DTC Annual Operating Plan 2021

Director's Office

Director's Office Staff and Non-Salary Expenses

Motivation

The Developmental Testbed Center (DTC) is a distributed facility with components residing at the National Center for Atmospheric Research (NCAR) and the National Oceanic and Atmospheric Administration's (NOAA) Global Systems Laboratory (GSL). In addition to a distributed staff, all DTC activities involve extensive interactions with external partners in both the research and operational communities. The DTC Director is responsible for the overall coordination of DTC activities and maintaining strong ties with the community. Due to the distributed nature of the DTC, the Director must rely on staff at the respective institutions to oversee the staffing, budgets and reporting to assure accountability. The DTC external management structure also requires administrative support for external meetings that goes beyond the day-to-day administrative support for staff contributing to DTC activities.

Project Description

The DTC Director's Office provides administrative and management support for all DTC activities. This support includes: (i) overseeing and coordinating the annual planning process (both internally and externally), (ii) managing and coordinating all DTC activities, (iii) conducting DTC workshops and tutorials, (iv) interacting with DTC partners [e.g., NOAA's National Centers for Environmental Prediction (NCEP) Environmental Modeling Center (EMC), and the Air Force] on collaborative efforts, (v) creating and maintaining the DTC web site, (vi) coordinating the preparation and distribution of a quarterly DTC newsletter, and (vii) providing administrative support for DTC management meetings.

Project Deliverables

- Quarterly reports to EC
- Reports to sponsors
- Quarterly DTC newsletter

Sponsors: NOAA (PoP: 4 May 2021 - 3 May 2022), UFS R2O Project (PoP: 1 July 2021 - 30 June 2022), Air Force (PoP: 1 February 2021 – 31 January 2022), NCAR (PoP: 1 October 2020 – 30 September 2021)

Community Interactions and Outreach

Model Evaluation Tools (METplus) Users' Workshop and Tutorial

Motivation

The enhanced Model Evaluation Tools (METplus) is envisioned to be a community-based, state-of-the-science verification and diagnostics framework designed to accommodate the evaluation needs of the broader community, including students, researchers and developers, educational institutions, federal agencies, and the private sector. To support this goal, it is important to bring together a diverse group of scientists and researchers working on the various aspects of verification, validation, and diagnostics for a range of applications (subseasonal-to-seasonal, medium- and short-range weather, hurricane, space, air quality, etc.) to discuss their experiences with METplus and learn from each other. Inviting the broader community to take part in such a gathering will open up communications regarding the state of METplus, including how it can be used to evaluate the UFS, and provide an opportunity to learn how to contribute to the advancement of this community system, ultimately resulting in forecast improvements. To facilitate the discussions and learning, an in-person METplus Tutorial would provide additional benefit to the participants of this event. This format would be similar to the WRF User's Workshop where the first and last day of the week have traditionally been focused more on training users with in-depth keynote talks (first day) and mini-tutorials on select topics (last day). Hosting a joint tutorial/workshop event will efficiently allow participants to learn about the tools and then see how users in the community have applied them.

The successes achieved in other DTC workshops (e.g., DTC 2021 UFS Evaluation Metrics Workshop and 1st UFS Users' Workshop) will pave the way for the DTC to lead the organization of the 1st Joint METplus Users' Workshop and Tutorial.

Project Description

The DTC proposes to host the 1st Joint METplus Users' Workshop and Tutorial to be held in the winter of 2022 in Boulder, Colorado with additional remote access. It is anticipated that the joint event will be delivered over the equivalent of five days. A planning and organizing committee will be made up of members from the UFS Verification and Validation Cross-Cutting Team, which includes individuals from the academic, government, and private sectors and will strategize how to attract participation from the broader community by providing a diverse workshop agenda with pertinent session topics. The DTC will also communicate closely with the UFS Steering Committee and Working Groups to ensure proper coordination among all relevant and interested parties. The current plan is to host an in-person workshop/tutorial in the early part of 2022, but the exact format and timing will be determined in summer 2021 based on an assessment of the COVID-19 pandemic.

The DTC will provide logistical support for the workshop, such as hosting a workshop website, facilitating event registration, and assuring event participants receive all relevant logistical information. If the workshop is held in a virtual or hybrid format (i.e., virtual and in-person), conferencing services from the UCAR multimedia services will be employed to ensure a smooth online meeting experience. If the event includes an in-person aspect, the DTC proposes to sponsor travel for students and postdocs to participate in the workshop in order to provide opportunities for the next-generation workforce. The DTC will establish and advertise the application process and students will be selected based on criteria put together by the workshop planning and organizing committee with an eye towards providing the broadest community exposure for the UFS. Finally, the DTC will solicit feedback from the workshop participants with regards to improving future workshops through a post-workshop survey.

Project Deliverables

- 1st Joint METplus Users' Workshop and Tutorial
- Feedback survey report for 1st METplus Users' Workshop and Tutorial

Sponsors: NOAA (PoP: 4 May 2021 - 3 May 2022), UFS R2O Project (PoP: 1 July 2021 - 30 June 2022)

Unified Forecast System (UFS) Training

Motivation

The National Oceanic and Atmospheric Administration (NOAA) is looking to engage a wide sector of the numerical weather prediction (NWP) community with the goal of making significant strides towards improving the forecast skill of its Numerical Weather Prediction (NWP) modeling suite. As part of this process, NOAA's operational NWP system is moving towards a unified modeling suite across all spatial (regional and global) and temporal (weather, sub-seasonal and seasonal) scales. At the center of this plan is the Unified Forecast System (UFS), which uses GFDL's Finite-Volume Cubed-Sphere (FV3) as the atmospheric dynamical core. Engaging a broad sector of the NWP community in the advancement of the UFS requires a framework that includes well-defined code management practices (including regression testing protocols), open access to code and datasets, thorough documentation, and active user support. Providing training to educate and engage the user community in this complex system will be essential to NOAA achieving its goal of broad community engagement.

Project Description

In November 2020, the DTC hosted the 1st UFS Medium-Range Weather (MRW) Application training event. This event familiarized the participants with the application components and encouraged them to use and, ultimately, further develop the system within the UFS framework. The DTC proposes to host a 2nd UFS training event during AOP 2021. With the up-coming release of the Short-Range Weather (SRW) Application, the second training will focus on the SRW Application. While the training will be hosted by the DTC, a successful training event will require a strong collaboration with, and contributions, from colleagues at the Environmental Modeling Center (EMC) and other NOAA laboratories (including GSL, GFDL and NSSL). It is important to keep in mind that the funding associated with this proposal only covers the costs associated with the DTC contributions. Prior to committing the DTC to hosting this event, it will be imperative that NOAA identify resources that will support the critical contributions from subject matter experts (SMEs) not affiliated with the DTC, whether through in-kind commitments or separate funding support.

DTC staff will be responsible for initially organizing the structure of the training, including determining the content and organization of the lectures and lining up SMEs to present the lectures. The training materials will cover scientific and technical details for each component, including pre-processing, the atmospheric model, connection to the Common Community Physics Package (CCPP), post-processing, and the application workflow. The training will also provide in-depth information needed for developers to transition techniques from research to operations (R2O), including topics such as code management protocols, adding variables to the output, adding a new physics suite, etc. The DTC will contribute to the associated documentation and training materials needed to ensure the information is clear and concise. DTC staff will also build hands-on practical sessions to foster the learning process. All of the training materials will be made available to the participants during the event through a webpage, which will be opened to public access following the event.

The timing of the training event will be determined through close collaboration with individuals, organizations, and SMEs to ensure it works well for all those involved in the preparation and presentation of materials during the event. As soon as the logistics for timing and content of the training have been determined, including whether it will be an in-person or virtual event, an announcement and associated registration page will be made available to the community. In particular, the DTC will reach out to NOAA-funded principal investigators (PIs) to ensure they are aware of this training opportunity.

Project Deliverables

- Organize 2nd UFS training and announce to the community, with emphasis on NOAA-funded PIs
- Host 2nd Annual UFS training focusing on the SRW applications

Sponsors: NOAA (PoP: 4 May 2021 - 3 May 2022), UFS R2O Project (PoP: 1 July 2021 - 30 June 2022)

DTC Visitor Program

Motivation

Maintaining strong ties to both the research and operational NWP communities is critical to the success of the DTC's mission. The DTC Visitor Program provides an opportunity for the DTC, as well as our operational partners, to develop stronger ties with the research community, as well as serving as a mechanism for making research innovations available for consideration by the DTC's operational partners.

Project Description

The DTC Visitor Program supports visitors to work with the DTC to test new forecasting and verification techniques, models, model components, and DA approaches for NWP and to perform diagnostic evaluations of the current operational systems. It also offers an opportunity for visitors to introduce new NWP and verification techniques into the community codes supported by the DTC. The goal of this program is to provide the operational weather prediction centers (i.e., NCEP and Air Force) with options for near term advances in operational weather forecasting and to provide researchers with NWP codes that represent the latest advances in technology. The DTC offers the opportunity for two types of projects: 1) projects undertaken by the Principal Investigator (PI), and 2) projects undertaken by a graduate student under the direction of the PI. Successful applicants for the first type of project are offered up to two months of salary compensation, and travel and per diem, where the two months could be distributed over several weeks during a one-year period. Successful applicants for the second type of project are offered up to one year of temporary living per diem stipend and travel expenses for the graduate student to work with the DTC in Boulder, Colorado, or with DTC operational partners, and travel and per diem for up to two two-week visits to the DTC by the project PI. Researchers have a year to complete their project. The proposal is to allocate $100 K from the NOAA funds to support the visitor program and submit a proposal to NSF to match this $100 K. From the NOAA funds, $78 K would be allocated to support visitor projects and the additional $22 K would cover computing support costs for the visitors.

Project Deliverables

- Visitor project reports and transition of new NWP technology to community codes, as appropriate

Sponsors: NOAA with potential matching funds from NSF

Community System Support

Data assimilation software support and community engagement

Motivation

All current NCEP global and regional operational modeling systems use the Gridpoint Statistical Interpolation (GSI)/Ensemble Kalman Filter (EnKF) data assimilation (DA) systems, where the GSI with hybrid ensemble-variational (EnVar) DA is used for their deterministic forecasts and EnKF is used for ensemble DA. The DTC currently provides user and developer support for these DA systems and contributes to their code management. NOAA is in the process of pivoting to focus its development efforts on the Joint Effort for Data Assimilation Integration (JEDI) system and will be gradually incorporating this next generation DA system into its operational systems. With the recent public release of JEDI, NOAA is ready for the DTC to ramp down its general GSI/EnKF community support, community developer support, and code management activities.

Project Description

The DTC will ramp down user and developer support and code management for NCEP's two operational DA systems: GSI and EnKF. Through to the end of 2021, the DTC will continue community support activities, including reviewing and testing proposed code changes using the unified Multiple-Platform Multiple-Case (MPMC) testing suite developed by the DTC, providing feedback and suggestions on code development and outreach, hosting visitors, and assisting users with committing their code to the repository. The unified GSI/EnKF authoritative repository is on GitHub and available to the public but the

DTC is maintaining a community fork of the authoritative repository to hold additional libraries and compiling guidance for the general community. The DTC will step back from responding to forum requests and plans to stop responding by 1 October 2021. The current community website and the community fork of the authoritative repository will be updated to capture the evolution of the authoritative repository and then become permanent frozen resources for community users by the end of 2021. After 31 December 2021, DTC will stop all data assimilation software support activities.

This work will be conducted as a collaborative effort between NCAR and GSL.

Project Deliverables

- Data assimilation support for visitors, code contribution, code review/test.
- Ramp down all activities and stop support by 31 December 2021.

Sponsors: NOAA (PoP: 4 May 2021 - 31 December 2021)

Hurricane system software support and community engagement

Motivation

The state-of-the-art HWRF end-to-end system has been supported by the DTC for the past decade. By supporting the HWRF system to the community at large, NCEP receives more feedback on the model's performance, which leads to model improvements. In addition to its use by the community at large, recipients of Hurricane Forecast Improvement Project (HFIP) and the DTC Visitor Program grants rely on a stable code repository and documentation to conduct their research. The HWRF system undergoes substantial annual upgrades that are making great strides towards improving its forecast skill. To ensure a stable code base, strong code management protocols and frequent code integrity tests are critical. To avoid divergence of development efforts and ensure new development can be easily integrated into the centralized HWRF repository, it is imperative that developers work on the same code base that includes the latest changes in NCEP's 2021 version of the operational HWRF model. As NCEP progresses towards the implementation of the hurricane application of the Unified Forecast System (UFS), development efforts for the HWRF system are expected to slow. Increased and distributed development activity is anticipated for the UFS hurricane application, called the Hurricane Analysis and Forecast System (HAFS). In order to ensure distributed development for HAFS sees the same successes as the HWRF system, a code management and support structure that fits within the parameters of the entire UFS effort must be established and disseminated to HAFS developers. Providing strong governance and support will lead to more rapid transition of research developments to operations (R2O) and ultimately to improved HAFS forecasts.

Project Description

This proposal includes software support and community engagement activities for both HWRF and HAFS. A need for continued HWRF support at this time has been expressed, specifically for developer support and code management activities. However, we propose a steady decrease in HWRF support to accommodate increased HAFS engagement between 4 May 2021 and 1 July 2022. The anticipated proportion of funding is 50% HWRF, 50% HAFS on 4 May 2021, with a steady decrease resulting in discontinuation of all HWRF activities by 1 July 2022.

HWRF

Code management

The DTC currently hosts the HWRF code repository, which is comprised of a sophisticated set of scripts plus eight components: WRF atmospheric model, WRF Preprocessing System (WPS), Gridpoint Statistical Interpolation-Ensemble Kalman Filter (GSI-EnKF) data assimilation system, *hwrf-utilities* (which includes several libraries and a vortex initialization package), ocean-atmosphere coupler, MPIPOM-TC ocean model, Unified Post Processor (UPP), and the GFDL Vortex Tracker. The DTC proposes to continue to maintain the HWRF code repository and coordinate the links to all external source code components. Integrity of the HWRF repository will be tested as needed through consistency checks, which are tests to ascertain that code changes not intended to alter the answer of the operational HWRF configuration indeed do not do so. In addition, DTC will continue to maintain the HWRF build system, a set of tools designed to efficiently compile and install all components of the HWRF system. Unforeseen issues that arise from routine High Performance Computing (HPC) maintenance and upgrades and integration of bug fixes from the operational system will be addressed in order to provide an up-to-date and stable system for operational enhancements and/or upgrades and ongoing development. The code management of the HWRF system is the foundation of the HWRF user and developer support activities, and is imperative for all proposed activities described below. As focus of development shifts from HWRF to HAFS, the DTC proposes to lower their overall level of effort for the HWRF system to allow for increased engagement in supporting community engagement with HAFS development.

Developer support

The DTC proposes to continue to facilitate the use of code management tools by HWRF developers who are external to EMC. This facilitation will be done through assistance and repository access for developers, as well as through conducting regression tests and consistency checks on the developments, as applicable. If deemed a high priority, the DTC will make changes to the HWRF system to allow for better usage of the NOAA Jet system (e.g., enabling additional tasks to run on the currently underutilized kjet partition). This effort would only be undertaken if increased utilization of Jet would support HWRF development during the realtime demonstration and the work fits within the resources allocated for HWRF developer support. In addition to code management support for HWRF developers, the DTC will provide developer support by addressing in-depth questions from developers that are posted to the dedicated HWRF Developers' Forum to support cutting-edge research and provide an opportunity for developers to respond to peers. Particular emphasis will be given to supporting remaining HFIP principal investigators in accomplishing the development funded by their grants. Additionally, support for HWRF developers funded by the DTC Visitor Program will be provided, as needed. The DTC will continue to host the HWRF Developers Committee meetings, which is an important mechanism to ensure HWRF developers are aware of important code updates, serves as a platform for information exchange, and ensures that development in the research community is undertaken in a way that is compatible with the operational HWRF model. The HWRF Developers Committee meetings also ensure code commits are well communicated and follow proper code management protocols. Finally, the DTC will maintain the mailing lists used by the HWRF developers and centralize the overall communication among HWRF developers.

It is expected that the majority of HWRF developers will shift to HAFS in the coming year. Therefore, the DTC plans to gradually shift focus from HWRF to HAFS as the community makes this change. Legacy support for HWRF will still be available via web forums.

User support

The DTC proposes to maintain basic support for existing publicly-released systems. The DTC will continue to support users in troubleshooting compilation and run-time issues using the HWRF Users online forum. This support forum, which is separate from the HWRF developer forum, includes all components of the full end-to-end HWRF system for the advertised capabilities of HWRF v4.0a, released in November 2018. As demand for HAFS support increases, HWRF user support will be discontinued. The community-driven web forums for both HWRF user support and the stand-alone GFDL Vortex Tracker will continue to be hosted on the DTC website, but DTC staff will no longer monitor the postings starting 1 October 2021.

HAFS

Code management

The UFS hurricane application (HAFS) development is rapidly evolving, with a targeted operational implementation date in 2022. In order to help meet this goal, increased code management and governance is necessary to ensure the HAFS development is properly coordinated with the larger UFS effort. Establishing clear development protocols following the GitFlow process are critical to assure effective distributed development. Given the nature of the code management for the earth system components (source code and authoritative repositories) within the UFS where the expertise for each component resides at various institutions, the DTC proposes to focus its HAFS code management efforts predominately on the scripts and workflow. In addition to working with our EMC partners to establish and enforce a HAFS governance strategy, the DTC will assist with running regular regression tests following syncs with the authoritative repository to ensure code integrity. To support distributed development, the DTC will continue to test the HAFS system on multiple platforms (e.g. Hera, Orion, Jet and possibly Cheyenne).

Developer support

Developer support for the HAFS system will be focused on developers external to EMC (university and industry focused). The DTC will establish guidance for developers on how best to develop within the HAFS repository and provide training materials on this topic. Support for integrating innovations into the HAFS community repository will be provided. The HWRF Developers Committee meetings will be transitioned to the HWRF/HAFS Developer Committee in order to provide a platform for information exchange on the HAFS system and aid in shifting HWRF developers over to the HAFS system. In collaboration with EMC, the basic developers guide currently under development by EMC will be expanded and made available to HAFS developers. Documentation and training materials will primarily focus on the workflow and the hurricane application itself, rather than the individual components. A dedicated HAFS support forum will be established as part of the UFS Users' Forum, where DTC staff will contribute to the UFS support effort by monitoring the UFS Users' forum and answering questions that fall within the DTC staff's expertise. Support for DTC Visitor Program PIs will remain an important avenue for R2O for HAFS, and will be pursued as community HAFS developers are identified.

Project Deliverables

HWRF

- Unified HWRF scripts and code maintained with code integrity tested through regression and consistency checks, as applicable
- HWRF community user support provided through 1 October 2021 via HWRF Users' forum
- HWRF developer support provided via HWRF Developers' forum

HAFS

- HAFS scripts and workflow maintained with code integrity tested through regression and consistency checks, as applicable
- Support provided to the HAFS community via UFS Users' Forum
- Updated/expanded documentation on using the HAFS workflow available to developers
- New developments contained in HAFS repository branches ready for testing by EMC and DTC staff

Sponsors: NOAA (PoP: 4 May 2021 - 3 May 2022), UFS R2O Project (PoP: 1 July 2021 - 30 June 2022)

Improving the Hurricane Analysis and Forecast System (HAFS) Workflow Usability, Portability, and Testing Capabilities

Motivation

As NOAA and its community partners continue to develop the Unified Forecast System (UFS), workflows are needed that satisfy the requirements of a diverse range of users and developers, including those performing basic and applied research, transitioning research to operations, and working in operations. Researchers desire flexible, hierarchical experimentation and testing that can be used to evaluate modeling systems in general and their innovations in particular. They also require workflows that can be easily ported to university supercomputers and personal workstations with host environments that differ markedly from those used in operations. In contrast, transition-to-operations (T2O) activities require streamlined workflows that can be used to run hundreds of model cycles to determine if a new model configuration results in a forecast benefit. T2O work also requires accurate timing and load balancing information that can be used to perform operational runs efficiently.

As development continues in the Hurricane Analysis and Forecast System (HAFS), the new UFS-based model for hurricane prediction, a flexible, community-friendly workflow is needed that allows researchers and T2O personnel to advance the system. A robust workflow would eliminate the need for each developer to create their own workflow. It also would make T2O more efficient, since operational staff would be able to test research innovations without having to spend time integrating them into the workflow. Ideally, developers also would be able to utilize hierarchical testing capabilities to evaluate their innovations without having to perform end-to-end model runs, saving time and resources. These new tools and efficiency improvements would facilitate forecast improvements by allowing more innovations to be tested in the operational system in less time.

Project Description

The overarching objective of this project is to build a prototype HAFS workflow that will serve the needs of the research, T2O, and operational communities. To meet this challenge, the project team will draw upon three sources of existing infrastructure to build the HAFS T2O workflow: 1) the Configuration manager of Research and Operational Workflows (CROW), 2) the Hurricane Weather Research and Forecast (HWRF) system workflow, and 3) the Community Data models for Earth Prediction Systems (CDEPS). An early goal of the project is to establish an authoritative UFS workflows repository in GitHub that can be used as a centralized source of code and a place to capture requirements for the evolving workflow development effort. Feedback from the community will then be solicited to determine the set of requirements that must be met by the HAFS workflow and the extent to which each of the existing sources of infrastructure are appropriate for addressing those requirements. The GitHub issue tracker will be used for this purpose, with user surveys and small discussions with HAFS developers complementing this information. The collected requirements then will be used to inform a community review of the CROW software to determine its suitability for the HAFS workflow. Representatives from academia, private industry, the National Center for Atmospheric Research (NCAR), the National Weather Service (NWS), and NOAA research will be invited to attend the review. Lectures and live demonstrations will be conducted to familiarize review participants with CROW and the existing HAFS workflow so that they can provide informed feedback.

Once HAFS workflow requirements have been determined collaboratively, the next phase of the project will focus on interfacing either CROW or a CROW alternative (depending on the outcome of the review) with the framework for forcing coupled models with external datasets provided by CDEPS. This capability will allow HAFS developers to use canned atmospheric and oceanic datasets from reanalyses, external models, or field campaigns to force the atmospheric and oceanic model components in HAFS.

This hierarchical testing approach will reduce the number of feedbacks between model components in the coupled HAFS, making it easier for developers to study individual processes in the modeling system by reducing nonlinear process interactions. Close collaboration with NCAR's Climate and Global Dynamics Laboratory staff, who will make the HAFS components CDEPS compliant, will be necessary for this stage of the project to be successful. The resulting prototype HAFS T2O workflow will be capable of benchmark testing that simulates the behavior of an operational workflow. That workflow might resemble the following sequence:

1. Configure and build the coupled atmosphere-ocean-wave model (independent of the initial conditions or ICs).
2. Start the forecast on demand when a tropical disturbance forms. If multiple tropical cyclones are present, trigger more than one set of nests within a single parent or multiple parents, each with a set of nests.
3. Initialize the model (from pre-generated ICs, or with ICs generated through vortex initialization and/or DA, which could involve cycling).
4. Run four cycles a day (0, 6, 12 and 18z) out to 5 days.
5. Rerun the forecast each day until there is no longer a tropical disturbance.

The resulting prototype HAFS T2O workflow may require simplifications, such as starting from prepared initial conditions rather than running a full data assimilation system and/or using one or more static nests instead of moving nests. However, the workflow will be designed with the ability to add these more complex elements easily as the development effort matures.

Project Deliverables

- Establish an authoritative UFS workflows repository in GitHub with CROW code as the starting point, implement a community governance strategy, set up a system for initial and ongoing capture of requirements (e.g., through an issue tracker), and initiate the collection and organization of workflow requirements for UFS and HAFS in particular (Complete).
- Review the design and implementation of CROW with community partners (Complete).
- Demonstrate that the HAFS components can interact with CDEPS for building and running simple forecast model configurations (Complete).
- Plan and document the design of the HAFS T2O workflow for subsequent milestones based on collected requirements and review with technical and scientific partners (Complete).
- Using a combination of CDEPS and CROW (or a CROW alternative), demonstrate a workflow for a HAFS configuration that is suitable for simplified benchmarking that is part of a transition to operations, including the ability to do cycling (without full DA).

Sponsors: Hurricane Supplemental (PoP: 1 July 2019 - 30 June 2021)

CCPP software support & community engagement

Motivation

The Common Community Physics Package (CCPP), which is composed of a library of physical parameterizations (CCPP-Physics) and associated infrastructure (CCPP-Framework), provides an important infrastructure for supporting the research-to-operations (R2O) transition of broad community innovations in physical parameterizations and suites to NOAA's Unified Forecast System (UFS) operational applications in order to improve numerical guidance. CCPP-compliant interfaces have also been adopted for atmospheric composition parameterizations, exemplifying one of the expansions of the CCPP functionalities. The host model-physics interface is provided by the CCPP-Framework, effectively replacing classical physics drivers. It relies on metadata describing host-provided and physics-requested variables together with external files describing physics suite construction to auto-generate this software layer. Although being developed as a model-agnostic component, its initial design was focused around the finite-volume cubed sphere (FV3) dynamical core of the UFS and the CCPP Single Column Model (SCM). The focus has since widened, especially in light of the NOAA-NCAR Memorandum of Agreement, and today the CCPP-Framework is at various stages of integration with the NRL NEPTUNE model, and all NCAR flagship models. The decision to jointly develop and use the CCPP-Framework provides an opportunity to leverage the improvements and additions made by NCAR and the broader research community. Limitations of the current system are being addressed with a next-generation code generator (*capgen.py)*, developed primarily by NCAR's Climate and Global Dynamics Laboratory. It is important that the DTC remains part of the CCPP-Framework development effort to assist and direct the work in a way that ensures an optimal solution for the UFS. Particular concerns are runtime performance and memory consumption, but at the same time user-friendliness tailored to the needs of NOAA internal (e.g., at EMC) and external developers. The CCPP-Physics has undergone rapid development and all physics development for the UFS has transitioned to the CCPP. Its leading role in the initial development of the CCPP, and its extensive expertise with the package, make the DTC the ideal organization to continue to engage in development and support of this critical piece of infrastructure. Steady management and curation of the repositories will result in consolidation of the CCPP use at EMC and the broader UFS community and facilitate a smooth transition to operations.

Project Description

The DTC is proposing to continue to collaborate with EMC and physics developers to make physics available for the community to use and improve. The *ccpp-physics* and *ccpp-framework* code repositories will be maintained by DTC staff and code management and governance will facilitate community contributions, including in the area of atmospheric composition. Regression tests will be conducted before contributions are accepted to maintain code integrity and platform portability. The DTC will work with primary code developers and other distributors of CCPP-compliant atmospheric physics, such as NCAR, to minimize duplication of parameterizations.

One new major community release of the CCPP will be distributed to support the needs of the various UFS applications. If needed, a minor release can be provided to incorporate bug fixes and minor updates. With each release, extensive pre-release testing will be performed. Updates to the technical and scientific documentation will be made available to the user community with each release. User support will be provided through an online forum, and DTC staff will prioritize support for projects funded by or of interest to NOAA.

The DTC will create tools to aid CCPP usability, such as the generation of a "map" of how a variable is used in a suite and a logger/error handler that replaces writing to stdout/stderr and captures stacktraces, both of which will be facilitated by the transition to the next-generation code generator. Furthermore, the DTC will continue to modernize and improve the code with further compliance to standards.

Project Deliverables

- Support to EMC in using CCPP for research and operations in the UFS.
- Code management and governance for the *ccpp-physics* and *ccpp-framework* repositories.
- Transition of selected advancements in the CCPP-Framework developed by NCAR such as the next-generation code generator to the UFS.
- One major public release with updated documentation, online tutorial, user and developer support.
- Tools to aid CCPP usability.

Sponsors: UFS R2O Project (PoP: 1 July 2021 - 30 June 2022)

Develop robust testing for CCPP-framework to ascertain portability and assure that innovations do not harm existing capabilities

Motivation

A software testing framework that will furnish robust testing results as development of the CCPP continues is required, where automated testing of software can provide high confidence in the software produced by community and operational contributors. Such a testing framework should include basic unit testing and portability, as well as functional and computational testing of integrated atmospheric models. While such development would benefit the CCPP-framework immediately, it will become crucial in the near future as more and more modeling systems will be using the CCPP, with different organizations developing the CCPP-framework simultaneously. Opening the use and development of the CCPP-framework and CCPP-physics to the community is expected to increase the number of systems and compilers that need to be supported, and at some point, will become infeasible to test manually.

Project Description

Initial work will focus on establishing an automated unit testing environment that can run nightly, as well as be triggered for all code change requests. The tests will utilize the continuous integration (CI) capability provided by the Travis CI platform available with github.com. The auto-generated code will be included in this testing, where the tests will create simple caps and run tests to verify code integrity.

Additional work will focus on functional testing of existing model system capabilities, including the FV3 integration with CCPP. This testing will need to be able to run on multiple platforms. To facilitate broader community engagement, the testing framework will also provide the ability to include additional host models that are CCPP compliant. The addition of tests for these host models would be the responsibility of those groups. The goal of this work will be to easily re-build baseline results, and test multiple compiler vendors and multiple configurations. The integration of this work with the existing code management practices for the UFS Weather Model will also be included as part of functional testing.

In addition to the tests described above, computational efficiency tests will include run-time performance metrics and assessments of the memory footprint using baseline configurations and computing platforms. Various methods will be used to compare the new results against the baselines, including direct bit-for-bit match, as well as statistical equivalence.

Project Deliverables

- Unit testing framework integrated with repository for continuous integration testing (Complete).
- Unit testing framework extended to include functional and regression tests.
- Capability to evaluate computational performance included in the testing framework.

Sponsors: Hurricane Supplemental (PoP: 1 August 2019 - 31 July 2021)

CCPP SCM software support & community engagement

Motivation

The CCPP SCM plays two critical roles for UFS physics development and testing. First, within the physics Hierarchical Testing Framework (HTF), it serves as a simple and economical platform for understanding interactions among physics schemes within a suite. Second, it serves as a simple host model for rapidly developing and testing CCPP-compliance. Given these roles, it is important that the SCM code keeps pace with changes within the CCPP-physics, CCPP-framework, and the UFS Atmosphere model component. Further, periodic public releases together with comprehensive documentation and tutorials provide a consistent link with both the research and operational communities and help to foster these communities' joint participation in UFS development and evaluation activities.

Project Description

While the companion hurricane supplemental funded SCM project (see AOP2021-SW-HU-SCM: Complete the development and implement version 1 of the Hierarchical Testing Framework) focuses on the development of new features, capabilities, and improving the CCPP SCM user interface, it does not provide for the support of existing capabilities or routine software updates necessary to stay up-to-date with the expanding CCPP or UFS Atmosphere. One of the primary goals of this project is to continue to provide such updates to the authoritative GitHub repository on an as-needed basis throughout the performance period. Support to the community will be facilitated via the use of online forums, updates to the DTC website, an online tutorial, and updates to existing documentation. A public release coinciding with one major CCPP public release will provide a stable version for the growing user base. CCPP SCM code management and governance will facilitate community contributions, leveraging (and a part of) the general CCPP governance being established.

Project Deliverables

- CCPP SCM regression tests to maintain integrity of repository.
- CCPP SCM community repository with clear governance and leadership in the code management, as part of a general CCPP governance.
- CCPP SCM user and developer support, including updates to website describing supported capabilities and online tutorial.
- CCPP SCM public release.
- CCPP SCM interface consistent with advances in ccpp-physics, ccpp-framework, and UFS Atmosphere.

Sponsors: UFS R2O Project (PoP: 1 July 2021 - 30 June 2022)

Complete the development and implement version 1 of the Hierarchical Testing Framework

Motivation

NOAA has identified atmospheric physical parameterizations as one of the important areas targeted for focused investment and development with the goal of advancing its Unified Forecast System (UFS). As part of this strategy, NOAA programs have funded the development of the Common Community Physics Package (CCPP), a library of parameterizations and suites that is supported to the community and can be used for testing and development through the use of software interfaces created by the CCPP-framework. Parameterizations accepted for inclusion in the CCPP encompass both operational suites and innovations intended for operational consideration.

Intrinsic to the CCPP is the concept of Hierarchical Testing Framework (HTF; also called Hierarchical System Development), where parameterizations should be assessed using several "tiers" of modeling configurations, arranged in a simple-to-complex hierarchy, where the CCPP Single Column Model (SCM) is one such tier. Testing a physical parameterization innovation within the HTF structure allows one to objectively address how well it represents the physical processes it was designed to encompass in relative isolation from parameterizations for other processes. This capability is important because parameterization suites are often tuned/optimized as a package, such that better overall skill is achieved sometimes through compensating errors within different parameterizations in the suite, rather than optimal performance of each physics scheme. The sequential addition of model feedback adds levels of complexity to the interpretation of results as testing proceeds toward a potential operational (and thus more complex) configuration. Results of testing provide information for ongoing and iterative model development and improvement.

Project Description

Developing the capability to run the CCPP SCM using an arbitrary subset of a physics suite, from standalone parameterizations through full CCPP physics suites, involves modifications to existing CCPP suite definition files (SDFs). This development also involves either an augmentation to forcing data to account for the parameterization tendencies that have been turned "off", or the addition of replacement interstitial parameterizations that provide variables needed for the parameterizations that remain "on". Initialization and forcing of the SCM are provided by atmospheric profiles from model output, and/or field program data sets, and/or synthetic data.

Model output in the form of the necessary profiles and tendencies for the SCM will be generated from the CCPP components of the UFS Atmosphere model, where these profiles will then be used to drive the SCM in whatever configuration is necessary to explore the response of a given subset of physics, from standalone parameterizations to full physics suites. Should these model-generated profiles coincide with the occurrence of a field program, additional process-level verification measurements would be available for model (SCM) validation in addition to the typical NWP profile observations.

Field program data sets will also provide the necessary forcing to drive the SCM, and the validation information to evaluate the SCM behavior and performance. The current set of observational cases for the CCPP SCM include maritime shallow and deep convection, stratocumulus-to-cumulus transition maritime cases, and continental shallow and deep convection. This set of cases will be augmented with additional field program data sets to greatly broaden the range of meteorological and climatic regimes to be used for physics testing, with input solicited from physics developers. Similarly, synthetic data sets will be used to examine the response of the model physics for "typical" (realistic) atmospheric conditions, as well as for more extreme cases thereby providing a "stress test" for parameterizations. Other synthetic data comes from Large Eddy Simulation (LES) numerical experiments, where LES model output can then be used to understand the characteristics of turbulence and convection at various scales, and thereby help to better estimate (and bound) terms in boundary-layer and convective parameterizations. As such, SCM-based analysis will be complemented using readily available pre-computed LES output where available (e.g. with field campaign-based cases). We will also explore the possibility of adding a publicly-available LES model to the HTF in order to generate synthetic observations for SCM analysis where pre-computed LES data is not available.

In its current state, the CCPP SCM utilizes separate scripts to prepare case input and forcing data prior to running the model via the command line and separate (unsupported) scripts for analyzing its output. Combining these functions into one software package will lead to a more usable, cohesive tool and put this software on par with what is done at other global operational centers. The software should have the ability to ingest prepared data, visualize it as necessary, and provide for its easy modification prior to running an experiment. Given its relatively low computational requirements, a SCM model run may be completely configured, executed, and initially plotted and analyzed from within a single user interface. More in-depth analysis will be facilitated by outputting a common (netCDF) format for potential inclusion into a third-party software package.

Project Deliverables

- Code capability and documentation for driving SCM using UFS Atmosphere input/output
- Code capability and documentation for additional SCM field campaign cases (Completed)
- Demonstrate/Document running SCM with arbitrary physics subset

- Code capability and documentation for SCM visualization/analysis
- Initial LES capability in Hierarchical Testing Framework
- Community release of integrated Hierarchical Testing Framework

Sponsors: Hurricane Supplemental (PoP: 1 August 2019 - 31 July 2022)

Unified Forecast System (UFS) Short-Range Weather (SRW) Application software support & community engagement

Motivation

The Unified Forecast System (UFS) is a community-based, coupled, comprehensive Earth modeling system. The UFS applications span local to global domains and predictive time scales from sub-hourly analyses to seasonal predictions. The UFS is designed to support an active research program and to be the source system for NOAA's operational earth system prediction forecasts. Engaging a broad sector of the NWP community in the advancement of the NOAA modeling suite will require a framework that includes well-defined code management practices (including regression testing protocols), community access to code and datasets, documentation, and user support.

Given the cultural differences between the research and operational communities, defining a framework that meets the needs of both groups is not necessarily straightforward. The research community needs flexible and simple tools that support basic research and allow graduate students to quickly engage and pursue research projects. In contrast, EMC requires software infrastructures that minimize performance impacts and failures. As the NWS looks to its key national partners (i.e., NOAA research laboratories, NCAR, Navy, NASA, and the academic community) to join in an effort towards a unified modeling system, it will be important to clearly define a framework that meets the needs of all these groups. Due to its distributed nature, DTC staff are well connected with on-going efforts at NCAR and ESRL directed at unifying modeling efforts and engaging the research community. DTC staff also have well-established relationships with EMC staff and are aware of the needs of the operational community.

To optimize the use of available resources and to maximize the return on investment over the long term, it will be important to carefully assess the best approaches for setting up and effectively supporting a community modeling infrastructure that meets the needs of the research and operational communities. To engage the broadest aspects of the research community, such an infrastructure will also need to support two tiers of contributors: 1) developers who will need to engage directly with the code repositories and have active communication mechanisms to allow timely sharing of information across all development groups, and 2) general users conducting research with a public release of the code.

Project Description

The UFS Short-Range Weather/Convective-Allowing Model (SRW/CAM) capability is undergoing rapid development in an effort to advance the limited area model (LAM) version of the FV3. A number of operational and research partners are collaborating on this quickly-evolving code base to continually advance the system, with the DTC contributing as a leading developer of the workflow scripts. This accelerated development is expected to continue through the anticipated 2024 operational implementation of the Rapid Refresh Forecast System (RRFS) that will be based on the FV3-LAM. To ensure success, the need for robust governance of repositories and extensive regression testing is critical. Several foundational pieces for maintaining the UFS SRW Application have been established, including all component repositories openly accessible through Github with associated code management plans and code review committees established for each associated repository. Due to the multiple facets and large scale of this system, improvements to the governance process for the DTCmanaged regional_workflow and ufs-srweather-app repositories will be made throughout the next PoP based on experience with the process throughout the year. In addition, communication is key, thus, regular engagement with relevant UFS working groups/application teams will continue so the DTC UFS SRW App team can remain aware of relevant activities happening across the UFS enterprise.

It is also essential to regularly maintain and enhance a series of regression tests to ensure the scripts remain in a working state after each commit to the regional_workflow repository. As mentioned above, while the code management for software packages used by the workflow is handled by external repositories for each component, the DTC will remain responsible for ensuring regression tests for each task defined within the end-to-end UFS SRW Application (currently including the forecast model and pre- and post-processing components) are sufficient and are expanded as new capabilities are introduced over the next year (including functionality related to data assimilation, ensemble framework, and verification tasks). The regression tests will be maintained across the supercomputing platforms readily available to the DTC, which will also ensure portability across this subset of systems, and will be made available for community users to run on additional platforms of interest. As development of the UFS SRW Application continues, consideration will be given priority to allow the community workflow to run as seamlessly as possible on different supercomputers with a simple change to a user-defined machine variable. The DTC will also assist community developers with the governance protocol when the developers would like to contribute scripts and utilities to the regional_workflow repository. As contributions are made to the SRW Application, requirements will also be placed on maintaining existing documentation to update or include any new information necessary for each commit.

User support will continue to be offered for both developers and the general community through the web-based UFS Users' Forum. DTC staff will contribute to answering questions within their area of expertise, while non-DTC Subject Matter Experts (SMEs) will monitor and address questions related to their specific components.

Due to the state of rapid development on this effort, the DTC will work closely with EMC, the UFS SRW/CAM Application Team (AT), other NOAA laboratories, and EPIC to ensure the scope of the work plan evolves in an appropriate manner that satisfies requirements for both the operational and research communities.

Project Deliverables

- Community UFS SRW Application repository review committee led by DTC staff as defined in the developed code management protocols
- End-to-end regression test updated and enhanced for the community UFS SRW Application repository
- Community UFS SRW Application enhanced with new tasks as development of a full system matures
- Regular regression testing conducted on a variety of platforms
- SRW Application documentation updates coordinated with developers for all major commits to the repository
- UFS Users' Forum (CAM Application portion) monitored and questions answered as needed to facilitate community support

Sponsors: NOAA (PoP: 4 May 2021 - 3 May 2022)

UFS Medium Range Weather App software support & community engagement

Motivation

Through the NOAA Research to Operations (R2O) project, NWS is looking to engage a wide sector of the numerical weather prediction (NWP) community with the goal of making significant strides towards improving the forecast skill of its global weather prediction model. Engaging a broad sector of the NWP community in the advancement of the NOAA modeling suite will require well-defined code management practices (including regression testing protocols), community access to code and datasets, documentation, and user support. For the past year, the DTC has been working closely with UFS Medium Range Weather Application (MRW App) developers and has contributed to two public releases (v1.0.0 in March 2020 and v1.1.0 in October 2020). This work has focused on the development of a portable community-friendly atmosphere model that is also used for operations, as well as the associated documentation. Key contributions from the DTC have been in the area of UFS Weather Model (WM) code management, with updates to the regression tests (RTs) and the establishment of the NCAR Cheyenne, NOAA Jet, and NOAA Gaea as additional Tier 1 platforms, that is, platforms on which regression tests (RTs) are regularly conducted. DTC is the primary group performing RTs on Gaea and collaborates with EMC in conducting them on Cheyenne and Jet. The RTs conducted on Cheyenne are particularly important because they constitute the only RT set that invokes the GNU compiler, which is critical for cloud-computing applications. In addition, DTC has staged datasets for the RT on the Amazon Simple Storage Service (S3) platform, a first step to enable the community at large to conduct RTs on their own, which will reduce the burden of the WM code managers and streamline transition to operations.

Project Description

In the next PoP, code integrity will continue to be maintained through contributions to the WM code management, including coordination with other UFS code managers to advance the code base, review of proposed innovations, enhancement to RTs with removal of deprecated configurations and addition of new ones, execution of RTs on Gaea (DTC primary), Jet, and Cheyenne, and maintenance of the software stack on selected platforms used by the UFS community.

The DTC will contribute to a new community release of the MRW App. Updates to the technical and scientific documentation will be led by DTC, with contributions from non-DTC subject-matter experts (SMEs), and made available to the user community. The DTC will also be a key contributor to the pre-release testing.

The DTC will continue contributing to the MRW App support effort by monitoring questions posted to the UFS Users' Forum and providing responses to those questions that fall within the DTC staff's expertise. Non-DTC SMEs for each component of the MRW App are expected to provide more in-depth support for their specific components. DTC staff will prioritize support for projects funded by or of interest to NOAA.

As the complexity of the MRW App increases with new capabilities, such as coupling with the ocean, sea ice, and waves, as well as data assimilation, additional resources, whether at the DTC or undertaken by another entity, will be needed to provide a consistent level of support. Additional resources would also be required to extend support to encompass support for developers to add new capabilities to the MRW App, as the scope of this proposal is limited to supporting users in exercising existing capabilities.

Project Deliverables

- Support the community in using the UFS Medium-Range Weather Application releases.
- Support EMC in the preparation of one release of the UFS Medium-Range Weather Application.

Sponsors: UFS R2O Project (PoP: 1 July 2021 - 30 June 2022)

UPP software support & community engagement

Motivation

To serve as a bridge between operations and research, the DTC provides a framework for the two communities to collaborate in order to accelerate the transition of new scientific techniques into operational weather forecasting. This framework is based on software systems that are a shared resource with distributed development. The current operational systems are a subset of the capabilities contained in these software systems. Ongoing development of these systems is maintained under version control with mutually agreed upon software management plans. The Unified Post Processor (UPP) is one such system the DTC supports to the community to facilitate operations to research (O2R) and research to operations (R2O) transitions. The UPP provides the capability to take raw model output and compute a variety of diagnostic fields and interpolate to pressure levels or other vertical coordinates. Output from the UPP is in National Weather Service (NWS) and World Meteorological Organization (WMO) GRIB2 format and can be used directly by visualization, plotting, or verification (e.g. Model Evaluation Tools (MET)) packages, or further downstream post-processing (e.g. statistical post-processing techniques). Currently, the UPP is used in operations with the Global Forecast System (GFS), Global Ensemble Forecast System (GEFS), North American Mesoscale (NAM), Rapid Refresh (RAP), High Resolution Rapid Refresh (HRRR), Short Range Ensemble Forecast (SREF), and Hurricane WRF (HWRF) applications. In addition, the UPP is being implemented as the post-processing component for Unified Forecasting System (UFS) applications, including the Medium Range Weather (MRW) and Short-Range Weather (SRW) applications. Given the UPP will be an important component of the public releases for these applications, it is essential that community support for the UPP continues.

Project Description

The DTC proposes to continue to collaborate with EMC to make the UPP tool available to the research community. The UPP repository will be maintained by DTC staff in coordination with EMC staff in a manner such that updates and enhancements may be contributed by, and shared between, both the operational and research communities. The code management plan will continue to be updated in coordination with EMC to reflect related changes to code development and contribution procedures as they evolve. The DTC will continue to be a critical contributor to UFS public release preparations for the UPP component, as well as providing user support and facilitating post-processing and diagnostic investigations and advancements through O2R and R2O efforts. Community release(s) of UPP will be distributed in coordination with UFS application releases, with bug fix release(s) distributed as needed. The proposed tasking and associated budget described here plans for contribution to one major and one minor release of a UFS application that includes UPP during the period of performance. With each release, extensive testing of UFS-Atmosphere NEMSIO and NetCDF output will be performed and the full suite of tests will be run on computing platforms available to the DTC using a variety of compilers. The DTC will work with EMC to progressively expand the set of shared tests that can be used to test portability, as well as bit-for-bit regression testing on operational systems. DTC staff will also work with non-EMC contributors to add new tests to ensure proper function of newly integrated capabilities, as needed. Updates to documentation (including the UPP User’s Guide and appropriate sections in the users’ guides for the UFS applications, online tutorial, wiki, etc.) will be made available to the community with each release or as needed. Documentation alignment with UFS applications and public releases will continue as existing and new UFS applications with a UPP-based post-processing component are released. The existing UPP container will be updated with new releases and made available on Github, with corresponding documentation on how to use it added to the UPP website. User support for UFS applications will be provided by the DTC through the online UFS forum. While forum usage is still spinning up, an emphasis on populating the UPP forum with useful information and previously encountered frequently asked questions will be made a priority to provide additional upfront resources for information. Emphasis for user support will be placed on supporting principal investigators focused on diagnostic or process-oriented evaluations to ensure new developments within the post-processing software are made available to both operations and the research community. The DTC's UPP team will continue training on UFS applications as they are developed in an effort to provide support for those applications upon release. The DTC will continue to collaborate with EMC on the re-engineering of the UPP code base with DTC's involvement focused on reviewing code development, beta testing as progress is made (especially in regards to portability), ensuring community needs are represented, and taking on other community-pertinent tasks mutually agreed upon by both the EMC and DTC teams.

Project Deliverables

- Code releases aligned with UFS community application releases; including updated corresponding documentation
- Community user support, including: general support through the UFS online forum and developer-focused on as-needed basis
- Assistance with EMC's UPP re-engineering effort with emphasis on testing to ensure portability
- Revised code management plan that reflects new repository and contribution procedures
- Collection of use cases for regression testing
- Updated Docker container

Sponsors: NOAA (PoP: 4 May 2021 - 3 May 2022)

DTC METplus NOAA Community Support and Development

Motivation

The Model Evaluation Tools (MET) was developed by Developmental Testbed Center (DTC) over a decade ago to provide state-of-the-science verification tools to the atmospheric science community. MET consists of a series of tools designed to help users with pre-processing, data inspection, and calculation of both traditional and spatial statistics. Aggregation of those statistics and attributes can be performed using the MET analysis packages or through the accompanying METviewer and METexpress database and display systems. METplus is the Python-based framework around the components and includes wrappers for each tool and libraries to provide low-level workflow between the tools

The DTC METplus team has been collaborating with other verification and diagnostics teams on developing the unified verification framework called METplus, with MET, METviewer, and METexpress at its core. There are also underpinning components to the database, analysis, and display systems including METdatadb, METcalcpy, and METplotpy. METplus projects with NOAA provide the foundation of a unified verification capability for the Unified Forecast System (UFS). It should be noted that work has also begun to determine how METplus fits into NCAR's System for Integrated Modeling of the Atmosphere (SIMA). Both the UFS and SIMA efforts feed directly into the NCAR-NOAA Memorandum of Agreement (MOA).

During 2020, the METplus development community expanded beyond NCAR, NOAA Global Systems Laboratory (GSL), and NOAA Environmental Modeling Center (EMC). Additionally, the US Air Force (AF) has adopted aspects of METplus for its operational use and the Naval Research Laboratory (NRL) is working on adopting METplus and has started to contribute capability in the areas of Aerosols, Data Assimilation, and Ensembles. Finally, the Met Office of the United Kingdom and Unified Model partners, such as the Australian Bureau of Meteorology and South African Weather Service, are in the process of migrating to METplus and plan to contribute to it. With this expansion of the development community, the necessity of a well-supported infrastructure and governance to ensure code viability and integrity is paramount. Community contributions to METplus outside the DTC Charter members will be provided through explicit funding and in-kind contribution from those organizations.

Project Description

This proposal includes work performed through the DTC's core NOAA/OAR and UFS R2O funding. Overall, the DTC METplus community software support and development will be focused on serving the needs of NOAA, NCAR, and the USAF users, along with the broader research community. This proposal includes the work to further align METplus with the UFS infrastructure and making it more accessible to the entire UFS community. To do this, the DTC needs to provide support to users and contributors, governance for inclusion of methods under the METplus framework, development of additional capability to support the ensuing fully-coupled UFS, and the maintenance and packaging of the METplus code for coordinated releases. OAR funding will be used for Community Support, Governance, Code Maintenance, and Releases. UFS R2O project funds will be used for METplus Development.

Support: METplus is the last DTC package to move completely away from help desk to forums due to the rapidly expanding community and active nature of the user community via help desk, so there will be some focused help desk support during CY2021-22. A METplus forum will be developed and released in Qtr1-2 CY2021 with the full transition to the forum by Qtr 2 CY2022. Help desk/forum support for NOAA users, as well as Office of Science and Technology Integration (OSTI) and Weather Program Office (WPO) contributor support, will be provided by this project.

Governance, Code Maintenance, and Releases: Another activity of this project will be to provide public releases of METplus to the community. Over the past two years, much of the work associated with preparing for releases has been absorbed by individual METplus projects. If an enhancement is added by a project external to the DTC, the unit test and documentation for that feature (or use case) is added as part of that project. Additionally, we have moved our testing activities to GitHub Actions, which performs continuous integration testing every time there's a pull request to add something to the repository. However, a cohesive activity is still needed to bundle up the code, ensure consistency across tools and wrappers, develop and test installation procedures, make sure all aspects of the release are documented, physically tagged, and made available on the DTC website. DTC must fill that role. A governance group has been formed to include the core contributing organizations to METplus, including NCAR, GSL, EMC, NRL, and Met Office. During a recent governance meeting, the group recommended that the METplus team should maintain the release schedule of one to two major releases per year to allow the community to have expeditious access to new verification and diagnostic methods during the rapidly evolving unification activities both at NCAR, NOAA, and other entities. All releases will include final packaging of code, documentation (both downloadable and on-line), and updates to the online tutorials.

The transition to community development requires a shift in activities to continue to open up the METplus infrastructure to contributions from external partners. Initial progress on this task has been made but additional activities are necessary to solidify the framework, including: 1) repository maintenance; 2) supporting collaborators in the addition of the manage externals cap to their contributed packages; 3) maintenance of continuous integration testing for pull requests to the GitHub repositories; 4) maintenance and expansion of systems to check to see if the contribution is accompanied by sufficient documentation; and 5) augmentation of required tests used in the nightly builds.

Development: The METplus framework is broken into several components to allow for the most flexible application of the tools and interoperability with other applications. There are now seven repositories, including the METplus umbrella repository with wrappers and use-cases, MET (core statistical tools), METviewer (deep-dive data analysis), METexpress (pre-defined plots), METdatadb (database and tools), METcalcpy (calculations necessary for analysis), and METplotpy (plotting routines). The repositories are drawn together as the METplus evaluation framework using manage_externals, developed by the Community Earth System Modeling (CESM) project. The DTC will be responsible for the development of the core METplus tools, as needed, based on the priorities set forth by NOAA collaborators. The development listed above is intended to continue to advance METplus for use in the evaluation of the coupled UFS while serving the needs of the individual UFS application teams, such as the Short Range Weather (SRW), Medium Range Weather (MWR), and others. Jason Levit, the Verification, Post-Processing, and Product Generation Branch Chief at EMC, has prioritized global ensemble verification, Subseasonal-to-Seasonal (S2S), process-oriented diagnostics, and initial coupled model evaluation for CY2021-2022.

Development will be optimized through coordination with other core contributors (e.g., NCAR, AF, NRL and Met Office). Examples of development include: 1) enhancing MET to provide integrated capability for computing statistics and diagnostics that require use of the MET libraries and configuration options; 2) enhancing the user interfaces of METviewer and METexpress to improve usability and add functionality; 3) continued enhancements to loading features of METdbload and exploration of a federated database of distributed METdatadb instances for use by the user interfaces; 4) expansion of the METcalcpy computation layer and METplotpy plotting layer for use by the user interfaces, as well as on the command-line; 5) expansion of plotting functionality to incorporate visualization options driven by community contributions and user needs; and 6) a concerted effort to fully leverage the interfaces between METplus and the Unified Post-Processor (UPP) and Joint Effort for Data assimilation Integration (JEDI).

Outreach: We propose to hold the 1st Annual METplus User's Workshop, which is described in a separate narrative. Beyond this, METplus leads will participate in appropriate UFS and Community activities as needed and appropriate. These activities will include the UFS Verification and Validation Application Team (V&V AT), UFS R2O Cross-Cutting Infrastructure (CCI) Team, American Meteorological Society Probability and Statistics Committee, and others. The METplus team will also make 1-2 presentations at appropriate conferences.

Project Deliverables

- METplus helpdesk and forum for the NOAA community (NOAA)
- Priority contributor support of 3-6 OSTI and WPO funded projects targeted for METplus integration (NOAA)
- METplus releases, bug fixes, documentation, and on-line tutorials (NOAA)
- Maintenance and review of community repository governance (NOAA)
- Two to four (2-4) new features per core component (MET, METviewer, METexpress, METplotpy and METcalcpy, METdbload) (UFS R2O)
- Two to four (2-4) METplus use-cases per year for UFS priority applications (UFS R2O)
- Early prototype of a federated database system using two databases (UFS R2O)
- 1-2 presentations at appropriate conferences (UFS R2O)

Sponsors: NOAA (PoP: 4 May 2021 - 3 May 2022), UFS R2O (PoP: 1 July 2021 - 30 June 2022)

DTC NCAR Base METplus Community Support and Development

Motivation

The Model Evaluation Tools (MET) were developed by the Developmental Testbed Center (DTC) over a decade ago to provide state-of-the-science verification tools to the atmospheric science community. The goal was to develop a framework that included both traditional statistics and new approaches while also making it platform independent and extensible. Advanced verification techniques that were incorporated into early versions of MET were developed under NCAR base funding. The initial funding for MET development came from the Air Force, with NCAR and NOAA supporting the development a year or two later. In recent years, the tools have been extended into a unified verification, validation, and diagnostic framework called METplus, which encompasses Python wrappers to provide low-level automation, database and display systems for analysis, and a suite of Python-based libraries to replace the R-statistics computation and plotting layer within the framework. This project is focused on continued development and support of METplus to address the needs of the community.

Project Description

In addition to supporting the research community, the DTC METplus team has been incrementally preparing METplus to provide, in the 2-5-year timeframe, capability to evaluate coupled model frameworks such as NOAA's Unified Forecast System (UFS) and NCAR's System for Integrated Modeling of the Atmosphere (SIMA). These efforts feed directly into the NCAR-NOAA Memorandum of Agreement (MOA) for developing common infrastructure when possible. While each of the DTC partners provide funding support for METplus, the work described in this proposal focuses on serving the needs of NCAR and the broader research community. The scope of this work includes code management, support and training, and METplus development to incrementally advance METplus toward full support of coupled-model evaluation.

One activity of this project will be to provide public releases and repository maintenance of METplus to the community. Much of the work associated with preparing for releases has been absorbed by external METplus projects. If an enhancement is added by a project external to the DTC, the unit-test and documentation for that feature or use-case are added as part of that project. However, there still needs to be one place to bundle up the code, perform cross-platform testing, make sure all aspects of the release are documented, and physically make the tag and release available on Github. The DTC fills that role by overseeing repository governance procedures and using continuous integration (CI) framework to provide additional software integrity assurances. It also coordinates online assets such as User's Guides, tutorials, and training videos. Costs of these support activities will be shared proportionally between NCAR and NOAA. Currently, the AF project contributes to the release by supporting resources for Fortify cybersecurity compliance.

The METplus team is slowing the release cadence from once per 5-8 months to 9-12 months to allow the community to have expeditious access to new verification and diagnostics while hopefully not overwhelming the operational community. This fiscal year, there will be one coordinated major METplus release with several beta releases to facilitate better pre-release user testing of newly added features. The Coordinated Release (CR) will include METplus 4.0, MET 10.0, METviewer 4.0, METexpress 4.0.0, METdatadb 1.0, METcalcpy 1.0, and METplotpy 1.0 and is anticipated in March 2021. Release preparations will include the usual pre-release testing, final packaging of the code and documentation, and online training materials.

The MET helpdesk requests from the community for support have increased substantially over the past few years, including a ten percent increase during calendar year 2020 (through September). The DTC plans to transition the helpdesk to a forum during Q1 FY2021. It is anticipated that the first six-months to a year will require a similar amount of interaction while the METplus team encourages the community to start answering questions. For this reason, a similar portion of funding will be used to support the staff in responding to forum questions while the community becomes engaged. Additionally, in an effort to expand the growing online training footprint, this project will add 1-2 new modules to the online tutorial and include video training to provide more verbal context to the exercises.

A major enhancement that has been requested by the community for many years is the ability to evaluate models on a native domain. With an increasing focus on process-oriented studies and hierarchical testing, it seems like this capability is critically needed now. Most recently, the SIMA community requested METplus develop this type of support for the Model for Prediction Across Scales (MPAS). This request represents a significant overhaul of how MET handles grids and will require a great deal of time and resources to complete. It is proposed that this development be stretched over a two-year period to give the METplus team sufficient time and resources to do it properly and efficiently. A reasonable target for Year 1 (FY2021) is to develop a prototype framework to accomplish evaluation on the native MPAS grid. Year 2 (FY2022) would then be focused on hardening and testing the capability.

While developing the support of native grid evaluation is critical and potentially costly, there is also a scientifically justified need to incorporate new methods requested by the community and being developed by NCAR/RAL statistician Dr. Eric Gilleland via an NCAR base-funded project focused on verification research. This fiscal year, the METplus team will work with Dr. Gilleland to include the transition of block boot-strapping to remove contemporaneous correlation from model comparisons, making them more statistically robust. The team will also extend the Distance Map metrics already available in MET to include a new measure, called GBeta, which provides a more interpretable measure of spatial errors. Additionally, 1-2 enhancements to METplus to support community will be added.

The proposal includes presentations at relevant NCAR-related conferences or workshops (i.e., WRF/MPAS Workshop) to ensure the community is aware of all that METplus has to offer. It is anticipated that travel is highly unlikely during FY2021 so no travel is included in the project.

Project Deliverables

- METplus helpdesk and forum support for the community not supported by NOAA, AF, NRL, and Met Office
- METplus releases, bug fixes, repository maintenance, documentation, and on-line training
- 1-2 new modules added to online tutorial, including video accompaniment
- Prototype framework to support evaluation on the native MPAS grid
- 2 METplus enhancements transitioned from NCAR-base verification project
- 1-2 METplus enhancements to support community needs
- 1-2 presentations at relevant NCAR-related conferences/workshops

Sponsors: NCAR (PoP: 1 October 2020 – 30 September 2021)

DTC METplus Air Force Support and Development

Motivation

The Model Evaluation Tools (MET) is developed and supported to the community via the Developmental Testbed Center (DTC). METviewer is the associated database and display system designed for in-depth analysis of MET output and routine plotting. The enhanced METplus Python-based framework includes MET and METviewer as the core components and makes it easier to set-up and run MET and METviewer. The Air Force 557th Weather Wing (557 WW) is currently using MET for their operational verification package and plans to extend the system to use METviewer and potentially METplus. To facilitate this use, AFLCMC requires these three packages routinely pass cyber-security scans using the SonarQube software package. Additionally, MET helpdesk routinely fields 5-15 emails per month (on new or open issues) from 557 WW staff. With the adoption of MET and METviewer in operations, and the review of METplus, it is expected these interactions will continue at the same or higher level. Many times, MET development priorities are revealed via the helpdesk activities that are not captured under other AF Verification and Validation tasks, making it difficult to respond to 557 WW needs for minor changes to the tools. This inability to be responsive makes the tools less useful and forces the staff to develop work-around solutions that may be less than optimal. To address this challenge, this activity covers AFLCMC validated METplus development efforts, as well as the transition of requested community-developed capabilities to the supported METplus repositories.

Provide Support to Sustain 557 WW Instantiations of MET and METviewer

Project Description

The DTC will transition to SonarQube for ensuring code security and maintain its subscription to perform static source code analysis on MET and METviewer prior to all releases. The findings will be provided to AFLCMC/HBAW-OL Cybersecurity to review and provide recommendations for software fix actions. DTC will address these software fixes to comply with Defense Information Security Agency Security Technical Implementation Guides (DISA STIG). With remaining funds, DTC will provide prioritized help-desk or forum support to 557 WW verification staff. This project will provide validated code changes to MET, METviewer, and METplus that are not captured under other tasks. Requests for change will be validated by the lead command with the assistance of AFLCMC. Finally, the project will provide virtual (Year 1) and potentially in-person training (Year 2 and 3) at the 557 WW as COVID precautions allow.

Project Deliverables

- Transition to (Year 1) and maintain (Year 2-3) SonarQube license
- MET, METviewer, and METplus releases pass SonarQube scans
- Prioritized helpdesk or forum support
- Minor modifications to software as requested via AFLCMC
- Virtual (Year 1) and In-person training (Year 2 and 3) for 557 WW staff

Sponsors: Air Force (PoP: 1 February 2021 – 31 January 2024)

Transition NCAR/MMM PANDA-C Verification Efforts into the METplus framework.

Project Description

The NCAR Mesoscale and Microscale Meteorology Laboratory (MMM) has been working with the 557 WW to identify additional datasets for use in cloud verification and to develop scores for cloud height and layering. Their work, referred to as Prediction and Data Assimilation for Cloud (PANDA-C), is based on MET and the included Python-Embedding capability that allows MET to call user-defined Python scripts to pre-process data prior to use in the tools. These PANDA-C methods are now slated for transition into the METplus framework.

NCAR/MMM explored the use of five sources of “truth” through their project. These sources included three observation-based sources: Satellite ClOud and Radiative Property retrieval System (SATCORPS), Earth Polychromatic Imaging Camera (EPIC), and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO). The remaining two sources are analysis-based sources: European Center for Medium Range Weather ReAnalysis (ERA-5) and Modern-Era Retrospective analysis for Research and Applications (MERRA-2). The ERA-5, MERRA-2, and SATCORPS datasets are gridded, while EPIC and CALIPSO measurements were treated as point-based observations. Python scripts were developed to read the point-based observations, interpolate them to a grid, and then run by the MET Grid-Stat tool through Python-Embedding. The Python-based interpolation capability is similar to the newly developed MET Point2Grid tool and will be reviewed to determine if additional capability is needed in the MET tool prior to integrating MMM’s capability into MET. MMM configured MET to read in all five data sources, and to compute traditional categorical statistics (e.g., Probability of Detection) for both physical thresholds and climatologically-based percentile thresholds. MET was also configured to compute statistics that synthesize skill across many thresholds, such as the receiver operator characteristic (ROC) curve.

METplus use-cases, or example configurations, will be developed around the MET configuration files specified by the PANDA-C project and supported to both 557 WW and the greater community. The DTC will use the sample data provided to MMM for testing and the development of use-cases. Year 2 and 3 options are included to have the DTC integrate additional verification capability developed by MMM through their activities with 557 WW into METplus

Project Deliverables

- If needed, MET modified to replicate PANDA-C ingest strategies
- 7-10 METplus use-cases developed and ready for next scheduled METplus release
- 1-2 METplus use-cases demonstrating MMM developments (Year 2 and 3 Options)
- Presentation at appropriate conference

Sponsors: Air Force (PoP: 1 February 2021 – 31 January 2024)

Enhancing community collaborations through containerization of NWP system components and cloud compute platforms

Motivation

A core mission of the DTC is to assist the research community in efficiently demonstrating the merits of model innovations and development. Support of end-to-end NWP containers is an effective approach for fulfilling this mission. Through the use of container technology, complete software systems can be bundled (operating system, libraries, code, etc.) and shipped to users in order to reduce spin-up time, leading to a more efficient setup process. Over the past several years, end-to-end NWP software components [including WRF Pre-Processing System (WPS), Weather Research and Forecasting (WRF) model, Gridpoint Statistical Interpolation (GSI) data assimilation, Unified Post-Processor (UPP), NCAR Command Language (NCL), Python plotting, Model Evaluation Tools (MET), and METviewer] were implemented into Docker containers to better assist the user community. The work conducted by DTC staff leveraged and complemented previous efforts of the National Science Foundation-sponsored Big Weather Web (http://bigweatherweb.org/) project that initially established NWP software containers for the WPS, WRF and NCL components. Through this complementary work, a full WRF-based end-to-end NWP system was established. Information detailing how to run the DTC NWP containerized system on a local machine or on a cloud platform using both Docker and Singularity containers has been established and is provided on the DTC website (http://dtcenter.org/community-code/numerical-weather-prediction-nwp-containers). With the establishment of these resources, focus is now shifting to maintaining and increasing the functionality and usability of the containers while continuing to publicize the availability of the tools. At the same time, we do not want to overlook the opportunity containers and cloud computing provide in terms of fostering an interest and excitement in NWP while educating the next-generation workforce. With worldwide access to large compute resources and containerized components that decrease the burden of the initial startup process, these tools promote an innovative teaching tool to integrate NWP directly into a course curriculum using hands-on learning.

Project Description

During FY2021, the DTC is proposing to maintain the current WRF-based NWP Docker and Singularity containers for use on local machines as well as on Amazon Web Services (AWS) as new versions of the components are released. In addition, the online tutorial and documentation created to step users through building and running the DTC end-to-end NWP containerized system will be preserved and updated accordingly. All of the established container images are made publicly accessible on DockerHub. Automated builds are in place for these images, which occurs by watching a tag or branch from the source code repository and automatically rebuilding and republishing the corresponding images on DockerHub as changes are made. This protocol will remain a requirement to ensure updates are maintained and easily accessible by the user community. Community support for specific questions regarding containers or cloud computing aspects of the end-to-end system will be provided to users running the DTC containers, which is essential to attracting and maintaining an active user community. General questions related to running the components themselves will be referred to the respective component's support forum for assistance.

During the summer of 2019, NCAR staff (and members of the DTC that would be participating in this project) leveraged additional funding from RAL through the Equal Opportunity Funds to work directly with Dr. Sam Ng and his students in the Forecasting Lab course at Metropolitan State University of Denver to expose the undergraduates to NWP systems through the use of software containers running in the cloud. This collaboration was highly successful and a rewarding opportunity that significantly impacted the students' experience during the beginning of the fall semester. In order to build on that experience and to engage with additional universities/students, we propose to aggressively reach out to other faculty members/programs to build new connections and opportunities to integrate exciting new hands-on content into their classrooms. Through our connection with UCAR's Significant Opportunity in Atmospheric Research and Science (SOARS) program, we will reach out to faculty at universities that traditionally serve underrepresented students, in particular. Once connections have been made with select programs, work will commence to build curriculum based on the DTC NWP containerized system that can be integrated into relevant courses offered by each program. The COVID-19 pandemic has created a unique opportunity in that the use of technology and remote participation has become commonplace. Given that, it is proposed to provide live, yet virtual, training in select courses during the spring semester of 2021. The details of integrating these innovative teaching tools into course curriculum necessitate close collaboration with university faculty members to identify appropriate courses for this type of hands-on learning. Even if universities do not have access to local compute resources, cloud computing and containers provide an environment that makes it easier to engage with them through other highly accessible systems. Developing classroom content during this period of performance provides a jumping off point to harden that content during FY2022 and record material to more broadly distribute to interested university faculty to integrate into in their future classes.

Given the unique demands on faculty this academic year as they pivot and adapt their course plans due to the evolving COVID-19 pandemic, we propose a conditional alternative in the event that we are not able to establish a firm connection with a university and faculty partner to integrate this work into a spring semester course. In this case, to continue promoting the use of these tools in university classrooms, an offering of a fee-based workshop, targeted at university faculty members who would like to learn about the established containerized DTC end-to-end NWP system in order to integrate it into their course curriculum, will be held during the summer of 2021. With hopes of having an in-person tutorial, flexibility will be necessary to pivot to a virtual experience depending on circumstances. Content provided during the workshop will be based on lessons learned from interactions with previous university programs. The goal is to engage with a larger number of programs to enhance students' experience and excitement for NWP. The workshop fee would cover participant costs while the requested project funds would cover staff time for workshop preparation and participation. Consideration for the ultimate timing of this workshop will attempt to leverage the occurrence of other relevant events in Boulder that may attract the same participants of interest (e.g., WRF Workshop, Unidata Workshop) if the workshop is able to be held in person.

Project Deliverables

- Update existing DTC Docker images with recent releases of each software component
- Maintain all DTC NWP images on DockerHub
- Update documentation for running on local or cloud-based platforms as necessary
- Establish connections with at least one new university program to build topical curriculum with the goal of integrating into a relevant course for hands-on learning opportunities in the Spring of 2021 (Contingent - Connection identified no later than 1 December 2020)
- Host workshop during summer 2021 (Contingent - Final decision made by 1 December 2020)

Sponsors: NCAR (PoP: 1 Oct 2020 - 30 Sep 2021)

Transition of software support and community engagement from DTC to EPIC

Motivation

The goal of the Earth Prediction Innovation Center (EPIC) is to advance weather modeling skills, reclaim and maintain international leadership in the area of Earth System Modeling, and improve the transition from Research to Operations (R2O) by supporting the development of the community Unified Forecast System (UFS). EPIC will facilitate public availability and UFS source code updates so that researchers from academia, public and private sectors can participate in the development of the UFS code for both the NWP research community and for operational NOAA models.

The Development Testbed Center (DTC), whose mission is to provide a bridge between NWP research and operations, has extensive experience in the areas of software support and community engagement in the use of NWP systems for improving weather prediction skills. As EPIC is established, it can benefit from the DTC know-how to more efficiently stand up its services to the community.

Project Description

The DTC provides software support and community engagement opportunities for a number of UFS components and applications, i.e., the UFS Weather Model (WM), the Unified Post Processor (UPP), the UFS Short-Range Weather Application (SRW App), the UFS Medium-Range Weather Application (MRW App), and the UFS Hurricane Application (HAFS). This support is in the areas of code management, code releases, user and/or developer support, and training/tutorials, responsibilities that are envisioned to become part of EPIC. Given the DTC's extensive experience in these areas and its current responsibilities, it will be important for the DTC to work closely with EPIC to assure a smooth and efficient transition of these responsibilities. An important component of this transition will be training provided to EPIC by the DTC on current protocols and software tools prior to handing off responsibility to EPIC. A list of priorities and a corresponding work plan for *what to transition* to EPIC will be created in collaboration with EPIC management; examples of responsibilities for the UFS WM, MRW, SRW and Hurricane Apps, and UPP that are candidates for transition to EPIC include:

Code Management: Manage codes for UFS components and Apps with GitHub tools (including issues, pull requests, code review, and wikis), develop and perform regression testing, perform "cross-repository maintenance" (assure consistency among interrelated repositories), and maintain and expand software portability. Lead the developer committees and associated governance for each.

Code Releases: Coordinate, write and review documentation updates; perform platform portability testing; disseminate UFS code releases and corresponding required data sets, create cases for Graduate Student Tests.

User Support: Answer questions from users and developers about UFS components and applications (WM, MRW App, SRW App, Hurricane App, UPP).

Training/Tutorials: Prepare and conduct tutorials and training for the UFS SRW, MRW, and Hurricane Apps, including UPP.

It should be pointed out that the primary development and support for the Common Community Physics Package (CCPP) development and corresponding use of the Hierarchical System Development (HSD) approach, as well as the METplus (verification) software package, will remain in DTC, but help will be provided by the DTC to EPIC in their use of these software packages where applicable.

This work will be conducted as a collaborative effort between NCAR and GSL. DTC will conduct this project over the next two years through FY22, with a clear timeline outlined as part of the work plan deliverable.

Project deliverables

- Work plan detailing what roles and responsibilities will be transitioned from the DTC to EPIC and a timeline for this transition, with final work plan commensurate with support, to be negotiated between DTC and the EPIC program office after the EPIC contract award.
- Training and transition completed for at least one software component, as agreed upon within the work plan.

Sponsors: NOAA [PoP: 4 May 2021 - 30 September 2022)

Testing and Evaluation

Rapid Refresh Forecast System (RRFS) Development and Retirement of Regional Mesoscale Modeling Systems

Motivation

Within the NOAA operational model unification effort taking place under the UFS umbrella, a key area of interest is the evolution of the North American Mesoscale (NAM), Rapid Refresh (RAP), High-Resolution Rapid Refresh (HRRR), and High-Resolution Ensemble Forecast (HREF) systems to a new, unified FV3-based deterministic and ensemble storm-scale system, to be known as the Rapid Refresh Forecast System (RRFS). The ongoing transition from the existing NOAA prediction systems to the UFS is a major multi-year undertaking with the new RRFS system targeted for initial operational implementation in late 2023.

The most overarching benefit to the U.S. weather enterprise is focusing human resources and expertise from across the meteorological community on a single, shared system and avoidance of duplicative efforts. The evolution toward this developmental paradigm reflects a broad consensus that only with such a shared system, and an associated shared collective expertise, can NOAA maximize forecast skill across the many model applications. In addition, simplification of the operational NCEP suite of models will allow for optimization of existing and future high-performance computer resources and a reduction in overhead of software maintenance related to resources spent on maintaining multiple dynamic cores.

A successful transition to the Rapid Refresh Forecast System (RRFS) will involve the phased retirement of several regional prediction systems currently in operation at NCEP, with the RRFS subsuming the roles of several of the regional systems, complemented by the continued advancement of the Global Ensemble Forecast System (GEFS). Regional systems planned for retirement include the Short-Range Ensemble Forecast (SREF) System, the NAM model and its associated nests, the HREF, RAP, and HRRR. A significant challenge in reaching a unified endpoint is the retirement of the SREF system, which is currently comprised of ARW and NMMB members, a mix of physics parameterization schemes, and features diversity in sources of initial conditions.

Project Description

The progression toward the eventual RRFS implementation requires coordinated development across several, interconnected areas spanning the dynamic core, data assimilation, and chosen physics suite. Integral throughout this process is careful objective and subjective diagnostic analysis of forecast output in the form of case studies and metrics. To this end, the DTC's role in this UFS-R2O sub-project will consist of comparing legacy systems to future configurations of the unified system with the hopes of retiring frozen applications while at the same time testing and evaluating the chosen physics suite for the future RRFS implementation as incremental changes are made throughout the project.

As we move toward the RRFS, it is necessary to approach legacy system retirement in an order that does not interrupt upstream/downstream dependencies. Given that the SREF system depends upon both the NAM and RAP systems as a source for initial conditions, these models cannot be retired prior to the SREF itself. Ideally the SREF will be subsumed by the GEFS, as the latter continues to move toward the resolution of the SREF (16 km). However, at present, there are significant outstanding issues that still need to be understood and addressed to facilitate retirement of the SREF. An FY22 upgrade represents the earliest possible time at which the GEFS could allow for the retirement of the SREF, moratorium notwithstanding. During the current period of performance (PoP), the DTC has begun engaging in an assessment of retirement feasibility by conducting forecast performance comparisons of the legacy ensemble systems (SREF and HREF) to the GEFS through the use of Model Evaluation Tools (MET) and scorecards. This work is scheduled to continue into the next PoP with a completion by the end of September 2021. In addition, during the next PoP, the DTC will also conduct forecast performance comparisons of the deterministic legacy regional systems (NAM and RAP) to the operational GFS – again, using MET and scorecards. This work will occur later in the period of performance due to the fact that it will be necessary to retire SREF prior to opening up the opportunity of retiring upstream systems, including RAP and NAM.

By retiring legacy systems from the operational suite, implementation of the RRFS into operations becomes both scientifically and computationally feasible. The UFS Short-Range Weather/Convection-Allowing Model (SRW/CAM) Application Team has determined that the initial RRFS physics suite baseline will include the following schemes: Thompson microphysics, MYNN PBL and surface layer, Noah-MP land surface scheme, GSL gravity wave drag, and RRTMG for longwave and shortwave radiation. While preliminary testing of this physics suite is being conducted in the current PoP, continued development to address instability issues has delayed the official creation of a benchmark test of the baseline physics suite. Once a benchmark is established, it will be used to facilitate configuration comparisons in the future as optimization and improvement to the physics suite progresses. In addition, advancements to refine and optimize a reliable and skillful forecast ensemble with stochastic physics at CAM scales will be examined during the PoP. If those results indicate insufficient spread/error statistics, a multi-physics approach to the forecast ensemble may be considered, enabled by CCPP. This testing will leverage the UFS SRW/CAM Application workflow, including tasks to efficiently conduct verification through the use of MET. As configurations are compared, a CAM scorecard created using METviewer will be used to identify weaknesses and strengths of each configuration.

Project Deliverables

- Performance of the RRFS baseline physics suite monitored through testing and evaluation as optimization/improvement continues
- UFS-CAM ensemble with stochastic physics examined

- Legacy operational ensemble systems (SREF and HREF) forecast performance comparison to GEFS completed using MET and scorecards
- Legacy operational deterministic regional systems (NAM and RAP) forecast performance comparison to GFS using MET and scorecards

Sponsors: UFS R2O (PoP: 1 July 2021 - 30 June 2022)

Testing and Evaluation of UFS Physics for Coupled Medium-range Weather and Subseasonal Forecasting

Motivation

Forecast uncertainties are the consequence of imperfect model initialization, dynamics, and physics. Among these factors, advancing physical parameterizations is essential to continuously improve the representation of physical processes and the overall predictive skill in the weather-to-seasonal forecasts. To ensure that the improvements of model physics will be properly implemented in the Unified Forecast System (UFS) and to encourage developers to actively engage in the developmental process, it is necessary to adopt a testing and evaluation (T&E) procedure that is agile (frequent, fast, automated), in-depth, neutral, collaborative, and operation-relevant but not operation-prescriptive. The Developmental Testbed Center (DTC), an established NOAA testbed with a long-term track record of testing innovations for the National Centers for Environmental Prediction (NCEP), is well-positioned to conduct this T&E activity.

The objective of this proposal is therefore to provide objective evaluation and actionable suggestions to thoroughly inform decisions on the physics development of the UFS, and to ensure that the evaluation methods adopted can be usable for the broader community after completion of the project. The effort is expected to explicitly and continuously advance the model physics with the ultimate goal to improve the overall capability of the UFS.

Project Description

Unlike conventional and routinely adopted T&E of forecasting systems, the proposed work will provide information that can support and influence the developmental process of model physics. The work will have the following foci:

1) The T&E seeks to primarily explain the systematic biases in the operational GFSv16 physics suite. In addition to the critical issues listed in the *UFS Development Goals and Priorities* [such as Planetary Boundary Layer (PBL) biases, 2-m temperature and precipitation biases over the CONUS, and tropical cyclone track errors beyond day 5], other biases particularly related to stratocumulus and shallow and deep convection will be identified using benchmark datasets including reliable observations and reanalysis.

2) The root causes and error contributions from physical parameterizations will be diagnosed by analyzing the physical tendencies and applying the "UFS Column Replay Capability"[1] and "Process Isolation Capability"[2] from Common Community Physics Package (CCPP) Single-Column Model (SCM)

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[1] *Code capability to force a SCM with saved dynamical tendencies and initial condition from a previous run of regional or global model.*

[2] *Code capability to use an arbitrary subset of active physical parameterizations of a physics suite (regardless of the forcing or initial conditions) and to allow the omitted physics to be substituted with a data component. The data component is obtained from a previous run of the SCM.*

following the Hierarchical System Development (HSD) framework. The latter two capabilities are not yet available, but are expected to be delivered by a companion DTC project in time to be used for this project (See AOP2021-SW-HU-SCM: Complete the development and implement version 1 of the Hierarchical Testing Framework).

3) After assessing how the physics innovations affect the overall forecast skill of GFS physics suite in Year 1, the DTC will evaluate the full physics suite for the Global Forecast System (GFS) v17 and Global Ensemble Forecast System (GEFS) v13 in Year 2, both due to be implemented in operations in 2024.

4) To help transition the tested physics to the coupled model, the DTC will use the HSD framework to investigate the tropical processes and phenomena that are influenced by air-sea interaction. The efforts are expected to include, but not be limited to, evaluating tropical cases using the CCPP SCM.

5) All the evaluation metrics adopted are expected to be "evidence-based and process-oriented" and consistent with the spirit of the DTC's contribution to the selection of an advanced physics suite for GFS v16. For example, the metrics for evaluating the PBL structure and evolution may include the vertical profiles of dynamic and thermodynamic fields, spatial and temporal variations of PBL height and the PBL-related cloud and precipitation development. In addition to the in-house diagnostic metrics, the unified metrics emerging from METplus and the V&V WG for timescales from synoptic to seasonal will be considered.

Project deliverables

- Contribution to the test toward GFS v17/GEFS v13 through diagnostics and verification
- Report on the evaluation of the physics innovations proposed for GFS v17/GEFS v13 and beyond using HSD

Sponsors: UFS R2O (PoP: 1 July 2021 - 30 June 2022)

Accelerated completion of the architecture and capabilities of the physics Hierarchical Testing Framework (HTF) coupled to the Common Community Physics Package (CCPP)

Motivation

NOAA has identified atmospheric physical parameterizations, and the Common Community Physics Package (CCPP), as one of the areas targeted for focused investment and development with the goal of advancing the Unified Forecast System (UFS). Intrinsic to the CCPP is the concept of hierarchical system development and testing. Parameterizations should be assessed using several "tiers" of modeling configurations, arranged in a simple-to-complex hierarchy. Testing a physical parameterization innovation within such a structure allows one to objectively address how well it represents the physical processes it was designed to encompass in relative isolation from parameterizations for other processes.

In addition to configuring the modeling system in simplified ways, such as using the CCPP Single Column Model (SCM), hierarchical testing also calls for executing the system in a variety of ways, ranging from individual case studies that illustrate systematic errors, all the way to comprehensive experiments that use a large sample to statistically quantify the model's forecast performance.

Project Description

The first goal of this project is to augment the hierarchical testing framework (HTF) in two ways. First, by adding capability to the CCPP to output tendencies and other information from physical parameterizations to assist with the development and tuning of the parameterizations and suites. And second, by creating a comprehensive set of case studies for evaluating model innovations. The resulting

HTF tools will be made available to the research community through a documented public release of the codes and datasets needed to run and evaluate the cases. Another goal of this project is to use the HTF tools, including the SCM and case studies, to document shortcomings of the current UFS physics suite, and to provide avenues for model development.

Developing the capability to output tendencies and other information from physical parameterizations involves modifying the CCPP and its hosts (UFS and SCM) to create a compile-time or run-time option to output the necessary fields. In addition to the ability of outputting tendencies, the capability to output additional variables from the parameterizations will be added to enable developers to output selected intermediate tendencies from sub-processes within the parameterization.

The development of the case studies will start with the creation of a catalog of cases that are representative of model biases, with a focus on tropical cyclone, severe-storm pre-convective environment, continental nocturnal/stable planetary boundary layer (PBL) and continental winter storm/stable PBL. The catalog of cases will be developed with input from EMC (especially its Model Evaluation Group) and the UFS Physics Working Group. and will be revised and augmented in Year 2 of the project.

Once the cases are identified, meteorological case studies will be created. Model analyses and observations will be used to describe the state of the atmosphere during the event. Forecast verification diagnostics and statistics, the latter computed with the Model Evaluation Tools, will be used to document how the operational and developmental UFS configuration performed during the event. Baselines will be created utilizing the operational physics suite.

In the last year of the project, all capabilities will be fully packaged, documented, and distributed as part of the HTF. This package will include a website to provide access to code, datasets, and information, as well as an online tutorial.

Another aspect of this proposal is to use the HTF to assess the shortcomings of operational and developmental physical parameterizations. For this assessment, the case studies described in the previous paragraphs will be utilized along with the CCPP SCM. This assessment will focus on relating well-documented systematic model biases to the tendencies produced by each of the parameterizations. This project will relate the parameterization behaviors to the model biases. These relationships will be discussed with the physics developers to provide avenues for future model development and testing.

Project Deliverables

- Catalog of case studies that illustrate systematic errors of the operational and developmental UFS (Completed)
- Code capability and user documentation on case studies that demonstrate systematic biases (Completed)
- Code capability and user documentation on additional case studies that demonstrate systematic biases
- Report on hierarchical testing of physics innovations
- Code capability and user/developer documentation on output tendencies and other information from parameterizations (Completed)
- Community release of integrated HTF

Sponsors: Hurricane Supplemental (1 July 2019 - 30 June 2022)

Physics testing and evaluation for hurricane application

Motivation

NOAA's NWS plans to implement a configuration of the FV3-based Unified Forecast System (UFS) targeted at producing the best possible tropical cyclone (TC) numerical guidance in operations. This configuration has been dubbed the Hurricane Analysis and Forecast System (HAFS). When it is ready, HAFS will complement the numerical guidance provided by the operational medium-range weather configuration of the UFS (the Global Forecast System; GFS) and will replace the existing operational limited area models used for tropical cyclone guidance, the Hurricane Weather Research and Forecast system (HWRF) and the Hurricanes in a Multi-scale Ocean-coupled Non-hydrostatic model (HMON).

NOAA's plan for the development of HAFS is comprehensive and involves development and testing on a variety of aspects of the modeling system, such as the grid configuration (global, nested, regional standalone, etc.), the data assimilation and initialization, the atmospheric physics, the coupling with ocean, wave, and land models, and the postprocessing. This project focuses on informing the way forward with respect to the atmospheric physics parameterizations and suites that can be used in HAFS to maximize the forecast skill.

The starting point for HAFS physics is the global weather configuration of the UFS that was implemented operationally in early 2019 (GFS v15). Given that HWRF is a high-performing model for TC forecasting, there is interest in testing HAFS with the HWRF physics. Additionally, there is interest in testing HAFS with a suite similar to what is used in GFS v15, but with customizations for the hurricane problem. It is a long-term goal of the UFS to unify physics for all scales and applications, and this project will support this goal by providing information regarding the performance of HAFS with various suites, with an eye toward the future reduction of the number of parameterizations and suites used with the UFS.

Project Description

In the first phase of this project, the HWRF parameterizations (see Table 1) will be made compliant with the Common Community Physics Package (CCPP), which enables their use with any UFS application. While some of these schemes are also used by the GFS, and as such are already available in the CCPP, the versions of these schemes used in HWRF are not necessarily identical to that used in GFS. The approach to including the HWRF physics in CCPP will differ depending on whether a similar parameterization already exists in the CCPP, as shown in Table 1.

Table 1. Parameterizations used in the HWRF suite and their disposition for this project.

Type	**Scheme**	**Disposition**
Microphysics	Ferrier-Aligo	New. Add to CCPP
PBL	EDMF	Modify existing GFS v15 scheme in CCPP to emulate HWRF behavior
Deep cu	saSAS	Modify existing GFS v15 scheme in CCPP to emulate HWRF behavior
Shallow cu	saSAS	Modify existing GFS v15 scheme in CCPP to emulate HWRF behavior
Radiation	RRTMG	Modify existing GFS v15 scheme in CCPP to emulate HWRF behavior
Surface layer	GFDL	New. Add to CCPP
Land surface	Noah	Add to CCPP. Even though the CCPP already has a Noah LSM, the version of Noah implemented in the GFS is substantially different from the version in HWRF.

In the second phase of this project, HAFS will be tested with the HWRF suite using two configurations pre-defined by the master plan for HAFS development: 1) *Prototype HAFSv0.a*, a limited area domain with 3-km spacing over the North Atlantic basin (AL), and *2) Prototype HAFSv0.b*, a 13-km global configuration with a static 3-km nest centered over the AL. The details of this test, as well as the determination of a second suite to be tested, will be outlined in a test plan to be created before the test starts.

The objectives of this test are to provide an initial demonstration of incorporating HWRF physics into CCPP aimed at ascertaining that the physics have been successfully connected to the UFS and are running stably and to provide initial guidance to EMC for the selection of the physics suite for HAFS. Therefore, the test will be limited to a set of a few priority AL tropical storms (identified in consultation with EMC). Test results will be evaluated using standard metrics used for tropical cyclone forecast assessments, such as position (track) error, as well as TC intensity bias and error. All metrics will be computed using the Model Evaluation Tools for Tropical Cyclones (MET-TC) package. Results obtained with the HAFS v.0a and v0.b configurations will be analyzed to inform EMC and other groups working on HAFS development.

Project Deliverables

- HWRF parameterizations in CCPP
- Successful initial HAFS v0.a and v0.b runs using the HWRF suite (Complete)
- Test plan (Complete)
- Report on test results (Complete)
- Communication of results at conference

Sponsors: Hurricane Supplemental (PoP: 1 August 2019 - 31 July 2021)

DTC Verification and Validation Support for US Air Force

Motivation

The AF supports a vast profile of operational forecasting needs and, therefore, requires skillful numerical guidance for a broad spectrum of weather and forecasting applications. From routine weather to high impact events, the AF requires the need to both forecast and evaluate atmospheric phenomena that occur globally, often over data sparse regions. In addition, the AF's numerical weather prediction (NWP) modeling suite is continually evolving as technical and scientific upgrades are made to its operational Global Air-Land Weather Exploitation Model (GALWEM) forecasting system, which is based on the UK Met Office's (UKMO) Unified Model (UM). A key component of the upgrade cycle is robust testing and evaluation to ensure upgrades and/or new implementations are performing the same or better than the current operational capability. A critical first step to ensure testing efforts are addressing project goals, using appropriate verification methodologies, and identifying available datasets is establishing robust test plans, and prior to executing a full testing and evaluation effort, a verification or validation workflow must be set-up to output necessary statistics to address the research questions at hand. Objectively analyzing and interpreting the results is imperative to the decision-making process. To address the need for ensuring robust evaluation of the current and future GALWEM forecast systems, the AF has requested the DTC's assistance with a number of verification and validation efforts. The DTC has extensive experience with both setting up and executing testing and evaluation efforts, including targeting what variables and verification measures should be included, identifying necessary datasets, setting up verification and validation workflows rooted in using the enhanced Model Evaluation Tools (MET) framework, and performing objective analysis on statistic output.

Evaluate Latest LIS Upgrades on GALWEM Performance (LIS plus LIS Options)

Project Description

A critical component of NWP systems is the Land Information System (LIS), which produces land surface states and fluxes that are used downstream in the forecast model. Under previous funding, the DTC was charged with conducting an evaluation of an upgraded version of the LIS's impact on the overall GALWEM forecast system performance. Within this prior tasking, methodologies, workflows, and MET configurations were established to provide robust statistical evaluation of the upgraded LIS against the designated benchmark. With the AF planning future LIS upgrades in the coming years, it is imperative to capture and document the impacts of the LIS on overall model performance. To assist the AF with making evidenced-based decisions and to help inform decisions regarding future operational implementations, the DTC will assess the impact of an upgraded LIS by completing a comprehensive evaluation effort. For year 1, the DTC will conduct an objective evaluation of GALWEM forecasts using the upcoming LIS release against the benchmark, GALWEM output initialized with the current operational version of LIS. Evaluation data will include a single 3-month season and make use of the same methodology, measures, and parameters developed for the prior LIS evaluations. The DTC will work closely with the AF to further define any necessary aspects of the test plan, and the test plan will be provided to the AF prior to the evaluation. Upon completing the evaluation, the DTC will deliver a teleconference briefing of the results and a final written report to the AF. In addition, communication as needed with the AF and its partners, including teleconferences, will aid in the forward progression of the tasking. The DTC will rely on the AF and its partners to provide the data sets necessary for the evaluation. The cost estimate is based on the assumption the DTC will be working with model data in GRIB2 format. Budgets for years 2 and 3 include options for the DTC to evaluate the impact of subsequent LIS releases using the same methodologies as year 1.

Project Deliverables

- Test plan in coordination with the AF
- Teleconference briefing of evaluation results
- Final written report

Sponsors: Air Force (PoP: 1 Feb 2021 - 31 Jan 2024)

Support for 557 WW Model Upgrades and Implementation (Upgrade/Implementation Options)

Project Description

As the AF's operational system is agile and continually evolving, the AF has requested DTC assistance with developing test plan(s) for evaluating scientific and technical upgrades and/or implementations for components within the GALWEM forecast system. Specific tasking will be identified and validated by AF Lead Command, and the DTC will work closely with the AF to define detailed aspects of the test plan(s), including what system component(s) will be evaluated, what key science and/or technical questions will be addressed in the test(s), what variables and measures will be targeted, and identifying necessary data sets and time periods to include in the test(s). The test plan(s) will be delivered to the AF, and the DTC will also be responsible for setting up and sharing the necessary MET and METviewer configuration files to be used in the full evaluation, which will be executed by the AF. In addition, communication as needed with the AF, including teleconferences and in-person visits, will aid in the forward progression of the tasking.

The DTC will only require a small amount of sample model data, in GRIB2 format, and some observation data, if not readily available, from the AF to assist with establishing a test plan and setting up the necessary MET configuration files.

The total funding estimates are broken down to give options for providing support in 2021-2023, up to 2 times per year. Each option has been budgeted to provide the same level of effort and includes estimates for necessary METplus development needed to add new capabilities to address project goals.

Project Deliverables

- Test plan in coordination with the AF
- MET configuration files and/or METviewer configuration files

Sponsors: Air Force (PoP: 1 Feb 2021 - 31 Jan 2024)

Veracity Testing of the Global Synthetic Weather Radar Product (GSWR Options)

Project Description

Retrospective Evaluation of GSWR Product

The Global Synthetic Weather Radar (GSWR) product was developed by Massachusetts Institute of Technology-Lincoln Laboratory (MIT-LL) to address gaps in traditional radar coverage and outputs several radar-based variables, including composite reflectivity, Vertically Integrated Liquid (VIL), and echo tops. An analysis and forecast are produced using machine learning techniques and leveraging model output from GALWEM and observation data from satellites and weather radars. The DTC was previously funded by the AF to evaluate GSWR prototypes, and within this work, the DTC established evaluation methodology, observation datasets, and appropriate verification measures to use in GSWR veracity testing. In addition, the GSWR products are undergoing continued development; given that the AF supports a vast profile of operational forecasting needs, including atmospheric phenomena that occur over data sparse regions, the AF is interested in evaluating future improvements of the GSWR products.

To verify the GSWR product has been constructed appropriately and to monitor how well GSWR compares to ‘truth’ datasets, the DTC will complete evaluations comparing the GSWR output against appropriate observations and analyses leveraging and building upon previously funded efforts. The DTC will include data sources from the prototype evaluation including Multi-Radar Multi-Sensor (MRMS) data, NEXRAD Level II data, and European Meteorological Network (EUMETNET) data. The same traditional (e.g., Gilbert Skill Score, frequency bias, and probability of detection) and spatial-based verification measures (e.g., Fractions Skill Score) included in the prototype testing of GSWR will be included in all future veracity testing. Prior to each retrospective test, a test plan will be constructed and delivered to the AF, detailing the methodology, time periods, verification datasets, and verification measures. Upon conclusion of each retrospective veracity test, a briefing of the results will be provided as well as a written final report summarizing the results. Cost estimates assume that all GSWR veracity testing will take place on the Air Force Weather (AFW) Virtual Private Cloud (VPC), as it did for the prototype evaluation. For these tests, the DTC is dependent on the AF providing the GSWR data and VPC technical support from AF and its partners. All options assume the evaluation will be for a maximum of two seasons.

For the first test option exercised, the DTC will add the capability to use National Aeronautics and Space Administration's (NASA) Global Precipitation Measurement (GPM) Mission data and any additional data sources that are applicable and are available. Additional spatially-based verification methods, such as the Method for Object-based Diagnostic Evaluation-Time Domain (MODE-TD) tool, which applies a time dimension to MODE and allows for feature tracking through time, will also be explored. Python-embedding capabilities to read the geoTIFF format in METplus will also be added. The cost estimates for subsequent GSWR tests for a given year (same cost for each subsequent test for a given year) assume that these tests will use the evaluation system and observation data set established for the first test. Cost estimates for the first test for subsequent years include the costs associated with keeping up-to-date on AWS security requirements and upgrading METplus and its various components to the latest versions.

Project Deliverables

- Test plan in coordination with the AF
- Teleconference briefing of evaluation results
- Final written report

Sponsors: Air Force (PoP: 1 Feb 2021 - 31 Jan 2024)

Real-time Evaluation of GSWR Product

The workflow established for the GSWR prototype evaluation is focused on a retrospective approach. This option will build upon the capability from the most recent retrospective evaluation (i.e., the established GSWR prototype testing or from a retrospective evaluation option, if funded) to create a workflow for real-time evaluation. The DTC will work with the AF to identify any time constraints on the necessary timing of the throughput to consider which verification measures will be included in the real-time evaluation (i.e., ensure latency of obtaining observation datasets and time needed to run MET is appropriate). The real-time workflow will include pulling and staging necessary data, running METplus, and having an end goal of producing METviewer scorecards, accessible via a web page. For this activity, the DTC is dependent on the AF providing the GSWR data and VPC technical support from AF and its partners. The cost estimates for this activity assume that the AF will take over maintenance and monitoring of the real-time workflow established by the DTC.

Project Deliverables

- MET configuration files and/or METviewer configuration files
- METviewer scorecards available for real-time evaluation

Sponsors: Air Force (PoP: 1 Feb 2021 - 31 Jan 2022)

Blended Modeling Product Evaluation (Blended Option)

Project Description

The Air Force is exploring the use of the UK Met Office's (UKMO) Integrated Model post-PROcessing and VERification (IMPROVER) probabilistic post-processing system. To assist the AF with making evidenced-based decisions regarding the potential future use of IMPROVER, the DTC will perform a comprehensive evaluation effort comparing IMPROVER blended model products against current AF post-processing capabilities to assess the improvements and/or degradations. The DTC will work closely with the AF to define the necessary aspects of the test plan, including what variables and measures will be targeted and identifying necessary data sets and time periods to include in the test. The AF has listed aviation hazards as a potential area of focus; necessary regional and/or global verification datasets will be explored with input from subject-matter experts, and both traditional and more advanced verification methods [e.g., neighborhood methods, High Resolution Assessment (HiRA) method] will be included in the evaluation. The DTC will work closely with the AF to further define any necessary aspects of the test plan, and the test plan will be provided to the AF prior to the evaluation. Upon completing the evaluation, the DTC will deliver a teleconference briefing of the results and a final written report to the AF. In addition, communication, as needed, with the AF and its partners, including teleconferences and in-person visits, will aid in the forward progression of the tasking. To successfully execute this task, the DTC will need assistance from the AF and/or its partners to acquire the necessary post-processed model output, in MET-compliant format. Due to the need to provide the DTC with a potentially large dataset, it is encouraged that discussions regarding data transfer plans occur early in the evaluation effort.

Project Deliverables

- Test plan in coordination with the AF
- Teleconference briefing of evaluation results
- Final written report

Sponsors: Air Force (PoP: 1 Feb 2021 - 31 Jan 2022 or 1 Feb 2022 - 31 Jan 2023)

Dust Evaluation (Dust Options)

Project Description

Dust events and the reduced visibility from such events are a complex forecasting and evaluation challenge that directly impact AF operations. To directly address this operational forecasting need, the AF and UK Met Office (UKMO) are currently funding an initiative with the U.S. Army Engineer Research and Development Center (ERDC) Cold Regions Research and Engineering Laboratory (CRREL) to improve dust forecasting. In addition, previous DTC tasking was charged with exploring available datasets and verification methodologies in relation to dust and visibility. To assist the AF with the evaluation of dust properties in their regional modeling systems, with particular focus on visibility at the surface and aloft, the DTC will perform a comprehensive evaluation effort using the methodologies investigated and developed under previous funding. A data survey from previous funding showed benefit to using METeorological Aerodrome Reports (METAR) data from surface stations, Aerosol Robotic Network (AERONET) data, which is a collection of ground-based remote-sensing aerosol networks, and Visible Infrared Imaging Radiometer Suite (VIIRS) satellite data when evaluating dust and visibility. In addition to the observations listed, other satellite platforms may be of benefit and may potentially be explored in this tasking. The evaluation will include traditional grid-to-point and grid-to-grid verification as well as more advanced verification such as neighborhood methods, distance-based measures, and object-based methods, including the Method for Object-based Diagnostic Evaluation (MODE) and MODE-Time Dimension tools. The DTC will work closely with the AF to further define any necessary aspects of the test plan, including identifying necessary data sets and time periods for the test to ensure robust results, and the test plan will be provided to the AF prior to the evaluation. Upon completing the evaluation, the DTC will deliver a teleconference briefing of the results and a final written report to the AF. In addition, communication, as needed, with the AF and its partners, including teleconferences, will aid in the forward progression of the tasking. In order to successfully execute this task, the DTC will need assistance from the AF and/or its partners to acquire the necessary model output, in MET-compliant format. Due to the need to provide the DTC with data, it is encouraged that discussions regarding data transfer plans occur early in the evaluation effort. The total funding estimates are broken down to provide options for dust evaluation over North Africa in year 2 and over East Asia and Australia in year 3.

Project Deliverables

- Test plan in coordination with the AF
- Teleconference briefing of evaluation results
- Final written report

Sponsors: Air Force (PoP: 1 Feb 2022 - 31 Jan 2024)

Optimizing Ensemble Design for Use in the RRFS

Motivation

One aspect of the NOAA model unification effort is the desire to replace both deterministic and ensemble storm-scale regional modeling systems currently in the operational suite with a UFS-based system to be known as the Rapid Refresh Forecast System (RRFS), with the new RRFS system targeted for initial operational implementation in early 2024. While this approach would provide a more unified and sustainable operational forecast system, achieving this goal is particularly challenging in the context of replacing the current multi-dycore, multi-physics based High-Resolution Ensemble Forecast (HREF) system with a single-dycore, single physics system. An ensemble based solely on the Finite-Volume Cubed-Sphere (FV3) model core requires ensuring sufficient spread with forecast quality meeting or exceeding the current performance of the HREF. Therefore, with a number of questions still remaining, it is essential to investigate different ensemble design methods prior to finalizing plans for the RRFS ensemble.

To this end, previous High Resolution Rapid Refresh (HRRR)-based ensembles have been tested in the context of the Hazardous Weather Testbed (HWT)-Spring Forecast Experiment (SFE), including versions employing time-lagged and stochastic physics options. Forecasters felt that the HRRR Time-Lagged Ensemble (HRRRTLE) was qualitatively on par with the more computationally-expensive HRRR ensemble (HRRRE) without stochastic physics, while quantitative analysis has shown that the stochastic physics version of the HRRRE was able to approach the skill of the HREF. In addition to these assessments, on-going work through the UFS-R2O and High Impact Weather Testbed (HIWT) projects at GSL, EMC, NCAR, and CIRA are focusing on initial testing of an RRFS ensemble. To begin answering questions related to ensemble design, the UFS-R2O activities at GSL and EMC are specifically focusing on ensemble-based data assimilation, cycling, and general RRFS configuration design, while the HIWT work between CIRA and NCAR is focusing on transitioning stochastic physics from the WRF-ARW and the global FV3 into the Limited Area Model (LAM) version of the FV3.

To support the on-going work of the UFS-R2O and HIWT projects in a collaborative and synergistic way, two complimentary questions that the DTC would like to answer under the auspices of this project include: 1) Can time-lagging quantitatively produce ensemble forecast quality on par with (or better) than a traditional ensemble? And 2) What are the relative advantages to model uncertainty through use of stochastic physics or analysis uncertainty through the use of initial condition/lateral boundary condition (IC/LBC) perturbations when trying to optimize ensemble spread/skill ratio? Through the exploration of these questions, the DTC strives to establish some critical ensemble design approaches that help guide decisions for the future RRFS ensemble.

Project Description

For the first and second year of the project, a quantitative comparison between two RRFS-based ensembles will be conducted using data produced during the 2021 HWT-SFE. This assessment will investigate the forecast quality impact on the probabilistic fields between a nine-member single-initialization RRFS ensemble that uses a variety of approaches to contribute to spread (random initial and boundary-condition perturbations, stochastic physics perturbations and a time-lagged ensemble from individual members from separate initializations. The time-lagged RRFS ensemble will also consist of nine members taken from two RRFS ensembles (four members from an RRFS ensemble initialized at 00Z and five members from the same RRFS ensemble, but initialized at 12Z). Once the necessary datasets have been staged in Year 1, MET's *ensemble-stat* tool will be used to combine the ensemble members and output summary fields. MET currently supports a number of smoothing options (e.g., Gaussian) as well as more advanced methods for outputting summary information, such as the neighborhood ensemble probability (NEP) and neighborhood maximum ensemble probability (NMEP) methods. These methods will be consistently applied to both ensembles and will be compared and contrasted to understand the impact on forecast performance. This work will continue into Year 2.

Since representing analysis uncertainty can be just as important to forecast accuracy and creation of appropriate spread, a literature review will be conducted in Year 2 to learn more about the variety of methods that can be used for IC/LBC perturbations in preparation for work later in Year 2 and into Year 3. For example, the team is aware of a number of options, including: IC/first guess and LBC fields for individual ensemble members that can be obtained from different regional/global deterministic or ensemble models, perturbations added through the use of white noise, or bred vectors.

In Years 2-3, following EMC and GSL UFS-R2O-based development of an FV3-LAM-based RRFS ensemble prototype, the DTC will run a series of retrospective cold-start, non-DA cases with the defined configuration of the RRFS ensemble at the time of testing, employing an initial condition perturbation method of choice (chosen based on investigation during Year 2) to assess its impact on forecast spread and accuracy. An equivalent configuration will be run with stochastic physics accounting for model error (employing stochastically perturbed parameterizations (SPP) and ad-hoc stochastic physics) but without IC/LBC perturbations. These two ensemble subsets will then be compared using the same MET ensemble-based metrics from Year 1-2, allowing for a direct assessment of effective spread and its impacts on forecast quality from both methods. These results will also be compared to data from the version of the RRFS ensemble (including model physics uncertainty and DA) contributed to the 2022 HWT-SFE to determine if these techniques improve the spread-to-error ratio of the ensemble and should therefore be used in future RRFS ensemble versions. This comparison will be undertaken in coordination with the HIWT project.

For each of the ensemble configurations described above, a number of traditional and newer, more advanced verification metrics and techniques available within the enhanced Model Evaluation Tools (METplus) verification package will be utilized to examine a variety of model output fields. Not only is it important to assess large-scale environmental fields, such as temperature, moisture, and wind, in the context of convection-permitting forecasts, it is also important to investigate the performance of severe weather attributes such as simulated reflectivity, updraft helicity, and other instability parameters. As forecasts move to higher resolution, it is important to consider the appropriate verification measures to show the strengths and weaknesses of these convection-permitting ensembles. In this regard, neighborhood probabilities will be constructed to evaluate the performance at different spatial scales using the Fractions Skill Score (FSS). When assessing model performance both physical and percentile thresholds may be considered, the latter of which helps to control for bias in the model output. To evaluate ensemble performance, statistics will include measures such as spread, error, spread-skill ratio, reliability, and sharpness. Examining the distribution of variables through the use of probability density function (PDF) and cumulative distribution function (CDF), as well as joint histograms across multiple variables (e.g., CAPE and dew point temperature) will also be useful to assess model climatologies and relationships between fields. From discussions with NOAA's Storm Prediction Center (SPC), there is strong interest in examining model performance specifically in areas that are conducive to storm initiation (for example, areas of high CAPE). In this context, an analysis within masked regions of interest will be performed using tools such as the Method for Object-based Diagnostic Evaluation (MODE) and the new extension called multivariate MODE that allows for super objects to be defined using multiple fields. Finally, to summarize the large number of metrics and variables assessed, a CAM scorecard will be created.

Project deliverables

- Evaluation of ensemble-based verification using RRFS-based ensemble datasets through the use of METplus to assess relative advantages/disadvantages of the time-lagged ensemble approach (Years 1 and 2)

- MET-based evaluation of analysis and model uncertainty representation in the RRFS ensemble to inform future ensemble design (Years 2 and 3)
- Results presented at relevant conferences/workshops (Years 2 and 3)

Sponsors: NOAA (PoP: 4 May 2021 - 3 May 2024)

Toward a Unified Physics Package for the UFS Applications: Advanced Physics Testing, Evaluation and Improvement

Motivation

An ultimate goal of establishing the Unified Forecast System (UFS) is to support the development of a unified physical parameterization suite that can be applied with minimal modification to all UFS applications, from convection-permitting to subseasonal-to-seasonal (S2S) scales. A successful transition to a unified physics package will involve phased retirements of some schemes and adoptions of new advancements. A carefully tailored testing and evaluation (T&E) plan with innovative T&E tools is imperative to the process of unification, aiming at retaining the essence of retiring schemes while ensuring that forecast products across scales are enhanced or at least not degraded.

Project Description

The objective of the proposed study is to facilitate the unification of the model physics by identifying physics suites that adapt across scales and applications through applying the established DTC T&E procedure[3] that follows the Hierarchical System Development (HSD) paradigm. This project will build on the evaluations conducted through the NOAA UFS Research to Operations (R2O) Project and UFS-related Oceanic and Atmospheric Research (OAR) funded projects by considering larger sample sizes and additional multiscale processes and phenomena. The effort will facilitate a continuous evaluation of the operational physics candidates and the integration of GEFSv13 into GFSv17, which are planned to be implemented operationally around 2024, through a close collaboration with the physics developers contributing to the UFS R2O physics subproject. And finally, this project offers holistic and HSD-based T&E for improving model physics in Earth system models by applying a strategy that includes a Single Column Model (SCM), Limited Area Models (LAMs) and global models.

The proposed activity focuses on selected physical processes and weather and S2S phenomena that are multiscale in nature and can provide ideal testbeds to evaluate not only the model physics across scales but also the interdependencies between parameterizations. These processes/phenomena include: planetary boundary layer (PBL) processes over the contiguous United States (CONUS) and the ocean [the latter with a focus on Atlantic tropical cyclones (TCs)], and processes related to gravity wave drag (GWD). The work seeks to answer the following questions:

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[3] The procedure is designed to be agile (frequent, fast, automated), in-depth, neutral, collaborative, and operations-relevant but not operations-prescriptive.

1. *How well are these processes/phenomena represented by using the physics suites that are currently operational? And what major deficiencies in the physics schemes prevent them from reasonably representing these processes/phenomena?*
2. *How can we enhance a physics suite through assessing physics schemes and understanding errors/biases to improve the representations of these processes/phenomena in the forecasts across scales and applications?*
3. *Can the overall predictive skill of the UFS applications be improved by using the enhanced physics suite? If so, by how much?*

Question 1 will be answered through comprehensively evaluating the performance of the UFS applications in representing the selected processes and phenomena. In addition to the existing DTC in-house verification and diagnostic metrics for the PBL processes, the MET-TC and the GWD diagnostics (such as TC genesis and track density functions, absolute vertical momentum flux, and kinetic energy spectra) soon to be available in METplus will be used for evaluating TC activity and physical processes associated with GWD.

Question 2 will be tackled by advancing the physics scheme candidates for GFSv17/GEFSv13 through communicating with the physics developers for further enhancements in the schemes, and then running, testing and assessing the Common Community Physics Package (CCPP) SCM and the UFS LAM simulations for the selected cases with both top-down and bottom-up HSD-based T&E approaches. The cases include the Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO), the Global Energy and Water Exchanges (GEWEX) Atmospheric Boundary Layer Study (GABLS) cases, the Atlantic TCs and the cases for testing GWD in the DTC OAR-funded *Physics Across Scales/PBL* project, along with additional TC cases from the UFS Case Studies project. The diagnostics will focus on the interactions between physics components, particularly the turbulent mixing, surface layer, subgrid convection, GWD, cloud microphysics and radiation. The T&E effort particularly aims at providing a holistic understanding of a) the performance of the Mellor–Yamada–Nakanishi–Niino (MYNN) PBL scheme (candidate for GFSv17/GEFSv13) in representing the boundary layer processes over both land and the ocean and how this scheme interacts with the other parameterizations, where we will focus on the temperature inversions during stable PBL events and how the marine atmospheric boundary layer influences TC structure and intensity, and b) whether and how the Unified Gravity Wave Physics (uGWP; also a candidate for GFSv17/GEFSv13) improves the orographic and non-orographic drag and the predictive skill of Quasi-Biennial Oscillation (QBO). The vertical profiles and distributions of thermodynamic variables, turbulent fluxes, QBO dynamics, and physics tendencies will be examined. Moreover, we will work towards providing a statistically-meaningful assessment for the temporal means and variations of the selected processes/phenomena through batching and streamlining multiple simulations to evaluate against the observations/reanalyses. The project will also leverage the *DTC UFS Evaluation Metrics Workshop* to identify and adopt metrics that are relevant to these processes/phenomena.

Question 3 will be addressed by evaluating the overall performance (beyond the selected processes/phenomena) of the enhanced physics suite in UFS LAM runs over the tropical belt, North Atlantic, and the CONUS and at least one warm-season global forecast configuration. To measure improvements, the LAM and global forecasts will be assessed against operational forecasts, a reanalysis (such as ERA5) and reliable surface, upper-air and satellite observations, and the "Prototype 8" coupled runs conducted by the UFS R2O Coupled Model Development Subproject. The METplus verification and diagnostics framework will be employed for evaluating the surface and PBL parameters over the CONUS, the Atlantic TC diagnostics, and the processes related to GWD.

Project deliverables

- Test plan for informing the refinement of an enhanced physics suite that adapts across scales and applications through HSD-based T&E (Year 1)
- Report on the evaluation of current operational physics suites in representing selected processes/phenomena (Year 1)
- Report on the evaluation of the overall performance of regional and global forecasts using enhanced physics suite (Year 2)
- Briefings to physics developers on findings from the HSD-based T&E (Year 2)
- Presentations at conferences and/or workshops (Years 1 and 2)

Sponsors: NOAA (PoP: 4 May 2021 - 3 May 2023)

Hierarchical Testing for Improvement of Stochastic and Deterministic Physical Parameterizations

External collaborators with independent funding - Subject Matter Experts (SMEs):
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Motivation

Advancing physical parameterizations is a key way of improving the skill of the Unified Forecast System (UFS). However, physical parameterizations are approximate solutions to physical processes occurring in a grid-box and are as such a source of forecast model uncertainty. Examples of model errors associated with physical parameterization schemes are unresolved subgrid-scale variability being treated as a grid-box mean, parameter uncertainty, structural errors, physical processes that have been excluded, incomplete calculations of a process, and inherent process uncertainty. Parameterization schemes are often tuned using ad-hoc methods and informed by expert knowledge; however, objective methods derived from physical constraints can be used to better inform the development of deterministic and stochastic schemes. Parameterizations need to be continually improved and the uncertainty in their representation must be addressed by stochastic methods, which aim to select a random state that is consistent with the resolved state, but sample a subgrid-realization. A comprehensive review of such stochastic parameterization schemes can be found in Berner et al. (2017).

Project Description

In this proposal we aim to use objective methods to inform the development of deterministic and stochastic schemes. The key method proposed here is to compare the state variables and tendencies in a convection-permitting high-resolution simulation against a lower-resolution parameterized-convection simulation. This is achieved by "coarse-graining" the high-resolution simulation (i.e., computing spatio-temporal averages) onto the grid of the lower-resolution simulation (Shutts and Palmer, 2007; Christensen et al., 2018; Christensen, 2020). The premise is that, if the parameterizations work perfectly, the statistics of the state variables in the coarse-grained higher-resolution simulation should match those of parameterized lower-resolution simulations. In reality, discrepancies are typically found in this type of comparison, and can be used to improve the physical parameterizations. Additionally, the high-resolution distribution contains information about the subgrid-scale uncertainty that can be used to objectively inform stochastic parameterizations.

Recently, the resource requirement of setting up such coarse-graining experiments has been reduced by a novel method proposed by Christensen et al. (2018). Here, a high-resolution simulation ("nature run") is coarse-grained and used as forcing for an array of single column models (SCMs). Forcing the SCMs in this way removes the problem of the convection-resolving and -permitting models tending to drift away from each other, and enables one to focus on the physical parameterization aspects. Since different parameterizations suites can be easily compared against a single or several nature runs, this method has been proposed as the protocol for the "Model Uncertainty Model Intercomparison Project" (MUMIP) as a joint project of the WMO Working Group on Numerical Experimentation (WGNE) and the WWRP Working Group on Probability, Dynamics and Ensemble Forecasting (PDEF). As such it represents a collaboration with significant international and domestic groups, and presents an opportunity for informing UFS development. DTC will collaborate directly with the NCAR MMM, NOAA PSL, U. Oxford, MetOffice, and Météo-France. The UK MetOffice and other groups that use SCMs will be running their SCM arrays using the same forcing data, facilitating a comparison of results across this project.

This project will be executed with two components: (1) Conduct runs using the Common Community Physics Package (CCPP) SCM with one or more physics suites relevant to NOAA, and (2) produce diagnostics from these runs to inform parameterization development.

The DTC proposes to run an array of SCM simulations forced by coarse-grained high-resolution model output. The primary forcing, to be used by all international participants, will come from the high-resolution German weather service Icosahedral Nonhydrostatic (ICON) model, which was run with 3-km grid spacing as part of the DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains (DYAMOND) project, in which NOAA was a participant. The ICON model was chosen for use in this proposal because (a) the high-resolution version was scientifically validated, and (b) the high temporal frequency output (three-hourly) needed for the SCM were saved. The ICON output will be coarse-grained and provided by collaborator Prof. Hannah Christensen as part of MUMIP. Additionally, DTC will coarse-grain a 3-km global Unified Forecast System (UFS) simulation provided by the NOAA Global Systems Laboratory. Testing and evaluation of the UFS model will be conducted by comparing the differences between the ICON and UFS tendencies.

Coarse-grained data will be generated over a 40°x40° area over the ocean to avoid complications with land model inconsistencies between the SCM and the high-resolution model. A resolution of approximately 0.2° will be used for the coarse-grained data in order to make the results relevant to the Global Ensemble Forecast System (GEFS) development, which currently runs at C384 (~25 km) resolution and remains the target ensemble resolution for the next GEFS implementation. In order to use this forcing data, the CCPP SCM will ingest forcing fields using the DEPHY format, an international standard agreed upon at a workshop organized by Météo-France in the summer of 2020. This capability is currently under development and will be available by the proposed start date of this project. SCM forecasts will be launched every 3 h and run for 3 h. The first hour of the simulation will be discarded since it is considered spinup, and the third hour will be used to intercompare the SCMs free running output with the coarse-grained ICON 3-hourly model output.

The SCM will use physical parameterizations contained in the CCPP. At least two suites will be used to assess the generality of the results. The first suite will represent GFS v16. The second suite has not yet been determined, but could be a suite being developed for implementation in the Rapid Refresh

Forecast System (RRFS; suite RRFS_v1alpha) or a typical physics configuration of the NCAR Model for Prediction Across Scales (MPAS) to consolidate the NOAA-NCAR collaboration under the MoA and demonstrate interoperability of the physics between MPAS and the SCM. The use of the MPAS suite will depend on its availability in CCPP prior to the start of the project and its ease of use in the SCM.

The SCM output will be made available to the SMEs to conduct diagnostics that will inform the development of stochastic and deterministic parameterizations, e.g., those used in the UFS. DTC will also take on the task of developing diagnostic tools and analyzing the systematic differences between the SCM and coarse-grained high-resolution tendencies. Diagnostics to be computed are:

- **Probability Density Functions (PDF) of SCM tendencies**
  - Intercompare the SCM distributions with the distributions of the coarse-grained high resolution data-set. Assess the mean, median and standard deviation in the vertical of individual parameterized processes.
  - Intercompare the SCM distributions with output from other international collaborators.
- **Conditional Probability Density Function (cPDF) of modelled physics tendencies**
  - Following Christensen (2020), physics tendencies from the coarse-grained high-resolution run(s) can be determined as P = T - D, where T is the total tendency of a state variable between two time-steps and D is the dynamic tendency. PDFs of P, conditioned on the physics tendencies produced by the SCMs (with different intervals) will be computed in order to assess systematic differences and obtain an objective estimate of subgrid-scale uncertainty.
- **Data-base of model-error samples for stochastic parameterization development**
  - A database of state-dependent systematic bias, error, and model uncertainty will be made available to DTC, NOAA and other collaborators for possible use in cycled ensemble-based data assimilation (sampling error).

Furthermore, DTC will collaborate with the SMEs to quantify subgrid-scale uncertainty and characteristics of convection. A report on the testing and evaluation results, which will serve to inform further parameterization development, will be created.

This project supports diversity by connecting the DTC with three women scientists that have agreed to serve as collaborators and subject-matter experts (Judith Berner of NCAR, Lisa Bengtsson of CU/CIRES at NOAA PSL, and Hannah Christensen of University of Oxford). They are each funded through their own projects and do not require any funding from DTC. Dr. Bengtsson is the co-lead of the UFS R2O MRW/S2S Physics subproject, which ensures a strong applicability of these results to the UFS. She is also contributing to the UFS R2O Coupled model subproject in which stochastic physics for the coupled system is developed (Sub-Project leads are Fanglin Yang, Avichal Mehra, EMC and PI for stochastic physics is Philip Pegion, PSL).

Relevance to NOAA

- Testing and evaluation of GEFS physics suite at operational resolution.
- Testing and evaluation of the UFS at 3 km resolution.
- Objective information for improvement of deterministic and stochastic parameterizations.
- NOAA visibility strengthened by involvement in an international project. (If desired coarse-grained UFS can be made available to project partners for further evaluation and testing by other operational and research centers as part of MUMIP.)

Project Deliverables

- Simulations using an array of CCPP SCMs forced by coarse-grained **ICON** high-resolution runs (Year 1).

- Initial report on status of SCM simulations (Year 1).
- Diagnostic tools developed and applied to inform deterministic and stochastic physics development (Year 2).
- Initial report on findings (Year 2).
- Simulations using an array of CCPP SCMs forced by coarse-grained **UFS** high-resolution runs (Year 3).
- Diagnostic tools developed in year 2 will be refined and applied to inform deterministic and stochastic physics development (Year 3).
- Report on findings (Year 3).

Sponsors: NOAA (PoP: 4 May 2021 - 3 May 2024)

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