Unified Forecast System Research-to-Operations (UFS-R2O) Project Proposal

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Executive Summary

This is a proposal to coordinate a large community of researchers, both inside and outside the National Oceanic and Atmospheric Administration (NOAA), to improve numerical weather and climate prediction by further developing and analyzing the Unified Forecast System (UFS), with the ultimate goal of improving the skill of NOAA's operational forecast models. The dual goals of developing modeling innovations suitable for transition from research to operations (R2O) and broadening the access and usage of UFS by the research community are addressed. This UFS-R2O Proposal is being submitted at the invitation of the Office of Science and Technology Integration (OSTI) of the National Weather Service (NWS), specifically the Modeling Program, and the Weather Program Office (WPO) of NOAA Research (Oceanic and Atmospheric Research or OAR), specifically the Earth Prediction Innovation Center (EPIC), Joint Technology Transfer Initiative (JTTI) and Next Generation Global Prediction System (NGGPS) Programs.

Previously, NOAA had established Working Groups, as part of its Strategic Implementation Planning (SIP) process, and Application Teams designed to develop and address scientific and technical priorities for forecast improvement. This proposal focuses on two Application Teams, namely the Medium Range Weather (MRW) and the Subseasonal-to-Seasonal prediction (S2S) team and the Short Range Weather (SRW) and Convection-Allowing Model (CAM) team, which have both developed key foci for research and development. In particular, the MRW/S2S team has identified five priorities:

- Reduce biases of thermodynamic and wind fields in and near layers of high static stability in the lower atmosphere.
- Improved representation of tropical and stratospheric variability, including equatorially trapped tropical modes such as the Madden Julian Oscillation (MJO) and the quasi-biennial oscillation (QBO) in the stratosphere.
- Implementation of a coupled (atmosphere/aerosols/land/ocean/sea-ice/waves) ensemble prediction system in NOAA operations, including data assimilation and reforecast capabilities.
- Improved quantification of model uncertainty in ensemble forecasts, particularly near model component interfaces.
- Advance initialization of (coupled) model forecasts, through improved use of observations and advances in data assimilation algorithms.

The SRW/CAM team has identified four priorities:

- Implement a low-latency Three-Dimensional Real-Time Mesoscale Analysis, updated every 15 minutes, for real-time nowcasting/situational awareness and as the 'analysis of record'.
- Develop a unified Rapid-Refresh Ensemble Forecast System for regional CAM scales to simplify the operational product suite (replacing the current North American Mesoscale – NAM; Rapid Refresh – RAP, Short-Range Ensemble Forecast – SREF systems; NAMnests, High-Resolution Rapid Refresh – HRRR and High-Resolution Ensemble Forecast – HREF system).
- Develop a Warn on Forecast ensemble prediction system, updated every 15 minutes, for ensemble/probabilistic prediction of severe weather.

- Establish connections between SRW-CAM efforts and Hurricane Analysis and Forecast System (HAFS), National Water Model (NWM), and Community Multiscale Air Quality (CMAQ).

There are substantial commonalities in both scientific and technical approaches that are needed to address both teams' priorities. Additionally, there is a requirement for infrastructure development that cuts across the work being done for global and regional forecast problems in order to simplify and unify the collection of software components used operationally and facilitate effective collaboration among community research partners using UFS for experiments and tests in support of the transition from research to operations. The required infrastructure includes modeling infrastructure, which will advance the development of the underlying UFS system architecture to support all UFS applications, and verification and post-processing capabilities that can assist in measuring progress and diagnosing model behavior. Therefore, the UFS-R2O Project will be organized into three main areas: MRW-S2S, SRW-CAM and Cross-Cutting Infrastructure (CCI). Within each of these areas, there will be several sub-projects, 12 in all, as follows:

MRW-S2S

- Coupled model development - Advance the skill of MRW/S2S forecasts with a next generation coupled ensemble prediction system based on the UFS, including improvements to the component models.
- Atmospheric composition - Improved representation of aerosol distribution and aerosol interactions with radiation on S2S timescales in the UFS.
- Data assimilation - Improved use of observations and advances in data assimilation methodology for initializing the UFS, including coupled data assimilation, reanalysis, and reforecasts.
- Atmospheric physics - Improved tropical variability and reduction of model biases through improvements in atmospheric physical parameterization suites.

SRW-CAM

- Three-Dimensional Real-Time Mesoscale Analysis (3DRTMA) - replacing current operational 2DRTMA with more advanced 3DRTMA using the JEDI framework.
- Rapid Refresh Forecast System - targeted to unify many regional and mesoscale systems in current operations with a more advanced RRFS for convection allowing forecast applications.
- Warn on Forecast - development of a novel, on-demand, short-term, rapidly updating, probabilistic ensemble prediction system.
- Hurricane forecast - advancing hurricane modeling capabilities within the UFS framework through the development of Hurricane Analysis and Forecast System (HAFS).

CCI

- Modeling infrastructure - extending the coupled modeling software, supporting the development of more advanced physics, and coordinating workflows suitable for research and operations.

- Verification and post-processing (VPP) - developing and refining a comprehensive set of diagnostic and statistical skill metrics, and a unified post-processing system for ensembles.

Each of the teams that have prepared the proposed work in these subsections is composed of highly qualified scientists from the research community, both inside and outside NOAA. Most of the teams have two leads each, one from NOAA and one from outside NOAA. As a result, it is anticipated that there will be substantial engagement across the community, including NOAA laboratories, NOAA Cooperative Institutes, and university faculty members.

The sub-project leads will conduct regular conference calls with all funded participants. The UFS-R2O project leads will attend these calls as needed. The UFS-R20 project leads will organize monthly calls including the sub-project leads to assess progress on project milestones and facilitate coordination across sub-projects and with the National Center for Environmental Prediction (NCEP) implementation schedules. Quarterly reports will be developed by the UFS-R20 project leads, using input from the sub-project leads, and presented to OAR/OSTI program office staff and OAR/NWS leadership. A more detailed management plan is included as an Appendix.

In the following three sections, the proposed work in each of these main areas is described, broken down for each sub-project. Each sub-section contains:

- A targeted set of substantive forecast and development goals, the science priorities needed to make progress toward them, along with a timeline for achieving these goals and for implementation. A concrete 2-year plan and a 5-year vision.
- A transition plan to operations, as well as a plan to establish multiple testing levels (gates) as the development moves towards implementation.
- Success metrics, including a combination of forecast skill, research, and technical achievements.
- Computing plans, including a carefully coordinated set of simulations, and strategies for obtaining allocations.
- Alignment with the UFS Strategic Implementation Plan (SIP) and a plan for how the UFS-R2O Project will interact with the rest of the UFS ecosystem, for example making use of the Steering Committee and Working Groups.

In addition, the following aspects are described where appropriate:

- Plans to engage forecast perspectives by working with appropriate Centers or field offices (e.g. NOAA Science and Operations Officers - SOOs) and to integrate forecast goals/priorities into the project verification and post-processing plans.
- Plans to engage and support the community in using the UFS.
- Plans to continue unification (as much as possible) of model components and infrastructure, including a timeline for unification.
- Data and software management plans, in coordination with the UFS, including e.g. code-sharing protocols, software documentation, testing protocols, etc.

Section 1: Medium Range and Subseasonal to Seasonal Applications

The UFS forms the core of NOAA's operational global modeling system for global weather, including the Global Forecast System (GFS) for medium range weather out to 16 days and the Global Ensemble Forecast System (GEFS) for subseasonal ensemble forecasts out to 45 days. Currently, the UFS consists of the FV3 dynamical core with the Common Community Physics Package (CCPP) for the atmosphere, MOM6 for the ocean, GOCART for aerosols, CICE6 for sea ice and WW3 for ocean waves. NOAH, NOAH-MP and RUC land models are currently available as options within the CCPP framework. The components are coupled using the NOAA Environmental Modeling System (NEMS), which is being superseded by the Community Mediator for Earth Prediction Systems (CMEPS). The Joint Effort for Data Assimilation Integration (JEDI) project will provide the data assimilation system to initialize the model forecasts using observations spanning all components of the coupled system.

The Medium-Range and Subseasonal-Seasonal (MRW/S2S) component of the UFS-R2O project is focused on transitioning cutting-edge research into the operational GFS and GEFS. The primary development foci for advancing the skill of NOAA's operational predictions of MRW/S2S timescales are:

- Diagnose the sources of and mitigate atmospheric model biases associated with parameterized physics deficiencies, especially those associated with layers of high static stability in the lower atmosphere that affect the initiation of convection and the representation of land-atmosphere interactions.
  - Improved representation of tropical and stratospheric variability, including equatorially trapped tropical modes such as the Madden Julian Oscillation (MJO) and the quasi-biennial oscillation (QBO) in the stratosphere.
- Implement a coupled (atmosphere/aerosols/land/ocean/sea-ice/waves) ensemble prediction system in NOAA operations, including data assimilation and reforecast capabilities.
- Improve quantification of model uncertainty in ensemble forecasts, particularly near model component interfaces.
- Improve initialization of (coupled) model forecasts, through improved use of observations and advances in data assimilation algorithms.

These objectives are the driving force for advancing the GFS and GEFS over the next five years, and the plan for addressing them is organized into five sub-projects. Briefly, the sub-projects and their primary deliverables over the next two years are as follows:

- Coupled Model Development
  - Identify and mitigate systematic biases in the coupled system, particularly at and near the surface.
  - Extend and refine stochastic parameterizations of model uncertainty for all coupled system components, particularly near the component interfaces.
  - Develop an end-to-end ensemble forecast system (including data assimilation), assess performance and implement operationally as GEFS v13.
  - Improve the numerical consistency and conservation properties of the FV3 component of the UFS.
  - Identify and mitigate systematic biases in the NOAH-MP land model so that it can replace NOAH in GFS v17 and GEFS v13.
- Atmospheric Composition

- Overarching goal: Improved representation of aerosol distribution and initial inclusion of aerosol interactions with radiation on S2S timescales for GEFS v13. Major supporting goals are:
    - Create global aerosol emissions processing system for GEFS v13.
    - Create biomass burning emissions system for S2S timescales for GEFS v13.
    - Improved representation of aerosol species and vertical profiles, quality control and bias correction procedures in a JEDI-based AOD data assimilation system for GEFS v13.

- Data Assimilation (DA)
  - Transition JEDI into operations for use in the Global Data Assimilation System (GDAS) as a replacement for the current GSI system for atmospheric DA (joint with coupled DA/R&R sub-project).
  - Using JEDI, perform an intercomparison of hybrid 4D-EnsembleVar and hybrid ensemble 4D-Var algorithms for atmospheric applications.
  - Perform a 30-year reanalysis of the ocean/sea-ice system based on JEDI/SOCA (Sea-ice Ocean Coupled Assimilation) for testing and validation of SOCA and for use in the Climate Prediction Center (CPC) ocean monitoring applications.
  - Develop a JEDI-based capability for assimilation of snow and soil moisture data in stand-alone (land) and coupled systems.
  - Deliver a complete set of unified forward operators and associated quality control for JEDI.
  - Transition a coupled data assimilation system based on JEDI to initialize all state components of the operational GFS v17 and GEFS v13 (joint with Data Assimilation sub-project).
  - Develop and test new coupled data assimilation strategies, such as strongly coupled data assimilation, so that they are available for future operational implementations beyond GFS v17 and GEFS v13.
  - Develop the capability for routine generation of reanalyses of the coupled state, and ensemble re-forecasts from those reanalyses, using cloud compute resources. Deliver a reforecast dataset that can be used to calibrate products based on GEFS v13.
- Atmospheric Physics
  - Select and implement a new microphysics scheme from CCPP suitable for both global and convection-allowing scales and implement in GFS v17.
  - Mitigate known model biases resulting from physics deficiencies (including the representation of low-level stable layers) in GFS v16, implement GFS v17.
  - Through a multi-agency collaborative effort, develop a next-generation moist physics suite (leading to a better representation of tropical modes of variability).
  - Implement an updated Unified Gravity-Wave Parameterization (UGWP version 1) for GEFS v13 and GFS v17 that improves forecasts in the stratosphere and mesosphere.

1.1 UFS-R2O MRW/S2S Sub-project -- Coupled Model Development

UFS-R2O Task: : Coupled Model Development
Team: MRW/S2S
Sub-project area: Coupled Model Development
Sub-Project Leads: Avichal Mehra and Fanglin Yang (EMC), Christiane Jabnolowski (UMich)
Sub-project organizations proposed for: NOAA/NCEP/EMC, NOAA/ESRL/PSL, George Mason University (GMU), University of Michigan (UMich)

Sub-project Narrative

1. Sub-Project Overview.

This sub-project is aimed to develop a coupled ensemble prediction system, which consists of GFS, MOM6, CICE6, CMEPS and WWIII, for medium-range weather and subseasonal to seasonal forecasts for operational implementation at NCEP in 2024. The project focuses on a) improved couplings between components, performing testing and evaluation of prototypes; and, b) developing and refining stochastic parameterizations in the land, atmosphere, and ocean to improve coupled data assimilation and ensemble prediction.

To build a state-of-the-art coupled forecast system requires the participation of all SIP working groups to develop model physics, dynamics, coupling infrastructure, coupled data assimilation and verification and validation strategies. This sub-project is focused on the application of the coupled system for medium-range weather and S2S forecasting. The goal is to develop a coupled model suitable for medium-range and S2S forecasting, to incorporate and test new and improved science and technology presented by the WGs in the coupled system, to investigate model forecast biases and feedback to the developers, to set up and test the system in the NCEP operational environment, and ultimately to put together the best performing coupled GFS-MOM6-CICE6-WWIII system for operational implementations of GFS v17 and GEFS v13 in 2024.

Ensemble prediction is an essential part of this coupled system. This sub-project will also develop and refine parameterizations in the coupled UFS to provide more physically based, process-level stochastic representations of model uncertainty. This is expected to improve ensemble spread and reduce systematic error, both in coupled data assimilation and free forecasts. In coordination with the physics development application team, a long-term vision is to include a capability of modeling the stochasticity that is intrinsic to physical processes on subgrid scales in the advanced UFS physics suite for operations.

2. Sub-Project Justification and Technical Approaches.

The UFS mission is to create more accurate forecast guidance using the UFS for applications that span local and global domain and predictive time scales from sub-hourly to seasons. Currently the

NCEP Environmental Modeling Center is using the uncoupled Global Forecast Systems (GFS) for high-resolution deterministic medium-range weather forecast and the uncoupled Global Ensemble Forecast Systems (GEFS) for medium-range global ensemble prediction. The current S2S forecast system is an extension of the seasonal forecast system, Climate Forecast System (CFS v2), which was implemented in operations in March 2001.   Version 15 of the GFS was implemented in June 2019 for operational medium-range weather forecast. It consists of the GFDL Finite- Volume Cubed-Sphere Dynamical Core (FV3) and improved model physics. Work is now underway towards building the GEFS v12 and GFS v16 for implementation in 2020 and 2021. They are still built upon the uncoupled atmospheric model.

Coupled atmosphere-land-ocean-ice models have long been used for climate prediction and seasonal forecasting. However, more recent research and applications in a few leading international NWP centers have shown that even on the medium-range weather timescale the interactions between the atmosphere, ocean, wave and sea-ice can provide extra predictive skills. The UFS is envisioned to be a community-based coupled comprehensive Earth system modeling system, which includes GFS, MOM6, CICE6, WWIII component models and the CMEPS coupler.

EMC has been working with the community in the past couple of years to build the GFS-MOM6-CICE5-WWIII coupled forecast system. A set of prototype tests have been conducted without data assimilation to configure the system and to assess its forecast capability. These tests were conducted at the C384 (~25km) horizontal resolution with 64 layers in the vertical using the GFS v15 physics package. Initial conditions were converted from the CFSR for the land and atmosphere, CPC's 3D-Var analysis for the MOM6 ocean and CPC's ice analysis for CICE5. The coupling to WWIII is currently under development.

This project is aimed to use the aforementioned system to build a coupled NWP forecast system for operation in 2024. The atmospheric component will be upgraded to the GFS v16 configuration at the C768 (~13km) horizontal resolution with 127 layers extending to the mesopause in the vertical. GFS v16 physics package will be used for initial testing and evaluation. GFS v16 instead of CFSR will be used for producing the atmospheric and land initial conditions.

Continuous integration and evaluation will be exercised. The success of this project largely depends on the work carried out by different SIP working groups and the EMC coupled model development team. It requires close collaboration and coordination to configure and optimize the system for its best computational performance, to update model physics and dynamics for reducing systematic biases, to test and evaluate different coupling and initialization methods, and to assess its performance at different spatial and temporal scales. For example, the Hierarchical Test Framework of the Developmental Testbed Center (DTC) will be used for diagnosing/validating physics in the coupled framework. The system will be tested with data assimilation included after its initial evaluation. Weakly coupled DA within the JEDI framework will be used to produce initial conditions separately for the land-atmosphere, ocean, sea-ice and wave subcomponents. While the coupled system will be configured and tested for forecasts at both the medium-range and S2S timescales, the integration of the GEFS 13 into GFS v17 requires more effort, especially for GEFS initialization and perturbation in the coupled system.

Ensemble prediction is an essential part of this coupled system. It is designed to accurately predict forecast uncertainty, including their spatial and temporal relationships. Uncertainty estimates in a coupled prediction system will require: (a) proper estimation of coupled state initial-condition uncertainty, and (b) accurate representation of the uncertainty due to forecast imperfections, including limited model resolution. This second consideration is commonly referred to as "model uncertainty." Continuing to address them in scientifically valid and computationally tractable ways is the focus of this project component. Through cycled data assimilations, misrepresentations of model uncertainty in short-term forecasts can degrade the quality of ensemble background forecasts that are used in data assimilation. Hence, we seek model uncertainty representations that will provide realistic estimates of the background-state forecast uncertainty, both in the representation of forecast variance for overall weighting of background forecast vs. observations, and in the spatial covariances and cross-state covariances. Accurate representations of these allow observations from one state component to realistically spread in space and time and to modify another state component. For longer-lead free forecasts, improved stochastic parameterizations will help provide more accurate estimates of coupled-state forecast probabilities, which can be further improved with statistical postprocessing.

Furthermore, this sub-project will assess and advance the conservation properties of the FV3-based model families (with a particular focus on the total energy, angular momentum, entropy, and potential vorticity), promote the thermodynamic consistency of the FV3 dynamical core and its various Common Community Physics Package (CCPP)-based parameterizations, advance the consistency of the physics-dynamics coupling and the coupling strategies to other UFS components, evaluate pathways how to embed new physical paradigms, enhance the consistency of tracer correlations, support the consistency of nested and stretched configurations, and provide insight into the FV3 damping characteristics, fixer and filling mechanisms, and numerical stability (Jablonowski and Williamson, 2011). Enhancing the FV3 design, consistency, stability and conservation is paramount for the long-term success of the UFS and its envisioned key applications. The impact of the FV3 numerical and design adjustments will be assessed across a wide span of spatial and temporal scales that utilize a hierarchy of model configurations with increasing complexity. These include dry and idealized moist FV3 setups as e.g. defined by the Dynamical Core Model Intercomparison Project (DCMIP; Ullrich et al., 2017), or by Whitehead et al. (2015), Yao and Jablonowski (2016), Thatcher and Jablonowski (2016), Lauritzen et al. (2014, 2019) and others. In addition, aqua-planet simulations, forecast configurations with active land and prescribed sea ice distributions and sea surface temperatures, and coupled simulations will be utilized. The FV3 research will take advantage of both the UFS and NCAR's upcoming CESM2.2 modeling frameworks. The latter provides readily an access to idealized FV3-based model configurations.

The land tasks in this sub-project address both the evaluation framework and land model developments in a coordinated way. As shown by e.g. Dirmeyer et al. (2018) the skill of weeks 3-4 forecasts of temperature and precipitation over continental areas is dependent on the antecedent soil moisture conditions and the forecast model's ability to properly represent the processes linking land anomalies, surface fluxes, and atmospheric physics. This impact is evident on day one, with peak impact on forecast skill during week 2 (Dirmeyer and Halder 2016, 2017). Models lacking proper coupled land-atmosphere behavior will underperform in situations like droughts and heat waves, and will be prone to systematic biases in temperature, humidity and precipitation. The goal is to ensure equal, and achieve superior, model performance with Noah-MP as the future operational land model in UFS. The Noah-MP land system model (LSM) is a community-based model that was developed specifically to address known limitations of the Noah LSM and to use multiple options for key land-atmosphere interactions. It improves upon Noah in multiple ways. For example, it uses (1) a tiled approach to separate vegetation and bare soil, (2) Ball-Berry stomatal resistance related to photosynthesis (Ball et al., 1987), (3) a dynamic vegetation scheme, (4) a multi-component, separate vegetation canopy (Niu et al., 2011) (5) a two-stream radiative transfer approach along with shading effects necessary to achieve proper surface energy and water transfer processes including under-canopy snow processes (Dickinson, 1983; Niu and Yang, 2004), (6) a multi-layer snow pack with liquid water storage and melt/refreeze capability and a snow-interception model describing loading/unloading, melt/refreeze capability, and sublimation of canopy-intercepted snow (Yang and Niu 2003; Niu and Yang 2004), (7) multiple options for surface water infiltration and runoff and groundwater transfer and storage including water table depth to an unconfined aquifer (Niu et al., 2007). These additional features have the potential to significantly improve the realism of land-surface, hydrology, and atmosphere interactions, but they also significantly increase the complexity of the model and thus the degree of difficulty in optimizing its performance.

This sub-project will develop a hierarchical testing approach, including a single-column coupled land-atmosphere modeling system to isolate and quantify the impacts of individual components before systematically increasing complexity and inherently introducing non-linear, difficult to track interactions. The scope of this work is to identify the causes of those uncertainties, provide solutions and ensure the successful implementation of Noah-MP in GFS v17. Multivariate statistics using daily mean and hourly data will be used to evaluate model process fidelity, in the form of land-atmosphere coupling metrics developed under the Global Energy and Water Exchanges project (GEWEX). This provides a direct pathway to diagnose problem areas in the model process chain, which enables identification of specific parameterizations, even specific subroutines, that are the source of poor model performance. These metrics are used for model evaluation at many operational forecast centers around the world, and address both the separate and joint behavior of land and atmosphere models in representing the effect of land state anomalies (foremost is soil moisture, but also snow cover and vegetation states) on lower atmospheric states, boundary layer characteristics, cloud formation and precipitation. Metrics are based on sensitivity (dB/dA where A is a driver and B a response, each can be states or fluxes), covariability, breakpoints (e.g., critical soil moisture values where fluxes change abruptly), budgets and feedbacks (e.g., triggering of cloud formation across a range of Bowen ratio).

The evaluation results will inform the following development tasks:

- Install and tune Noah-MP in the UFS through the CCPP physics framework and work towards a fully coupled LSM component via the Earth System Modeling Framework (ESMF)/NUOPC cap.
- Use a hierarchical testing framework to evaluate and compare the performance of the predecessor model Noah and the future operational Noah-MP LSM, and develop a thorough understanding of interactions with other physical parameterizations in a simplified dynamical framework.
- Compare the performance of the two LSMs within the UFS for different applications across all relevant scales.

The land project will thereby provide well-tested, understood, and optimized LSM options for UFS applications and research. Moreover, it will provide a foundation for the unification of LSMs and promote broader community engagement in improving those critical issues.

3. **For those projects that involve UFS development (either forecast model or data assimilation), please include a description of how you will measure progress.**

The coupled model will be developed for both weather and subseasonal-seasonal forecasts. For the weather application, GFS v16 forecast capability will be used as the baseline. The metrics that have been used in the past for making decisions of GFS implementations and documented in the GFS v16 Evaluation Plan will be adopted for measuring the progress of the coupled model development. Headline forecast skills including 500-hPa height anomaly correlation, CONUS precipitation equitable threat scores (ETS), hurricane track and intensity scores shall not be degraded. For the S2S application, GEFS v12 and CFS v2 forecast capabilities will be used as the baseline. In addition to assessing model forecasts of 2-m temperature and precipitation that are of interest to forecasters, the ability of the model to predict the sources of S2S predictability (NAO, MJO, etc.) will be evaluated as well. S2S prediction skills largely depend on the capability of the model in capturing the observed low frequency phenomena (QBO, MJO, NAO, SSW, Rossby wave packets) and have the appropriate teleconnection patterns. More details are documented in the UFS Development Goals and Priorities for Medium-range and S2S applications document. A target for measuring progress is the reliability of forecasts of S2S sources of predictability, such as the spread-error relationship of index based forecasts (RMM, NAO).

Stochastic physics will be evaluated at both weather and S2S time-scales, where GEFS v12 will be used as a baseline for medium range forecasts and the UFS without stochastic physics will be used as a baseline for S2S time-scales. Ensemble metrics will be used to measure progress as well as model variability estimates for S2S time-scales (such as frequency distribution, space-time frequency diagrams, MJO index etc.). A test-plan will be detailed as a first milestone.

The land related tasks will measure progress in comparison to the current Noah LSM baseline model in both stand-alone and coupled land-atmosphere mode. In addition, comprehensive comparisons to observations will be provided that utilize GMU's multivariate evaluation framework. In particular, the LSM progress will assess the overall forecast skill scores, and the biases of (1) soil temperature and moisture, (2) surface temperature and 2-meter air temperature, (3) surface dew point and 2-meter dew point, and the (4) surface energy components.

The consistency and accuracy of the FV3 atmospheric component will be evaluated via conservation properties (energy, angular momentum, entropy, potential vorticity), correlations between passive tracers, assessments of the physics-dynamics interactions as well as the impact of diffusive mechanisms.

4. Two Year Plan and Five Year Vision:

Two Year Plan:

Timeline	FY 20	FY21				FY22		
Milestone	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
1. EMC: GFS-MOM6-CICE6-WWIII-CMEPS coupled model development. a) continue to conduct C384L64 benchmark test with GFS v15 physics to improve forecasts of SST, sea-ice, T2m, precipitation, air-sea fluxes and atmospheric and oceanic circulations etc., b) develop a workflow for the coupled system that serves for the development at EMC and the community and for future operation at NCO, c) complete the coupling to WWIII, d) update CICE5 to CICE6, e) migrate to more advanced CMEPS mediator, f) update to GFS v16 physics and transition to CCPP physics package, g) conduct prototype coupled NWP forecast at C768L127 resolution, i) experiment with JEDI-based data assimilation system, j) test updated stochastic physics from Milestone 3, k) prepare prototype coupled NWP experiments at C768L127 resolution and S2S experiments at C384L127 resolution.	a, b, c	a, b, d, e	a, b, f	a, b, f, g	a, b, g	g, i	i, j	i, j, k
2. GMU: a) coordinate with EMC conducting benchmark tests with GFS v15 physics and diagnose systematic biases related to SST, and air-sea interactions, precipitation and atmospheric circulations. b) assist EMC in testing the CMEPS mediator. c) coordinate with EMC conducting benchmark tests with updated CICE6 and diagnose systematic biases in precipitation and atmospheric circulations. d) coordinate with EMC conducting benchmark tests with GFS v16 physics - CCPP physics package and evaluate model biase. e) coordinate with EMC conducting prototype coupled NWP forecast at C768L127 resolution, f) prepare and submit publications with results from C768L127 cases. g) coordinate with EMC different coupling strategies for NWP and S2S applications. h) prepare and submit publications with the results based on the S2S application.	a, b	b, c	c, d	d, e	e, f	f, g	g, h	f, h

3. PSL: stochastic physics (a) land / land-atmosphere; identify key parameters controlling land surface sensible and latent heat flux partition, and test perturbing these parameters, and directly perturbing the soil moisture and temperature. Deliver (a1) results, (a2) code, (a3) article. (b) Atmosphere: continue develop/ test process-level stochastic physics for the atmosphere; (b1) test-plan, (b2) results, (b3) code, (b4) article. (c) (c1) Ocean and ocean-atmosphere: test and tune the extant SPPT → ocean vertical mixing. (c2) [possible] Stochastic Gent–McWilliams ocean parameterization. (c3) [possible] Stochastic physics for inter-relationships between ocean temperature, salinity, and currents.	c1 b1	a1,	a2, c2	c1	a3, c3 b2	b3		b4
UMich: Embed model diagnostics into FV3-based models to analyze diffusion properties, conservation leaks and inconsistencies.	x	x	x	x				
UMich: Improve FV3 consistency via tailored numerical design choices and evaluate their impact.				x	x	x	x	x
GMU: Develop UFS data ingest to apply multi-variate diagnostic metrics to land and coupled land-atmosphere configurations.	x	x	x	x				
EMC:Develop and refine the Noah-MP code structure	x	x	x	x				
EMC: Design, implement and test Noah-MP physics upgrades				x	x	x	x	x
GMU: Use multivariate land-atmosphere process diagnosis to inform Noah-MP model developments for UFS' FV3GFS-based suite.				x	x	x	x	x

5. Five-Year Vision.

Conduct prototype tests with data assimilation included. Explore different model initialization methods in the JEDI framework with weakly coupled subcomponents. Evaluate model performance in the coupled system. Configure the coupled system to run parallel experiments for pre-implementation evaluation. Update and optimize the entire system, including the coupled model, workflow, post-processing and product generation, to follow NCEP model implementation standard. Engage the user community for evaluation. Perform reanalysis and reforecast to support GEFS v13. Prepare for GFS v17 and GEFS v13 implementations.

Implement a suite of stochastic parameterizations that are physically consistent with the advanced physics suite in the coupled UFS at parameterized process levels. The implementation will provide accurate estimates in cycled data assimilations and of the forecast uncertainty at S2S time scales of each state component, with concomitant improvements in the resulting atmospheric variability of extremes. We expect that simple parameterizations of ocean-state uncertainty, simple representations of surface-wind uncertainty, and simplified treatments of uncertainty in the land-states and parameters controlling the land surface sensible- and latent-heat flux partition would be ready for advanced testing in the GEFS in ~2021-2022, with more complex and accurate representations ready for advance testing a year or two later, including sea-ice uncertainty, coupled ocean/sea-ice uncertainty, and additional land parameter uncertainty due to within grid-cell heterogeneity. We will also work together with the physics application team to develop an advanced atmospheric physics parameterization suite in the coupled UFS for operations that is inherently stochastic for uncertainty representations at process level. The atmospheric parameterization suite will contain a holistic stochastic uncertainty representation for moist physical processes, integrating the Cellular Automata (CA) based stochastic convection and PBL mixing parameterizations with a stochastic cloud microphysics parameterization, as well as additional contributions from the land state and parameter uncertainty. In this integration, we will also develop a physically consistent "backscatter" for projecting subgrid stochastic process fluctuations onto resolved-scale flows.

6. Interdependencies with other projects/EMC planned implementation timelines and/or any major risks and issues.

This sub-project depends on the work of all SIP Working Groups, including Physics, Dynamics, Marine, DA, System Architecture, Post Processing, Ensemble, Air Quality, land and V&V. For the first two years, work progresses made by the DA, Physics, and System Architecture WGs are the most critical to this project.

For the development of stochastic physics, we expect extensive collaborations with the model physics group, the land-surface team, marine models, and with coupled DA developers and their projects.

Risks/Issues:
a) lack of adequate computational resources;
b) coordination with other sub-projects and SIP working groups;
c) hiring of experts with relevant subject-matter expertise.
d) The UFS roadmap outlines an ESMF/NUOPC coupling option for the LSM which will become an alternative to the current CCPP-based coupling strategy for the land component. Such a development effort is currently unfunded.
e) lack of sustained funding beyond FY2020

7. Specify how organizational base-resources (in-kind) will be leveraged for this sub-project.

EMC federal employees and contractors funded by NOAA base resources will contribute to the development and implementation of GFS v17 and GEFS v13.

ESRL/PSL is investing base resources and has matching funds from other projects to improve process diagnostics, which will be leveraged to speed the development of stochastic parameterizations. PSL has some base resources devoted to coupled data assimilation, ensemble prediction system development, and data-assimilation development. These investments are manifested in part in funding the federal scientists for their work and their project management.

8. Please provide an estimate of compute resource requirements, both in terms of CPU hours per month and disk storage.

It is estimated GFS v16 (C768L127), to be implemented for operation in Q2FY21, needs 850 nodes on WCOSS to meet operational product delivery time requirement. GFS v16 is uncoupled and only consists of the atmosphere model and a one-way-coupled wave model. The coupled model development will first be carried out using the C384L64 configuration and move onto C384L127 for the S2S application and C768L127 for weather application. Most of the development will make use of EMC's existing allocations and be conducted on NCEP operational computers (WCOSS) and NOAA R&D computers including Hera, Jet, Orion and Gaea. The current allocation for EMC fv3-cpu account on Hera, which is primarily used for GFS v16 model development, is 5-million core hours per month. We need an extra 15-million hours per month on R&D computers for the coupled model development. The estimated extra R&D disk usage is 500 TB.

Coupled stochastic physics development currently uses a configuration of the UFS coupled model (C384 atmosphere, ¼-degree ocean and ice) and costs about 2200 core hours per 35-day forecast. Reducing the atmosphere resolution to C96 reduces the cost to about 950 CPU hours per forecast. In order to get decent statistics, 10-member ensembles need to be run for at least 10 years of hindcasts, and a minimum of 4 start dates per year. Thus each experiment would cost 367000 core hours, and 2 TB of storage (at C96 resolution). We can expect to average one experiment per month, for a total of 4.4M CPU hours per year and 24Tb of storage.

The total requirement, not covered by existing allocations, is 184.4M core hours per year and 524Tb of storage.

In addition the University of Michigan collaborators require 2.04M CPU hours per year and 2 Tb of storage.

9. Summary of known team members and institutions (expected FTE commitment), including what resources are leveraged, including federal salaries or synergistic projects.

Name/ organization	**Subject matter expert/milestone effort**	**Commitment level (FTE)**	**Amount leveraged (if any)**	**What is leveraged? (office space, time, computing)**
EMC, Coupled Model Development	3 existing contractor FTE's covering Coupled Model Diagnostics; MOM6 Coupling; Physics and Reanalysis and Reforecast activities; 1.5new hires for Sea Ice Coupling, Coupling Strategy, and Bias Reduction. Develop the coupled system and implement GFS v17/GEFS v13 for operation. They will work on developing and testing different coupling and initialization methods, reducing model systematic biases, conducting and evaluating parallel experiments for implementation, and carrying out GEFS v13 reanalysis and reforecast tasks	4.5 FTE /year +publication and travel support	2.1 FTE EMC federal employees who are working on the coupled system project 4.5 FTE Contractors supported by SLA funding	Existing HPC allocations on WCOSS, Jet, Gaea, Hera and Orion; NCWCP office space.
EMC, Land Model Development	Refine the Noah-MP code structure, define a hierarchical testing framework and improve Noah-MP via optimal physics upgrades, define	2.6 FTE /year +publication and travel support		In-kind support: M. Ek (NCAR), E. Shevliakova (GFDL), T. Smirnova (ESRL)

	LSM roadmap			
PSL Stochastic Physics	Clara Draper (land), Lisa Bengtsson and Jian-Wen Bao (atmosphere); Phil Pegion, Steve Penny, others TBD (ocean, software engineer/computations)	~2.7 FTE /year +publication and travel support	Whitaker and Hamill each 0.1 FTE	Lab, computational facilities.
GMU, Coupled Model Development	Two graduate students (TBD) will be fully supported. The graduate students will run the various configurations of the model versions to speed up the generation of data for model evaluation. The students will also contribute to model evaluation. Co-PI Stan will be partially supported to coordinate the activities of the Global Weather Application Team with the other co-leads. After projects are funded, the AT co-leads will organize regular teleconferences with the members of projects funded to address the objectives of AT.	2.1 FTE/year +publication and travel support		GMU office space, local computing facility
GMU: Land Model Development	Define multivariate process diagnosis, evaluate and inform the Noah-MP land model design & coupled land-atmosphere model behavior	Paul Dirmeyer 0.08; Postdoc 1.0		In-kind support: M. Ek & R. Dunlap (NCAR)
UM: Dycore Development	Improve accuracy and physical consistency of the FV3 dynamical core, evaluate FV3 model design choices	Christiane Jablonowski 0.16; Grad Student 1.0		In-kind collaborator support: P. H. Lauritzen (NCAR), L. Harris (GFDL)

1.2 UFS-R2O MRW/S2S Sub-project Atmospheric Composition

UFS-R2O Task: S2S Atmospheric Composition

Team: MRW/S2S
Sub-project area: Atmospheric Composition
Sub-Project Leads: Ivanka Stajner (NWS/EMC), Gregory Frost (OAR/ESRL/CSL)
Sub-project organizations proposed for: NOAA/OAR/ESRL/GSL, NOAA/OAR/ARL, NOAA/OAR/ESRL/CSL, UCAR/JCSDA, NOAA/NESDIS/STAR. NOAA/NWS/NCEP/EMC is participating in-kind.

Sub-Project Narrative

1. Sub-Project Overview.

Over the past 4 years, participants in this sub-project developed substantially improved 5-day aerosol prediction in the GEFS v12-Aerosol member, demonstrating a successful R2O transition. The 2016 National Academies Study on the Future of Atmospheric Chemistry Research identified a priority to "*Advance the integration of atmospheric chemistry within weather and climate models to improve forecasting in a changing Earth system*". Furthermore, the European Centre for Medium-Range Weather Forecasts (ECMWF) demonstrated that incorporating aerosols in their model improves prediction of weather for weeks 3 and 4 (Benedetti and Vitart, 2018), motivating the goals proposed here.

This project will develop improved representation of atmospheric aerosols in the MRW/S2S system targeted for global subseasonal prediction in GEFS v13. Potential use of predicted aerosol in atmospheric physics, starting with aerosol feedback on radiation, will be coordinated with the physics area. Assimilation of aerosol optical depth (AOD) to constrain aerosols and potential use of aerosols in radiance assimilation will be coordinated with the data assimilation (DA) area. Much of DA development will be leveraged from EMC and GSL in-kind contributions. The 5-year vision for UFS includes CAM-resolution inline air quality predictions for the U.S. and atmospheric composition prediction beyond aerosols globally, including aerosol feedback on weather and S2S prediction.

The specific goals for next two years are:

1. **Key goal: Improved representation of aerosol distribution and initial inclusion of aerosol interactions with radiation on S2S timescales for GEFS v13**

and four major supporting goals:

2. **Global aerosol emissions processing system based on HEMCO for GEFS v13**
3. **Biomass burning emissions for S2S timescales for GEFS v13**
4. **Quality control and bias correction procedures for AOD data assimilation for GEFS v13**
5. **Assist AOD data assimilation system development with focus on improved representation of aerosol species and vertical profiles for GEFS v13**

2. Sub-Project Justification and Technical Approaches.

NOAA/NCEP currently uses a standalone system based on an old GFS version with a spectral dynamical core for 5-day operational aerosol prediction. Over the past 4 years, investigators on this sub-project developed substantially improved 5-day aerosol prediction that will be included in the FV3-dynamical-core-based GEFS v12-Aerosol member (planned implementation in calendar year 2020). With this implementation NCEP will remove the standalone aerosol prediction system from operations and begin integration of aerosol prediction into the UFS through GEFS.

The work proposed here for the first two years will extend aerosol prediction in the UFS from 5 days to S2S timescales. The Key Goal of this work is: *Improved representation of aerosol distribution and initial inclusion of aerosol interactions with radiation on S2S timescales for GEFS v13.* This Key Goal is supported by model improvements (see Goal 1a below), emissions improvements (Goals 2, 3), and the development of improved aerosol representation in an AOD data assimilation (DA) system (Goals 4, 5).

This sub-project directly supports the following UFS MRW/S2S application priorities:
1 c) Reduce temperature biases in the troposphere, SST biases, and sea-ice biases - Update aerosol climatology, improve use of aerosols in microphysics
5 e) Improved data assimilation - algorithms, use of observations/obs QC and bias correction

The global aerosol prediction development proposed here for years 1 and 2 supports UFS Atmospheric Chemistry and Air Quality applications in three ways: by improving operational global aerosol predictions, by extending their range to S2S scales, and by improving lateral boundary conditions for operational air quality predictions for the United States.

The sub-project team includes participants from NOAA and NOAA Cooperative Institutes. The proposed work develops the UFS aerosol component for GEFS v13 operational predictions. This aerosol component code will be provided to the broader scientific community through NASA's public repository. The emissions development includes coordination and integration of tools with NASA and the GEOS-Chem community. Evaluations of model performance will include METplus community tools as they become available.

Relationship to EPIC

Due to computational needs for integrations at S2S timescales, this sub-project would benefit from software engineering efforts that EPIC may provide to make codes more robust, portable and efficient on NOAA's and community computer architectures. Should cloud computing resources become available to the project, EPIC support of UFS codes in the cloud will be helpful. EPIC community support experts could help share and support the codes developed here with the broader community.

Technical approach

Goal 1a: Model improvements

EMC and GSL have been collaborating to upgrade the coupled state-of-the-art UFS atmosphere-ocean-sea ice model (FV3/MOM6/CICE5), introducing partial land/sea masks to reduce coastline ambiguities created by the disparate oceanic and atmospheric grids, in order to improve global conservation and local accuracy of surface fluxes. GSL led the development of the GEFS v12-Aerosol member now running in real time at GSL and EMC, and planned for operational implementation in 2020.

For Goal 1a, GSL will incorporate the aerosol direct effect into the coupled FV3/MOM6/CICE5 model in anticipation that this physical process will help reduce model bias on S2S time scales. GSL will quantify the impact of the aerosol direct effect on global prediction at sub-seasonal time scales through sensitivity experiments to evaluate relative contributions of aerosols from different emissions sources (wildfires, dust, and human activity).

Initial model evaluation and testing will be done on July - August 2016 simulations compared with aircraft observations from the Atmospheric Tomography Mission (ATom, https://espo.nasa.gov/atom/content/ATom). During the development of GEFS v12-Aerosol, these ATom data were used to evaluate and improve model predictions of aerosol composition, emissions, and removal, to test meteorological predictions, and to diagnose coupling issues between model components.

After the initial testing shows that the model is working properly, we will perform two extended experiments to demonstrate that the modeling system is ready for operational implementation. We will participate in an aerosol impact experiment (Working Group for Numerical Experimentation, WGNE) to compare our results to those from other operational centers (ECMWF, UK Met Office, JMA, etc.). The participation in this experiment will require a minimum of 340 simulations (months of May and September, 2003 - 2019) with a forecast length of 32 days, an ensemble of 5 members, and 2 runs (one with predicted aerosols, one with climatological aerosols). Results will first be evaluated within NOAA before passing output to the WGNE evaluation group. Towards the end of the funding period we will test the model in GEFS v13 setup for the year 2019. This will require a total of 365 simulations with predicted aerosols, each with a length of 35 days. Results can be compared to the operational setup and to AERONET, VIIRS and MODIS AOD observations.

Goals 2 and 3: Emissions improvements

An emissions processing system will be developed to provide model-ready emissions data for global aerosol predictions in GEFS v13 for S2S timescales, initially as a standalone system and later to be incorporated as an inline UFS component. The Harvard-NASA Emission Component (HEMCO) will be used as the foundation of this emissions processing system for the UFS. HEMCO (Keller et al., 2014) is a stand-alone software component for computing emissions used in global atmospheric chemistry models including the NASA/Harvard GEOS-Chem model and the GEOS Earth system model. Collaborative partnerships have been established with the GEOS-Chem group at Harvard and the software engineering and ESMF groups at the National Center for Atmospheric Research (NCAR). This project will be closely coordinated with our partners' efforts to update and extend HEMCO's capabilities, especially as required for NOAA UFS.

Tasks for Goals 2 and 3 include: (i) merge the current NOAA Air Resources Laboratory (ARL) version of HEMCO with the latest version available from Harvard and coordinate with the GEOS-Chem group and NCAR on HEMCO infrastructure and capabilities; (ii) incorporate real-time GBBEPx biomass burning emissions from NESDIS into the HEMCO framework; (iii) generate emissions for and perform a one-year evaluation simulation with EMC to demonstrate viability of HEMCO-processed emissions for GEFS-Aerosol; (iv) develop a blended climatological/predicted biomass-burning emissions product and incorporate it into HEMCO; (v) improve dust emissions capabilities using satellite-based albedo data; (vi) evaluate HEMCO-based emissions with blended biomass-burning emissions and improved dust algorithm; (vii) coordinate with NCAR in their development of a NUOPC cap for HEMCO to allow it to interface with other UFS components.

Chemical Sciences Laboratory (CSL) will evaluate the emissions system outputs with observations from the 2019 NOAA/NASA Fire Influence on Regional to Global Environments and Air Quality campaign (FIREX-AQ). FIREX-AQ observations of wildfires and agricultural burning collected by aircraft and ground-based platforms will be used to test the emissions system's predictions of fire location, emissions strength, plume rise and evolution of fire plumes for periods up to 6 weeks. Improvements to the emissions system over longer time periods will be evaluated with AERONET, VIIRS and MODIS AOD observations.

Goals 4 and 5: AOD data assimilation system

This sub-project will contribute to the JEDI-based VIIRS and MODIS AOD data assimilation development targeted for GEFS v13. Major tasks will include: an instrument dependent procedure (e.g., quality control, data thinning, bias correction) for Goal 4, and JEDI infrastructure development (e.g., forward operator, background error representation) for Goal 5. Goal 4 requires close collaboration between STAR and in-kind contributors from EMC and GSL. Goal 5 requires close interaction between the evaluation group (ARL, CSL) and in-kind contributors from EMC and GSL.

Evaluations of the DA system by CSL and ARL will focus on assessing the assumed relationship between AOD and the individual aerosol chemical components and their vertical distribution. Detailed observational data on the chemical composition and radiative properties of aerosols from different types of sources collected with high vertical and horizontal resolution during the ATom and FIREX-AQ aircraft field campaigns provide rigorous constraints on the integrated quantity of AOD, which results from a combination of multiple types of aerosols with different light scattering and absorbing properties with varying concentrations, particle sizes and vertical distributions.

3. For those projects that involve UFS development (either forecast model or data assimilation), please include a description of how you will measure progress.

The success of the atmospheric composition sub-project will be measured with respect to the following criteria:

1) Improved accuracy of 5-day aerosol predictions compared to GEFS v12-Aerosol;

2) Aerosol predictions extended to S2S time scales and exceeding the skill of the GEFS v12 aerosol climatology;

3) Representation of aerosol radiative impacts included on S2S time scales and evaluation of these impacts on meteorological fields.

Several approaches will be used to assess progress in meeting these criteria. The accuracy of aerosol predictions out to 6 weeks will be assessed by comparisons to aircraft field data, as detailed in the technical approach above. Aerosol predictions will also be compared to AERONET and satellite-based AOD observations. In addition, S2S model results for aerosol properties will be compared to reanalysis from IFS (CAMS), MERRAero, and AERONET data by the WGNE group. Commonly used S2S comparisons will be applied for the meteorological variables, in addition to comparing to reanalysis data from ERA5.

4. Two Year Plan and Five Year Vision.

B = Begin, + = in progress, **C** = Complete. Y1 = Q4 FY20-Q3 FY21. Y2 = Q4 FY21-Q3 FY22								
Timeline	FY20	FY21				FY22		
Milestone	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Key overall milestone: Improved representation of aerosol distribution and initial inclusion of aerosol interactions with radiation on S2S timescales for GEFS v13								
1. Model upgrades								
1.2 Merge GEFS-Aerosol code with NASA repository version	B	+	+	**C**				
1.3 Include aerosol radiation interactions in GEFS					B	+	+	**C**
1.4 Evaluate use of updated aerosol climatology for S2S prediction					B	+	+	**C**
1.5 Improve dust prediction for GEFS					B	+	+	**C**
1.6 Evaluate ongoing model improvements					B	+	+	**C**
2. Global aerosol emissions processing system based on HEMCO for GEFS v13								
2.1 Develop initial emissions datasets for GEFS v13 using HEMCO	B	+	+	**C**				

2.2 Refine emissions emissions datasets for GEFS v13 using HEMCO					B	+	+	**C**
3. Biomass burning emissions for S2S timescales for GEFS v13								
3.1 Provide inputs for biomass burning emissions calculations	B	**C**						
3.2 Provide climatological and develop prediction of real-time biomass burning emissions for S2S applications	B	+	+	**C**				
3.3 Evaluate improvements to emissions		B	+	**C**				
3.4 Develop a blending approach between prediction and climatology for biomass burning emissions for S2S applications					B	+	+	**C**
3.5 Evaluate improvements to emissions					B	+	+	**C**
4. Quality control and bias correction procedures for AOD data assimilation for GEFS v13								
4.1 Develop quality control of AOD data for DA	B	+	+	+	+	+	+	C
4.2 Develop bias correction for AOD data	B	+	+	+	+	+	+	C
5. Assist AOD data assimilation system development with focus on improved representation of aerosol species and vertical profiles for GEFS v13								
5.1 Assist JEDI AOD assimilation development with a focus on how increments project on individual aerosol species*	B	+	+	+	+	+	+	C
5.2 Assist JEDI AOD assimilation development with a focus on vertical aerosol profiles*	B	+	+	+	+	+	+	C

* EMC and GSL will leverage other support for JEDI AOD assimilation system development

5. Interdependencies with other projects/EMC planned implementation timelines and/or any major risks and issues.

Significant interdependencies

- WPO-funded SLA project at EMC for development of a coupled modeling system for S2S forecasting is required for EMC participation and success of this sub-project
- UFS Atmospheric Composition depends on UFS System Architecture and Infrastructure

- UFS Atmospheric Composition feedback on weather and S2S prediction requires coordination with UFS Atmospheric Physics
- Data assimilation for UFS Atmospheric Composition requires coordination with UFS Data Assimilation and JEDI infrastructure

Risk/Issue

- Adequate computing resources are critical for project success
- Project success depends on NESDIS providing satellite estimates of fire emissions and aerosol optical depth. In case of data anomalies due to satellite (SNPP or NOAA-20) or sensor (VIIRS) failure, the project will be at risk.

6. Specify how organizational base-resources (in-kind) will be leveraged for this sub-project.

- GSL will contribute base funding to ensure radiation coupling and will work with GFS/MOM6/CICE-aerosols for the first year of the project. This includes enabling the use of CCPP with a coupled chemistry run that includes aerosols. GSL will also contribute base funding for the active participation in a Working Group for Numerical Experimentation (WGNE) on aerosol impacts on S2S, using the operational setup and radiation coupling with aerosols. GSL will also contribute base funding towards milestones 1.3 and 1.4, which both will require a large number of retro-runs. Mariusz Pagowski at GSL will participate in this project with an in-kind project on AOD data assimilation supported by the WPO.
- EMC supports participation of Ivanka Stajner in coordinating the overall project. EMC contributions by Jeff McQueen, Daryl Kleist and contract staff include coordination with aerosol modeling and data assimilation activities in development of a coupled modeling system for sub-seasonal to seasonal forecasting (WPO SLA). EMC contributions by Ivanka Stajner, Jacob Carley, Daryl Kleist and contract staff include coordination with high-resolution air quality prediction, AOD data assimilation and impacts of aerosols on physics (FY19 Disaster Supplemental: Improving Forecasting of Hurricanes, Floods, and Wildfires).
- CSL will contribute base funding to process aircraft field observations used in the model evaluation milestones and to support the participation of Gregory Frost in coordinating the overall project and advising contractor staff.
- STAR scientist Kondragunta’s time on this project, advising contractor staff and working on satellite products (fire emissions and AOD uncertainties) will be covered by base funding.
- ARL scientist Saylor’s time on this project, advising contractors and coordinating with other collaborators will be covered by base ARL funding.

7. Please provide an estimate of compute resource requirements, both in terms of CPU hours per month and disk storage.

The total computing requirement, not covered by existing allocations, is 6.5M CPU hours per year and 85 TB of storage.

<u>Justification</u>: one 32-day simulation will be used for the initial development and testing of the system during the ATom period. This will require many reruns for testing and tuning. The participation in the WGNE experiment requires a minimum of 340 simulations (months of May and September, 2003 - 2019) with a forecast length of 32 days, an ensemble of 5 members (could be a 6hr-time lagged initialization, or available ensembles from GEFS), and 2 runs (one using aerosol climatologies, one with predicted aerosols). For the final test in GEFS v13 mode, the one year period (2019) will require a total of 365 simulations with a length of 35 days (1 year, one run per day, with predicted aerosols). A configuration of the UFS coupled model (C384 atmosphere, ¼-degree ocean and ice) costs about 2200 core hours per 35-day forecast. We estimate one run with simple chemistry will cost about twice as much. The compute resource requirements for all these model experiments are estimated to be approximately 4M core hours. The WGNE experiment (for submission to the international comparison project) will require 10 vertical levels (1000, 925, 850, 700, 500, 300, 200, 100, 50 and 10 hPa) for 3D variables and 40 2D variables, with daily time resolution. We estimate needing 25-30 TB of disk storage for the modeling and evaluation work in this sub-project. The emissions work will require 0.5M core hours/yr and 25 TB of storage. For the data assimilation work, HPC or cloud computing for development and testing will require at least 1.5M core hours and storage for test data of 30 TB.

8. Summary of known team members and institutions (expected FTE commitment), including what resources are leveraged, including federal salaries or synergistic projects.

Name/ organization	**Subject matter expert/milestone effort**	**Commitment level FTE**	**Amount leveraged (if any)**	**What is leveraged? (office space, time, computing)**
Ivanka Stajner/ NOAA/NWS/EMC	Overall coordination: milestones 1, 2, 3, 4, 5		0.05 FTE	Time
Georg Grell, Shan Sun/ NOAA OAR GSL	Milestone 1		1.5 FTE	Time
Kate Zhang, Raffele Montuoro/ NOAA OAR GSL, CU-CIRES	Milestone 1	0.6 FTE (1st year) 0.6 FTE (2nd year)		
Rick Saylor/ NOAA OAR ARL	Milestones 2 and 3		0.1 FTE	Time
Patrick Campbell/NOAA	Milestones 2 and 3	0.4 FTE		

OAR ARL, George Mason U.				
Barry Baker/NOAA OAR ARL, U. of MD-Baltimore Co.	Milestones 1 and 5	0.2 FTE		
Daniel Tong/NOAA ARL, George Mason U.	Milestone 3	0.2 FTE		
Gregory Frost/ NOAA OAR CSL	Overall coordination: milestones 1, 2, 3, 4, 5		0.1 FTE	Time
Stuart McKeen/ NOAA OAR CSL, CU CIRES	Milestones 1.6, 3.3, 5.1, 5.2	0.33 FTE		
Rebecca Schwantes/ NOAA OAR CSL, CU CIRES	Milestones 1.6, 3.3, 5.1, 5.2	0.33 FTE		
Shobha Kondragunta NESDIS/STAR	Coordination of work related to Milestones 3.1, 4.1, and 4.2		0.05 FTE	Time
Xiaoyang Zhang, NESDIS/STAR SDSU	Milestone 3.1	0.25 FTE Year 1		
Ethan Hughes, NESDIS/STAR through IMSG	Milestone 4.1 and 4.2	0.25 FTE Year 2		

1.3 UFS-R2O MRW/S2S Sub-Project: Data Assimilation Reanalysis & Reforecasts

UFS-R2O Task: MRW/S2S Data Assimilation
Team: MRW/S2S
Sub-project area: Data Assimilation
Sub-Project Leads: Daryl Kleist (NOAA/NWS/NCEP/EMC); Yannick Tremolet (UCAR/JCSDA), S.G. Penny (CIRES & NOAA/PSL); S. Frolov (CIRES & NOAA/PSL)
Sub-project organizations proposed for: NOAA/NWS/NCEP/EMC, NOAA/OAR/PSL, JCSDA

Sub-Project Narrative

1. Sub-Project Overview.

This project is focused on the accelerated development and transition of the next generation data assimilation infrastructure for the Unified Forecast System (UFS), the Joint Effort for Data assimilation Integration (JEDI), coordinated and led by the Joint Center for Satellite Data Assimilation (JCSDA). The JEDI project will be the backbone for performing data assimilation across the variety of UFS applications. In order to meet the goals for improved data assimilation as outlined by the global weather application team priorities, investment in continued JEDI development, transition, and testing needs to be expanded. JEDI will be critical for realizing a unified data assimilation system for any coupled application of the UFS. Transitioning to JEDI will also accelerate innovations and science development across a whole range of data assimilation issues. This project ensures continued development in JEDI infrastructure, executing the transition plan from the current operational data assimilation infrastructure for atmospheric data assimilation, the Gridpoint Statistical Interpolation (GSI).

An additional part of the infrastructure for realizing improved initial conditions and concomitant forecasts is related to the processing and utilization of observations. This project has significant emphasis on continued investment in the improved use of observations for realizing improved medium range forecast skill. This includes improved use of currently available observations as well as preparations for a new generation of observations that will be deployed within the next several years. Additional investment is needed in the pre-processing, quality control, and front-end handling of observations for use in assimilation. This project ensures alignment of the elements of the JEDI project (observation database and unified forward operator) that should be targeted for the re-engineering of the currently operational "observation pre-processing."

It is also important to consider that the system that will be utilized for UFS applications will fundamentally be coupled to other non-atmospheric components, requiring the initialization of states for the ocean, sea ice, waves, land, and more. Therefore this project not only includes the development of data assimilation for marine and land components of the UFS, but also includes the development of a scientifically validated coupled data assimilation (CDA) capability. In particular, there is a significant effort underway to build out a JEDI-based marine assimilation system for a MOM6 (ocean)-CICE5/6 (sea-ice) application for the purposes of monitoring (e.g. to replace the legacy Global Ocean Data Assimilation System - GODAS). Additionally, this project will emphasize the usage of JEDI for building an initial capability for the initialization of soil moisture and snow within the land component of the UFS. These components will be used to develop a baseline weakly coupled data assimilation (WCDA) capability for the UFS. Since coupled reforecasts are a requirement for GEFS v13, a major component of this sub-project involves the production of a coupled UFS reanalysis and reforecast (R&R) product ahead of the GEFS v13 operational implementation.

In the immediate short term, the main forecast system target for the efforts contained in this project are GFS v17, GEFS v13, and the SFS v1 thereafter. More specific sub-project tasks within the first two years include transition from GSI to JEDI for the atmosphere, replacement of legacy GODAS systems with JEDI-based SOCA (sea-ice, ocean and coupled assimilation) application including a fully completed ocean/sea-ice reanalysis, initial capability for soil moisture and snow assimilation, leveraging of IODA/UFO components for observation pre-processing re-engineering, and algorithm inter-comparison results from global NWP testing. As this project involves general infrastructure development activities for data assimilation, follow on operational targets will include things such as the Hurricane Analysis and Forecast System (HAFS), Rapid Refresh Forecast System (RRFS), among others.

2. Sub-Project Justification and Technical Approaches.

JEDI Development and Support Activities (JCSDA Core Funding)

JEDI is a unified data assimilation for all partners of the JCSDA. It leverages modern software development methodologies (Agile), techniques (generic and object-oriented programming) and tools (cloud-based version control, continuous integration, containers). JEDI is not a specific or new data assimilation methodology, rather it implements several algorithms, including world leading algorithms such as 4D-Var, in a generic manner that all partners can use. An important aspect of the project is the generic handling of observations and related processes such as observation operators, quality control and bias correction through its UFO and Interface for Observation Data Access (IODA) components.

Within the wider JEDI project, the scope of this proposal is to support some of the core aspects of the system, including:

- the overall management of the project,
- the design and development of the structure of the software,
- the development of generic abstract layers for UFO and OOPS,
- the development of generic deterministic and ensemble data assimilation algorithms,
- the development of the observation data handling (IODA),
- the infrastructure for portability (containers, cloud) and computational efficiency,
- the documentation efforts, training of users and community support.

Assimilation Algorithms and JEDI Integration

As JEDI infrastructure and development are being expanded and accelerated (e.g. by disaster relief appropriations funding), it is becoming critical to emphasize and expand the operational transition relevant activities within the project. Although an initial transition plan was put together for getting from GSI to JEDI over a four-year time span for atmospheric data assimilation, there is still a significant effort necessary to define what a “transition” might look like and the requirements therein. This effort will ensure the establishment of the necessary expertise from the operational perspective (NWS/NCEP) in order to understand and facilitate the operationalization of JEDI and components therein. The initial focus will be on testing the components as outlined in the transition plan, integrating the components into the global-workflow supporting the weather application/Global Forecast System to start, and begin documenting acceptance and readiness. Part of this effort will involve co-development with JCSDA partners to accelerate the readiness of the components. The expertise established will ensure successful smooth transition and operationalization of JEDI-based data assimilation as part of the planned GFS v17/GEFS v13.

As the starting point for informing future decision making around the algorithm choices for use in the global weather application, a JEDI-based inter-comparison project will be carried out to document the performance for use in a global weather application:

1. Hybrid 4DEnVar (as in current operations)
2. Hybrid 4DVar (Leveraging tangent-linear and adjoint components of FV3 already developed)
3. EDA versus EnKF/LETKF for perturbation update

The inter-comparison effort will be carried out in such a way as to generate evidence (both cost & performance) to make an informed decision moving forward. Additional consideration will be given to the non-atmospheric components and coupled data assimilation (see companion proposals on coupled DA, reanalysis/reforecast, land assimilation, and marine assimilation).

Improved Assimilation of Observations

a. **Use of new observations.**

A number of new satellite instruments will become available in the next five years including Metop-SG (Second Generation) in 2022 and Meteosat Third Generation (MTG) in 2023, and new data assimilation developments are required to accommodate these. In particular, MTG will carry the first operationally-available hyperspectral sounder in geostationary orbit, MTG-IRS, which will combine high-vertical resolution with a 30-minute refresh rate. There will need to be development of processing and techniques to use the large volume of data produced from this instrument and to better exploit the temporal information. As MTG-IRS data will be distributed via principal component scores, we will initially be exploring the use of this type of data using CrIS and IASI as proxies. Metop-SG also has a payload of new and improved instruments that will need to be tested and assimilated in the timeframe of this document.

b. Improved use of existing observations.

The main areas for development in the use of observations in this period are:

- Development and application of spectrally correlated observation errors. Operational assimilation of correlated observation errors for CrIS and IASI is currently in pre-operational testing. This capability needs to be extended to other instruments, both in clear-sky and all-sky situations.

- Extension of all-sky radiance assimilation to precipitating regions, land, and the infrared. ECMWF in particular is showing major impact from the use of humidity-sensitive channels in an all-sky framework.
- Improved use of Atmospheric Motion Vectors (AMVs). This includes refinement of the current configuration for the GOES-R series and the introduction of situation-dependent observation errors.
- Improved use of aircraft-based and other conventional observations. This includes a better understanding of the effect of spatially correlated errors and biases on the use of aircraft data. Work also needs to be performed to ensure TAC-to-BUFR data migration for radiosonde and surface observations does not interrupt continued provision of these data.
- Continued work on improving the assimilation of GPS RO data including ground-based ZTD.

c. Transition to JEDI IODA/UFO.

Successful transition of existing operational DA systems to JEDI requires application and testing of generic JEDI components designed to ingest, process, assess and simulate the wide range of observations used in those systems—specifically, the Unified Forward Operator (UFO) and the Interface for Observation Data Access (IODA).

The transition to operations is driven by technical and scientific requirements defined by NOAA/EMC, NASA/GMAO, and the other JCSDA partner agencies. Accordingly, and subject to those requirements, the proposed work involves two major tasks: (1) to implement the capability in JEDI to assimilate all observation types currently used in operations, and (2) to provide and improve the methods, tools and infrastructure needed to support this and other work with observations. The project will also include the development of a plan and execute a milestone to complete the transition from the current "observation processing re-engineering effort" to design and implement JEDI/UFO and IODA components to solve all of the observation pre-processing and quality control programs that run immediately after decoding and ingest of all currently available observations in NOAA operations.

Marine Data Assimilation & Hybrid GODAS

The scope includes creating the next generation GODAS for climate monitoring, technology applicable to S2S, and weather forecast systems. Also, through the process of creating an operational product, critical infrastructure for the marine, and eventually coupled DA operational analysis products are developed. As described below, the technical approach is an iterative three-phased approach which permits the continuous movement from development to testing to deployment.

Phase 1. Build and Compile**:** This phase includes applying and conducting foundational research required for optimizing each component of the UFS. Specifically, the proposed system leverages community components and integrates their upgrades, GFS-MOM6-CICE5/6 coupled for the atmosphere, ocean, and ice model capabilities; JEDI and SOCA for the data assimilation and the observations handling, the METplus for the validation of the forecast and the EMC workflow.

Output from Phase 1 will be used to develop a hybrid DA approach, a scientific leap for the operational capabilities for marine analysis within the UFS. The adoption of hybrid approaches has several scientific benefits but also increases the complexity of the system (e.g., ensemble forecast, variational and ensemble Kalman Filter DA, and more).

Phase 2. Testing: The undisrupted testing of the system and its subsystems is required to establish the stability and maturity for operational implementation. The testing is focused on the target product of this work, the 30-year ocean and sea-ice reanalysis by FY21, and leverages the accumulated experience and available tools of the partners and the scientific community.

Phase 3. Implementation: The objective is to maintain, at any given time, a system candidate for implementation without interfering with its continuous improvement. The final step for each development cycle is the operational implementation on an annual basis, with the first implementation in FY2023. The outcome from this sub-project provides the basis for which the marine component of the weakly coupled data assimilation effort is built upon.

Land Data Assimilation

The land surface determines the lower boundary conditions of the atmosphere, and interacts with weather and climate through regulation of energy and mass fluxes over a range of temporal and spatial scales. This makes land surface initialization of critical importance. However, in contrast to all other major NWP centers, the existing global NOAA/NCEP GSI DA does not currently ingest land-relevant observations. Additionally, NOAA does not have a unified land DA system that can be applied to either a stand-alone or coupled (land/atmosphere) model.

Therefore, this proposal will support and improve capacity for land data assimilation using a unified JEDI DA system. The focus within this sub-project is developing a stand-alone mode for an offline land surface model that provides land initial conditions to the UFS, and for generating land-only reanalysis products. This work is highly synergistic with the UFS Coupled DA sub-project, and ongoing work with NOAA's OWP National Water Model. Our strategy is to build towards a unified approach whereby a single framework for land DA will work across a range of possible land surface modeling applications within the UFS.

Coupled Data Assimilation/Reanalyses and Reforecasts

The work directly supports SIP project 6.3, and is a key capability for initializing UFS ensembles in GEFS for medium-range weather forecasting and S2S forecasting applications. It also affects the initialization and bias correction of hurricane, marine, and cryosphere applications, with potential future relevance to space weather, coastal impacts, and air quality. This work introduces improved DA methodology for the coupling of atmosphere, ocean, sea ice, ocean surface wave, and land-surface initialization. Development of strongly-coupled data assimilation (SCDA) science and infrastructure is a core component of this work on the 3-5 year time scale. Additional expected outcomes include reduced biases in sea surface temperature (SST), sea ice, and surface winds; improved mid-latitude geopotential skill; improved ensemble forecast spread; and reduced initialization shocks in the UFS forecasts. The work supports initialization of the UFS, across multiple components and timescales, using the JCSDA Joint Effort for Data Assimilation Integration (JEDI) software framework. We will leverage existing standalone assimilation efforts, for example the JEDI-FV3 (for the atmosphere), JEDI-SOCA (for marine applications such as ocean and sea ice, and planned developments for wave models and general coupled DA), and JEDI-LAND (supporting new land data assimilation capabilities). The JEDI-SOCA development referenced here is directly related to the previously described marine data assimilation/ hybrid-godas effort.

A WCDA baseline system will be developed using a hybrid ensemble-variational approach (e.g. 4D-EnVar for the deterministic forecast and 4D-LETKF to update the ensemble members). 'Weakly coupled' indicates that observations in one state component will not directly affect other state components during the analysis update, however there is an indirect influence due to the forecast/background being fully coupled. Model components include: atmosphere, ocean, land, waves, and sea ice. This project assumes that DA capabilities for individual components have been developed outside of this effort, as a dependency. We will implement WCDA with the DA components available in year 1 (we note that the atmosphere, ocean, and sea ice are most mature at this time). The WCDA system will be the basis for the research SCDA prototype system that focuses on realizing an effective cross-domain coupling at multiple space and time scales, aiming to eliminate discontinuities in the coupled analysis by utilizing observations across domain boundaries via forecast error covariances.

This new WCDA will be used to produce an ensemble reanalysis from which reforecasts will be initialized. The targeted reanalysis period will cover 1993 (TOPEX/Jason altimetry became available in Oct. 1992) to present at a resolution of roughly ¼ degree in both the atmosphere and ocean. While the WCDA system is weakly coupled, a coupled forward operator may be used to include the effects of the full coupled state when computing observation equivalents in model space. In year two, the system will be exercised using a preliminary low-resolution (~1 degree) 'scout' version of the system, in order to resolve any problems with the system components. Full resolution R&R production will begin soon after the code freeze for the GEFS v13 operational system.

Reforecasts are a critical component of the current NCEP/EMC concept of operations for GEFS, as they serve as the most effective tool to bias-correct and calibrate GEFS forecasts and derivative products. This need is recognized by the Medium-Range to S2S Application Team (MRW-S2S AT) development priorities and goals document. At this time, a 20-year atmosphere-only R&R effort is nearing completion, and will be used to support GEFS version 12 (GEFSv12). However, because GEFS version 13 (GEFS v13) will be based on a fully coupled UFS, GEFSv13 will require a new set of (coupled) reanalyses and reforecasts.

With the GEFS v12 reanalysis project now ending, as of yet there is no plan to maintain ongoing R&R activities to support future GEFS upgrades. In order to achieve the MRW-S2S AT goal of implementing a coupled UFS for operational ensemble prediction at medium-range to S2S timescales, a dedicated team is needed to support the ongoing development and execution of R&R, similar to what has been developed at the European Centre for Medium-range Weather Forecasts (ECMWF) through the Copernicus project.

In order to minimize the impact on existing NOAA high performance computing (HPC) systems (which are already heavily taxed), we plan for the production of R&R to be performed using cloud services. This is an ideal application for cloud computing, since R&R require a large amount of compute resources for a relatively short period of time (6-12 months) and is envisioned to be performed relatively infrequently (whenever the accumulated forecast system upgrades are large enough to significantly change the forecast error statistics, roughly every 3 years).

We integrate several independent SIP development efforts, including JEDI, UFS model development, stochastic physics upgrades for the coupled system, and workflow development for cloud computing. The main challenges in the early stages of the project will be integrating all of these efforts, testing and validating the workflow, and the preparation of input observational datasets in cloud storage. A system for monitoring and diagnosing problems with the R&R run will need to be developed, leveraging existing tools wherever possible.

This project must be sustained over the long term (to five years and beyond) in order to support future upgrades to the operational S2S ensemble prediction system. Our vision is that in addition to delivering R&R datasets for calibration and bias correction, this project will focus on identifying avenues for improvement of the UFS by repeatedly exposing the coupled system to all available observations. Years 3-5 will be devoted to upgrading the R&R system in preparation for GEFS v14, possibly including SCDA.

An ongoing R&R capability will aid in UFS development by providing a robust dataset for identifying and diagnosing model deficiencies, and provide a testbed for evaluating new DA developments (such as coupled DA). The R&R will provide a high-quality scientifically validated dataset for increasing opportunities in artificial intelligence and machine learning applications. Having the datasets reside in the cloud will make them more accessible to the user community and amenable to novel analysis techniques (including those based on machine learning).

The end-to-end workflow for the UFS, runnable in the cloud and including data assimilation will be made available to the research community - a key goal outlined in the EPIC vision document. As such, this project would serve as an ideal demonstration to serve the EPIC mission. Support from EPIC software engineers and cloud-based HPC would greatly enhance the proposed R&R effort. Major components of this effort are the setup and configuration (on both HPC and cloud platforms) of the UFS and JEDI data assimilation system, preparation of observation data, and workflow design and management - all of which align with EPIC’s goals.

3. For those projects that involve UFS development (either forecast model or data assimilation), please include a description of how you will measure progress.

The reference point for atmospheric data assimilation is the current operational GSI. For the UFO, comparisons will be performed w.r.t. the GSI *observer*, measuring differences in simulated observation values, QC decisions and bias estimates. For the JEDI data assimilation system as a whole, two main types of metrics will be used to measure progress: forecast skill and computational efficiency. Two important and early deliverables of the project will be the definition of transition plans for the elements being developed into EMC and operations, and of the exact metrics to be used for measuring progress through finalization of the requirements document and testing protocol. Additional benchmarks will include new capabilities for improved use of observations using JEDI components.

More specifically, GFS version 16 (to be implemented in February2021) will be the benchmark for the atmospheric data assimilation component. In addition to explicit comparison of innovation statistics (O-F), skill from forecasts initialized from JEDI (and sub-components therein) will use GFS v16 as the baseline, considering the standard suite of metrics used to judge operational GFS forecasts. This includes, but is not limited to, 500 hPa anomaly correlation, precipitation over CONUS, root-mean-square error relative to self analysis and observations, etc. The explicit requirements and benchmarking for JEDI subcomponents will be contained in a milestone for a detailed plan to be delivered by Q3FY20.

For the marine data assimilation sub-task, the benchmark will be the execution of the complete ocean/sea-ice reanalysis to meet the requirements for use in the Climate Prediction Center operations for ocean monitoring. Specific benchmarks relative to the legacy Global Ocean Data Assimilation System (GODAS) products have already been developed and agreed upon in the formal project plan.

For the Coupled DA /R&R subtasks, a baseline capability for the project is a functional and cycling WCDA system for the UFS. We will measure improvement in observation-minus-forecast (OMF) of the WCDA system versus the uncoupled UFS forecast (e.g. atmospheric forecast and analysis only, driven by persistent SST) to validate the WCDA system and further improvements to the system. Our initial target is any positive improvement (i.e. reduction in OMF deviation) compared to the uncoupled forecast. We will use existing/forthcoming products as benchmarks, including: interpolated CFSR for atmos/ocean/ice/land, GEFSRR v12 for atmosphere, and JCSDA SOCA reanalysis (produced for the DA UFS-R2O sub-project) for ocean/ice. The SCDA system will target improvement in OMF metrics over the WCDA system as a baseline. Due to the complexity of the application, we will establish a 'scorecard' system to simultaneously evaluate metrics across multiple domains. Specific processes will be identified for further more in-depth validation at various timescales (e.g. MJO, air-sea coupling, as well as traditional short and medium range forecast scores).

4. Two Year Plan and Five Year Vision:

The proposed project shares the 5-year vision with the UFS and it serves UFS as its fundamental component towards the seamless analysis and prediction of the Earth system, Atmosphere-Ocean-Sea ice-Land. The expected deliverables of the first two years are:

- JEDI capabilities ready for the transition to operations and use in the NCEP Global Data Assimilation System (e.g. replacement of GSI for atmospheric DA)

- Pathway toward solution for the observation data access (Research Repository for Data and Diagnostics) and complete set of unified forward operators and associated QC
- JEDI-based capability for assimilation of snow and soil moisture data in stand-alone (land) and coupled systems
- Completed 30-year ocean and sea-ice analysis based on MOM6+CICE5 – the marine capability for the coupled analysis system
- Results from Hybrid (4DEnVar versus 4DVar) inter-comparison study for deterministic DA using FV3-based GFS

Which are required for the technical and scientific upgrade and the successful implementation of the next-generation operational forecasting systems, starting with the GFS v17 / GEFS v13.

Two Year Plan:

Timeline	FY20		FY21				FY22		
Milestone	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Cross-Milestones									
0a. Defines transition plans for obs pre-processing, UFO and JEDI DA			x	x	x	x			
0b. Define metrics for measuring progress of UFO and DA applications			x	x	x	x	x	x	x
Milestone 1: JEDI Core Support and Infrastructure Development									
1a. Observation data handling (IODA) with Fortran, C++, and Python interfaces			x	x	x	x	x	x	x
1b. JEDI software releases with documentation and community support		x	x	x	x	x	x	x	x

1c. Generic variational solvers including Hybrid 4DEnVar, 4DVar				x	x	x	x		
Milestone 2: Algorithm Intercomparison Results and Transition for Operations									
2a. Prototype testing of JEDI replacement of GSI for GFS/Weather application		x	x	x	x	x			
2b. Transition of JEDI for development within EMC, socialization and training for most developers				x	x	x	x	x	x
2c. Results from hybrid intercomparison (Hybrid 4DVar versus 4DEnVar study for GFS/GDAS)					x	x	x	x	
Milestone 3: Improved Use of Observations									
3a. Demonstrate use of principal components in assimilation of existing hyperspectral infrared radiances (prep for MTG-IRS)					x	x	x	x	x
3b. Functional equivalent of all observations operators in UFO	x	x	x	x					
3c. Full developed QC and bias correction for all UFO-based assimilation	x	x	x	x	x				
3d. Full acceptance of JEDI/UFO for all instruments used in NWP application (replacement of GSI observer)			x	x	x	x			
3e. Prototype of IODA/UFO replacements for components of			x	x	x	x	x	x	

observation processing re-engineering									
Milestone 4: Marine Assimilation Component									
4a. Prototype system for marine reanalysis applications compatible with the global workflow	x	x	x						
4b. Hybrid DA capabilities for Ocean/Ice based on JEDI	x	x	x	x					
4c. 30 years reanalysis of global ocean (1989-2020)			x	x	x	x	x	x	x
4d. Scientific evaluation of the reanalysis, targeting the operational implementation of the system				x	x	x	x	x	x
Milestone 5: Land Assimilation Component									
5a. Model interface and prototype GLDAS-like capability via JEDI	x	x	x	x					
5b. IODA converters for snow observations with accompanying tests			x	x	x	x			
5c. IODA converters for soil moisture observations with accompanything tests					x	x	x	x	
5d. Preliminary results from assimilation of snow and soil moisture observations using JEDI (prototype stand-alone)								x	x

Coupled DA and R&R tasks

Timeline	Project Year 1				Project Year 2			
Milestone	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Milestone 1: Development and Implementation of the WCDA system								
1.a Development and testing of the WCDA prototype (including the workflow) at low (1°) resolution	x	x	x	x	x	x		
1.b Upgrade WCDA/UFS to target R&R resolution (1/4°)					x	x	x	x
1.c Calibration of the ensemble spread and stochastic physics in the UFS						x	x	x
1.d Develop detailed test plan, including details on validation metrics	x							
1.e complete generic JEDI LETKF solver	x	x	x	x	x			
Milestone 2: Reanalysis and Reforecasts								
2.a Preparation of observational datasets for re-analysis in the new JEDI Interface for Observation Data Access (IODA) format		x	x	x	x	x	x	x
2.b Development of web-based monitoring, verification and diagnostic tools					x	x	x	x
2.c Development of R&R workflow on cloud computing platform				x	x	x	x	x
2.d Low-resolution scout runs to test the cloud computing workflow.						x	x	x

Milestone 3: Development of SCDA prototype								
3.a Research on transition from WCDA to SCDA (e.g. error covariance localization)					x	x	x	x
3.b Implementation of coupled observation operators in JEDI					x	x	x	x
3.c Research multiscale initialization methods					x	x	x	x

3-5 year vision

Collaborations under JCSDA are managed on a yearly cycle, with quarterly reviews by all the JCSDA partners, and an Annual Operating Plan discussed and approved by all JCSDA partners. Collaboration with other federal agencies (NASA, US Navy, US Air Force) brings many invaluable benefits to the project. This proposal constitutes an important part of NOAA's contribution to the JCSDA under that governance.

JEDI aims at incorporating world leading data assimilation algorithms and methods, including 4D-En-Var and 4D-Var, and at expanding on GSI capabilities for a better and more timely use of all observations, enabling of coupled data assimilation for the Earth system and more efficient use of new computer architectures. Within a 5-year period, it is expected JEDI will replace GSI for many (most) data assimilation applications at NOAA.

In the following years, JCSDA will continue to support the evolving needs of its member organizations. The development of generic capabilities for UFO, quality control and bias correction algorithms will continue and expand requiring stable core support. The core team will continue to improve JEDI and include new worldwide developments in data assimilation science, and to propose innovative data assimilation solutions. Support for portability and efficient use of new computer architectures will expand. Comparisons of the same scientific data assimilation methods with the different models interfaced with JEDI will be performed to enhance the robustness of scientific evidence.

It is expected this project will continue to support the base of the JEDI development and maintenance upon which many scientific advances will grow, as well as some significant scientific developments regarding the use of observations and data assimilation methodology for coupled systems. This project will also support the development of the observation data store (R2D2) and accompanying software as a community focus point around improving the use of observations. It will also fund some of the concrete scientific advances related to new observations, improve use of existing observations, marine and land data assimilation.

It is expected this project will continue to support the transfer of new developments by JCSDA, the federal partners of JCSDA and the wider scientific community into EMC and NOAA operations. This could include opening the door to future implementation of even more forward-looking algorithms such as particle filters. Within five years, it is hoped that most (if not all) of the legacy observation processing software that is run at NOAA will be replaced by JEDI-based components. The goal is simply to have JEDI serve as a fully mature system for research, development, and operations for all aspects of the UFS.

The 3-5 year vision for the Coupled DA/R&R portion of this project is described in the following table.

	Year 3				Year 4				Year 5			
Milestone	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Future task 1: Reanalysis from 1993-present and Reforecasts using WCDA system												
1.a Production ¼-degree resolution reanalysis with WCDA system	x	x	x	x								
1.b Production ¼-degree resolution reforecasts from WCDA reanalysis initial conditions			x	x	x	x						
1.c Evaluation of the WCDA R&R					x	x	x	x				
Future task 2: Reanalysis from 1993-present and Reforecasts using SCDA system												
2.a Production ¼-degree resolution reanalysis with SCDA system					x	x	x	x				
2.b Production ¼-degree resolution reforecasts from SCDA reanalysis initial conditions							x	x	x	x		
2.c Evaluation of the SCDA R&R									x	x	x	x
Future task 3: Development of SCDA system												
3.a Scout SCDA runs at target resolution	x	x	x	x								

Future task 4: Transition of CDA to operations												
4.a Modification of WCDA UFS R&R system for NCO requirements	x	x	x	x								
4.b Modification of SCDA prototype for NCO requirements					x	x	x	x				

5. **Interdependencies with other projects/EMC planned implementation timelines and/or any major risks and issues.**
   - Adequate HPC

6. **Specify how organizational base-resources (in-kind) will be leveraged for this sub-project.**
   - In kind support will be provided by NOAA in the form of time for some federal staff as outlined below, HPC and storage, as well as office space.

7. **Please provide an estimate of compute resource requirements, both in terms of CPU hours per month and disk storage.**

Computing requirements for JCSDA are averaged for each year although in practice computing and storage needs will be ramping up continuously throughout the period. JCSDA currently has no significant allocations so the requests from JCSDA are new requests. The non-cloud HPC requests would be for testing and evaluation of components as is standard practice for running NWP and global data assimilation cycling experiments. While possible to leverage some allocation/projects under RDHPCS, some new allocation may be required to fully realize the algorithm intercomparison study (in particular for year 2).

Type	**Year 1**		**Year 2**		**Total**	
	Core Hours per year	Storage	Core Hours per year	Storage	Core Hours (total)	Storage
HPC	60M	500 Tb	60M	500 Tb	120M	500 Tb
Cloud (JCSDA)	60M	2 Pb	240M	20Pb	300M	20 Pb
Total	10M	2.5 Pb	25M	20.5Pb	420M	20.5 Pb

We consider the compute requirements for the Coupled DA/R&R portion of this project separately below. We estimate the computational costs using the actual run-time of two free running UFS forecasts as a basis: (1) C384L64 atmosphere and 1/4°L75 for the ocean and ice and (2) C96L64 and 1/4°L75 ocean and ice. Estimates below are for a configuration with 80 ensemble members. We extrapolate the cost of the high resolution analysis will be 30M CPU hours per year (2.5M/mo) of reanalysis and 400 Tb of archive storage. For the low-resolution, we estimate the cost of 3M CPU hours per year (0.25M/mo) of reanalysis and 24Tb of storage. It is possible that the cost estimate of the low resolution analysis will be reduced once we know the exact timing of running a coupled UFS forecast at currently non-existent C96L64 and 1°L75 configuration. We caution that these estimates are preliminary and are likely to be adjusted once the complete system is developed. This is a new request for computer allocation.

We expect that to support our work plan, we will need to conduct the following number of simulation-years at low and high resolution in the year 1 and 2 of the project.

Type of simulation	Year 1			Year 2		
	Years of sim.	CPU hours	Storage (Tb)	Years of sim.	CPU hours	Storage (Tb)
Low-res. HPC	2	6M	48Tb			
Low-res. Cloud	4	12M	96Tb	20	60M	480Tb
High-res. HPC				2	60M	800Tb
High-res. Cloud				4	120M	1.6Pb
Total HPC		**6M**	**48Tb**		**60M**	**0.8Pb**
Total Cloud		**12M**	**96Tb**		**180M**	**2.1 Pb**

Additionally, we estimate that staging approximately 30 years of observational data will require about 140Tb of storage. We also note that it may be possible to develop a medium-resolution system with atmosphere at C192L64 and ocean-ice at 1/4°L75 resolution. We estimate that this system would yield a 50% saving compared to the high-resolution system at C384L64-1/4°L75 resolution.

8. Summary of known team members and institutions (expected FTE commitment), including what resources are leveraged, including federal salaries or synergistic projects.

Name/ organization	Subject matter expert/milestone effort	Commitment level FTE	Amount leveraged (if any)	What is leveraged? (office

				space, time, computing)
Milestone 1: JEDI Core Support and Infrastructure Development				
JCSDA Core/JEDI Current Staff TBD	JEDI code portability, efficiency and support	3.0		
Milestone 2: Algorithm Intercomparison Results and Transition for Operations				
Daryl Kleist		0.2 (in-kind)	100%	
Rahul Mahajan		0.2 (in-kind)	100%	
Jeff Whitaker		0.2 (in-kind)	100%	
EMC New Hire 1	JEDI Integration and Transition. Hybrid intercomparison project.	1.0	50% coordinated as in-kind to JCSDA AOP	Leverage collective work in JEDI Project in JCSDA 2020 AOP
EMC New Hire 2	JEDI Integration and Transition, emphasis on weakly coupled DA and reanalysis.	1.0	50% coordinated as in-kind to JCSDA AOP	Leverage collective work in JEDI Project in JCSDA 2020 AOP
Milestone 3: Improved Use of Observations				
EMC Current Staff 1	Correlated observation errors	1.0	50% coordinated as in-kind to JCSDA AOP	Leverage collective work in OBS Project in 2020 JCSDA AOP
EMC Current Staff 2	Atmospheric Motion Vectors	1.0	50% coordinated as in-kind to JCSDA AOP	Leverage collective work in OBS Project in JCSDA 2020 AOP
EMC Current Staff 3	VarQC, Conventional Obs DA	1.0		
EMC Current Staff 4	Aircraft assimilation	1.0		
Milestone 4: Marine Assimilation Component				
EMC Current Staff 1	EMC Marine DA Task lead	1.0	50% coordinated as in-kind to JCSDA AOP	Leverage collective work in SOCA Project in JCSDA 2020 AOP

EMC Current Staff 2	Marine Obs QA/QC	1.0	50% coordinated as in-kind to JCSDA AOP	Leverage collective work in SOCA Project in 2020 JCSDA AOP
EMC Current Staff 3	JEDI Interface for Marine Models	1.0	50% coordinated as in-kind to JCSDA AOP	Leverage collective work in SOCA Project in JCSDA 2020 AOP
Milestone 5: Land Assimilation Component				
Daryl Kleist		0.05 (in-kind)	100%	
EMC New Hire 3		1.0	75% coordinated as in-kind to JCSDA AOP	Leverage collective work in Apps/LAND Project in JCSDA 2020 AOP (link

Coupled DA/R&R Tasks

Name/ organization	**Subject matter expert/milestone effort**	**Commitment level FTE**	**Amount leveraged (if any)**	**What is leveraged? (office space, time, computing)**
Milestone 1: Development of WCDA system				
Penny (PSD)	CDA theory and applications / WCDA system design and planning	0.25		complementary projects supporting CDA R&D, travel budget
Frolov (PSD)	CDA theory and system development	0.75		
TBD (PSD)	Setup, testing, and evaluation of WCDA system and workflow	0.5		
TBD (EMC)	Setup, testing, and evaluation of WCDA system and workflow	0.5	EPIC Funded	Will also provide in-kind contribution to JCSDA
TBD (EMC)	JEDI atmosphere DA	0.25 (no cost)	100%	JCSDA atmosphere (FV3) development
Milestone 2: Reanalysis and Reforecasts				
Frolov (PSD)	Coupled DA and R&R for S2S applications	0.25		
Whitaker (PSD)	Ensemble DA and reanalysis	0.25 (no cost)	100%	
TBD (PSD)	R&R technical activities - setup, execution,	1.0		

	monitoring, verification and validation of output			
TBD (EMC)	R&R technical activities - JEDI & workflow support	0.5	EPIC Funded	Will also provide in-kind contribution to JCSDA
Shlyaeva (PSD)	R&R scientific activities - Scientific evaluation of R&R datasets, CDA infrastructure in JEDI	0.5		
Milestone 3: Development of SCDA prototype				
Penny (PSD)	Developing new Ocean/Atmos CDA methods	0.25		complementary projects supporting CDA development
Draper (PSD)	Land/Atmos CDA	0.25 (no cost)		

1.4 UFS-R2O MRW/S2S Sub-project Atmospheric Physics

UFS-R2O Task: MRW/S2S Physics (with 5 year vision for merge with SRW/CAM physics)
Team: MRW/S2S
Sub-project area: Physics
Sub-Project Leads: Jian-Wen Bao (PSL)and Lisa Bengtsson (PSL)
Sub-project organizations proposed for: NOAA/ESRL/PSL, NOAA/ESRL/GSL, NOAA/NCEP/EMC, DTC-NCAR, DTC-ESRL/GSL, NRL, CIRES/SWPC

Sub-Project Narrative

1. **Sub-Project Overview.**

The choice of model physics for GFS v16 has been finalized. Although the new model configuration is expected to perform better than GFS v15, systematic model errors are anticipated to persist, such as 1) 2-m temperature biases over land, 2) errors in the representation of thermodynamic and wind fields in and near layers of high static stability, 3) premature dissipation and erroneous propagation of equatorial waves, 4) poor representation of tropical variability related to convectively coupled equatorial waves, including the MJO, 5) poor representation of stratospheric equatorial wind oscillations, 6) degraded tropical cyclone track forecasts, especially beyond day 5, and 7) too-rapid progression of mid-latitude synoptic-scale waves.

Many of these known deficiencies appear to be related to the model physics, which for the most part have been part of the GFS for many years and only incrementally improved with each new implementation. In the spirit of the community modeling effort that provides the foundation for the emerging UFS, we will create and deploy a NOAA-led multi-agency task force consisting of developers, diagnostic experts, and subject-matter experts to diagnose the role that model physics plays in perpetuating systematic model errors. Therefore, we propose to employ a two-pronged approach to mitigate physics-related model deficiencies in future implementations of the operational global and regional forecast systems.

The effort is closely linked to the sub-project "Coupled Model Development" of this UFS proposal. One part of the effort will focus on relatively high readiness-level testing at EMC with the goal of upgrading the microphysics for GFS v17/GEFS v13. Microphysical parameterization is the central component of any moist physics suite and EMC has considerable experience with multiple viable schemes that already exist in CCPP. Thus, we will leverage this expertise and perform diagnostics, evaluation, and optimization to ensure that one of these relatively advanced schemes will replace the GFDL microphysics in GFS v17/GEFS v13. Simultaneously, we will draw from the experience and insights of the OAR and NRL elements of our team to design a completely new moist-physics suite around the selected microphysics package, again drawing largely from the code base, algorithms, and design strategies of existing CCPP schemes, but striving for a truly innovative and holistic combination of best practices and targeted performance improvements.

This broader effort will target amelioration of the specific GFS deficiencies noted above but will also ensure that key strategic goals of EMC can be achieved. For example, one high priority will be to improve GFS/GEFS capabilities for prediction of severe-weather parameters and PBL structures, so that regional models such as the SREF and NAM can be sunsetted by 2024 without degradation of services for key stakeholders (a key goal of the SRW/CAM-AT), while another will be to work closely with the coupled model development sub-project to enhance capabilities for S2S prediction of long-lived phenomena such as the MJO.

This multiple readiness-level effort represents a paradigm and cultural shift for NOAA and the broader community, invoking the true spirit of community development and applying the combined innovative capacity, creativity, and group synergy of the task force. The overarching objective of this sub-project for the first two years is thus threefold: (1) to establish a multi-agency task force bound by mutual interests, (2) to address the physics improvement needed for the GFS v17 (and GEFS v13) implementation, and (3) to start developing an advanced moist physics suite that will be implemented in the UFS through a unified effort across the MRW and SRW deterministic and stochastic physics development teams.

2. Sub-Project Justification and Technical Approaches.

Task 1: Develop the Next Generation Moist Physics Suite in the Global UFS for Operations – A Multi-agency Collaborative Effort.

Developing advanced physics for operations in NOAA's UFS is essential for the reduction of errors in weather and seasonal forecasts. To accelerate the development of advanced physics in the global UFS, the multi-agency task force will use advanced ideas, insights, and theories to address, in the short term, the performance deficiency of the GFS v16 physics suite for targeting the implementation of the GFS v17 and to further develop, in the long term, an advanced physics suite in the UFS beyond GFS v17. The multi-agency task force will work on the following specific tasks:

(1) Using operational performance metrics, judiciously select a multi-moment microphysics scheme from CCPP and optimize it in the GFS v16 configuration to ensure that it exceeds the performance of the current suite before the end of this two-year sub-project and is available for implementation in GFS v17/GEFS v13 and RRFS v2.

(2) Identify root causes for the physics-related systematic errors in the GFS v16 on medium-range scales via T&E and advanced, process-oriented diagnostics.

(3) Based on the findings from the outcome of deliverable/milestone (2), propose, test and evaluate effective methods to eliminate or alleviate the deficiency in the performance of the GFS

v16 physics suite via improving components of the operational physics suite (e.g., subgrid convection and cloudiness) and their interaction with each other and with the newly implemented multi-moment microphysics scheme.

(4) Develop the foundation for a new unified (CCPP-compliant) moist physics suite for the coupled UFS to incorporate innovations, state-of-the-science and software-engineering capabilities, and optimal performance targeted UFS applications for all scales. The development will be closely tied to the Coupled Model Development project and incorporate stochastic physics representation.

Task 2: Resolved-scale Dynamics and Sub-grid Wave Physics, their Interactions and Impact on the Medium-Range, S2S and Climate Predictions of FV3GFS-UFS.

This task studies interactions between resolved-scale wave dynamics and sub-grid gravity wave (GW) physics at variable model resolutions of GFS, and quantifies impacts of these interactions on the medium-range, subseasonal-to-seasonal and multi-year climate predictions. We identify the performance deficiencies of the current GW drag scheme in GFS v16 and address them during development and tests of UGWP-v1, targeting its release for the GFS v17 implementation. We will start incremental development of an advanced suite of UGWP schemes in the UFS that will incorporate the following: a) physics-based representation of GW sources; b) scale-aware representation of GW effects; and c) tune-ups and comparisons of GW solvers. This collaborative effort between CIRES/SWPC, GSD and EMC will pursue four subtasks:

(1) Perform diagnostics and sensitivity studies that identify the deficiency in the performance of the GW physics of GFS v16 for medium-range forecasts in the mountainous areas and regions of GW "hotspots" observed from space and resolved by the high-resolution UFS models; suggest and evaluate first approaches for the scale-aware description of GW physics.

(2) Develop and optimize UGWP suite of CCPP for orographic and non-stationary GWs using the GFS v16 configuration and improve the performance of the current GFS v16 GW scheme; release UGWP-v1 for the pre-implementation tests and verifications in GFS v17 and GEFS v13.

(3) Continue to test and evaluate the performance of UGWP-v1 at different horizontal resolutions to eliminate the deficiency of its performance with the novel suite of GFS v17 physics; orchestrate impact of GW physics with dynamics of resolved mesoscale waves.

(4) Perform seasonal and multi-year tests of GFS v17 with scale-aware schemes of UGWP-v1 and verify results by the reanalysis products and middle atmosphere observations; evaluate and further refine the improved UGWP-v1 in medium-range predictions (GEFS v13).

Accomplishing the first two sub-tasks will provide a good start for the incremental development and version-based releases of the advanced UGWP suite in the UFS and initiate close collaborations with other UFS application teams (subtasks 3-4). Relying on the results from the first 2 years, we will initiate developments of other components of the UGWP suite important for the stochastic physics of ensemble-based data assimilation (spontaneous triggering of GWs) and support advanced upper atmosphere physics of FV3WAM (tidal-GW interactions).

Task 3: Testing and Evaluation of UFS Physics for Coupled Medium-range Weather and Subseasonal Forecasting.

Unlike conventional and routinely adopted T&E of forecasting systems, this task will provide information that can support and influence the model physics developmental process through a T&E procedure that is agile (frequent, fast, automated), in-depth, neutral, collaborative, and operation-relevant but not operation-prescriptive. The work will have the following foci:

- The T&E seeks to first primarily explain the systematic biases in the operational GFS v16 physics suite. In addition to the perpetuating systematic model errors, other biases particularly related to stratocumulus and shallow and deep convection will be identified using benchmark datasets including reliable observations and reanalysis.

- The root causes and error contributions from physical parameterizations will be diagnosed by analyzing the physical tendencies and applying the "UFS Column Replay Capability" and "Process Isolation Capability" of the Common Community Physics Package (CCPP) Single-Column Model (SCM) These capabilities are currently being developed as part of the DTC Hurricane Supplemental 1A-2-2b and are considered tools for the Hierarchical System Development (HSD).

- The role of a coupled atmosphere-ocean-ice forecast system in generating the extended-range forecasts and subseasonal prediction will be investigated by comparing atmosphere-only and coupled configurations (with MOM6 ocean model and CICE5 sea ice model). As the coupled configurations become available, capabilities offered through the Common Infrastructure for Modeling the Earth (CIME) will be adopted to plug-and-play different component models and control component feedbacks. The T&E effort will feedback to the UFS sub-project "Coupled Model Development" for building a best performing coupled GFS-MOM6-CICE6-WWIII system for the operation of GFS v17/GEFS v13 in 2024.

- Physics innovations (such as the development of "an advanced moist physics suite" and "UGWP-v1") that are relatively mature and involve close research-and-operational collaborations will be examined to funnel efforts from the research community to the operational physics (including GFS v17/GEFS v13 and beyond).

- All the evaluation metrics adopted will be "evidence-based and process-oriented" and consistent with the spirit of DTC's contribution to the selection of an advanced physics suite for GFS v16. 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.

This task is expected to explicitly and continuously advance the model physics with the ultimate goal to improve the overall capability of the UFS. After completion of this 2-year sub-project, evaluation methods adopted are likely to become usable for the broader community.

3. Two Year Plan and Five Year Vision.

Two year plan.

The 2-year plan is outlined in the table below:

Timeline	**FY20**	**FY21**				**FY22**		
Milestone	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
1) Form a multi-agency task force for moist physics. (GSL, PSL, EMC, NRL, DTC)	x							
2) Outline a test plan. (GSL, PSL, EMC, NRL, DTC, CIRES/SWPC)	x							
3) (a) Select a multi-moment microphysics scheme from CCPP and (b) optimize it in the GFS v16 configuration, targeting GFS v17 GEFS v13 implementation. (EMC, PSL, GSL, NRL)			(a)					(b)
4) Identify root causes for the key systematic errors in the performance of the GFS v16 physics suite (with new microphysics) on medium-range scales. (DTC, PSL, GSL, EMC, NRL)					x			
5) Propose, test and evaluate effective methods to eliminate or mitigate the deficiencies seen in the performance of the GFS v16 (with new microphysics), and further test and evaluate the methods in GFS v17/GEFS v13. (EMC, GSL, PSL, NRL, DTC)								x
6) Develop and test UGWP-v1 using GFS v16, targeting GFS v17. (GSL, CIRES/SWPC, EMC)				x				
7) Deliver UGWP-v1 to EMC for tests in the pre-implementation version of GFS v17.								x

(GSL, CIRES/SWPC, EMC)								
8) Deliver the foundation for a unified moist physics suite for testing for GFS v17, with expectations for significant additional improvements through continued development in ensuing years. (EMC, GSL, PSL, NRL)								x
9) Assess physics innovations (proposed for GFS v17/GEFS v13 and beyond) including the advanced moist physics to be developed in Task 1 by applying the Hierarchical Developmental System (HSD). (DTC)								x

5-year vision.

The longer term vision of this sub-project includes development of a new moist physics suite including; cloud microphysics, subgrid convection, stratocumulus and turbulent mixing. In this suite, cloudiness plays various parallel roles and should be unified as much as possible. Contrary to today's operational suite, all components with mixing processes leading to a change in the moisture budget will be unified, such that the same basic microphysical processes are used for all cloud types and phase changes, resolved- and subgrid-scale. In addition, we aim to design the suite to adapt in complexity when necessary to computationally optimize the physics suite across atmospheric scales and applications. An example being the ability to use a 2-moment cloud microphysics scheme for the CAM scales, while minimum complexity of prognostic variables in the microphysics scheme will be investigated for seasonal predictions. The development will consist of a prototype high-performing, next-generation moist physics suite; targeted for GFS v17/GEFS v13 and RRFS v2 implementation around 2024, pending evidence-based justification, with expectations for significant additional improvements through continued development in ensuing years. The 5-year vision for the development and upgrade of the advanced suite of UGWP will include: a) physics-based representation of GW sources; b) improvements in the resolution-sensitive specification of wave fluxes and spectra; c) tune-ups and comparisons of GW solvers; and d) interaction GW physics with other GFS parameterizations (PBL, convection and eddy diffusion).

4. Interdependencies with other projects/EMC planned implementation timelines and/or any major risks and issues.

This sub-project depends on the work of the following UFS-R2O projects: Coupled Model Development (role of coupled ocean/ice on clouds and convection, stochastic physics development), atmospheric composition, SRW/CAM (RRFS v2 physics development), verification and postprocessing, DTC (especially CCPP support), and land surface model development. The project is strongly dependent on the EMC planned implementation and testing timeline for GFS v17 and RRFS v2.

5. Specify how success will be measured.

The success of the physics development will be measured in performance relative to the baseline, here defined as GFS v16. Guidance from the HSD, operational metrics, and Model Evaluation Group (MEG) evaluation will be used to determine the performance of any new physics development. One milestone is listed as to develop an implementation and incremental test plan.

6. Estimate of compute resource requirements, both in terms of CPU hours per month and disk storage.

The CPU hours are estimated for the whole sub-project. It is anticipated that the initial development will use lower resolution uncoupled simulations, whereas the final stages of the development needs to be tested in the fully coupled high resolution, meeting operational product delivery time requirements. On Hera, using 432PE's, one 35-day forecast uncoupled GFSv16 (127 levels) experiment at C384 resolution uses ~3500 CPU hours, the coupled equivalent (C384 atmosphere, ¼-degree ocean and ice) is about ~8000 CPU hours. For the whole sub-project (including all teams), on all resources (WCOSS, Hera, Jet, Orion and Gaea) to do research/development and to acquire sufficient statistics, we thus anticipate the use of 12M CPU hours/year, and 100TB in storage, we will to the extent possible leverage existing resources.

7. Specify how organizational base-resources (in-kind) will be leveraged for this sub-project.

EMC federal employees and contractors funded by NOAA base resources will contribute to the development and implementation of GFS v17 and GEFS v13. ESRL/PSL and ESRL/GSL are contributing in-kind to the development of the new physics suite. ESRL/GSL will also contribute to the development and implementation of RRFS v1 and v2.

8. Summary of known team members and institutions (expected FTE commitment), including what resources are leveraged, including federal salaries or synergistic projects.

Breakdown of FTE-effort, including an explanation of how NOAA base resources (in-kind) will be leveraged. The leveraging of other projects or base-resources should include estimated (base-funded or leveraged) FTE contributions.

Name/ organization	**Subject matter expert/milestone effort**	**Commitment level FTE**	**Amount leveraged (if any)**	**What is leveraged? (office space, time, computing)**
ESRL/PSL: Jian-Wen Bao, Lisa Bengtsson, 1 new hire, 1 TBD CIRES@PSL staff	Convection and microphysics development. Stochastic physics. Model physics interaction/evaluation. Milestones: 1, 2, 3, 4, 5, 8	FY 2020-2021: New hire + 1 TBD CIRES@PSL staff. FY2022: New hire + Lisa Bengtsson Total 1.5 FTE/year	Jian-Wen Bao. 3 months/yea r FY2020-2021: Lisa Bengtsson 2 months	Computational resources, time, office space, coordination.
ESRL/GSL: Georg Grell, Joseph Olson, others TBD	Convection, boundary layer turbulence, gravity wave drag and cloud physics. Milestones: 1, 2, 3, 4, 5, 6, 7, 8	FY 2020-2021: Joseph Olson .2FTE, 2 @ 0.5 FTE CIRES@GSL FY2022: Joseph Olson .5 FTE, 2 @ 0.5 FTE CIRES@GSL Total 1.5 FTE/year	FY2020-2022: Georg Grell .2FTE	Computational resources, time, office space, coordination.
DTC-GSL: Ligia Bernardet (PI), others TBD	CCPP, testing and evaluation, applying HSD for R2O Milestones: 1, 2, 4, 5, 9	Total 0.5 FTE/year		
DTC-NCAR: Weiwei Li (PI), others TBD	CCPP, testing and evaluation, applying HSD for R2O Milestones: 1, 2, 4, 5, 9	Total 0.5 FTE/year		Non-HPC computational resources

NRL: James Doyle, Yi Jin	Convection and microphysics development. Model physics interaction/evaluation. Milestones: 1, 2, 3, 4, 5, 8	FY 2020-2021: Doyle (0.1 FTE) Jin (0.12 FTE)		Computational resources for diagnostics, analysis and 1D modeling available locally at NRL
CIRES/SWPC: Valery Yudin	Unified gravity wave physics Milestones: 6,7	FY 2020-2021: TBD FY 2022: TBD Total 0.5 FTE/year		Computational resources
NCEP/EMC: Fanglin Yang	Convection, PBL/turbulence, microphysics, GWD development. Model physics interaction/evaluation/optimization. Milestones: 1-9		Contractors, in-kind Fanglin Yang, 0.1 FTE in-kind	Computational resources, time, office space, implementation insights

Total MRW/S2S Computer Resource Requirements.

Summary table showing breakdown by sub-project (cloud, NOAA research HPC, vs other HPC). CPU hours per year/Tb storage (not covered by existing NOAA HPC allocations). The data in this table will be used to develop an allocation request for NOAA cloud and HPC resources.

Project/Type of HPC	NOAA HPCS	Outside NOAA HPCS	Cloud
Coupled DA/R&R	Yr1: 6M, 48Tb Yr2: 60M, 800Tb		Yr1: 12M, 96Tb Yr2: 120M, 1600Tb
Coupled Model Dev	184.4M/ 524Tb (yrs 1&2)		
Atmos Composition	6.5M/85Tb (yrs 1&2)		

Model Components	1M/1Tb (yrs 1 & 2)	6M/6Tb (yrs 1 & 2) (for university collaborators)	
Data Assimilation	Yr1: 60M/500Tb Yr2: 60M/500Tb		Yr1: 60M, 2000Tb Yr2: 240M,20000Tb
Atmos Physics	12M/100Tb (yrs 1&2)		

Section 2: Short-Range Weather/Convection Allowing Model Applications.

The UFS will form the foundation of NOAA's regional operational modeling services, a transition which is underway and will continue for the next several years. In line with global UFS applications, the transition to regional UFS applications will include consolidation around the FV3 dynamical core at convection allowing model (CAM) scales (nominally 3-km grid spacing or less) that include stand-alone regional (SAR) configurations of FV3 with the Common Community Physics Package (CCPP) for the atmosphere and the Joint Effort for Data Assimilation Integration (JEDI) project will initialize the CAM forecasts using observations. A major benefit of the regional UFS transition will be simplification of the operational regional modeling suite that currently spans three dynamical cores and many combinations of physical parameterizations. This simplification will result in more efficient use of existing high performance computer and staff resources to advance scientific priorities. The proposals herein describe the technical milestones as part of this transition process while also ensuring the advancement of key scientific areas, such as high resolution modeling and data assimilation. Integral to these efforts is collaboration, both across the UFS application areas and across the wider scientific community. The plans for advancing the SRW/CAM applications, from predictive time scales of minutes to a week, in support of the future 3D Real Time Mesoscale Analysis system (3D-RTMA), the future Warn on Forecast System (WoFS), the future Rapid Refresh Forecast System (RRFS) that paves the path for unifying various regional and mesoscale systems currently in operations, and advancing hurricane prediction through the future Hurricane Analysis and Forecast System (HAFS) are organized into four sub-projects within this section. Briefly, each sub-project and their primary milestones over the next two years are described below:

1. 3D-Real Time Mesoscale Analysis System (3D-RTMA) -- updated every 15 minutes.
   a. Establish the 3D-UnRestricted Mesoscale Analysis, a 6-h time-delayed complement to the 3D-RTMA, which serves as the "Analysis of Record" for the NWS and fulfills the critical role of calibration in the National Blend of Models (NBM).
   b. Improve the efficiency and product latency for 3D-RTMA, both of which are critical features of a sub-hourly updated analysis system intended for situational awareness.
   c. Advance the 3D-RTMA to provide novel 3D analysis products, such as 3D cloud fractions, while maintaining the integrity of existing 2D analysis products, such as significant wave height. In addition we propose an effort to enhance the observation quality control. Every conventional observation counts in the 3D-RTMA and a more intelligent way of looking at observations individually is needed to advance the system.
   d. The 3D-RTMA effort must also begin transitioning to the JEDI framework, beginning with the proper interfaces, and transitioning to a focus on filling any gaps with the addition of new observation operators while reducing the latency of the products.

2. Warn on Forecast System (WoFS) -- forecasts to a few hours.
   a. Complete the assessment of the performance characteristics for FV3 SAR at 3 km for WoF ensemble prediction as well as for HREF/RRFS use.
   b. Begin transition to the JEDI data assimilation system: software, forward operators, infrastructure. This will require a stepped approach where FV3 SAR/GSI-EnKF is tested, then the full FV3 SAR/JEDI system.
   c. Assess the cost/benefit from a 1 km WoF system (i.e., is it worth the 10-15x cost?)

3. Rapid Refresh Forecast System (RRFS) -- forecasts to a few days, and retirement of legacy regional mesoscale modeling systems.

a. Fundamental steps toward the realization of the RRFS.
b. Implementation of HREFv3, featuring the introduction of the FV3 dynamic core in operations at convection-allowing resolution.
c. Development and establishment of a baseline configuration of the RRFS system, including dynamics, physics, and vertical resolution.
d. The advancement and testing of the data assimilation framework, which includes the introduction of ensemble-based data assimilation methods at convection-allowing scales.
e. A parallel effort to begin transitioning data assimilation development efforts to JEDI.
f. A focused effort on the convective-scale assimilation of GOES-16 all sky radiance observations.
g. The application of a machine learning approach for bias correcting GEFS output critical to forecasting hazardous weather.
h. An intercomparison of the GFS/GEFS and existing regional suite to obtain a comprehensive understanding of objective differences and allow for the identification of areas requiring improvement, in consultation with stakeholders, to facilitate retirement of regional systems.
i. As a risk reduction effort, we propose the development and testing of a unified, FV3-based limited area ensemble system at 9 km resolution covering the same region as the current RAP/NAM. Such an effort is required to account for the possibility that the GFSv17/GEFSv13 will not be ready to subsume the roles of the existing mesoscale modeling suite. Therefore, to allow for the retirement of legacy dynamic cores and modeling systems, a risk reduction strategy is proposed.

4. Hurricane including the Hurricane Analysis and Forecast System (HAFS) -- forecasts to a week.

a. Operational upgrade and maintenance of the Hurricane Weather Research and Forecasting (HWRF) model & Hurricanes in a Multi-scale Ocean coupled Non-hydrostatic (HMON) model. Different possible configurations (storm-centric, basin-wide) for HWRF, HMON and HAFS will be tested and chosen based on improvements in forecast skill and available production compute resources.
b. Continue development of Hurricane Analysis and Forecast System (HAFS) data assimilation (HAFS-DA, hereafter) including TC initialization, atmosphere and ocean coupling, physics upgrades, and adding telescopic moving nests. These will be primarily driven and leveraged by Hurricane Supplemental resources and timelines.
c. JEDI implementation for HAFS-DA; this will also be leveraged with Hurricane Supplemental funded tasks for JEDI development facilitated by code sprints and in conjunction with FV3-CAM and FV3-Global DA advancements.
d. Conduct real time HFIP experiments for HAFS, HWRF & HMON including ensembles.

The following four sections describe each sub-project in detail, including technical approaches, milestones, and budgets.

2.1 UFS-R2O SRW/CAM Sub-Project: 3D-RTMA

UFS-R2O Task: SRW/CAM 3DRTMA
Team: SRW/CAM
Sub-project area: 3DRTMA
Sub-Project Leads: Jacob Carley/EMC and Curtis Alexander/GSL
PIs: Jacob Carley/EMC and Curtis Alexander/GSL
Sub-project organizations proposed for: NOAA/NWS/EMC and NOAA/ESRL/GSL

Sub-project Narrative

1. **Sub-project overview.**

The Real Time and UnRestricted Mesoscale Analysis systems (RTMA and URMA, respectively) are two-dimensional variational analysis systems that provide hourly analyses of surface sensible weather elements for purposes of situational awareness, verification, and calibration. Both systems provide analyses at an approximate grid-spacing of 2.5 km and support CONUS, Alaska, Hawaii, Puerto Rico, and Guam. The RTMA runs every hour and provides situational awareness while the URMA system runs 6 hours later to accommodate late arriving data and is therefore used for verification and bias correction. There is also a Rapid Update version of the RTMA that runs every 15 minutes for CONUS to provide products to stake-holders needing low-latency analysis products to meet their mission needs, such as the aviation community. A primary stakeholder is the NBM, which uses the URMA system for calibration. In 2011 the RTMA/URMA system was approved as the Analysis of Record after passing through Gate 4 of the Operations and Services Improvement Process.

The 3D-RTMA/URMA system builds upon the operational 2D RTMA/URMA system, which is currently limited to fields that correspond to official National Weather Service (NWS) gridded forecasts, mostly surface fields. Extending the RTMA/URMA to three dimensions allows for the creation of highly useful nowcasting and situational-awareness products, including full-column representation of standard meteorological fields such as temperature, water vapor, and wind, as well as hydrometeors (i.e., clouds, precipitation of all forms). Analysis updates will be performed at sub-hourly intervals, at least every 15 minutes, with low product latency. Further, the 3D-RTMA/URMA system will directly leverage output from the Rapid Refresh Forecast System (RRFS) for its background field as well as the RRFS ensemble members in the data assimilation step, which will use JEDI. The 3D-RTMA/URMA system is planned for operational implementation in 3-4 years and will become the Analysis of Record, and replaces the 2D RTMA/URMA/RTMA-RU systems.

2. **Sub-Project Justification and Technical Approaches.**

The 3D-RTMA project, which is in its final year of support by a complementary JTTI project, is at a readiness level of 6, with demonstration of a prototype system in a relevant or test environment, and therefore it requires the following efforts noted here to advance it toward operational readiness. This effort will be conducted in coordination with the "MRW/S2S Data Assimilation" project.

(1) Establish 3D-URMA to complement 3D-RTMA: The first milestone of Task 1 focuses on establishing the component of the RTMA that serves as the "Analysis of Record", i.e. the UnRestricted component that executes 6 hours later than the Real Time system to accommodate late arriving data. The URMA counterpart to RTMA fulfills a critical role in bias correction and calibration for the NBM. The 3D-UnRestricted Mesoscale Analysis will also fulfill a need for a 3D, high-resolution, gridded analysis product suitable for verification. In year 2 the CONUS coverage will be extended to OCONUS regions currently supported by the conventional 2D system, which includes Alaska, Hawaii, and Puerto Rico. Guam will also be considered as it is currently supported by the hourly 2D-RTMA system.

(2) Improving efficiency and latency: The utility of the 3D-RTMA as a situational awareness tool depends on its efficiency, speed, and scalability. Development is required to optimize the system such that it provides high quality analyses with minimal product latency every 15 minutes or less. In the current configuration the analysis algorithm has inherent bottlenecks that prohibit scaling beyond 360 processors. Fundamental algorithm enhancement through the use of Beta line filters in conjunction with a multigrid solver is underway, with coordinated testing in both GSI and JEDI through existing EPIC funds (currently funded through FY20 and anticipated through FY21). This work is expected to dramatically improve the scalability and speed of the 3D-RTMA system. Additional refinements to the analysis/solver strategy will be tested including use of "climatological" ensemble perturbations to replace a static background error covariance (bypassing recursive filter) in the hybrid EnVar analysis for additional speed. This is also an area where EPIC engineers could assist in optimization of code to meet performance goals.

(3) Improve analysis products: With support, we will ensure the existence and quality of 2D analysis fields in the 3D system. While several of these fields do already exist, such as 2m temperature, fields such as significant wave height and max/min temperature do not. Additional work is required to ensure these fields, which are required by the NBM, are present in the final product. Additionally, new products from the 3D-RTMA require novel post-processing techniques typically not required in conventional post-processing of model output. Such fields include those typically obtained as byproducts from the model integration, such as radiative fluxes and radar reflectivity. Such fields are important components of the 3D-RTMA system; however, it is cost-prohibitive to execute a single timestep of the model to obtain these fields. Therefore, additional development is required to extract this information in an efficient manner. Observation quality

control is a critical component of RTMA. Every conventional observation counts in the 3D-RTMA and a more intelligent way of looking at observations individually is needed to advance the system. Currently, the 2D-RTMA systems only tend to examine observations as belonging to a group (METAR, mesonet, mesonet from the accept list, etc.) with the exception of standard quality control procedures, like outlier checks. This work will involve the adoption of enhanced quality control that leverages station-specific history of observation innovations to implement a variety of quality control tests (e.g. climate, statistical, stuck instrument, etc.). Such efforts would be coordinated with efforts proposed in the “MRW/S2S Data Assimilation” project through the Interface for Observation Data Access (IODA, a part of JEDI).

(4) <u>JEDI Transition:</u> Finally, this project also must transition from the NOAA GSI system to the JEDI framework, which will offer advanced data assimilation techniques and capabilities. This is expected to be a longer-term effort that will begin in the first year of the project, starting with building proper interface components and adding forward operators that are unique to RTMA applications (such as visibility and sky cover), in coordination with the “MRW/S2S Data Assimilation” project.

3. Two Year Plan and Five Year Vision.

Timeline	FY20	FY21				FY22		
3D-RTMA	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
1 Establish 3D-URMA to complement 3D-RTMA, support OCONUS								
1.1 Establish 3D-URMA over CONUS	X	X	X	X				
1.2 Establish 3D-RTMA/URMA over OCONUS					X	X	X	X
2 Improve latency								
2.1 Test refined and highly scalable background error covariance algorithm						X	X	X
2.2 Test additional analysis/solver strategies including use of ensemble perturbations in EnVar to replace static error covariances			X	X	X	X	X	X
3 Improve analysis products								
3.1 Add missing analysis fields to 3D-RTMA (e.g., significant wave height, max/min temp)	X	X	X	X				
3.2 Develop enhanced post-processing for novel output products					X	X	X	X
3.3 Develop enhanced observation quality control			X	X	X	X	X	X
4 JEDI Transition								
4.1 Begin transition to JEDI introducing appropriate interface to ingest background fields	X	X	X	X				
4.2 Adopt and introduce forward operators			X	X	X	X	X	X

The longer-term (3-5 yr.) vision includes the implementation of the 3D-RTMA/URMA system over CONUS and OCONUS replacing the 2D-RTMA system [year 3-4].

In addition, the 3D-RTMA/URMA system will fully transition to the JEDI framework within the next 5 years, and the effort will be conducted in collaboration with the "MRW/S2S Data Assimilation" project. Of particular note is the development of an in-memory, continuously run analysis framework that JEDI will enable. In such a system there are considerable gains in efficiency because there is no need for individual jobs/tasks to stop/start. This capability is envisioned as a critical technical capability to enable the future success of the 3D RTMA system with its sub-hourly updates and low-latency requirements.

4. Interdependencies with other projects/EMC planned implementation timelines and/or any major risks and issues.

Significant interdependencies

- SIP - Many projects, highlights are as follows
  - *UFS-R2O SRW/CAM*
  - *UFS-R2O MRW/S2S Data Assimilation*
  - *UFS-R2O Cross-cutting Application Verification and Post Processing*
- [JTTI] Extending the Real-Time Mesoscale Analysis-Rapid Update (RTMA-RU) to 3 Dimensions for Whole Atmosphere Situational Awareness and Analysis of Record
- [FY19 EPIC] Development of a Multigrid Background Error Covariance Model for High Resolution Data Assimilation

Risk/Issues

Improving product latency to an appropriate level to meet stakeholder needs will require significant scientific and engineering development along with sufficient high performance computing. The ultimate implementation of the 3D-RTMA is strongly dependent upon the EMC planned implementation and testing timelines.

5. Specify how success will be measured.

The success of the 3DRTMA development will be measured in performance (analysis fit to observations, physical consistency of fields) relative to the baseline, here defined as the 2DRTMA system. Guidance from the NOAA testbeds, operational metrics, and Model Evaluation Group (MEG) evaluation will be used as appropriate to assess performance.

6. Estimate of compute resource requirements, both in terms of CPU hours per month and disk storage.

The CPU hours are estimated for the whole sub-project. Owing to the low latency and fast-turn around needs for the 3D-RTMA system, a single execution must take place in under 15 minutes. As development advances, this number will decrease. Current CONUS executions use about 360 PEs on WCOSS and run in about 15 minutes. This system executes continuously throughout a 24 hour period. Therefore a single day is comprised of 96 cycles. For a single experiment this equates to about 260k core hours per month. To accommodate sufficient testing and development we estimate needing 8.4M core hours per month (100.8M per year) and 50 TB in storage. We will to the extent possible leverage existing resources.

7. Specify how organizational base-resources (in-kind) will be leveraged for this sub-project.

- EMC federal employees and contractors funded by NOAA base resources will contribute to the development and implementation of 3D-RTMA.
- GSL federal employees and cooperative institute (CU/CIRES, CSU/CIRA) staff will contribute in-kind to the development and implementation of 3D-RTMA at approximately 2.0 FTEs.
- Dedicated NOAA R&D Jet HPC resources will be leveraged for some real-time experimental development, demonstration and testing.

8. Summary of known team members and institutions (expected FTE commitment), including what resources are leveraged, including federal salaries or synergistic projects.

Name/ organization	**Subject matter expert/milestone effort**	**Commitment level FTE**	**Amount leveraged (if any)**	**What is leveraged? (office space, time, computing)**
3D-RTMA				
EMC Dr. Jacob R. Carley	PI	0.1 FTE	100%	Time
GSL PI: Dr. Curtis R. Alexander	PI	0.1 FTE	100%	Time
Milestone 1 Establish 3D-URMA to complement 3D-RTMA, support OCONUS				

EMC	Current Data Assimilation Developer	1 FTE		Computing
GSL	Current Data Assimilation Developer	1 FTE		Computing
GSL	Current Data Assimilation Developer	1 FTE (in-kind)	100%	Time, Computing
Milestone 2 Improve latency				
EMC	Current Data Assimilation Developer	1.7 FTE (in-kind)	100%	Time, computing
GSL	Current Data Assimilation Developer	1 FTE		Computing
GSL	Current Data Assimilation Developer	2 FTE (in-kind)	100%	Time, computing
Milestone 3 Improve analysis products				
EMC	Current Data Assimilation Developer	1 FTE		Computing
EMC	Current Downscaling Developer	1.0 FTE (in-kind)	100%	Time, computing
GSL	Current Data Assimilation Developer	1 FTE		Computing
GSL	Current Data Assimilation Developer	1 FTE (in-kind)	100%	Time, computing
Milestone 4 JEDI Transition				

EMC	Current Data Assimilation Developer	1 FTE		Computing
EMC	Current Data Assimilation Developer	0.75 FTE (in-kind)		Computing
GSL	Current Data Assimilation Developer	1 FTE		Computing
GSL	Current Data Assimilation Developer	2 FTE (in-kind)	100%	Time, computing

2.2 UFS-R2O SRW/CAM Sub-Project: RRFS and Retirement of Legacy Models

UFS-R2O Task: RRFS and Retirement of Legacy Models
Team: SRW/CAM
Sub-project area: RRFS
Sub-Project Leads: Jacob Carley/EMC and Curtis Alexander/GSL
PIs: Jacob Carley/EMC, Curtis Alexander/GSL, Kimberly Hoogewind/NSSL, Jamie Wolff/DTC, Xuguang Wang/MAP, Ming Xue/CAPS
Sub-project org's proposed for: NWS/EMC, ESRL/GSL, OU/SoM/MAP, OU/CAPS, DTC

Sub-project Narrative

1. Sub-Project Overview.

1.1 RRFS: Develop dynamic core, data assimilation, and physics.

The process of evolving the NOAA NWP production suite from the broad and diverse range of model components to a community-based unified system is a major undertaking that includes the evolution of global, regional, and storm-scale prediction systems; Dynamic Core, Data Assimilation, and

Physics Suite components; and deterministic and ensemble prediction systems. Accordingly, within the NOAA model unification effort, a key area of interest is the evolution of the NAM, RAP, HRRR, and HREF systems to a new unified deterministic and ensemble storm-scale system, to be known as the Rapid Refresh Forecast System (RRFS). This new system is targeted for initial operational implementation in late 2023 as a planned replacement for the NAMnest, HRRR, HiResWindows and HREF.

This ongoing unification effort to move from the existing NOAA prediction systems to the UFS is a major multi-year undertaking. Benefits of this NOAA model unification to the UFS will be far-reaching and include many aspects such as: (i) simplification of the operational NCEP suite of models to optimize use of existing and future high-performance computer resources, (ii) reduction in overhead of software maintenance, and related resources spent on maintaining multiple dynamic cores, (iii) growing engagement of a community development paradigm for broad contributions to the development of earth system prediction capability, (iv) development of a fully coupled data assimilation/dynamic core system that will greatly minimize I/O and facilitate advanced data assimilation techniques that require access to in-memory model states, and (v) modularization of the dynamic core and physics suite for agile development. 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 we maximize forecast skill across the many model applications.

1.2 Retirement of Regional Mesoscale Modeling Systems.

A successful transition to the Rapid Refresh Forecast System (RRFS), as described in Annex 7-Project 3 of the FY19-21 SIP, will involve the phased retirement of several regional prediction systems currently in operation, and largely frozen, at NCEP. This is in part because the RRFS will subsume the roles of several of the regional systems and the continued advancement of the GFS/GEFS will complement this process. Regional systems planned for retirement include: the SREF, the North American Mesoscale model (NAM) and the Rapid Refresh (RAP). Currently the following systems are frozen and are only being maintained: the NAM, the SREF, and the component NMMB and ARW dynamic cores of the HREF. The RAP (and HRRR) have one final upgrade scheduled for Q3FY20 prior to freezing its development.

A significant challenge in reaching a unified endpoint is the retirement of the SREF system, which is currently comprised of ARW and NMMB members, with a mix of physics parameterization schemes, and features diversity in sources of initial conditions. Retiring the SREF will also remove a significant downstream dependency of the RAP and NAM, which are both also planned for retirement. The majority of regional development efforts now focus on unification around the FV3 dynamic core and the RRFS system, which is a significant simplification of the NCEP production suite. The planned end state for this regional unification effort is FY25, where a combination of the RRFS and the Warn-on-Forecast system (WoFS) complement the GEFS as the primary atmospheric prediction systems in the NCEP production suite. This effort represents a considerable step toward the unification and simplification of the production suite, paving the way for efficient adoption of the UFS.

2. Sub-Project Justification and Technical Approaches.

Task 1: RRFS: Develop dynamic core, data assimilation, and physics

The development toward the eventual implementation of the RRFS requires coordinated development across several, interconnected areas spanning dynamic core, data assimilation, and physics suite. Integral throughout this process is careful objective and subjective diagnostic analysis of forecast output in the form of case studies and metrics.

(a) HREFv3: The first milestone of Task 1 focuses on bringing the HREFv3 implementation to fruition. This is an important milestone in the overall context of the advancement to the RRFS as it represents the initial implementation of the FV3-SAR system in the production suite by way of retiring a legacy NMMB-based member and replacing it with an FV3-SAR member.

(b) Model and Ensemble Configuration: A primary step in RRFS development is establishing a configuration of the dynamic core that is well-suited for the convective-scale. This includes testing parameters related to damping, diffusion, advection, etc. Such efforts will be done in close coordination with efforts described in the “SRW/CAM WoF” sub-project. An optimal baseline for vertical resolution is another critical milestone, as a sufficiently high model top is needed to facilitate the effective assimilation of satellite radiance observations, but not so high as to introduce model stability issues. Further, we will seek a configuration that features enhanced resolution in the boundary layer owing to the relative importance of the accurate representation of boundary layer processes. In addition, baseline settings will be selected for time-stepping, damping/filtering, advection, and similar options. The SRW/CAM Application Team recently came to consensus regarding a physics baseline that focuses on the following schemes: Thompson microphysics, MYNN turbulence and surface layer, Noah-MP land surface scheme, and RRTMG for longwave and shortwave radiation. This decision was based on years of experience in operational NWP as well as over a decade of physics-based experiments at CAM scales in NOAA testbeds, especially through the Community Leveraged Unified Ensemble (CLUE). Work on physics will involve: a) completing the transition of development efforts to the new baseline configuration along with documenting/benchmarking the forecast performance of the physics baseline, b) efforts to address biases using tools developed by NOAA Testbed Project funded collaborators (e.g. NCAR), and c) adding/tuning stochastic components to physics to develop a reliable and skillful ensemble at CAM scales. It is worth noting that the current body of scientific literature, as well as results from NOAA testbeds, continues to indicate insufficient spread/error statistics in CAM ensembles, even when stochastic physics are employed. In order to mitigate issues with under-dispersion a multi-physics approach to the forecast ensemble may be considered, which is enabled by the Common Community Physics Package (CCPP). Future efforts, stretching into the 5 year vision, will be closely coordinated with the longer term development addressed in the sub-project "MRW/S2S physics development", specifically for the development of the new advanced moist physics suite, which is aimed to be unified across all components of the moist physics, and scale-aware for different applications.

(c) Data Assimilation Algorithms: Data assimilation activities will focus first on leveraging state-of-the-art capabilities in current form from the NOAA GSI-based data assimilation system, borrowing heavily from lessons learned in tests with the HRRR Ensemble data assimilation system that is a part of the HRRRv4. In addition, this is an opportunity to execute and transition innovations from numerous CAM data assimilation collaborative efforts funded by e.g. NOAA JTTI/Testbed programs. The first test version, resources permitting, will feature a hybrid/ensemble data assimilation capability (~40 members) and a deterministic forecast component. Later this will be expanded to include an ensemble forecast component (~10 members).

(d) JEDI Transition: While the data assimilation algorithm effort advances, a parallel effort will begin to start the transition to the JEDI framework, first starting with building the appropriate interface to JEDI for FV3-SAR and following closely thereafter with the adoption of the forward operators. As the JEDI project matures, developers will continue to transition efforts to the new paradigm where important algorithmic upgrades will take place over the following 3-5 years, such as enhancements for nonlinearity and non-Gaussianity, multiscale data assimilation, coupled land-atmosphere data assimilation, etc. This is enabled through close engagement with the “MRW/S2S Data Assimilation” project.

(e) GOES-16 All Sky Radiance Assimilation: Efforts will continue to not only maintain assimilation capabilities with the current suite of observations, but will expand to include emerging observations, such as GOES all sky radiances. This milestone complements other tasks and efforts and proposes to extend the FV3-SAR hybrid/ensemble data assimilation system with the capability of assimilating the GOES-16 all sky radiance (water vapor and cloud sensitive channels) observations to improve the forecast skills of the RRFS through (1) identifying the optimal FV3-SAR model configuration for convective scale forecasts verified against the GOES-16 radiance observations, and (2) accelerating the optimization of the configuration of GOES-16 all sky radiance assimilation in RRFS. Item (1) additionally facilitates the identification of FV3-SAR configuration for convective scales as discussed in task 1 (2).

Task 2: Retirement of Regional Mesoscale Modeling Systems

The regional modeling portion of the NCEP production suite has numerous dependencies and is complex. A primary example is depicted in Fig. 1, which shows the downstream and upstream dependencies for the current SREF system. This task describes the necessary initial steps toward retiring the legacy mesoscale modeling suite as a complementary effort toward unification under RRFS.

Ideally the NAM, RAP, and SREF systems can be subsumed by the Global Forecast System (GFS) and the Global Ensemble Forecast System (GEFS), as they approach comparable spatial resolution. However, at present, there are significant outstanding issues that preclude taking this step with the current and next iteration of the GFS/GEFS because they do not yet address outstanding issues sufficiently enough to facilitate retirement of the legacy mesoscale systems. For example, the SREF remains the preferred ensemble system for day-2 and day-3 forecasts, most notably for convective and aviation weather. Feedback generally notes that 1) the GEFS does not accurately portray boundary layer thermodynamic structure (inherited from the GFS) and 2) is often under-dispersive in the day-1 to day-3 time range. These two outstanding issues are current, known, scientific impediments in retiring the SREF and replacing it with the GEFS. Similar challenges are present when considering NAM/RAP and the GFS. This outstanding issue is a priority in the "MRW/S2S physics development" project for GFSv17/GEFSv13, which is expected to be implemented in the FY24 timeframe. To facilitate the process of retiring legacy systems considerable effort is needed to investigate potential ways in which we can accelerate the retirement of these legacy systems while still meeting stakeholder needs.

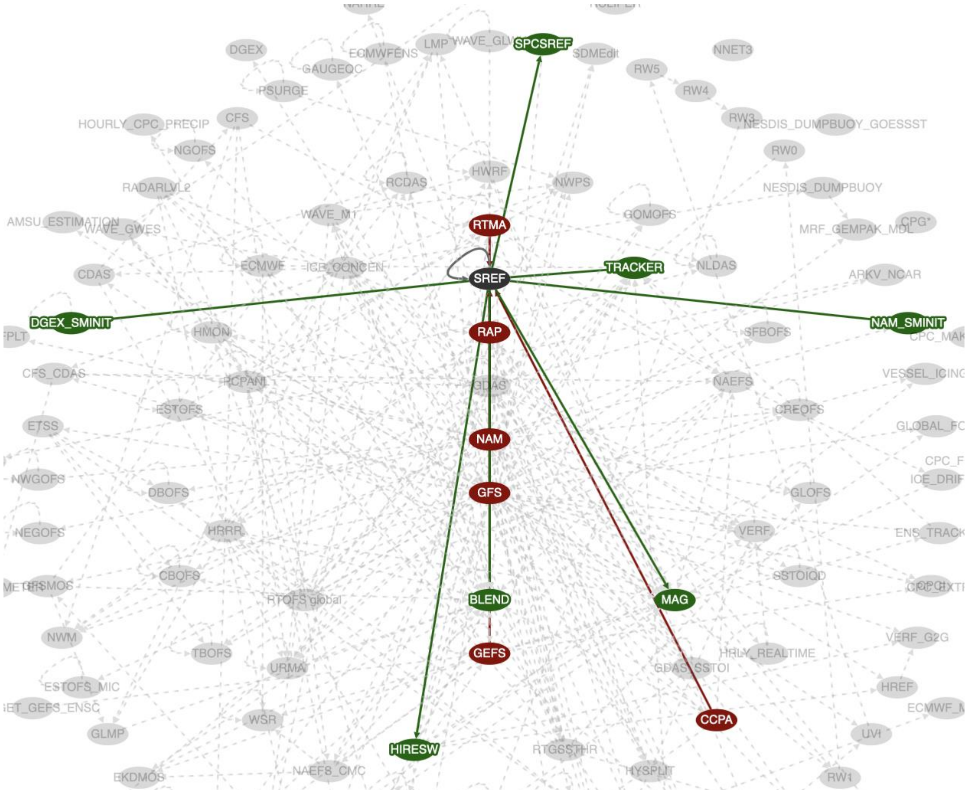

Fig.1 Downstream (green) and upstream (red) dependencies on the SREF in the NCEP production suite.

(a) A Machine Learning Approach for Bias Correcting the GEFS: Three years of GEFS retrospectives will be examined with an initial focus on 2-D surface variables (e.g., 2-m temperature, 2-m dewpoint) and severe weather parameters (CAPE, CIN, vertical wind shear) during the warm season. Machine learning techniques will be leveraged to diagnose and correct any identified seasonal, regional, and/or weather regime dependent biases. The bias-corrected GEFS output will be used to generate SREF “look-a-like” products for evaluation within the Hazardous Weather Testbed Spring Forecast Experiment. This exploratory research and resulting testbed evaluations will be used to inform a potential path forward for GEFS to fulfill stakeholder needs for medium-range weather applications.

(b) Intercomparison of Operational Ensemble Systems: Robust and thorough intercomparisons of the GFS/GEFS and existing regional suite are necessary to obtain a comprehensive understanding of objective differences, gaps, and subsequently identifying areas of improvement. This will be done using Model Evaluation Tools (METplus) metrics and scorecards. In addition, as a part of this effort NSSL/SPC plan to have a formal forecasting/evaluation activity during the SFE to support this effort. SPC plans to begin producing the SREF "look-a-like" products from the GEFS in the future, to enable practical intercomparisons for convective fields. Finally, this task also includes a critical effort to establish requirements to accommodate retiring these legacy systems through direct coordination with stakeholders and the "MRW/S2S physics development" project, ensuring physical processes critical to predicting hazardous convective weather are properly represented in the GFS/GEFS - thus facilitating retirement of the legacy mesoscale systems.

(c) Development of a Mesoscale Risk-Reduction Ensemble: A risk reduction strategy is required should the GFS/GEFS be unable to meet stakeholder requirements for retiring the legacy mesoscale modeling suite. Such an approach must be aligned with the goals of unification and simplification of the production suite. Therefore this project focuses on development and testing of a FV3-SAR based mesoscale ensemble run at 12 km grid-spacing covering the RAP/NAM domains as a risk reduction factor. This effort envisions the testing of a mesoscale ensemble (9 km) and a convective-scale (3 km) ensemble covering North America and most of the United States, respectively. The mesoscale ensemble system will cover a domain similar to those of RAP and NAM, and serves to primarily cover synoptic and larger mesoscale systems (e.g., fronts) while the RRFS ensemble serves to cover mesoscale convective systems and individual thunderstorms. Given that the GFS data assimilation system will be running at ~13 km grid spacing, and utilizes satellite and other data well over the ocean, we plan to use GDAS ensemble initial conditions to initialize the mesoscale ensemble, and GEFS forecasts to provide the lateral boundary conditions. The hypothetical RRFS ensemble can be nested within this mesoscale ensemble, using consistent physics parameterization schemes.

3. Two Year Plan and Five Year Vision.

Timeline	FY 20	FY21				FY22		
Task 1. RRFS	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
1.1 HREFv3								
1.1a Finalize testing and hand off HREFv3 with SAR member to NCO	X							

1.1b Following NCO testing, HREFv3 implemented	X	X						
1.2 Model and Ensemble Configuration								
1.2a Selection of physics suite baseline appropriate for CAM scales using CCPP	X							
1.2b Establish dynamic core baseline and vertical resolution	X	X						
1.2c Create a forecast performance benchmark of the baseline physics suite with METplus		X	X	X	X			
1.2d Optimize and improve physics selected in Task 1.2a following completion of Task 1.2b			X	X	X	X	X	X
1.2e Refine and optimize forecast ensemble with stochastic physics		X	X	X	X	X	X	X
1.2f Evaluate and optimize physics suites for use in multi-physics mesoscale ensemble for **Task 2.3**.	X	X	X	X	X	X	X	X
1.2g Merge community and operations workflows and update/maintain support for advanced developments data assimilation and ensemble tasks	X	X	X	X	X	X	X	X
1.3 Data Assimilation Algorithms								
1.3a Establish FV3 real-time deterministic with GSI-based hybrid/ensemble data assimilation	X							

1.3b FV3 real-time ensemble forecasts with GSI-based hybrid/ensemble data assimilation		X	X	X				
1.3c Refine and optimize real-time data assimilation algorithm, which may include analysis of ensemble perturbations, background error, hybrid weights, inflation, etc.					X	X	X	X
1.4 JEDI transition								
1.4a Establish FV3-SAR Interface in JEDI	X	X	X					
1.4b. Forward operators for convective-scale (e.g radar, super-obbing)				X	X	X	X	X
1.5 GOES-16 All Sky Radiance Assimilation								
1.5a Integrate GOES-16 ABI water vapor and cloud sensitive channel radiance (i.e. all sky radiance) simulator from CRTM with FV3-SAR model outputs and perform test with case studies	X							
1.5b Perform cold-started FV3-SAR deterministic forecasts with 10-20 high impact convective weather cases over CONUS using the baseline dynamic core, vertical resolution and physics configuration recommended by SRW/CAM AT group; apply capability in FY20Q4 and verify all sky radiance forecasts from FV3-SAR against the ABI radiance observations	X							

1.5c Perform additional FV3-SAR deterministic forecasts with varying dynamic core parameters, vertical resolution and physics schemes recommended by SRW/CAM AT and verify corresponding all sky radiance forecasts against the ABI radiance observations			X					
1.5d Continue the evaluation from FY21Q2 and select the best model configuration for ABI all sky radiance assimilation based on FY21Q1-2 efforts. Document results in peer reviewed papers. Provide codes developed to EMC and EPIC for evaluation and addition to UFS through JEDI. Begin FV3-SAR all sky radiance assimilation by identifying cases, designing and starting cycled DA experiment				X				
1.5c Continue reference ABI all sky radiance cycled DA experiment in FV3-SAR from FY21Q3 with detailed tuning of DA parameters (e.g. cycling frequency, inflation, localization etc) with a case study.					X			
1.5f Extend the reference ABI all sky radiance experiments in FY21Q4 with additional 10-20 cases.						X		
1.5g Perform experiments with improved ABI all sky radiance assimilation methods such as adaptive thinning and adaptive observation error estimation and evaluate with respect to the reference experiments							X	

1.5h Complete evaluation of all experiments. Provide codes developed to EMC and EPIC for evaluation and addition to UFS through JEDI. Document results for peer reviewed papers.								X
Task 2. Retirement of Regional Meso. System	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
2.1 A Machine Learning Approach for Bias Correcting the GEFS								
2.1a Begin work to define and document biases in 3-year retrospective GEFS database	X	X						
2.1b Begin development of machine learning bias correction			X	X				
2.1c Evaluate bias-corrected GEFS in Spring Forecast experiment for severe weather applications in Hazardous Weather Testbeds.				X				X
2.1d Continue development of bias correction for GEFS based on SREF via ML from 3-year retrospective GEFS data base.					X	X	X	X
2.2 Intercomparison of Operational Ensemble Systems								
2.2a Conduct comparisons of legacy ensemble systems SREF and HREF to GEFS via METplus and the use of scorecards.		X	X	X	X			
2.2b Conduct comparisons of deterministic legacy regional systems NAM and RAP to GFS via METplus and the use of scorecards.				X	X	X	X	

2.2c SPC begins producing “SREF-lookalike” products from GEFS.	X	X	X	X				
2.2d Coordinate with stakeholders (e.g. SPC, AWC) on developing requirements for the retirement of legacy regional systems. Leverage metrics from **2.2a** and **2.2b**.			X	X	X	X		
2.2e Coordinate with "MRW/S2S physics development" on addressing requirements identified in **2.2d**			X	X	X	X	X	X
2.3 Development of a Mesoscale Risk-Reduction Ensemble								
2.3a Development of mesoscale ensemble for risk reduction.	X							
2.3b Evaluate mesoscale risk-reduction ensemble in NOAA testbeds.				X	X	X	X	X
2.3c Continue development and commence testing of mesoscale risk-reduction ensemble.		X	X	X				
2.4d Evaluate GEFS, SREF, HREF, and mesoscale risk-reduction ensemble in NOAA testbeds.					X			

The longer-term (3-5 yr.) vision includes:

- RRFS
  - Operational implementation of RRFSv1 [years 3-4]
  - Coordination with the "MRW/S2S physics development" project, specifically for the development of the new advanced moist physics suite, which is aimed to be unified across all components of the moist physics, and scale-aware for different applications.

In addition, the development and adoption of an increasingly sophisticated microphysics parameterization is a significant factor toward enabling effective assimilation of radar data under the context of both the RRFS and WoFs. [years 3-5]

- ○ In close collaboration with the "MRW/S2S Data Assimilation" project we plan to complete the transition to JEDI, which includes development efforts on nonlinear and non-Gaussian data assimilation, multiscale, and coupled land-atmosphere data assimilation.
- Mesoscale Model Retirement
- ○ Consideration of adopting ML bias correction into GEFS post-processing (possibly GEFSv17)
- ○ If risk-reduction is needed, consider adopting a mesoscale ensemble to facilitate SREF retirement. Following results of testbeds and stakeholder evaluations, consider retiring the SREF.

<u>Retired codes</u>: NAMnests (NMMB), HRRR (WRF-ARW), HREF and component models; NAM (NMMB), RAP (WRF-ARW), SREF, NARRE

4. Interdependencies with other projects/EMC planned implementation timelines and/or any major risks and issues.

<u>RRFS</u>

- SIP - Many projects, highlights are as follows
    - *UFS-R2O MRW/S2S Physics*
    - *UFS-R2O SRW/CAM/3DRTMA*
    - *UFS-R2O SRW/CAM/WoFS*
    - *UFS-R2O MRW/S2S Data Assimilation*
    - *UFS-R2O Cross-cutting Application Verification and Post Processing*
- Joint Technology Transfer Initiative and OWAQ
    - *Advancing Frequently-Updating Storm-Scale Ensemble Data Assimilation and Prediction Towards Operations*
    - *Implementation and testing of stochastic perturbations within a stand-alone regional (SAR) FV3 ensemble using the Common Community Physics Package (CCPP)*
- FY18 Hurricane Supplemental - Improving Forecasting and Assimilation Portfolio
    - Project 1A-4b: *Accelerate SAR FV3 SRW/CAM Development*
    - Project 1A-5: *Accelerate FV3-based ensemble prediction system*
- FY19 - EPIC
    - *Improving Spread-Skill via Stochastic Physics for Convection Allowing Model Ensembles*
    - *Development of a multigrid background error covariance model for high resolution data assimilation*
- FY19 Disaster Supplemental

- *Prototype UFS based RRFS (Rapid Refresh Forecast System) on the Cloud*

Retirement of Models

- UFS-R2O Cross-cutting Application Verification and Post Processing
- FY18 Hurricane Supplemental - Improving Forecasting and Assimilation Portfolio
  - Project 1A-4b: *Accelerate SAR FV3 SRW/CAM Development*
  - Project 1A-5: *Accelerate FV3-based ensemble prediction system*
- FY19 - EPIC
  - *Improving Spread-Skill via Stochastic Physics for Convection Allowing Model Ensembles*

Development of the dynamic core, data assimilation, and physics for RRFS will require significant supercomputing resources and constitute risks. In addition, the retirement of regional systems is strongly dependent on GEFSv13 and GFSv17 meeting requirements outlined by stakeholders. HREFv3 and RRFS are strongly dependent upon the EMC planned implementation and testing timelines.

5. Specify how success will be measured.

The success of the RRFS development will be measured in performance relative to the baseline, here defined as HREFv3 for ensemble guidance and the HRRRv4/NAM Nest for deterministic guidance. Guidance from the NOAA testbeds, operational metrics using METplus, and Model Evaluation Group (MEG) evaluation will be used as appropriate to assess performance.

The success of the mesoscale model retirement effort will be evaluated by measuring performance of existing legacy systems against corresponding replacement systems. In some cases this is the RRFS (e.g. HREF), in others this is the SREF or NAM. Coordination with the NOAA testbeds, use of operational metrics using METplus, and Model Evaluation Group (MEG) evaluation will be used as appropriate to assess performance.

6. Estimate of compute resource requirements, both in terms of CPU hours per month and disk storage.

The CPU hours are estimated for the whole sub-project. On Orion, using 1440 PE's, one 36 hour forecast at 3km grid-spacing over the CONUS, with no history writes, and 60 vertical levels uses approximately 1800 CPU hours. Considering this project features a heavy reliance on ensembles, we estimate 18M CPU hours/year for a single member and closer to 180M CPU hours/year for 10-member 3km ensemble forecasts. Storage needs for deterministic and ensemble testing will be near 1000 TB. We will to the extent possible leverage existing resources.

7. Specify how organizational base-resources (in-kind) will be leveraged for this sub-project.

- EMC federal employees and contractors funded by NOAA base resources will contribute to the development and implementation of HREFv3 and RRFSv1/v2 as well as the retirement of legacy regional modeling systems.
- GSL federal employees and cooperative institute (CU/CIRES, CSU/CIRA) staff will contribute in-kind to the development and implementation of the RRFS at approximately 6.0 FTEs.
- Cloud HPC resources will be leveraged from an FY19 Disaster Supplemental Project. This project is expected to provide roughly 6.5M CPU hours per year for 2 years along with an approximate 250 TB in storage.
- Dedicated NOAA R&D Jet HPC resources will be leveraged for some real-time experimental development, demonstration and testing.
- CAPS will leverage NSF Xsede supercomputing, estimating 240K CPU hours/month and disk storage of approximately 60 TB of storage for each year of the project.
- MAP can leverage NSF Xsede supercomputing for approximately 45K CPU hours/month in year 1 and 83K CPU hours/month in year 2. MAP estimates a need for approximately 300TB of storage.

8. Summary of known team members and institutions (expected FTE commitment), including what resources are leveraged, including federal salaries or synergistic projects.

Name/ organization	**Subject matter expert/milestone effort**	**Commitment level FTE**	**Amount leveraged (if any)**	**What is leveraged? (office space, time, computing)**
Task 1 RRFS				
EMC Dr. Jacob R. Carley	PI	0.1 FTE	100%	Time
GSL Dr. Curtis R. Alexander	PI	0.1 FTE	100%	Time
Milestone 1.1 HREFv3				
EMC	Current Physics Developer	0.5 FTE *note* work covers		Computing

		only one quarter		
EMC	Developer and Implementer	0.9 FTE (in-kind)	100%	Time, computing
Milestone 1.2 Model and Ensemble Configuration				
EMC	Current Physics Developer	2 FTE		Computing
EMC	Current Model Developers	4.5 (in-kind)	100%	Time, computing
GSL	Current Model Developer	1 FTE		Computing
GSL	Current Model Developer	6 FTE (in-kind)	100%	Time, computing
CAPS PI: Prof. Ming Xue	University Researcher(s)	1		Computing: NSF Xsede Supercomputers
DTC PI: Jamie Wolff	Research Scientist; Verification	0.5		NCAR's other NOAA projects including DTC, OWAQ, and OSTI activities, and non-HPC computational resources
Milestone 1.3 Data Assimilation Algorithms				
EMC	Current DA Developer	0.5		Computing
EMC	Current DA Developer	2.0 (in-kind)	100%	Time, computing
GSL	Current DA Developer	1 FTE		Computing
GSL	Current DA Developer	6 FTE (in-kind)	100%	Time, computing

Milestone 1.4 JEDI transition				
EMC	Current DA Developer	0.5		Computing
GSL	Current DA Developer	1 FTE		Computing
GSL	Current DA Developer	6 FTE (in-kind)	100%	Time, computing
Milestone 1.5 GOES-16 All Sky Radiance Assimilation				
University of Oklahoma MAP Lab PI: Dr. Xuguang Wang	University Researcher(s)	1.5		Computing
Task 2 Retirement of Reg. Meso. Sys.				
Milestone 2.1 A Machine Learning Approach for Bias Correcting the GEFS				
NSSL PI: Dr. Kimberly Hoogewind	Researcher	0.33		Time
Milestone 2.2 Intercomparison of Operational Ensemble Systems				
EMC	Verification Experts	0.75 (in-kind)	100%	Time, computing
DTC PI: Jamie Wolff	Research Scientist; Verification	0.5		NCAR's other NOAA projects including DTC, OWAQ, and OSTI activities, and non-HPC computational resources
Milestone 2.3 Development of a Mesoscale Risk-Reduction Ensemble				
CAPS PI: Prof. Ming Xue	University Researcher(s)	1		Computing: NSF Xsede Supercomputers

2.3 UFS-R2O SRW/CAM Sub-Project: Warn on Forecast

UFS-R2O Task: SRW/CAM-WoF
Team: SRW/CAM
Sub-project area: SRW/CAM / RR / DA
Sub-Project Leads: Lou Wicker and Adam Clark (NSSL)
Sub-project organizations proposed for: NSSL, GSL, WPC, SPC

Sub-project Narrative:

1. **Sub-project overview.**

As part of the NWS plan to improve forecasts and warnings, NSSL has developed a short-term, rapidly updating, probabilistic ensemble prediction system called Warn-on-Forecast. Currently the WoF system is based on WRF-ARW/GSI-EnKF. As part of the UFS, NSSL will begin the transition to the FV3 SAR and JEDI systems. WoF currently uses a 3 km horizontal grid and a data assimilation frequency of 15 minutes. Research is underway to justify the cost of a 1 km ensemble for the WoF system using the ARW. As such, NSSL will move WoF toward using the FV3 SAR via the following approach:

- Complete the assessment of the performance characteristics for FV3 SAR at 3 km for WoF ensemble prediction as well as for HREF/RRFS use.
- Using the WoF WRF-ARW cycled analyses, replace the WRF-ARW 18 member forecast ensemble with the FV3 SAR.
- Begin transition to the JEDI data assimilation system: software, forward operators, infrastructure. This will require a stepped approach where the FV3 SAR/GSI-EnKF is tested first, then the full FV3 SAR/JEDI system.
- Assess the cost/benefit from a 1 km WoF system (i.e., is it worth the 10-15x cost?)

Completion of these tasks will help improve the application of the FV3 core for convective scale forecasts for both the 0-6 hour and even the next day forecast applications such as the HRRR, HREF, etc. The work proposed here will be closely coordinated with GSL, AOML, and EMC to leverage their efforts in CCPP-base physics suites, stochastic methods for CAM scales, and data assimilation methods in the new JEDI system. Closer collaboration on convective-scale data assimilation methods between CONUS and hurricane applications should lead to a more unified approach for predicting high-impact weather over the next 5-10 years. NSSL is the leader in the use of ensembles for probabilistic prediction of high-impact convective weather due in major part to the development of the WoF system. We believe that the methods developed here can be applied to a variety of problems and applications over the next decade to improve the prediction of severe and high-impact weather events via the inclusion of uncertainty in the NWP products.

Finally, the work supported by this R2O project heavily leverages other funding from NSSL's base and other external funding. Over the two year proposal, NSSL is contributing nearly 35 months of in-kind support from our staff over the two year project.

2. Sub-Project Justification and Technical Approaches.

Transition of the FV3 SAR in the WoF system by the end of two years will require the completion of a number of technical challenges before it can be successful. A complete validation of the FV3 SAR as a replacement core for the WoF system for both 3 km and 1 km convective storm prediction, currently being researched by NSSL, remains an outstanding issue yet to be resolved**.** Recent work by Reames and Wicker (2020, see Fig. 1 below) demonstrates there are *large differences* between the convective-scale solutions being generated by the FV3 SAR and WRF ARW. During the NGGPS model core evaluation process, ***the FV3 SAR was never extensively vetted as a replacement model for the WRF-ARW for convective applications. Combined with the lack of documentation regarding the formulation of the non-hydrostatic dynamic core of FV3,*** this has considerably slowed our progress toward understanding why these differences exist. As the WRF-ARW has been very successfully used for convective-scale research and prediction for almost 20 years, NSSL feels strongly that a complete vetting process is needed to explain the current differences. NSSL already received funding from OWAQ in 2018 to begin the examination to investigate the performance characteristics. This led to the discovery of large differences (Fig. 1) while testing FV3 in our WoF system. Unfortunately, the ***lack of relevant and <u>detailed</u> <u>documentation</u>*** from the developers of FV3 is a severe obstacle to our evaluations and assessments. NSSL will disseminate the results from the evaluation with GSL, EMC, AOML, and GFDL. Eventually, this effort will help document the core system more completely and if changes are needed, to facilitate those improvements as rapidly as possible. Dynamical core development is central in the RRFS development plan.

After the performance characteristics of the FV3 SAR are evaluated and validated, NSSL will then move toward replacement of the WoF system using the FV3 SAR core. The first step will be to use the FV3 SAR as the forecast model for the 6-hour ensemble forecasts in the WoFs. This will require the completion of a CCPP implementation of the two-moment Mansell microphysics which is currently used by the WoF system. Early tests using this approach have already been performed for two case days and exposed some important differences in convective-storm structure between the two model cores.

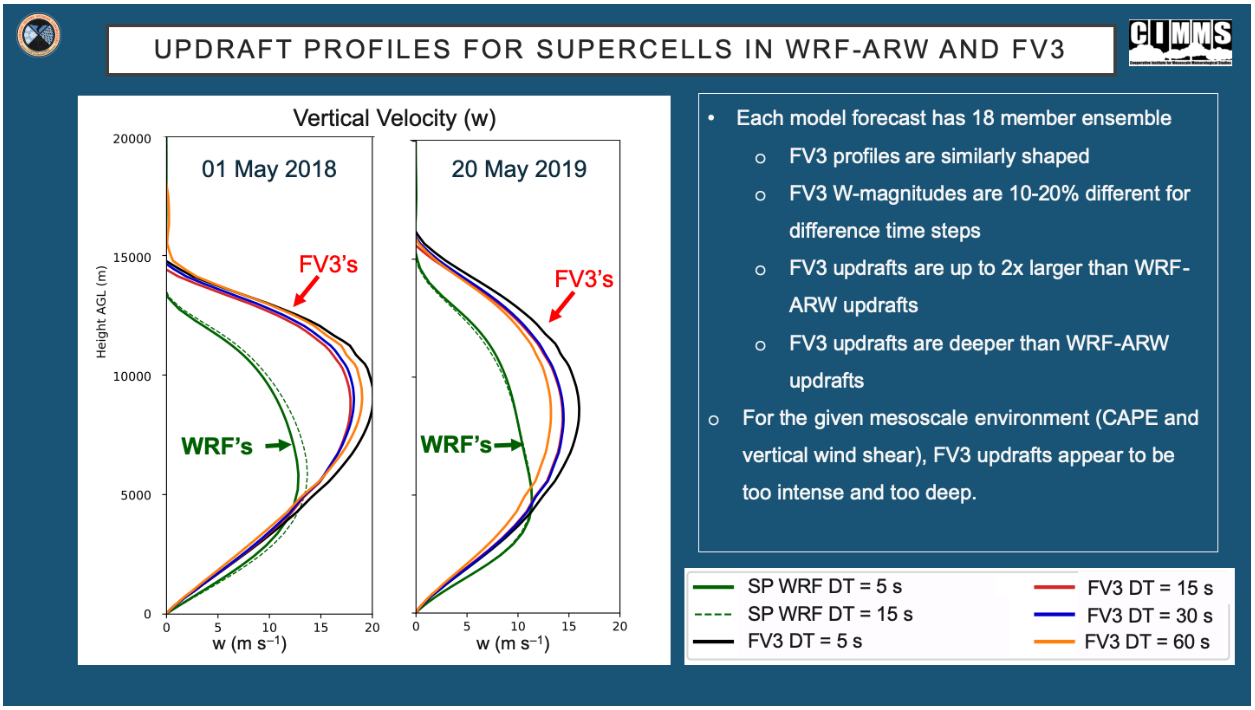

Figure 1: Updraft profiles from supercells within the WRF-ARW and FV3 models run from two Warn on Forecast case days. Results are generated by finding supercell storms using updraft helicity and radar reflectivity thresholds and then compositing the storms for each model, each day, and for various time steps. Each profile is a composite of ~O(300) storms sampled from each forecast's 18 ensemble members every 5 minutes for a 4 hour period. Reames and Wicker (2020).

After the FV3 SAR/GSI-EnKF system has been validated against the WRF-ARW/GSI-EnKF system we will then replace the GSI-EnKF with the JEDI system. The WoF system required over 5 years of development, and reimplementation with a new model and new data assimilation system will require at least a year of development and testing. Use of the FV3 SAR will require retuning or reimplementing much of the ancillary software used in the current data assimilation system. These tools are strongly model dependent (NSSL has used other convective models for cycled data assimilation and found this to be the case). These include adaptive inflation, additive noise methods, and ensemble stochasticity. This work will require a strong collaborative effort with GSL, EMC, and AOML as they will need many of the same software tools.

Finally, during the two-year period the WoF science team will also focus on whether warnings and storm-scale details (tracks, intensities, etc) will benefit from using increased grid resolution. This includes increasing the vertical resolution as well; we believe that eventually the vertical resolution will have to be < 300 m for the free atmosphere and < 50 m in the planetary boundary layer. This is close to what the ECMWF is currently using in their global model (~140 levels). Recent work by Potvin and Flora (2015) suggests that while 1 km forecasts may provide more reliable forecasts for low-level rotation, the limits of predictability may severely limit the length of time that the forecast is useful for these scales of motion. NSSL is also studying novel techniques, from information theory, to carefully understand under what conditions 1 km forecasts may be more or less useful.

Regarding EPIC, we see two areas which could benefit from what it is currently envisioned to do. First, depending on GFDL's reengagement, EPIC could help with core documentation and perhaps examine the code for ways to encourage an open development model. This may include restructuring or refactoring the code as well as improving its performance. FMS, the flexible modeling system, is the message-passing interface for the FV3. There is little expertise outside of GFDL for FMS. If it remains to be the underlying technology for the UFS then more expertise is needed (along with documentation etc.) Second, there is no implementation plan for the WoF system for operations at NCEP (though one is being discussed). The resource requirements for the current 3 km WoF system are modest, but the current concept of operations from NSSL's viewpoint is an adaptable system used by the major weather centers when needed (e.g., WPC and SPC). We feel the WoF application would be most applicable to a on-demand cloud-computing environment for operations - but beyond the technical hurdles, using a on-demand cloud capability needs to be planned and managed in some way by NCEP and the NWS. EPIC could help in bringing that concept of operations to fruition in the coming years. As it stands now, operational implementation of WoF is not likely to occur before the latter half of the 2020s so this is a lower priority item in the entire R2O proposal.

3. Two Year Plan and Five Year Vision:

Timeline	FY20	FY21				FY22		
Milestone	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Assessment and validation of FV3 core for convective prediction	x	x	x					
FV3 SAR for WoF ensemble Forecasts						x	x	x
JEDI development and testing				x	x	x	x	x
1 km R&D for WoF	x	x	x	x	x	x	x	x

The five year vision is to have a WoF system based on FV3 SAR and JEDI running on demand on cloud-HPC resources for both experimental real-time runs for the Storm Prediction Center in the

Hazardous Weather Testbed and for the Weather Prediction Center for significant flash flooding events. This would require support from NSSL and others for both the NWP system and the development of a cloud-based post-processing/visualization capability, and cloud-based HPC resources to run for each day for 100-150 days per year.

4. Interdependencies with other projects/EMC planned implementation timelines and/or any major risks and issues.

- RRFS project
  - Development of complete HRRR physics, land surface, and stochastic physics
  - Risk level: small
- JEDI project
  - Completion of a basic ensemble-based DA capability (LETKF)
  - Additional software development for convective scale DA within JEDI.
  - Risk level: medium

5. Specify how success will be measured.

All deliverables are subject to funding.

- FV3 core assessment and validation: At the end of the first year, a report will be generated describing our tests and validation of the FV3 core. Depending on collaborations with EMC and GFDL, a mathematical description of the non-hydrostatic core may be available. If there are changes to the code needed - a plan forward will be created.
- FV3 SAR for WoFs ensemble forecasts: Retrospective runs using the FV3 SAR using the WoFs ARW analyses will be done for the 2020 season. This will also be used as part of the validation process. If the evidence supports the switch to the new core without significant degradation, then a replacement of ARW forecasts with SAR could occur by 2022. Performance will be measured using our current object-based assessment system (WAF, Skinner et al. 2018).
- JEDI development: Testing of WoFs system within JEDI. Initial success will be testing the JEDI-LETKF and adding changes to the codes where needed (we do this for GSI-EnKF). All changes will be submitted to the code base.
- 1 km R&D: A number of non-R20 projects are examining this issue. NSSL already has publications about the information content of 1 km versus 3 km forecasts submitted. Success will be to have an estimate of the cost-benefit ratio for the 3 vs 1km system, relative to other augmentations such as ML applied to WoFs.

6. Estimate of compute resource requirements, both in terms of CPU hours per month and disk storage. *(since most of the work is done locally and the HPC load is strongly seasonally dependent, we are presenting things in yearly increments - divide by 10 if monthly needed).*

NSSL’s local computing environment for WoFs

- ~35M core hours per year.
- 1.2 PB fast online storage
- 1 PB auxiliary storage for data analysis

- Realtime WoFs (40 days experimental runs)
  - Computing: ~1M core hours per year (forecasts for HWT/SPC/WPC).
  - Storage: 150 TB (3-4 TB per day).
- Research WoFs
  - Computing for WoFs 3km: 10M core hours per year.
  - Storage: 1 PB with compression.
  - Computing for WoFs 1 km: 10M core hours (cannot do a lot here, yet).
  - Storage: >> 1 PB. (Development of lossy compression methods crucial here)

7. Specify how organizational base-resources (in-kind) will be leveraged for this sub-project.

- NSSL will contribute directly:
  - 2 months of senior FTE for SME core evaluation and JEDI development
  - Internal HPC resources for development
  - 2 months of CIMMS scientist SME for forecast evaluation/validation.
  - 2 months in year 2 for potential HWT assessment (for WoF FV3 SAR forecasts)

8. Summary of known team members and institutions (expected FTE commitment), including what resources are leveraged, including federal salaries or synergistic projects.

Breakdown of FTE-effort,. including an explanation of how NOAA base resources (in-kind) will be leveraged. The leveraging of other projects or base-resources should include estimated (base-funded or leveraged) FTE contributions.

Name/ organization	**Subject matter expert/milestone effort**	**Commitment level FTE**	**What is leveraged? (office space, time, computing)**
Milestone 1: *Assessment and validation of FV3 core for convective prediction*			
PI: Lou Wicker NSSL	Research Scientist ZP5 SME: Dynamics & NWP	0.167	Time

NSSL	Research Scientist I scientist/programer	0.5	Salary, office etc.
Internal Computing			Leveraged in-house resources (including power, staff, maintenance)
Milestone 2: *FV3 SAR for WoF* Ensemble *Forecasts*	**FCSTs**		
NSSL	Research Scientist II Scientist SME: verification	0.167	Time
NSSL	Research Scientist I	0.25	Time, running HWT experiments
NSSL	Research Scientist III	0.25	Time, running WPC experiments
NSSL	Research Associate III	0.33	WoF operations manager
Internal Computing			Leveraged in-house resources (including power, staff, maintenance)
Milestone 3: *JEDI development and testing*			
PI: Lou Wicker NSSL	Research Scientist ZP5 SME: Dynamics & NWP	0.167	Time
NSSL	Programmer/Cloud Comp	0.5	Completely funded senior computer scientist.
Internal Computing			Leveraged in-house resources (including power, staff, maintenance)
Milestone 4: *1 km R&D for WoF*			
NSSL	Research Scientist ZP4 SME: Model/Predictability	0.167	Time

NSSL	Post-doc	0.5	Time
Internal Computing			Leveraged in-house resources (including power, staff, maintenance)

2.4 UFS-R2O SRW/CAM Sub-Project: Hurricanes

UFS-R2O Task: SRW/CAM Hurricanes
Team: SRW/CAM
Sub-project area: HFIP-Hurricanes
Sub-Project Leads: Avichal Mehra (NWS/NCEP/EMC) & Xuejin Zhang (AOML/HRD)
Sub-project organizations proposed for: NOAA/EMC, NOAA/AOML/HRD, NCAR/RAL, NOAA/ESRL/GSL and University of Oklahoma

Sub-project Narrative

1. Sub-project overview.

A. Operational upgrade and maintenance of HWRF & HMON. Different possible configurations (storm-centric, basin-wide) for HWRF, HMON and HAFS will be tested and chosen based on improvements in forecast skill and available production compute resources.

B. Continue development of Hurricane Analysis and Forecast System (HAFS) data assimilation (HAFS-DA, hereafter) including TC initialization, atmosphere and ocean coupling, physics upgrades, and adding telescopic moving nests. These will be primarily driven and leveraged by Hurricane Supplemental resources and timelines.

C. JEDI implementation for HAFS-DA; this will also be leveraged with Hurricane Supplemental funded tasks for JEDI development facilitated by code sprints and in conjunction with FV3-CAM and FV3-Global DA advancements.

D. Conduct real time HFIP experiments for HAFS, HWRF & HMON including ensembles.

Implementation Targets.

- UFS-HAFS v0.1 (2020 HFIP real-time demo)
- HWRF v13.1 (for NWS operations 2021)
- HMON v3.1 (for NWS operations 2021)
- UFS-HAFS v0.2 (2021 HFIP real-time demo)
- UFS-HAFS v1.0 or HWRF v14 or HMON v4 (**tentative**, NWS operations in 2022)

2. Sub-Project Justification and Technical Approaches.

In response to Section 104 of the Weather Research Forecasting Innovation Act of 2017 to (1) Improve the prediction of rapid intensity change and track of hurricanes; (2) Improve the forecast and communication of surges from hurricanes; and (3) Incorporate risk communication research to create more effective watch and warning products, NOAA decided to accelerate the development of HAFS to provide high-resolution hurricane predictions within the operational FV3-based Global Forecast System (FV3GFS) under guidance of the Hurricane Forecast Improvement Program (HFIP) in the Unified Forecast System (UFS) framework. Meanwhile, current hurricane operational models: HWRF and HMON will still provide superior operational products for hurricane forecasts especially in intensity (Figure 1) to address HFIP's priorities. In this transitional period, the Environmental Modeling Center (EMC) at the National Centers for Environmental Prediction (NCEP) adopted two parallel approaches that can satisfy both NOAA's operational imminent needs and address future requirements. EMC currently provides high-resolution deterministic tropical cyclone forecast guidance in real-time to the National Hurricane Center (NHC) for the North Atlantic (NATL) and Eastern North Pacific (EPAC) basins; to the Central Pacific Hurricane Center (CPHC) for the Central North Pacific (CPAC) basin; and to the United States Navy's Joint Typhoon Warning Center (JTWC) for all other tropical ocean basins including Western North Pacific (WPAC), North Indian (NIO), South Indian (SI) and South Pacific (SP). The current and proposed hurricane prediction systems have to continue to fulfill the above requirements.

Operational HWRF and HMON performed well for both of the major landfalling hurricanes in the Atlantic basin, namely, Florence and Michael in the 2018 Hurricane season. While operational GFS performed the best for tracks for both these storms, HWRF and HMON had very similar track errors up to 72 hours. Overall, HWRF had the best intensity forecast performance, even outperforming NHC official forecasts for some of the forecast intervals for these storms (not shown).This proposed project will undertake the following four tasks:

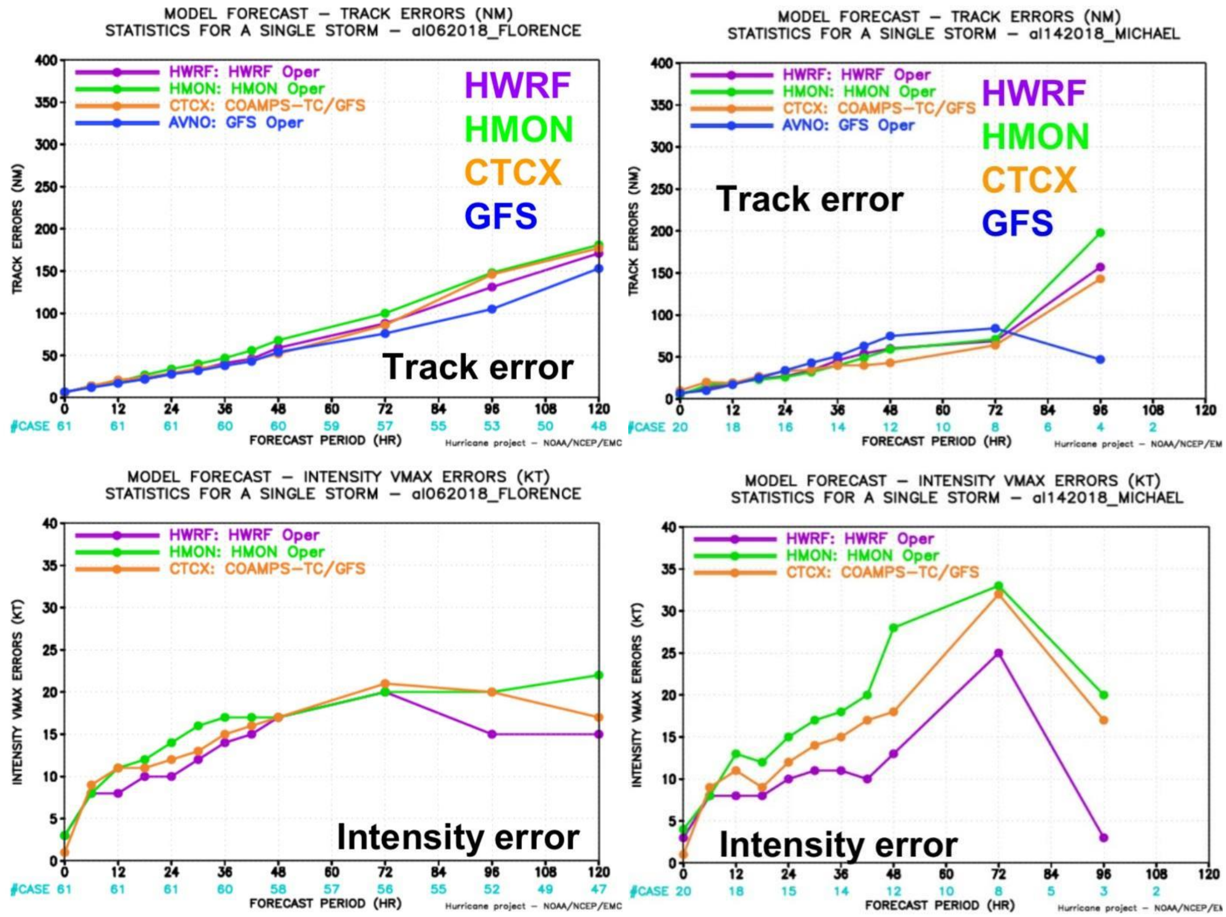

Figure 1: **Track (top) and Intensity (bottom) forecast verification for (left) Hurricane Florence and (right) Hurricane Michael using operational models.**

Task A

Current operational hurricane forecast systems namely -- the Hurricane Weather Research and Forecast (HWRF) and Hurricanes in a Multiscale Ocean-coupled Non-hydrostatic (HMON) modeling system provide operational products to U.S. forecast centers. HWRF became operational at NCEP starting with the 2007 hurricane season for the NATL and EPAC basins and has grown ever since in its applications for tropical cyclone forecasts for all global ocean basins by 2014. HMON became operational in the 2017 hurricane season for the NATL, EPAC and CPAC basin. HWRF modeling system is a fully coupled system with active interactions with ocean and waves, and has telescoping moving nests with the highest resolution nest operated at 1.5 km resolution that moves along the predicted path of the tropical cyclones. HMON modeling system is actively coupled to the HYCOM ocean model, and has telescoping moving nests with the highest resolution nest operated at 2 km resolution that moves along the predicted path of the tropical cyclones.

Both HWRF and HMON are upgraded annually to adjust, maintain and improve upon current operational performance. These regular upgrades address known critical issues in the current operational HWRF and HMON systems and are required to keep the model performing at the optimal levels compared to the current operational system. Hurricane upgrades are usually listed as annual **NWS AOP Milestones.**

In FY 22, we will also evaluate advanced HAFS versions for operational transition. Their performance will be evaluated against those of operational HWRF/HMON models to check their appropriateness for initial operational capability within available resources using the same metrics and baselines currently deployed for annual upgrades. Upgrade testing usually involves thousands of verifiable storm cycles from the previous two to three seasons and standard verification tools are used to assess improvements in Tropical Cyclone track, intensity, structure and precipitation forecasts in all global ocean basins from both operational systems.

Task B

The development of the HAFS is consistent with the Strategic Implementation Plan (SIP) for the Unified Forecast System (UFS). This proposed project is an extension of the integrated HAFS development plan under the Improving Forecasting and Assimilation (IFAA) portfolio of the Bipartisan Budget Act of 2018 (Disaster Related Appropriation Supplemental (DRAS) outlined in plans 1A-4, 3A-1, 3A-2, 3B, 4A.2, and 4A.2. The IFAA-DRAS is accelerating the Initial Operational Capability (IOC) of HAFS including the moving nest, operation & research workflows, initial tests and evaluations for hurricanes of existing physics parameterizations, advancement of hurricane appropriate physics implementation, and operational products for hurricane forecasts. The FY19 Disaster Supplemental (OAR support, pending) will accelerate our ability to initialize the hurricane vortex and its environment with advanced DA methods, together with proper treatment of physics and workflow within the HAFS-DA system. The HAFS-DA system is necessary to produce a high-resolution high-quality analysis using all available observations to evaluate model guidance and provide a historical record of events for storm attributes not analyzed by the NHC. In the real-time system, HAFS-DA will provide initial and boundary conditions for the HAFS, existing high-resolution operational regional hurricane forecast systems HWRF and HMON, and complement other future UFS regional systems proposed under the SRW/CAM task. It is anticipated that several more years (2 to 3 years) of DA development will be required for HAFS to catch up with ongoing HWRF/HMON developments and forecasts. The outcomes of this task are detailed in the Appendix.

The goals of the proposed task are to: (1) Leverage the NWS' global DA development and OAR's HAFS-DA development efforts under IFAA-DRAS FY18 and FY19 supplemental; (2) Streamline transitions from research and development to operational implementation; (3) Consolidate and optimize the usage of developmental resources (human resource and R&D HPC resources) across the NOAA and academia communities.

Task C

Along with Task B, the integration of GSI-based and JEDI-based implementation for HAFS-DA will be developed; this task will also be leveraged with Hurricane Supplemental funded tasks for JEDI development facilitated by code sprints and in conjunction with FV3-CAM and FV3-Global DA advancements. The workflow and new DA methodology will be developed specifically for hurricane vortex and for the static/moving nest HAFS system. The goals of this proposed task are to: (1) Train for DA and model developers for accelerating HAFS development; (2) Integrate JEDI code and HAFS; (3) Implement cutting-edge DA methods in HAFS.

Task D

Every year, HFIP real-time experiments are designed using versions of operational models (HWRF, HMON) and next-generation (HAFS) models which test and evaluate new techniques and strategies for model forecast guidance prior to testing for possible operational implementation. These experiments also allow for testing techniques that cannot be tested on current operational computers because of size and time requirements, but can instead be tested on NOAA's RDHPCS hardware. While operational models have to work within the allowed operational computing resource limitations, HFIP real-time experiments assume that resources will be found to greatly increase available computer power in operations above that planned for the next two to five years. The purpose of these experiments is to demonstrate that the application of advanced science, technology, and increased computing will lead to the desired increase in accuracy, and other improvements of forecast performance. Because the level of computing necessary to perform such a demonstration is larger than can be accommodated by the current operational computing resources, these are designed for running on available research and development (RDHPCS) machines. The primary purpose is to evaluate the strengths and weaknesses of promising new approaches that are testable only with enhanced computing capabilities. The progress of these real-time runs are evaluated after each season to identify techniques that appear particularly promising to operational forecasters and/or modelers. These potential advances can then be blended into operational implementation plans through subsequent model upgrades, or further developed outside of operations with subsequent testing. In general, these experiments represent cutting-edge approaches that have little or no track record; and therefore are not used by NHC forecasters to prepare their operational forecasts or warnings. However, it is often the case that some real-time experimental models produce forecast guidance that is potentially useful to forecasters (for example, real-time HAFS track forecasts in the 2019 season were provided to NHC forecasters for additional guidance).

These experiments allow for extensive evaluation and innovative research but they do have to meet certain predefined standards for improvement over existing techniques. This testing usually involves running the models or new techniques over the demonstration period (August 1 to October 31) which are the peak three months of the hurricane season. This process expedites the availability of real-time advances to forecasters by one or more years and serves as a proof of concept for both the developmental work and augmented computational capabilities. These real-time experiments will be conducted for the next two or more years on available RDHPCS resources including the new MSU computer (Orion) and/or available cloud servers as part of Hurricane Supplemental tasks.

3. Two Year Plan and Five Year Vision.

Timeline	FY20	FY21	FY22

Milestone	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
HWRF v13.1				Operational Implementation					
HMON v3.1				Operational Implementation					
HFIP Real-time experiments							HWRF, HMON and HAFS		
HAFS/HWRF /HMON								Operational Implementations (tentative plans)	

During the **next five years**, successful outcome of this project provides us with the following new capabilities for NOAA/NWS/NCEP:

Initial operational capability of the FV3-based Hurricane Analysis and Forecast System (HAFS) with multiple moving nests following multiple storms in a regional, basin-wide or global parent domain. The long term goal is to embed these moving nests/regions in the global Unified Forecast System with two-way feedback between the nests and the parent domain. It is anticipated that the HAFS will gradually replace the existing operational HWRF and HMON systems under the strategy of NOAA's UFS framework when its skills and deliverables meet the requirements of the relevant stakeholders.

4. Interdependencies with other projects/EMC planned implementation timelines and/or any major risks and issues.

- Significant interdependencies

The work here is performed in close collaborations with the following SIP groups:

- SRW/CAM Application Team
- MRW/S2S Application Team
- Marine WG

- Data Assimilation WG
- Physics WG
- Infrastructure WG
- Verification and Validation WG

The work here also leverages ongoing developments with the following current (HSUP-1) and proposed (HSUP-2) activities including:

HSUP-1 Projects (1A-3, 1A-4, 3A-1 and 3A-2)

HSUP-2 Projects (HU-1, HU-2, HU-3, HU-4 and FL-4)

This project also has a significant interdependency on the **UFS model infrastructure project**, which proposes a gradual transition of Developmental Testbed Center (DTC) code management and developer support resources from HWRF to HAFS over the next two years. Establishing robust code management and developer support practices in HAFS will be critical to facilitating research-to-operations transitions in the new system.

- Risk/Issue

1. Lack of concordant HPC resources to perform transition to operations (for HWRF & HMON) and HAFS development
2. Delay in hiring of new personnel for Hurricane Supplemental projects

5. Specify how organizational base-resources (in-kind) will be leveraged for this sub-project.

- Organization, who, what

EMC will use Hurricane Supplemental funding to help with HAFS development.
AOML/HRD and partner universities (University of Miami, UMD and OU) will also use Hurricane Supplemental funding to help with HAFS-DA development.

6. Please provide an estimate of compute resource requirements, both in terms of CPU hours per month and disk storage.

NCEP/EMC will leverage existing allocations on WCOSS, Hera, Jet and Orion to complete the proposed tasks. AOML/HRD has requested an allocation of 5M CPU hours per month and 300 TB disk space for HAFS-DA development and T&E on Orion and/or NOAA RDHPC for HSUP-2 tasks. Reservation allocations on NOAA HPC are required for Task D during the real-time demo.

7. Summary of known team members and institutions (expected FTE commitment), including what resources are leveraged, including federal salaries or synergistic projects.

Breakdown of FTE-effort including an explanation of how NOAA base resources (in-kind) will be leveraged. The leveraging of other projects or base-resources should include estimated (base-funded or leveraged) FTE contributions.

Name/ organization	**Subject matter expert/milestone effort**	**Commitment level FTE**	**Amount leveraged (if any)**	**What is leveraged? (office space, time, computing)**
Milestone 1 title	HWRF & HMON transition (Task A)		1 FTE (AOML/HRD) 3 FTE (EMC)	Labor and HPC resources
Members(provide names if possible)				
Milestone 2 title	HFIP Real-Time experiments (Task D)		1 FTE (AOML/HRD) 3 FTE (EMC)	Labor and HPC resource
Members				
Milestone 3 title	HAFS development (Tasks B, C and D)	3 FTE	4 FTE total (from HSUP-1, EMC) 5 FTE total (from HSUP-2, AOML/HRD, EMC and university collaborators)	Labor, HPC Compute, Storage Disk, office)
Members			EMC: 4 FTE HRD: 3 FTE University collaborators: Jonathon Poterjoy (UMD), Xuguang Wang (OU)	

Appendix: Task B&C Milestones

The measurements of TASK B outcomes are:

- Develop, test, and evaluate DA capability in the regional HAFS static nest (HAFS-DA v0.0 TRL5).
- Develop, test, and evaluate DA capability in the regional HAFS moving nest (HAFS-DA v0.1 TRL5/6).
- Provide Initial Operational Capability (IOC) of the HAFS-DA system including initial research and operational workflow (HAFS-DA v1.0 TRL6/7).
- Transition IOC to FOC (Final Operational Capability) of the HAFS-DA system (HAFS-DA v1.1 TRL7/8).

Timeline	FY20		FY21				FY22		
Milestone	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
HAFS-DA v0.0				Research and development					
HAFS-DA v0.1						Test and evaluation			
HAFS-DA v1.0							HAFS demo		
HAFS-DA v1.1								Operational Implementations (tentative plans)	

The measurements of TASK C outcomes are:

- New DA and model developers with both UFS/HAFS and DA expertise for research and community.
- JEDI for HAFS-DA capability.
- HAFS-DA with cutting-edge DA method for satellite, TDR radar, special field program, etc.

Timeline	FY20	FY21	FY22

Milestone	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
HAFS-DA v0.0				Research and developme nt with JEDI					
HAFS-DA v0.1						JEDI capable			
HAFS-DA v1.0							Cutting-edge DA method implementation		
HAFS-DA v1.1								Operational Implementation (tentative plans)	

Total SRW/CAM Computer Resource Requirements.

Summary table showing breakdown by sub-project (cloud, NOAA research HPC, vs other HPC). CPU hours per year/Tb storage (not covered by existing NOAA HPC allocations). The data in this table will be used to develop an allocation request for NOAA cloud and HPC resources.

Project/Type of HPC	**NOAA HPCS (including Orion)**	**Outside NOAA HPCS**	**Cloud**
3DRTMA/URMA	Yr1: 100.8M, 50 TB Yr2: 100.8M, 50 TB		
WoFS	Yr1: 21M, 1000 TB Yr2: 21M, 1000 TB		
RRFS/Regional Model Retirement	Yr1: 180M, 1000 TB Yr2: 180M, 1000 TB	Yr1: 3.42M, 360 TB Yr2: 3.876M, 360 TB	Yr1: 6.5M, 250 TB Yr2: 6.5M, 250 TB

Hurricane	Yr1: 60M, 300 TB Yr2: 60M, 300 TB		

Section 3: Cross-cutting Applications

The UFS is a dynamic system involving contributions from the Earth science modeling and software infrastructure communities. Since multiple community software packages are being integrated together, a clear system architecture design is critical to ensure that the system evolves into a unified whole. The system architecture must ensure that the set of software components and their interconnections lead to an end product with the scientific and computational qualities required to meet NOAA's operational mission. Many of these software packages are being actively integrated. The sub-projects under Cross-cutting Applications are focused on integration of modeling infrastructure and verification and post-processing software used across UFS Applications.

The goals of the system architecture are to simplify and unify the collection of software components used across the NCEP Production Suite; ensure reliability, maintainability and computational performance of the UFS; and facilitate meaningful engagement of community research partners to obtain and run UFS experiments and tests in support of research to operations activities. A unified system architecture should enable community development partners to learn just one software system in order to experiment with and run multiple UFS Applications. To accomplish this, all UFS Applications draw from the same pool of components and infrastructure and exhibit a shared system architecture.

The UFS is based on a set of foundational decisions that provide a stable cross-cutting scaffolding for developing the set of applications identified to meet NOAA's operational forecast requirements using a community-based modeling system. These decisions include all of the modeling components listed in the MRW/S2S and SRW/CAM Application Team section, the choice of FV3 as a common atmospheric dynamical core, an ESMF/NUOPC-based coupled model architecture, use of the Common Community Physics Package/Single Column Model (CCPP/SCM) Hierarchical Testing Framework (HTF) as the dynamics-physics interface, data assimilation through JEDI, post-processing through the Unified Post-Processor (UPP) and a to-be-developed companion package, the Unified Ensemble Post-Processor (UEPP), the Community Atmospheric Model Post-Processing System (CAMPS), and the National Blend Model (NBM), as well as use of the enhanced Model Evaluation Tools (METplus) for verification and diagnostics. Many of these elements, such as ESMF/NUOPC and CCPP, do not directly impose specific scientific choices, but instead are frameworks designed to support systematic evaluation of different scientific choices, such as substituting different ocean models in a coupled simulation, or evaluating different physics parameterizations. The UFS system architecture, therefore, is designed to be sufficiently flexible to support experimentation of different science options and sufficiently reliable and performant to meet operational requirements.

The plans for developing a cross-cutting framework for the UFS applications include two sub-projects, one focused on modeling infrastructure and the other focused on post-processing and verification. Briefly, the major objectives of the two sub-projects over the next two years are:

(a) Common Modeling Infrastructure:

- The ESMF/NUOPC coupled modeling infrastructure will be extended to address new scientific and technical coupling requirements for UFS global and regional applications. This includes advancing the CMEPS mediator in the UFS S2S system, enhancements to NUOPC coupling interfaces, performance optimization for high resolution grids, and advancements to the NUOPC Unified Driver interface to the JEDI DA system.
- Advancements will be made to support evaluation of atmospheric physics through new releases of the CCPP, SCM, and HTF, including community support and repository maintenance.
- Application-specific user support will be provided for the UFS Medium-Range Weather and UFS Hurricane Applications.
- Work will begin to coordinate UFS workflows across applications. The project will be coordinated through regular calls among core developers (EMC, ESRL, NCAR, DTC, and JCSDA), holding a UFS Workflow workshop, and working with the Verification and Post-Processing sub-project to incorporate automatic generation of standard model diagnostics through the workflow.

(b) Verification and Post-Processing Infrastructure:

- METplus will be extended beyond current capability to perform routine evaluation MRW/S2S and SRW/CAM AT priority fields. This will include functionality to evaluate coupled models and produce scorecards that provide innovative methods for systematically synthesizing the relative performance of developmental systems versus baseline systems.
- The Unified Ensemble PostProcessor software package will be delivered to work with existing and future global and regional ensemble prediction systems, including producing value-added products such as ensemble means, spreads, distribution quantiles, basic raw event probabilities.
- The CAMPS community-hosted statistical post-processing software that replicates basic MOS functionality will be completed.
- One or more NBM components will be adapted to a community infrastructure, including public hosting of this software and associated test data.
- One or more advanced statistical postprocessing algorithms for high-impact variables, such as precipitation amount and type, leveraging reforecasts from the GEFS and/or ECMWF systems, will be developed and transitioned to operations.

3.1 UFS-R2O CCI Sub-project: Modeling Infrastructure

UFS-R2O Task: Modeling Infrastructure
Team: Cross-cutting
Sub-project area: Modeling Infrastructure
Sub-Project Leads: Rocky Dunlap/NCAR, Arun Chawla/EMC
Sub-project organizations proposed for: NOAA/EMC, NCAR/CGD, DTC at NCAR/RAL, DTC at NOAA/GSD, GMU

Sub-Project Narrative

1. **Sub-Project Overview.**

The Unified Forecast System (UFS) development requires strong infrastructure support that includes code management, coupled model development, workflow development, connection with data assimilation systems, pre-processing tools, website management, documentation and community support for UFS applications. This cross-cutting project advances the development of the underlying UFS system architecture that supports all UFS applications (MRW, S2S, SRW,, HAFS, Marine/Cryosphere, Coastal, Space Weather, and Air Quality).

Within the first two years, multiple community infrastructure packages will be advanced and new capabilities will be integrated into the overall architecture to be leveraged by UFS applications. A new release of the Earth System Modeling Framework (ESMF), v8.1, will address new requirements of UFS coupled models. The Common Community Physics Package (CCPP) library of physics and associated framework will be advanced with new releases integrated into UFS. The CCPP Single-Column Model (SCM) will be supported for use as part of the UFS Hierarchical Testing Framework (HTF). A framework for supporting distributed development for the Hurricane Analysis and Forecast System (HAFS) will be developed and implemented. The interface between the data assimilation framework (JEDI) and the coupling layer (NUOPC) will be refined and optimized. The aging NEMS Mediator will be retired and replaced by the Community Mediator for Earth Prediction Systems (CMEPS).

Staff at EMC and DTC will support specific applications, addressing code unification, regression testing, and needs that arise in the community, including users of the UFS Medium-Range (MRW) Weather Application release and the developers of the HAFS. Finally, work will begin on coordinating workflow implementations across UFS applications.

2. **Sub-Project Justification and Technical Approaches.**

UFS applications are increasingly complex and moving toward coupled models in almost all contexts. Modeling infrastructure provides core functionality such as coupling interfaces for model components, parallel grid remapping, inter-component communication, options for evaluating atmospheric physics suites, and other utilities needed for model development on high-performance platforms. These capabilities simplify implementation and evaluation of different scientific schemes and promote community engagement with UFS models. This project addresses major infrastructure advancements that are needed over the next two years to support the full scope of UFS application requirements and the forecast goals articulated by the MRW/S2S, CAM and HAFS Application Teams.

The project will work along several paths: extend ESMF/NUOPC coupled modeling infrastructure; advance capabilities for physics evaluation through CCPP and the SCM; provide application-specific support; and coordinate UFS workflow activities across applications.

(a) Extend ESMF/NUOPC Coupled Modeling Infrastructure

The Earth System Modeling Framework (ESMF) and the National Unified Operational Prediction Capability (NUOPC) Layer provide the core coupling infrastructure for UFS applications. ESMF/NUOPC will also interoperate with other parts of the UFS infrastructure including the Common Community Physics Package (CCPP) framework, to support interoperable physics and facilitate running physics parameterizations concurrently and/or on different grids than the host model; and "in-core" and strongly coupled data assimilation systems that need to interact directly with active model components through a unified NUOPC Driver interface.

The proposed activities are (1) extend ESMF and the NUOPC Layer to address new scientific and technical coupling requirements, (2) provide base support to the ESMF core development team for regular testing, porting, and user support activities, (3) support UFS coupled modeling applications including integration of new model components and enhancements to NUOPC "caps," (4) advance the CMEPS mediator and its integration, testing, and validation, and (5) extend and optimize the JEDI/NUOPC Unified Driver approach to interfacing model infrastructure with the DA system.

New development in the ESMF core framework will be included in the next public release of ESMF, version 8.1. These include support for coupling with very high resolution grids (e.g., 3km global), improved support for hybrid parallelism (threading) and shared memory options, new runtime grid/mesh and sparse-matrix multiply validation options and diagnostics, completion of the transition to the Mesh-Oriented Database (MOAB) as a more optimized internal mesh data structure, advances to the "creep fill" extrapolation method, and removal of redundant "proxy objects" to reduce the memory footprint. If cloud computing resources are available, performance tests of key operations will be conducted.

The ESMF team has a robust support mechanism, typically initiated by users by emailing esmf_support@ucar.edu. This has proven critical to quickly addressing infrastructure needs within the UFS. Actual support tasks include answering technical questions, researching and fixing issues in the library, implementing optimizations, and adding new features. Tight coordination between

NOAA and ESMF developers provided by the support list enable "co-development" of UFS applications with the coupling infrastructure.

The CMEPS mediator is being jointly developed by NCAR, NOAA/EMC, and NOAA/GFDL and is part of the NOAA-NCAR MoA. It is used in NCAR's Community Earth System Model (CESM) and is being integrated into the UFS S2S (FV3GFS-MOM6-CICE5) and HAFS applications as the coupler. Important upcoming tasks include testing CMEPS fractional grid capability in UFS S2S (to improve coastline conservation), integrating the CICE6 ice model, transitioning the WW3 model to couple through CMEPS instead of directly to the atmosphere and ocean component, and ensuring CMEPS supports wave model restarts. A data-driven approach to specifying coupling field remapping and merging will be implemented; this will expedite routing new coupling fields and improve readability of the field mapping between components. CMEPS will be validated and the older NEMS Mediator will be deprecated and retired, and all new mediator development will happen within CMEPS. Finally, CMEPS governance processes will be established to manage code changes and updates between NOAA and NCAR.

The interface between the JEDI data assimilation system and the ESMF/NUOPC coupling layer will be refined and optimized. A joint model/DA "tiger team" organized under the System Architecture WG proposed a Unified Driver that allows the JEDI software to invoke and access the data of any single or coupled combination of UFS model components (e.g. atmosphere, ocean) through a top-level model driver, which is implemented using the NUOPC Layer software. Advancing the implementation of this Unified Driver and demonstrating its use is a key aspect of introducing JEDI into the UFS system architecture. The prototype Unified Driver approach will be extended to provide a common build system, a more generic interface with technical documentation, fixes to DA/model time synchronization issues, and optimizations for 3D data exchanges.

(b) <u>Advance Capabilities for Physics Evaluation through CCPP and SCM</u>

The DTC proposes to continue to collaborate with EMC and physics developers to make atmospheric model 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. Regression tests will be conducted before contributions are accepted to maintain code integrity and platform portability. Cases of duplicate parameterizations will be addressed along with primary code developers and other distributors of CCPP-compliant atmospheric physics, such as NCAR.

At least one new community release of the CCPP will be distributed annually, with intermediate releases distributed as needed to incorporate bug fixes and/or support the needs of the various UFS applications. 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 develop and implement rules for variable standard names that build upon community standards, such as those proposed by the Earth System Prediction Capability (ESPC) Content Standard Committee, and provide developers with tools for discovery of existing variable standard names. The DTC also proposes to improve the usability of the framework by ensuring consistency between the suite definition file (SDF) and the UFS namelist and by providing methods that expedite and standardize the porting of parameterizations that use memory layouts and variables not available in the UFS. The standardization of how transformations are done provides simplicity and lowers the bar for interoperability and community engagement, with the understanding that optimization for runtime performance and memory usage needs to be done before operational implementation of schemes using auto-transformations. Additionally, 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 a logger/error handler that replaces writing to stdout/stderr and captures stacktraces, and improved compliance of CCPP physics codes with standards (for example, standardization of how constants are kept and propagated to all schemes).

The SCM is an important component of the Hierarchical Testing Framework (HTF) that provides a simplified framework for diagnosing interactions between schemes within a physics suite. As the capabilities of the CCPP advance, updates to the SCM will be needed to maintain consistency between the SCM and the CCPP framework and physics. Deliverables include support for EMC and the broader community in using SCM to advance atmospheric physics suites, establishment of governance and leadership structure, a regression testing framework, and a new SCM release with associated documentation.

(c) Provide Application-Specific Support

Support will be provided by EMC and DTC for the UFS Medium-Range Weather Application. DTC staff will monitor questions posted to the user forum and contribute responses to those questions that fall within the DTC staff's expertise. Given the plans to provide incremental releases as new capabilities reach maturity, the DTC team anticipates contributing to release preparations as appropriate under the auspices of maintaining a unified system. An annual UFS tutorial, encompassing both the MRW and Convective-Allowing applications is planned, given those two applications will have been released to the community.

EMC software engineering support will unify GFS v17 and GEFS v13 codebases and support implementing the first FV3-based seasonal model SFS v1. Regression tests will be significantly expanded and the preprocessing chain updated to handle all components in the coupled model.

Building on its experience with HWRF, the DTC will work with EMC and other HAFS developers to stand up a code management and governance structure for the UFS Hurricane Application. Effort will largely be focused on reviewing requirements and needs from the community and ensuring the HAFS effort is properly coordinated with the larger UFS effort. Given the nature of the code management of all the Earth system components (source code and authoritative repository) within the UFS and the expertise on each component residing at various institutions, the DTC proposes to focus code management efforts for the HAFS system, at least initially, on the scripts and workflow. This effort will include leveraging the use of GitHub issue tracking for workflow requirements. As requirements from the developer community are submitted via a Hurricane Supplemental project (PI: Evan Kalina), effort needed to address workflow requirements for HAFS will be identified. As development branches are created and merged into the master repository, code integrity of the HAFS scripts will be maintained via regression testing. Additional effort to coordinate the maintenance of stable scripts and workflow will be required as HAFS becomes more complex.

(d) Workflow Coordination

Workflow is a critical area of UFS with implications for both operations and researchers. Several prior efforts have looked broadly at workflows across UFS applications, including activities of a Workflow Focus Team in 2018, a UFS Workflows meeting held at NCAR in July 2019, and the UFS Public Release Workflow Focus Group. Results of these activities and current development activities of the Application Teams need to be synthesized and a practical path forward established. A clear statement is needed on the recommended design and implementation strategy for workflow across the UFS enterprise. Under this project, practical steps will be taken including establishing a regular coordinating call among EMC, ESRL, NCAR, DTC, and JCSDA workflow leads and holding a UFS workflow workshop. In addition, Co-PI Cash will coordinate across the Infrastructure and Verification & Post-Processing Working Groups to incorporate the automatic generation of standard model diagnostics directly into standard UFS workflows.

(e) EPIC

Since the nature of EPIC is still evolving (based on the recent draft EPIC Strategic Plan FY2020-FY2025), EPIC-contract software engineers, cloud-enabling experts or community support experts could enhance the efforts outlined in this Infrastructure proposal via additional staffing and (cloud) compute resources if they are well-integrated into these Infrastructure activities.

3. For those projects that involve UFS development (either forecast model or data assimilation), please include a description of how you will measure progress.

For the major infrastructure packages covered under this project, the general approach to testing and validation is to (1) verify correctness of the infrastructure package in isolation through each package's independent test suite, and (2) validate the infrastructure package in context by running

UFS application regression tests and demonstrating that either answers do not change, or, if they do, that the answer changes are expected, well-understood, and documented.

ESMF has an extensive test suite and nightly regression tests on a large number of platform/compiler combinations. Standard development practice is to add tests to the suite as new capabilities are added to the framework. Updated versions of the ESMF library are provided to NOAA on a regular basis through beta snapshots installed on NOAA machines (e.g., Hera). Innovations added to the CCPP Framework will be assessed with the framework regression test being developed under Hurricane Supplemental funding when it becomes available. CCPP innovations will be subjected to the regression tests associated with UFS applications before being committed to the master branch. The SCM integrity will be assessed through the regression tests being developed as part of this project.

For HAFS, a consistency check will be performed on any infrastructure developments that are not intended to change the HAFS forecast to verify that they are indeed non-answer changing. Standard regression tests that are currently run on new HWRF developments will also be adapted to the HAFS framework.

4. Two Year Plan and Five Year Vision:

Timeline	FY20	FY21				FY22		
Milestone	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Regular UFS workflow coordination calls established including EMC, ESRL, NCAR, DTC, and JCSDA	X	X	X	X	X	X	X	X
Workshop on UFS Workflows including delivery of a workshop summary report						X		
ESMF/NUOPC 8.1.0 software release	X	X	X					
Data-driven specification of coupling field remapping and merging in CMEPS			X	X				

JEDI/NUOPC interface for prototype in-core model estimate of observations	X	X	X					
Deprecation of NEMS Mediator and validation of CMEPS in UFS-S2S	X	X	X	X				
Updates to CMEPS for CICE6 integration	X	X						
Updates to CMEPS for WW3 integration		X	X	X				
Profile report indicating optimization needs for coupled UFS model		X	X					
Optimized coupled UFS model			X	X				
Initial meeting of CMEPS Change Review Board to prioritize major development tasks						X		
ESMF/NUOPC 8.2.0 software release				X	X	X	X	X
JEDI/NUOPC prototype with 3D data exchange and optimizations					X	X		
Workflow status technical report							X	X
Expanded UFS S2S regression test suite with Continuous Integration testing			X	X	X	X	X	X
GSI updated with JEDI components	X	X	X					
Completed migration of EMC web pages to new template	X	X	X	X	X	X	X	X

Support to EMC in using CCPP for research and operations in the UFS	X	X	X	X	X	X	X	X
Code management and governance for the *ccpp-physics* and *ccpp-framework* repositories	X	X	X	X	X	X	X	X
Transition of selected advancements in the *ccpp-framework* developed by NCAR to the UFS	X	X	X	X	X	X	X	X
CCPP public release with updated documentation, user and developer support	X	X	X	X	X	X	X	X
Capability to auto-convert variables and auto-transform arrays in CCPP				X				
Assured consistency between SDF and UFS atmospheric namelist				X				
Rules for CCPP variable naming and developer tools for existing CCPP variable discovery				X				
Tools to aid CCPP usability								X
Development of CCPP SCM regression tests to maintain integrity of repository				X				
CCPP SCM community repository with clear governance and leadership in the code management	X	X	X	X	X	X	X	X
CCPP SCM user and developer support, including	X	X	X	X	X	X	X	X

updates to website describing supported capabilities								
CCPP SCM interface consistent with advances in ccpp-physics, ccpp-framework, and UFS Atmosphere				X				X
CCPP SCM public release				X				X
UFS MRW App: support to user community and to EMC in release preparation	X	X	X	X	X	X	X	X
Preliminary governance strategy for the HAFS repository posted to the UFS Github wiki	X	X	X	X				
HAFS scripts and workflow maintained with code integrity tested through regression and consistency checks, as applicable	X	X	X	X	X	X	X	X
Support provided to HAFS community via UFS Users' Forums					X	X	X	X
New developments contained in HAFS repository branches ready for testing by EMC and DTC staff					X	X	X	X
Annual UFS Users' Tutorial for the MRW and CAM applications	X				X			

Within 5 years, the GFS and GEFS systems will have converged into a common codebase with CMEPS supporting both. CMEPS will be extended and validated to support ensemble configurations. Also within the 5-year period, all UFS applications containing an atmosphere will have transitioned to employ the CCPP in research and operations. There will be an active community of researchers (inside and outside NOAA) running UFS coupled systems and clear mechanisms will be in place for receiving, testing, and integrating code changes from community partners.

5. Interdependencies with other projects/EMC planned implementation timelines and/or any major risks and issues.

- Significant interdependencies:
  - CMEPS is being brought into HAFS to couple the UFS atmospheric model and HYCOM. CMEPS testing and development will be coordinated across the Medium-Range Weather, S2S, and HAFS applications to ensure that changes made in one application are compatible with all applications.
  - CCPP is used in multiple developmental and upcoming operational implementations, requiring close coordination with application teams.
  - Releases and user support for the Medium-Range Weather application should be closely coordinated with those for other applications.
- Risks:
  - Application support was requested of the ESMF team for multiple coastal coupling applications, and specific support for these coupled applications is not included here.
  - Support was requested, but is not included here, to extend the CCPP Framework to advanced UFS system architectures (including the ability to use a NUOPC cap over a CCPP suite for land, radiation, and chemistry use) and to next-generation computation architectures, such as GPUs. To implement a robust 5-year vision, these developments should be reconsidered as additional resources become available.
  - Support is requested here for support of the MRW application with current capabilities. If additional capabilities become available, such as coupling with ocean and sea ice, or data assimilation, additional resources will be needed.

6. Specify how organizational base-resources (in-kind) will be leveraged for this sub-project.

- ESMF core team (~10FTEs) includes in-kind contributions from NASA, Navy, and NCAR; framework support is shared among developers to leverage most relevant expertise, typically at .2FTE per developer
- DTC at NCAR infrastructure through other UFS-related funding (NCAR, OAR, GSD)
- DTC at GSD infrastructure through other UFS-related funding (HFIP, OAR, GSD)

7. Please provide an estimate of compute resource requirements, both in terms of CPU hours per month and disk storage.

Activity	CPU hours/year	Disk storage
CMEPS testing and validation in UFS S2S	2.4M (Hera) - may be shared with existing S2S core-hours	20TB (Hera) - shared with existing S2S storage
DTC development and testing of CCPP, UFS MRW App support and pre-release testing, HAFS code management and support	3.384M (Hera) 6M (Jet) 1.2M (Orion) 1.2M (Gaea) 0.36M (wcoss)	141 TB (Hera) 170 TB (Jet) 50 TB (Orion) 50 TB (Gaea) 10 TB (wcoss)
ESMF/NUOPC performance testing on the cloud	12,000 hours of Amazon c5n.18xlarge or similar instances	100 GB

8. Summary of known team members and institutions (expected FTE commitment), including what resources are leveraged, including federal salaries or synergistic projects.

Name/ organization	Subject matter expert/milestone effort	Commitment level FTE	Amount leveraged (if any)	What is leveraged? (office space, time, computing)
NCAR/CGD/ESMF	**Gerhard Theurich** - ESMF technical lead **Bob Oehmke** - regridding **Ufuk Turuncoglu** - CMEPS/coupled apps **Dan Rosen** - coupled apps **Ryan O'Kuinghttons** - Python/regridding **Rocky Dunlap** - ESMF core team manager	2.5FTE	ESMF base support of ~6FTE from federal grants	Developer time for user and application support
NOAA/EMC	Current staff - engineering support, code optimization and DA support Current staff - engineering support, coupled modeling	5 FTE	Engineering team at EMC ~ 25 FTE	Office space, time and computing resources

	Current staff - engineering support, ensemble modeling Current staff - engineering support, pre processing Current staff - webmaster			
DTC-NCAR	**Mike Ek** - PI for this effort **Louisa Nance** - DTC Director Other staff TBD: Project scientists, software engineers.	2.5 FTE (approx at this time)		DTC at NCAR infrastructure through other UFS-related funding (NCAR, OAR, GSD)
DTC-GSD	**Ligia Bernardet** - PI for this effort Other staff TBD	2.3 FTE (approx at this time)	~2 FTE	DTC at GSD infrastructure through other UFS-related funding (HFIP, OAR, GSD)
GMU	**Ben Cash -** PI for this effort	0.4 FTE		

3.2 UFS-R2O CCI Sub-project: Verification and Post-Processing

UFS-R2O Task: Cross-Cutting Application
Team: Cross-cutting
Sub-project area: Verification and Post-Processing
Sub-Project Leads: Tom Hamill (ESRL/PSD) and Jason Levit (EMC)
Sub-project organizations proposed for: EMC, MDL, DTC-NCAR, UW/CIMSS, PSD, DTC-GSD, AFS11

Sub-project Narrative:

1. **Sub-project overview.**

Developing other components of the UFS such as physical parameterizations and ensembles depends on accurate, easy-to-use software for verifying, and evaluating UFS Earth System Model (ESM) application output. Also, the ultimate usefulness of the UFS guidance can be improved significantly through statistical postprocessing, i.e., the adjustment of model guidance using discrepancies between past observations and forecasts. The outcome of the work proposed here is in direct support of these larger objectives. The proposed work also reflects the current priorities of the UFS application teams through the creation of extensible community software for post-processing and verification tasks. During the two-year period, the funded personnel and agencies will both create and/or enhance software tools and perform rigorous verification and evaluation of proposed UFS modeling systems targeted for real-time operations within NOAA. The UFS software development activities include a targeted release of (a) METplus additions of new metrics and verification algorithms for UFS applications in METplus wrappers, MET, METviewer, and METexpress. Through in-kind contributions, the EMC V&V team and Model Evaluation Group (MEG) will evaluate and verify the upcoming model implementations, in coordination with the broad UFS community and NWS field: (a) HRWF v13/HMON v3, (b) GEFS v12, (c) RTOFS v2, (d) NWPS v1.3, (e) HREF v3, and (f) GFS v16. In addition, the V&V/MEG team will work closely with DTC and UW-CIMSS to enhance verification and evaluation methodologies and strategies. These align with major priorities in Annexes 12 and 13 (Postprocessing and Verification) of the NGGPS Strategic and Implementation Plan.

2. Sub-Project Justification and Technical Approaches.

The EMC V&V team creates and uses tools, algorithms, and methods to verify and validate all EMC environmental prediction systems before implementation into National Weather Service (NWS) operations. The V&V group will conduct thorough evaluations of the UFS suite with NWS internal and external partners via the V&V's MEG, and by assisting model developers by providing tools to test model development, using the METplus software system. Ultimately, the V&V/MEG personnel create transparency in the model development process, providing an independent assessment of model performance. Additionally, the AFS Analysis and Nowcast Branch (AFS11) will contribute to and utilize METplus for their V&V effort to meet NWS field's short-term forecasting needs. A metrics workshop will be hosted by the Developmental Testbed Center (DTC) to assist V&V/MEG and UFS community in solidifying the assessment targets. Prioritization of the enhancements that will be added to METplus will be driven by MRW-AT and CAM-AT priorities, as well as the workshop recommendations. During the workshop, metrics requirements for the following areas will be explored: 1) Diagnostics for identifying sources of biases listed as AT priorities; 2) air, sea, land, cryosphere interactions for a coupled system; 3) ensemble metrics, and 4) physical and dynamical strengths and weaknesses (e.g. PBL errors, surface temperature errors, etc) at all temporal scales.

To support MEG model evaluation efforts, researchers at UW-CIMSS will work with operational model developers and various end users to explore new methods to synthesize the copious amounts of information that could be shown on verification scorecards for model evaluation, in an effort to create a more streamlined approach. This will be accomplished by researching methods to examine the most statistically significant information needed in scorecard displays. In addition, this multi-faceted, multi-institutional project, will focus on enhancements through continued development of each element of METplus core components as well as development of new methods to be integrated in years 3-5. The goals for years 1-2 include incorporating metrics to support evaluation of the coupled system, continued expansion of METplus, especially support for Python-based capability, and testing and inclusion of new metrics. Several aspects are already under development but will require additional attention to fully support UFS development. These include: 1) quantitative verification of sea-ice model output; 2) direct evaluation of PBL to establish biases; 3) diagnostics to explore the MJO and atmospheric teleconnections; 4) measures to evaluate hurricane track errors and diagnostics to guide developers; and 5) evaluation capabilities for global and regional ensembles, atmospheric composition and air quality and for severe weather proxies. Evaluation and diagnostics capabilities that will be added to METplus during this project include the development of process-oriented diagnostics to identify 1) the source of the cold surface temperature, SST, and PBL biases, 2) biases driven by gravity wave drag and upward transport of adiabatic heating, and 3) sources of cloud cover and precipitation biases, and 4) the evaluation of atmospheric and ENSO teleconnections. For graphical plotting, METviewer and METexpress will be enhanced to draw data from multiple databases and use these new METplus algorithms and create dynamic plots using the already established cloud-based system.

The Earth Prediction Innovation Center (EPIC) could be used to create documentation, provide user support, and act as a Center of creativity for funding new and innovative post-processing and verification techniques. EPIC cloud computing support could assist with the creation of a community-based verification and evaluation system, driven by METplus, and using the METviewer and METexpress data analysis tools.

3. Two-Year Plan and Five-Year Vision:

Timeline	FY2020	FY2021				FY2022		
Milestone	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Model evaluations: Complete (a) Test plan for each evaluation, (b) HRWF v13/HMON v3, (c) GEFS v12, (d) NWPS v1.3, (e) RTOFS v2, (f) HREF v3, and (g) GFS v16 evaluations, (h) enhanced EMC verification and evaluation web pages and METviewer/METexpress with community-reviewed metrics, (i) high-resolution CAM ensemble evaluation strategy, (j) coupled ensemble atmosphere-ocean model evaluation strategy	a, b, c	d, e, f	g			h		i, j
Metrics and diagnostics additions to METplus (defined above): (a) Metrics Workshop, (b) coupled system metrics, (c) verification of sea-ice output, (d) PBL diagnostics, (e) MJO and teleconnection diagnostics, (f) hurricane track diagnostics, (g) ensemble evaluation			a	d, f	c,g			b, e, h

capabilities, (h) enhanced database capabilities								
Process-oriented diagnostic additions to METplus: (a) cold surface temperature and SST, (b) gravity wave drag and upward transport of adiabatic heating, (c) sources of cloud cover and precipitation biases, (d) evaluation of atmospheric and ENSO teleconnections				a	b			c
Verification scorecard reduction: (a) Test plan, if desired, (b) initial strategy formulation, (c) SRW scorecard reduction complete, (d) MRW scorecard reduction complete	a, b				c			d

Five-year vision statement:

By 2025, the Post-Processing and Verification software systems will be much more mature, at TRL 9 and implemented in the cross-cutting infrastructure and available to medium-to extended range (MRW) and convection-allowing model (CAM) applications. The code will be fully documented with user support through EPIC.

4. Interdependencies with other projects/EMC planned implementation timelines and/or any major risks and issues

- This project directly supports the development, evaluation, diagnosis, and post-processing of all modeling systems within the MRW/S2S-AT and SRW/CAM-ATs and is dependent on the implementation of those applications.

5. Specify how organizational base-resources (in-kind) will be leveraged for this sub-project.

EMC: Jason Levit (.1 FTE), Geoff Manikin (.5 FTE), Logan Dawson (1.0 FTE), Alicia Bentley (1.0 FTE) , AFS11: YJ Kim (.1 FTE), Tatiana Gonzalez (.5 FTE)

6. Summary of known team members and institutions (expected FTE commitment), including what resources are leveraged, including federal salaries or synergistic projects.

Allocations assume ~ 2 trips/year for planning meetings, plus related journal articles. More complete budget breakdowns available upon request.

Name/ organization	Subject matter expert/milestone effort	Commitment level FTE	Amount leveraged (if any)	What is leveraged? (office space, time, computing)
EMC Evaluations and Metrics	EMC MEG/V&V team	0 FTE	9.85 FTE federal and contract support	EMC's Model Evaluation Group and Verification Group expertise, EMC office space and computing infrastructure
DTC-GSL Evaluations and Metrics	Bonny Strong, PI Other staff TBD: scientists, software engineers	1.15 FTE	0.25 FTE	GSL's verification and software expertise, office space, computing infrastructure, project management
DTC-NCAR Evaluations and Metrics	Tara Jensen, PI Other staff TBD: scientists, software engineers, statisticians	1.95 FTE	3.5 FTE	NCAR's other NOAA projects including OWAQ, and OSTI Activities, and non-HPC resources
UW-CIMSS Verification Scorecard Reduction	Jason Otkin, Coda Phillips	0.25 FTE	.025 FTE federal support	UW-Madison SSEC/CIMSS supercomputing facilities
AFS11 Evaluations and Metrics	YJ Kim, Tatiana Gonzales	0.6 FTE	1.4 FTE federal support	AFS's verification and evaluation expertise, AFS11 office space

7. **Measures of progress** (detailed test plans forthcoming)**.**

- Evaluation and metrics: Success measured in the completion of formal UFS application evaluation, and deployment of new verification metrics, scorecards, and webpages.

8. **Computer resource requirements** (*relative to current allocations*).

Project	CPU hours/month	Disk storage
c. Evaluation and metrics	200,000 (Hera and WCOSS), 0.5Kdb.r4.large and m5.xlarge instances on Amazon Web Services for METviewer and METexpress	20TB (Hera and WCOSS), 10TB Yr1: 5TB, Yr2: 10TB on (Amazon Web Services)

Total CCI Computer Resource Requirements.

Summary table showing breakdown by sub-project (cloud, NOAA research HPC, vs other HPC). CPU hours per year/Tb storage (not covered by existing NOAA HPC allocations). The data in this table will be used to develop an allocation request for NOAA cloud and HPC resources.

Project/Type of HPC	NOAA HPCS (including Orion)	Outside NOAA HPCS	Cloud
Model Infrastructure	Yr1: 1,112K; 431 TB Yr2: 1,012K; 431 TB		Yr1: 36K; 100 GB Yr2: 36K; 100 GB
Verification and Post-Processing	Yr1: 400K; 25 TB Yr1: 400K; 25 TB		Yr1: 6K; 5 TB Yr2: 6K; 10 TB
Total Cross-Cutting	Yr1: 1,612K; 456 TB Yr1: 1,612K; 456 TB		Yr1: 42K; 5.1 TB Yr2: 42K; 10.1 TB

Total Project Computer Resource Requirements

	NOAA HPC	Outside NOAA HPC	Cloud
MRW/S2S	Yr1: 269.9 M; 1.3 PB Yr2: 323.9 M; 2 PB	Yr1: 6 M; 6 TB Yr2: 6 M; 6 TB	Yr1: 72 M; 2.1 PB Yr2: 360 M; 21.6 PB
SRW/CAM	Yr1: 361.8 M; 2.35 PB Yr2: 361.8 M; 2.35 PB	Yr1: 3.4 M, 360 TB Yr2: 3.9 M, 360 TB	Yr1: 6.5 M, 250 TB Yr2: 6.5 M, 250 TB
Cross-Cutting	Yr1: 1.612 M; 456 TB Yr2: 1.612 M; 456 TB		Yr1: 42 K; 5.1 TB Yr2: 42 K; 10.1 TB
Total	Yr1: 633.3 M; 7.7 PB Yr2: 687.3 M; 4.8 PB	Yr1: 9.4 M; 366 TB Yr2: 9.9 M; 366 TB	Yr1: 78.5 M; 2.4 PB Yr2: 726.5 M; 21.9 PB

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