A Summary of C-SHiELD v2025 Performance During the 2025 Spring Forecasting Experiment Period

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Key Points:

- A new v2025 version of the FV3-based Global-Nested C-SHiELD was developed for the 2025 Spring Forecasting Experiment.
- Significant improvements to radar reflectivity and precipitation prediction skills were found, on par with the operational HRRR but with lower biases for heavy rain rates.
- These improvements come entirely from optimization of the physical parameterizations, again demonstrating the FV3 Dynamical Core's power for convective-scale prediction.

1 Introduction

The Spring Forecasting Experiment (SFE) of the Hazardous Weather Testbed (HWT; Clark et al 2024 and references therein) is an annual experiment in which forecasters, researchers, and students are invited to evaluate forecasts from operational and experimental convection-allowing models (CAMs) in an operational environment during the mid-Spring peak of central US severe weather. A focus for evaluating CAMs is on how they meet the needs of severe weather forecasts for National Weather Service operations, principally on 12–36 hour forecast lead times. The SFE mostly focuses on the CAM simulated reflectivity fields, but also evaluates precipitation, updraft helicity, and the thermodynamic environment before and during storms.

The Geophysical Fluid Dynamics Laboratory (GFDL) has developed the global-nested Continental System for High-resolution prediction on Earth-to-Local Domains (C-SHIELD; Harris et al. 2019) to demonstrate the feasibility of extended-range (0–5 day) convective-scale prediction. This is one configuration of SHiELD (Harris et al. 2020), a seamless modeling system that couples the nonhydrostatic GFDL Finite-Volume Cubed-Sphere Dynamical Core (FV3) to a modified version of the physics from the Global Forecast System (GFS). While C-SHiELD has been contributed to the SFE each year since 2017, in 2025 a major upgrade of C-SHiELD was done following significant advances in other kilometer-scale SHiELD configurations (Zhou et al. 2024). Specific goals for C-SHiELD v2025 were to improve the structure of convective storms during the SFE period, improve the radar reflectivity skill, and establish better precipitation biases and skill.

In this technical memorandum, we briefly describe the improvements to the new C-SHiELD v2025, and the resulting skill improvements using standard validation metrics for both simulated reflectivity and precipitation during the 2025 SFE period. A forthcoming paper will describe C-SHiELD's forecast performance in more detail and for a broader range of phenomena and seasons.

2 C-SHiELD v2025 Configuration

C-SHiELD v2025 uses the same global configuration as the 13-km SHiELD v2022 (Zhou and Harris 2022, Zhou et al. 2022), adding a 3-km nest over the Contiguous United States (CONUS;

Figure 1, left). The most substantial update in C-SHiELD v2025 is to upgrade the GFDL Microphysics (MP) scheme on the nested domain to version 3 (Zhou et al., 2022). GFDL MP version 3 includes numerous revised microphysical processes to improve storm structure and intensity. The most important of these are more realistic particle size distributions for cloud water and cloud ice, and the use of a climatological aerosol field to estimate cloud droplet number concentration in the cloud water autoconversion. The maximum terminal velocities of snow and hail were increased, which helps to reduce overly-strong reflectivity in the model. Hail-related collection efficiencies are also optimized, and the radar reflectivity diagnostic is upgraded to incorporate wet-coated particle effects (Tong and Xue 2005), improving the realism of simulated reflectivity fields.

C-SHiELD v2025 was further optimized by adjusting the entrainment and detrainment rates in the shallow convection, and the snow albedo treatment, dynamic vegetation, and rain-snow partitioning in Noah-MP to improve the surface temperature representation. Updates in the planetary boundary layer scheme, including revisions to the non-local mixing formulation and mixing length, helped to reduce the surface moisture biases. To enhance computational efficiency, the radiation time step was extended to 1 hour from the 30 minute timestep used in the previous C-SHiELD v2023. In both C-SHiELD v2023 and v2025, the nested domain uses no deep convective parameterization and applies the more advanced Noah-MP (Niu et al. 2011) instead of the NOAH LSM (Land Surface Model; Ek et al. 2003) for the global domain. Noah-MP was found to present smaller surface temperature and dew point biases in the CONUS than the NOAH LSM.

Note that no changes to FV3's solver, timestepping, or configuration have been done for C-SHiELD v2025; minor changes were made to apply a very weak vertical background diffusion (timescale 1200 s), and to alter the dissipative heating so it does not spuriously apply cooling. These changes may improve numerical stability but do not otherwise affect the solution.

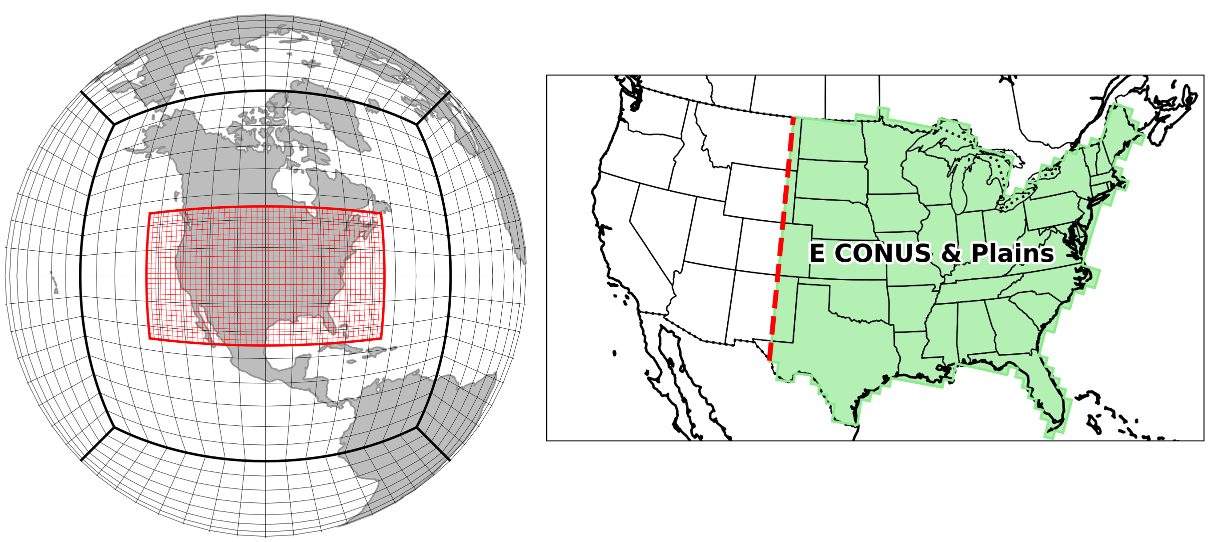

Figure 1: (Left) Schematic of C-SHiELD's global (black) and nested (red) domains. (Right) Eastern CONUS and Great Plains validation domain used in this paper.

3 Results

C-SHiELD has been running in real-time at 00Z and 12Z daily cold-started from GFS Analyses, out to 126 hours since 1 April 2025. Here we present 12–36 hour forecasts initialized at 00Z as this is the focus for the SFE. The analysis is performed for the five weeks of the SFE period, 26 April – 30 May 2025, including weekends and over the entire Eastern US plus the Great Plains region, defined as the CONUS east of the 105th West meridian (Figure 1, right).

We validate composite radar reflectivity against the national Multi-Radar/Multi-Sensor System (MRMS) product (Smith et al. 2016) and 6-hour accumulated precipitation against the National Centers for Environmental Prediction (NCEP) Stage IV merged observations (Du 2011). Several common metrics for severe local storm prediction are used to examine the forecasts: 1) frequency bias (FBIAS; absolute count), 2) Success Ratio (SR; 1 minus the False Alarm Ratio), 3) Probability of Detection (POD), and 4) Critical Success Index (a function of POD and SR). Validations do not use neighborhood methods, but doing so does not qualitatively change the results.

The forecast skill of simulated radar reflectivity is shown on the performance diagram in Figure 2. At all three different thresholds of radar reflectivity intensities (30, 40, and 50 dBZ), the POD of C-SHiELD v2025 (red) is much higher than the previous C-SHiELD v2023 (green). Meanwhile, C-SHiELD v2025 shows skill approaching that of the operational HRRR (High-Resolution Rapid Refresh; blue) and exceeding it at both 30 dBZ and 50 dBZ thresholds. The SR is lower in C-SHiELD v2025, which has a high bias in high reflectivity thresholds, than in C-SHiELD v2023, which instead had a low bias. This means that the False Alarm Ratio will necessarily be higher in C-SHiELD v2025 than in C-SHiELD v2023, and the SR lower. As a result, both C-SHiELD versions have similar CSI, slightly lower than the HRRR.

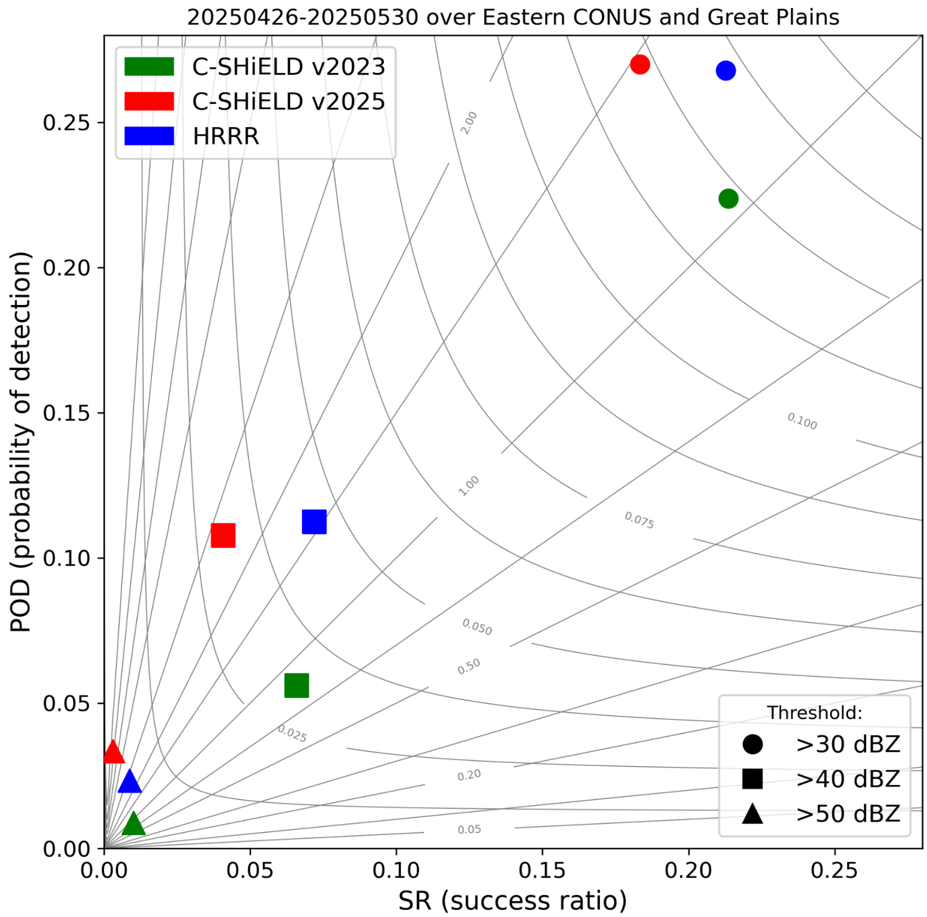

Figure 2: Performance diagram (SR vs. POD) for CONUS-wide radar reflectivity at three different thresholds during the 2025 SFE. Gray lines from bottom left corner to top and right are frequency bias (1:1 diagonal meaning neutral) while gray hyperbolas are CSI.

A similar performance diagram based on the 6-hour precipitation is shown in Figure 3. For all three thresholds, 40 mm/6 hr (about 1.6 in), 56 mm/6 hr (about 2.2 in; very heavy precipitation) and 72 mm/6 hr (about 2.8 in; extreme precipitation), C-SHiELD v2025 is better in CSI, POD, and SR than C-SHiELD v2023. For the 40 mm/6 hr and 72 mm/6 hr thresholds, C-SHiELD v2025 shows better CSI and SR than the HRRR, although its POD is lower. For the 56 mm/6 hr threshold, C-SHiELD v2025 has CSI on par with, and better SR than, the HRRR. Noticeably, C-SHiELD's frequency bias of precipitation is much less than that of the HRRR at all thresholds. We note that the two heavier thresholds occur more sporadically, the vast majority coming in no more than 4 specific days in May 2025, and will be very sensitive to the particular time period studied.

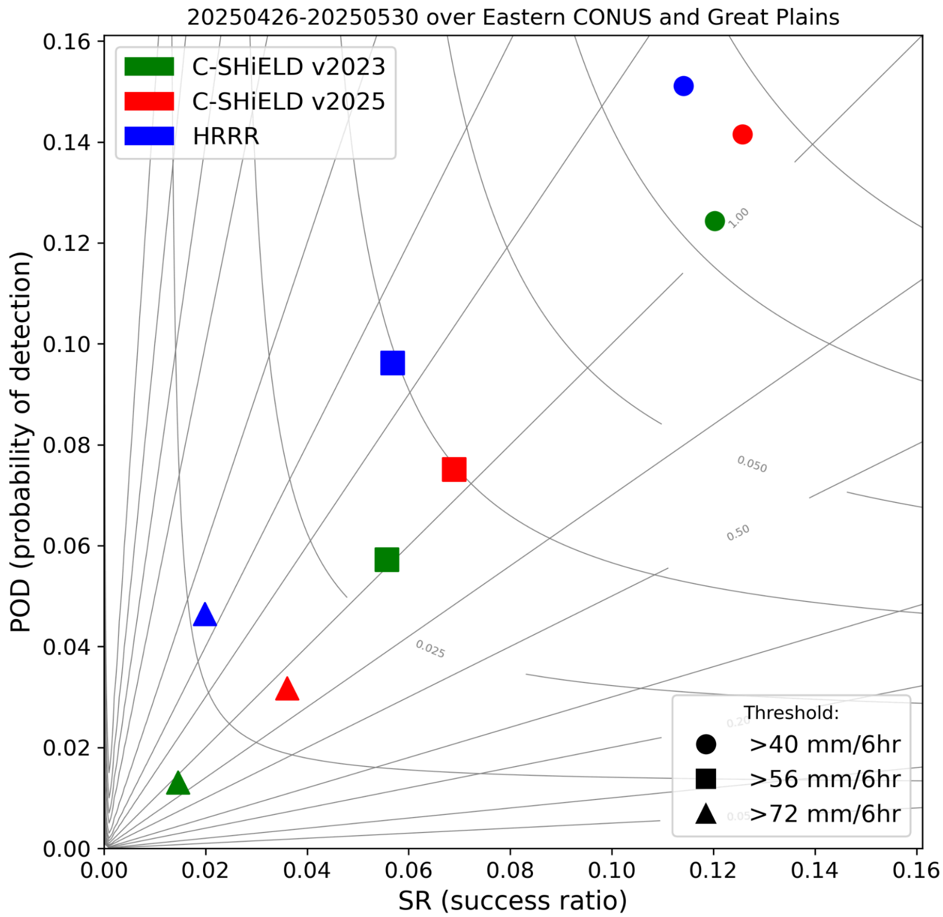

Figure 3: As in Figure 2, but for 6-hour accumulated precipitation.

We also examine the models' performance across the full spectrum of thresholds of radar reflectivity and precipitation to get a better understanding of aggregate forecast behavior (Figure 4). Both C-SHiELD v2025 and the HRRR have a high bias in radar reflectivities, especially at high thresholds. The bias in C-SHiELD v2025 is directly attributable to the inclusion of wet-coated snow in the radar reflectivity diagnostic (Tong and Xue 2005) in addition to wet-coated hail. A set of C-SHiELD v2025 re-forecasts (red dotted line in Figure 4) without the wet-coated snow in the reflectivity diagnostic found biases smaller than the HRRR for reflectivity thresholds larger than 35 dBZ, verifying our assertion. Future versions of C-SHiELD will consider the effect of wet-coated snow more closely; however note that as this is only a diagnostic it has no effect on the numerical solution itself.

C-SHiELD v2025's POD for composite reflectivity is on par with the HRRR at all thresholds, and is better below 30 dBZ, which represent stratiform precipitation regions and anvils. These regions are usually not considered in the context of hazardous weather, but they have a significant impact on radiation and thus the local energy budget, which can further influence medium-range and longer predictions, as well as solar energy applications.

Both versions of C-SHiELD have a nearly-neutral bias in precipitation across all thresholds, and lower than that of the HRRR, which again has a high bias amplifying at higher thresholds. There is still a low bias in light precipitation rates in both C-SHiELD versions. Work will continue to improve the representation of drizzle and light rain in C-SHiELD. C-SHiELD v2025's POD is lower than that of the HRRR for all thresholds, being the closest at 40 mm/6 hr. The higher POD in the HRRR can be traced in part to the HRRR's high precipitation frequency bias.

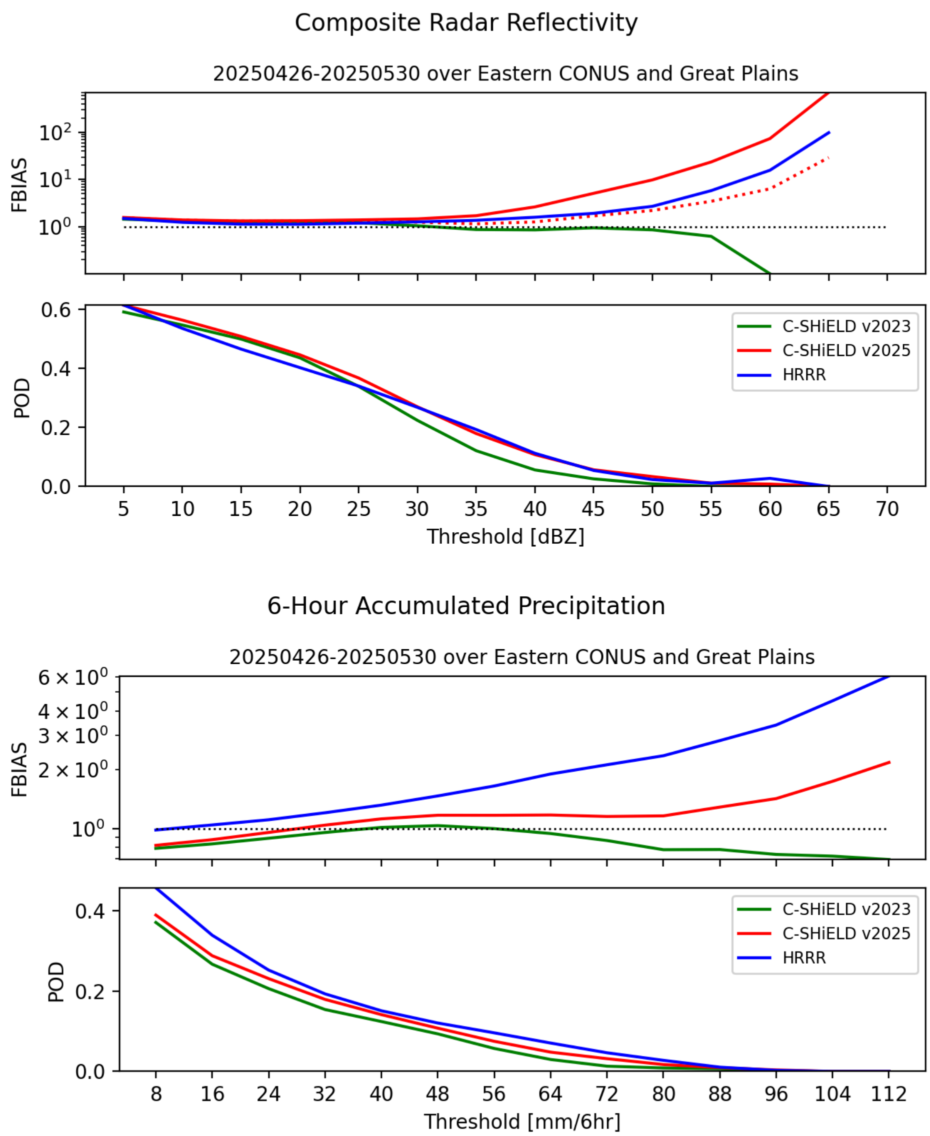

Figure 4: Forecast verification metrics as a function of thresholds. Top two panels are for radar reflectivity, bottom two panels are for 6-hour precipitation rates. The red dotted line represents re-forecasts with the water-coated snow reflectivity disabled.

4 Conclusion and Implications

The needs of operational short-range (0–36-hour lead time) severe local storm prediction are significantly different from those of medium-range prediction or of tropical prediction. Severe convection, especially the violent storms common in the central United States, are distinct from convective events covering much of the rest of the world (Emanuel 1989; Prein et al. 2025). CAMs for US severe weather are also developed differently, especially in terms of initialization, microphysics, and turbulent parameterization, and a heavy emphasis is placed on qualitative model aspects rather than on synoptic-scale evolution. The lack of connection to synoptic-scale evolution brings some struggles to models designed for US continental convection to simulate tropical mesoscale convective systems, e.g. poor forecasts in diurnal cycle and mesoscale convective system frequency (Song et al. 2024; Feng et al. 2025). This also poses a challenge for extended-range severe weather prediction, which will require either a global variable-resolution model (Zhou et al. 2019) or a global storm-resolving model (Feng et al. 2023) which needs to support skillful simulations of both large-scale weather patterns and of individual storm events. C-SHiELD was designed to meet these challenges.

The new C-SHiELD v2025 shows considerably improved radar reflectivity and precipitation skill compared to the earlier C-SHiELD v2023, and is competitive with the operational HRRR considered to be the benchmark for severe weather prediction. This is an especially remarkable achievement given that the development of the new C-SHiELD was compressed into a few months (January–April 2025) and had contended with several external disruptions including the involuntary departure of a key developer. It is also noteworthy that unlike most severe-weather prediction models that use specialized radar data assimilation, land initialization, and physics suites developed exclusively for CONUS prediction, the current C-SHiELD configuration is cold-started from GFS analyses and uses a general-purpose physics suite originally derived from the GFS.

These results confirm the strength of FV3-based models for simulation and prediction across all spatial scales. This reaffirms the capabilities of FV3-based convective-scale models for severe weather prediction (Zhang et al., 2019; Potvin et al. 2019; Harris et al. 2019), in line with successes in kilometer-scale and finer simulations of tropical cyclones (Hazelton et al. 2024; Gao et al. 2024; Chen et al. 2025), of radiative-convective equilibrium (Jeevanjee and Zhou, 2022; Arnold et al. 2020), and global storm-resolving modeling (Judt et al. 2021; Cheng et al. 2022; Bolot et al. 2023).

Previously, a few FV3-based models for very short-range severe weather prediction showed poor radar reflectivity skill and too much heavy precipitation. Claims were circulated that these were attributable to perceived flaws in FV3's construction, focusing on the minor choice of horizontal grid staggering (Skamarock 2008; Carley et al. 2023). Given the significant improvements in radar reflectivity skill and the near-neutral precipitation biases in C-SHiELD v2025, *due only to improvements in the physics*, and concomitant improvements in other FV3-based models in 2025, we can categorically reject these claims.

Development of C-SHiELD will also continue if personnel and resources permit. The next near-term focus will be to improve the microphysics and planetary boundary layer parameterizations, while the longer-term development plan will include revision of the land surface model and integration of river routing and subgrid hydrology (Shevliakova et al., 2024), improved land-surface initialization and interaction, Predicted Particle Property (P3) capabilities in the microphysics (Milbrandt et al., 2025), and multi-nest capability through Tele-SHiELD. Further comprehensive evaluation of C-SHiELD is continuing, while other C-SHiELD application research has been on-going, including the medium-range and subseasonal predictions (cf. Zavadoff et al., in revision; Hosek et al., in review), and of other phenomena and seasons, especially cold-season events (Han et al., 2025).

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References

Arnold, N. P., Putman, W. M., & Freitas, S. R. (2020). Impact of Resolution and Parameterized Convection on the Diurnal Cycle of Precipitation in a Global Nonhydrostatic Model. *Journal of the Meteorological Society of Japan. Ser. II, 98*(6), 1279-1304. https://doi.org/10.2151/jmsj.2020-066

Bolot, M., Harris, L. M., Cheng, K. Y., Merlis, T. M., Blossey, P. N., Bretherton, C. S., et al. (2023). Kilometer-scale global warming simulations and active sensors reveal changes in tropical deep convection. *npj Climate and Atmospheric Science, 6*(1), 209. https://doi.org/10.1038/s41612-023-00525-w

Carley, J., Alexander, C., Wicker, L., Jablonowski, C., Clark, A., Nelson, J., et al. (2023). Mitigation Efforts to Address Rapid Refresh Forecast System (RRFS) v1 Dynamical Core Performance Issues and Recommendations for RRFS v2. Office note (National Centers for Environmental Prediction (U.S.)), 516. https://doi.org/10.25923/ccgj-7140

Chen, J.-H., Marchok, T., Bender, M., Gao, K., Gopalakrishnan, S., Harris, L., et al. (2025). Closing the gap — Hurricane Prediction Advances in the US FV3-based Models. *Bulletin of the American Meteorological Society*, BAMS-D-24-0036.0031. https://doi.org/10.1175/BAMS-D-24-0036.1

Cheng, K. Y., Harris, L., Bretherton, C., Merlis, T. M., Bolot, M., Zhou, L. J., et al. (2022). Impact of Warmer Sea Surface Temperature on the Global Pattern of Intense Convection: Insights From a Global Storm Resolving Model. *Geophysical Research Letters, 49*(16), e2022GL099796. https://doi.org/10.1029/2022GL099796

Clark, A. J., Jirak, I. L., Supinie, T. A., Knopfmeier, K. H., Harrison, D., Vancil, J., et al. (2024). Advancing Hazardous Weather Prediction in the 2024 NOAA Hazardous Weather Testbed Spring Forecasting Experiment. *Bulletin of the American Meteorological Society, 105*(11), E2180-E2183. https://doi.org/10.1175/BAMS-D-24-0249.1

Du, J. (2011). NCEP/EMC 4KM Gridded Data (GRIB) Stage IV Data. Version 1.0. UCAR/NCAR - Earth Observing Laboratory. https://doi.org/10.5065/D6PG1QDD

Ek, M. B., Mitchell, K. E., Lin, Y., Rogers, E., Grunmann, P., Koren, V., et al. (2003). Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model. *Journal of Geophysical Research: Atmospheres, 108*(D22), 8851. https://doi.org/10.1029/2002JD003296

Emanuel, K. A. (1989). Dynamical theories of tropical convection. *Australian Meteorological Magazine*, 37(1), 3–10. https://web.archive.org.au/awa/20231220144258mp_/http://www.bom.gov.au/jshess/docs/1989/emanuel.pdf

Feng, Z., Leung, L. R., Hardin, J., Terai, C. R., Song, F., & Caldwell, P. (2023). Mesoscale convective systems in DYAMOND global convection-permitting simulations. *Geophysical Research Letters*, 50, e2022GL102603. https://doi.org/10.1029/2022GL102603

Feng, Z., Prein, A. F., Kukulies, J., Fiolleau, T., Jones, W. K., Maybee, B., et al. (2025). Mesoscale convective systems tracking method intercomparison (MCSMIP): Application to DYAMOND global km-scale simulations. *Journal of Geophysical Research: Atmospheres*, 130, e2024JD042204. https://doi.org/10.1029/2024JD042204

Gao, K., Mouallem, J., & Harris, L. (2024). What Are the Finger-Like Clouds in the Hurricane Inner-Core Region? *Geophysical Research Letters, 51*(23), e2024GL110810. https://doi.org/10.1029/2024GL110810

Han, B., Zhou, L., Harris, L., Cheng, K. (2025). Evaluating Snowfall Forecasts Over the Midwestern and Eastern United States in the GFDL C-SHiELD Model. *Weather and Forecasting*, in press. https://doi.org/10.1175/WAF-D-24-0235.1

Harris, L. M., Rees, S. L., Morin, M., Zhou, L., & Stern, W. F. (2019). Explicit Prediction of Continental Convection in a Skillful Variable-Resolution Global Model. *Journal of Advances in Modeling Earth Systems, 11*(6), 1847-1869. https://doi.org/10.1029/2018MS001542

Harris, L., Zhou, L., Lin, S. J., Chen, J. H., Chen, X., Gao, K., et al. (2020). GFDL SHiELD: A Unified System for Weather-to-Seasonal Prediction. *Journal of Advances in Modeling Earth Systems, 12*(10), e2020MS002223. https://doi.org/10.1029/2020MS002223

Hazelton, A., Chen, X., Alaka, G. J., Alvey, G. R., Gopalakrishnan, S., & Marks, F. (2024). Sensitivity of HAFS-B Tropical Cyclone Forecasts to Planetary Boundary Layer and Microphysics Parameterizations. *Weather and Forecasting, 39*(4), 655-678. https://doi.org/10.1175/WAF-D-23-0124.1

Hosek, M.J., K.A. Hoogewind, A.J. Clark, L. Harris, K.-Y. Cheng, & L. Zhou. Quantifying the Value of Convection-Allowing Global-Nested Ensembles for Extended-Range Severe Weather Forecasting. Submitted to *Weather and Forecasting*.

Jeevanjee, N., & Zhou, L. J. (2022). On the Resolution-Dependence of Anvil Cloud Fraction and Precipitation Efficiency in Radiative-Convective Equilibrium. *Journal of Advances in Modeling Earth Systems, 14*(3), e2021MS002759. https://doi.org/10.1029/2021MS002759

Judt, F., Klocke, D., Rios-Berrios, R., Vanniere, B., Ziemen, F., Auger, L., et al. (2021). Tropical Cyclones in Global Storm-Resolving Models. *Journal of the Meteorological Society of Japan, 99*(3), 579-602. https://doi.org/10.2151/jmsj.2021-029

Milbrandt, J. A., Morrison, H., & Cholette, M. (2025). Impacts of Predicted Liquid Fraction and Multiple Ice-Phase Categories on the Simulation of Hail in the Predicted Particle Properties (P3) Microphysics Scheme. *Journal of Advances in Modeling Earth Systems, 17*(3), e2024MS004404. https://doi.org/10.1029/2024MS004404

Niu, G. Y., Yang, Z. L., Mitchell, K. E., Chen, F., Ek, M. B., Barlage, M., et al. (2011). The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements. *Journal of Geophysical Research-Atmospheres, 116*(D12), 116, D12109. https://doi.org/10.1029/2010JD015139

Potvin, C. K., Carley, J. R., Clark, A. J., Wicker, L. J., Skinner, P. S., Reinhart, A. E., et al. (2019). Systematic Comparison of Convection-Allowing Models during the 2017 NOAA HWT Spring Forecasting Experiment. *Weather and Forecasting, 34*(5), 1395-1416. https://doi.org/10.1175/WAF-D-19-0056.1

Prein, A. F., Wang, D., Ge, M., Ramos Valle, A., & Chasteen, M. B. (2025). Resolving Mesoscale Convective Systems: Grid Spacing Sensitivity in the Tropics and Midlatitudes. *Journal of Geophysical Research: Atmospheres, 130*(9), e2024JD042530. https://doi.org/10.1029/2024JD042530

Shevliakova, E., Malyshev, S., Martinez-Cano, I., Milly, P. C. D., Pacala, S. W., Ginoux, P., et al. (2024). The Land Component LM4.1 of the GFDL Earth System Model ESM4.1: Model Description and Characteristics of Land Surface Climate and Carbon Cycling in the Historical Simulation. *Journal of Advances in Modeling Earth Systems, 16*(5), e2023MS003922. https://doi.org/10.1029/2023MS003922

Skamarock, W. C. (2008). A Linear Analysis of the NCAR CCSM Finite-Volume Dynamical Core. *Monthly Weather Review, 136*(6), 2112-2119. https://doi.org/10.1175/2007MWR2217.1

Smith, T. M., Lakshmanan, V., Stumpf, G. J., Ortega, K. L., Hondl, K., Cooper, K., et al. (2016). MULTI-RADAR MULTI-SENSOR (MRMS) SEVERE WEATHER AND AVIATION PRODUCTS Initial Operating Capabilities. *Bulletin of the American Meteorological Society, 97*(9), 1617-1630. https://doi.org/10.1175/BAMS-D-14-00173.1

Song, J., Song, F., Feng, Z., Leung, L. R., Li, C., & Wu, L. (2024). Realistic precipitation diurnal cycle in global convection-permitting models by resolving mesoscale convective systems. *Geophysical Research Letters*, 51, e2024GL109945. https://doi.org/10.1029/2024GL109945

Tong, M., & Xue, M. (2005). Ensemble Kalman Filter Assimilation of Doppler Radar Data with a Compressible Nonhydrostatic Model: OSS Experiments. *Monthly Weather Review, 133*(7), 1789-1807. https://doi.org/10.1175/MWR2898.1

Zavadoff, M.L., K.-Y. Cheng, H. Lopez, D. Kim, R. West, K. Gao, J.-H. Chen, and L.M. Harris. Western US Subseasonal Atmospheric River Prediction in the Global-Nested GFDL SHiELD Model. Submitted to *Journal of Geophysical Research: Atmospheres*.

Zhang, C., Xue, M., Supinie, T. A., Kong, F., Snook, N., Thomas, K. W., et al. (2019). How Well Does an FV3-Based Model Predict Precipitation at a Convection-Allowing Resolution? Results From CAPS Forecasts for the 2018 NOAA Hazardous Weather Test Bed With Different Physics Combinations. *Geophysical Research Letters, 46*(6), 3523-3531. https://doi.org/10.1029/2018GL081702

Zhou, L. J., Lin, S. J., Chen, J. H., Harris, L. M., Chen, X., & Rees, S. L. (2019). Toward Convective-Scale Prediction within the Next Generation Global Prediction System. *Bulletin of the American Meteorological Society, 100*(7), 1225-1243. https://doi.org/10.1175/BAMS-D-17-0246.1

Zhou, L., & Harris, L. (2022). Integrated Dynamics-Physics Coupling for Weather to Climate Models: GFDL SHiELD With In-Line Microphysics. *Geophysical Research Letters, 49*(21), e2022GL100519. https://doi.org/10.1029/2022GL100519

Zhou, L. J., Harris, L., Chen, J. H., Gao, K., Guo, H., Xiang, B. Q., et al. (2022). Improving Global Weather Prediction in GFDL SHiELD Through an Upgraded GFDL Cloud Microphysics Scheme. *Journal of Advances in Modeling Earth Systems, 14*(7), e2021MS002971. https://doi.org/10.1029/2021MS002971

Zhou, L., Harris, L., Chen, J. H., Gao, K., Cheng, K. Y., Tong, M., et al. (2024). Bridging the Gap Between Global Weather Prediction and Global Storm-Resolving Simulation: Introducing the GFDL 6.5-km SHiELD. *Journal of Advances in Modeling Earth Systems, 16*(12), e2024MS004430. https://doi.org/10.1029/2024MS004430