Understanding and Improvement in Medium-Range Forecasts of Tropical Cycles

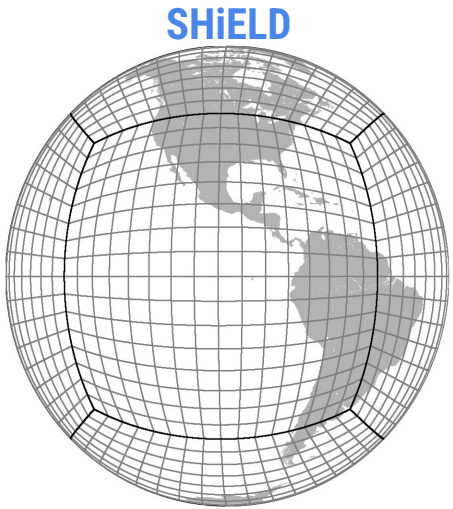
Kun Gao

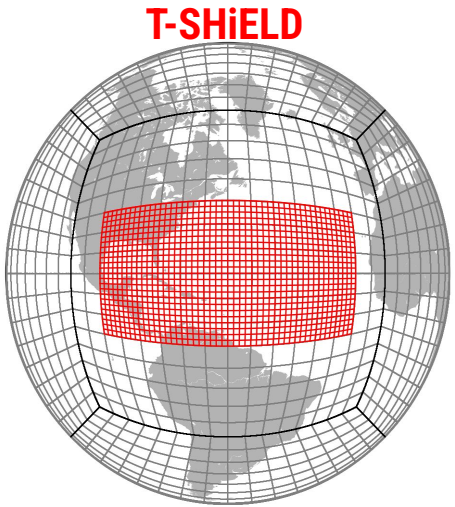
Q2: Concerning NOAA's key mission element of understanding, predicting, and projecting changes in the Earth System, how can GFDL drive further advances in these areas, including extremes and environmental hazards, through scientific innovation based on observations, theory, and modeling? Where are the strengths, gaps, and new frontiers?

GFDL experimental models for medium-range TC forecast

- **SHiELD:** backbone of GFDL SHiELD suite for experimental global weather predictions (***contributes to GFS/UFS***)
- **T-SHiELD:** two-way nested version of SHiELD optimized for km-scale hurricane predictions (***contributes to HAFS***)

Global 6.5km
Medium-range weather prediction





North Atlantic 3km
Hurricane prediction

Near-realtime experimental TC forecasts available at https://shield.gfdl.noaa.gov/

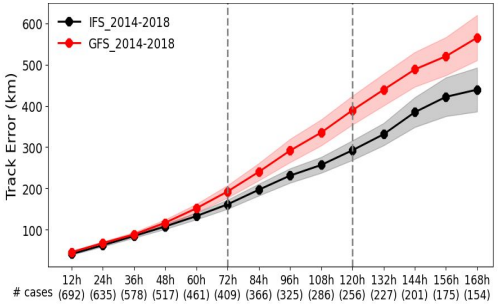
GFDL innovations that advanced operational TC forecasts in last 5 years

- GFDL FV3 dynamical core is used in the latest generation of NOAA operational global weather prediction model (GFSv16) and regional high-resolution hurricane models (HAFS-A and HAFS-B).
- The contributions of GFDL to the success of HAFS include, but are not limited to,
  - Multiple same-level and telescoping nesting capacity in FV3 (Mouallem et al. 2022)
  - Positive-definite tracer advection scheme in FV3 that improves intensity forecasts (Harris et al. 2020)
  - Updated GFDL vortex tracker that is built in HAFS code for positioning the moveable inner nest (public code)
  - A flexible vortex initialization scheme that facilitate the work flow of basin-scale HAFS (Gao et al. 2024)

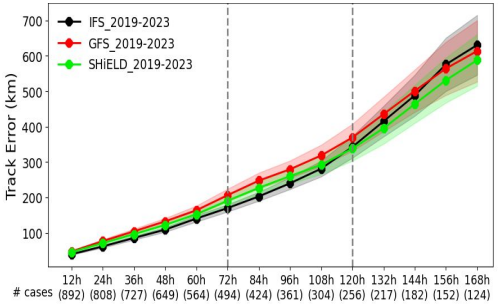
FV3 is advancing US operational TC forecasts

Improved track forecasts in FV3-based global models

2014-2018 mean error



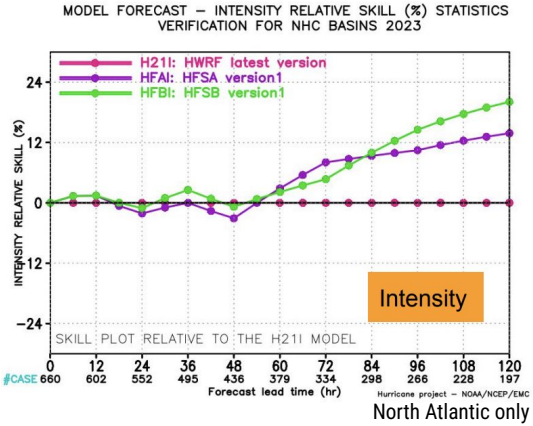
2019-2023 mean error



North Atlantic only

- GFS adopt FV3 as its dynamical core in 2019.
- The gap between GFS and IFS (ECMWF) in TC track forecast skill has been much reduced since then (Chen et al., BAMS, under review).

Improved intensity forecasts in FV3-based regional models



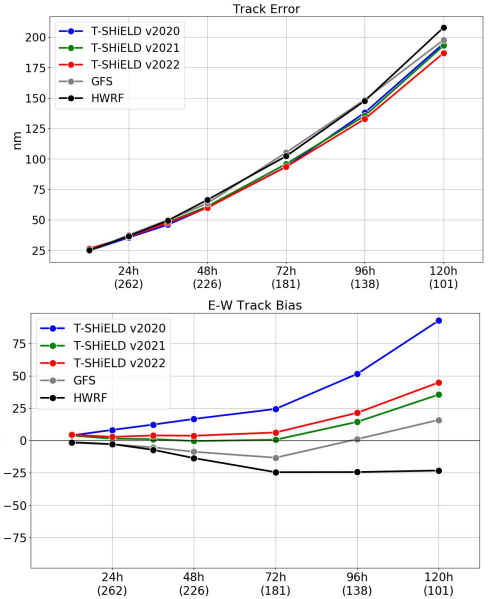
North Atlantic only

REF

- The new FV3-based operational hurricane model HAFS shows 10%-20% intensity improvement over the legacy HWRF.
- HAFS developments are led by NOAA/EMC and NOAA/HRD, with GFDL as a key collaborator.

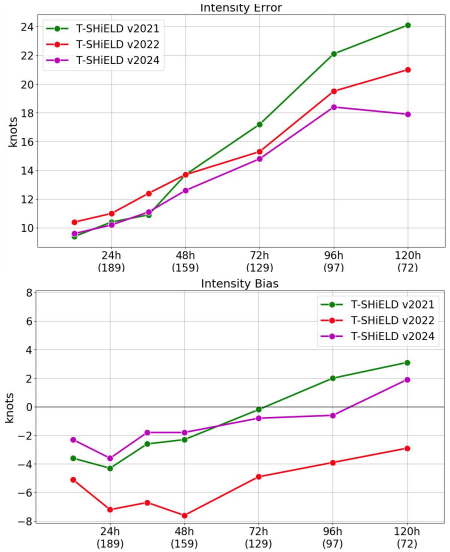
Steady year-to-year improvements in GFDL T-SHiELD

Track improvement



- Reduced track error and eastward bias from v2020 to v2022 due to improved synoptic-scale patterns
- T-SHiELD track performance remains excellent since v2022

Intensity improvement



- Reduced intensity error and bias from v2021 to v2024 due to better PBL and surface air-sea flux representations

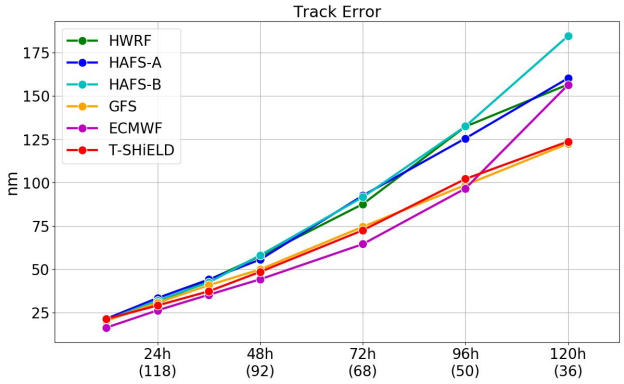
The year indicates the version of the model (2020, 2021, 2022, 2024)

Each plot is based on three-season mean stats

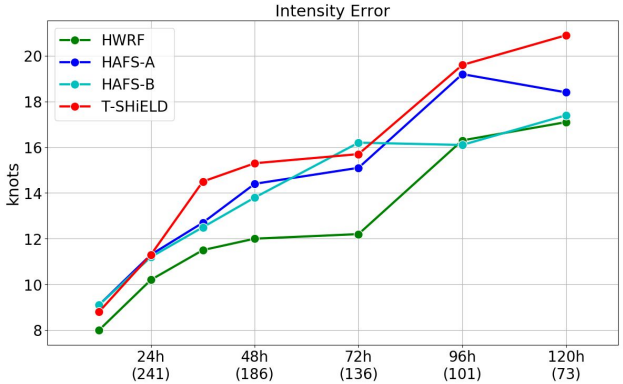
North Atlantic cases only

2024 North Atlantic Hurricane season performance

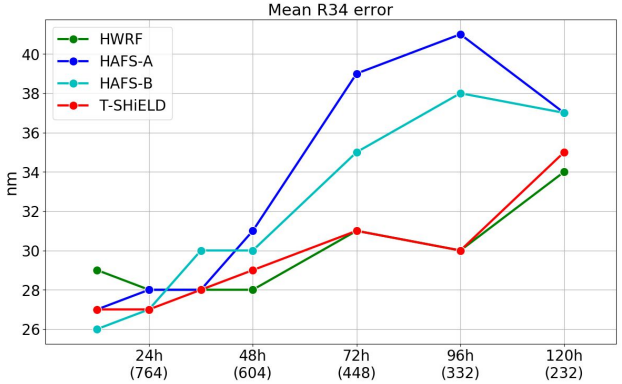
Track



Intensity



34 knots wind radii

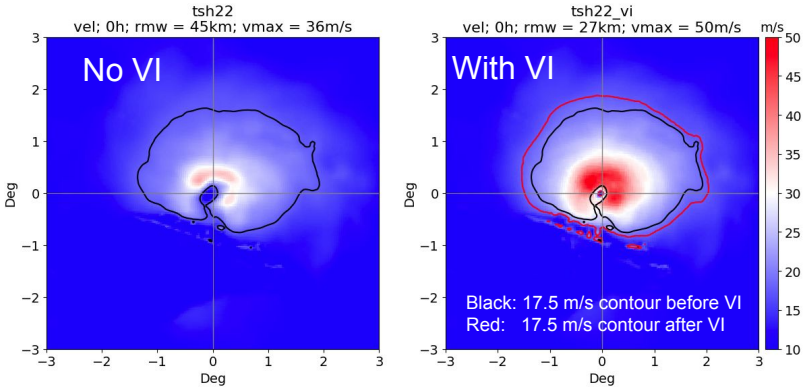


Verification done by Tim Marchok

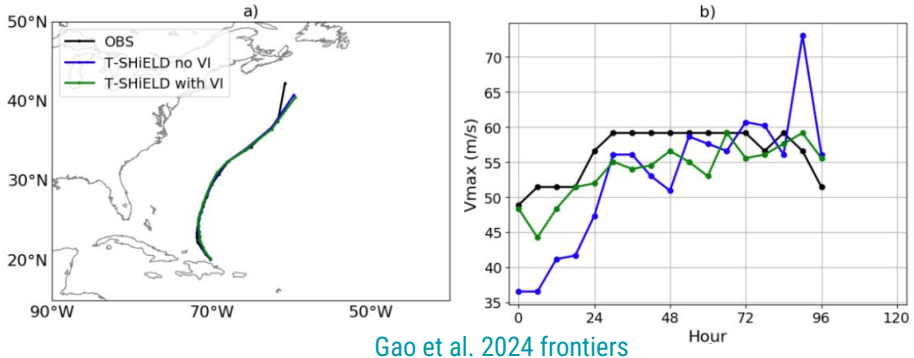
The latest version of T-SHiELD excelled in tracking and storm size prediction during the 2024 hurricane season, and its intensity forecasts were comparable to those of even higher-resolution models.

Effort on improving TC initialization

Surface wind speed in the initial condition



Prediction of Hurricane Fiona
initialized on 2022-09-20 00:00 UTC



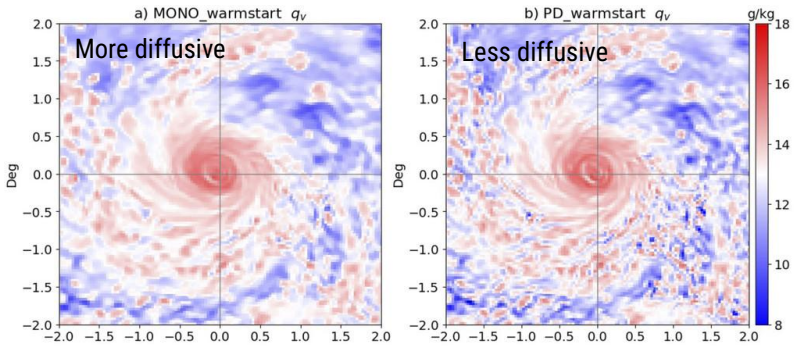
Gao et al. 2024 frontiers

- A vortex initialization (VI) scheme was implemented into T-SHiELD in 2023, which adjusts the intensity and size of the TC vortex in the initialization condition to match observed values.
- Same workflow will be applied to the global uniform SHiELD in the next season.

Understanding the science behind improved TC forecasting

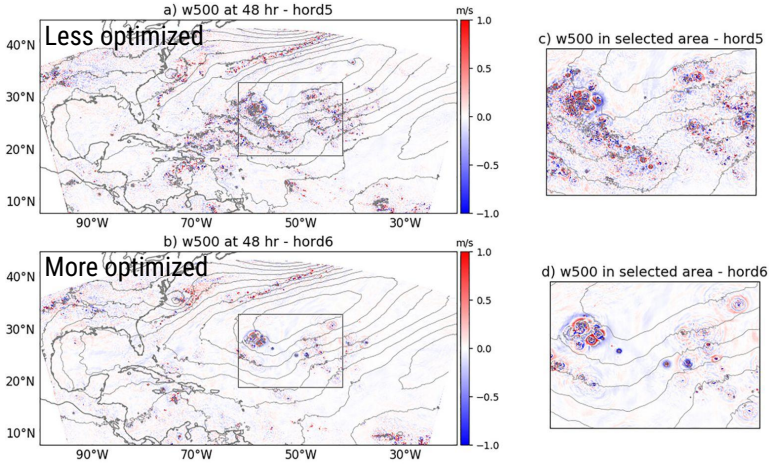
Understanding how the tracer advection scheme affects intensity prediction (Gao et al. 2021 JAS)

Key point: This study shows that a less-diffusive horizontal tracer advection scheme favors faster TC intensification rate via affecting the inner-core moisture distribution.



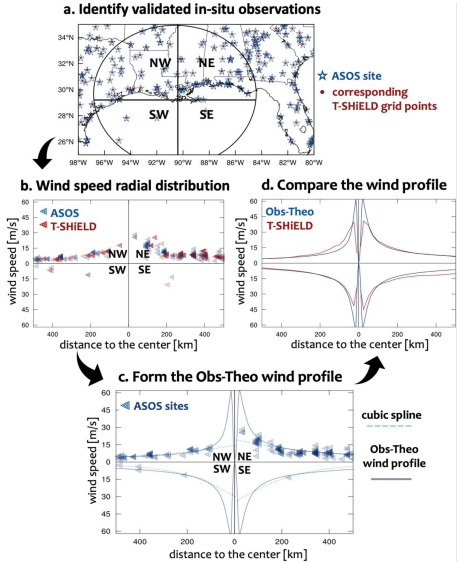
Understanding how the model resolved convection affects track prediction (Gao et al. 2023 GRL)

Key point: This study highlights that optimizing the resolved convection activity, for example, through the model's horizontal advection scheme, can lead to significantly improved TC track prediction.



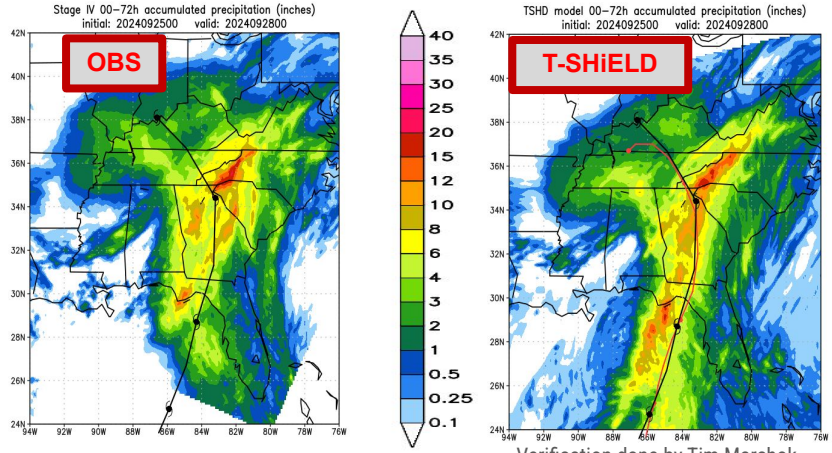
Predicting wind structure and precipitation of landfalling TCs

We developed a new framework that quantitatively evaluates the model predicted wind fields of landfalling TCs using sparse observations. Chen et al. 2023 GRL



GFDL T-SHiELD has been excellent in capturing the extreme rainfalls under landfalling TCs, including Helene (2024) and Ida (2021; Menemenlis et al. 2024 JAS).

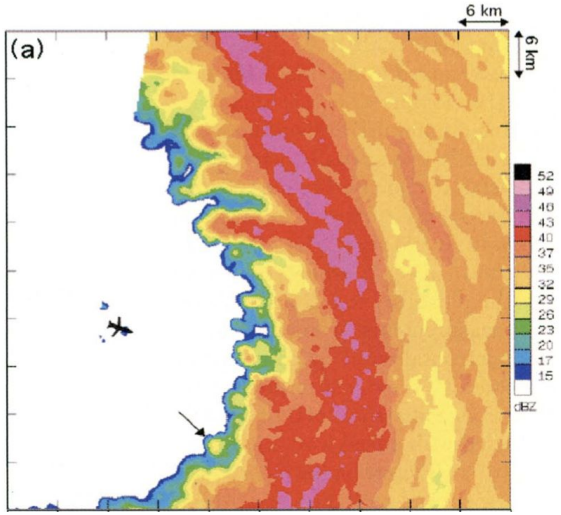
3-day accumulated rainfall
Hurricane Helene (2024)



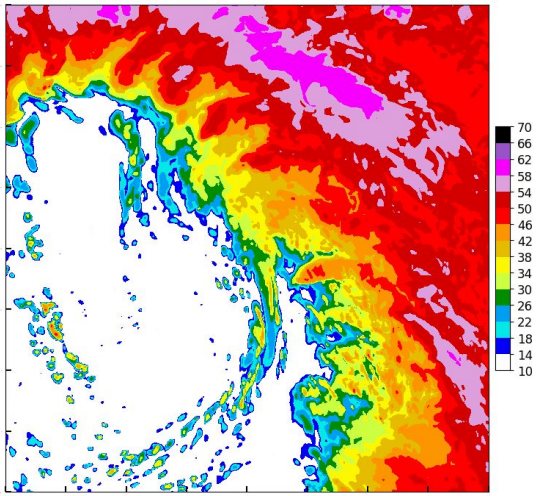
Verification done by Tim Marchok

New frontier: Simulating the entire TC at O(100m) resolution

- To support the need of next-generation hurricane models, we are increasing the resolution of our TC simulations to a 100m scale.
- Our experiments employ a two-level nesting strategy, with the innermost nest at a 125m nominal resolution covering TC inner core.
- Our results demonstrate better representations of finescale inner-core features and extreme wind gusts at this resolution.



Radar-observed Reflectivity
(Aberson et al. 2006 BAMS)



Simulated Reflectivity at dx=125m
(Gao et al. 2024 GRL)

Future Plan

- GFDL-based innovations have continued to enhance US TC forecasting over the past 5 years, most notably through the contributions to the new FV3-based operational global and regional models, continuing a legacy that dates back to the 1970s.
- We will focus on the following areas to tackle the challenges faced by the TC forecasting and modeling community.
    - **Sub-km scale application:** We are refining the resolution of T-SHiELD to sub-km regime to fully resolve the convection process and capture fine-scale structures, and improve the sub-grid closure scheme in FV3 to better represent dissipation processes at the turbulence-gray zone.
    - **Air-sea interactions:** We are developing a three-way-coupled SHiELD-MOM6-WWIII system, targeting understanding the small-scale air-sea coupled processes under TCs.
    - **Improved initialization:** We are exploring new AI-based avenues, which are more affordable and flexible than traditional DA, to better represent the initial TC structure in our global and regional prediction systems.