-upper troposphere: Best combo of performance & cost
- 50L improves RI accuracy and bias, but degrades intensity MAE beyond 48 h.

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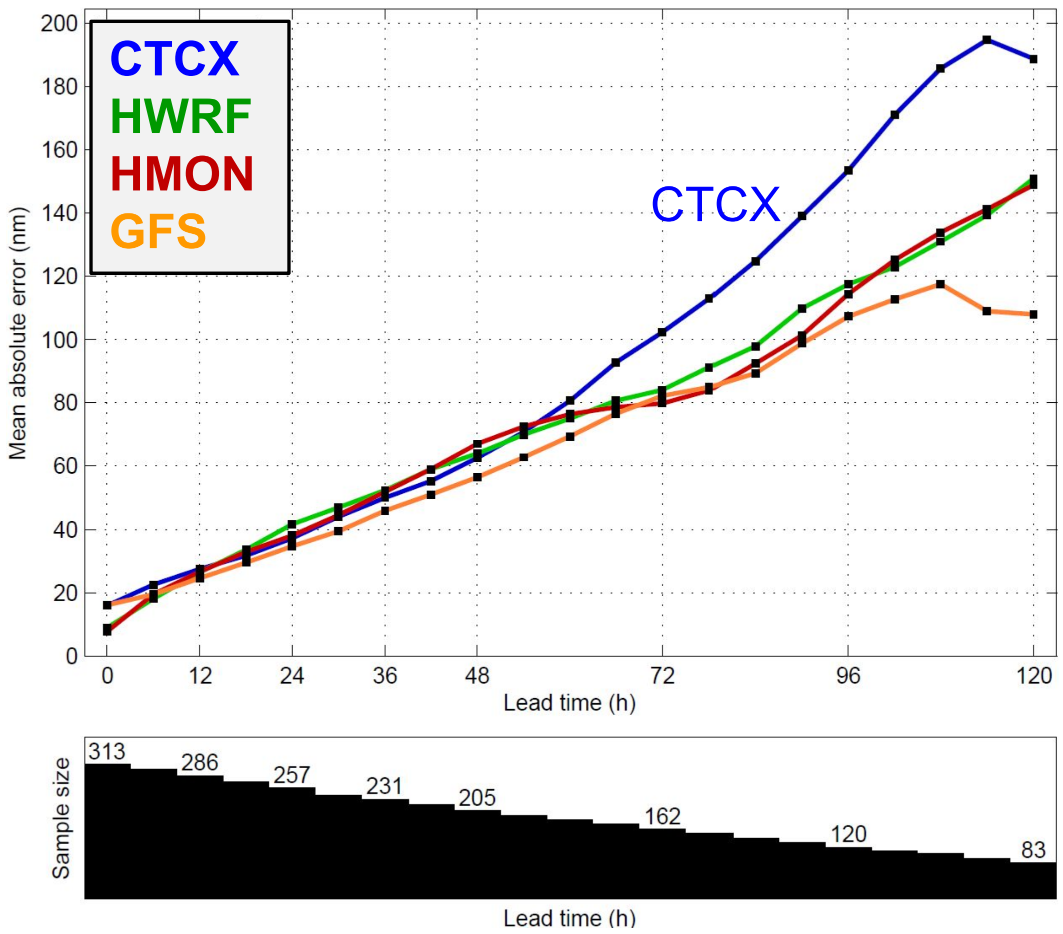
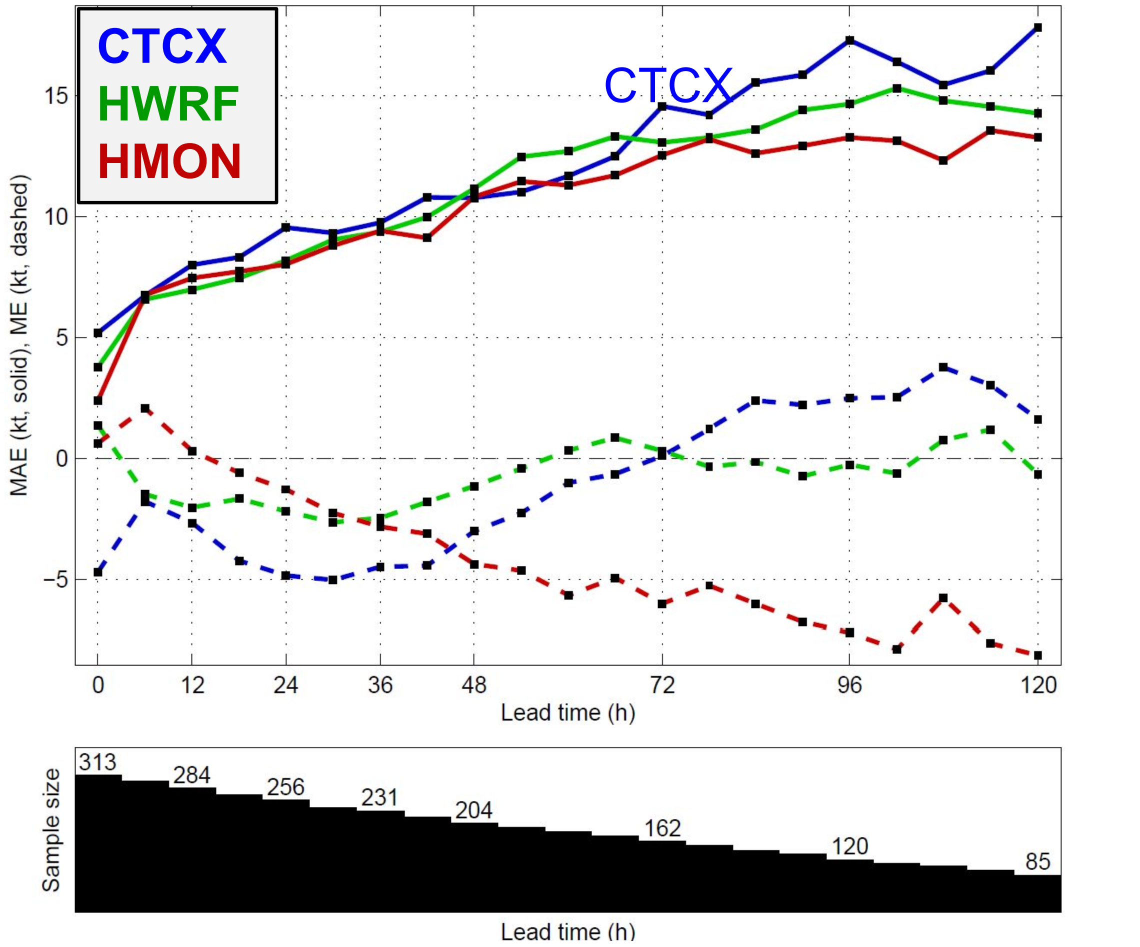
COAMPS-TC Performance
Atlantic Basin 2020-2021

2021 Track Mean Absolute Error (nm)



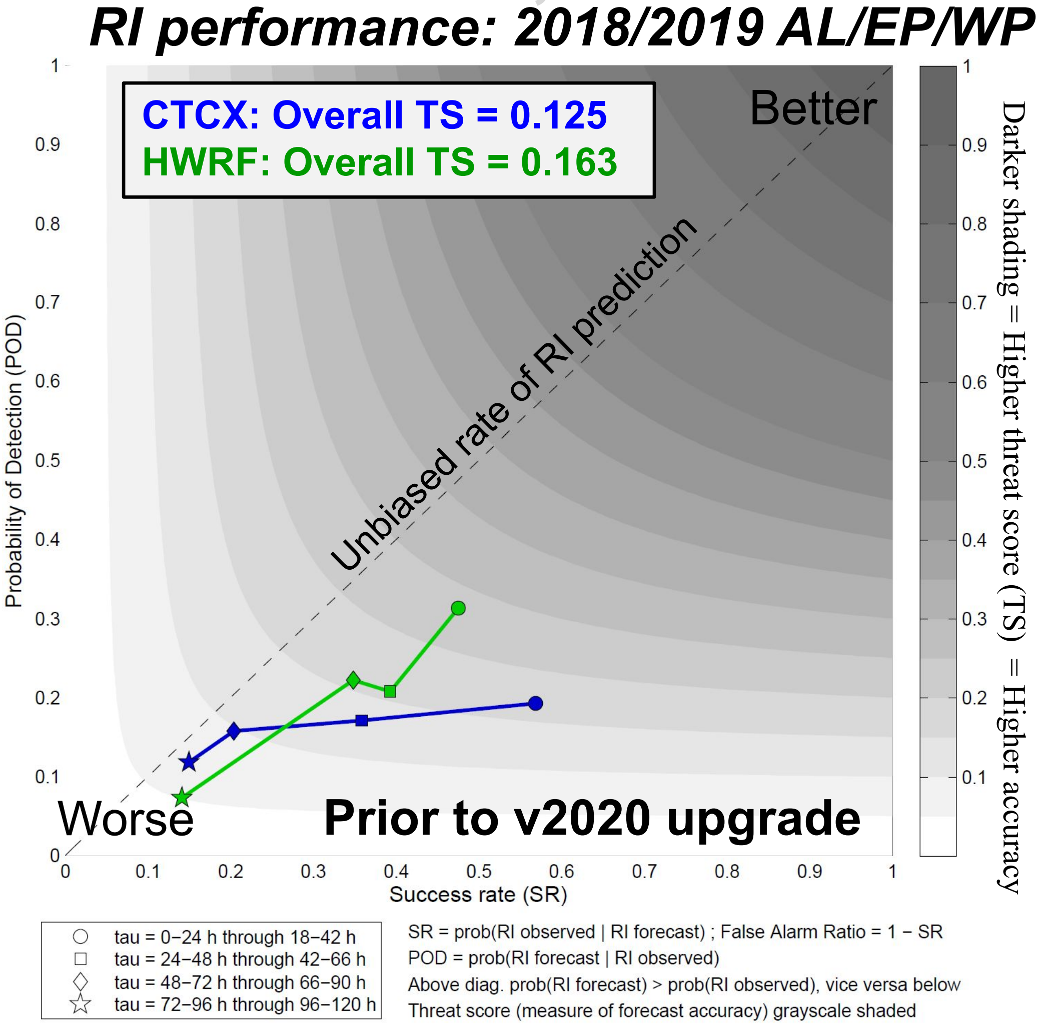
2021 ATL Intensity MAE (solid) and ME (dashed)

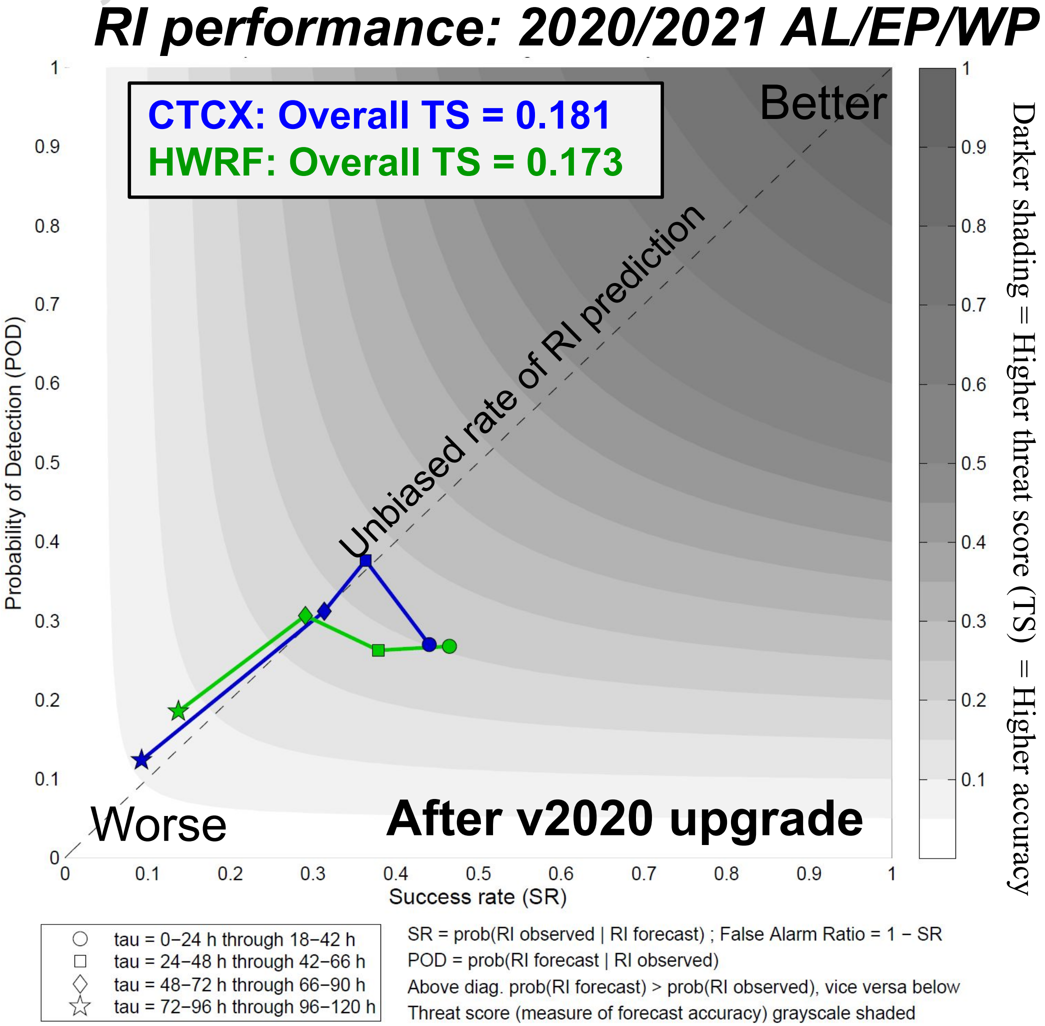


•Low track error for CTCX in 2020; CTCX virtually the same in 2021, yet track errors were worse
•Intensity errors similar to HWRF and HMON to 72h and trailed other models after by 1-2 kts.

COAMPS-TC RI Performance

Atlantic, Eastern Pacific, Western Pacific



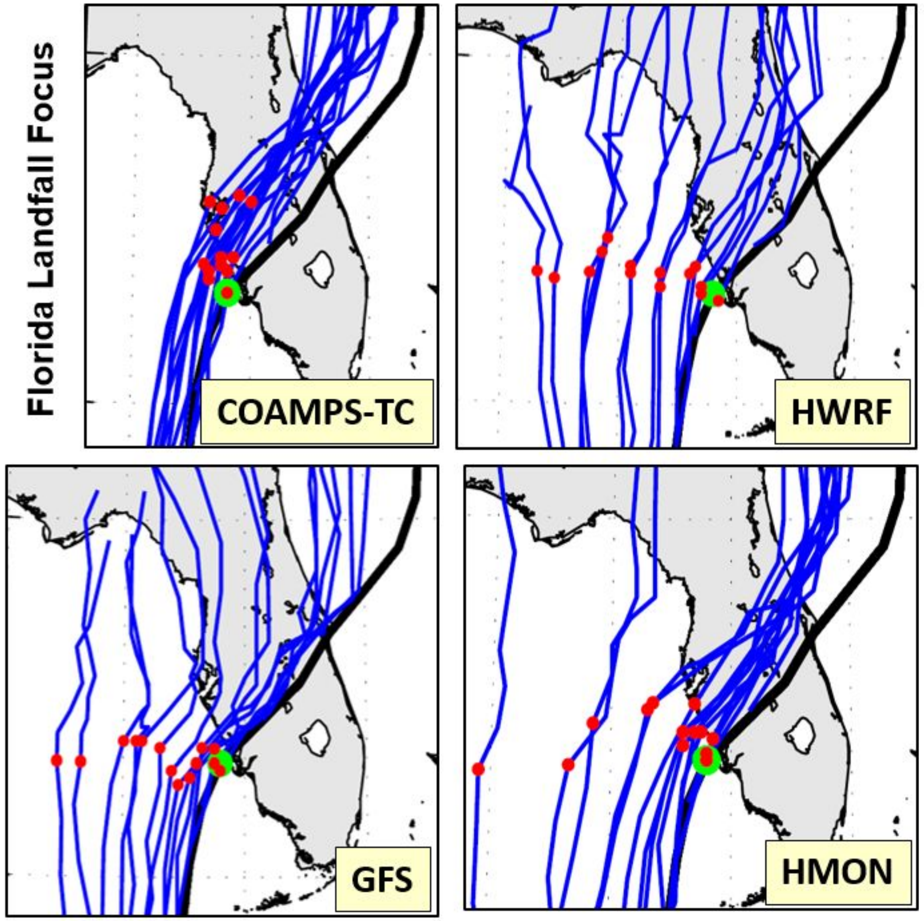


After physics and vortex initialization upgrades in 2020, COAMPS-TC showed considerably improved RI forecasts

COAMPS-TC Evaluation

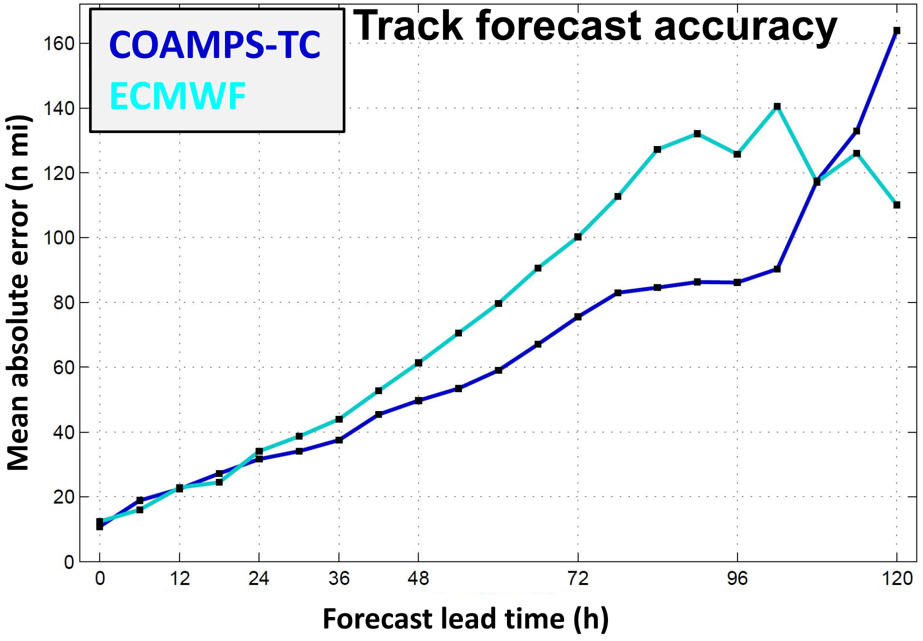
Hurricane Ian Track Forecasts

- Within 3 days of Florida landfall, COAMPS-TC forecasts did exceptionally well to predict the timing/location of landfall.
- Even for early forecasts 4 to 5 days in advance, COAMPS-TC predicted Ian to be a major hurricane in the Gulf of Mexico



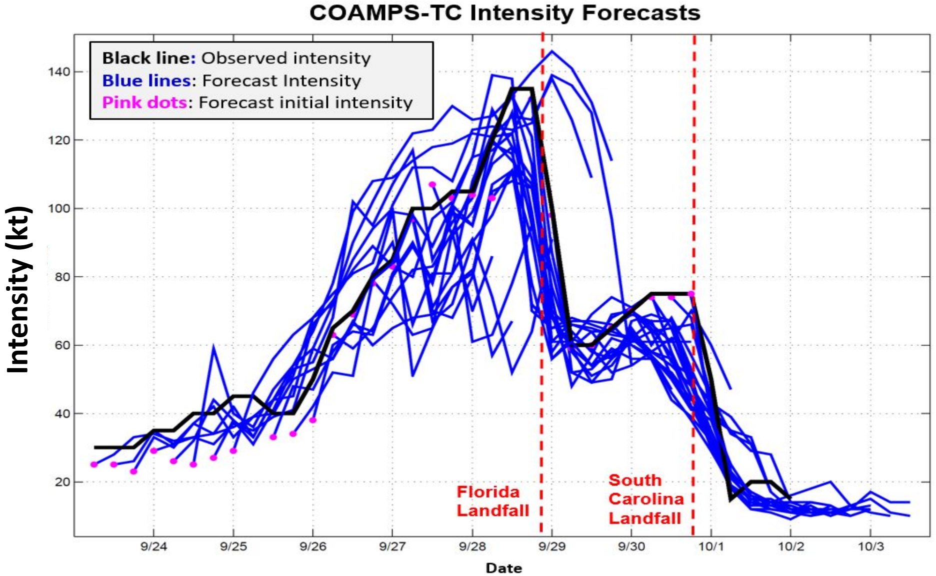
Blue lines: Forecast tracks
Red dots: Forecast TC positions at time of landfall

Black line: Observed track
Green dot: Observed TC position at time of landfall



Category 3: 96 - 112 kt
Category 4: 113 - 136 kt
Category 5: 137+ kt

	Forecast Peak Intensity (kt)		
Initial Time	COAMPS-TC	HWRF	HMON
25/18z	139	118	124
26/00z	128	117	132
26/06z	129	120	122
26/12z	111	121	119
26/18z	133	116	118
27/00z	111	121	123
27/06z	108	122	127
27/12z	118	128	126
27/18z	122	128	124
28/00z	119	128	129
28/06z	111	115	133
28/12z	133	142	139
Average	121.8	123.0	126.3



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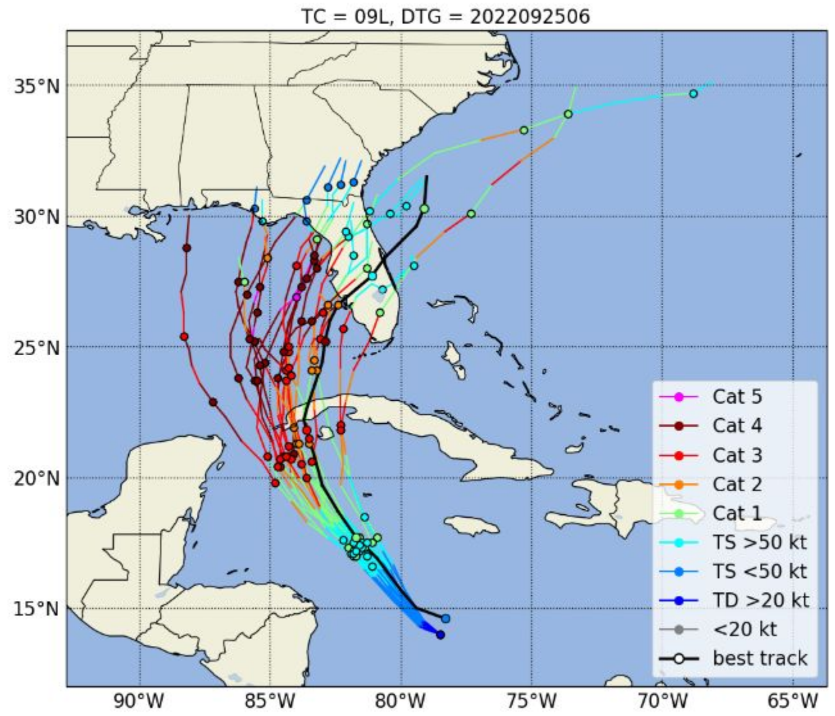
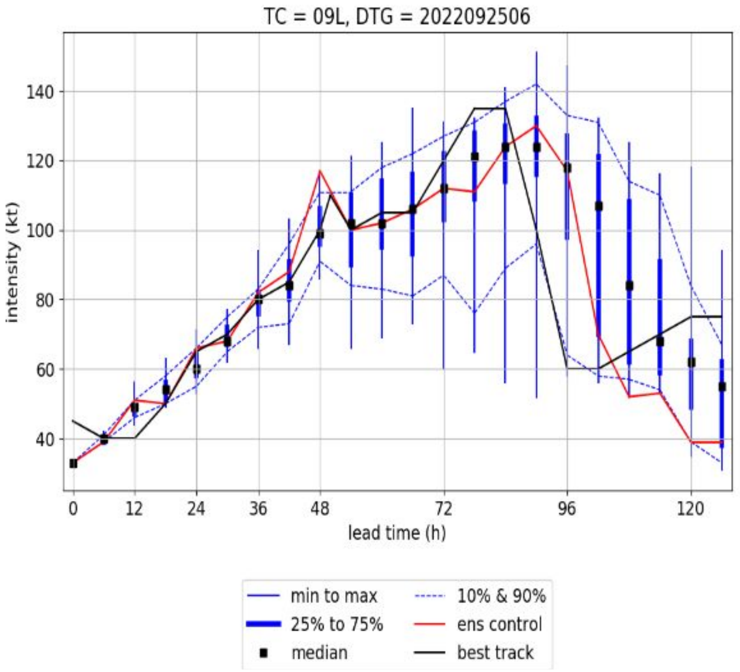
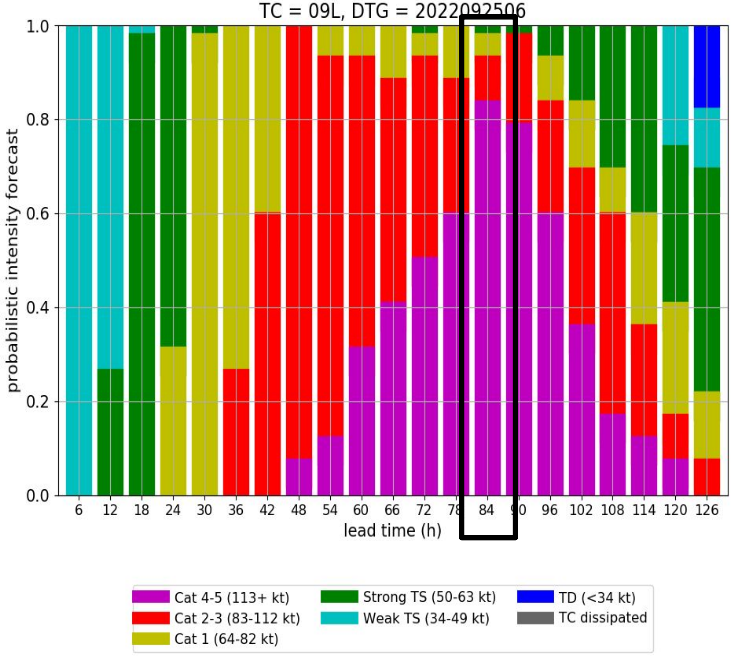
COAMPS-TC Performance

COAMPS-TC Ensemble Prediction for Hurricane Ian

85% prob Cat 4-5 at 84h!





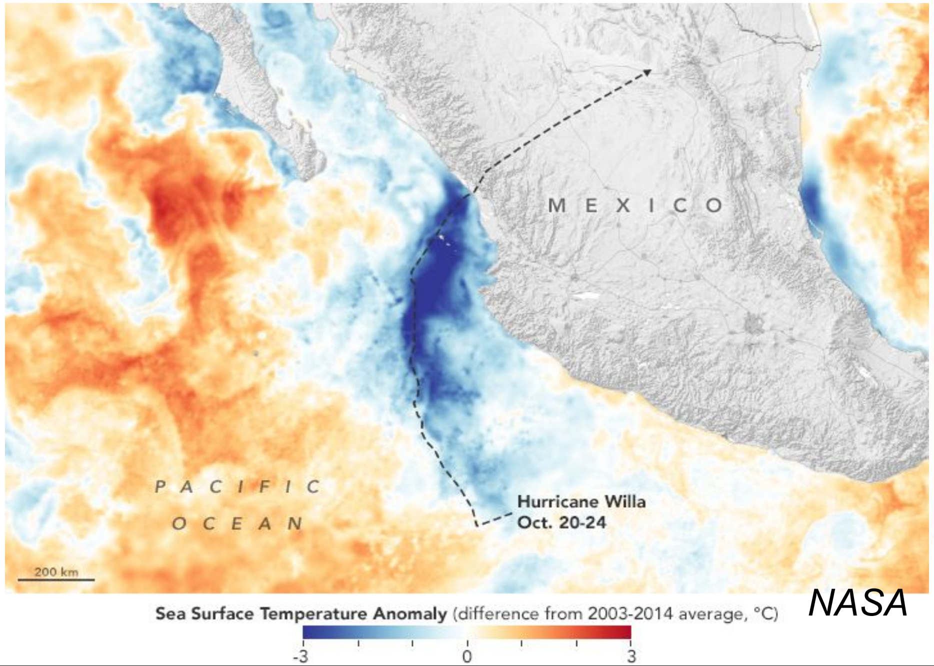


- COAMPS-TC Ensemble intensity forecast was extremely good for Ian
- 85% of ensemble members predicted Cat 4-5 at 84h; verification: Cat 4

Air-Ocean Coupling in Tropical Cyclones

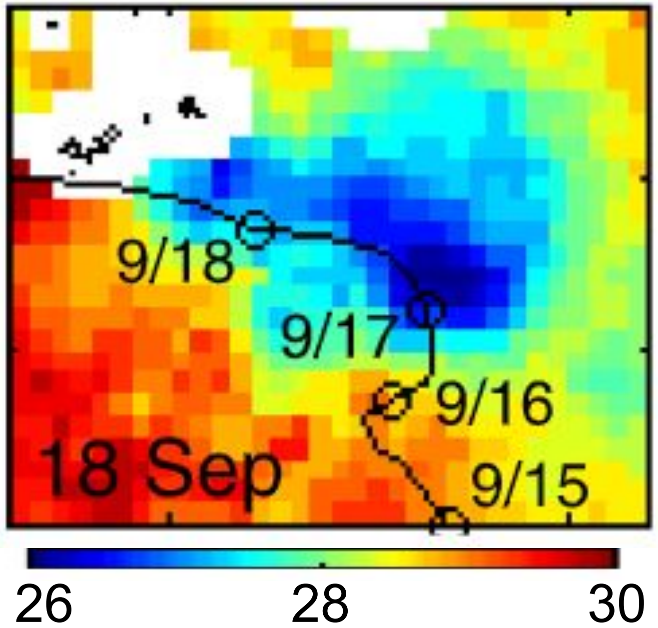
Upper Ocean Processes

SST Anomaly [Hurricane Wilma (2018)]



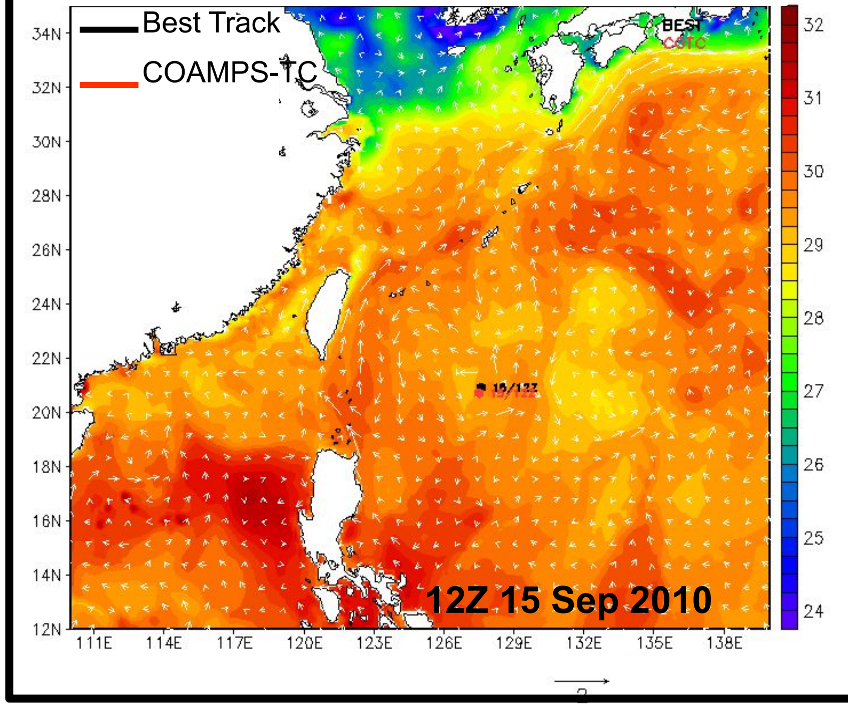
NASA

MW SST [TY Fanapi (2010)]



Mrvaljevic et al. (2013)

ITOP Typhoon Fanapi: SST (°C), Currents



- **Motivation:** Upper-ocean mixing results in SST cooling beneath TC core & in wake (Bender & Ginis, 2000; Cione & Uhlhorn, 2003; Chen et al., 2007)
- **Methods:** Air-sea & air-sea-wave coupling; 1-D simple ocean
- **Key Findings:**
  - Air-sea coupling reduces over intensification biases, particularly for slow moving storms
  - 1-D simple SST cooling allows for efficient testing

Coupled COAMPS-TC Capable of Capturing SST Wake of ~4˚C in Agreement with ITOP Observations

Air-Ocean Coupling in Tropical Cyclones

Upper Ocean Processes

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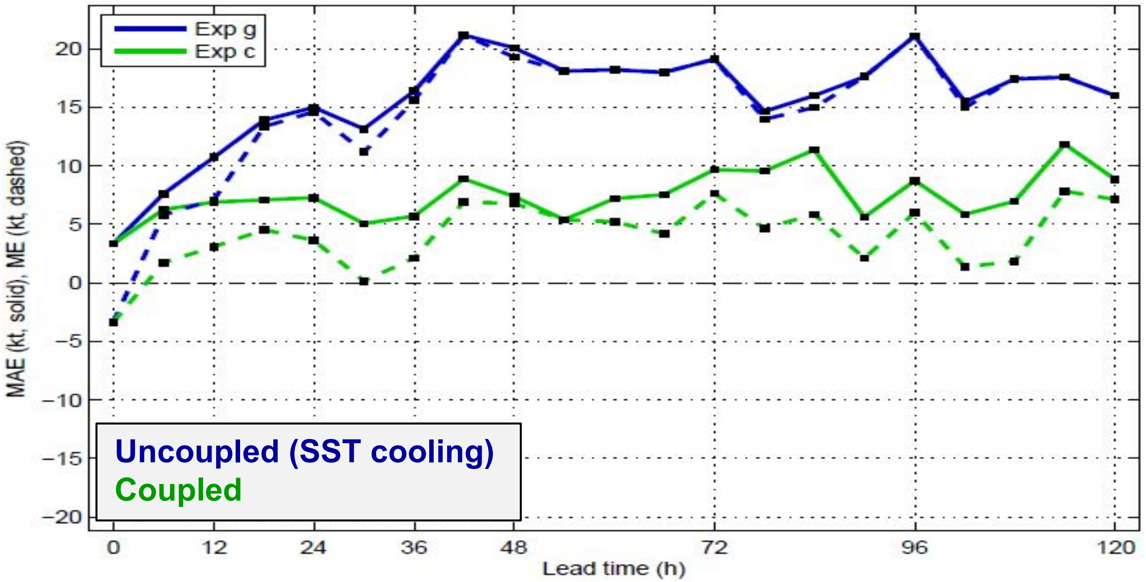
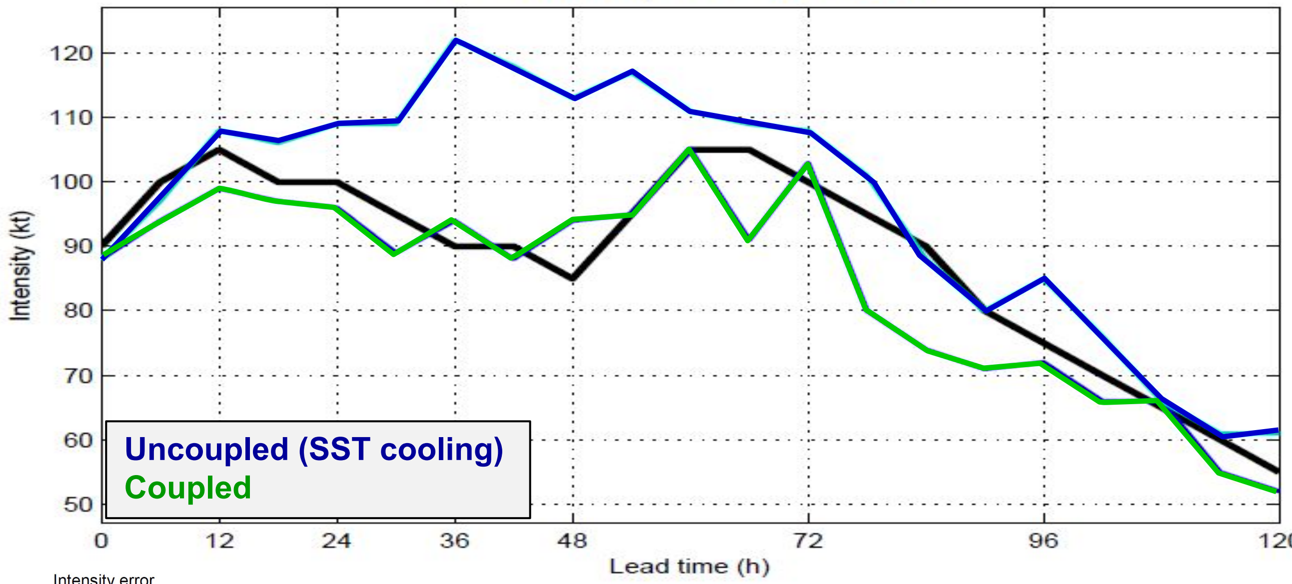
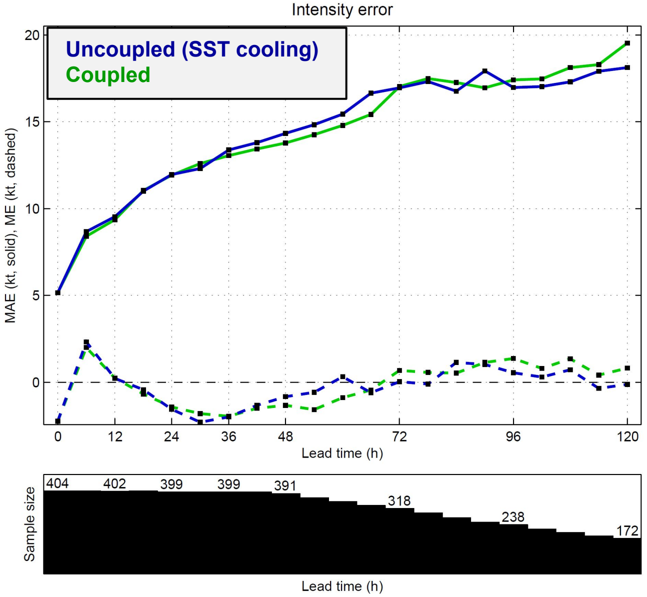
Hurricane Leslie (2012): Intensity Error & Bias

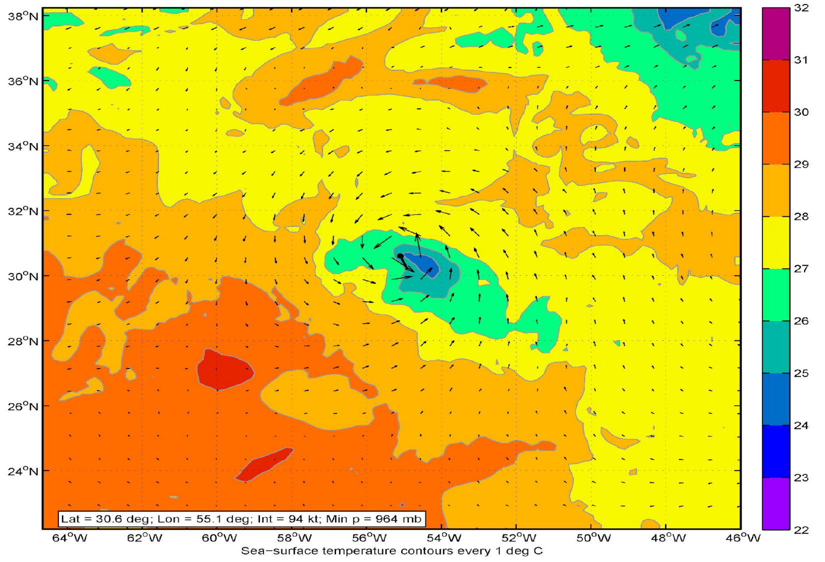


Hurricane Gaston (2016): Intensity Error



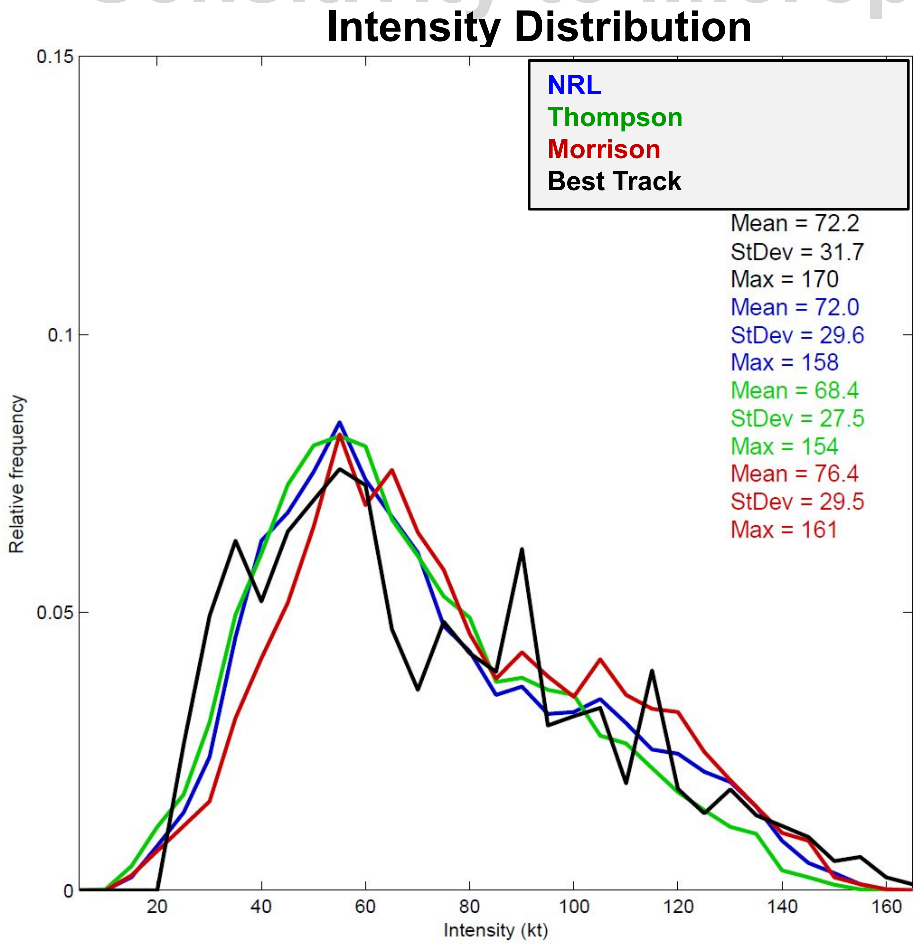
- For very slow-moving TC such as Leslie and Gaston with shallow mixed layers, the coupled model outperforms uncoupled model (with SST cooling) in intensity prediction
- Recently improved SST cooling parameterization is very close to the coupled system in intensity prediction.

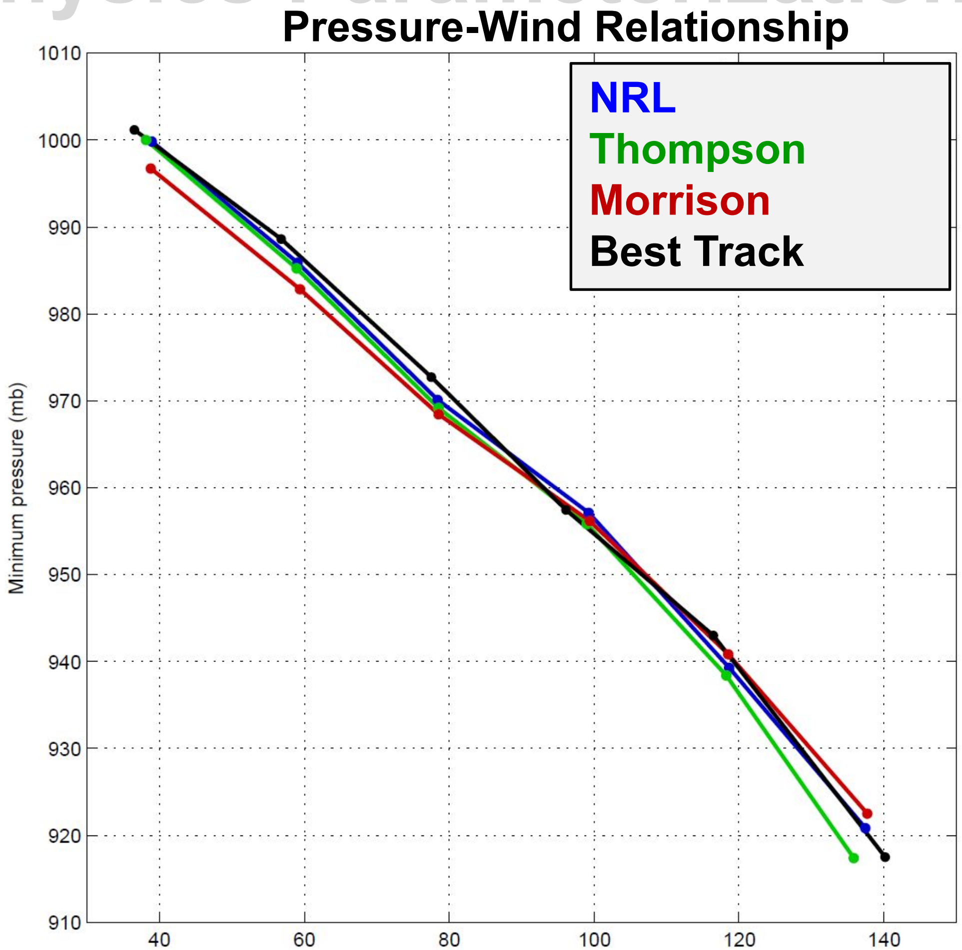




Microphysics

Sensitivity to Microphysics Parameterization





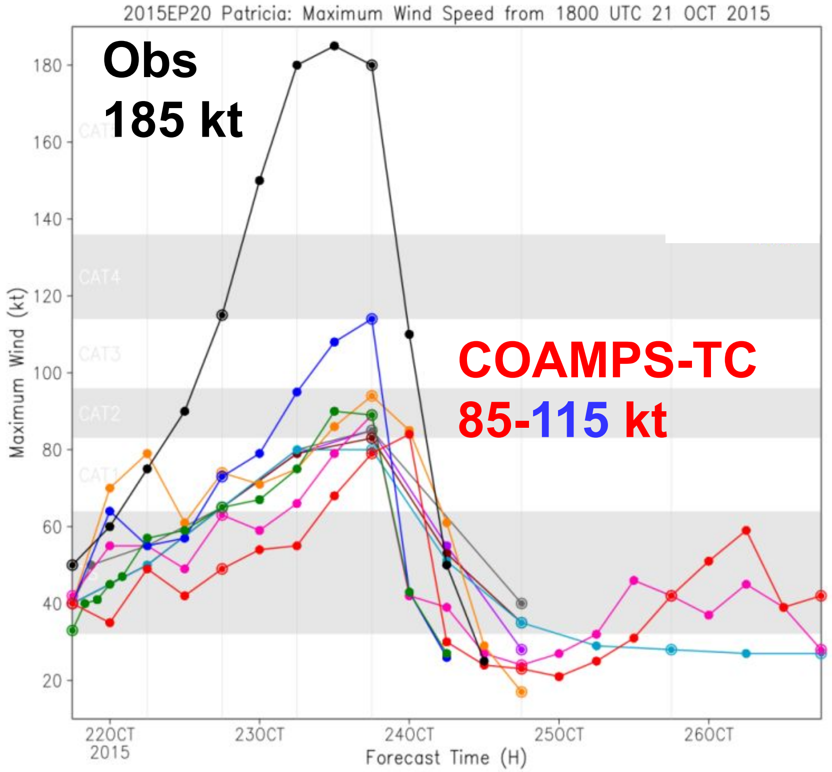
- Thompson has markedly less relative frequency above 105 kt intensity
- Morrison does not have enough weak intensities (< 50 kt)

- Difficult to improve on NRL P-W relationship: Thompson's pressure is a little low at high intensity; Morrison pressure a little low at low intensity

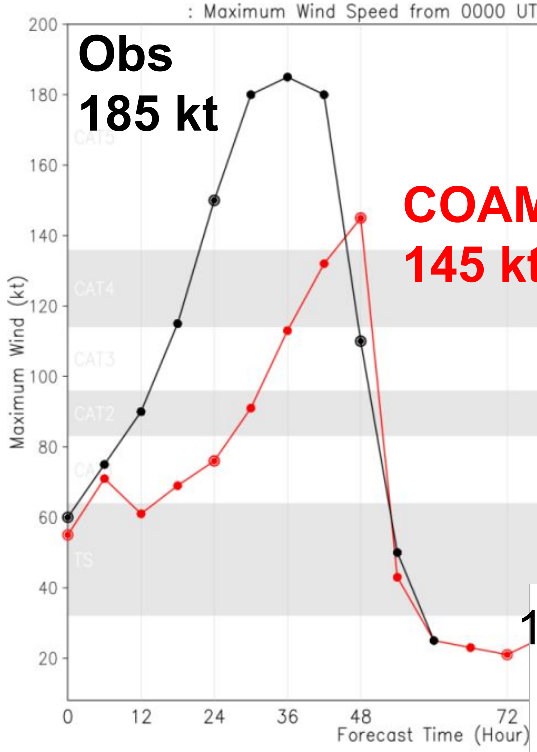
Sensitivity to Resolution

Horizontal Resolution: Hurricane Patricia

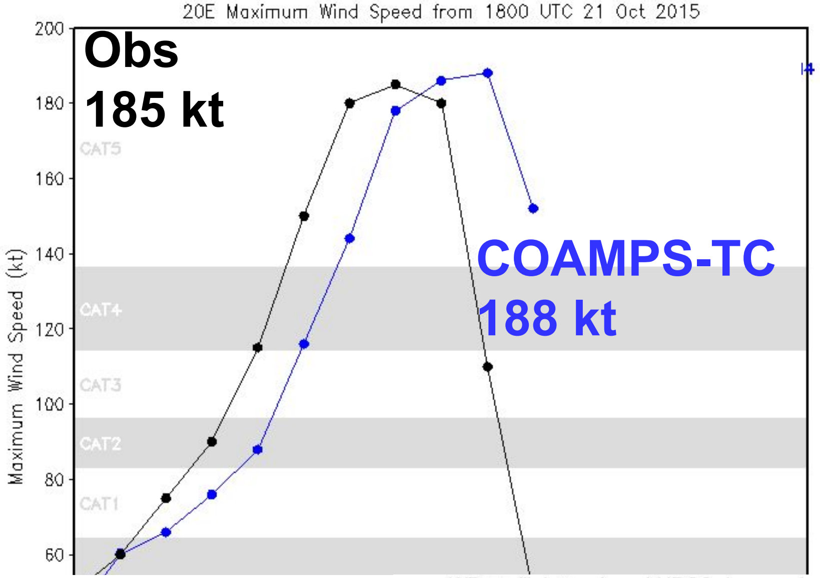
COAMPS-TC: ***5 km***



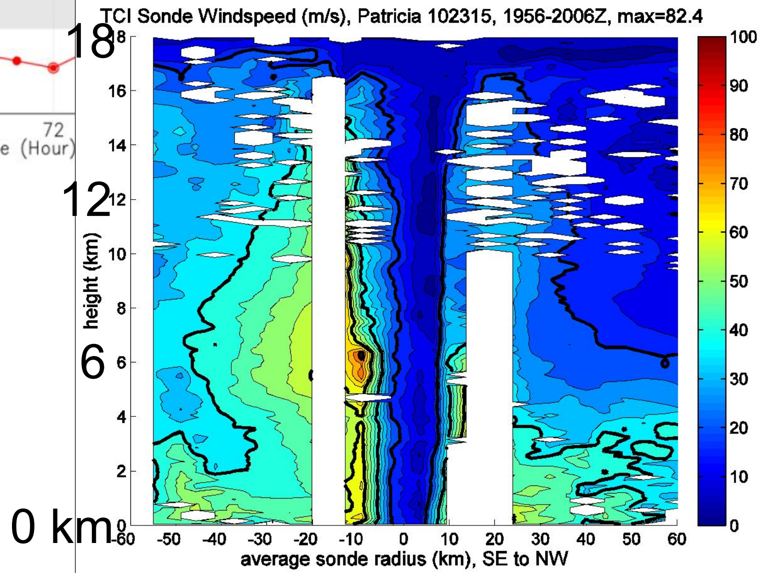
COAMPS-TC: ***1.67 km***

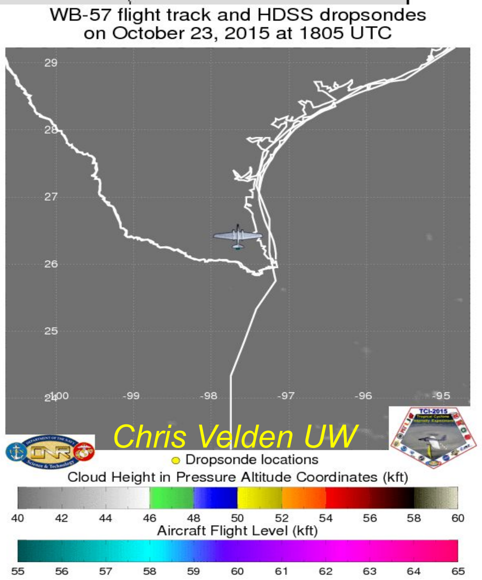


COAMPS-TC: ***0.89 km***



- Small TCs tend to intensify more rapidly than large TCs (Patricia observed in ONR Tropical Cyclone Intensity Exp.)
- High resolution is necessary (but not sufficient) to simulate a TC with a small RMW such as Patricia





Extra Ensemble Slides

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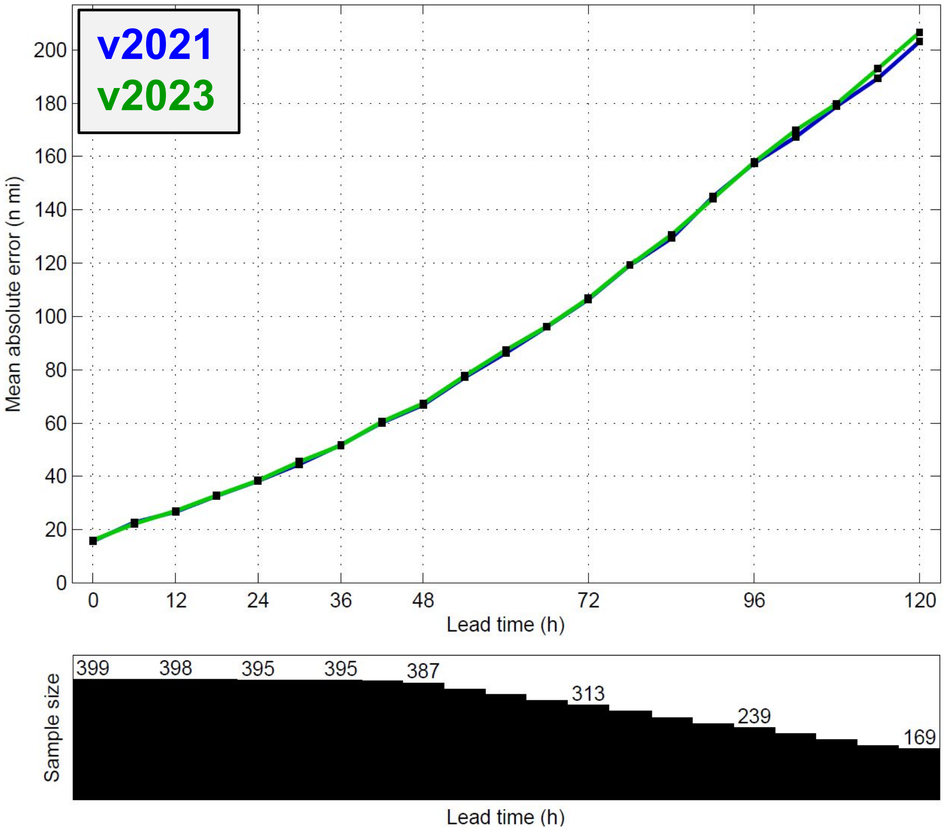
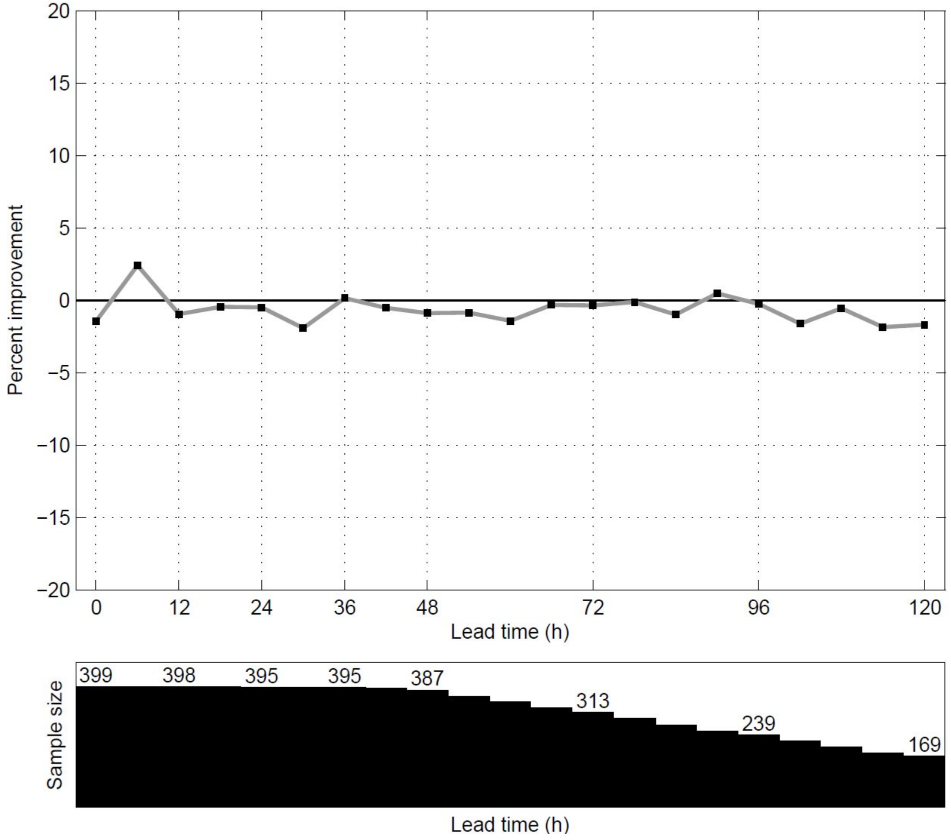
Full Sample Results: Track 399 cases from 87 TCs (2019-2021)

Track MAE



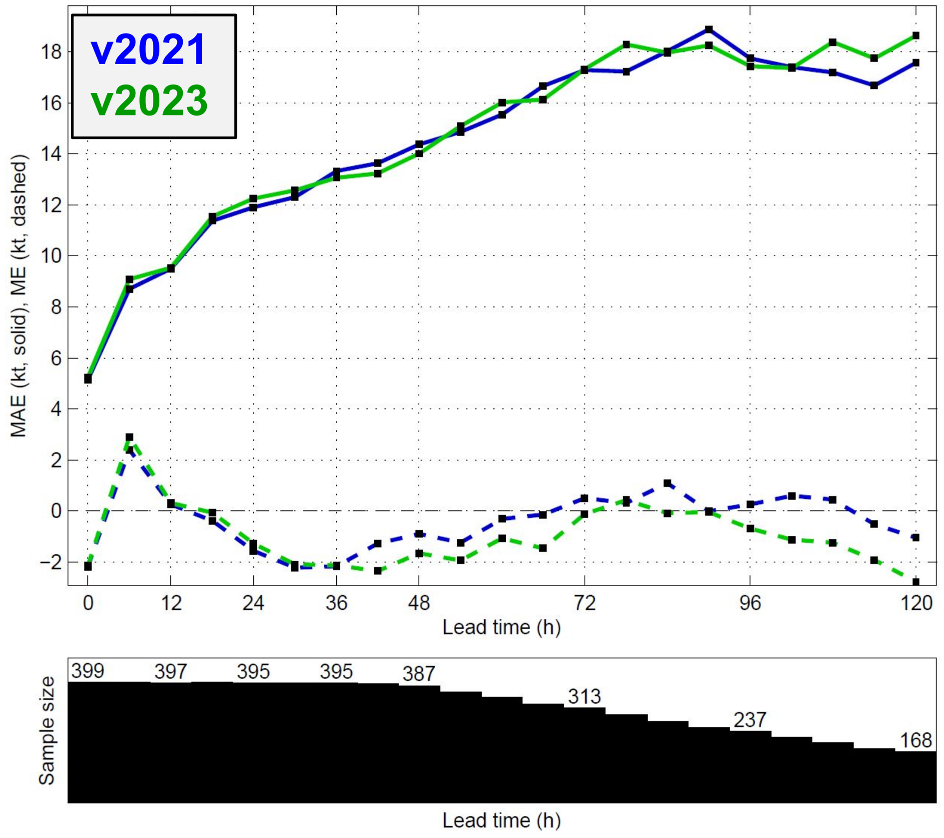
Percent improvement of v2023 w.r.t. v2021



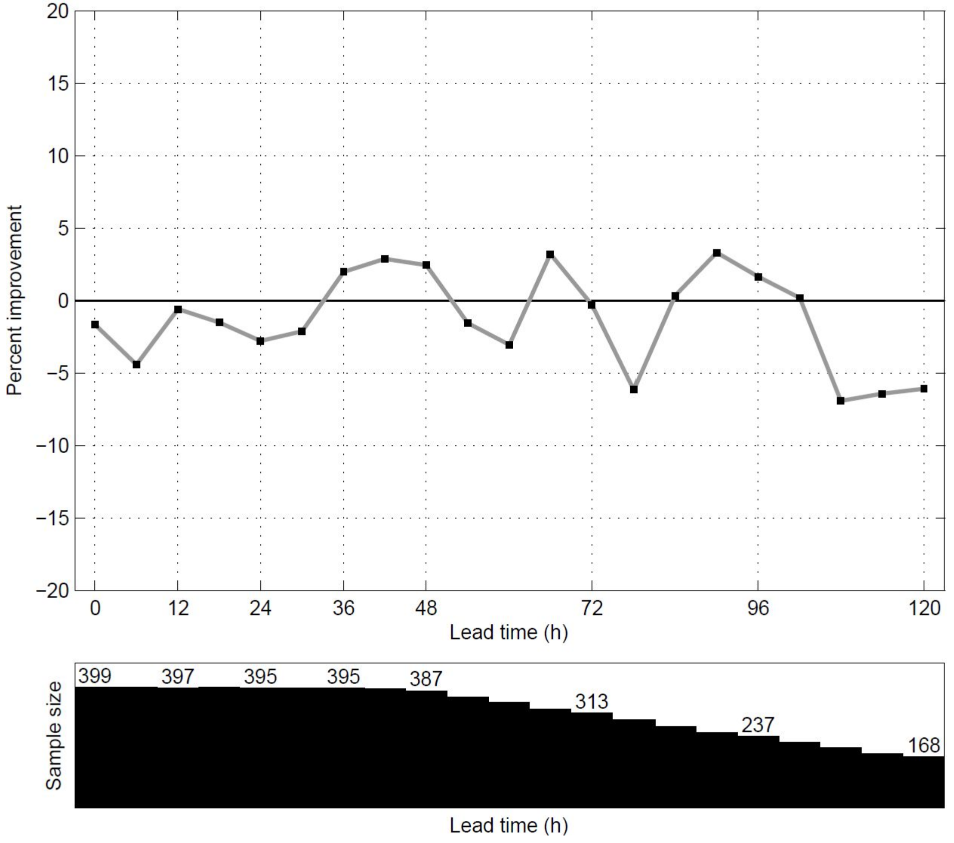
- Track predictions are meaningfully different between **v2023** and **v2021**, though the overall accuracy of the two sets of forecasts is nearly the same

Full Sample Results: Intensity 399 cases from 87 TCs (2019-2021)

Intensity MAE (solid) and ME (dashed)

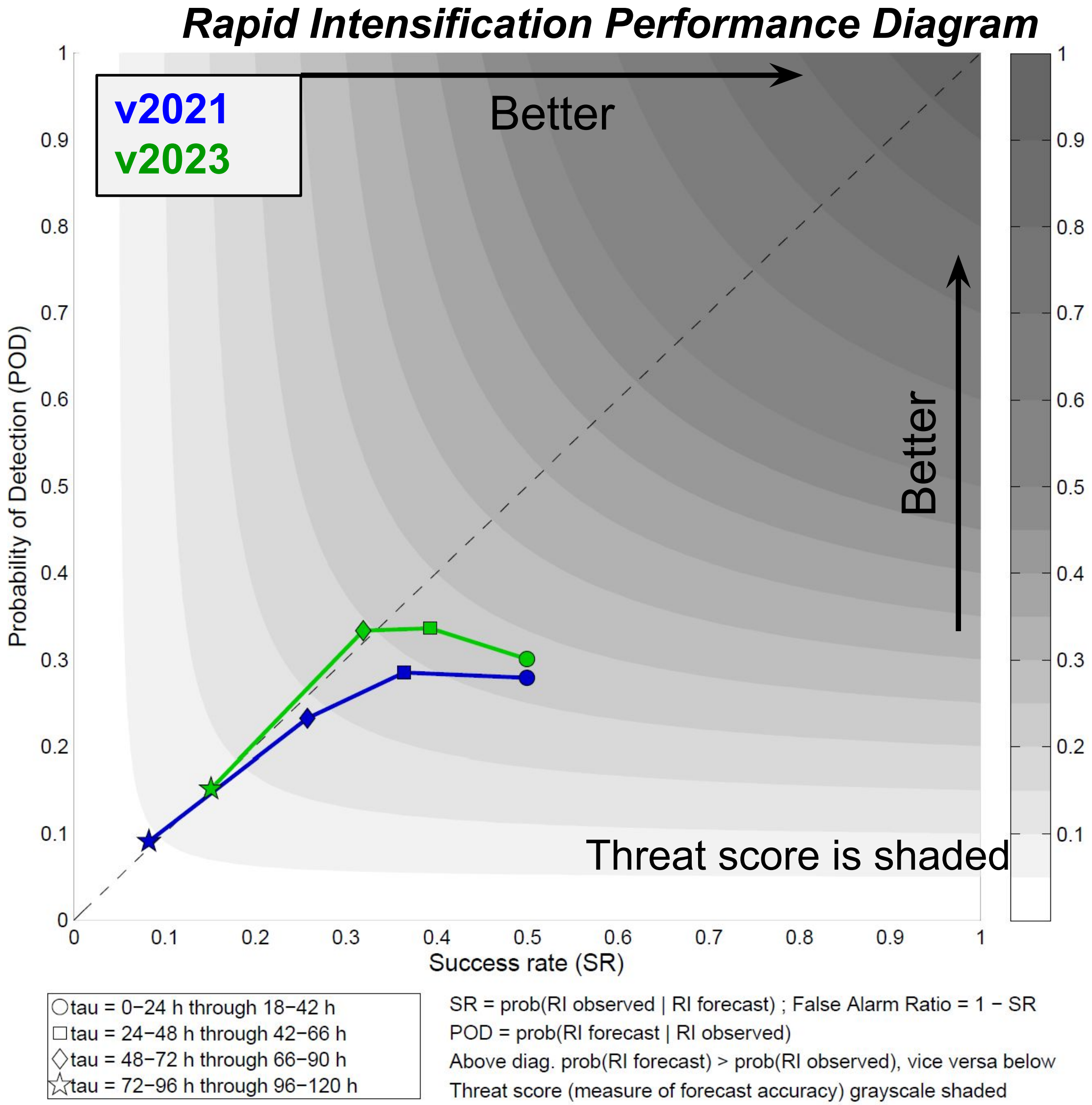


Percent improvement of v2023 w.r.t. v2021



- Like for track, intensity forecasts are different in **v2023** w.r.t **v2021** but the overall accuracy of the two sets of forecasts is very much similar. The average intensity forecast is slightly weaker in **v2023** w.r.t. **v2021**

Rapid intensification 399 cases from 87 TCs (2019-2021)



- In event-based prediction of RI, accuracy is improved in **v2023** w.r.t. **v2021** at all lead times, especially the middle lead times
- RI relative frequency is generally increased in **v2023** w.r.t. **v2021** (particularly at the early to middle lead times), and is closer to the observed relative frequency at all lead times
- The improvements to RI prediction are perhaps because **v2023** predicts smaller TCs on average, with less convection on the outskirts of the storm

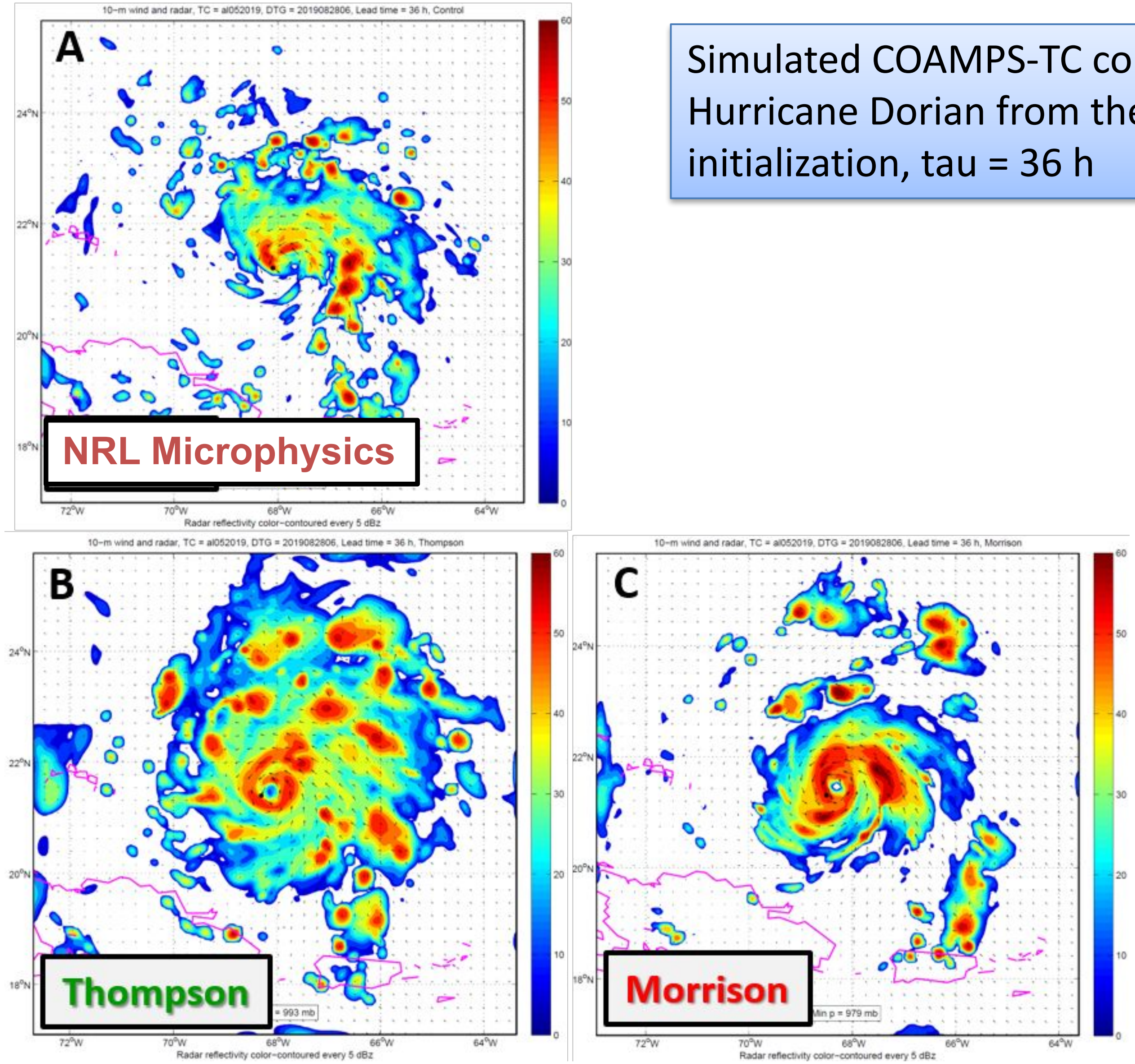
Threat Score

	0 - 24 h	24 - 48 h	48 - 72 h	72 - 96 h
v2021	0.22	0.19	0.14	0.05
v2023	0.23	0.22	0.19	0.08

RI relative frequency

	0 - 24 h	24 - 48 h	48 - 72 h	72 - 96 h
Observed	11.7%	9.7%	6.2%	3.4%
v2021	6.5%	7.6%	5.6%	3.7%
v2023	7.1%	8.3%	6.5%	3.4%

Sensitivity to microphysics: simulated reflectivity



Simulated COAMPS-TC composite radar reflectivity for Hurricane Dorian from the 0600 UTC 28 August 2019 initialization, tau = 36 h

- TC structure quite sensitive to microphysics scheme
- With Thompson and Morrison microphysics, Dorian closes off an eyewall earlier than with NRL microphysics
- Area of precipitation is much larger with Thompson than other two
- Core is most compact (and TC is also strongest) with Morrison

COAMPS-TC Ensemble *intensity* forecast sensitivity to microphysics

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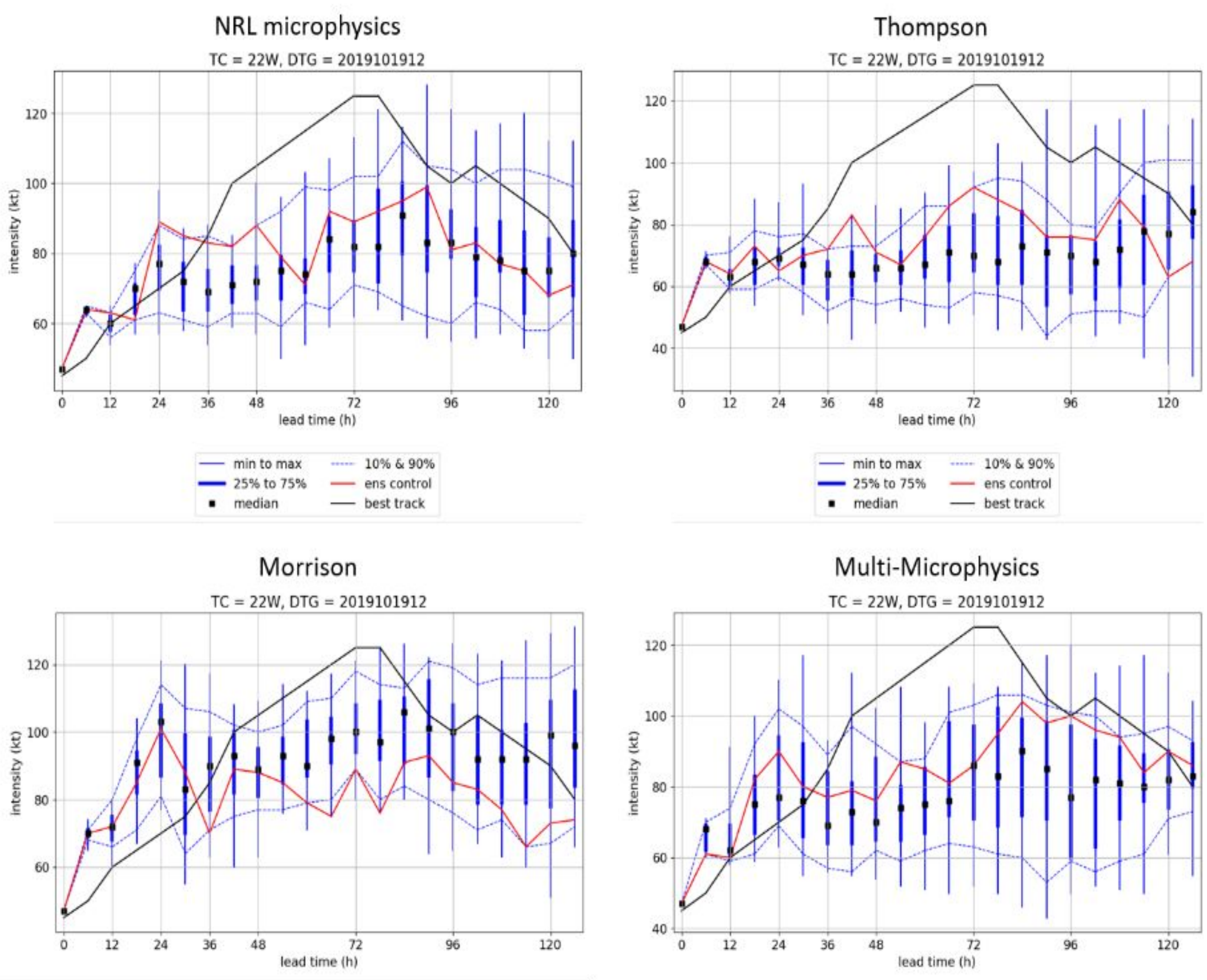
Typhoon Bualoi (2019)



COAMPS-TC Ensemble: Perturbed synoptic-scale ICs, BCs, vortex initial intensity, and drag coefficient

- 11 members run operationally at FNMOC
- 21 members run experimentally (demo mode) by NRL

- COAMPS-TC ensemble is spread-deficient for intensity, so improving spread for intensity is one of our objectives
- Consistent with results from deterministic testing, forecast using Morrison strongest at most lead times, Thompson weakest
- Spread is greatest with multi-microphysics ensemble, and forecast mean intensity error (perhaps) the least biased – subject to further testing

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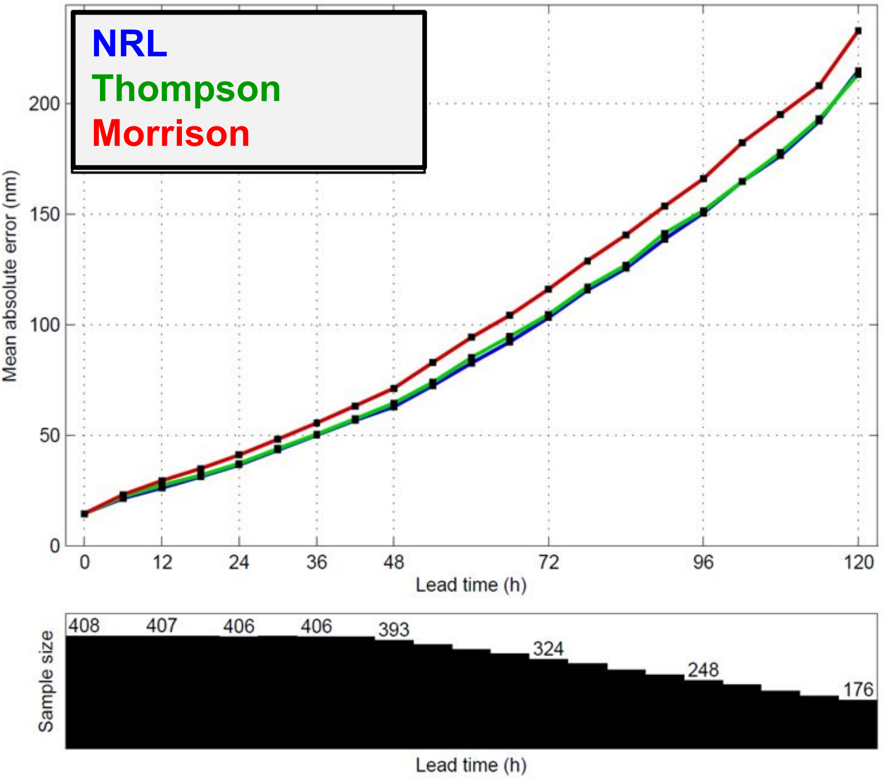
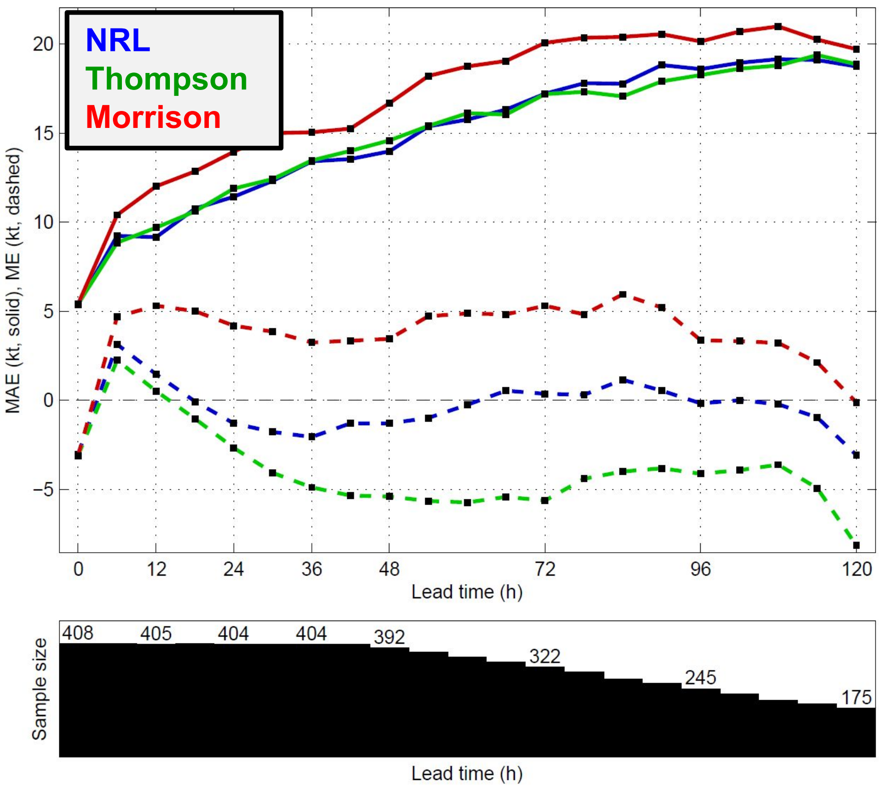
Microphysics

Sensitivity to Microphysics Representation

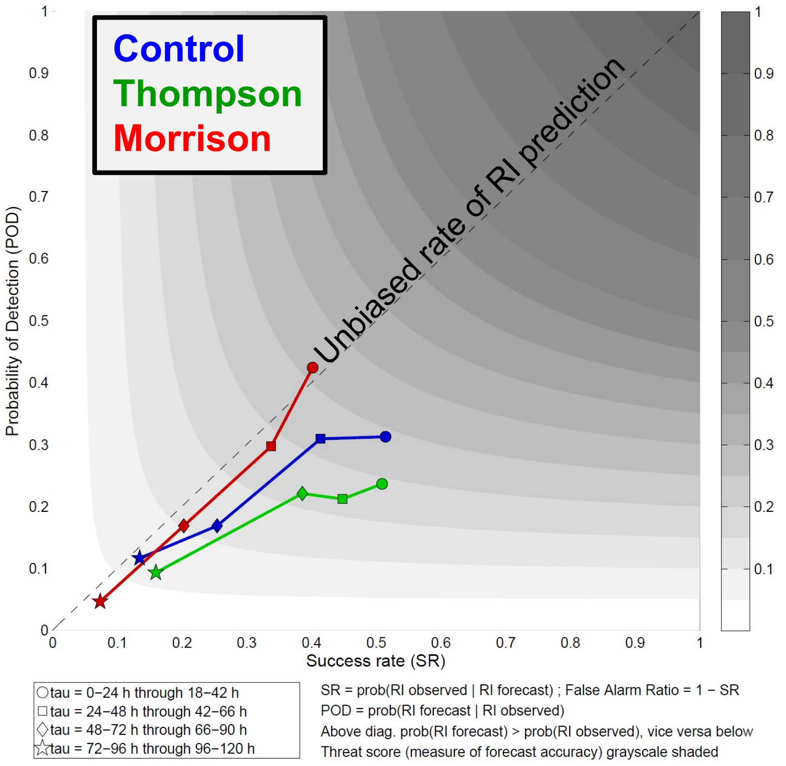
Track Mean Error (n mi)



Intensity MAE (solid) and ME (dashed)

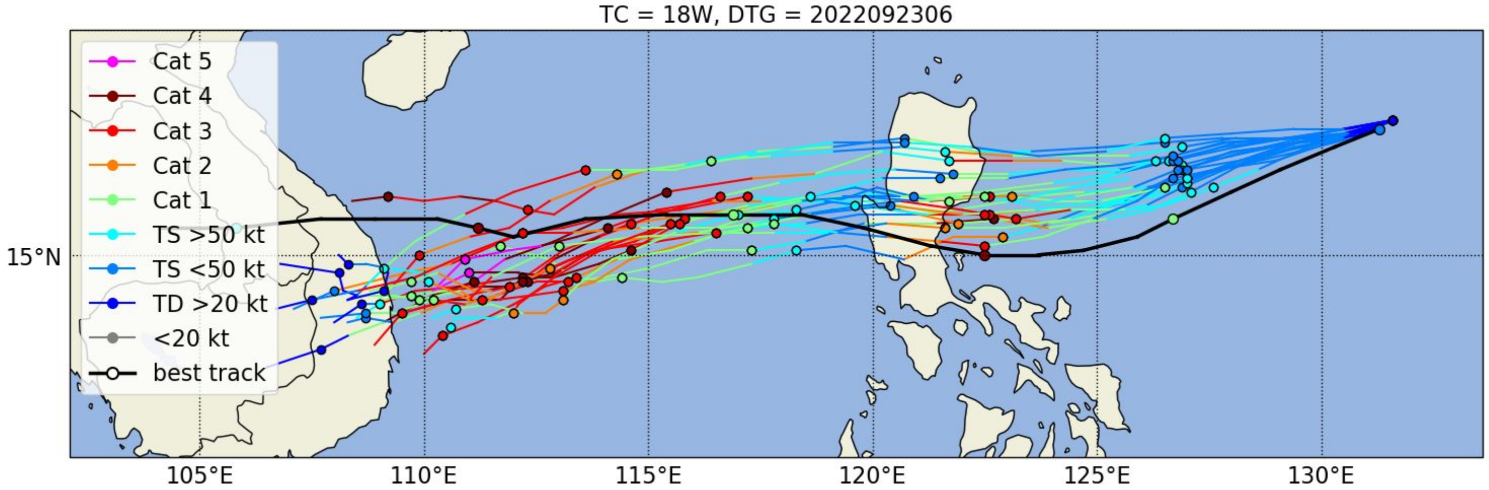


RI performance: 2018-2020 sample



- Thompson has a similar track bias as the NRL, but Morrison lags the NRL scheme by 10% or more.
- Thompson has weak intensity bias, but similar MAE w.r.t. NRL. Morrison is too strong with poor accuracy.
- The NRL scheme has the best RI accuracy, but Morrison has best RI relative frequency

Typhoon Noru (18W) - 2022092306



While ensemble was a bit too weak during first "extreme RI" stage, ensemble provided useful guidance that Noru would undergo RI, weaken due to land interaction, and then undergo RI again