2022-2023 Global-Nest Initiative Activity Summary: Recent Results and Future Plan

J.-H. Chen[1], A. Clark[3], G. Ge[4], L. Harris[1], K. Hoogewind[3], A. Jensen[4], H. Lopez[2], J. Mouallem[1,5], B. Zavadoff[2,6], X. Zhang[2], L. Zhou[1,5]

[1] NOAA Geophysical Fluid Dynamics Laboratory
[2] NOAA Atlantic Oceanographic and Meteorological Laboratory
[3] NOAA National Severe Storms Laboratory
[4] NOAA Global Systems Laboratory
[5] Program in Atmospheric and Oceanic Sciences, Princeton University
[6] Cooperative Institute for Marine and Atmospheric Studies, University of Miami

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J.-H. Chen[1], A. Clark[3], G. Ge[4], L. Harris[1], K. Hoogewind[3], A. Jenson[4], H. Lopez[2], J. Mouallem[1,5], B. Zavadoff[2,6], X. Zhang[2], L. Zhou[1,5]

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The Global-Nest Initiative takes new technologies developed at Geophysical Fluid Dynamics Laboratory (GFDL) and partners to create convective-scale digital twins of the earth system to better simulate and predict extreme weather events, their impacts, and their role within the broader earth system, and to create actionable information at all time scales.

This annual report describes the activities and results of the NOAA Global-Nest Initiative during Fiscal Year 2022-2023. Achievements of each participating NOAA laboratory are summarized individually based on their presentations in the first Global-Nest Initiative Annual Workshop held virtually on September 12, 2023 (Appendix A). Other details, including personnel arrangements (Appendix B) and contributed publications (Appendix C) from each laboratory, are also included in this report.

Geophysical Fluid Dynamics Laboratory (GFDL)

The GFDL System for High-resolution prediction on Earth-to-Local Domains (SHiELD) is a Finite-Volume Cubed-Sphere Dynamical Core (FV3)-based weather prediction system which is a holistically-designed unified prediction modeling system. The goals of the Global-Nest Initiative at GFDL are to create the 6-km flagship global SHiELD as the foundation for medium-range weather prediction, the 2-km nested C-SHiELD focusing on the Contiguous United States (CONUS), the 2-km nested T-SHiELD focusing on the North Atlantic, and the 3-km global storm-resolving X-SHiELD with a focus on extreme weather and climate events. During the development of FV3 and SHiELD, k-scale/eddy-scale studies, process modeling developments, and Graphics Processing Unit (GPU) accelerations are also considered.

GFDL Modeling Systems Continuous Integration/Continuous Development (CI/CD) streamlines the integration of community-contributed code submission for FV3 and SHiELD. The SHiELD near real-time system regularly runs and delivers the model performance based on Tier-1 configurations including the 13-km resolution global SHiELD, the 3-km resolution C-SHiELD, and the 3.25-km resolution T-SHiELD (in hurricane season) to the SHiELD public website. The 3.25-km resolution X-SHiELD has completed years-long simulations in current and warmed climate which demonstrates its ability for convective-scale global climate modeling. The data is available on NOAA Open Data Dissemination (NODD) cloud storage and Princeton University's Stellar heterogeneous cluster, and has been used by the Allen Institute for Artificial Intelligence (AI2) for machine learning and model emulation.

The main development progress of FV3, SHiELD, and Pace (Python-based FV3 with GFDL cloud microphysics scheme) contributed from GFDL are summarized below.

FV3 dynamical core

The two major updates implemented in FV3 dynamical core during 2022-2023 are the updated multiple grid nesting function and a new Duo-Grid capability, which are described briefly below.

- Updates in multiple grid nesting funcion
  Multiple grid nesting has been described by Mouallem et al. (2022). The following updates were added during the first year of the Global-Nest Initiative.
    - Enable nesting and multiple nesting in the solo core
    - A new idealized test case to simulate multiple tropical cyclones was created to take advantage of this functionality.
    - Enable adding multiple nests in doubly-periodic test cases using absolute coordinates.
    - A bug fix in reading the GFS (Global Forecast System) input data files for multiple grid nests
- Duo-Grid capability
  The newly developed Duo-Grid capability is a solution to the cubed-sphere grid imprinting. It makes the dynamical core's integration continuous across the edges and corners without the need for extra edge or corner handling. The halo remapping algorithm and Duo extension are directly implemented into the halo update message passing calls for each tile. This capability minimizes the data movement in CPU (central processing unit)/GPU hybrid systems which can benefit FV3 development on GPUs.

SHiELD model

During 2022-2023, SHiELD has incorporated many updates in its physics parameterizations, including the GFDL cloud microphysics (GFDL MP), Simplified Arakawa-Schubert (SAS) cumulus convection scheme, the turbulence kinetic energy based eddy-diffusivity mass-flux (TKE-EDMF) planetary boundary layer (PBL) parameterization, and the mountain blocking. Integrated dynamics-physics coupling and Cloud Feedback Model Intercomparison Project (CFMIP) Observation Simulator Package (COSP) were also built in SHiELD. Moreover, a newly developed C1536 configuration has been tested and finalized.

The major improvements from the above mentioned updates are listed below.

- Integrated dynamics-physics coupling
  This update allows the physics schemes to be called at a physically-appropriate time frequency, and also makes the heat transfer in the physics consistent with that in the dynamics. The dynamics-physics interaction is therefore enhanced. The statistics of large-scale atmospheric fields are improved.
- GFDL cloud microphysics scheme
  To improve the physical realism of the scheme, a realistic particle size distribution (PSD), PSD-based consistent microphysical quantities and processes, and aerosol-aware effects were adopted in the GFDL MP version 3 (Zhou et al. 2022). The newer version of GFDL MP also improved the energy conservation by adding a missing term in the latent heat, which was shown to contribute more cloud water and rain water in a single-storm experiment.
  Benefiting from the updated GFDL MP, the extreme precipitation bias shown in C-SHiELD was reduced with a more realistic light rain structure, and the position of squall line aligns better with the observations.
- SAS cumulus convection scheme
  In the 6.5-km SHiELD, the Arakawa-Schubert quasi-equilibrium assumption is adopted in the SAS scheme. The surface heat flux, height and temperature at low levels, wind, and radiation were improved by this update. The results demonstrated a possible solution for parameterizing the convection in the gray zone.
  Other improvements from the adjustments in the shallow convection also led to a better performance in the 6.5-km SHiELD, specifically by increasing the detrainment rate. Meanwhile, a significant reduction of the movement bias of the tropical cyclone forecast was found in T-SHiELD when decreasing the detrainment rate.
- TKE-EDMF PBL Turbulence parameterization
  Background diffusion in the PBL scheme regulates the low level cloud fraction as well as the surface temperature through dry air mixing at the cloud top. A

reduced background diffusion over the ocean can reduce the low cloud fraction and near surface temperature bias existing in the current 6.5-km SHiELD.

- Mountain blocking
  A grid-length dependent factor introduced by Kim and Doyle (2005) was used in the updated mountain block scheme in SHiELD. Although Kim and Doyle (2005) showed that the impact of mountain blocks should be enhanced in higher resolutions, we found that the scale-awareness factor is not sufficient and further enhancement is needed when the model resolution increases from 13 km to 6.5 km.
- COSP in SHiELD
  To directly compare with satellite observations, COSP version 2 has been implemented into SHiELD, with both online and offline options. The online option is suitable for high resolution configuration, e.g., X-SHiELD, while the offline option is best for lower-resolution configuration, e.g., SHiELD, C-SHiELD, and T-SHiELD.
- C1536 global SHiELD configuration
  Many adjustments were needed for updating the global SHiELD resolution from C768 (13 km) to C1536 (6.5 km), which included time steps, SAS cumulus schemes, mountain blocking, and the EDMF PBL turbulence parameterization. Compared to the C768 configuration, the newly developed C1536 SHiELD shows better global statistics in geopotential height, temperature, wind, water vapor, clouds, and radiation. The precipitation biases and the timing of precipitation diurnal cycle are also improved. C1536 global SHiELD can also better predict severe storms by showing better bow-shape structures in radar reflectivity and precipitation, with better cold pool locations.

Pace

Pace (Dahm et al. 2023) is a Python-based nonhydrostatic FV3 with GFDL cloud microphysics scheme (version 2) written in the GT4Py domain-specific language which can achieve portable high computational performance, especially on GPUs. The Pace project started from the collaboration between NOAA and Vulcan (later AI2) in 2019, then transitioned to NOAA and NASA in 2023. A newer version of Pace with GFDL cloud microphysics scheme version 3 is nearly finished. The integration of other physics is in-progress.

On-going activities and future plans at GFDL

- Multiple same level and telescoping moving nests (collaborating with AOML and Environmental Modeling Center (EMC))
- Duo-Grid optimization and application in a full-physics SHiELD configuration

- Doubly periodic idealized TC with telescoping nesting
- Implementing LMARS (Low Mach number Approximate Riemann Solver) into FV3
- Large Eddy Simulation and subgrid turbulence studies (collaborating with Clemson University, Florida International University, and AOML)
- Applying C1536 SHiELD on extreme weather event forecasts with detailed verifications and investigation.
- Updating the current global SHiELD near real-time configuration from C768 to C1536.
- Updating T-SHiELD and C-SHiELD configurations with the global C1536 base.

Atlantic Oceanographic and Meteorological Laboratory (AOML)

The main progress of AOML during the first year of Global-Nest Initiative is on the development of the microphysics scheme in hurricane forecasts and performing the detailed analysis of Madden Julian Oscillation (MJO) forecasts in the GFDL T-SHiELD.

Microphysics parameterization for hurricane forecasts

Figure 1 shows the roadmap to improve the bulk microphysics parameterization in UFS (Unified Forecast System)-HAFS (Hurricane Analysis And Forecast System). The microphysics properties obtained from the microphysics observations including the particle sizes, the hydrometeor categories, the number concentrations of cloud particles, and the PSDs. When combined with other flight level data, the distribution of hydrometeors in the storm-relative context, and the relationship between PSDs and the environment, can be obtained (Leighton et al. 2020).

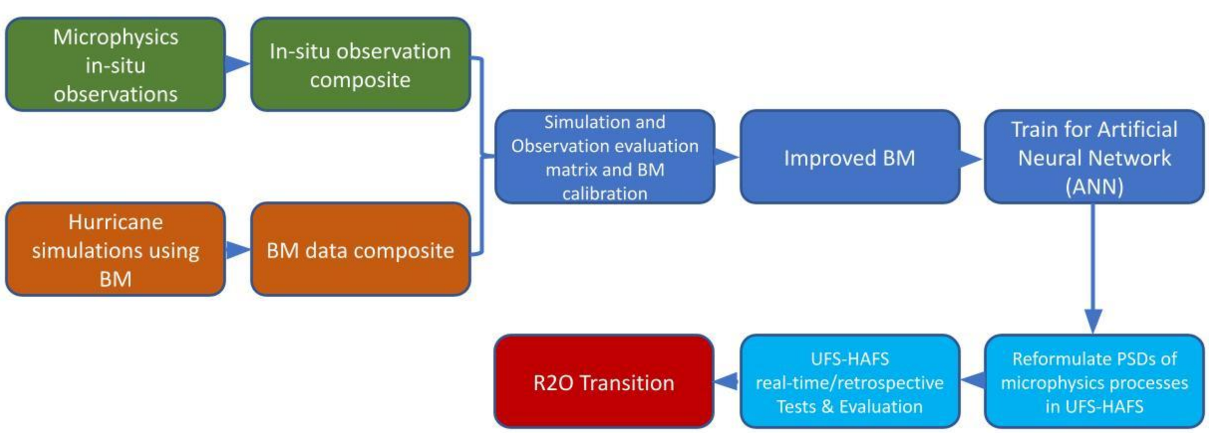

Figure 1 Roadmap to improve the bulk microphysics (BM) parameterization in UFS-HAFS at AOML. (adopted from Xuejin Zhang's presentation in the workshop)

Besides collecting more microphysics observation data and retrieving historical microphysics data from past hurricanes, the code to process the flight microphysics observations was also updated. A prototype of an AI (artificial intelligence)-based emulator is under development to uncover the complex relationship between the prescribed parameters and the environment variables. A paper to investigate the relationship between reflectivity and rainfall rate from rain size distributions in Hurricanes has been published in Geophysical Research Letters (Leighton et al. 2022). The work of improving the representation of raindrop size distributions using in-situ microphysics observations in hurricanes is under review (Leighton et al. 2023)

Madden Julian Oscillation (MJO) forecasts in GFDL T-SHiELD

The MJO is a large-scale convection-circulation couplet that propagates eastward from the Indian Ocean to the western Pacific with an average period of 40-50 days. The MJO is widely known as the dominant mode of tropical variability on subseasonal timescales. The maritime continent (MC) is a particularly difficult region for MJO prediction due to its complex orography, multi-scale ocean-atmospheric interactions, and strong diurnal convection. In this AOML and GFDL collaborative study (Zavadoff et al. 2023), a series of forecasts are produced using a T-SHiELD configuration with a global uniform 16 km resolution grid and a two-way nested nest with a nominal resolution of 4 km covering the Bay of Bengal and the MC. A set of 40-day forecasts were initialized with the operational GFS analysis on a daily basis from October 13, 2011 to November 30, 2011 and February 19, 2012 to March 4, 2012, for a total of 64 forecasts. The results showed that the nested grid reduces amplitude and phase errors and extends the model's predictive skill by about 10 days. These enhancements are tied to improvements in predicted zonal wind from the Indian Ocean to the Pacific, facilitated by westerly wind bias reduction in the nested grid. Results from this study also suggest that minimizing circulation biases over the MC can lead to substantial advancements in skillful MJO prediction.

On-going activities and future plans at AOML

For the development of microphysics parameterization for hurricane forecasts:

- Continue to collect observational data from different scenarios
- Continue to build the Bin microphysics capability
- Build the AI capability
- Port GFDL microphysics version 3 scheme to HAFS with EMC
- Calibrate GFDL microphysics by AI technology
- Implement in operational HAFS

For the MJO analysis:

AOML will continue analyzing and comparing the performance of different SHiELD configurations to the Global Ensemble Forecast System (GEFS), with a focus on long lead times (5-15 days). The model's ability to forecast MJO-related teleconnection patterns will be evaluated. Also, for severe weather events, variables to evaluate the models' forecast skill, e.g. convective available potential energy (CAPE), storm relative helicity, shear, will also be accessed.

National Severe Storms Laboratory (NSSL)

NSSL targets severe convective storm (SCS) subseasonal-to-seasonal (S2S) research in the Global-Nest Initiative. The goal is to connect climate variability or climate change and severe weather events to develop skillful 2-4 week predictions.

There are several on-going research projects at NSSL.

GEFS predictability (Berrington et al. 2023)

An evaluation of 20 years of 11-member GEFS version 12 reforecasts from 2000-2019 has been conducted based on convective parameters and composite indices. A couple of novel analysis methods are experimented, e.g. synoptic weather typing via self-organizing maps. This research tries to identify enhanced predictability periods and sources, and to train statistical models or a machine learning technique for an extended range forecast.

Case study (Hoogewind et al. 2023)

A series of severe weather outbreaks during 10-15 December 2021 has been investigated for understanding the predictability of this event across timescales running from hours to weeks.

Machine learning applications (Clark et al. 2023)

GEFS-based hazard guidance has been assessed in the NOAA Hazardous Weather Testbed (HWT) for the last 3 years with extremely promising results. The basic concept is that ensemble mean environment fields related to severe weather in GEFS reforecasts are trained against local storm reports (LSRs) using the random forest algorithm. Since the GEFS reforecasts have limitations, NSSL has developed its own version of the algorithm to test with 2020-2023 operational GEFS data.

Real-time Severe Weather Monitoring

A real-time severe weather monitoring site is under development:
https://apps.nssl.noaa.gov/s2s-severe/

Future plans at NSSL

NSSL plans to analyze the GFDL C-SHiELD forecasts during 2016-2020 to investigate the forecast improvement of using the 5-km CONUS nest in a global model on severe weather events, and the source of predictability.

NSSL will also continue to work on the S2S HWT severe weather experiments.

Global Systems Laboratory (GSL)

GSL just started their work for the Global-Nest Initiative. Their goal is to improve the prediction of landfalling atmospheric river (AR) events several days out. GSL has developed their global-nest workflow based on HAFS and modified to place a large high-resolution nest to cover most of CONUS and extended westerly to the central Pacific Ocean. However, the large nest configuration is computationally expensive. Based on a developed prototype global-nest domain with the modified GSL physics configuration, 25,000 cores on the NOAA HERA supercomputer are needed for a 5-day simulation. The model workflow has been ported to the GAEA C5 supercomputer which will help the model development progress.

Besides using a high-resolution nest in a global model, GSL also proposed the development of improving ocean coupling and scale-aware physics parameterizations, and enhancing the data assimilation (DA) technique in both global and nested domains. For physics development, starting from using a RRFS (Rapid Refresh Forecast System)-like physics suite, GSL aims to improve clouds and precipitation over the Pacific Ocean. Many parameterizations, including microphysics, sub-grid scale clouds, NSSLconvection, PBL, radiation, and gravity-wave drag schemes, will be updated or developed. The aerosol-aware version of the Thompson microphysics scheme is being developed (in conjunction with the MYNN (Mellor-Yamada-Nakanishi-Niino) PBL and the C3 convection schemes*) to provide physically consistent and realistic clouds, precipitation, and radiation across scales (from 13 km global to the 3-km nest). New warm-rain parameterization developments will also be tested. The goal of this development work is to improve prediction of both large-scale water vapor transport and cloud fields and fine scale orographically enhanced precipitation processes, necessary for the accurate prediction of the timing and overall impact of landfalling ARs.

For AR forecasts, hourly cycled global DA will be critical. Supplementary hourly cycling regional DA on the nested domain could better represent small-scale AR details by accounting for terrain. GSL plans to select 2 - 3 archived cases from winter 2022 - 2023 for retrospective tests which can be used for both physics and DA development. For each retro test, an hourly DA cycle will be applied for multiple days, followed by longer (3-5 day) free forecasts from the cycled initial fields to examine the forecast impact from the enhanced DA.

* The C3 scheme is a result of a collaborative project between GSL, Physical Sciences Laboratory, and EMC. The code base is the GF (Grell-Freitas) scheme, but several features from the SAS scheme have been added, such as recent implementations from Lisa Bengtsson (PSL).

Future plans at GSL

- Develop the aerosol-aware version of Thompson microphysics to be scale-aware
- Develop a prognostic sub-grid scale cloud scheme
- Develop and test new warm-rain parameterizations

Appendix A: Agenda of the 2023 Global-Nested Modeling Initiative Annual Meeting

Tuesday, September 12

1:00 - 1:10 Workshop opening remarks – V. Ramaswamy
1:10 - 1:15 Logistics –Jan-Huey Chen

GFDL Briefing (1:15 - 2:00)

1:15 - 1:30 An overview of the first year Global-Nest Initiative activities in GFDL – Lucas Harris
1:30 - 1:40 Major updates in FV3 Dycore development – Joseph Mouallem
1:40 - 2:00 Major updates in SHiELD model – Linjiong Zhou

AOML Briefing (2:00 - 2:40)

2:00 - 2:20 Hurricane Microphysics Observations and Modeling at AOML: A Progress Update – Xuejin Zhang
2:20 - 2:35 Improved MJO forecasts using the global-nested GFDL SHiELD model – Breanna Zavadoff
2:35 - 2:40 Potential application of SHiELD on the week-2 US tornado forecast – Hosmay Lopez

NSSL Briefing (2:40 - 3:00)

2:40 - 3:00 NSSL Year 1 Activities for GFDL's Global-Nest Initiative – Kim Hoogewind and Adam Clark

GSL Briefing (3:00 - 3:20)

3:00 - 3:20 An Overview of GSL's Global-Nest Model Development and Data Assimilation Initiatives – Anders Jensen and Guoqing Ge

3:20 - 3:30 Break
3:30 - 4:30 Future Plan Discussion

Appendix B: Personnel arrangements

GFDL

FY23 and FY24:

- Federal employee: 3 FTEs (Kaltenbaugh, Elbert, Chen)
- Cooperative Institute for Modeling the Earth System (CIMES), Princeton University: 8 FTEs (Chen, Cheng, Gao, Han, Hu, Mouallem, Yoon, Zhou)
- University Corporation for Atmospheric Research (UCAR): 1 FTE (Morin)

AOML

FY23:

- Federal employee: 3.25 FTEs (Lopez, Lee, Zhang, Black)
- Cooperative Institute for Marine And Atmospheric Studies (CIMAS), University of Miami: 1 FTE (Zavadoff)

FY24:

- Federal employee: 3.25 FTE (Lopez, Lee, Zhang, Black)
- Cooperative Institute for Marine And Atmospheric Studies (CIMAS), University of Miami: 2.5 FTEs (Zavadoff, Kim, Leighton, and a TBD)

NSSL

FY23:

- Federal employee: 0.44 FTE (Hoogewind)
- Cooperative Institute for Severe and High-Impact Weather Research and Operations (CIWRO), the University of Oklahoma: 0.5 FTE (Berrington)

FY24

- Federal employee: 1 FTE (Hoogewind)
- Cooperative Institute for Severe and High-Impact Weather Research and Operations (CIWRO), the University of Oklahoma: 0.5 FTE (Hosek)

All other contributions will be in-kind. (i.e. NSSL Feds, Clark and Galarneau).

GSL

FY23 and FY24:

- Federal employee: 0.5 FTEs (Jensen, Grell)

Appendix C : Contributed publications

GFDL

Chen, J.-H., L. Zhou, L. Magnusson, R. McTaggart-Cowan, and M. Köhler, 2023: Tropical cyclone forecasts in the DIMOSIC project—medium-range forecast models with common initial conditions. Earth and Space Science, 10(7), doi:10.1029/2023EA002821.

Chen, J., K. Gao, L. Harris, T. Marchok, L. Zhou, and M. Morin, 2023: A new framework for evaluating model simulated inland tropical cyclone wind fields. GRL, 50(16), doi:10.1029/2023GL104587.

Cheng, K.-Y., L. Harris, C. Bretherton, T. Merlis, M. Bolot, L. Zhou, A. Kaltenbaugh, S. Clark, and S. Fueglistaler, 2022: Impact of warmer sea surface temperature on the global pattern of intense convection: Insights from a global storm resolving model. GRL, 49(16), doi:10.1029/2022GL099796.

Dahm, J. P., E. C Davis, F. Deconinck, O. Elbert, R. George, J. McGibbon, T. Wicky, E. Wu, C. Kung, T. Ben-Nun, L. Harris, L. Groner, and O. Fuhrer, 2023: Pace v0.2: a Python-based performance-portable atmospheric model. Geoscientific Model Development, 16(9), DOI:10.5194/gmd-16-2719-20232719-2736.

Gao, K., L. Harris, M. Bender, J.-H. Chen, L. Zhou, and T. Knutson, 2023: Regulating fine-scale resolved convection in high-resolution models for better hurricane track prediction. GRL, 50(13), doi:10.1029/2023GL103329.

Harris, L., L. Zhou, A. Kaltenbaugh, S. Clark, K.-Y. Cheng, and C. Bretherton, 2023: A Global Survey of Rotating Convective Updrafts in the GFDL X-SHiELD 2021 Global Storm Resolving Model. JGR: Atmospheres, 128(10), doi:10.1029/2022JD037823.

Kwa, A., S. Clark, B. Henn, N. Brenowitz, J. McGibbon, O. Watt-Meyer, W. A. Perkins, L. Harris, and C. Bretherton, 2023: Machine-Learned Climate Model Corrections From a Global Storm-Resolving Model: Performance Across the Annual Cycle. JAMES, 15(5), DOI:10.1029/2022MS003400.

Magnusson, L., J.-H. Chen, L. Zhou, and coauthors, 2022: Skill of medium-range forecast models using the same initial conditions. BAMS, 103(9), doi:10.1175/BAMS-D-21-0234.1E2050-E2068.

Mouallem, J., L. Harris, and R. Benson, 2022: Multiple same-level and telescoping nesting in GFDL's dynamical core. Geoscientific Model Development, 15(11), DOI:10.5194/gmd-15-4355-20224355-4371.

Zhou, L., L. Harris, J.-H. Chen, K. Gao, H. Guo, B. Xiang, M. Tong, J. Huff, and M. Morin, 2022: Improving global weather prediction in GFDL SHiELD through an upgraded GFDL cloud microphysics scheme. JAMES, 14(7), doi:10.1029/2021MS002971.

Zhou, L., L. Harris, and J.-H. Chen, 2022: In The GFDL Cloud Microphysics Parameterization, Princeton, NJ, NOAA Technical Memorandum OAR GFDL, 2022-002, doi:10.25923/pz3c-8b96.

Zhou, L., and L. Harris, 2022: Integrated dynamics-physics coupling for weather to climate models: GFDL SHiELD with in-line microphysics. GRL, 49(21), doi:10.1029/2022GL100519.

AOML

Leighton, H., Black, R., Zhang, X., Marks, F. D. and S. G. Gopalakrishnan, (2020): Ice particle size distributions from composites of microphysics observations collected in tropical cyclones. GRL, 47, e2020GL088762, doi:10.1029/2020GL088762.

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Zavadoff, B, K. Gao, H. Lopez, S.-K. Lee, D. Kim, and L. Harris, 2023: Improved MJO forecasts using the experimental global-nested GFDL SHiELD model. GRL, 50(6), doi:10.1029/2022GL101622.

NSSL

Berrington, A. H., K. A. Hoogewind, A. J. Clark, and M. Taszarek, 2023: Predictability of Severe Convective Storm Environments in Global Ensemble Forecast System Version 12 Reforecasts. Mon. Wea. Rev. (to be submitted)

Hoogewind, K. A., T. J. Galarneau, V. A. Gensini, E. D. Loken, A. J. Clark, and H. E. Brooks, 2023: Multi-scale predictability of the severe weather outbreaks on 10-15 December 2021. Wea. Forecasting, (in preparation)

Clark, A. J., K. A. Hoogewind, A. Hill, A. Berrington, and E. Loken, 2023: Extended range machine learning severe weather guidance based on the operational GEFS. Wea. Forecasting, (in preparation)