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Diagnosing and Addressing Model Error in High-Resolution Tropical Cyclone Predictions

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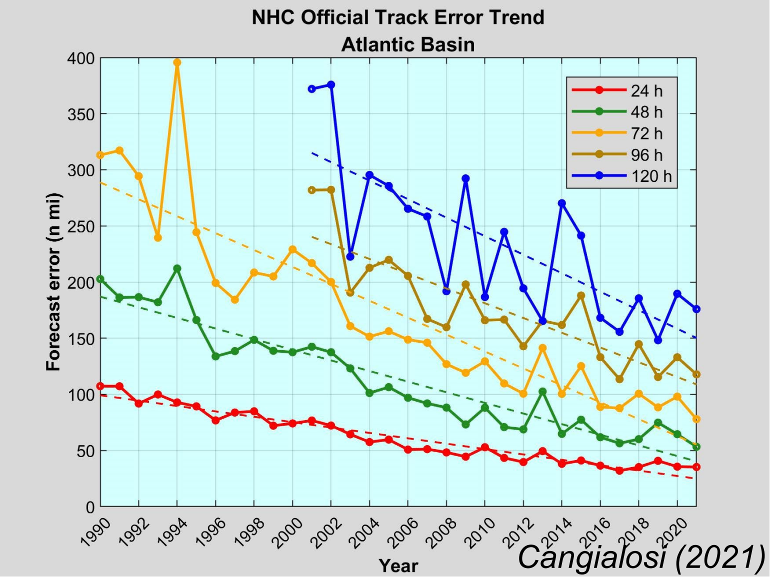
Outline

- Motivation and Background
- Regional Model Performance
- Surface and Boundary Layer, Air-Sea Coupling
- Cloud Microphysics
- Deep and Shallow Convection
- Horizontal and Vertical Resolution
- Summary and Recommendations

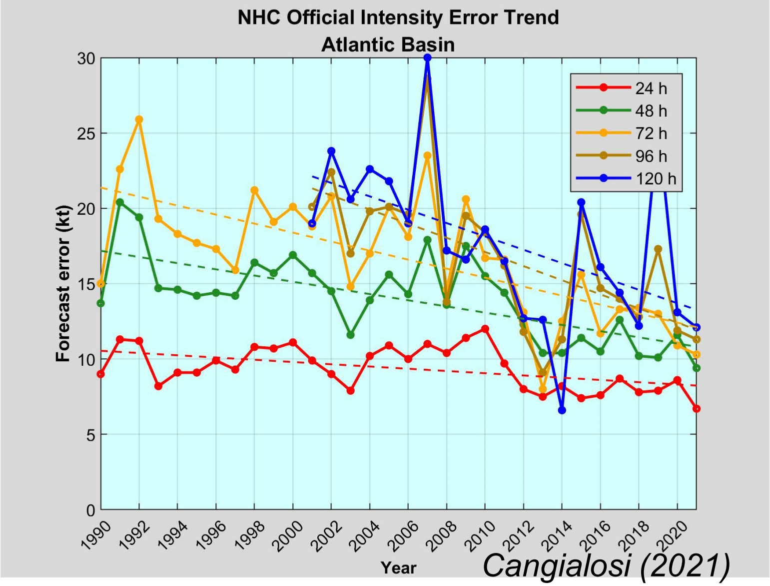
Motivation

- Property damage costs of TCs equal or exceed those of other natural catastrophes. Global estimates of TC damages are ~$29B USD/year; single storm up to ~$200B.
- Reliable forecasts of TC impacts (surge, flooding, winds), require accurate NWP and process representations of clouds, boundary layer, convection, radiation, and interaction with ocean.
- Track prediction has improved steadily, intensity forecast improvement has been slower.
- We use the U.S. Navy's regional COAMPS-TC modeling system to illustrate examples of systematic errors in TC track, intensity and structure (wind radii) forecasts and how we have addressed these.
- Which processes are the key to reduce track, intensity and structure systematic errors? What resolutions are needed? How should we evaluate TC forecast models?

Hurricane Ian Damage (USA Today)



Cangialosi (2021)



Cangialosi (2021)

COAMPS-TC
System overview

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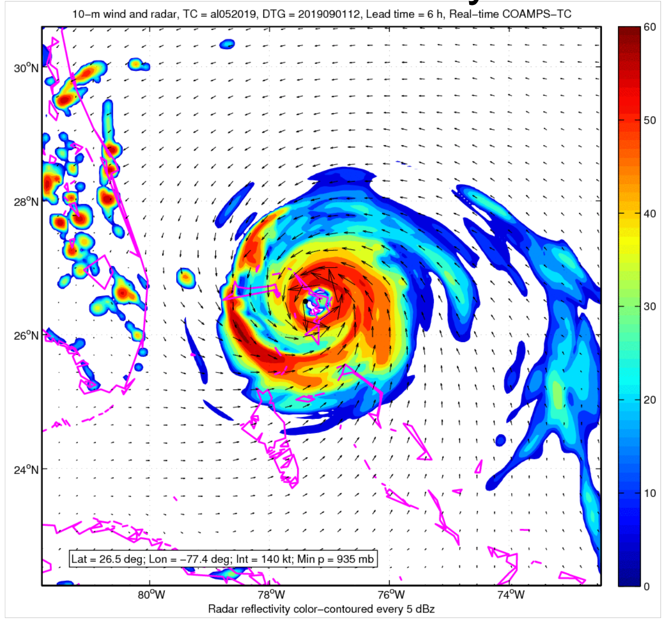
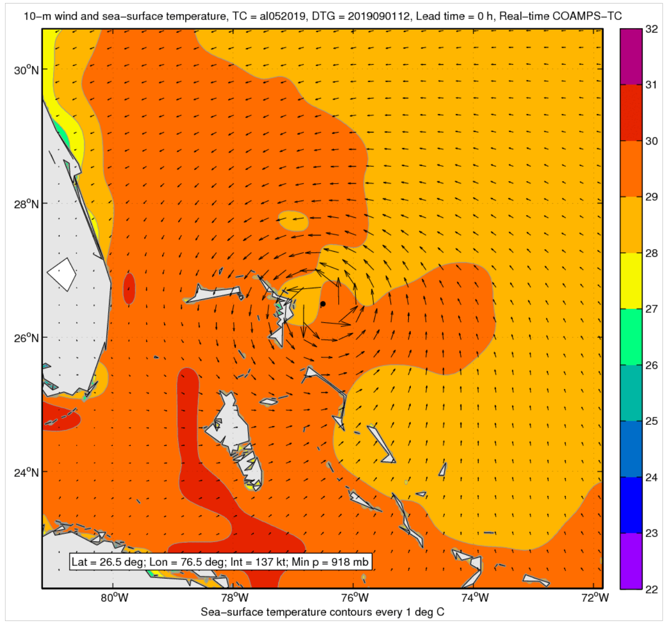
- COAMPS-TC is a specialized version of the U.S. Navy's mesoscale numerical weather prediction (NWP) model COAMPS, designed to predict (5 day) tropical cyclone (TC) track, intensity and structure (wind radii)
- Features: TC-following nested grid meshes (4 km on inner mesh, 40L)
  Specialized TC physics (drag coefficient; boundary layer; microphysics); TC Vortex initialization
  Coupled with NRL Coastal Ocean Model, NCOM
- Operational at Navy FNMOC: i) deterministic NAVGEM BCs (**<u>COTC</u>**) and NOAA GFS BCs (**<u>CTCX</u>**)
  ii) COAMPS-TC ensemble (11 member, 4 km resolution) based on NOAA GFS

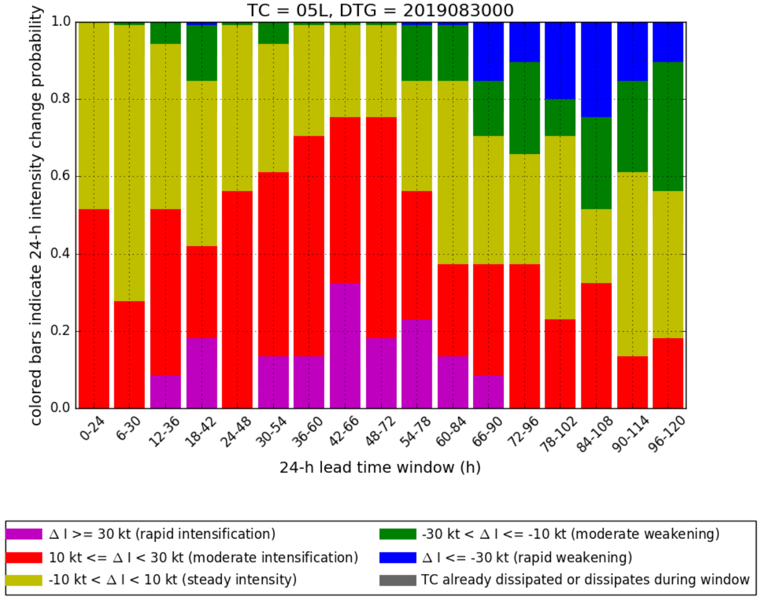
COAMPS-TC Deterministic (4km)
Dorian (05L) (12Z 1 Sep 2019)
Simulated Radar Reflectivity and 10-m Winds



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

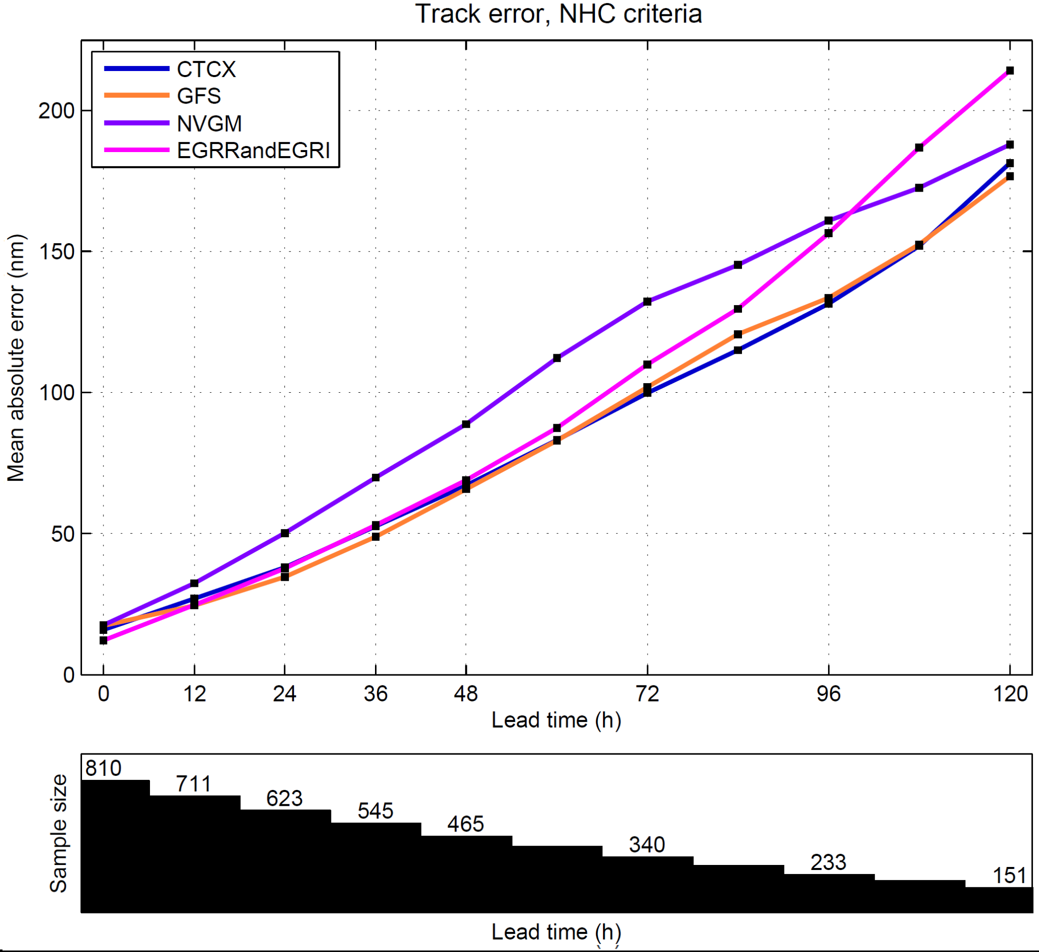


COAMPS-TC Evaluation

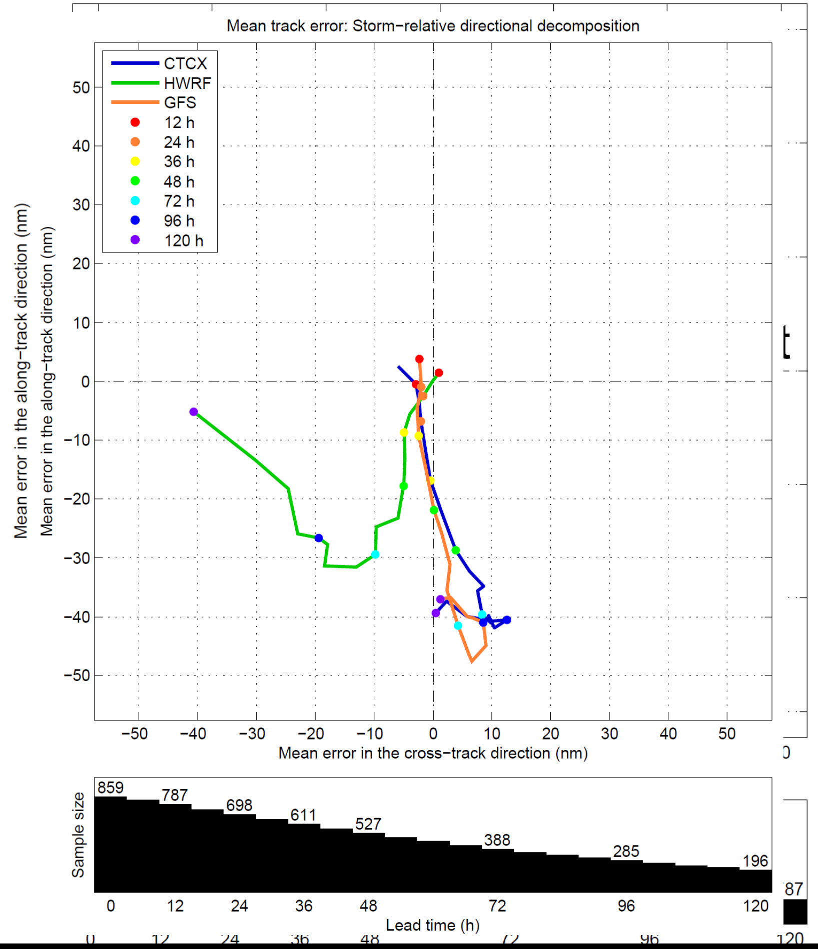
Track Verification

2022 AL/EP/WP

Track Mean Absolute Error (n mi)



Storm Relative Track Bias (n mi)

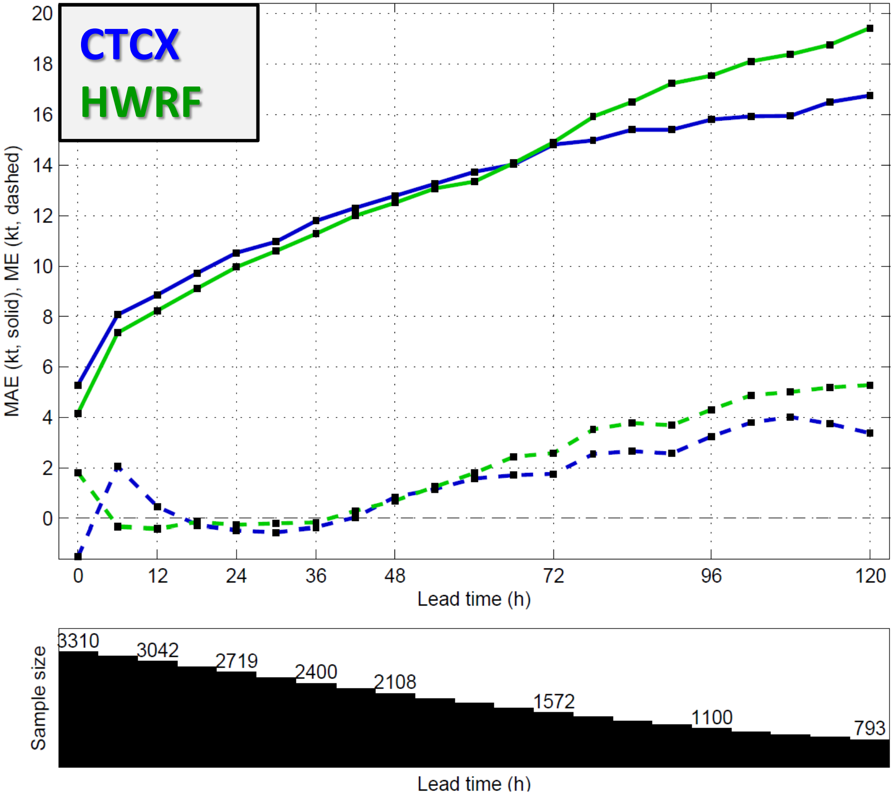


- CTCX track similar to the GFS and generally superior to the other regional and global models.
- CTCX has a small cross track bias and similar to the GFS.

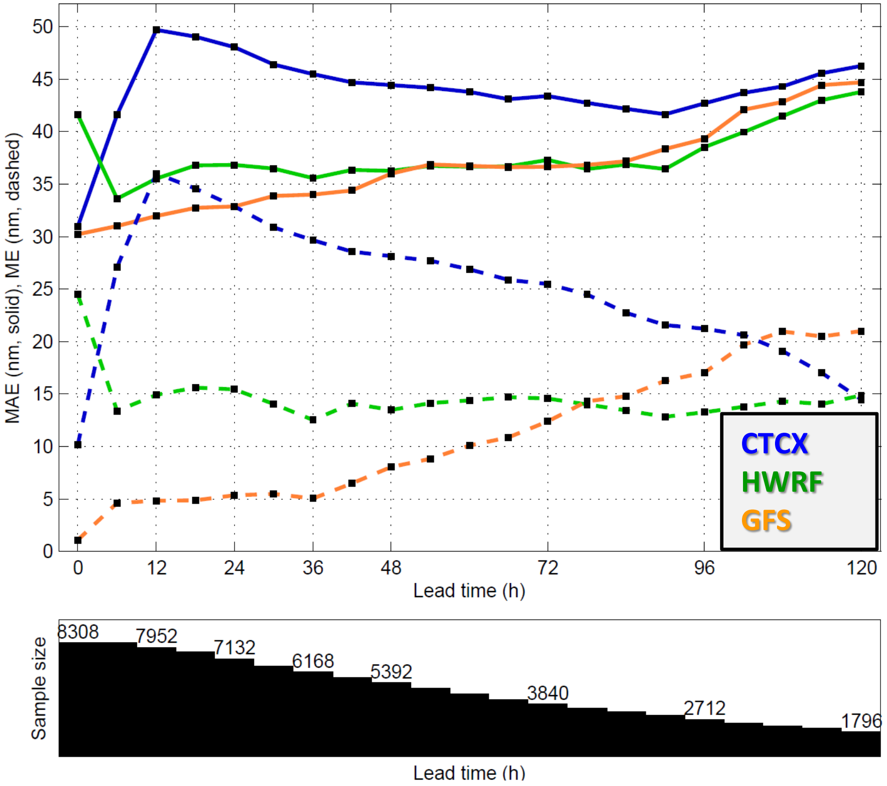
COAMPS-TC Evaluation
Intensity and Structure Verification

2020 AL/EP/WP/IO, 2021 AL/EP/WP/IO/SH, 2022 SH

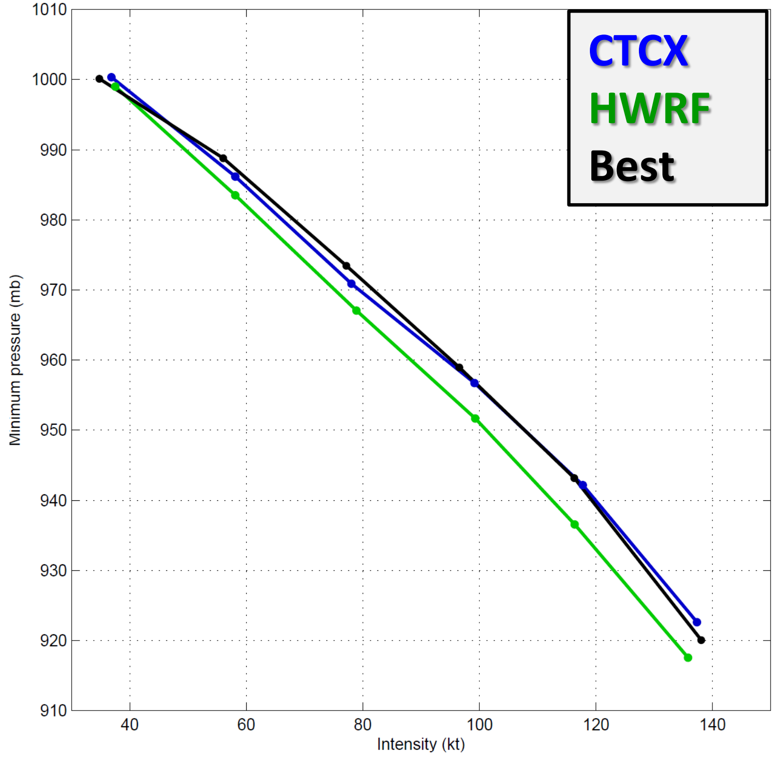
Intensity MAE (solid); ME (dashed)



Radius 34 kt Wind MAE (solid); ME (dashed)



Pressure-Wind Relationship



- CTCX intensity errors are similar to HWRF out to 72h, and lower in 72-120h range
- R34 predictions for CTCX are systematically larger and less accurate than for HWRF and GFS
- CTCX pressure-wind relationship is near best track – *What is the P-W relationship most sensitive to?*

COAMPS-TC Rapid Intensification (RI) Evaluation Atlantic Basin 2020-2021

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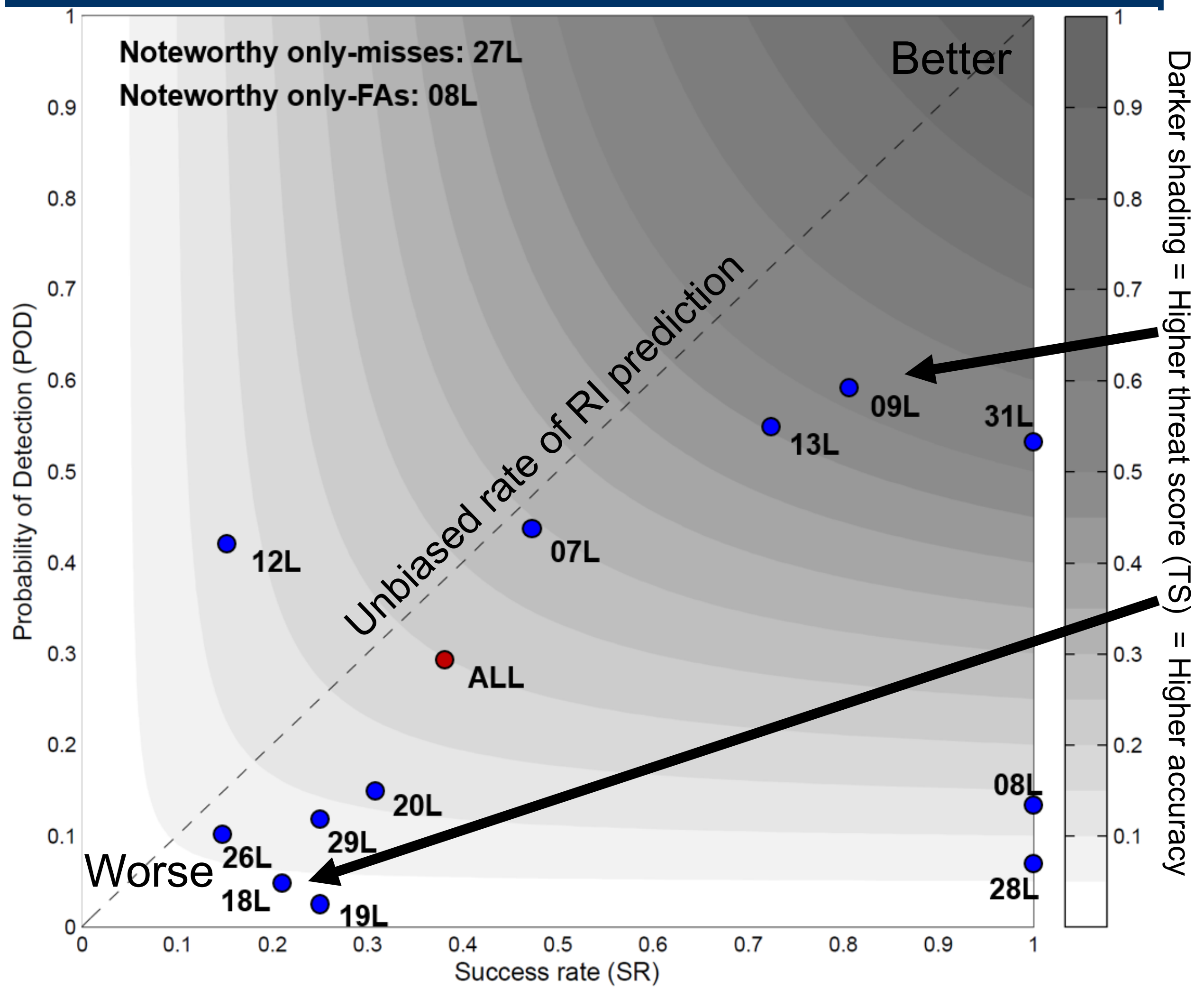
2020/2021 Atlantic Storm-by-Storm RI performance



Threat score is shaded (higher = better), unbiased rate of RI prediction along diagonal

2020 TCRI storms

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

2021 TCRI storms

- 07L: Grace
- 08L: Henri
- 09L: Ida
- 18L: Sam

The best CTCX RI forecasts are for storms with a prolonged period of RI with peak rate >= 55 kt / 24 h, and peak intensity >= Cat4. Ida (09L) is an example, as is GoM intensification of Grace (07L)

CTCX does not make great RI forecasts for all storms as described above, however. Poor forecasts were made for Delta (26L) and Sam (18L), which both had a very small inner core.

Henri (08L) was an unusual case in which CTCX consistently predicted RI but it did not occur

RI defined as a 30 kt intensity increase over 24h

COAMPS-TC Evaluation

Hurricane Ian Track Forecasts

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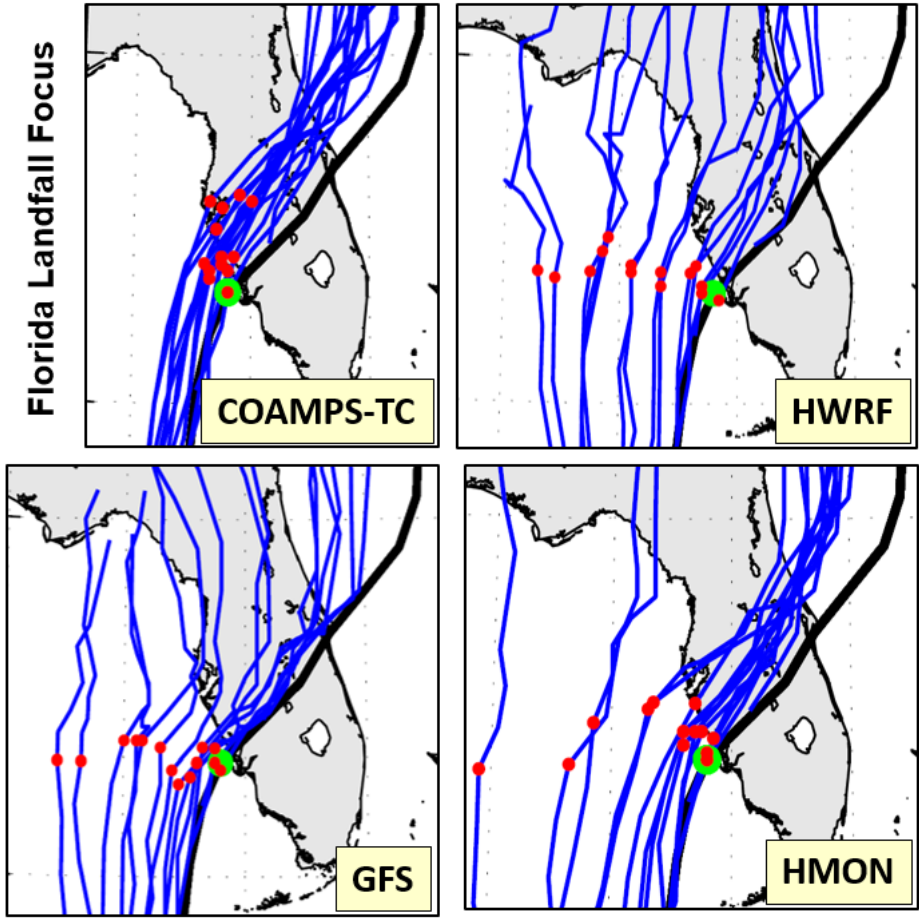
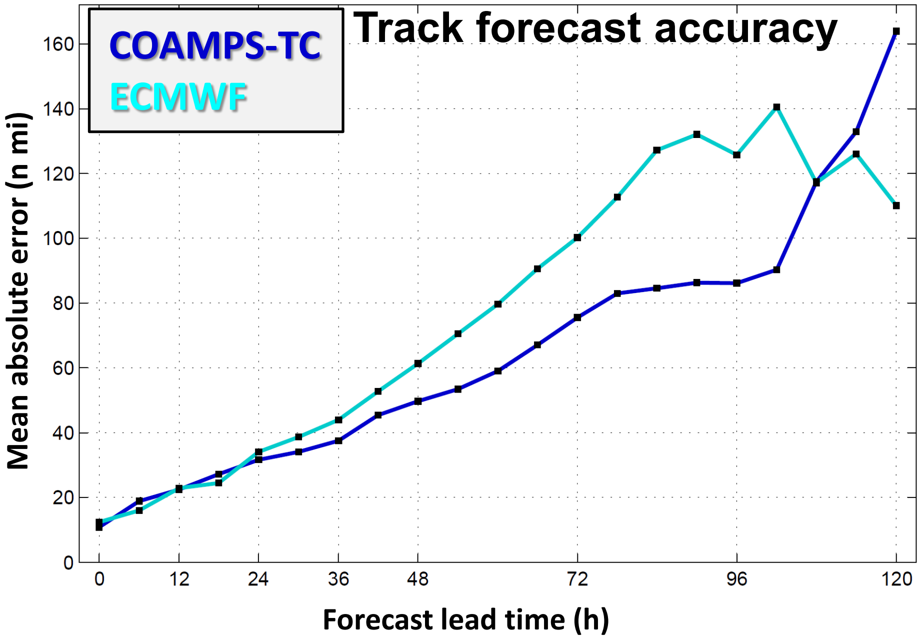
- Within 3 days of Florida landfall, COAMPS-TC forecasts did exceptionally well to predict the timing/location of landfall.
- Even for early forecasts 4 to 5 days in advance, COAMPS-TC predicted Ian to be a major hurricane in the Gulf of Mexico

Florida Landfall Focus



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

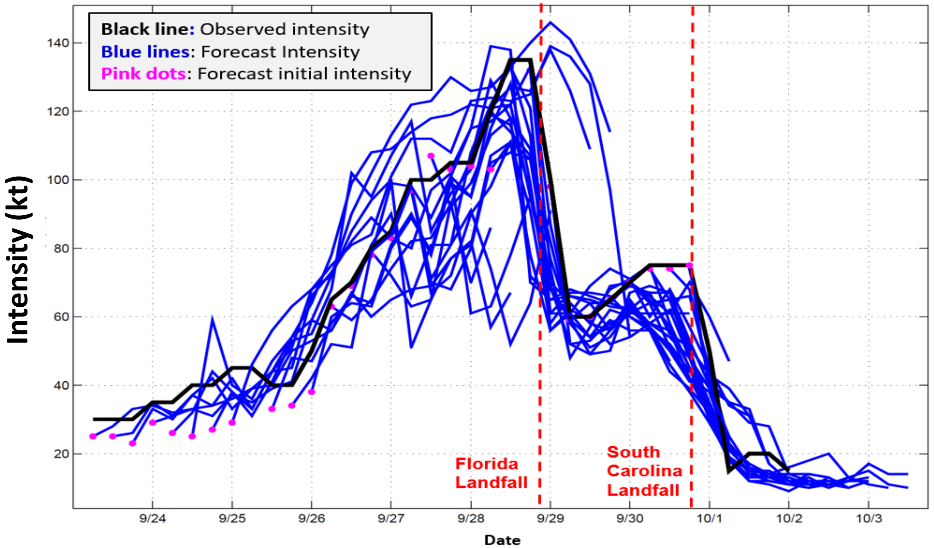
Black line: Observed track
Green dot: Observed TC position at time of landfall



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**

COAMPS-TC Intensity Forecasts



Surface Exchange and Boundary Layer Processes in Tropical Cyclones

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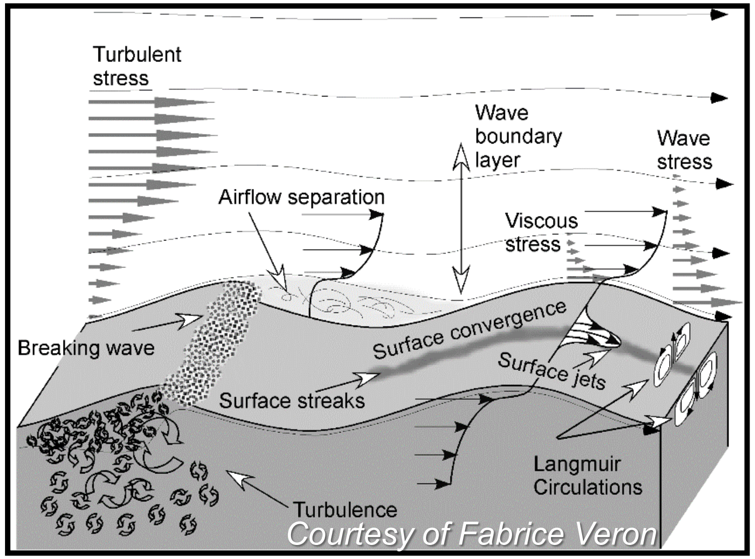
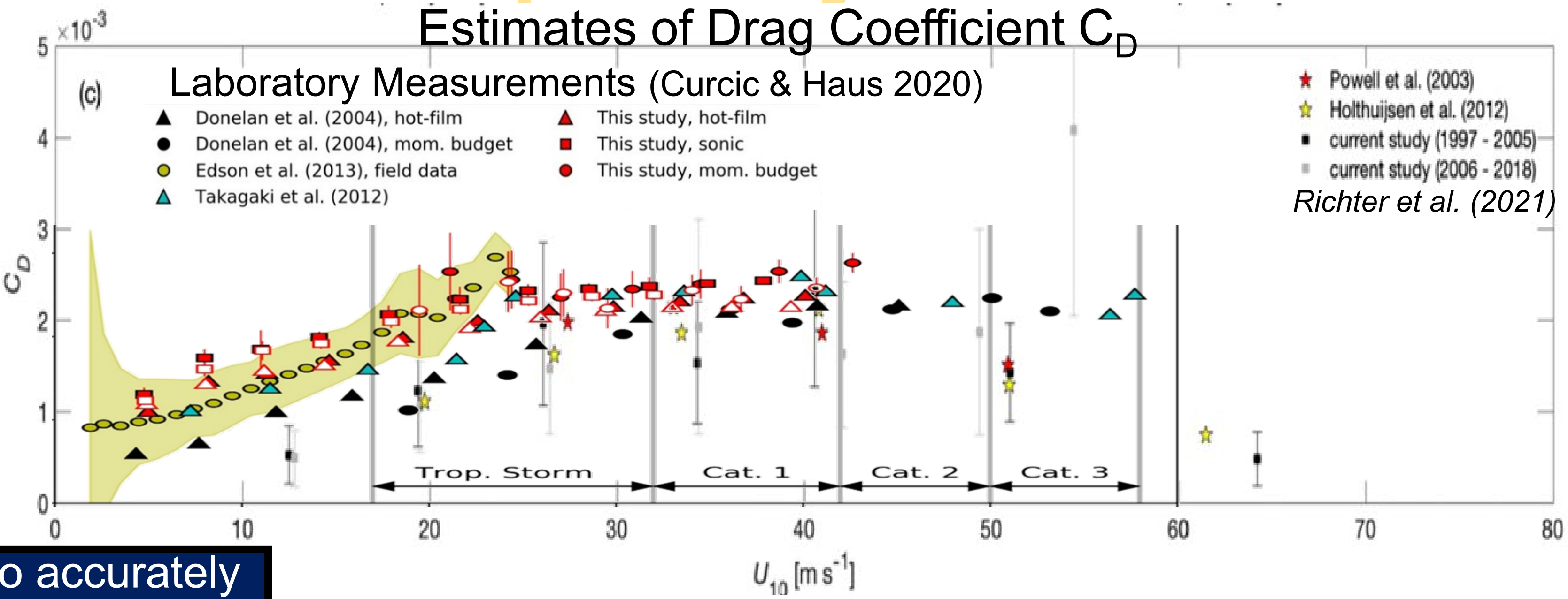
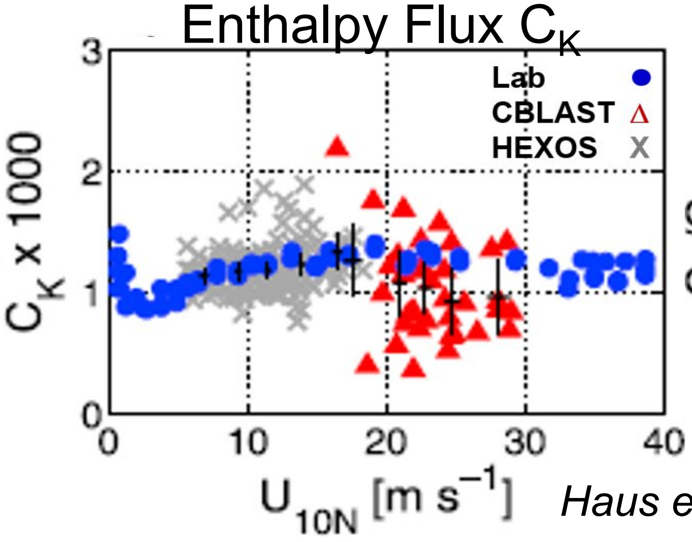
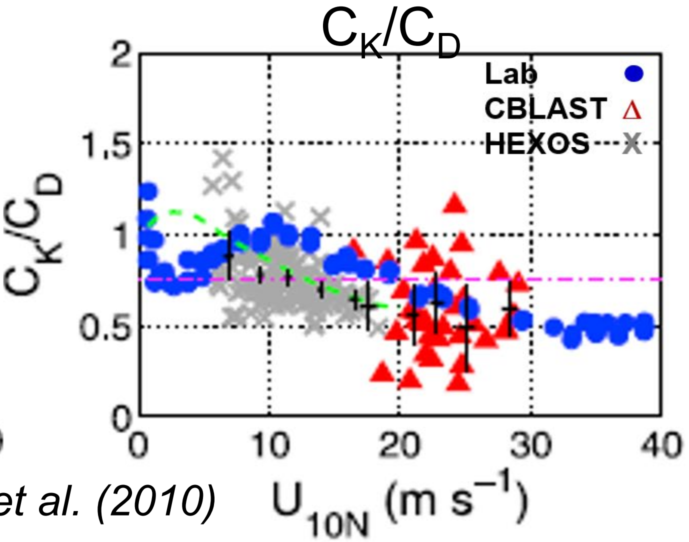






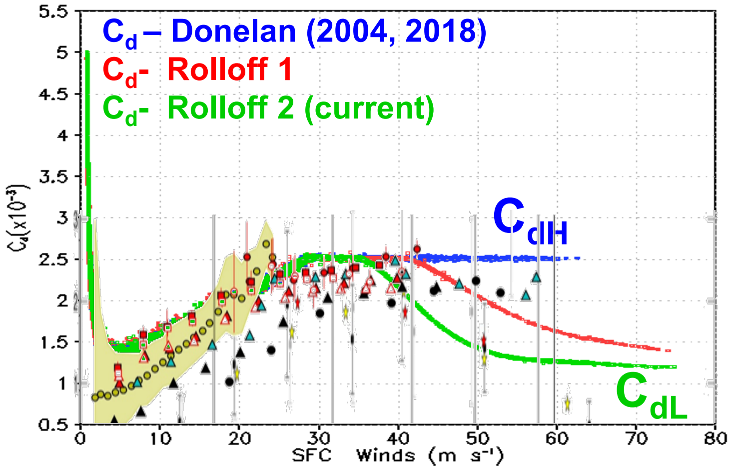
Haus et al. (2010)

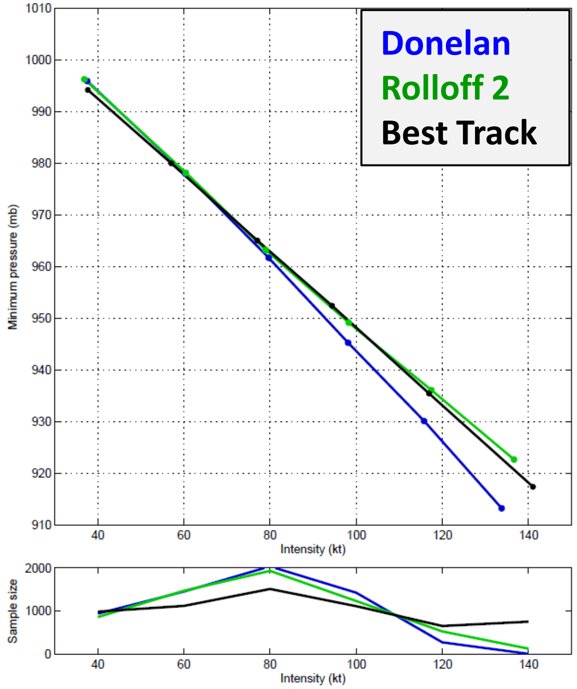


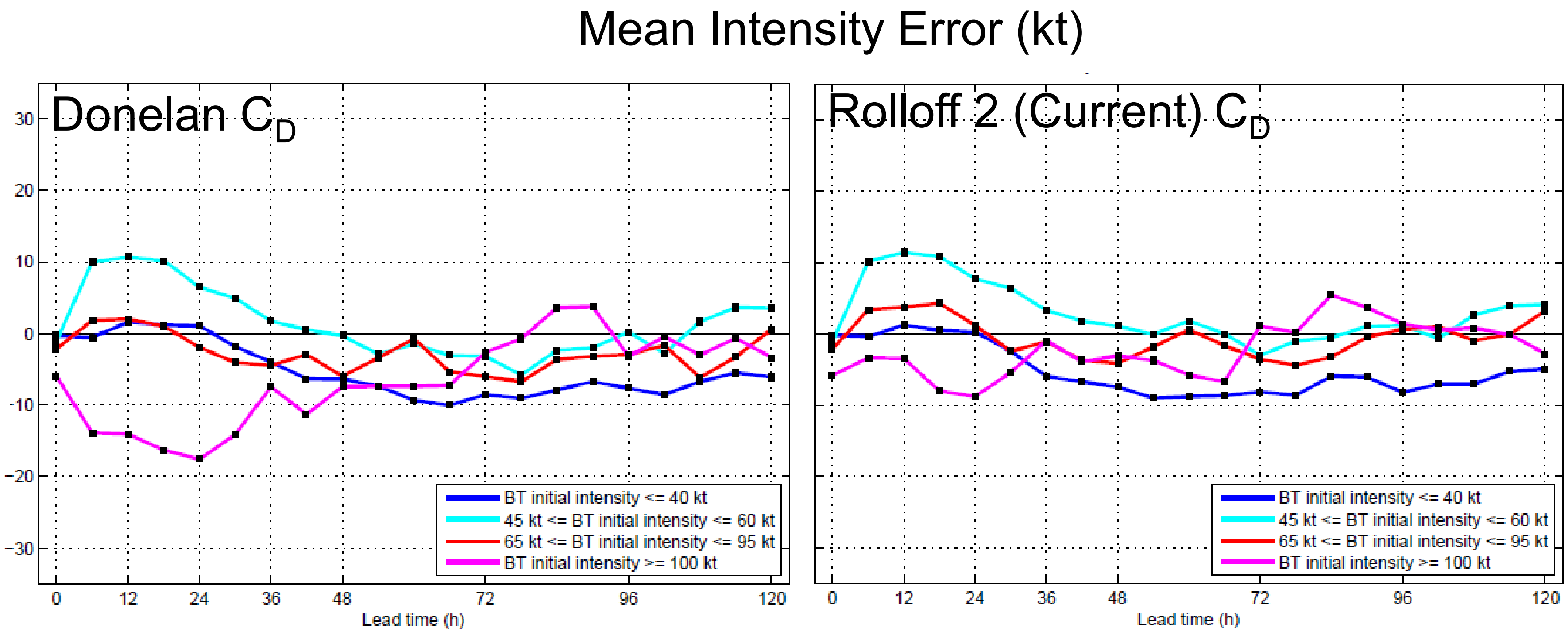
- Air-sea processes in TCs are crucial to accurately represent (fluxes, ocean mixing, spray) (Shay 2010; Holthuijsen et al., 2012; Bell et al. 2012; Nystrom et al. 2020)
- Estimation of air–sea momentum transfer in high winds use flux-profile method; C_D can be inferred from dropsondes (Powell et al. 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).

Surface Drag Parameterization

COAMPS-TC C_D Formulation







- **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

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

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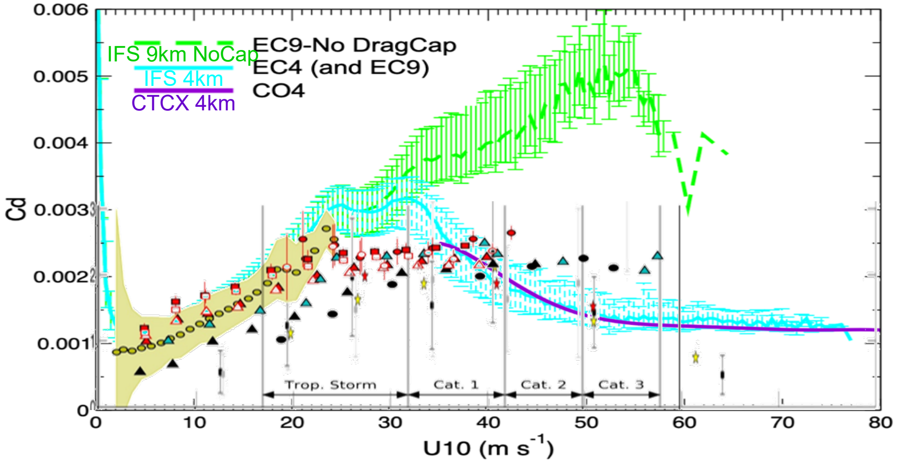
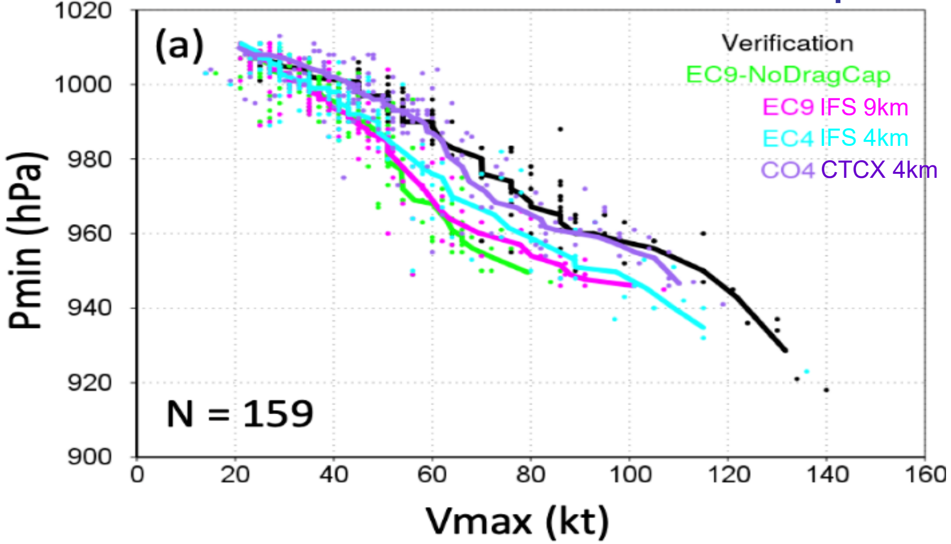
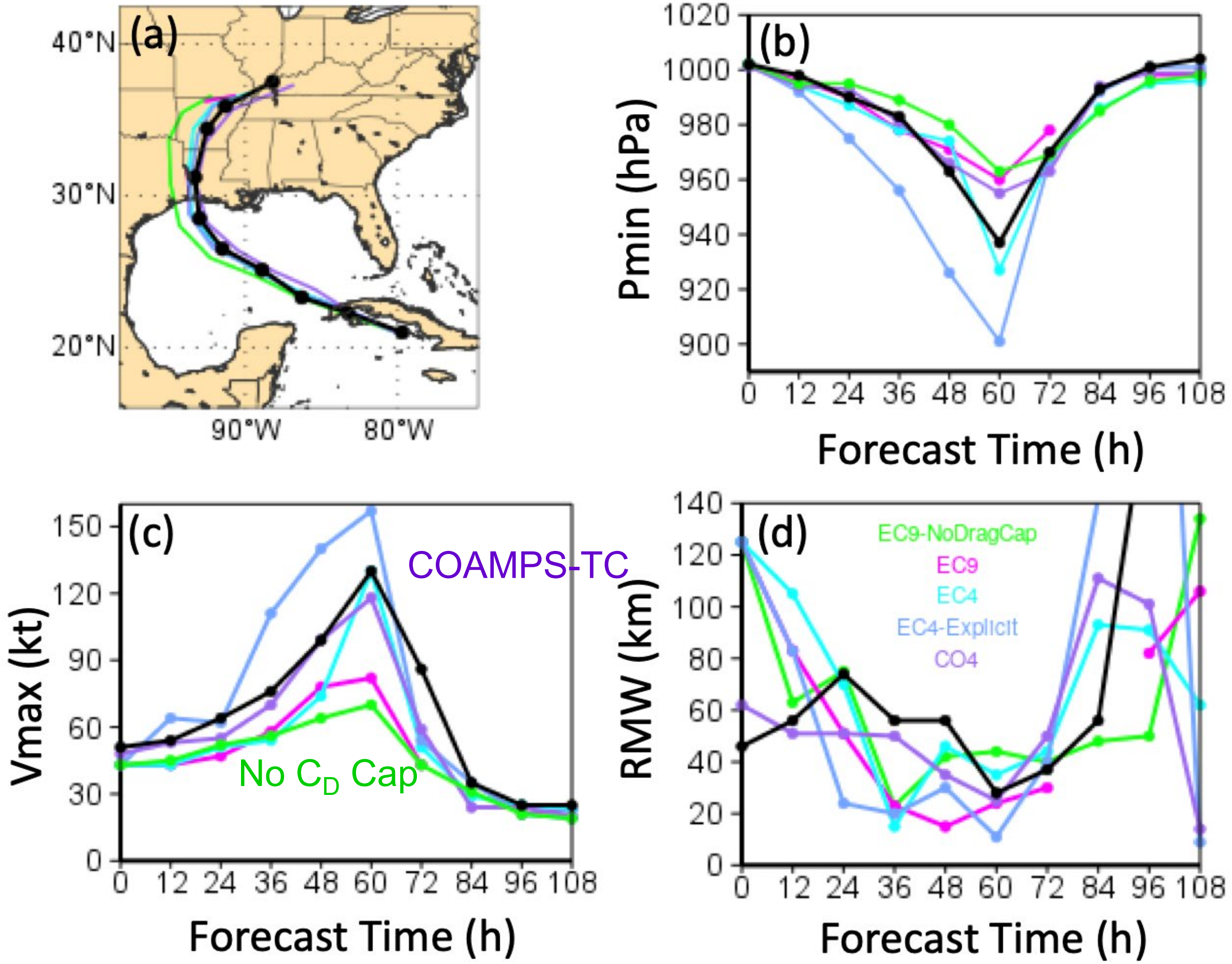
Comparison of ECMWF IFS & COAMPS-TC C_D



Pressure-Wind Relationship



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

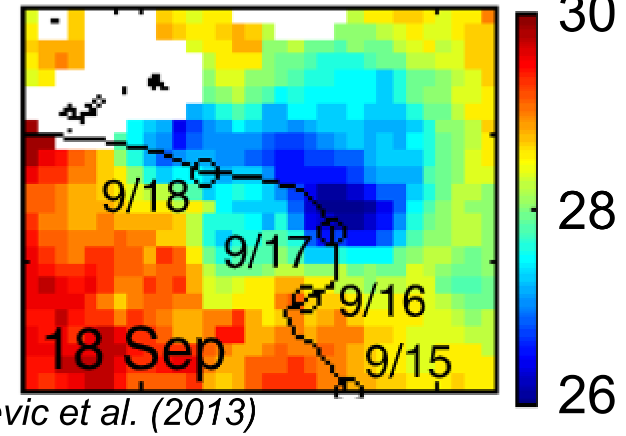


- ECMWF IFS also shows a similar large sensitivity to the C_D formulation

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

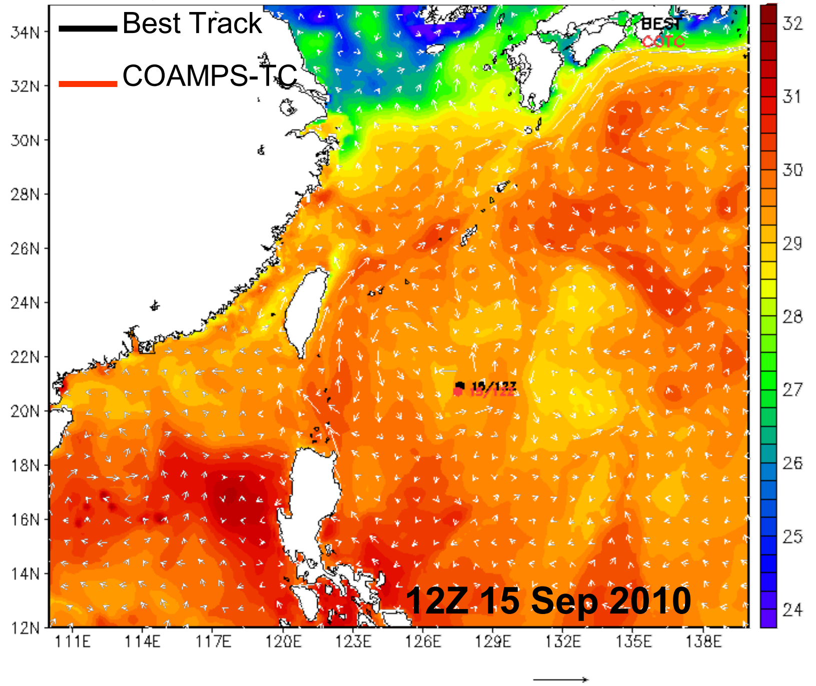
Air-Ocean Coupling in Tropical Cyclones
Upper Ocean Processes

Microwave SST [TY Fanapi (2010)]

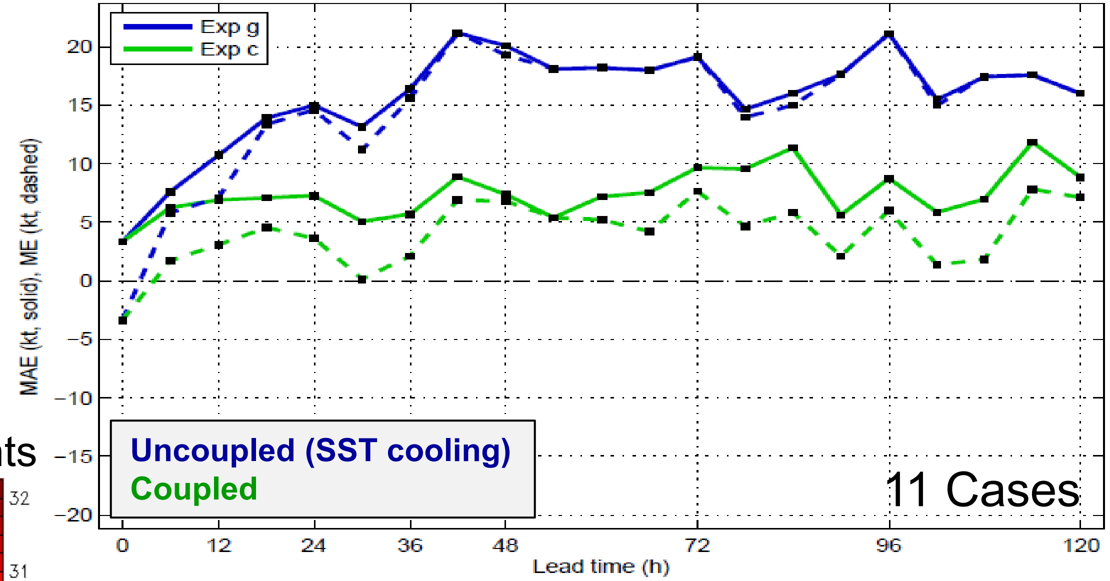


Mrvaljevic et al. (2013)

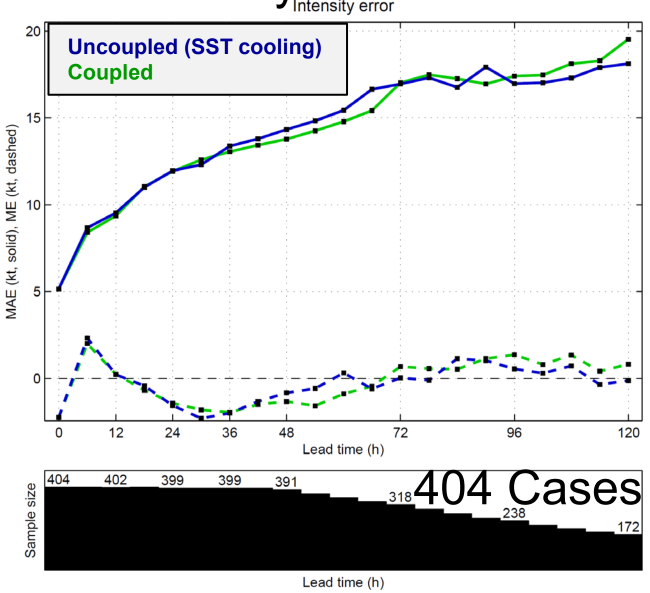
ITOP Typhoon Fanapi: SST (°C), Currents



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

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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

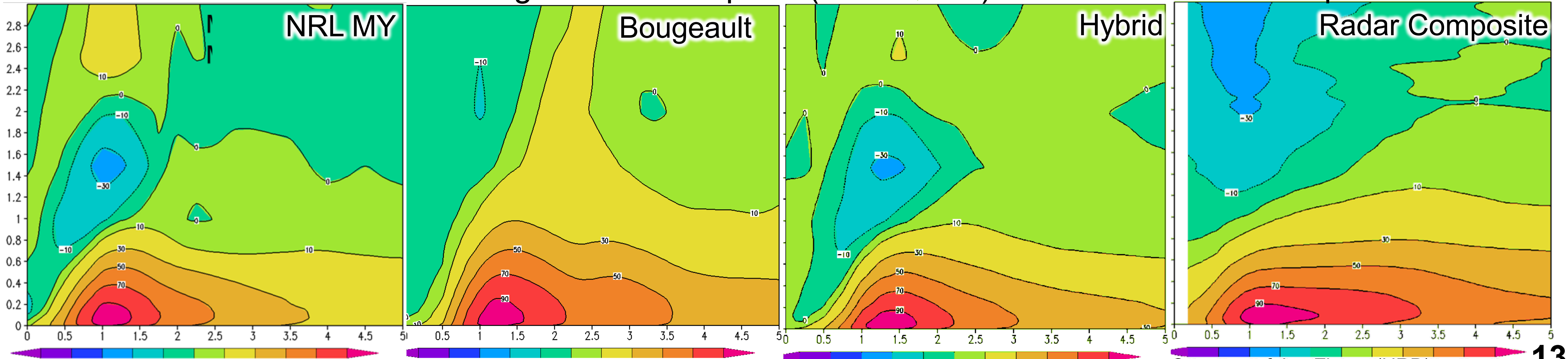
(modified Mellor and Yamada 1982)

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

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

Diffusion, Shear, Buoyancy, Dissipation, Advection

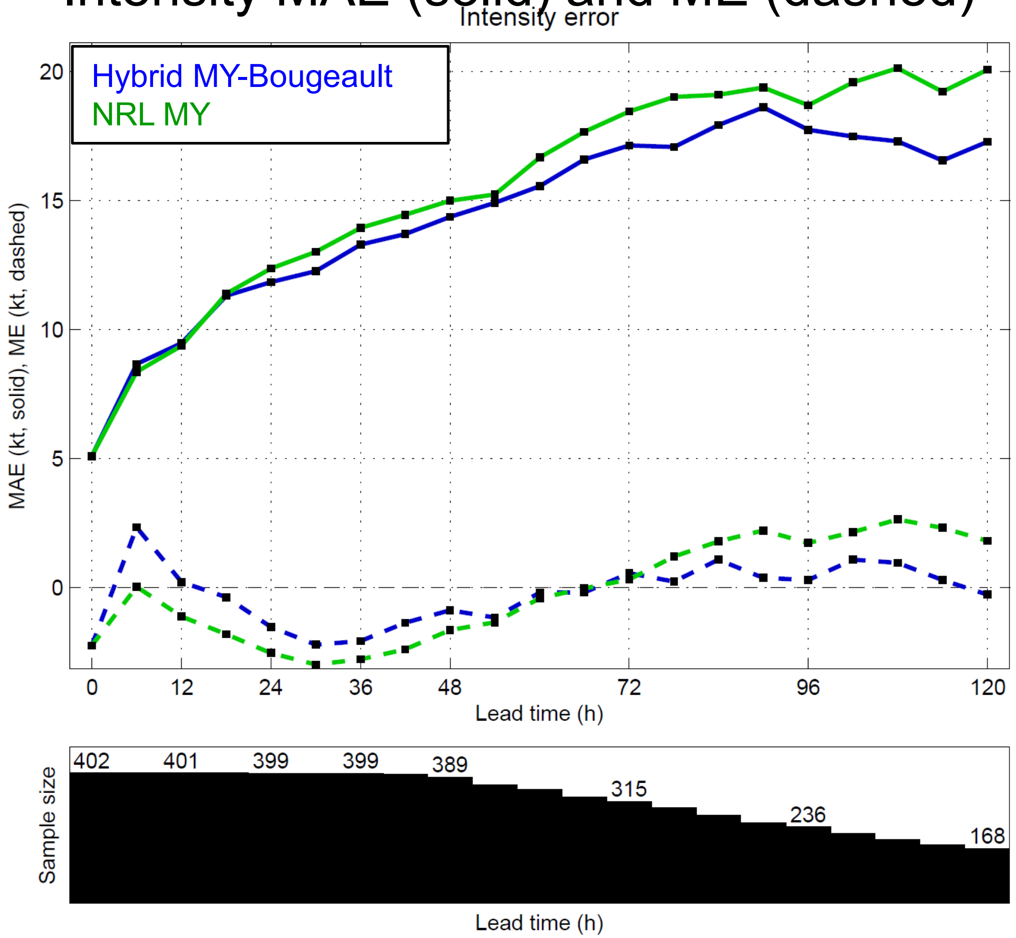
Azimuthal Mean of the Tangential Wind Speed (normalized) for an Idealized TC Experiment



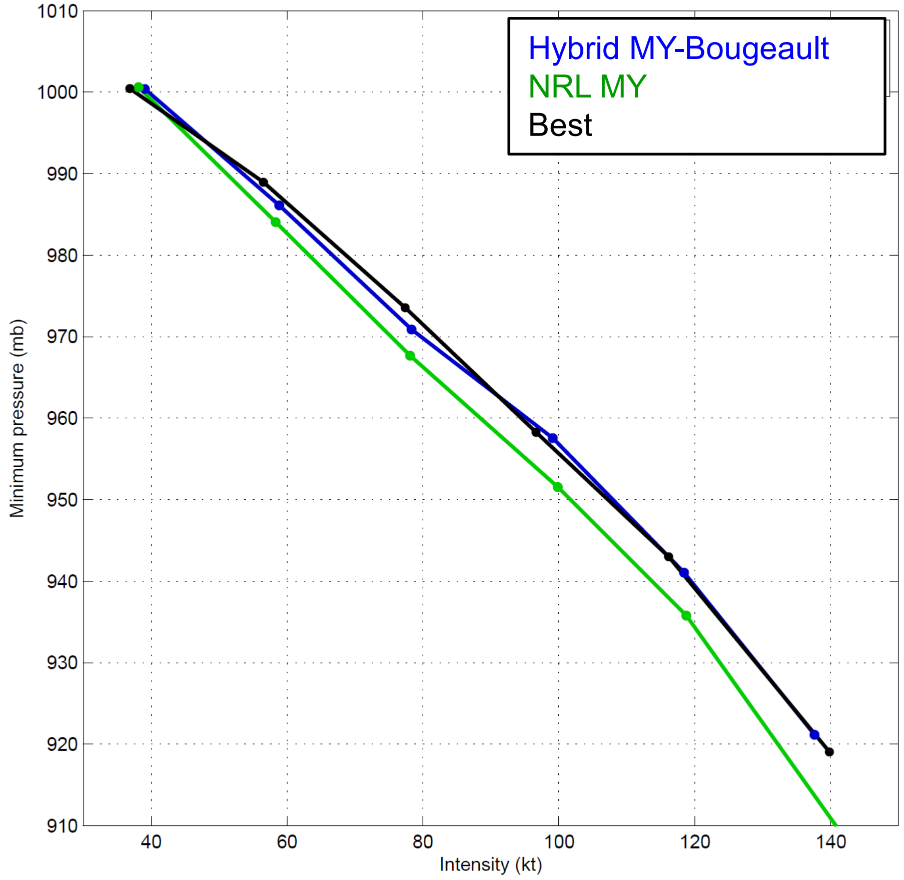
Courtesy of Jun Zhang (HRD)

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

Hurricane Boundary Layer
Dissipative Heating

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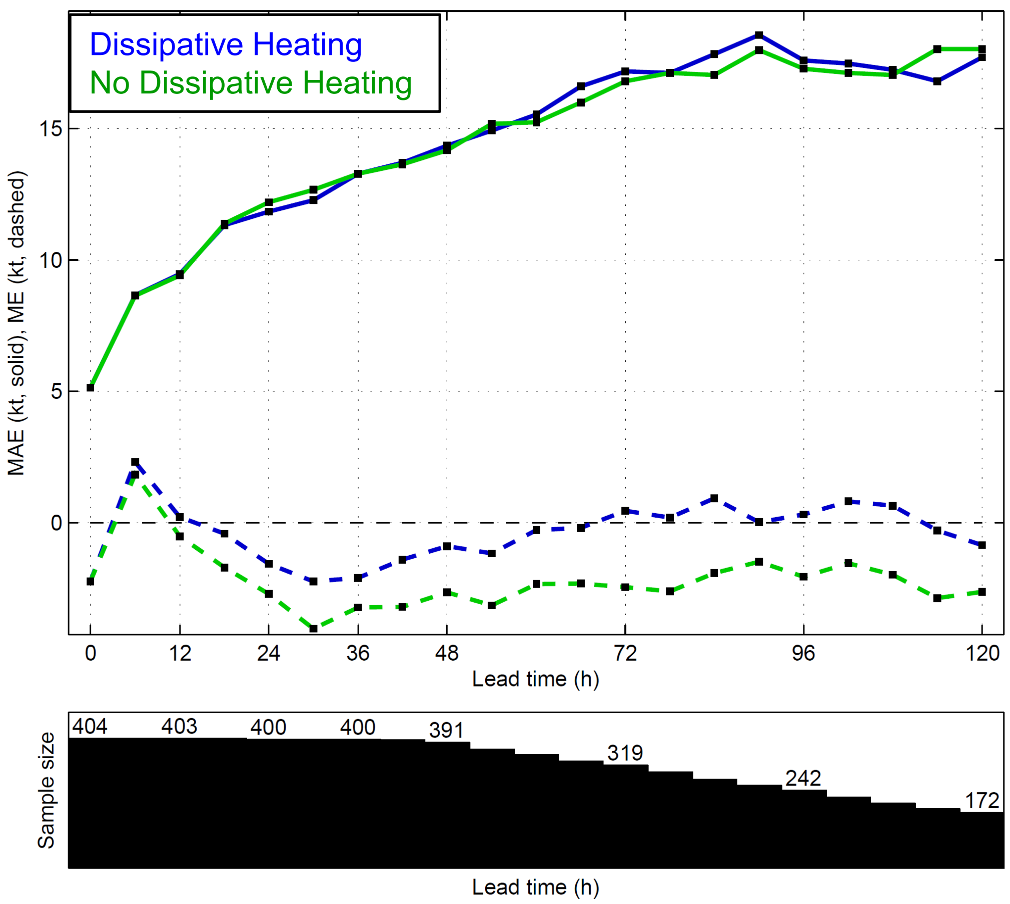
Dissipative Heating Parameterization

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

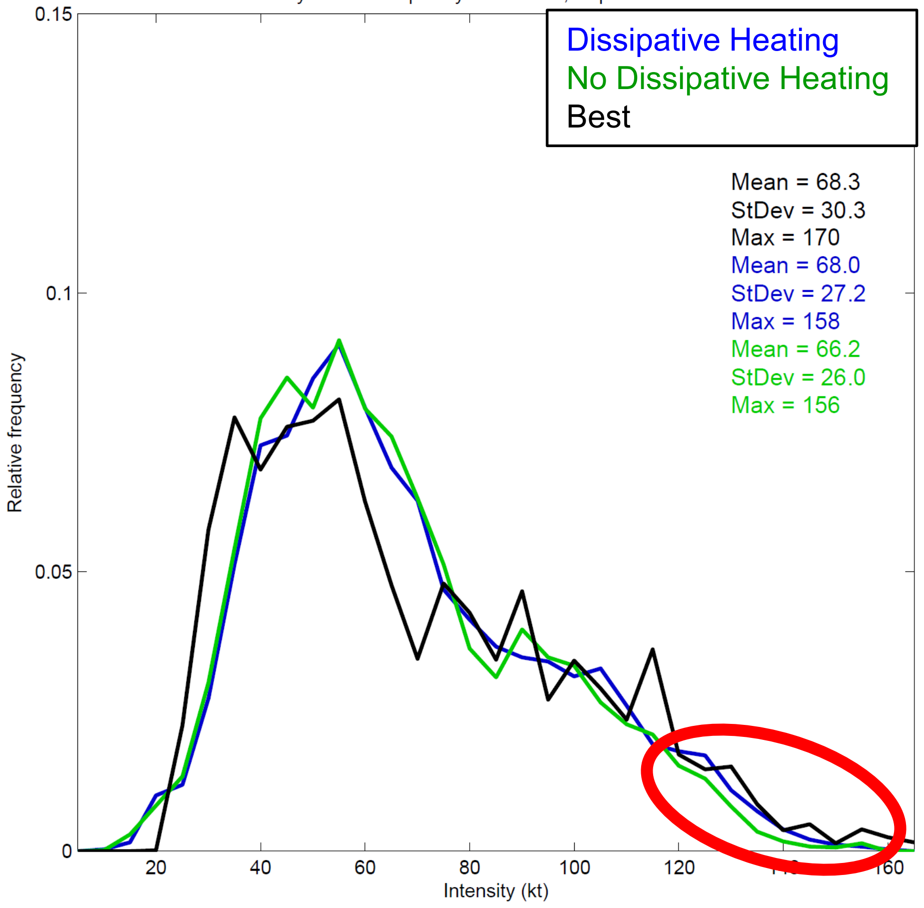
$$\varepsilon = -\tfrac{1}{2}[\partial(u'^2 + \upsilon'^2 + \overline{u'}^2) / \partial t]|_{diss}$$

Following Jin et al. (2007)

Intensity MAE (solid) and ME (dashed)



Frequency Distribution

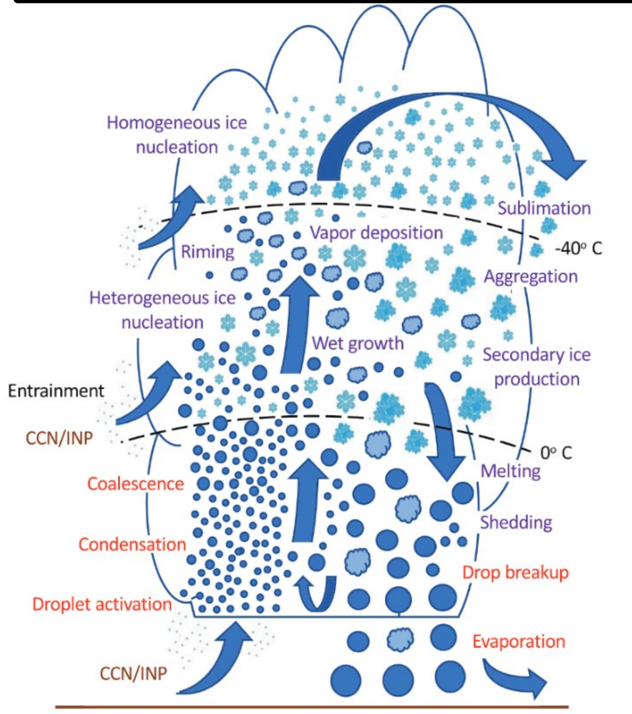


- Dissipative heating improves mean intensity bias by ~2-3 kt, especially for strong TCs
- Intensity relative frequency distribution is improved for strong TCs

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

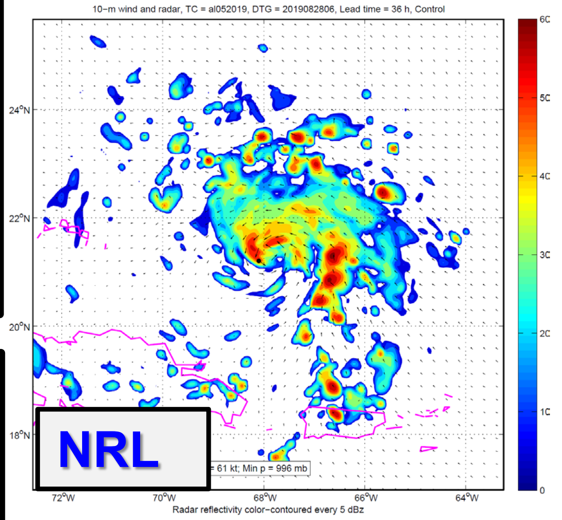


Morrison et al. (2020)

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

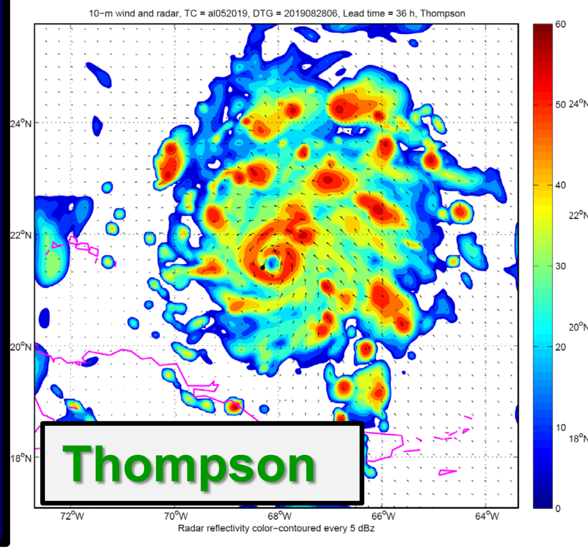
Simulated radar reflectivity, 36 h CTCX forecast for Hurricane Dorian

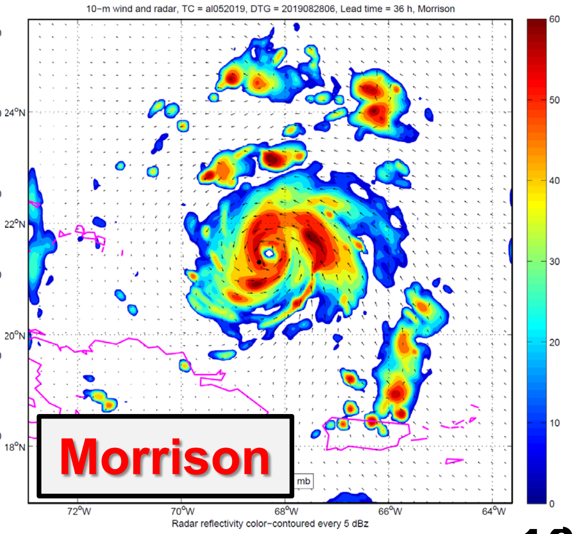


NRL (Control): *6 class microphysics with graupel*

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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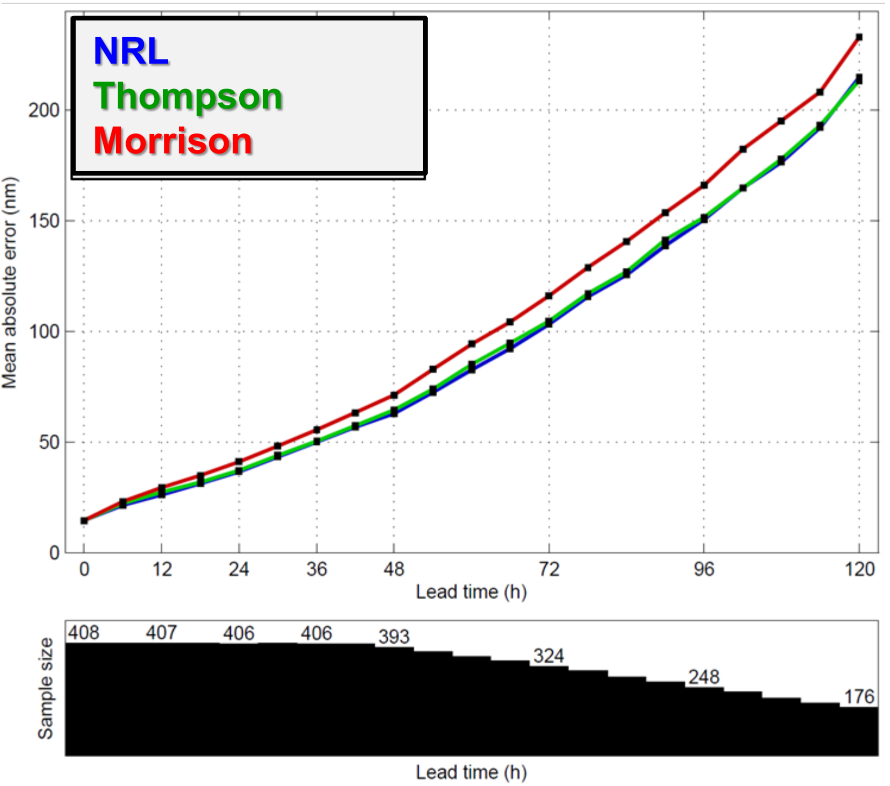
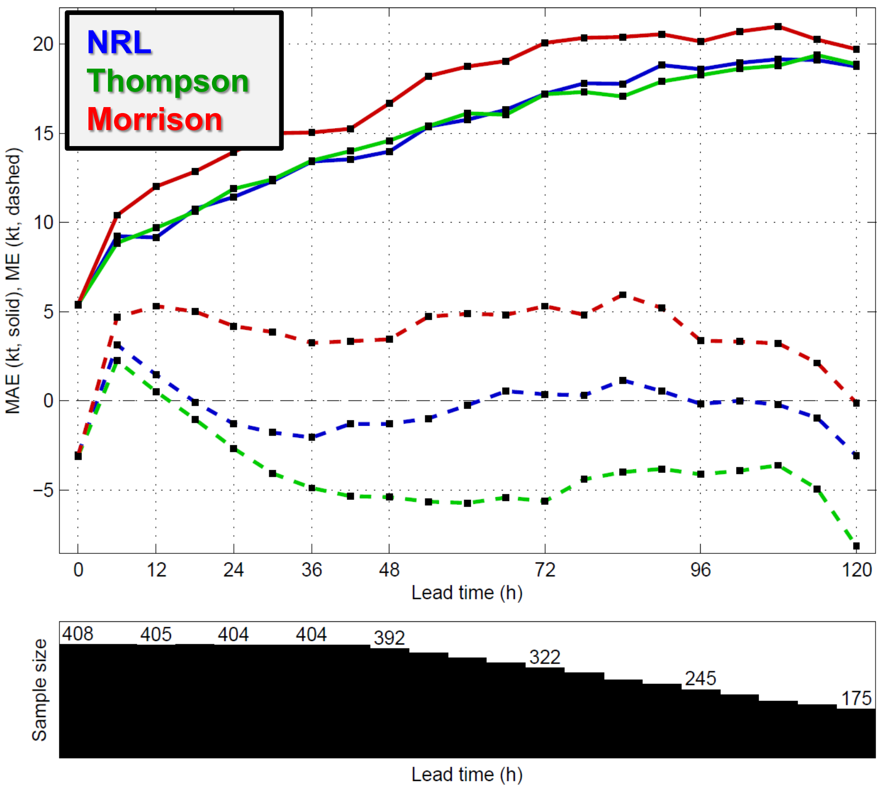
Microphysics

Sensitivity to Microphysics Representation

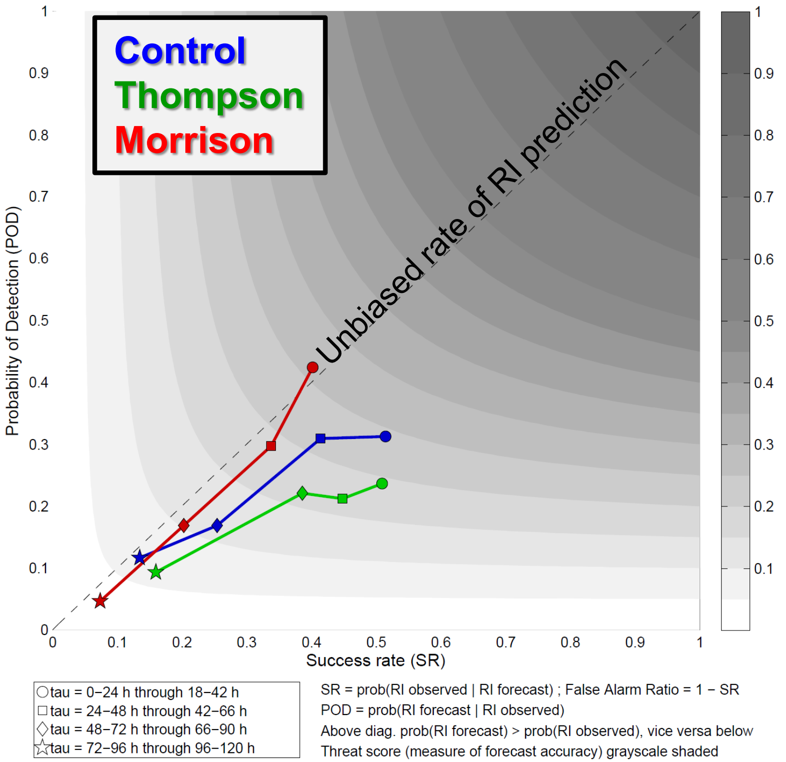
Track Mean Error (n mi)



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

Microphysics
Sensitivity to Microphysics Parameterization

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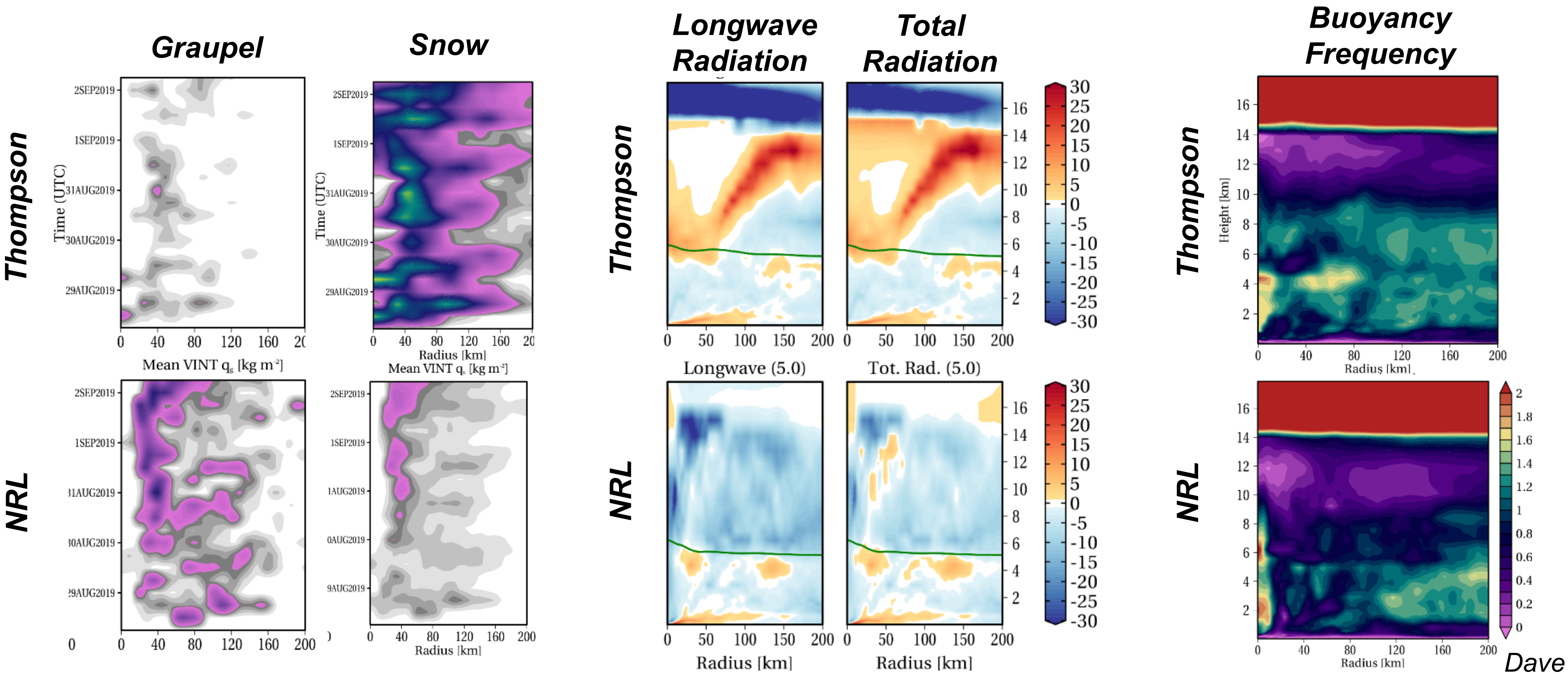
Why are tropical cyclones in Thompson systematically weaker than in the Control?



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

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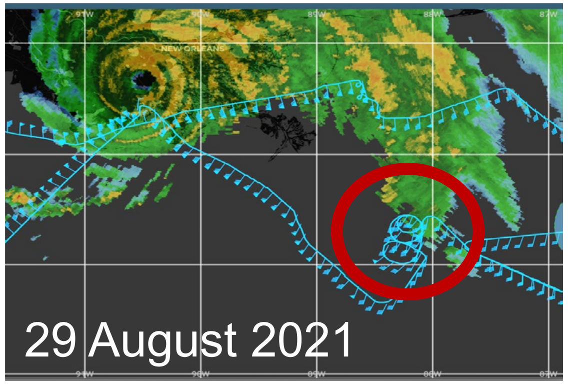
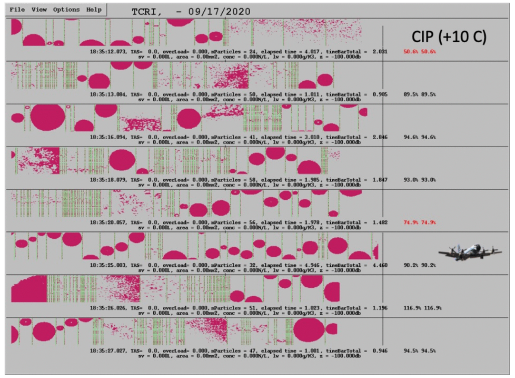
Microphysics Observations in Hurricane Ida

ONR TCRI Microphysics Observations

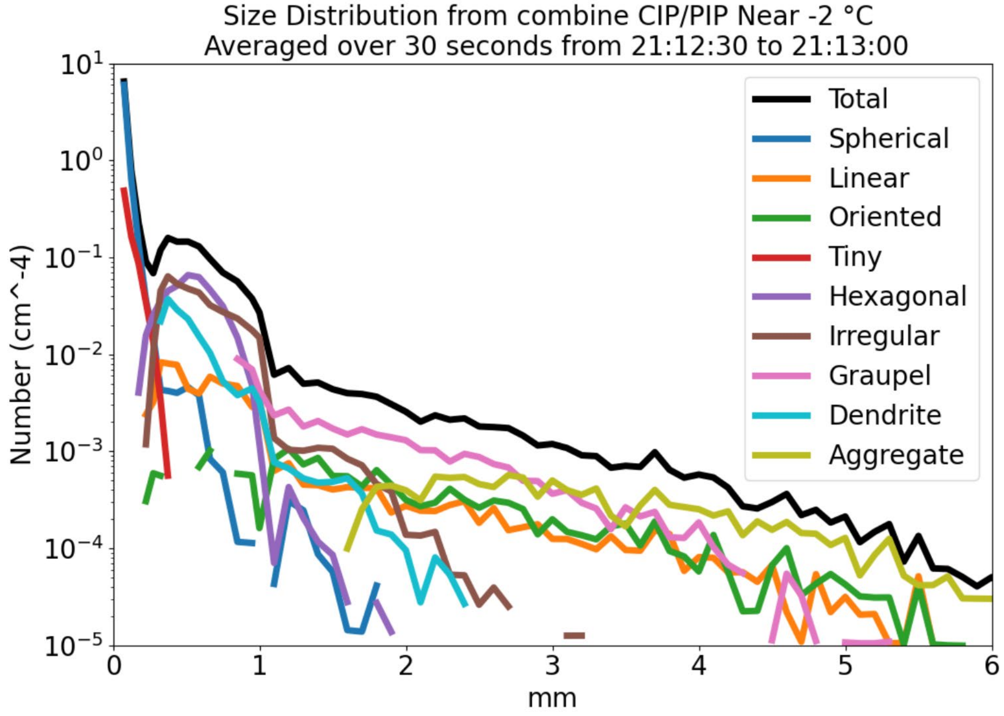
Hurricane Ida P3 track microphysical spiral

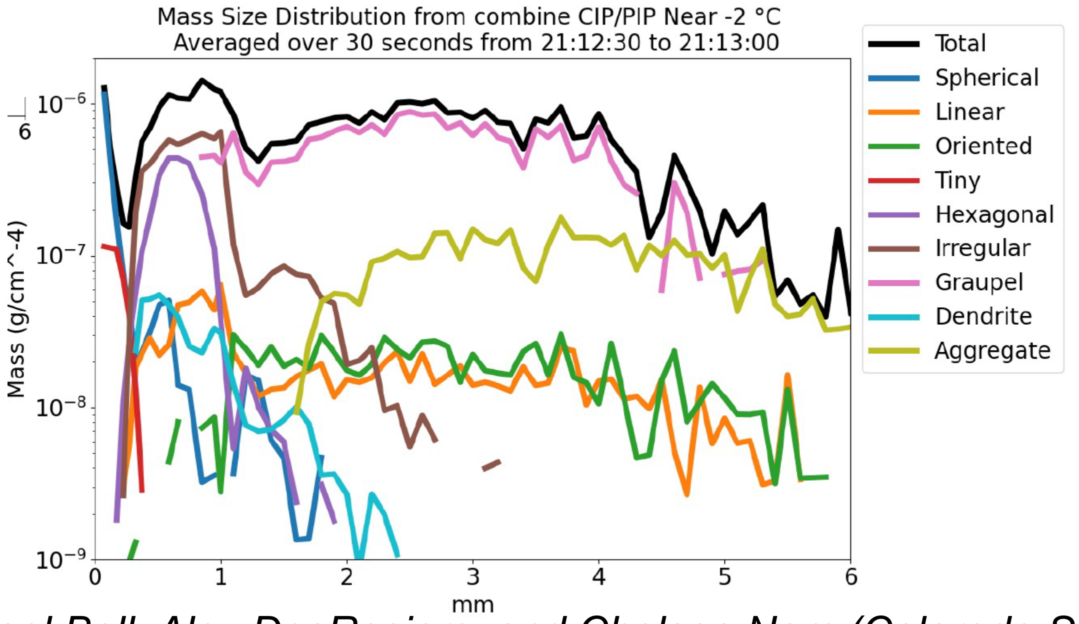


Hydrometeors transition from water to ice



- 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





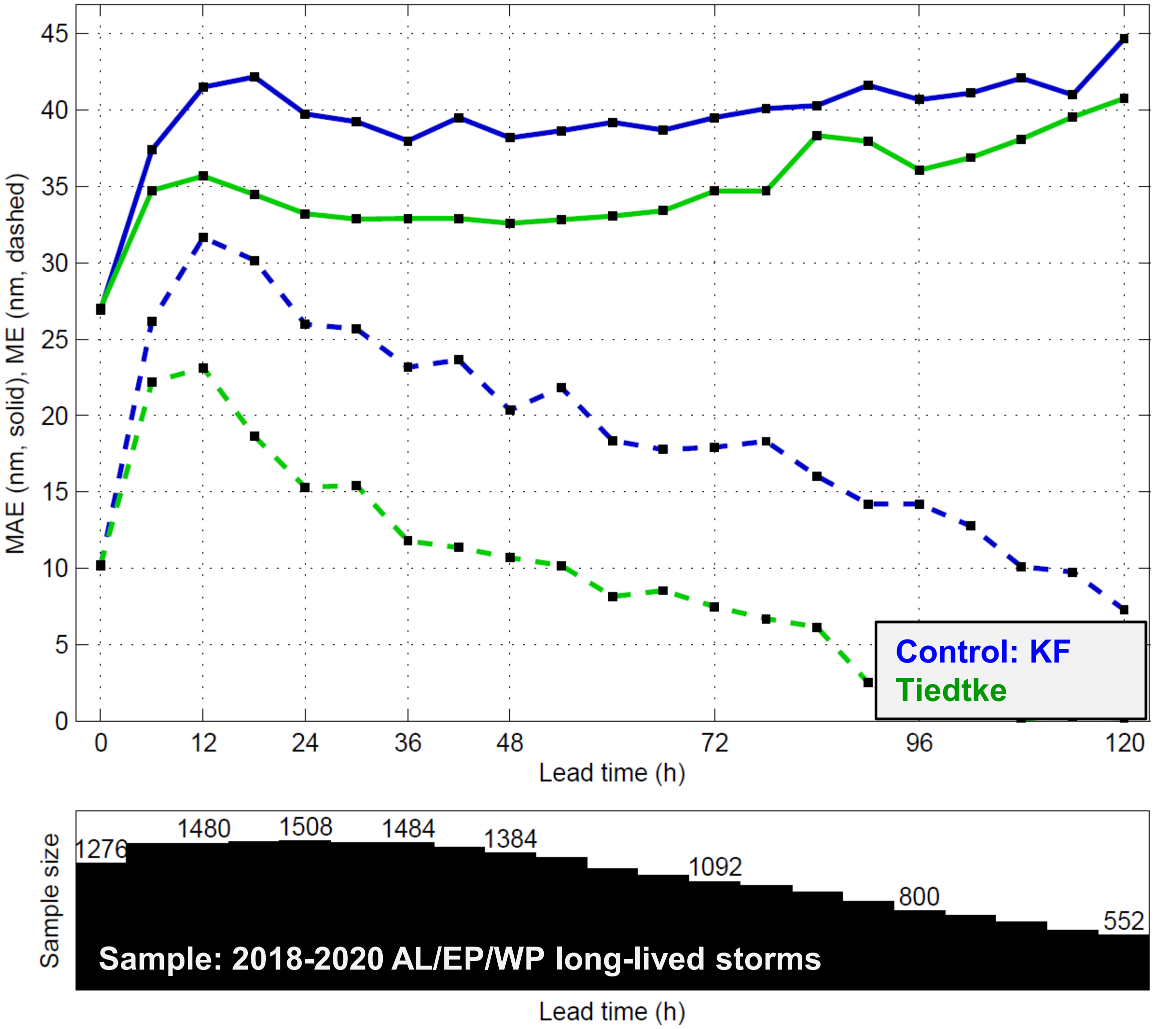
Michael Bell, Alex DesRosiers, and Chelsea Nam (Colorado State Univ.)
ONR TCRI Team and NOAA APHEX Team

Convection

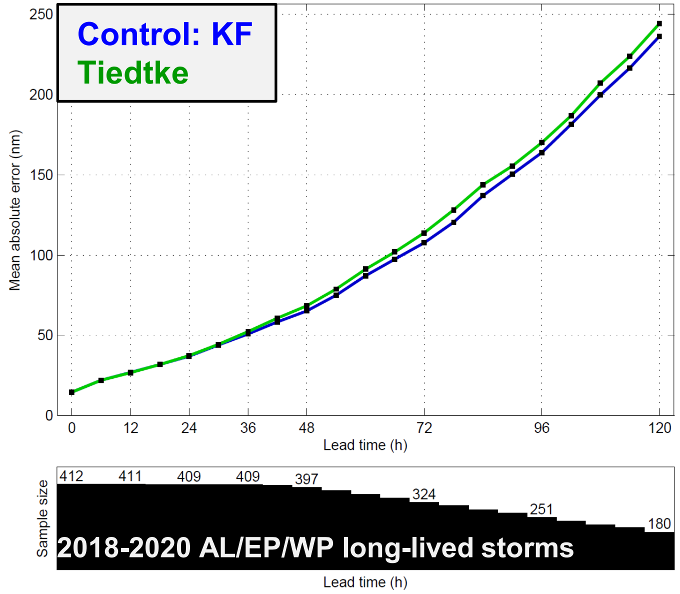
Deep Convection

- 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.

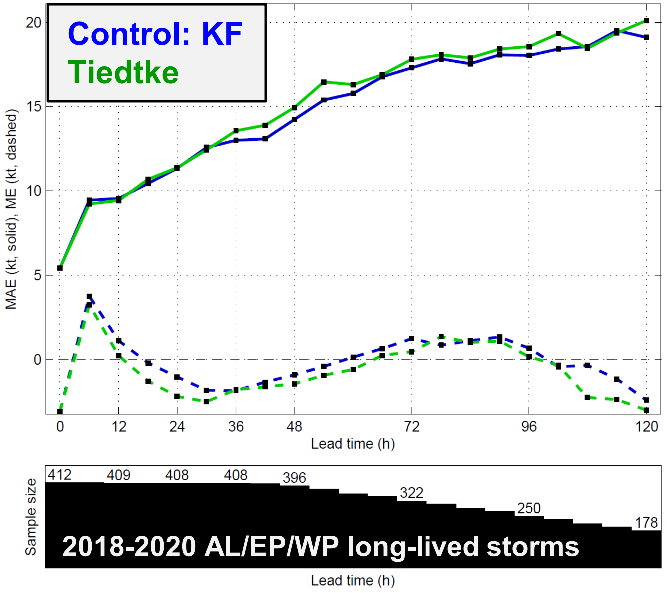
R34 MAE (solid) and ME (dashed)



Track Mean Absolute Error (n mi)



Intensity MAE (solid); ME (dashed)



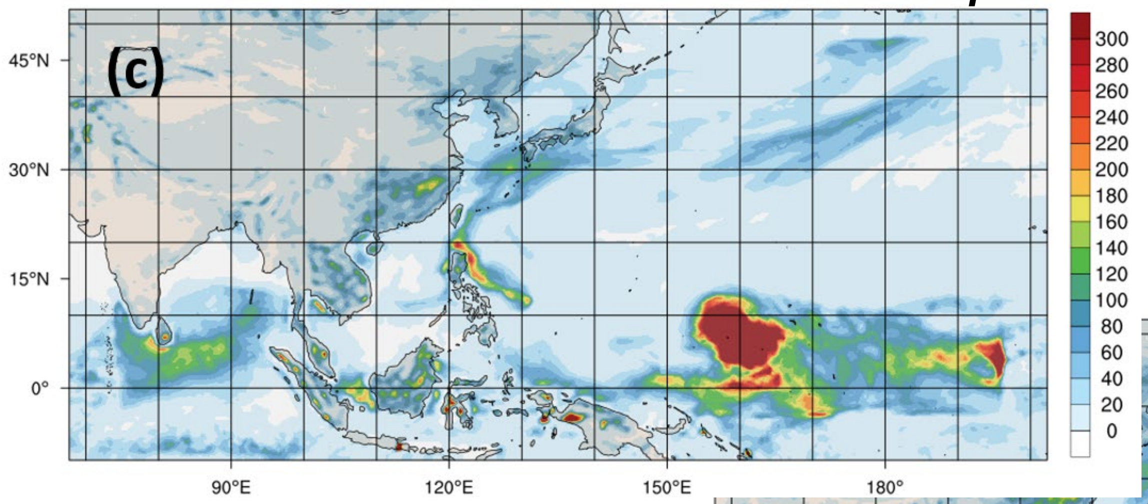
Tiedtke has a drier middle free troposphere than KF, which helps reduce positive bias in R34

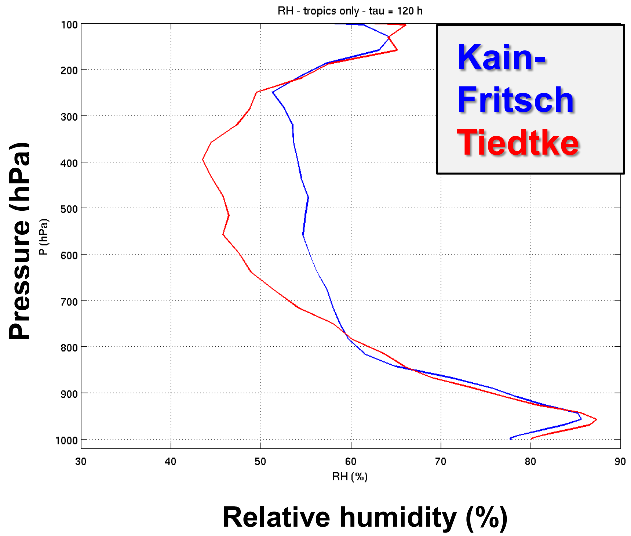
Convection

Deep Convection: Kain-Fritsch vs. Tiedtke

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

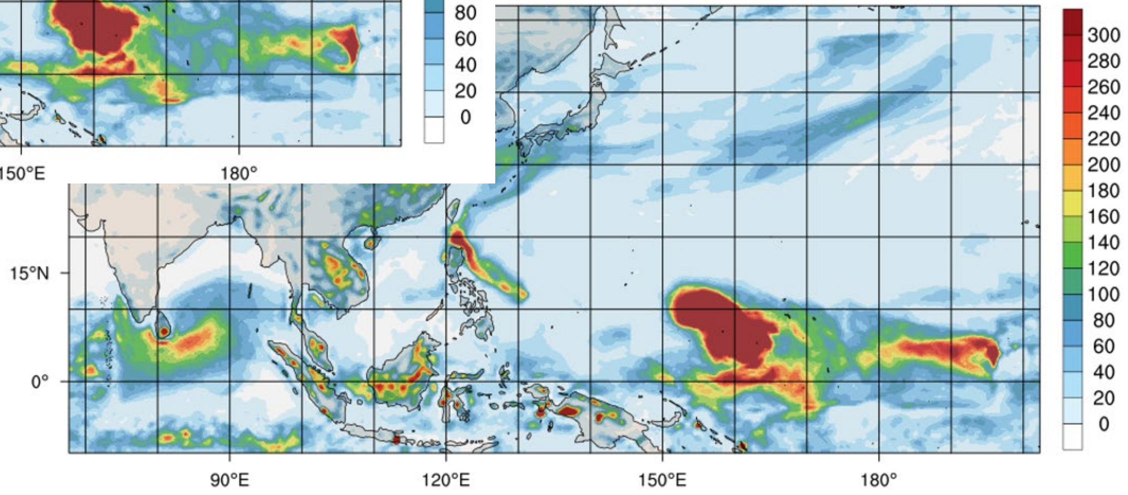
Tiedtke with reduced cw2rw Forecast Precip.



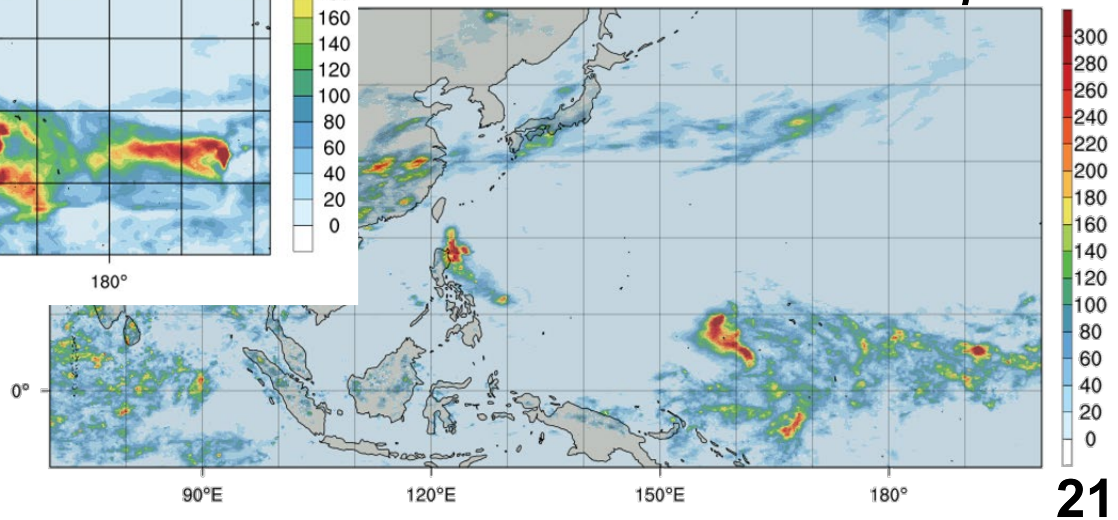


Tiedtke is much drier than KF in the free troposphere

Tiedtke Forecast Precip.



NASA IMERG Observed Precip.



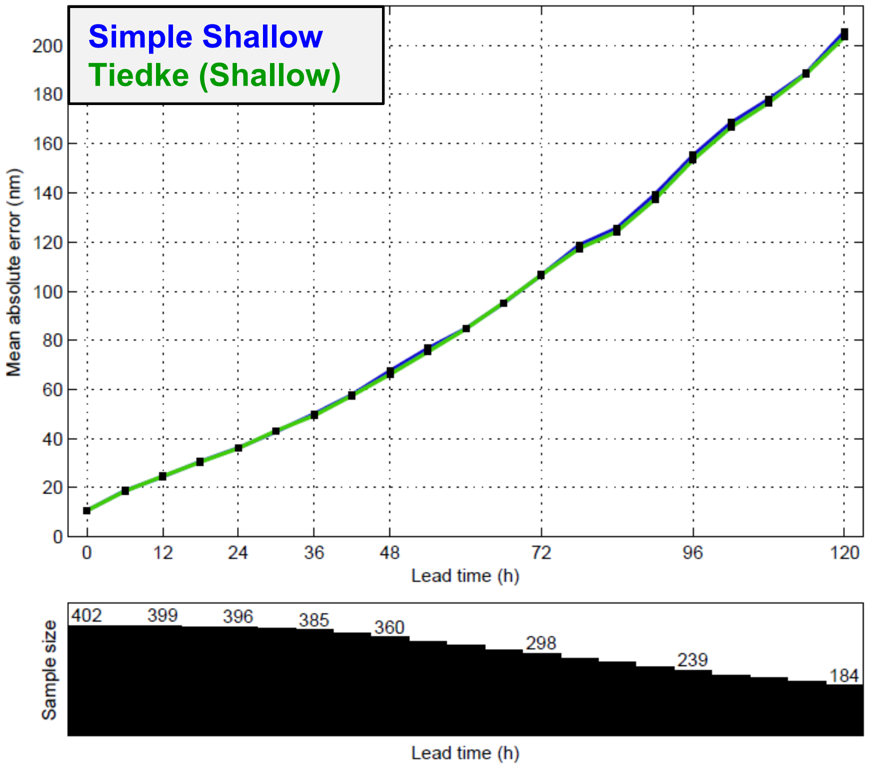
Reducing the cloud water to rain water conversion rate results in improved accumulated precipitation while maintaining most of the free-tropospheric drying

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

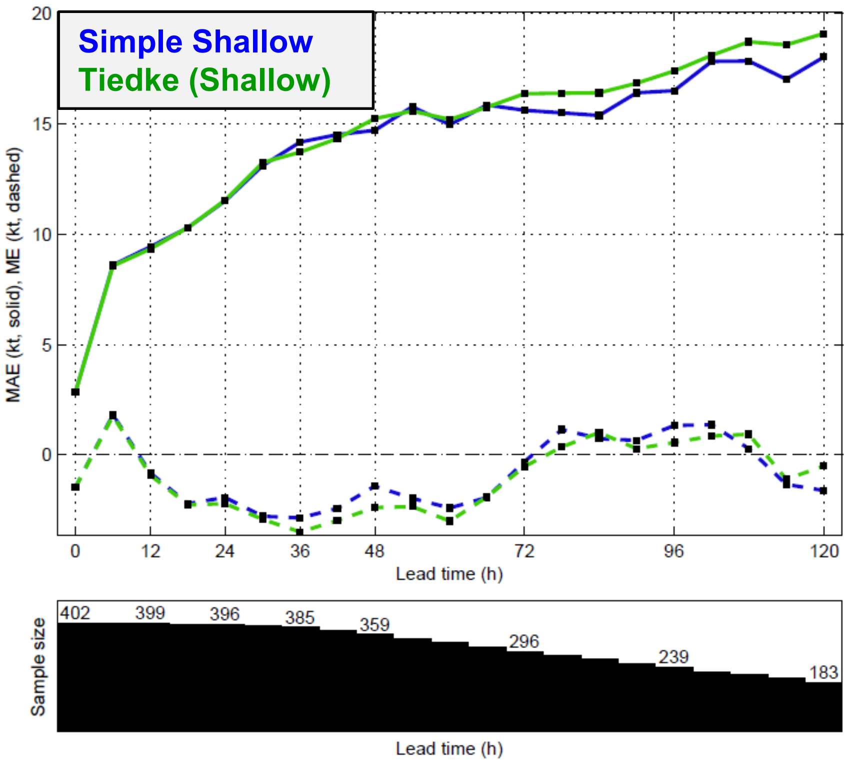
Convection

Shallow Convection

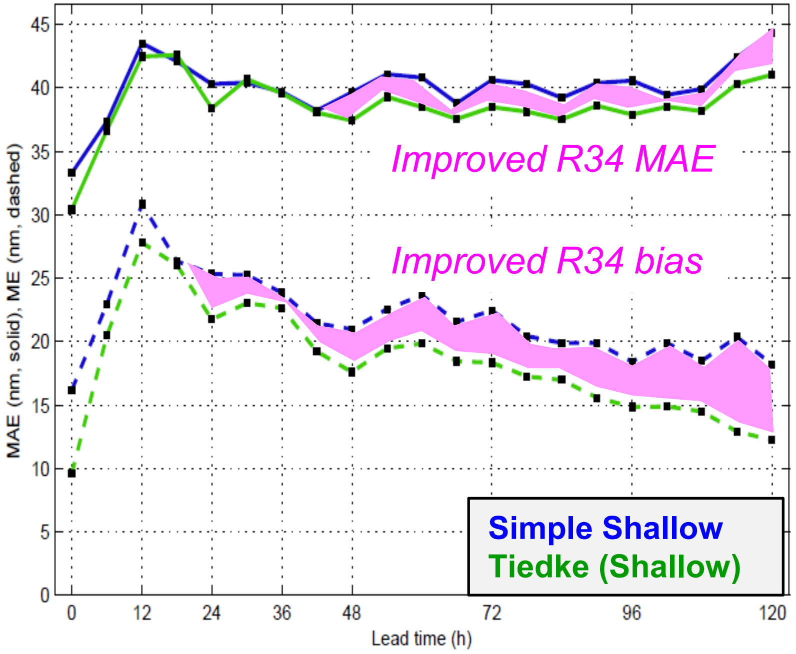
Track MAE



Intensity MAE (solid) and ME (dashed)



R34 MAE (solid) and ME (dashed)

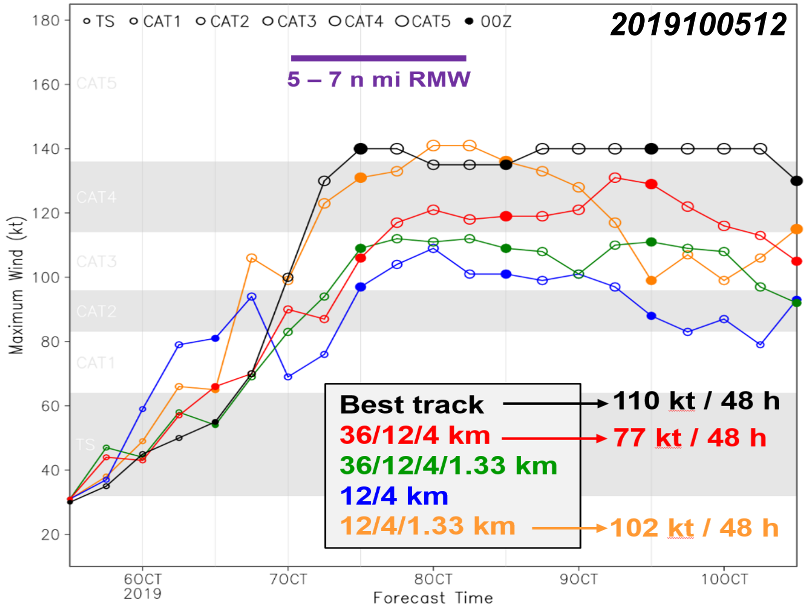


- Motivation: Impact of shallow and congestus convection parameterization on TC track (Han and Pan 2011; Torn and Davis 2012) and intensity and structure (Wang 2014; Parker et al. 2016)
- Methods: Sensitivity tests using a simple shallow convection and the Tiedtke shallow convection
- Key Findings:
  - 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

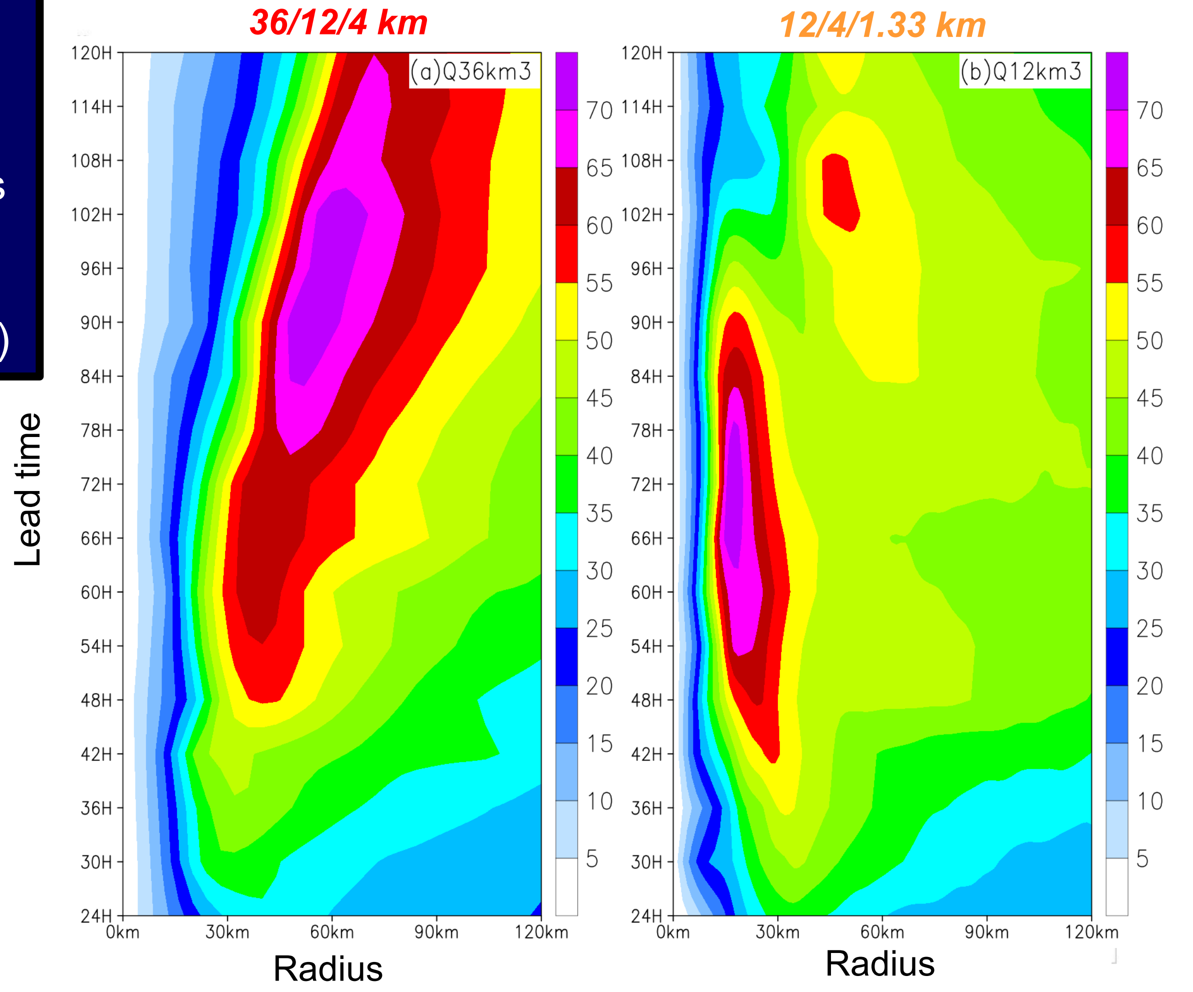
Sensitivity to Resolution
Horizontal Resolution

- 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

Sensitivity to Resolution
Horizontal Resolution: Hurricane Patricia

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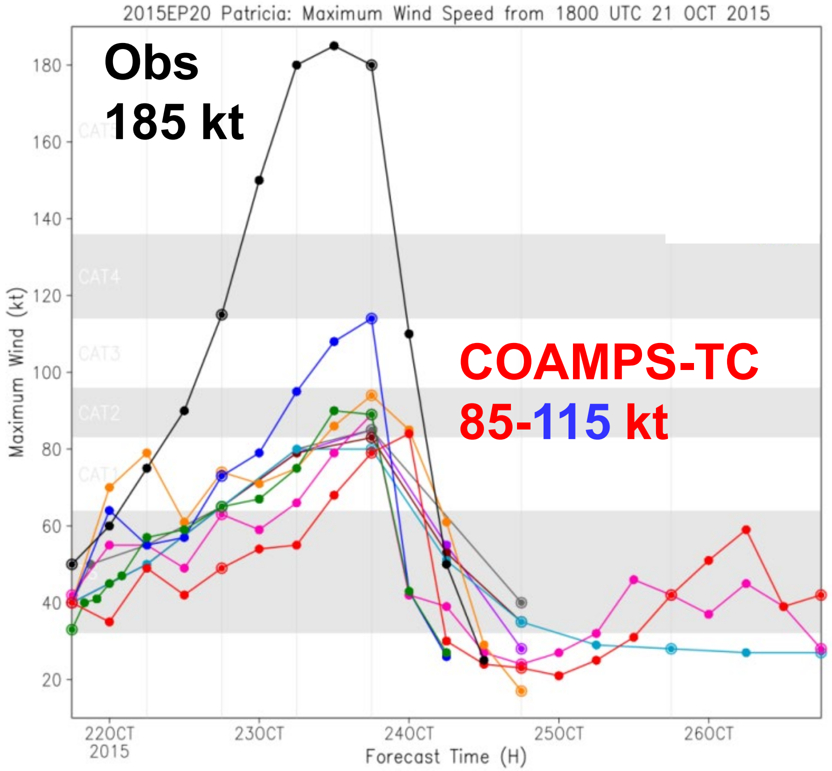
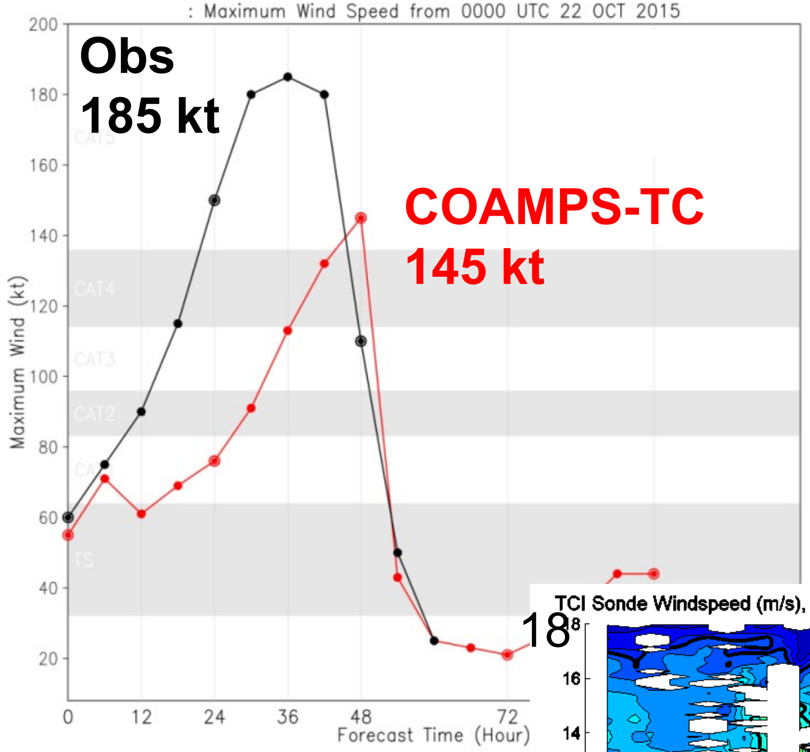
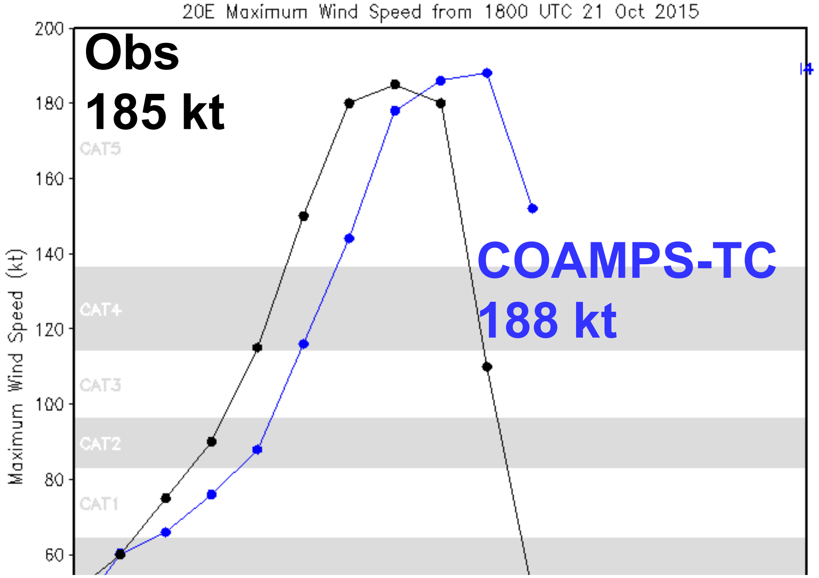
COAMPS-TC: ***5 km***



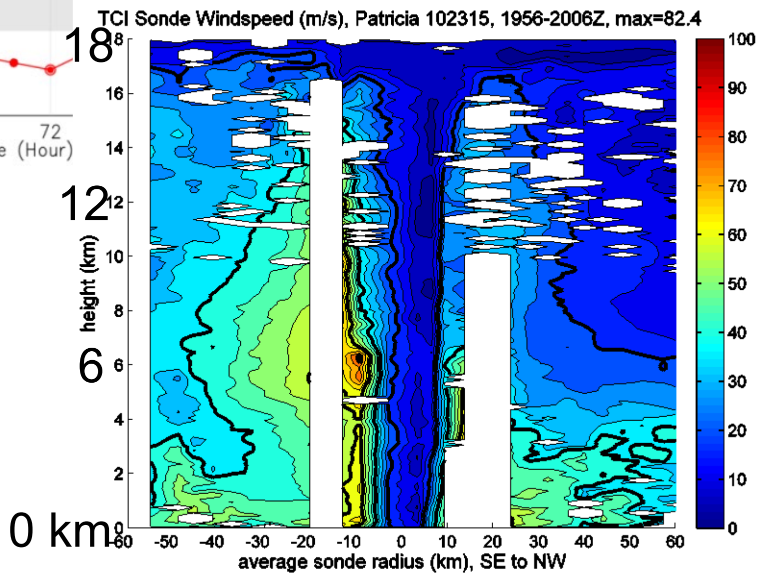
COAMPS-TC: ***1.67 km***

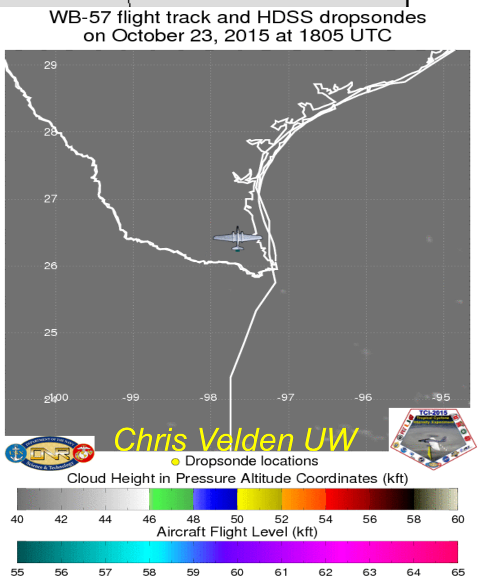


COAMPS-TC: ***0.89 km***



- 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



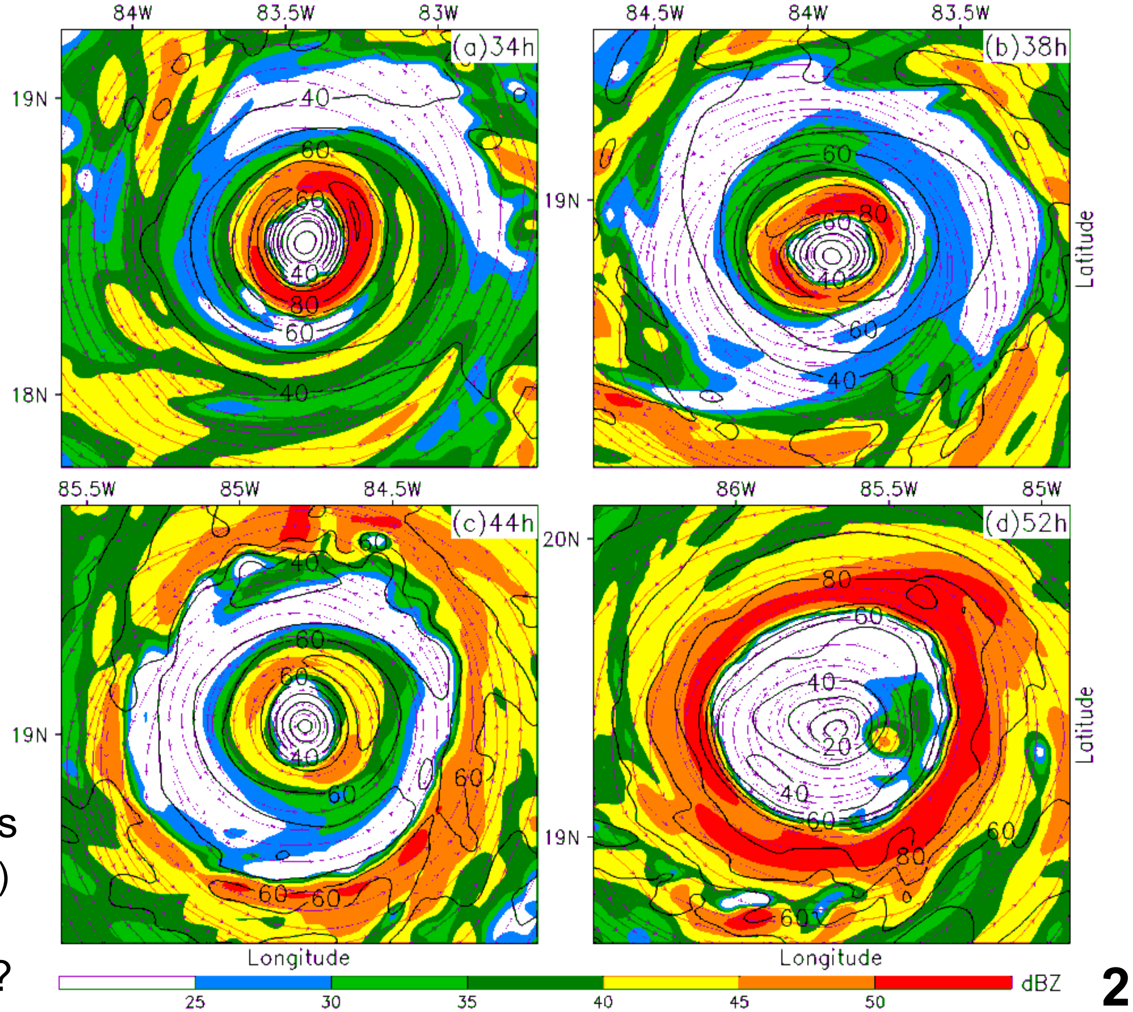


Sensitivity to Resolution

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

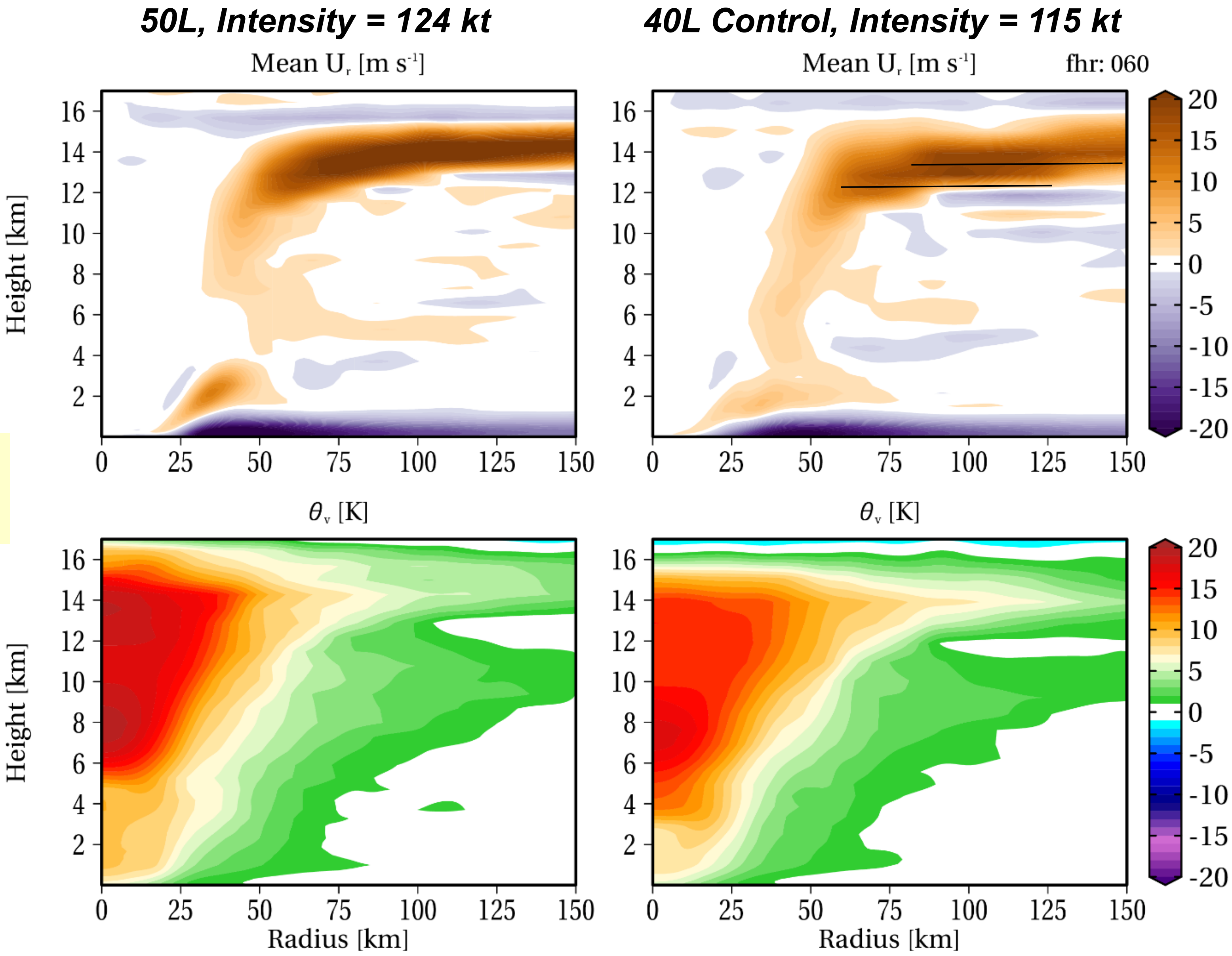


- ERCs form due to the interplay between annular heating and BL inflow
- During SEFs/ERCs, the maximum wind speed of the inner core weakens significantly after formation of the secondary eyewall (Sitkowski et al. 2011)
- Wind field then broadens, which has implications for impacts
- Can operational TC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

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



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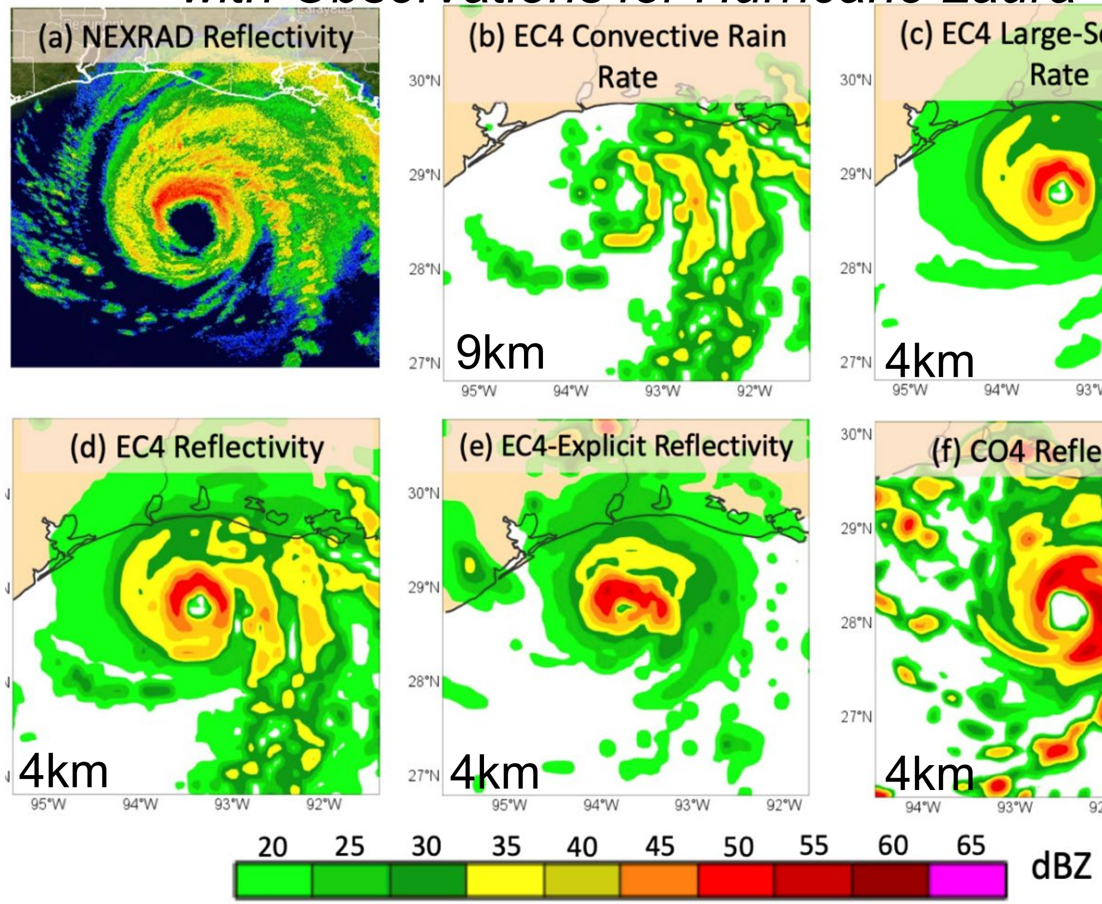
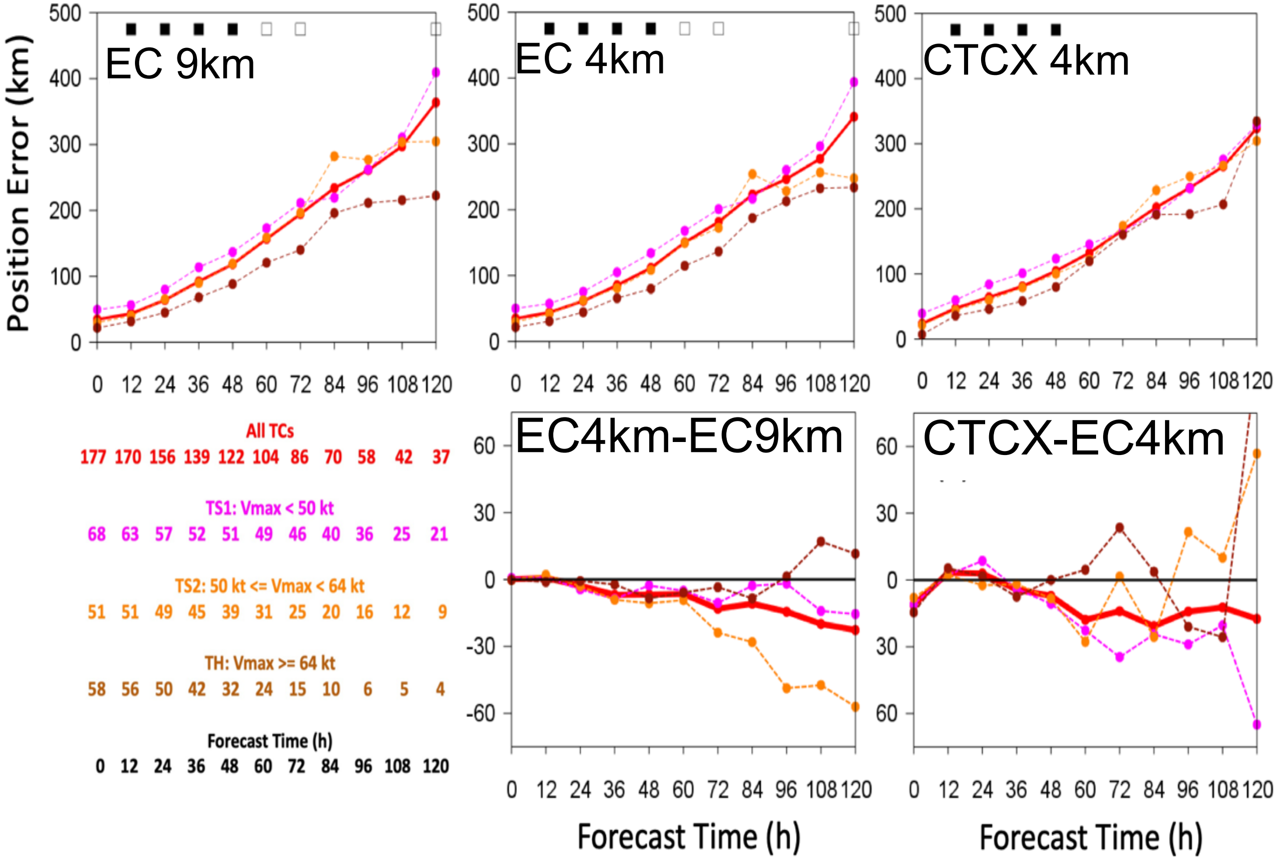
Future Outlook

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

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 (submitted)

- 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

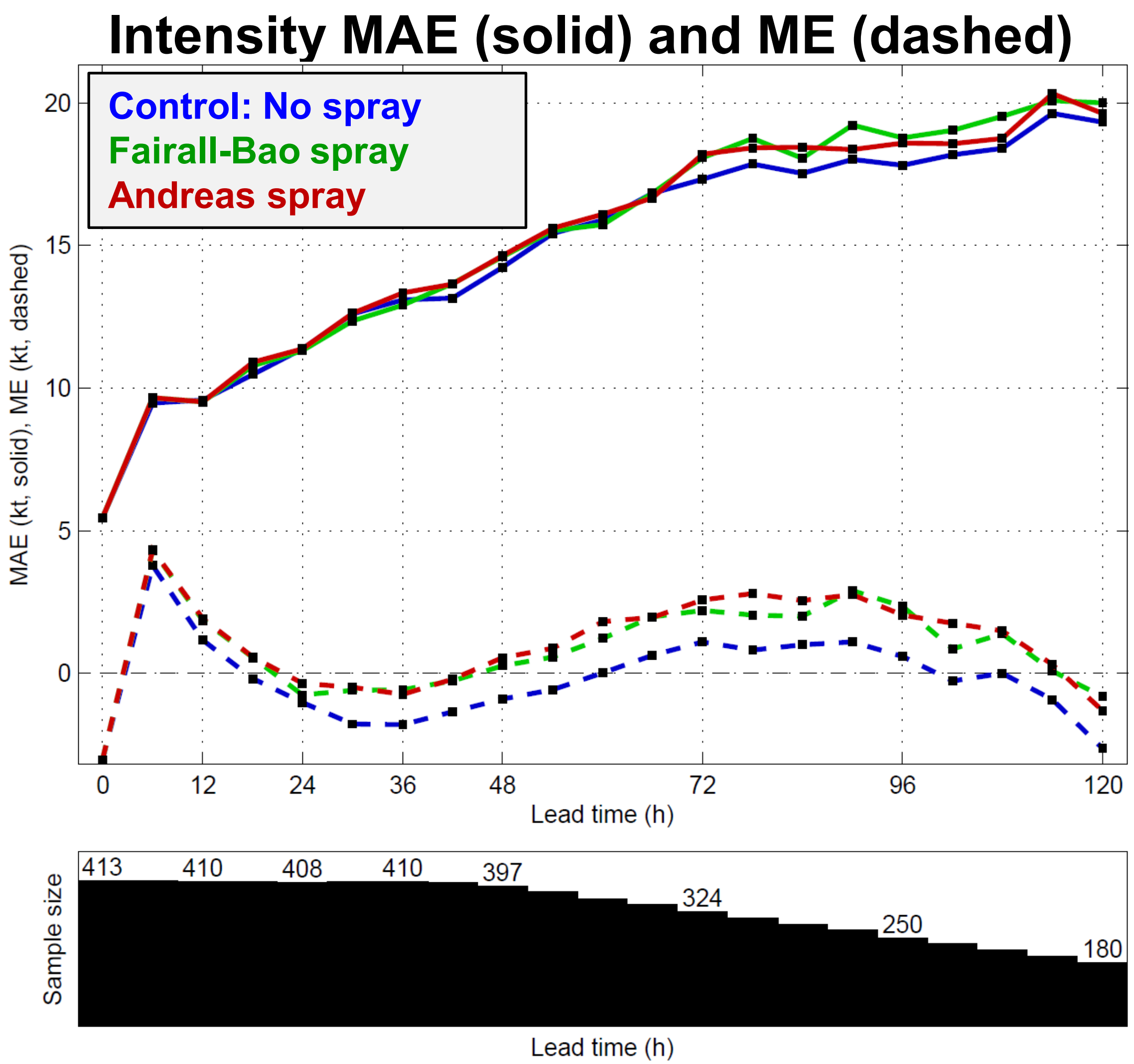
Summary and Recommendation

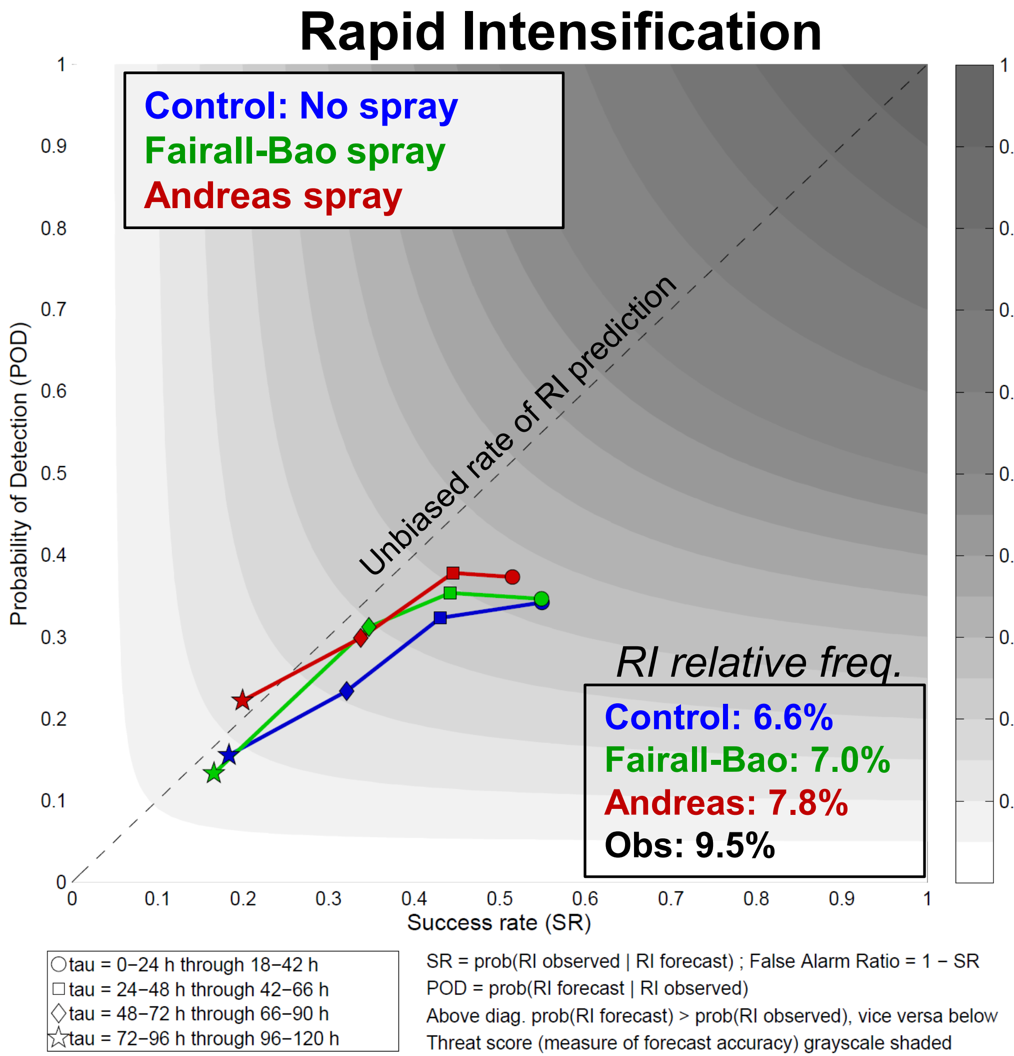
- **COAMPS-TC development provides insights into key systematic errors & how to address them**
  - Intensity systematic errors identified are most sensitive to:
    - C_D, air-sea coupling, boundary layer, microphysics, shallow & deep convection
  - Track systematic errors identified are most sensitive to:
    - Shallow & deep convection, cloud microphysics and radiation, boundary layer
- **Recommendations**
  - Use observations (aircraft, UxS, radar, drops, field programs…), LES to inform model development
  - 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, Laura, Ian), but other TCs that undergo RI remain a challenge (super RI events …)
    - Predicting secondary eyewall formation, moderately sheared TCs that intensify, inner core dynamics (roll circulations, TC gusts etc.)
  - Physics challenges: C_D, C_K, air-sea-wave coupling, boundary layer, microphysics, convection
  - Next Frontiers: i) TC prediction using coupled, convection-allowing, global models (including S2S); ii) Probabilistic impact based predictions (high-resolution ensembles); iii) LES modeling of TCs

Extra Slides

Air-Ocean Coupling in Tropical Cyclones

Sea Spray Processes



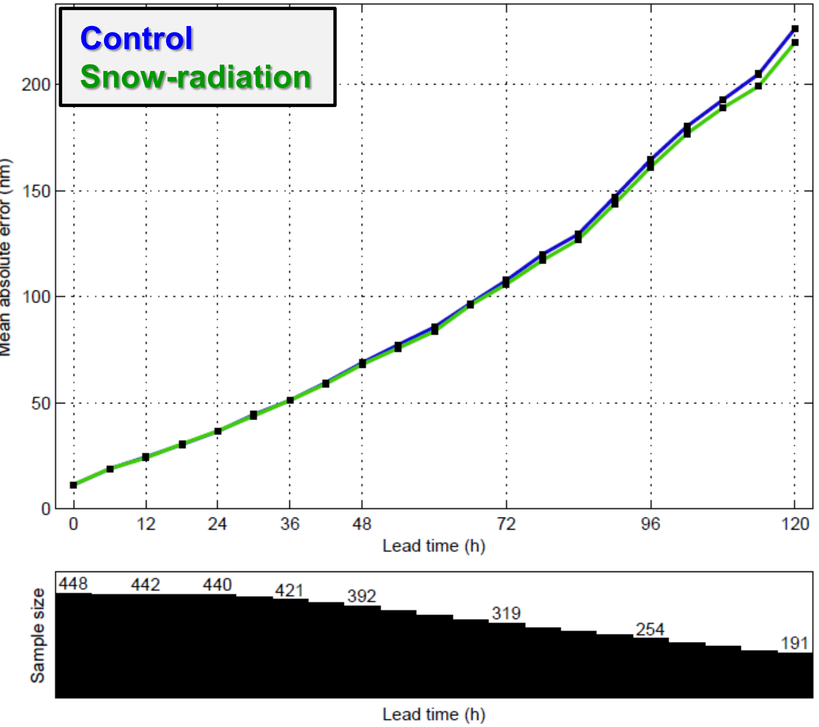


- Sea spray parameterizations (Fairall-Bao and Andreas) show improved RI statistics, however the mean absolute and mean errors are larger than the control

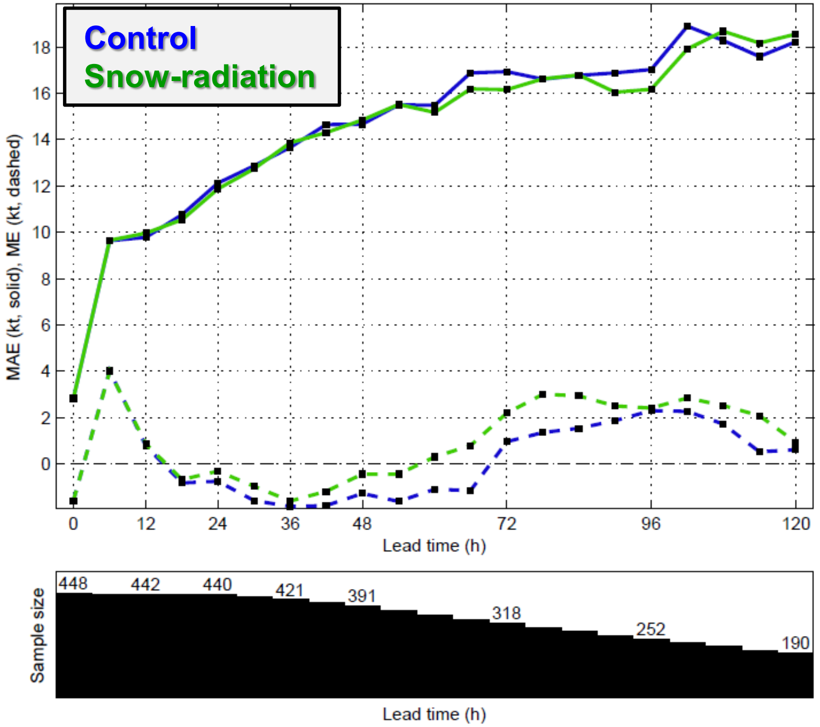
Microphysics
Microphysics and Radiation Interactions

Snow-Radiation Interaction

Track MAE

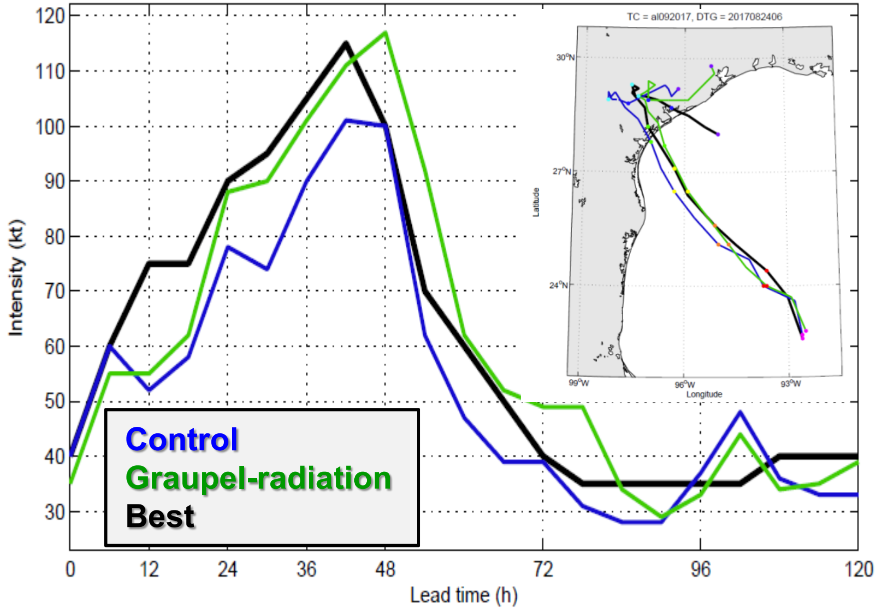


Intensity MAE (solid) and ME (dashed)



Graupel-Radiation Interaction

Hurricane Harvey (2017)

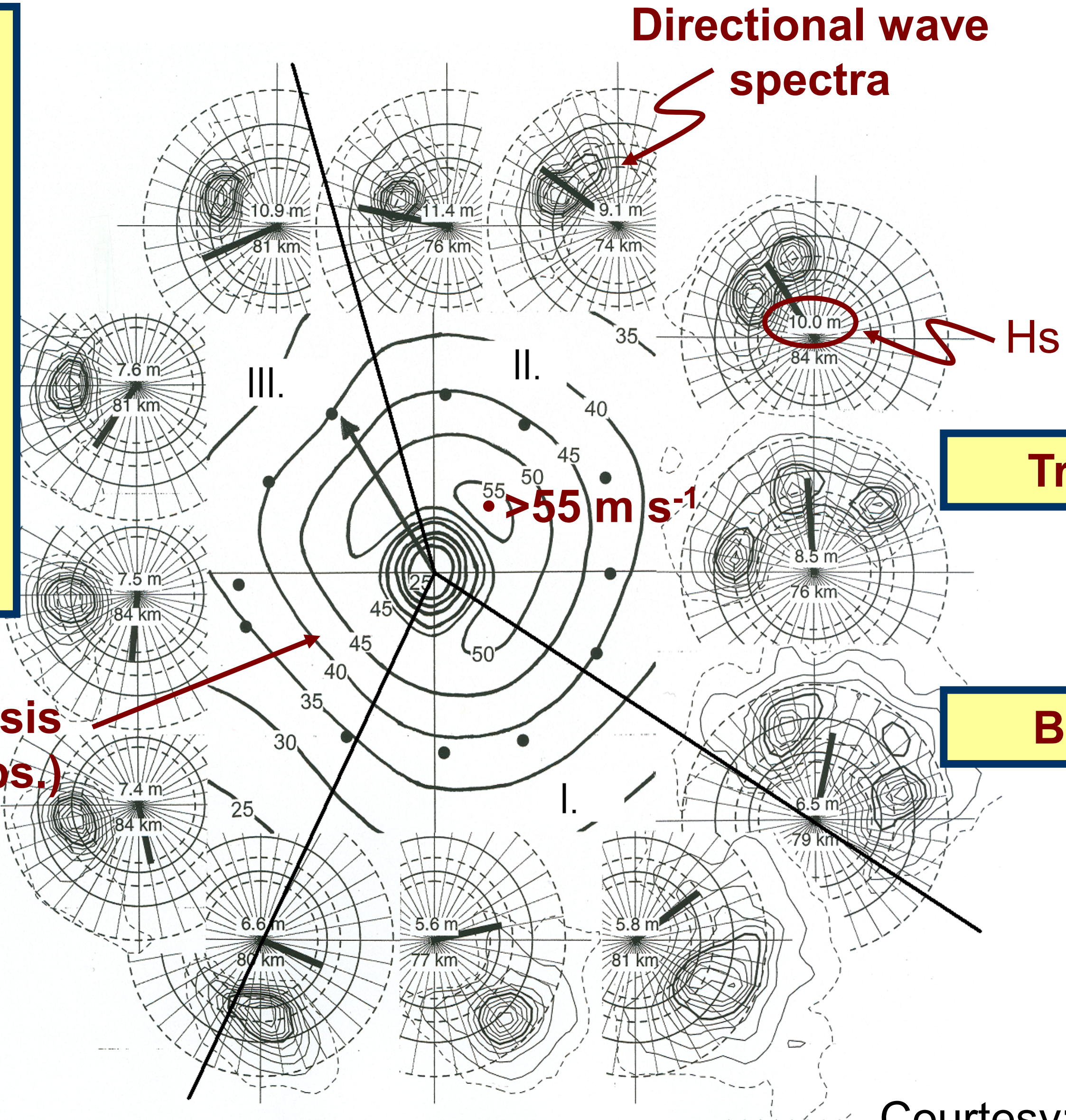


- Inclusion of interactions between snow and radiation show modest improvements in track and intensity errors
- Graupel and radiation interactions show improved intensity errors as well

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.

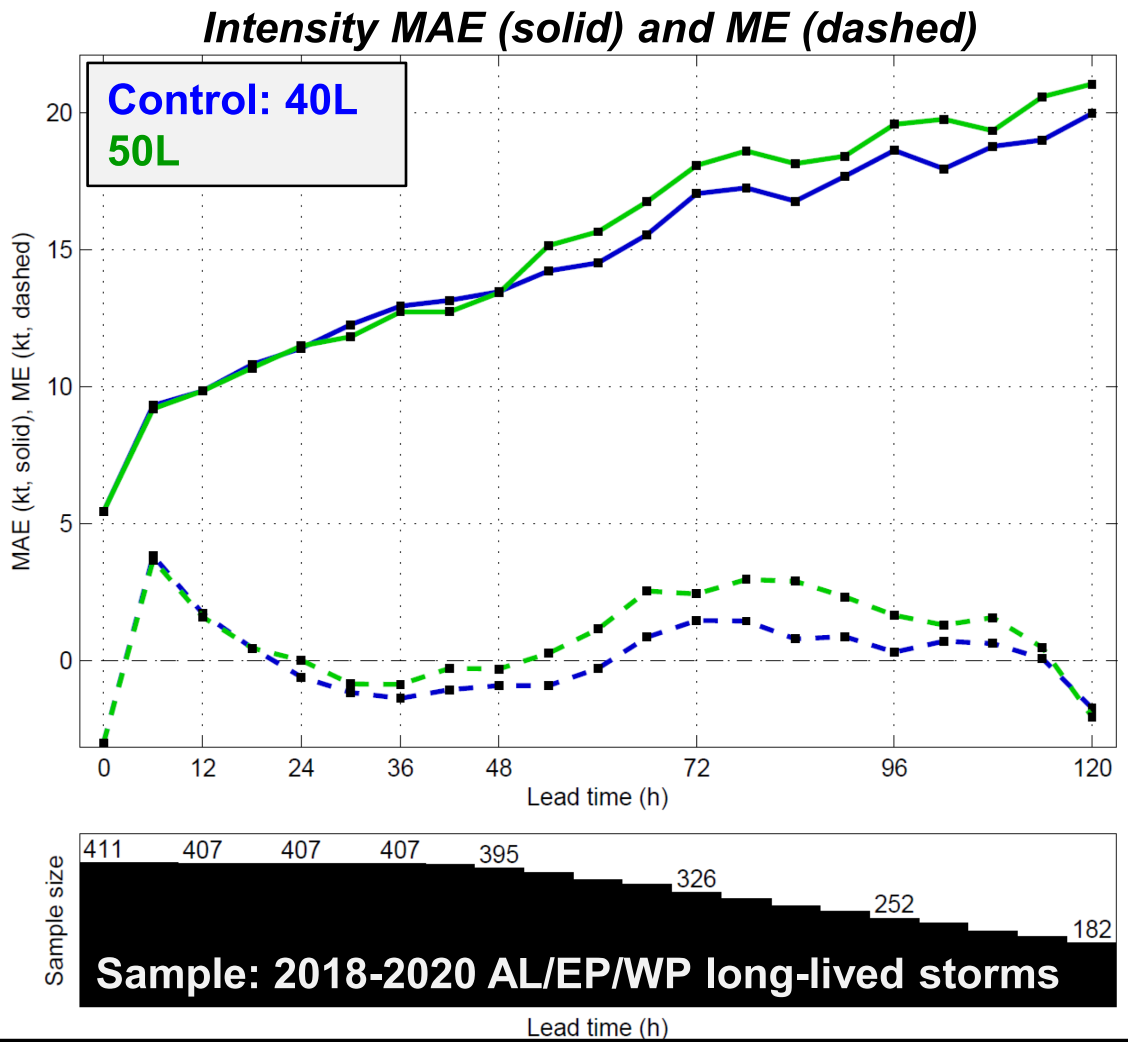


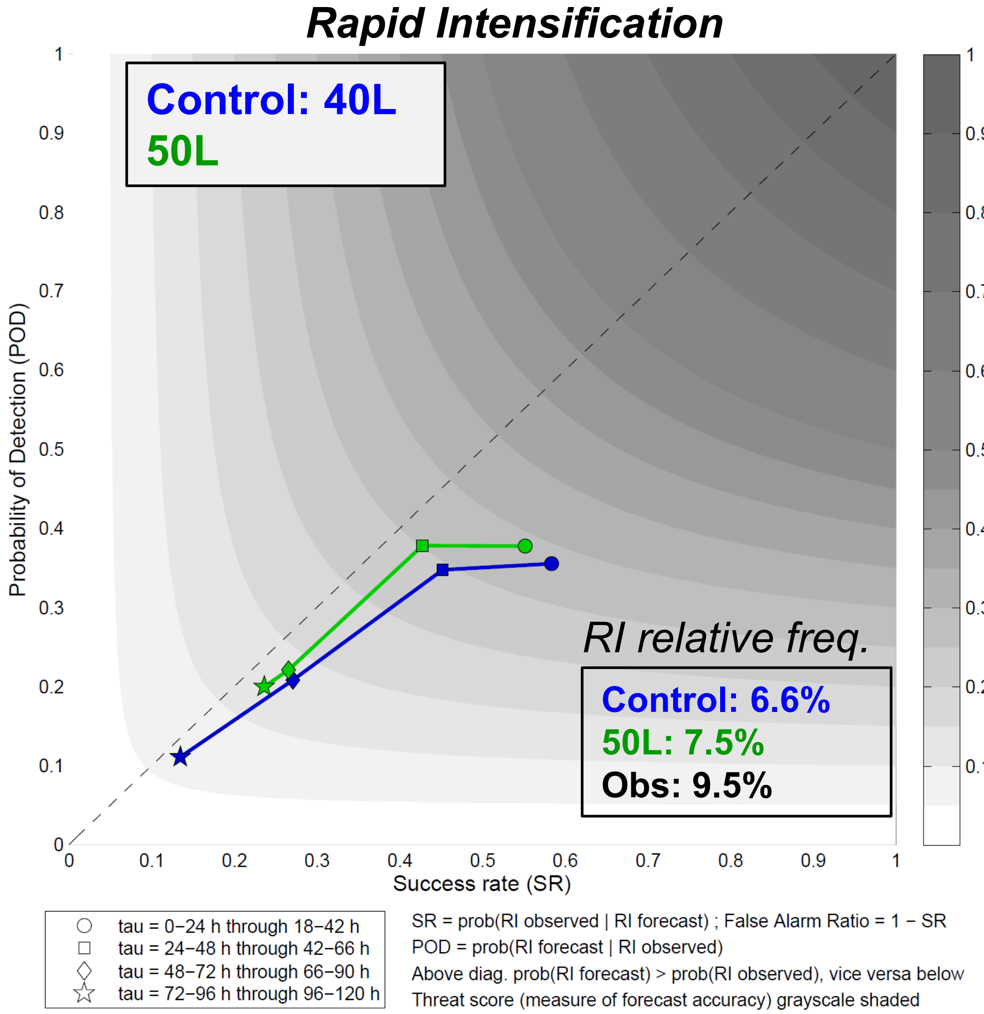
Black et al. (2007)

Courtesy: Ed Walsh

Sensitivity to Resolution

Vertical Resolution





- 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.

COAMPS-TC Performance
Atlantic Basin 2020-2021

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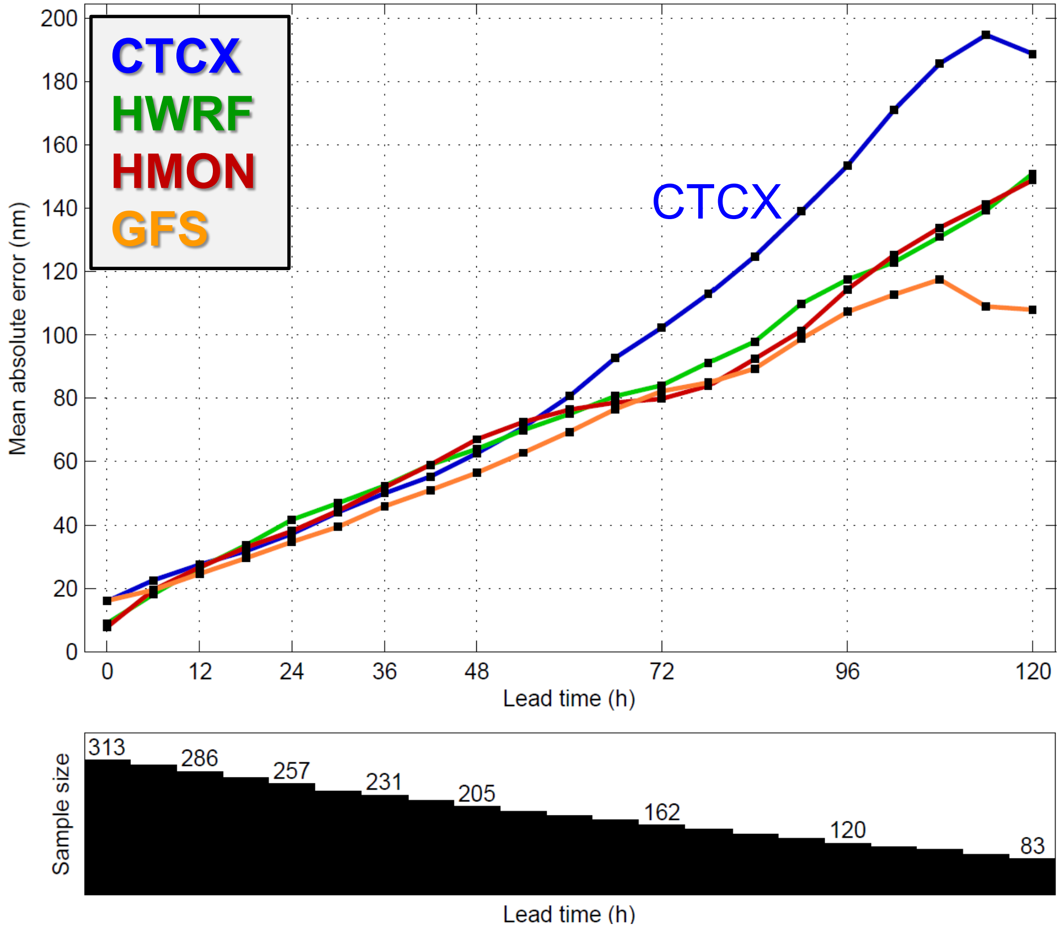
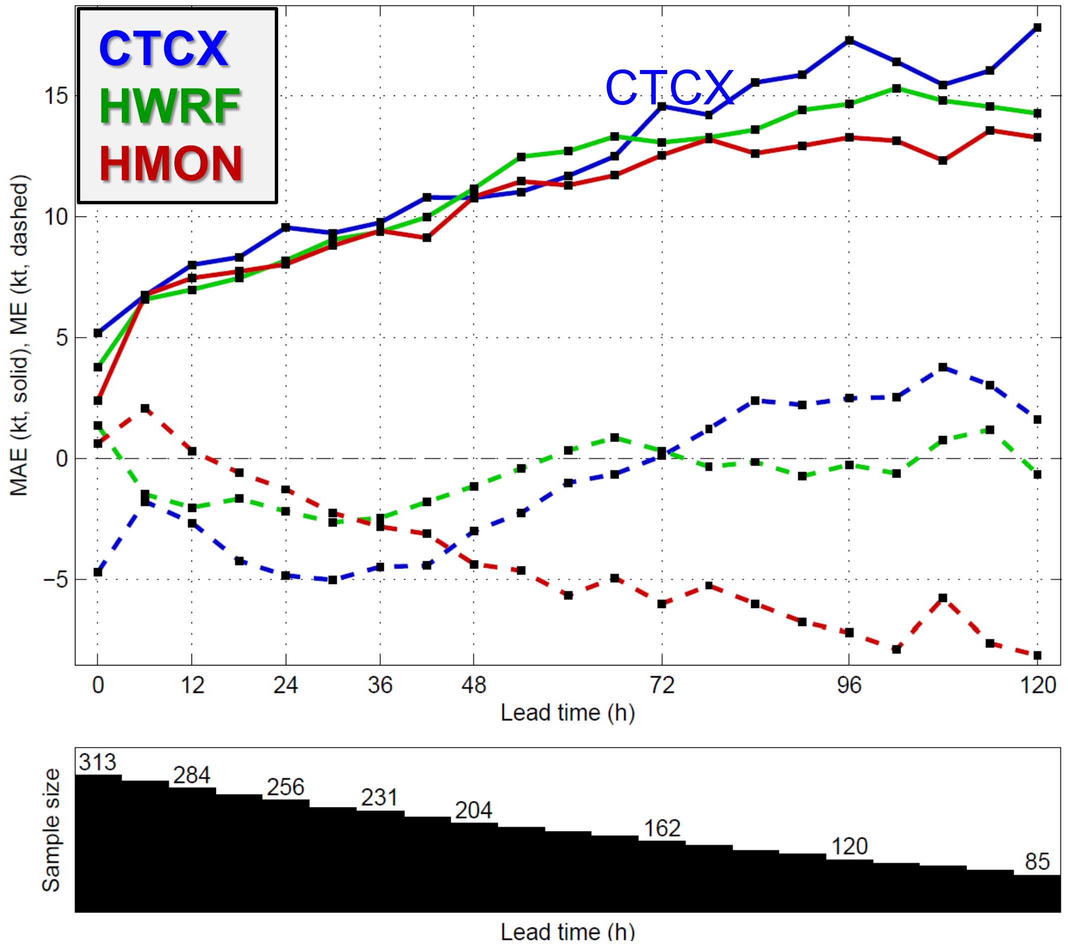
2021 Track Mean Absolute Error (nm)



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.

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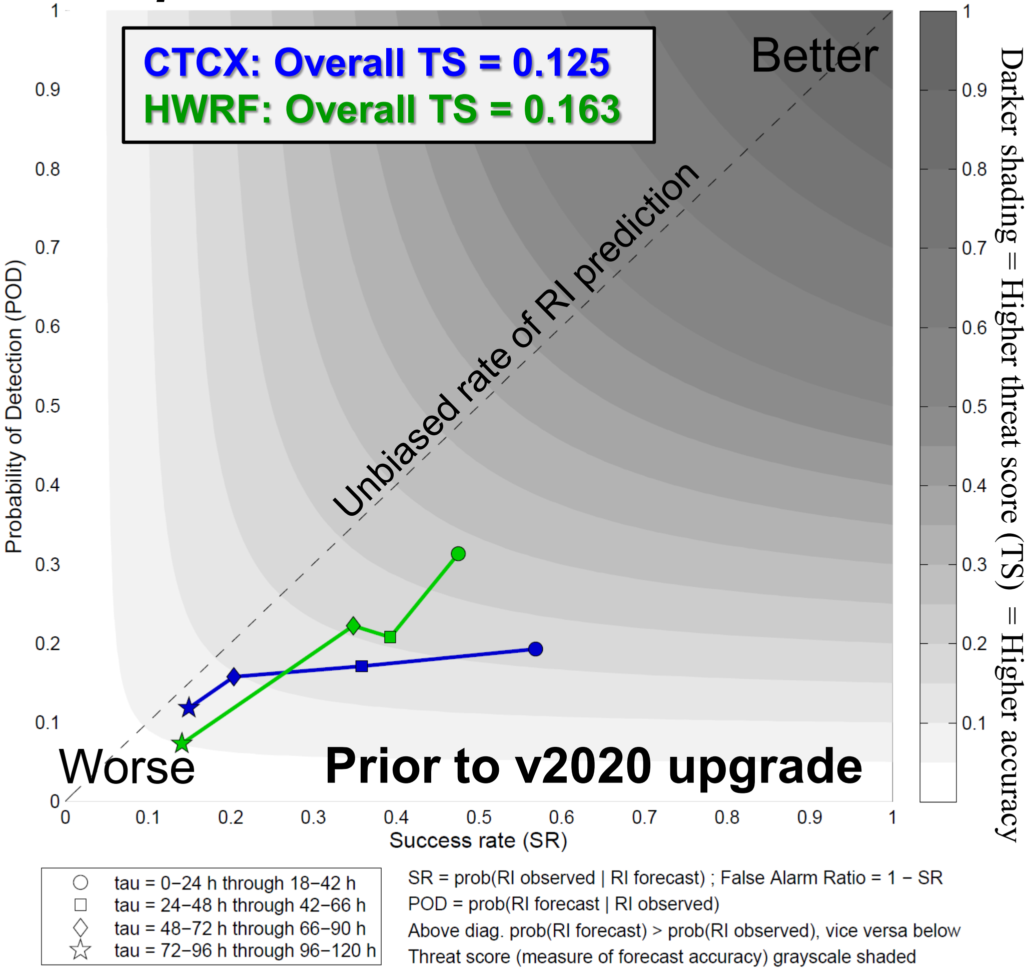
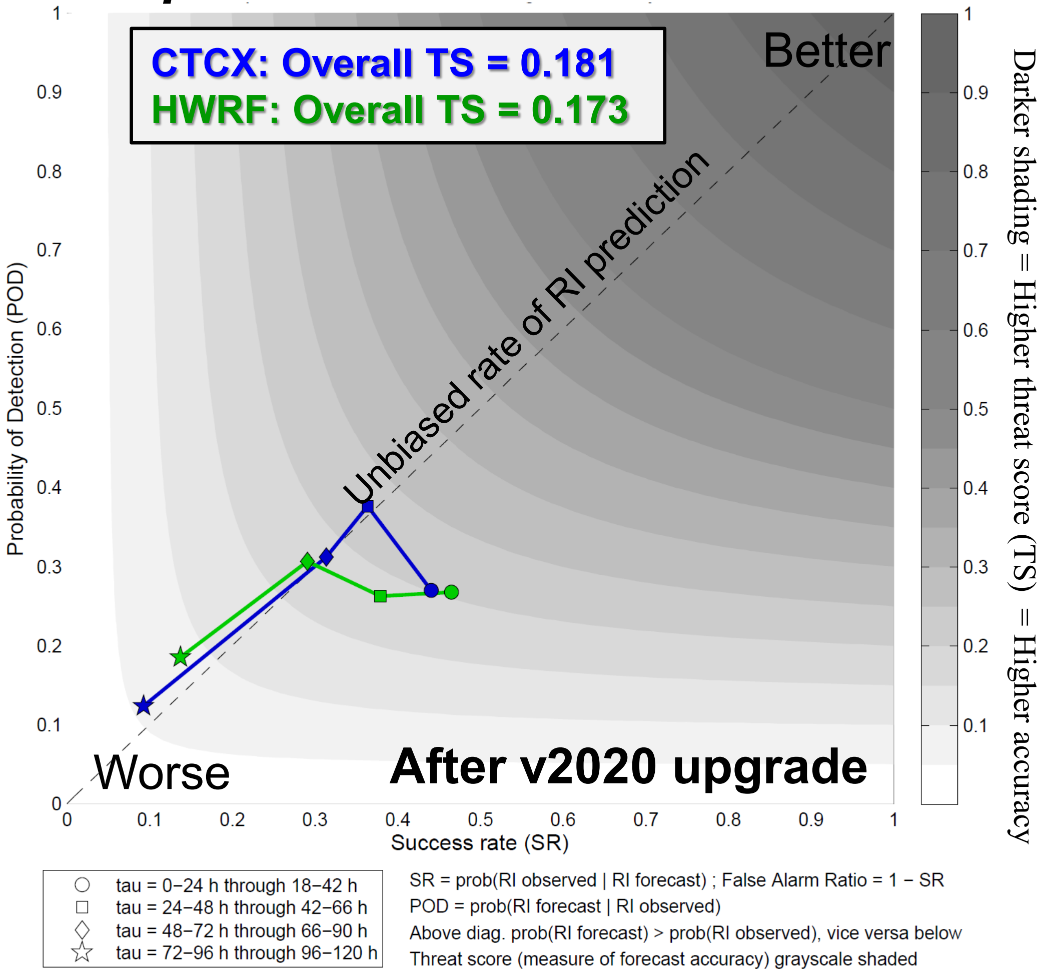
COAMPS-TC RI Performance
Atlantic, Eastern Pacific, Western Pacific

RI performance: 2018/2019 AL/EP/WP



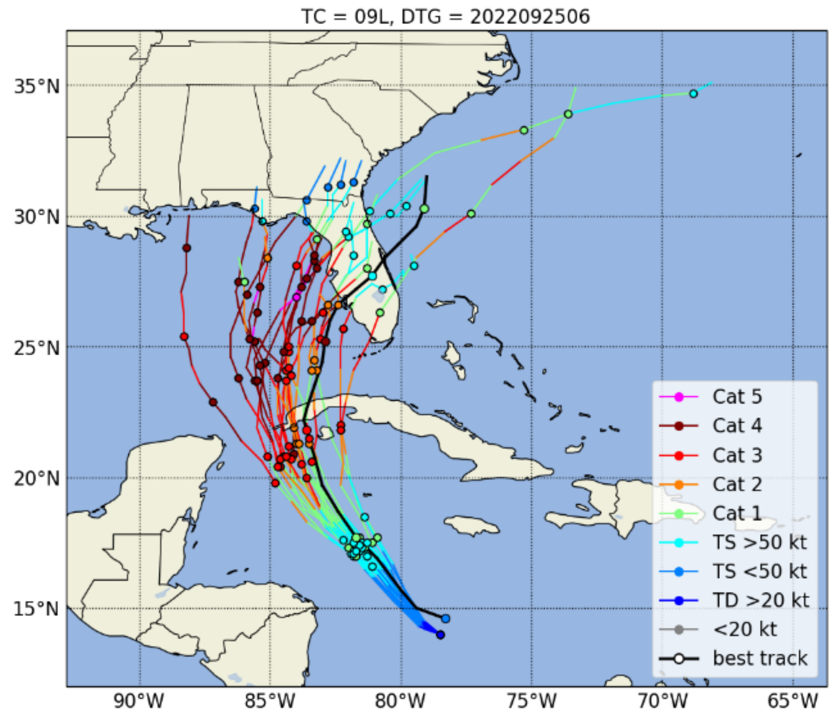
RI performance: 2020/2021 AL/EP/WP

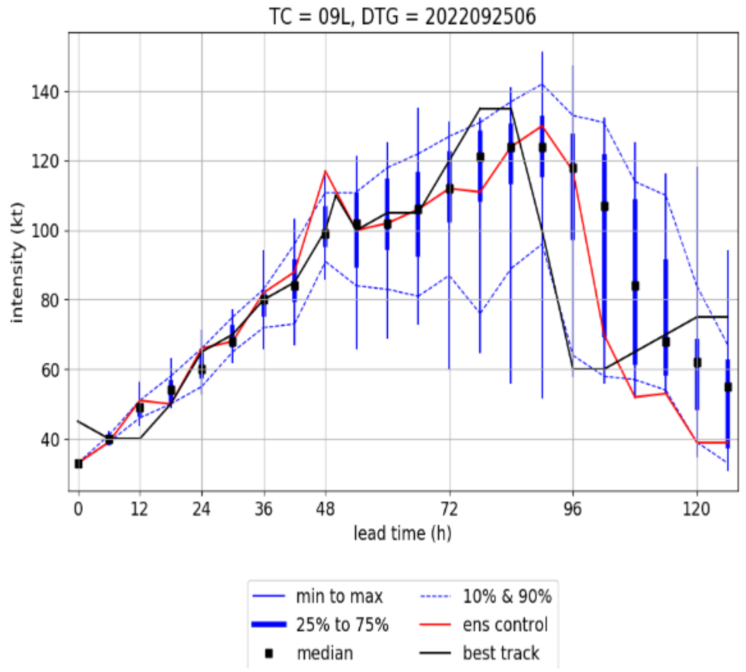


After physics and vortex initialization upgrades in 2020, COAMPS-TC showed considerably improved RI forecasts

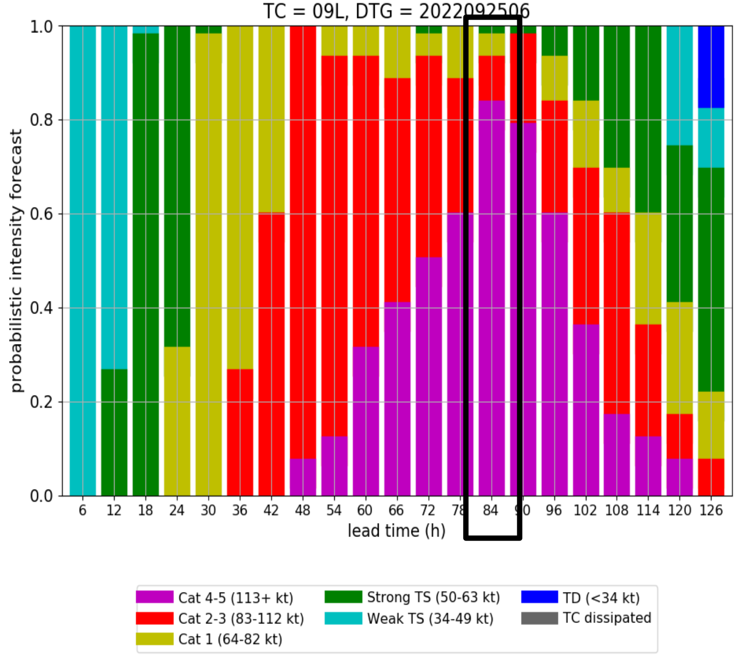
COAMPS-TC Performance

COAMPS-TC Ensemble Prediction for Hurricane Ian





85% prob Cat 4-5 at 84h!

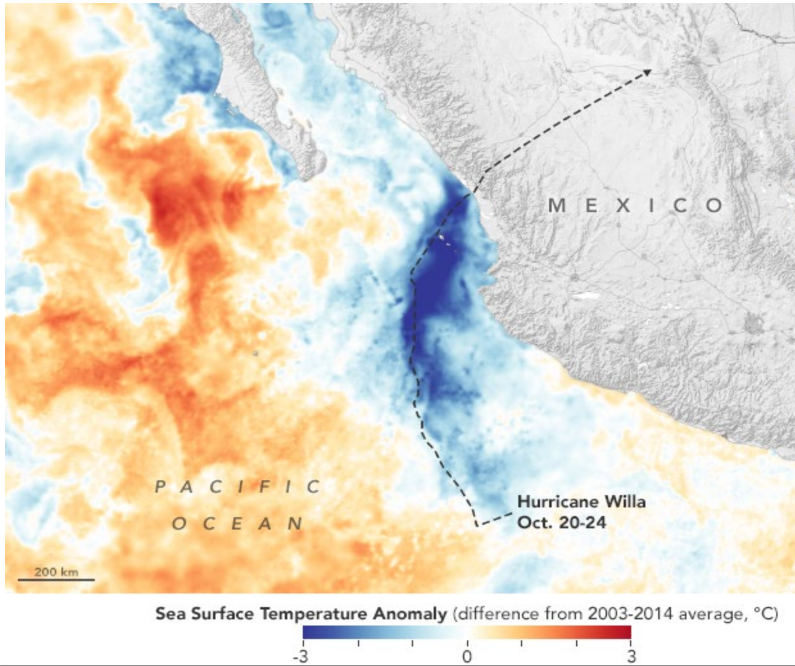


- COAMPS-TC Ensemble intensity forecast was extremely good for Ian
- 85% of ensemble members predicted Cat 4-5 at 84h; verification: Cat 4

Air-Ocean Coupling in Tropical Cyclones

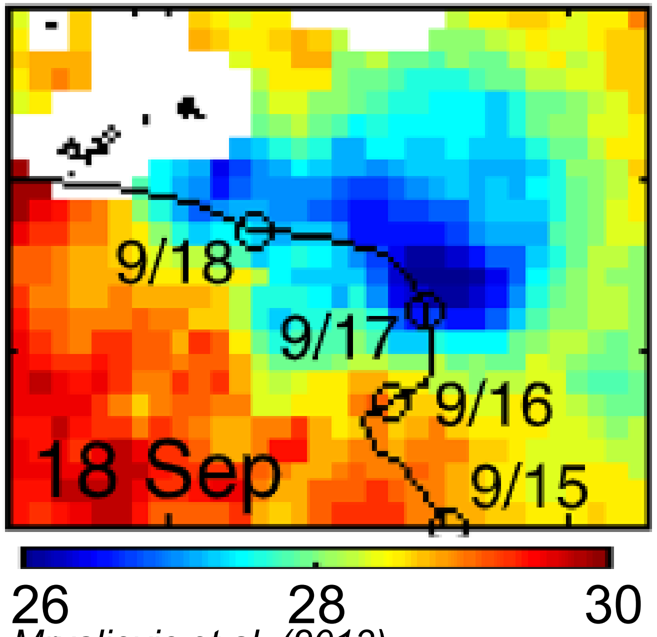
Upper Ocean Processes

SST Anomaly [Hurricane Wilma (2018)]

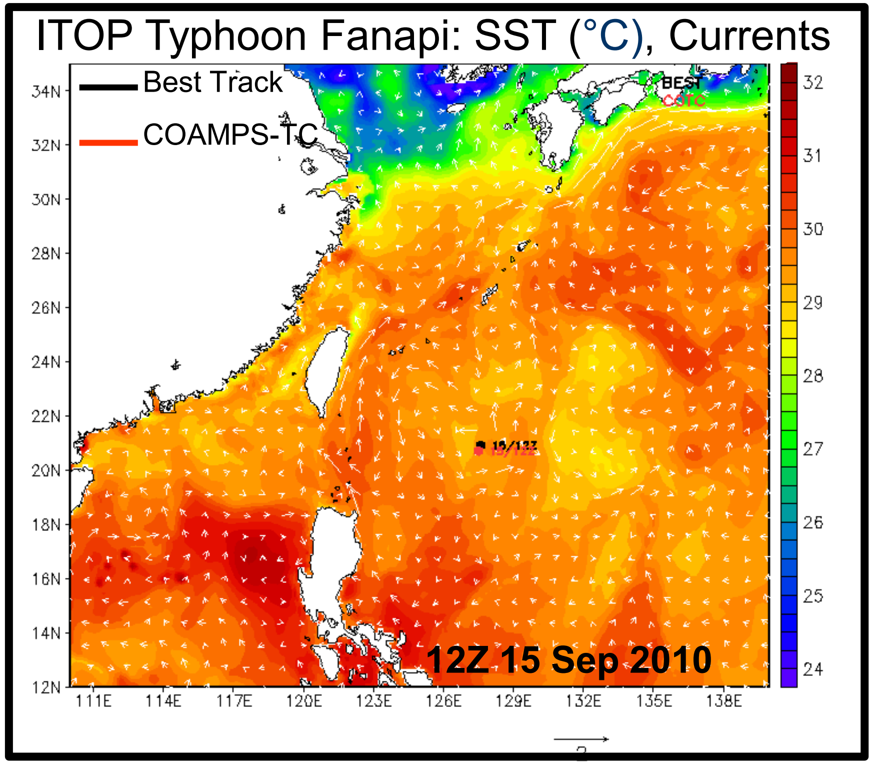


NASA

MW SST [TY Fanapi (2010)]



Mrvaljevic et al. (2013)



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

- 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

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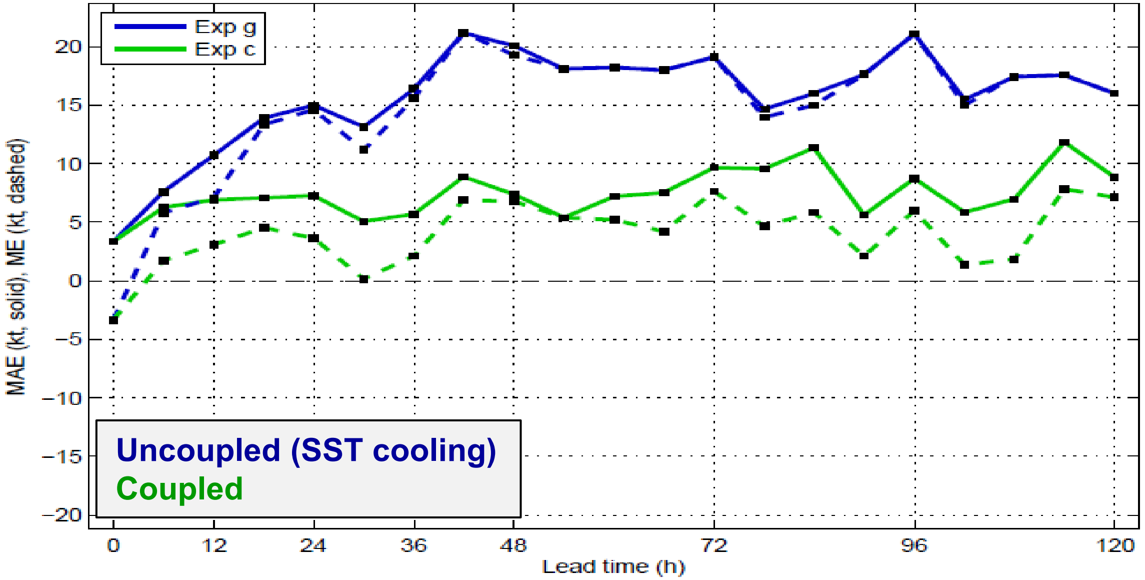
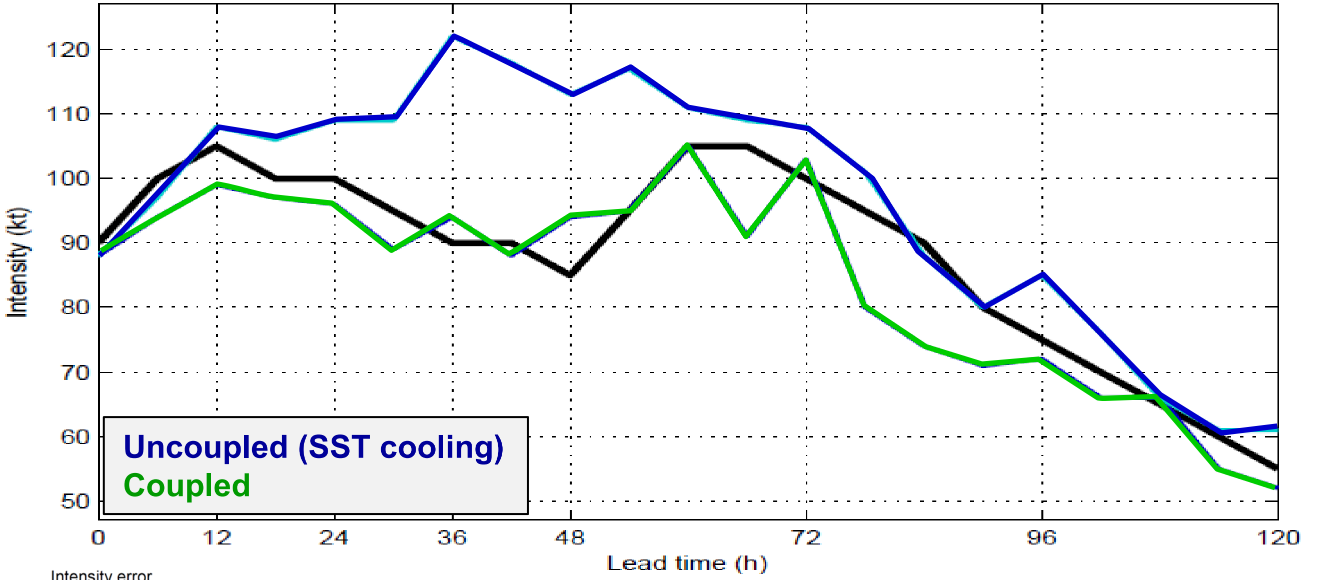
Air-Ocean Coupling in Tropical Cyclones

Upper Ocean Processes

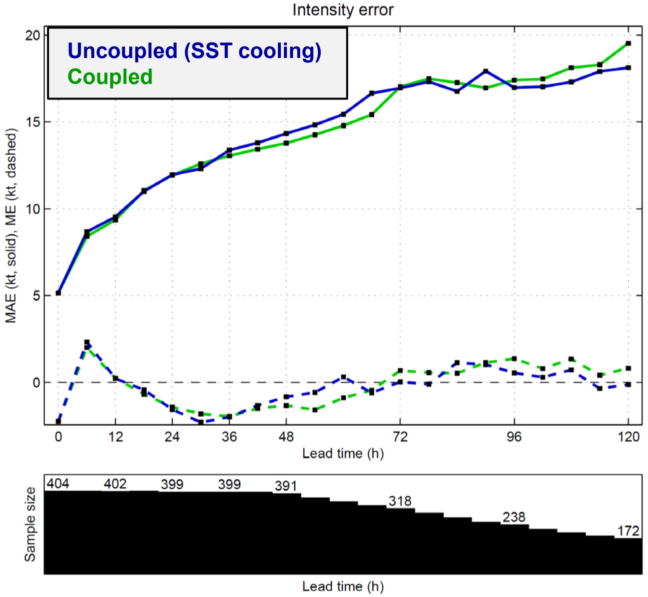
Hurricane Leslie (2012): Intensity Error & Bias

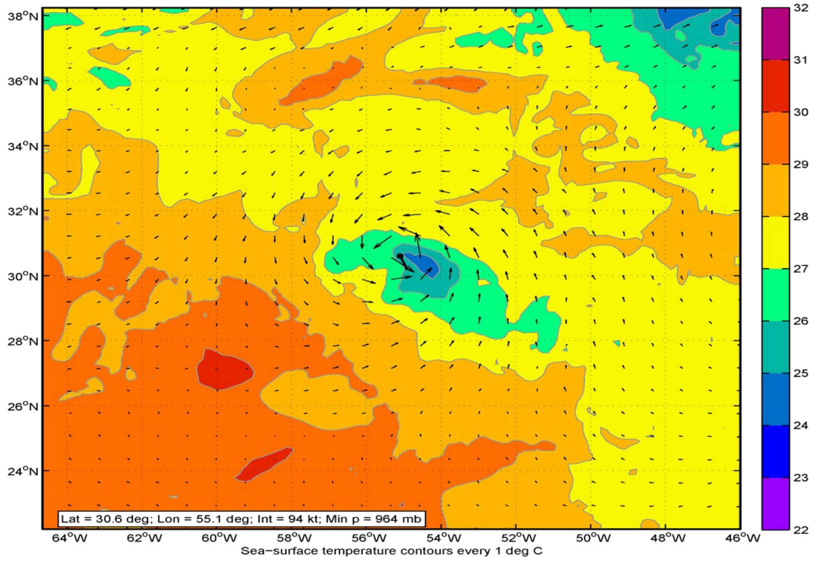


Hurricane Gaston (2016): Intensity Error



- 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.





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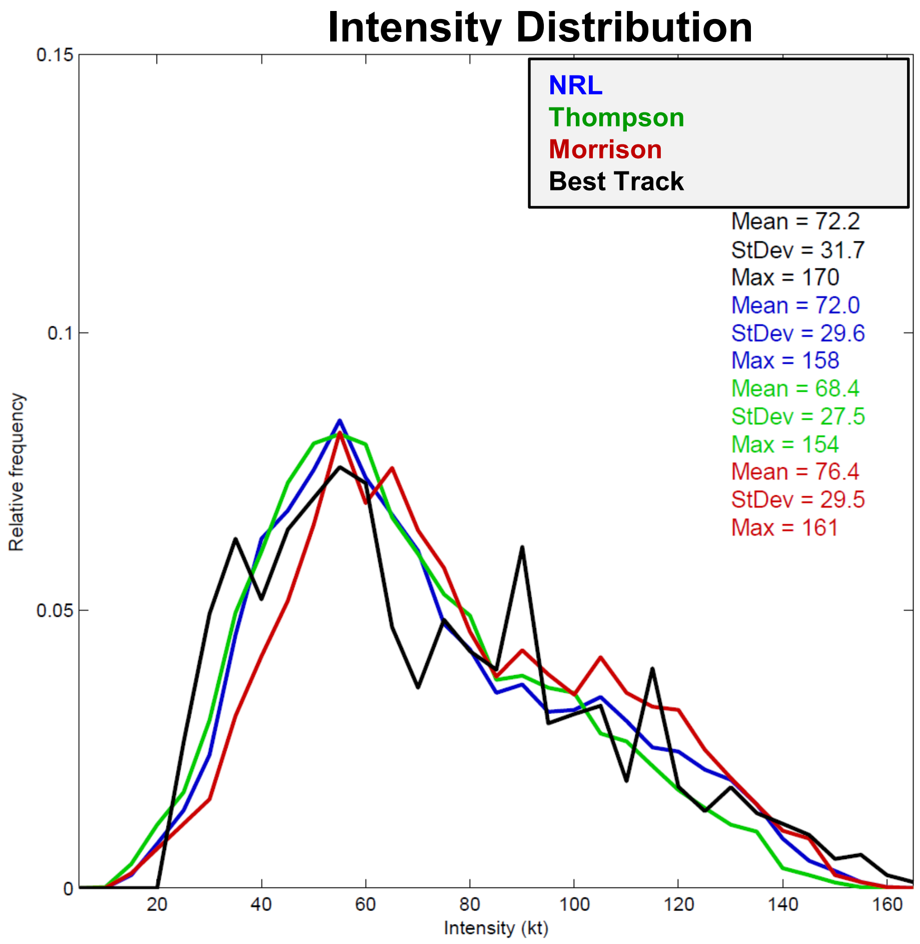
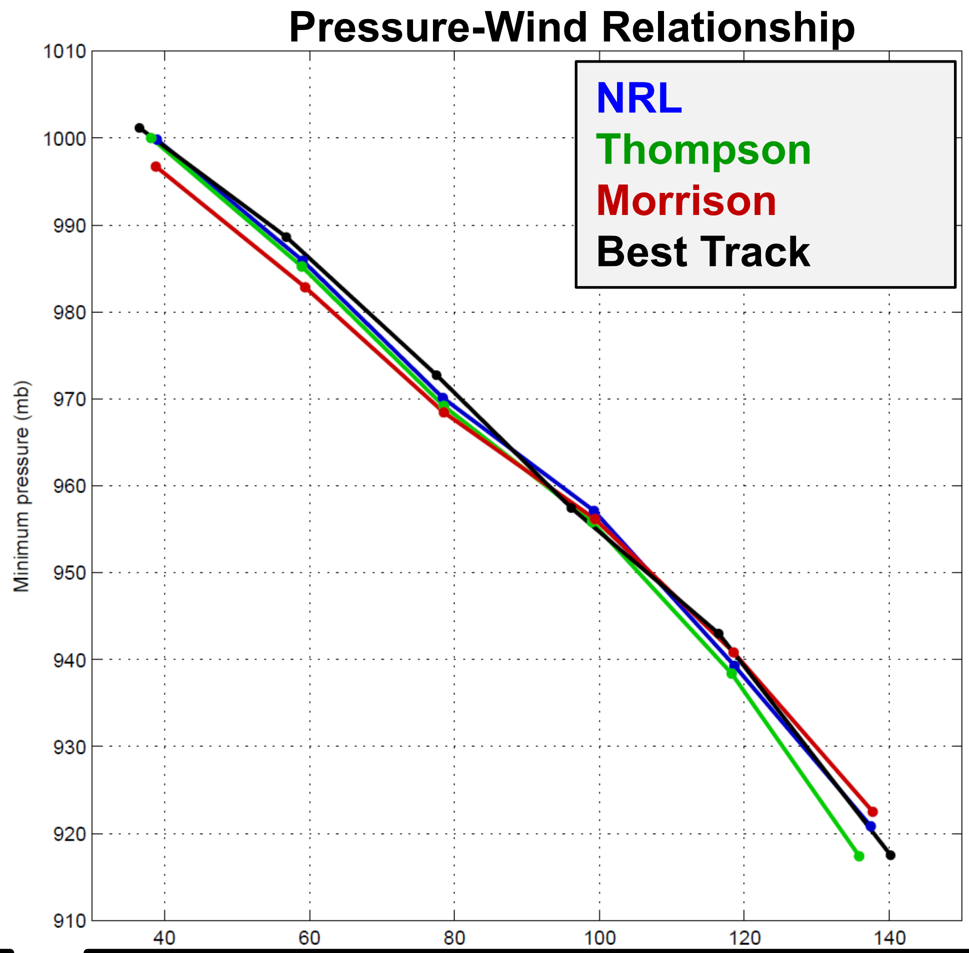
Microphysics

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