STRATEGIC IMPLEMENTATION PLAN

FOR EVOLUTION OF NGGPS TO A NATIONAL UNIFIED MODELING SYSTEM

First Annual Update (November 29, 2018)

INTRODUCTION

- COMMUNITY STRATEGY AND DEFINITIONS
- ADVANCING TOWARD THE NOAA UNIFIED FORECAST SYSTEM

ANNEX 1: NGGPS GLOBAL MODEL SUITES PLANNED FOR NCEP/EMC OPERATIONS

- Project 1.1: FV3-Global Forecast System (FV3-GFS):
- Project 1.2: FV3-Global Ensemble Forecast System (FV3-GEFS):
- Project 1.3: FV3-Seasonal Forecast System (FV3-SFS):

ANNEX 2: SYSTEM ARCHITECTURE

- Project 2.1a: Base support for ESMF and the NUOPC Layer
- Project 2.1b: Community Mediator Development
- Project 2.1c: Support for FV3GFS Coupling Projects
- Project 2.1d: Update and Optimize Component Model Interfaces
- Project 2.2: Advance Model Coupling Infrastructure for HAFS
- Project 2.3: System Architecture Design and Metrics for the Graduate Student Test

Annex 3: Infrastructure

- Project 3.1: Repository Management
- Project 3.2: Data Portal
- Project 3.3: Community Workflow

ANNEX 4: DYNAMICS AND NESTING

- Project 4.1: Stand-Alone Regional FV3 and Static High-Resolution Nests for Global FV3
- Project 4.2: Hurricane moving nests
- Project 4.3: Deep Atmospheric Dynamics (DAD) for FV3 Whole Atmosphere Model (WAM) and coupling to Ionosphere Plasmasphere and Electrodynamics Model (IPE)

ANNEX 5: MODEL PHYSICS

- Project 5.1: Selecting, Optimizing, and Implementing Advances in Model Physical Parameterization
- Project 5.2: Establishment of unified metrics covering weather to seasonal time scales
- Project 5.3: Collaborative framework for developing physical parameterizations

ANNEX 6: DATA ASSIMILATION

- Project 6.1: Observations
- Project 6.2: Data Assimilation Algorithms
- Project 6.3: Coupled Data Assimilation

Project 6.4: JEDI Data Assimilation Framework
Project 6.5: Rapidly updating global data assimilation system
ANNEX 7: CONVECTION-ALLOWING MODELS (CAM)
Project 7.1: Implementation of the RAPv5/HRRRv4 CAM ensemble analysis and hybrid deterministic HRRR forecast system
Project 7.2: Development of a SAR FV3 Meso/CAM replacement system for NAM/RAP/HREF-Member
Project 7.3: Developing a full CAM-scale ensemble DA and prediction system based on the SAR FV3 system
ANNEX 8: MARINE MODELS
Project 8.1: Ocean Data Assimilation (NCODA) to support RTOFS
Project 8.2a: FV3 based Hurricane Moving nests
Project 8.2b: Development of Coupled Atmosphere-Ocean-Ice Wave System for sub-seasonal to seasonal
Project 8.2c: Coupling wave models to Atmosphere systems
Project 8.2d: Coupled Ice-Ocean System for weather time scales
Project 8.3: Integrated Water Prediction (IWP) (3-5 years)
Project 8.4a: NexGen Ocean Model
Project 8.4b: Marine DA
Project 8.5: Ecosystems and Eco-Forecasting (3-5 years)
ANNEX 9: LAND SURFACE MODELS (LSM) AND HYDROLOGY
Project 9.1: Land Data Assimilation in FV3GFS/UFS
Project 9.2: NCEP Unified Land Data Assimilation System (NULDAS) Development
Project 9.3: Land surface model physics and system evaluation and selection
Project 9.4: Collaborative Development with National Water Model (NWM)
Project 9.5: Land-hydrology model system coupling with other earth-system model components
ANNEX 10: AEROSOLS AND ATMOSPHERIC COMPOSITION
Project 10.1: Atmospheric composition model component
Project 10.2: Data Assimilation for Atmospheric Composition
Project 10.3: Atmospheric composition emissions capability
ANNEX 11: ENSEMBLES
Project 11.1: FV3-GEFS implementation
Project 11.2: High-resolution global ensemble forecast system (HRGEFS)
Project 11.3: Ensuring consistency between global and regional ensemble systems
Project 11.4: Improve uncertainty treatments in the ensemble system to make them suitable for sub-seasonal forecasts and for a full spectrum of environmental prediction needs (mostly in planning).

ANNEX 12: POST-PROCESSING

Project 12.1: Transition all NOAA Operational Post Processing packages (ModPP, DiagPP, and StatPP) to support FV3 (FY19-21)

Project 12.2: Develop an ensemble visualization capability

Project 12.3: Develop/implement National Blend of Models (NBM) v3.2

Project 12.4: Develop station-based StatPP techniques for multi-model ensemble forecasts

Project 12.5: Integrate Weather Information Statistical Post-processing System (WISPS) into NCEP Production Suite

Project 12.6: Improve the accuracy of post-processed guidance through better science and better data

Project 12.7: Comparison and Validation of Post-Processing Techniques; Testbed for Post-Processing

ANNEX 13: VERIFICATION

Project 13.1: T&E for demonstration of operational readiness of prediction systems

Project 13.2: Unified verification and validation system

Project 13.3: Development of METplus and core component MET

Project 13.4: Robust METplus statistical database and display systems for UFS applications

Project 13.5: Develop protocol for community contribution to authoritative code repository

Link to SIP Milestones at a Glance (in separate document)

INTRODUCTION

The Unified Forecast System (UFS) is envisioned to be a community-based, coupled comprehensive Earth system modeling system. The UFS numerical applications span local to global domains and predictive time scales from sub-hourly analyses to seasonal predictions. It is designed to support the Weather Enterprise and to be the source system for NOAA's operational numerical weather prediction applications.

The UFS is designed to serve both the R&D and Operational communities engaged in the numerical prediction of the Earth System. The UFS is an end-to-end prediction system, starting with the identification of data needed for the prediction, their assimilation to create initial conditions, the forecast itself (deterministic or ensemble-based), and postprocessing and verification of the results. The UFS governance strives to facilitate the migration of research innovations into higher levels of technical readiness, targeting eventual implementation into Operational infrastructures across Federal agencies (Research to Operations, or R2O; this process is more completely described in a separate document). The UFS also facilitates the return of Operational requirements into the code being used by the R&D community, and so encompasses an R2O2R cycling as innovations appear.

This document is the UFS Strategic Implementation Plan (SIP) for FY 2019 - 2021. It is the first annual update to the initial SIP and describes the actions required of community participants in the next one to three years as they work together to evolve the UFS. This document is the result of planning meetings in January and August 2018, with activities in the interim focused around the Working Groups for each Annex. This year, the focus of the Annex updates has been on highlighting interdependencies between the projects described therein, and revising milestones and deliverables to align with anticipated resources. Consistent with the Strategic Vision for NOAA's Environmental Modeling Enterprise and the Roadmap for the Production Suite at NCEP developed by the NOAA Research Council, the end goal for the UFS is a community coupled model unified across time scales which simplifies the current NCEP production suite and benefits both research and operations.

The near-term focus of UFS development remains on activities funded by the Next Generation Global Prediction System (NGGPS) program, while the end goal will be a system to support unified Earth system modeling. The first delivery from the NGGPS program is the FV3GFS implementation planned for early 2019, which will be based on the recently-selected Finite Volume 3 (FV3) dynamical core. Operationally, this model will be referred to as GFS v15.0.

COMMUNITY STRATEGY AND DEFINITIONS

The UFS is designed as a community model that involves NOAA, other federal partners (e.g., NASA, DoD, JCSDA, etc.), and the broader research and academic community. Only with appropriate contributions from the entire U.S. modeling community will we be able to build the best national modeling system possible. The definition of "community" is important, and not all community efforts will be identical. We continue to learn from prior and ongoing community modeling efforts (WRF, CESM, WW3, MOM6, etc.) and apply best practices from these activities across the UFS.

Community approach: Different layers of community partners have specific roles/responsibilities.

- ***Core development partners*** (that regularly make substantial contributions) will be granted different roles and access than "users" that may run the model but not typically directly or actively contribute to its development.
- ***Trusted super-users*** may be established as a special, limited category that allow greater, early access than normal research users, in order to conduct early "beta" testing on the next model version still under development but not yet released to the full community.
- ***Users and Stakeholders***, while not contributing to the code in general, contribute requirements and needs and may drive the direction of development, resource allocations, and prioritization (within the NOAA mission space). These users are also critical as they can provide a level of in-depth evaluation of model performance that cannot be provided by super-users and core developers only. Along these lines, ***researchers*** are key stakeholders and should be engaged through Announcements of Opportunity (AOs) in order to increase the human capacity needed for long term (i.e., research funding supports students who will be skilled in the unified modeling technology and environment). For example, AOs from the Hurricane Forecast Improvement Program (HFIP) tripled the research community involvement in development of the Hurricane WRF (HWRF) model.
- ***Operational users***, due to constraints on reliability, timeliness, and security, will require a unique operational version of the modeling system. A significant goal will be to ensure that the overarching modeling system, while having different variants for research and operations, will have a consistent architecture and infrastructure that will allow improvements made on the research side to be smoothly transitioned into operations.

Governance: In order to effectively coordinate the activities and collaborative projects of the community partners, a community governance structure has been put in place. A key component of this is the UFS Steering Committee (UFS SC), which oversees activities of the Working Groups and provides scientific direction and recommendations for UFS activities. A Technical Oversight Board (TOB), which consists of program managers and directors of labs and production centers with equity in the UFS effort, guides the UFS SC and coordinates programmatic recommendations based on UFS SC recommendations. The roles of the UFS SC and TOB are described in their respective charters. The governance structure provides core partners a true voice in making strategic decisions regarding the community model, leverage an evidence-based decision-making approach, and ensure transparency across the community.

Communications and Outreach: Given the wide community interactions across numerous agencies, scientific disciplines, and diverse stakeholder groups, the UFS Communications and Outreach Plan Working Group efforts are critical to ensure consistent and effective messaging throughout the community. To this end, they have developed a comprehensive Communications and Outreach Plan. The plan encompasses communications related to the UFS and seeks to provide a careful and thoughtful set of proposed mechanisms to meet specific information, decision making, and community building needs. The Communication and Outreach WG supports all of the other WGs and the community at large.

ADVANCING TOWARD THE NOAA UNIFIED FORECAST SYSTEM

Tremendous progress has been made in FY 2018 on work described in the Annexes. Selected scientific and technical highlights include:

- The first instantiation of the UFS will be the FV3-based GFS (Project 1.1), approved for operational implementation in early 2019. This model has a horizontal resolution of about 13 km, and 64 vertical levels with a model top at 0.2 hPa. It uses the current physics suite in the operational GFS, but with a new microphysics scheme from GFDL (Project 5.1). The physics suite is connected to the FV3 dynamical core through an Interoperable Physics Driver (Project 5.3).
- The public release of the FV3 code (Project 1.1).
- Public code release for the Common Community Physics Package (CCPP, Project 5.3)
- The development of the Data Assimilation system for FV3GFS is complete (Project 6.2). Based on GSI and a Hybrid 4D Ensemble-Variational algorithm, it operates at a horizontal resolution of about 26 km and uses 80 ensemble members and upgraded satellite data streams.
- The first UFS coupled model is under development (Project 8.2b). Preliminary results based on 35-day integrations show good alignment with observations.
- A plan for the management of UFS code repositories available community-wide has been approved (Project 3.1).
- A Memorandum of Agreement between NCAR and NOAA for infrastructure development has been developed and coordinated by the participating organizations.

Next steps toward the UFS

There is a particular focus of the UFS on simultaneously simplifying and improving the operational Production Suite run at NOAA's National Centers for Environmental Prediction. The scope of the Production Suite demands that UFS numerical applications span local to global domains and predictive time scales from sub-hourly analyses to seasonal predictions. Thus, the UFS is necessarily based on coupled models, with a unified coupling infrastructure based on the Earth System Modeling Framework (ESMF) and a unified Data Assimilation System based on the forthcoming JEDI infrastructure. The UFS will be ensemble-based, with robust procedures for gathering model biases and other performance information through a standardized reforecast and reanalysis process. Crucial to the concept of the UFS is that applications are essentially specific configurations of a common code base, not separate codes built from the ground up.

The basis for UFS development is the FV3 dynamical core (dycore), a System Architecture (Annex 2), and companion Infrastructure (Annex 3) that are required for building applications out of the models. First among these applications resulting from the Next Generation Global Prediction System (NGGPS) program is the FV3-based Global Forecast System (FV3GFS, Project 1.1) will become operational in 2019. An FV3-based global ensemble prediction system (Projects 1.2, and 11.1) will be implemented in 2020, with consideration given to a high-resolution version of this (Project 11.2) and a better treatment of uncertainty in the ensemble system (Project 11.4). The FV3-based seasonal forecast system (Projects 1.3 and 8.2b) will provide model guidance out to 9 months. Global prediction will extend into the deep atmosphere with the development of Deep Atmospheric Dynamics (DAD) for an FV3-based Whole Atmosphere Model (WAM) coupled to an Ionosphere, Plasmasphere, and Electrodynamics Model (IPE) (Project 4.3).

The development of Advanced Physics (Project 5.1) for the follow-on implementation of FV3GFS in 2021 will include an assessment of several physics packages appropriate not just for global models, but for convection-allowing models (CAM, Annex 7) and seasonal prediction (Annex 8) as well. The Advanced Physics and all subsequent UFS physics packages will be expressed in the framework of a Common Community Physics Package (CCPP, Project 5.3), which is a collaborative framework for developing physical parameterizations. Physics development will be complemented by the development of a general unified atmospheric composition modeling system that will better account for trace gas effects of radiation as well as aerosol effects on radiation and clouds and will improve the handling of satellite observations by properly accounting for aerosol and trace gas effects during data assimilation. The development of a generic atmospheric composition component (Project 10.1) and its accompanying DA system (Project 10.2) will focus on how it should be integrated into the unified model system architecture for two-way interactive coupling with atmospheric physics and consistent coupling with dynamics. A unified emission system with the capability of providing model-ready, global anthropogenic and natural source emissions inputs for aerosol and gas phase atmospheric composition across scales will also be developed (Project 10.3).

Model development for the UFS is accompanied by a revitalization of global data assimilation techniques. This starts with the incorporation of new data types (Project 6.1), which will require significant development, the addition of new instruments that are continuations of existing observations, and development of new techniques for exploiting the information in the data. Hybrid (ensemble + variational) data assimilation in its various forms is the current state-of-the-science for environmental prediction and is expected to remain so over the next several years. This implies that the JEDI DA framework will be required to support several current technologies for a variety of applications. The UFS DA capabilities (Project 6.2) will utilize the JEDI framework to build out a project for global numerical weather prediction (FV3-GFS) inter-comparison between hybrid 4DEnVar (current technology) and Hybrid 4DVar (with adjoint) and do so within a rapidly updating (O(1-h)) global analysis system for atmospheric applications (Project 6.5).

In addition to global modeling, the UFS will provide a capability for regional modeling to provide high-resolution numerical guidance. A stand-alone regional model (SAR, Project 4.1) forms the technical core of this activity, from which a regional modeling application suite is being developed. These applications include an FV3-based replacement for the NAM/RAP (Project 7.2) and RAP/HRRR (Project 7.1) along with their associated ensemble prediction systems and data assimilation capabilities (Projects 7.3). A new Hurricane Analysis and Forecasting System (HAFS) is NOAA's next-generation multi-scale numerical model and data assimilation package, providing an operational analysis and forecast out to seven days, with reliable and skillful guidance on Tropical Cyclones (TC) track and intensity (Project 4.2). Key to this new prediction system is the development of nests that move with individual storms within the global model, and a coupling capability (Project 2.2) for these nests. How to ensure consistency between regional and global ensemble systems is under consideration (Project 11.3).

The next generation sub-seasonal to seasonal (S2S) forecast system (Project 8.2) will be based on the FV3GFS atmospheric model, the MOM6 ocean model, CICE5 ice model, GOCART chemistry model and WAVEWATCH III wave model coupled via the NUOPC/NEMS framework (Project 2.1). The long-term strategy for advanced Ocean Modeling (Project 8.4a) will be based on Arbitrary Lagrangian-Eulerian (ALE) coordinates along with a common ocean model framework for operations and research, suitable for both high-resolution, short time-scale work as well as coarser resolution, longer time scale modeling. The consolidation of marine (including both ocean and sea-ice) data assimilation activities into the JEDI framework (Project 6.4) has begun (Project 8.4b). This coupled modeling capability will integrate with a comprehensive NOAA Water Initiative, designed to give people and governments better access to the water information they need for their unique circumstances (Project 8.3) by means of collaborative development with the National Water Model (Project 9.4). Planning is underway for integrating the UFS with regional quasi near-real-time ecological forecasts, such as for Harmful Algae Blooms (HABs) and hypoxia (Project 8.5). The coupled models in the UFS will be accompanied by a coupled data assimilation capability that can initialize the fully coupled Earth system model to improve predictability from weather to S2S timescales (Project 6.3). This includes a comprehensive land DA system (Projects 9.1 and 9.2) for a comprehensive land surface model (Projects 9.3 and 9.5) coupled with other components in the UFS.

Access to and usability of UFS code and results is a requirement for engaging the community. A plan for building and managing code repositories has been developed as part of the UFS infrastructure (Project 3.1) and approved by the UFS Steering Committee. The proposed UFS repository management strategy places each UFS application (Seasonal Prediction, S2S, Weather Forecast, Regional, etc.) in a unique UFS umbrella repository comprised only of configuration files, with no source code. A configuration file will contain URL links to specific versions of model component code from external authoritative repositories; it is the combination of model component code and their configuration that forms the application. The UFS will establish a protocol for community contributions to authoritative code repositories (Project 13.5) as a way to increase community collaboration. The usability of these repositories and the end-to-end prediction system in regard to downloading code, building, changing, and testing the application, compiling it, running experiments, and evaluating output are measured by the proposed "Graduate Student Test" (Project 2.3).

A key element of the UFS-SC/EMC vision is the development of a unified suite of metrics and associated targets that covers all prediction scales (Project 13.2). For the UFS (Projects 13.3 and 13.4), this will be based on the community Model Evaluation Tools (METplus) developed at NCAR. This forms the core of an evidence-based evaluation of all components that is needed to ensure that new modeling systems are better than those being replaced. Plans for Testing and Evaluation (Project 13.1) have evolved substantially through community workshops like the one hosted in summer 2018 by the Developmental Test Center. The data that is examined for decision-making is provided by upgrades to the suite of postprocessing applications, first targeting FV3-based models (Project 12.1), augmented by an ensemble visualization capability (Project 12.2), improvements to WISPS (Project 12.5) and station-based statistical techniques for multi-model ensemble forecasts (Project 12.4), and the development of a testbed for evaluating postprocessing techniques (Project 12.7). A target of these improvements is the National Blend of Models (Project 12.3) and more broadly, the suite of applications that reside within the UFS.

Taken together, this portfolio of Projects (detailed in the Annexes which follow) embodies a path toward building out the UFS into a true community-based modeling system for numerical Earth System prediction.

<u>ANNEX 1</u>: NGGPS GLOBAL MODEL SUITES PLANNED FOR NCEP/EMC OPERATIONS

Given that NGGPS will be the foundation upon which a community based Unified Forecast System (UFS) is being built, it is important to start from the planned/funded NGGPS capabilities and timelines, so as to ensure that other additional community efforts are properly synchronized. Therefore this first Annex lays out the broad program deliverables and schedule for NGGPS functionality to be implemented at NCEP/EMC, to be followed by additional annexes for each community SIP Working Group's specific plan for additional exploratory or development project.

The first major NGGPS model package will be to replace EMC's legacy Global Forecast System (GFS) model, based on the Global Spectral Model (GSM) dynamical core, with a new version of the GFS that is based on FV3 dynamical core. As such, this new system is referred to as FV3GFS. This will signal the initiation of NOAA's Unified Forecast System (UFS) that is being built as a community model. The first operational version of the FV3GFS is planned for Q2FY19, with additional upgrades planned on a biennial basis starting in FY21.

The second major NGGPS model package will be to replace EMC's legacy Global Ensemble Forecast System (GEFS), based on the Global Spectral Model (GSM) dynamical core, with a new version of the GEFS that is based on FV3 dynamical core. As such, this new system is referred to as FV3GEFS. The first operational version of FV3GEFS is planned for implementation in Q2FY20. In addition to replacing the legacy GEFS, the forecast length for the new FV3GEFS will be extended to 35 days, therefore making it an operational ***Sub-Seasonal*** ensemble prediction system. FV3GEFS implementation will also be accompanied by 20-year reanalysis and 30-year reforecast datasets to meet the requirements of the stakeholders.

The third major NGGPS model package will be to replace EMC's legacy Climate Forecast System (CFS), a fully coupled seasonal-scale model based on the Global Spectral Model (GSM) atmospheric dynamical core, Modular Ocean Model Version 4 (MOM4), and a 3-layer thermodynamic ice model, with a new version that is based on the FV3 atmospheric dynamical core, Modular Ocean Model Version 6 (MOM6), and Los Alamos Sea Ice Model Version 5 (CICE5). Given that the old CFS name is a misnomer in that is provides predictions on *seasonal scales*, and not to long-range climate scales as the name implies, the "climate" part of the name will be dropped and replaced with the more accurate "seasonal" descriptor; as such, this new system will be referred to as the FV3-SFS. Coupled reanalysis and reforecasts will include in the development of FV3-SFS, targeted for implementation in FY22.

The next sections will cover the implementation activities of the three NGGPS global modeling systems targeted for operations at NCEP/EMC, to be followed by functional components of the broader community development efforts organized under the SIP Working Groups.

<u>Project 1.1: FV3-Global Forecast System (FV3-GFS)</u>:

Project overview: The NGGPS mission and objectives include NOAA/NWS/NCEP being the world's best and most trusted provider of deterministic and probabilistic weather forecast guidance across all spatial and temporal scales. Fundamental and central to this mission is the FV3-GFS and associated FV3 based Global Data Assimilation System (GDAS). The NOAA Environmental Modeling System (NEMS) framework will provide the infrastructure for developing the FV3-GFS, and will become the core component of the Unified Forecast System (UFS). Apart from providing forecast guidance over different time scales, the FV3-GFS also provides initial and boundary conditions for regional atmospheric and ocean models, space weather models, air quality models, and various other NCEP production suite applications. To properly service the customers, the forecasts must be available reliably and at the appropriate time within available resources.

Major Risks and Issues:

- ○ Computational resources dedicated for model development and for operations
- ○ Documentation, training, code management and access of codes by core partners and community
- ○ Demonstration of superior performance of FV3-GFS from scientific evaluation
- ○ Alignment with Unified Forecast System Development strategy

Major resources requirements:

- ○ Personnel:
  - ○ EMC (21 FTE): FV3-GFS Model development, physics, and DA
  - ○ ESRL (2 FTE); GFDL (3 FTE)
- ○ HPC for development: ~20 M CPU hrs per month on WCOSS, Theia, Jet and Gaea; ~500 TB scratch space and ~2 PB HPSS storage prior to implementation

Dependencies/linkages with other projects:

- ○ NEMS/ESMF framework advancements
- ○ ESRL/PSD DA integration including stochastic physics
- ○ Readiness and availability of data from GOES-16, JPSS (NOAA-20) and COSMIC-2
- ○ GFDL IPDv4; DTC/GMTB CCPP
- ○ Advanced Physics options recommended by SIP Physics Working Group
- ○ MET based verification and validation (delayed)
- ○ Refactored NCEP POST (UPP) and product generation (delayed)
- ○ Unified Workflow (CROW) (partially completed)
- ○ Transition to VLab and Code Management/Governance (done)
- ○ Joint Effort for DA Integration (JEDI) (delayed)

Core development partners and their roles:

- ○ NCEP/EMC: Model development (including physics and data assimilation), integration into NEMS framework and unified workflow, code management, retrospective and real-time experiments, testing and evaluation, transition to operations
- ○ ESRL/PSD and JCSDA: DA development support
- ○ ESRL/GSD; DTC/GMTB: CCPP. Physics development and T&E
- ○ ESRL/NESII: The NOAA Environmental Software Infrastructure and Interoperability (NESII) team provides ESMF/NUOPC advances and NEMS development and integration support.
- ○ Research activities funded by NGGPS, JTTI and other programs for R2O

Major Milestones:

FV3-GFS V1.0 (GFS V15):

- ○ Q2FY18: Implement FV3 dynamical core and physics driver into NEMS framework: Add FV3 cap to NEMS; develop FV3 write component; enable hourly output; develop regridding tools and NETCDF I/O; replace Zhao-Carr microphysics with advanced 6-class GFDL microphysics **(completed)**
- ○ Q2FY18: Adopt 4D-Hybrid DA for FV3-GFS: Prepare tools to develop initial conditions for FV3-GFS using NEMS-GSM analysis fields; transition the 4D-Hybrid En-Var data assimilation framework for FV3-GFS; configure and optimize the cycled data assimilation experiments including EnKF and stochastic physics **(completed)**
- ○ Q2FY18: Assimilation of GOES-16, JPSS NOAA-20 and COSMIC-2 data: Prepare FV3-GFS for assimilating new satellite datasets as they become available **(completed)**

- Q3FY18: Pre- and Post- Processing; verification and validation: generate downstream products and evaluate impacts on production suite dependencies **(completed)**
- Q3FY18: Performance evaluation of FV3-GFS: Conduct fully cycled forecast experiments; code optimization; performance evaluation; real-time data delivery to the field through para-nomads; perform pre-implementation testing through 3-year retrospective and real-time evaluation of FV3-GFS; and prepare model for transition to operations **(on target)**
- Q4FY18: FV3-GFS code hand-off to NCO **(on target)**
- Q2FY19: Replace GSM based GFS with FV3-GFSV1.0 (GFS V15) in NCEP operations **(on target)**

FV3-GFS V2.0 (GFS V16):

- Q1FY19: Integrate CCPP into FV3-GFS and establish Hierarchical Testing Framework to support testing and evaluation of advanced physics options
- Q2FY19: Configure increased vertical levels and higher model top configuration for data assimilation
- Q3FY19: Couple FV3-GFS with WaveWatch-III (two-way interactive) and evaluate forecast performance
- Q4FY19: Test and evaluate advanced physics configurations targeted for FV3-GFS V2.0 and finalize Advanced Physics configuration for FV3-GFS V2.0
- Q2FY20: Conduct fully cycled forecast experiments; code optimization; performance evaluation
- Q3FY20: Real-time data delivery to the field through para-nomads; perform pre-implementation testing through 3-year retrospective and real-time evaluation of FV3-GFS V2.0; and prepare model for transition to operations
- Q4FY20: Prepare FV3-GFS V2.0 for transition to operations through code hand-off to NCO
- Q2FY21: Implement FV3-GFS V2.0 (GFS V16) into operations

FV3-GFS V3.0 (GFS V17):

- Q4FY21: Roll out preliminary configuration for FV3-GFS V3.0 (GFS V17) under the UFS infrastructure and inputs from UFS community

FV3GFS Global Deterministic Model Implementations

Timeline	FY18		FY19				FY20				FY21			
Component	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
FV3GFS V1.0														
FV3GFS V1.0 (GFS V15)	Transition FV3GFSV1.0 into operations													
FV3GFS V2.0														
CCPP/HTF	Integrate CCPP into FV3-GFS and establish Hierarchical Testing Framework													
Vertical Resolution	Configure increased vertical levels and higher model top configuration for data assimilation													
FV3-WW3 Coupling		Couple FV3-GFS with WaveWatch-III (two-way interactive) and evaluate forecast performance												
Advanced Physics	Test, evaluate and finalize advanced physics configuration													
Cycled Experiments					Conduct fully cycled forecast experiments and performance evaluation									
Pre-implementation T&E							3-year retrospective and real-time evaluation of FV3-GFS V2.0							
Transition to Operations										Code hand-off and transition to operations				
FV3GFS V3.0														
Preliminary configuration										Develop preliminary configuration for FV3-GFS V3.0 (GFS V17) under the UFS infrastructure and inputs from UFS community				

Project 1.2: FV3-Global Ensemble Forecast System (FV3-GEFS):

Project overview: The FV3-GEFS project will assemble, test, and prepare for the implementation of an upgraded Global Ensemble Forecast System (FV3-GEFS) which will extend the weather forecast guidance to weeks 3&4 (35 days). The FV3-GEFS implementation will be accompanied by a ~20-year reanalysis and reforecast. The FV3-GEFS will be implemented within the NEMS framework using the FV3 dynamical core and IPDv4, and is consistent with the development and implementation plans for the FV3-GFS supported by NGGPS and CPO. The FV3-GEFS project will have close coordination with the FV3-GFS project, and the ESRL/PSD reanalysis project to ensure timely execution of the reforecasts leading to implementation of FV3-GEFS (GEFS V12) in operations. The model configuration for FV3-GEFS will include 2-Tier SSTs using calibrated CFS SST forecasts. A fully coupled FV3 atmospheric model to Ocean (GFDL Modular Ocean Model MOM6), Sea-Ice (CICE), and Land (Noah Land Surface Model) components is being developed for implementation in the next upgrade cycle for FV3-GEFS (GEFS V13). The data assimilation systems for the component models will be uncoupled. The FV3-GEFS reforecast experiments will rely on ESRL/PSD's atmospheric initial conditions based on the ~20-year atmospheric reanalysis project.

Major Risks and Issues:
- Computational resources dedicated for model development, tuning, and for operations, including procurement of disk space for reanalysis/reforecast ($150K sent to NCO for NOMADS disk augmentation in early FY2018).
- Timely execution of reanalysis/reforecast project, which in turn depends on computational resource availability and the stability of the FV3 model and data assimilation system. When the reanalysis is generated (using FV3), the FV3 system should be as close as possible to the eventual operational version.

Major resources requirements:
- Personnel:
  - EMC (18 FTE): Ensemble model development, coupled system development, Reforecasts, T&E and transition to operations
  - ESRL/PSD (~6 FTE): Reanalysis/reforecast and GEFS development in FY2017.
  - GFDL (TBD)
- HPC for development: ~25 M of CPU/month; ~500TB of disk space; ~5 PB of archive (tape) space

Dependencies/linkages with other projects:
- NEMS/ESMF framework advancements.
- Via collaboration with DA team, a stable, agreed-upon procedure for atmospheric ensemble initialization, via presumably 4D-En-Var system. We will need resolution of whether EnKF used in 4D-En-Var will be moved from the late to the early DA cycle, and then whether GEFS atmospheric initial conditions will be initialized from analysis perturbations (EnKF in early cycle) or from 6-h forecast perturbations (EnKF in late cycle).
- Reanalyses and reforecasts are available, data sent to key partners (MDL, CPC, NWC) prior to ops.
- ESRL/PSD stochastic physics methods successfully ported, tested, and verified in the FV3/NEMS framework (ESRL/PSD in collaboration with EMC staff).
- Transition to VLab and Code Management/Governance for coupled system components

Core development partners and their roles:
- NCEP/EMC: Ensemble Model development (including integration into NEMS framework and unified workflow); test ensemble perturbation methods (SPPT, SKEB, SHUM and land surface

parameter perturbations); test representation of process-level uncertainty in physics; ~30-year reforecasts including extension to weeks 3&4; determine optimal configuration for ensemble size and resolution; develop post-processing, bias corrections, and products for FV3-GEFS; conduct retrospective and real-time experiments, testing and evaluation, and transition to operations
- ESRL/PSD: Reanalysis project; development of stochastic physics methods; methods for postprocessing of model guidance in the National Blend of Models project.
- NCAR, NCEP/CPC, and others: Evaluation metrics and support for verification and validation

Major Milestones:

FV3-GEFS V1.0 (GEFS V12):
- Q2FY18: Prepare FV3-GEFS for reanalysis project: Develop and test low-resolution version of FV3-GFS and FV3-GDAS, and configure the model for reanalysis project **(completed)**
- Q3FY18: Determine ensemble configuration for FV3-GEFS: Configure for optimum no. of ensemble members, resolution, physics, and conduct preliminary testing for quality assurance and computational efficiency. **(completed)**
- Q2FY19: Produce ~20-year reanalysis datasets: Mainly ESRL/PSD activity. Determine configuration of the reanalysis system; develop observational database for reanalysis; prepare observational inputs; and produce reanalysis suitable for reforecasts and calibration. **(on target)**
- Q4FY19: Produce ~30-year reforecast datasets for FV3-GEFS: Finalize ensemble configuration and produce reforecasts consistent with the reanalysis data; extend the reforecast length to 35 days; conduct pre-implementation T&E; transition the system for operational implementation **(on target)**
- Q2FY20: Transition FV3-GEFS (GEFS V12) into operations **(on target)**

Other Milestones associated with this project:

Unification of Global Wave Ensembles into FV3-GEFS:
- Q2FY19: Couple FV3-GEFS to Wave Watch III ensembles: Integrate the wave model ensembles into FV3-GEFS using NEMS/NUOPC coupler; replace global wave model products with the wave coupled FV3-GEFS.

Unification of Global Aerosol Component into FV3-GEFS:
- Q2FY19: Couple Aerosol Model to FV3-GEFS: Integrate the aerosol chemistry module (GOCART) into FV3-GEFS (control member only) using NEMS/NUOPC coupler; replace operational NGAC products with the aerosol coupled FV3-GEFS

FV3-GEFS V2.0 (GEFS V13) (Combined with S2S Development for UFS Coupled Model; See Annex 8 Project 2b):

- Q4FY18: Development of Coupled FV3-MOM6-CICE5-WW3 model: technical demonstration of working of the UFS coupled system for S2S scales
- Q2FY19: Add NOAH-MP Land Surface Model into FV3-GEFS system
- Q1FY20: Test Coupled system out to week 3-4 using GEFS v12 configuration [Forecast only, full cycling when Marine DA is ready]
- Q1FY20: Development of DA capability for MOM6, CICE5, WW3, LAND, AEROSOL
- Q3FY20: Enhance Atmospheric and Marine Perturbation techniques to improve skill
- Q3FY20: Explore alternative physics options and test balance across air - sea interface
- Q3FY21: Reanalysis & Reforecast & Evaluation & Validation

● Q4FY21: Code hand-off to NCO for operational implementation

FV3GFS Global Sub-Seasonal Ensemble Model Implementations														
Timeline	FY18		FY19				FY20				FY21			
Component	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
FV3GEFS V1.0 (GEFS V12.0)														
20-year Reanalysis Project (ESRL/PSD)	Generate 20 year FV3GFS/GDAS based Reanalysis Data													
30-year Reforecast Project (EMC)		Produce ~30-year reforecast datasets for FV3-GEFS: Finalize ensemble configuration and produce reforecasts consistent with the reanalysis data; extend the reforecast length to 35 days												
Unification of Global Wave Ensembles		Integrate the wave model ensembles into FV3-GEFS using NEMS/NUOPC coupler												
Unification of Global Aerosol Component		Integrate the aerosol chemistry module (GOCART) into FV3-GEFS (control member only)												
Pre-implementation T&E				Conduct 2.5 year retrospective experiments and complete field evaluation										
Transition to Operations							Code hand-off and transition to operations							
FV3GEFS V2.0 (GEFS V13.0)														
FV3+MOM6+CICE5	Development of Coupled FV3-MOM6-CICE5-WW3 model													
Noah-MP Land Model		Add NOAH-MP Land Surface Model into FV3-GEFS system												
Coupled System Testing (forecast only)					Test Coupled system out to week 3-4 using GEFS v12 configuration									
Marine DA	Development of DA capability for MOM6, CICE5, WW3, LAND, AEROSOL													
Stochastic Physics					Enhance Atmospheric and Marine Perturbation techniques									
Advanced Physics for S2S Scales					Test alternative physics options and evaluate balance across air - sea interface									
Coupled Reanalysis and Reforecasts								Reanalysis & Reforecast & Evaluation & Validation						
Transition to Operations													Code hand-off to NCO for operational implementation	

Project 1.3: FV3-Seasonal Forecast System (FV3-SFS):

Project overview: The FV3-SFS project will develop the next generation seasonal forecast system based on the FV3 dycore. The seasonal forecast system will provide model guidance out to 9 months. FV3-SFS will include all the components that are being developed for the FV3-GEFS system (coupling between FV3, MOM6, WAVEWATCH III, CICE5) with focus on processes that occur at longer time scales than those for FV3-GEFS. (Note: There is a lot of overlap in processes at the week 3&4 scale of FV3-GEFS and the longer time scale of FV3-SFS and developments will be leveraged for both systems). The ensemble perturbations will be expanded to the ocean model to provide greater spread for the coupled system. The initialization of the other components (land, aerosol waves, ice) will also be developed.

● **This project will follow the S2S Development Schedule shown in GEFS V13 milestones.**

- **See Annex 8 Project 2b** (**Development of Coupled Atmosphere-Ocean-Ice Wave System for sub-seasonal to seasonal**)

ANNEX 2: SYSTEM ARCHITECTURE

System architecture can be defined as “the fundamental organization of a system, embodied in its components, their relationships to each other and the environment, and the principles that govern its design and evolution.”[1],[2] The UFS system architecture serves as the backbone of a unified modeling system, and must provide high performance, reliable technical and scientific functions for a range of different forecast products. The design of the architecture is relevant to research community partners because it must make it easy for them to perform runs and experiments, and participate as full partners in model development. The evolving system architecture is being designed to conform to a set of principles articulated by the System Architecture Working Group, available in an initial report, *System Architecture for Operational Needs and Research Collaborations*.

An initial conception of the system architecture (Fig. 1) is a layered, component-based structure, divided into (1) a Workflow Environment that includes a user interface and database of experiment metadata for previous runs, including metadata about input datasets and observations/analyses used for verification, (2) a Prediction Package layer that consists of a sequence of pre-processing, data assimilation, forecast, and post-processing jobs, (3) a Modeling and Data Assimilation Application layer that includes the coupling framework (the NOAA Environmental Modeling System, or NEMS), a prescribed interface between atmospheric physics and dynamics, model components, and data assimilation components, and (4) a layer of Libraries and Utilities. Each layer utilizes components, which can be defined as “composable” software elements that have a clear function and interface. The system architecture includes elements that are complete and others that are still in progress. The portion of the system diagram that relates to coupled modeling applications is shown in teal and black. NEMS is shown in teal and includes a main coupler, a space weather coupler, a driver, and tools for building applications and running specific cases.

Many questions with a bearing on system architecture require scientific research, with the answers relating either to Earth system processes and their interactions or to the impact on predictability and prediction skill as a function of lead time; e.g., intra- and inter-component interactions (aerosols in 3D interface; atmospheric columns shading each other at high resolution; coupling ocean and sea ice as “fast” process; lateral water movement at and below the land surface). All have a bearing on R2O and O2R (support). In addition to prioritizing the scientific agenda, the following are example critical-path projects that are needed to establish the SA in conformance with the principles articulated above.

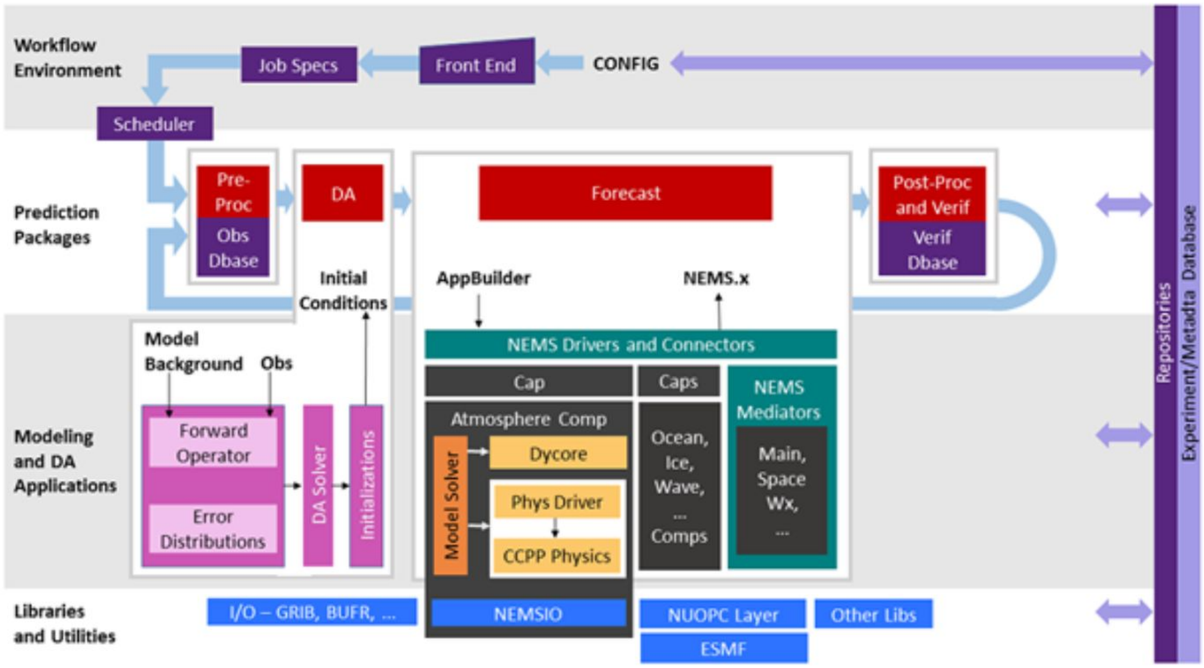

Figure 1. Diagram showing the four main layers in the unified modeling system architecture: Libraries and Utilities, Modeling and Data Assimilation Applications, Prediction Packages, and Workflow Environment. Purple boxes indicate parts of the Workflow Environment and databases, with thick light blue lines indicating sequence. Red boxes indicate executables while the thin lines around them represent scripts that invoke the executables. Teal boxes show NEMS infrastructure. Black boxes represent science components, caps, and mediator components. Orange boxes show subcomponents of the atmosphere model component. Pink boxes show parts of the data assimilation system. Blue boxes show utilities and libraries. The Prediction Package sequence shown is typical; it may change for different applications.

<u>Project 2.1:</u> Support for Coupling Infrastructure and Component Integration

Many of the projects in the SIP require coupling infrastructure and expertise. The NGGPS global model suites in development (Annex 1) use ESMF and the NUOPC Layer, which are well-established community software packages for building and coupling models. Other SIP projects, such as coupling of upper atmosphere to ionosphere (Annex 4), have also developed coupled systems using ESMF and the NUOPC Layer. These packages offer advanced features that are not available in other U.S. frameworks, including general grid representation and parallel remapping (2D and 3D), run-time sequencing of components, extensive documentation, and a large user base that includes federal centers and data/viz products like NCL and UV-CDAT. The ESRL/GSD NESII team coordinates the development and distribution of ESMF and the NUOPC Layer.

Development of the UFS creates demand for integration of new model components, the need to transfer component code with minimal code changes among GFDL, NCAR, EMC, NASA, and Navy centers, requests to add new features (such as specific output formats), requests for coupled system optimization, and requests for user support. This demand creates work for the NESII development and support team in three areas, defined here as three subprojects: 1) base support (routine questions, features, release preparation, installation, etc.), 2) development of a shared NUOPC-based mediator that can support the scientifically different CESM and GFDL coupling strategies, and 3) component integration projects.

Project 2.1a: Base support for ESMF and the NUOPC Layer

Project overview: ESMF and the NUOPC Layer are mature, portable, high-performance software packages. Although major development is complete, the continued viability of the software requires adding new feature requests, porting to new platforms, adapting to emerging computing architectures and new scientific directions, addressing user requests, running a training program, preparing releases, and offering extensive documentation. Base support for ESMF and the NUOPC Layer has been provided through contributions from multiple agencies, including NOAA.

Major Risks and Issues:

- Demand for ESMF and NUOPC Layer expertise for projects 1b and 1c directs resources away from basic development team activities like porting, testing, adding features, and releasing software. At the same time time it creates additional demands for these core functions.

Major resources requirements:

- Personnel:
  - NCAR/ESMF: 2 FTEs (There are in-kind contributions from NASA and Navy to make a standing core team of about 6)
- HPC for development:

Dependencies/linkages with other projects:

- NGGPS and other Annex projects that require coupling, see Project 1c.

Core development partners and their roles:

- NCAR/ESMF: Leads development of the ESMF/NUOPC software.
- GSD/NESII: Participates in ESMF development, coordinates NOAA requirements.
- NCEP/EMC: Communicates requirements; uses and tests the ESMF/NUOPC software.
- GFDL: Communicates requirements.
- NRL: Communicates requirements; uses and tests the ESMF/NUOPC software.

- NASA: Communicates requirements; uses and tests the ESMF software.
- DOE: Provides finite element mesh frameworks used in ESMF; uses the ESMF regridding software; ANL DOE partner in ESMF optimization project.

Major Milestones:

- Q1FY18: Delivery of the ESMF/NUOPC v7.1.0 release - includes cubed sphere grid creation shortcuts, higher order conservative interpolation method, memory and performance optimizations. (Completed Q2FY18)
- Q4FY19: Delivery of the ESMF/NUOPC v8.0.0 release, following the priorities set by the ESMF Change Review Board. Release contents and schedule: https://www.earthsystemcog.org/projects/esmf/schedule_1802

Project 2.1a Base support for ESMF and the NUOPC Layer

Base Support for ESMF and the NUOPC Layer							
Timeline	FY18		FY19				FY20
	Q3	Q4	Q1	Q2	Q3	Q4	Q1
ESMF/NUOPC v8.0.0 release							

Project 2.1b: **Community Mediator Development**

Project overview: This project will extend the capabilities of the NEMS mediator and transition it to a community-supported component within the CIME (Common Infrastructure for Modeling Earth) repository. The community mediator is being implemented in partnership with NCAR, GFDL, EMC, ESMF/NUOPC, and others, with the goal of developing a highly flexible tool that can support both CESM and GFDL coupling strategies. An early step, in progress, is to confirm that the GFDL scientific coupling strategy can be replicated using ESMF/NUOPC. This includes the exchange grid approach to conservative interpolation and implicit coupling. NEMS currently implements a CESM approach to coupling, with no exchange grid and all explicit interactions. In addition to promoting more direct technology transfers from research to operational centers, the community mediator will enable controlled experimentation with different coupling science techniques.

Major Risks and Issues:

- Coordination and communication among working groups.
- Minimal disruption and expended effort during any replacement of NEMS mediator is a requirement. Replication of previous results is desired.

Major resources requirements:

- Personnel:
    - NCEP/EMC: .5 FTE
    - GFDL: 1 FTE
    - NCAR: 1 FTE
    - GSD/NESII: 1 FTE
- HPC for development:

Dependencies/linkages with other projects:

- FV3-Global Forecast System - the FV3-GFS uses ESMF/NUOPC infrastructure to implement asynchronous write components. The implementation of ESMF/NUOPC for this FV3-GFS standalone use should be compatible with the implementation of the NUOPC cap set up for coupled interactions.
- FV3-Global Ensemble Forecast System - the FV3-GEFS is a customer for the community mediator.
- FV3-Seasonal Forecast System - the FV3-SFS is a customer for the community mediator.
- Other coupling efforts shown in the table in 1c may be customers for the community mediator. The NESII team is developing regional nested coupled models for Navy using NUOPC, and it may be possible to define a regional/nest community coupling approach.

Core development partners and their roles:

- NCEP/EMC: Integration and testing of the community mediator in the NEMS environment; communication of EMC requirements; contributions to design and implementation.
- GSD/NESII: Development of the underlying ESMF/NUOPC framework; partner in design and implementation of the community mediator.
- NCAR: Partner in design and implementation of the community mediator; communication of NCAR requirements; integration and testing of the community mediator in the CIME environment; development and support of CIME.
- GFDL: Partner in design and implementation of the community mediator; communication of GFDL requirements; integration and testing of the community mediator in the GFDL environment.

Major Milestones:

- Q4FY17: Couple CIME data components with the community mediator. (Completed Q4FY17)
- Q2FY18: Run the community mediator with all active CESM components. (Completed Q3FY18)

- Q3FY18: Develop and document a governance strategy for the community mediator. (Completed Q3FY18)
- Q4FY18: Demonstrate that ESMF/NUOPC Layer can replicate key GFDL coupling functions, including the exchange grid and associated data structures.
- Q4FY18: Demonstrate that the community mediator can replicate all NEMS coupling functions, and replace the NEMS mediator with the community mediator, updating mediator documentation.
- Q2FY19: CMEPS design plan for supporting multiple coupling science options. (HSUP 1A-3)
- Q2FY19: Validate GFDL coupled configuration with all active components using ESMF/NUOPC infrastructure and GFDL scientific coupling strategy against GFDL native configuration. (HSUP 1A-3)
- Q3FY19: Produce updated CMEPS User's Guide. (HSUP 1A-3)

Project 2.1b Community Mediator Development

Community Mediator Development										
Timeline	FY18		FY19				FY20			
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Replicate GFDL coupling functions with ESMF/NUOPC										
Replicate NEMS coupling functions with CMEPS										
CMEPS design plan for multiple coupling science options.										
Validate GFDL all active coupled configuration using ESMF/NUOPC										
Produce updated CMEPS User's Guide.										

Project 2.1c: Support for FV3GFS Coupling Projects

Project overview: There are multiple projects defined by other working groups which will integrate the FV3GFS with additional components within the NEMS framework. Developing these coupled applications to conform to a unified modeling system architecture will require ongoing coordination across working groups, evaluation of the system architecture, and refinements to the architecture. This project introduces practices which help to ensure that near- and mid-term decisions made by working groups that relate to the system architecture are open, informed, and evidence-based. This activity will require coordination with the governance working group.

Major Risks and Issues:

- Coordination among working groups.
- Open and informed planning and decision making.
- Closer coupling of ice and ocean model components is anticipated in the next five years, and may require merging these components.

Major resources requirements *and* **Dependencies/linkages with other projects**

GSD/NESII (or equiv. expertise) coupling infrastructure team:

NESII FTE	***Annex and Project***	***Task***
.5 FTE	Annex 1, P1	FV3-Global Forecast System - Participation in design and implementation of the asynchronous write component, starting to include aspects of post-processing.
.5 FTE	Annex 1, P2 and P3 Annex 8, 2b	FV3 Global Ensemble Forecast System and FV3-Seasonal Forecast System - assistance with integration of FV3-GFS, MOM6, CICE5 and later WAVEWATCH-III, and GOCART, assistance with specialized initialization and run sequences.
.2 FTE	Annex 4, P1 and Annex 7, P1	Design participation in development of the FV3-Regional standalone system. Annex 7, P1 (CAM) not sure of connection; looks like it requested NESII input.
.2 FTE	Annex 4, P2 and P3 Annex 8, P1 Annex 2, P2	Annex 4, P2 and P3 and Annex 8, P1: Design participation in FV3-based regional forecast systems with moving nests. Nesting and coupling demonstrated in NEMS with previous atmosphere but design may need to change for new atmosphere.

1 FTE	Annex 4, P4 Annex 2, P3	3D coupling of upper atmosphere with IPE ionosphere model. Demonstration of one way 3D coupling in NEMS with previous atmosphere is scheduled to transition to operations. Working on two-way coupling and generalization of space weather mediator for FV3-GFS. Contributions to coordination and analysis as well as infrastructure.
.2 FTE (ongoing)	Annex 5, P3, Annex 9, P5	Coordination with the physics team, on chemistry, land, and radiation components that may use concurrency/remapping.
.1 FTE (ongoing)	Annex 6, P1	Help using and optimizing ESMF grid remapping in the JEDI unified forward operator - demonstrated desired remapping. Prototyping of interaction between ESMF/NUOPC and JEDI at the model interface and driver level.
0 FTE	Annex 8, P2c	Ongoing support for FV3-GFS and WAVEWATCH-III coupling, currently focused on memory optimization.
.2 FTE (ongoing)	Annex 8, P3 and Annex 9, P5	Integrated water modeling - a demonstration of separate LIS land and WRF-hydro hydrology components with coupled atmosphere-ocean was completed, and next steps need to be determined. This is linked to questions of disposition of the land model. This also include support for Coastal Act coupling of ADCIRC and WAVEWATCH-III.
.5 FTE	Annex 10, P1	Integration of unified GOCART chemistry component with FV3-GFS is completed, now working on CMAQ chemistry component.

HPC for development:

Core development partners and their roles:

- NCAR/ESMF: Leads development of the ESMF/NUOPC software, assists with integration of components within the NEMS framework; expertise in community support.
- NCEP/EMC: Integration of components within the NEMS framework; communication of requirements.
- GFDL: Expertise in the science of component coupling; coupling of FV3 with MOM5/6 and ice.

- GSD/NESII: Partner in development of coupled systems within NEMS, including integration of CICE5, MOM5, and WAVEWATCH; expertise in ESMF/NUOPC and the NEMS mediator.

Major Milestones:

- 2QFY19 - Form project teams that include coupling infrastructure, workflow, and other relevant technical expertise with the Dynamics and Nesting, Land, DA, and other working groups as needed.
- 2QFY19 - In conjunction with the UFS Steering Committee, define design and implementation review processes for conformance with the UFS architecture.
- Major milestones involving coupled system infrastructure as defined by science working groups and the UFS Steering Committee.

Project 2.1c: Support for FV3-GFS Coupling Projects

Support for FV3GFS Coupling Projects												
Timeline	FY19				FY20				FY21			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Form project teams with other SIP WGs including Dynamics and Land												
Define review processes for conformance with the UFS system architecture												
Coupling support for UFS applications as required by SIP WG plans												

Project 2.1d: Update and Optimize Component Model Interfaces

Project overview: NUOPC caps are software that interfaces component models with the coupling infrastructure. The aim is to have one cap for each model component for use across organizations (i.e. one HYCOM cap). In the UFS, the NUOPC caps have evolved independently and quickly as capabilities and interfaces were rapidly added to components, sometimes by multiple centers. The design of the caps is inconsistent, and in some cases *ad hoc* and insufficiently documented. In particular, the FV3GFS cap has evolved quickly and has inefficiencies in its design, including unnecessary copies, and does not have a consistent approach to verbosity. An additional challenge is that the caps likely will need to interface with data assimilation software.

The design of the caps will become more critical as the UFS evolves, and continues adding complexity. This task is to focus on optimization and documentation of caps in UFS, especially those associated with additional capabilities or optimizations that are needed for hurricane prediction. The outcome will be direct, short-term improvements in performance and behavior of the UFS.

Major Risks and Issues:

- Coordination and communication among working groups, including DA and physics.
- Minimal disruption to ongoing UFS efforts is a requirement.

Major resources requirements:

- Personnel:
    - GFDL: .2 FTE
    - GSD/NESII: .4 FTE
- HPC for development:

Dependencies/linkages with other projects:

- Data Assimilation Working Group and the JEDI project, for ensuring smooth transition and optimized performance between JEDI and ESMF/NUOPC component interfaces, especially as coupled DA evolves.
- CCPP and related infrastructure, for ensuring that there is a smooth transition between physics interfaces and ESMF/NUOPC interfaces for components that may choose to use both/either, such as land, chemistry, and radiation.

Core development partners and their roles:

- NCEP/EMC: Integration and testing of changes in the NEMS environment; communication of EMC requirements; contributions to design and implementation.
- GSD/NESII: Development of the underlying ESMF/NUOPC framework; partner in design and implementation of the community mediator.
- GSD/NCAR/GMTB: Development of CCPP and associated infrastructure.
- NCAR: Partner in design and implementation of the community mediator; communication of NCAR requirements; integration and testing of the community mediator in the CIME environment; development and support of CIME.
- GFDL: Partner in design and implementation of the community mediator and FMS infrastructure; communication of GFDL requirements; integration and testing in the GFDL environment.

Major Milestones:

- Q1FY19: Coordinated cap and driver design plan with DA/JEDI and ESMF/NUOPC.

- Q4FY19: Updates to FV3GFS, ocean, and wave caps for hurricane modeling needs and for improved design (e.g. fewer data copies, consistent approach to verbosity).
- Q2FY20: Coupled DA/JEDI prototype demonstrating coordinated caps and drivers.
- Q3FY20: Optimized FV3GFS and other caps for v0.1 tests of HAFS.

Project 2.1d Update and Optimize Component Model Interfaces

Update and Optimize Component Model Interfaces										
Timeline	FY18		FY19				FY20			
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Coordinated design plan with DA/JEDI and ESMF/NUOPC										
Coupled prototype with DA/JEDI and ESMF/NUOPC interaction										
Updates to FV3GFS and other caps for HAFS and better design										
Optimized FV3GFS and other caps for v0.1 tests of HAFS										

Project 2.2: **Advance Model Coupling Infrastructure for HAFS**

Project overview: One of the more challenging unified modeling system architectural issues relates to nesting. Multiple moving nests in a single component require specialized and efficient infrastructure. The requirements on the infrastructure become more complex when that component is coupled to others, which may also be nested. There are up-front considerations that include the treatment of boundary values, capabilities of the grid remapping package and the component representation, the interaction of nests with land, ocean, wave, and potentially hydrologic components, and considerations of using one primary or multiple frameworks. This project entails engaging with the dynamics and nesting group to understand architectural implications of these issues, and to assess alternatives with subject matter experts.

Major Risks and Issues:

- Coordination among working groups
- Open and informed planning and decision making.

Major resources requirements:

- Personnel: See table in 1c.
- HPC for development:

Dependencies/linkages with other projects:

- FV3 static and moving nesting projects, including Moving Nests for FV3 (EMC Approach, includes development of DA and coupling to ocean/waves for hurricanes) (FY17/18-20)

Core development partners and their roles:

- AOML
- GFDL
- EMC
- GSD/NESII

Major Milestones:

- Q4FY19: FV3GFS static nest coupled to ocean (HYCOM or MOM6) and wave.
- Q3FY20: Performance analysis and optimizations to coupling as needed for v0.1 tests of HAFS.
- Q4FY20: Changes needed for Hurricane Supplemental applications integrated into a common CMEPS code base, with updated CMEPS User's Guide.

Project 2.2 Advance Model Coupling Infrastructure for HAFS

Advance Model Coupling Infrastructure for HAFS										
Timeline	FY18		FY19				FY20			
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
FV3GFS static nest coupled to ocean and wave										
Optimizations to coupling as needed for v0.1 tests of HAFS										
Changes for HAFS in CMEPS, with updated User's Guide										

Project 2.3: System Architecture Design and Metrics for the Graduate Student Test

Project overview: The Graduate Student Test (GST) defines the requirements for enabling capable graduate students studying meteorology, physical oceanography, land surface hydrology or climate dynamics to conduct research with operational codes held in common publicly accessible repositories. Separate GSTs may be needed for different applications, including the FV3-GFS, S2S, regional stand-alone and others. The GST includes steps for obtaining, being trained on, running, changing, testing, evaluating, and transitioning code. A scenario for how researchers outside NOAA might take up community codes to do original research such that it could undergo a transition to operations was also developed. This task is to create and assess metrics of the Graduate Student Test relevant to the UFS system architecture. Ongoing evaluation of the strategies for engaging graduate students will be used to evolve and refine the tasks.

Major Milestones:

- Q1FY19: Assess delivery of FV3GFS-MOM6-CICE5-CMEPS based on GST metrics.

Project 2.3a: Training

Project overview: Develop a course or mini-curriculum, possibly online, on how to use the codes and workflows associated with the ESMF/NUOPC/CIME/CMEPS suite.

Major Risks and Issues:

- Coordination among working groups
- Open and informed planning and decision making.

Major resources requirements:

- Personnel: TBD
- HPC for development: Minimal

Dependencies/linkages with other projects:

- Must be tightly coordinated with Infrastructure WG efforts to define workflows for various applications.

Core development partners and their roles:

- COLA/GMU

Major Milestones:

- Q2FY19: Develop syllabus of course.
- Q3FY19: Develop curriculum materials.
- Q1FY20: Online course up and running.

Project 2.3a Graduate Student Test: Training

Graduate Student Test: Training								
Timeline	FY19				FY20			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Develop syllabus of course.								
Develop curriculum materials.								
Online course up and running.								

Project 2.3b: Experience

Project overview: Exercise the various steps of the Graduate Student Test by engaging at least two students: a first-year graduate student and an advanced student. The milestones previous identified are listed below. For each milestone, the metrics include: (a) time to solution; (b) number of contacts needed to reach that milestone; and (c) a qualitative ease-of-attainment assessment.

1. *Get code*. Easily identify which code to get and which options are available. Access code on systems available to the public.

2. *Run code*. Easily obtain workflow (script) for given experimental setup, possibly including ensembles. Understand and access setups with active and passive (data) components and cold-start or DA-cycling runs.

3. *Change code*. Either parameterizations, components (models), or coupling strategies.

4. *Test code*. Have access to both standard unit/system tests and functional tests. Easily obtain test data sets.

5. *Evaluate code*. Easily obtain and use standard diagnostics of general behavior and individual processes.

Major Risks and Issues:

- Coordination among working groups
- Timing of public release and operational implementation
- Usage of pre-release (beta) codes by graduate students - potential for forking code and limiting value of development (e.g. unsuitable for transition to operations)

Major resources requirements:

- Personnel: TBD

- HPC for development: Substantial HPC resources, likely outside NOAA will have to be identified

Dependencies/linkages with other projects:

- Availability of HPC resources at facilities accessible to graduate students (possibly non-US)
- Availability of running code on relevant HPC platforms - may have to explore containerization or other form of deployment on non-NOAA systems

Core development partners and their roles:

- NCAR
- COLA/GMU
- University student participants.

Major Milestones:

- Q3FY19: Graduate students obtain credentials on repository and demonstrate facility in checking out code.
- Q3FY19: Graduate students run experiment with standard code.
- Q3FY19: Graduate students demonstrate capability to change the code and evaluate its effect and performance using both standard test harness assessment and customized evaluation methods.

Project 2.3b Graduate Student Test: Experience

Graduate Student Test: Experience								
Timeline	FY19				FY20			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Graduate students obtain credentials on repository and demonstrate facility in checking out code.								
Graduate students run experiment with standard code.								
Graduate students demonstrate capability to change the code and evaluate its effect and performance using both standard test harness assessment and customized evaluation methods.								

Project 2.3c: Transition

Project overview: Develop a clear technical pathway for transition from research to operations, accounting for evolving nature of public release and operational codes. Requires input from the UFS Steering Committee.

Major Risks and Issues:

- Coordination among working groups
- Policy for transition from research to operations - rules of engagement, responsible parties.

Major resources requirements:

- Personnel: TBD
- HPC for development:

Dependencies/linkages with other projects:

- Steering committee

Core development partners and their roles:

- EMC

Major Milestones:

- Q1FY19: Participation of members of the system architecture group in the development of a document describing the R2O transition.

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[1] See for example IEEE/ISO/IEC 42010-2011.

[2] The system architecture should be distinguished from the *software infrastructure*. The software infrastructure is a set of technical building blocks that represent a wide range of implementation options. The system architecture defines what choices are made and what is built; the software infrastructure is a set of tools for building it.

<u>Annex 3</u>: Infrastructure

The Unified Forecast System (UFS) Infrastructures group has purview over three different projects areas. Because these projects are unique, it was decided to disband the original NGGPS working group and create individual sub-groups dealing with Repositories, Data Portal, and Community Workflow. The only currently active sub-group is Repositories. The Community Workflow has been transitioned to the Software Architecture Working Group who has created a cross Annex focus group encompassing individuals from the Repository sub-group to address this issue. In Figure 1, the task plan for Infrastructure group is shown with a concurrent, three-pronged approach to attack the focus areas.

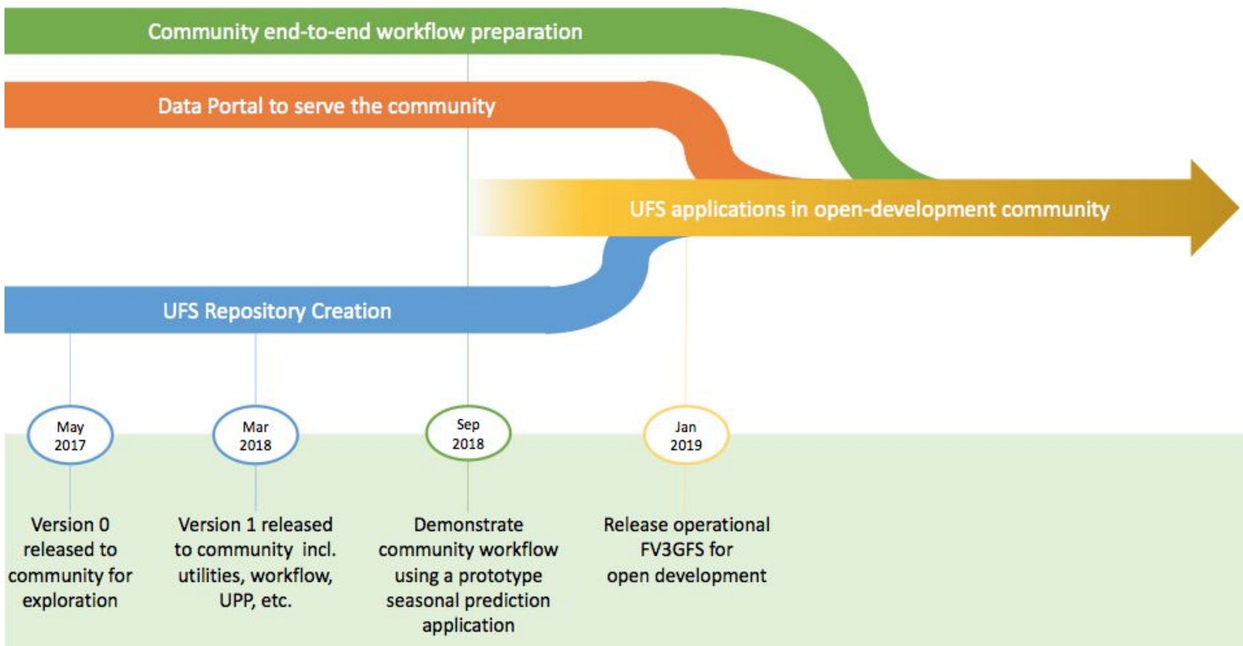

Figure 1: Three-pronged progression to open-development

Figure 2 is taken from a document in development to define research to operations (R2O). To quote a relevant section of the explanation:

> *"The segment at the top of the figure, labeled AB, is the primary realm of the UFS governance. The point A is at the interface with the community. The point B is at the handoff of an evaluated candidate for operations for transition into the operational protocol of NCEP Central Operations (NCO). At this handoff, the procedures of Environmental Equivalence 2 (EE2) Consolidated Document are applicable. The UFS governance has negotiated and informed interfaces at A and B; the UFS governance has influence at these interfaces."*

Based on the quoted section, the charter of the UFS Steering Committee and ensuing governances ends with the onset of transition to operation. Therefore the Repositories and Community Workflow processes apply only to the realm to the left of endpoint B.

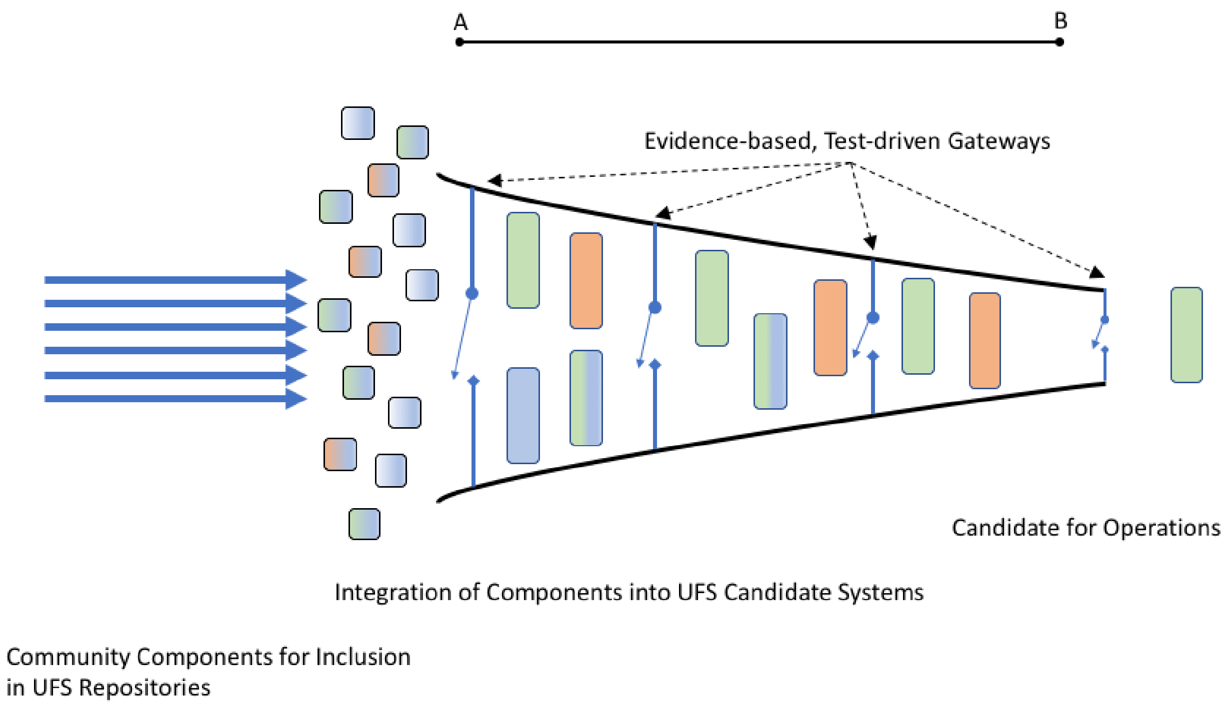

Figure 2: Development lifecycle

Although beyond the scope of this document, it is important to understand the relationship between NCO and community-available versions of operational UFS applications. Once a candidate for operations has been determined, NCO will acquire the complete source code for the specific application into a single repository on a dedicated repository server behind the firewall at NCEP/EMC. While it is understood that NCO engineers will need to make changes as the transition progresses, this does not mean the operational version will diverge from that available to the community. It will be the responsibility of the team leading the transition to ensure operational sources maintained within the NCO internal repository remain synchronized with those accessible by the community. The anticipated changes are to enhance performance, improve error handling, introduce/fix machine specific constructs, and increase readability.

Project 3.1: Repository Management

Project Overview: The Unified Forecast System (UFS) is a community-based, coupled comprehensive Earth system modeling system to support NOAA's operational numerical weather prediction system. The UFS is not a single application with support for hourly to seasonal timeframes, but instead is a collection of source systems used in building targeted applications for specific purposes. To be successful, the UFS must employ a common modeling architecture and associated infrastructure. In this context, infrastructure consists of three major areas: repository management, workflow, and open access to a data portal. The goal of this document is not to define the suite of applications that will exist within the UFS, but to lay out a strategy for managing community development within an application.

Defining a comprehensive, community-friendly repository strategy for the UFS, which also satisfies operational constraints, is a complex problem. The approach here is to define the elements of the strategy - repository types, locations, and key interaction processes - and use this defined terminology to describe a set of use cases (including actors and events).

The key principles are:

- Clearly define and communicate the UFS repository structure and practices
- Utilize open repositories to maintain transparency
- Facilitate collaboration between the community and different agencies
- Be flexible enough to support implementation of agency mission deliverables while allowing community contributors to focus on their goals
- Restrict development for each constituent component of the UFS to its own repository

Repository Management Strategy Overview

The proposed UFS repository management strategy places each UFS application (Seasonal Prediction, S2S, Weather Forecast, Regional, etc.) in a unique UFS umbrella repository. An umbrella repository contains no source code, but is comprised of configuration files. One configuration file will contain URL links to specific versions of model component code from external authoritative repositories. It is the combination of model component code that forms the application.

An authoritative repository is defined by the presence of a governance group and processes that indicate how changes are evaluated and incorporated, and when and how new reference versions are prepared for distribution. The use of authoritative repositories is central to the umbrella repository strategy, and must satisfy a baseline set of criteria:

A. The governance group is willing to participate in community development
B. The code management policies and processes are well documented
C. The regression testing procedures are well defined

The component code and the umbrella repository will exist in authoritative repositories. The authoritative repositories are typically associated with the original development teams, and are where code development and collaboration occur. Any specific code should lie in only one authoritative repository structure, and can be accessed by multiple UFS applications. Governance of component repositories will be a combination of the conditions and procedures defined by the UFS and the native governance of the authoritative repository.

Each UFS application will have its own umbrella repository with a designated “gatekeeper”. The gatekeeper is not responsible for the science, but is to ensure certain branches within the umbrella repository links to the appropriate versions of component authoritative repositories. A unique umbrella repository per application is necessary as different applications have different timelines for development and transition to operations. This also allows development groups working on different aspects of coupled modeling (weather scales, sub-seasonal, etc.) to work concurrently and independently (with some coordination).

Repository Governance

The National Earth System Prediction Capability (ESPC) Model Component Liaison committee is developing a set of guidelines for authoritative repositories. The Infrastructure Repositories sub-group has adopted these guidelines and added additional rules for authoritative repositories hosting UFS components. The rules are broken down into different categories which are summarized below.

General repository practices:

- An authoritative central repository for the model component exists.
- The repository uses a code versioning and management system, typically git or SVN.
- A governing or management body that sets and enforces policies for the repository exists.
- There are clear terms of use and there is a way for credentialed users to request access.
- Reference versions which incorporate selected code changes are delivered at semi-regular intervals (generally less than two years).
  - Each reference version has a unique ID (e.g. tag, revision number).
  - Incremental changes made to the code between reference versions are documented.Outdated and/or unsupported versions of the code are documented.
- The NUOPC cap for the component resides in the same authoritative repository as the model component code.

In addition, the following apply to “community” component models:

- Source code is either fully open or available through a registration process that takes less than a day.
- Policies are publicly documented, including:
  - A procedure for receiving, evaluating, reviewing and incorporating code changes.
  - A process for creating new branches/forks for development or implementation.
  - A process for making policy changes.
- Documentation related to the code is public.
- A support contact or mechanism (e.g. forum) for the code with some backup is provided - i.e., not a personal email.
- An issue tracking mechanism is provided.
- Initial response times for support and issue tracking are generally less than a week, though resolution may be longer.

UFS repositories:

- There is a well-defined, regression testing strategy, where applicable.

The rules listed above can be used as a cookbook for fostering new projects which may emerge as the UFS application space expands.

Repository Types and Locations

The UFS repository strategy has two repository types:

- Umbrella repository
- Component repository

Each component repository contains the source code for a unique component of the UFS application and, where applicable, the NUOPC cap. The umbrella repository contains the policies, documentation, and configurations required to link to the individual component repositories which, when brought together, define a give UFS application.

<u>Umbrella Repository</u>

An umbrella repository is essential to the UFS repository strategy, and defines a unique UFS application. The umbrella repository must contain, at a minimum:

- Documentation for the application
- Configurations to obtain the required component repositories
- Policies and processes

Each umbrella repository will have a governance body to be established as UFS applications are identified and created. The goals of the governance body are to define the policies and procedures. The governance body will appoint gatekeepers to assist in the repository maintenance and enforcement of the policies. Included in the policies will be the branch structure and workflow. At a minimum, the branch structure should include:

- Main branch -- Collection of approved changes from the community and operations
- Development branch(es) -- Contain features in development or requested to be included in the main branch
- Operational branch(es) -- Contain the current configuration and code used in operations
- Implementation branch(es) -- Contain features currently in testing for future operational releases. Once approved, updates will be merged into an operational branch

The main and operational branch will reside within the authoritative umbrella repository. Development and implementation branches may reside in separate forks. The gatekeeper, following the repository policies, will work with the developers to incorporate the changes back into the authoritative umbrella repository. Some development and implementation branches may reside within the authoritative umbrella repository to help facilitate collaboration and testing.

<u>Component Repository</u>

The component repository is where component code (model, library, utilities etc) resides. It should also contain documentation, regression test procedures and the NUOPC cap, where applicable. The component repository must also have a governance body that decides and implements the repository policies. The component repository governance body must also be willing to participate in community development, and work within the UFS repository policies and guidance.

While the branches structure of the component repository are defined by the component repository governance body, it is suggested the component repository use a similar branch scheme as the umbrella repository.

Prototyping the UFS Applications
The current UFS Applications are housed in a limited-access, repository server (VLab) at NCEP/EMC. A presentation to the UFS Steering Committee resulted in a recommendation for the Repositories Sub-Group to prototype two UFS applications - the UFS Weather Forecast Application and the UFS Seasonal Prediction Application. Once the issues with the prototypes have been ironed out, the applications can be pushed to an open-development site, such as GitHub.

The prototyping process accounts only for the initial components comprising a specific UFS application. As the applications evolve and further components are incorporated, they will be added to the umbrella repository (e.g. chemistry and aerosols, land, radiation, etc.)

UFS Weather Forecast Application (NEMSfv3gfs)
The current NEMSfv3gfs git repository contains a regression workflow system, the NEMS mediator source code referenced as a sub-module, and the FV3GFS source code referenced via a second sub-module. The prototype envisioned by the Infrastructure Repositories Sub-Group would first take the FV3GFS source code and

- Reference existing authoritative repositories for model components
- Separate currently non-managed model components into authoritative repositories placed in an open-development revision control platform such as GitHub

The list of authoritative repositories for model source code would be (* denotes existing authoritative repository):

NEMS*
FMS infrastructure*
FV3 dynamical core
Interoperable Physics Driver (IPD)
GFS physics
Stochastic physics
FV3GFS atmospheric driver system (incl. NUOPC cap, write component, etc.)
NCEPlibs*

Once source code repositories are completed, the next step is to create a repository for an interim workflow. It is understood that a community workflow may not be ready when the FV3GFS system goes operational in Q1CY19 and the first open-development release of the FV3GFS system will need to rely upon the workflow system released with the beta version 1 in March 2018. A decision would need to be made at this point as to whether the build system and pre-processing toolsets should be separated from the execution workflow when creating repositories.

With the authoritative repositories in place for the model source, application libraries, toolsets, and build system and workflow, the FV3GFS umbrella repository can be created to contain:

manage_externals toolset
configuration files

- to update *manage_externals* to latest version, if needed
- for *manage_externals* to clone/download the above-listed repositories via unique identifiers
- input to the build system for creating an executable for a specific compiler
- tells the workflow to access a data portal and download ICs
- defines an experiment configuration for use by the workflow

UFS Seasonal Prediction Application

The UFS Seasonal Prediction App is an extension of the UFS Weather Forecast App with coupling to an ocean, ice, and wave model. Starting from the UFS Weather Forecast App:

NEMS*
FMS infrastructure*
FV3 dynamical core
Interoperable Physics Driver (IPD)
GFS physics
Stochastic physics
FV3GFS atmospheric driver system (incl. NUOPC cap, write component, etc.)
NCEPlibs*

one would need the following additional existing authoritative repositories:

MOM6
CICE5
WaveWatch III

This prototype will differ from the UFS Weather Forecast app in a few significant areas. The NEMS mediator may be replaced with the Community Mediator for Earth Prediction Systems (CMEPS). It is also the ideal vehicle for establishing a community workflow.

Major Milestones: EMC management has committed to prototyping UFS Weather Forecast App in preparation for the operational release in Q1CY19. The timelines for prototyping should be as follows:

- Migration Plan for Weather Forecast and Seasonal Prediction Umbrella repository by August 2018 to address:
    - creation of different authoritative repositories

    - existing repositories to be moved to an open-development repository server
    - plans for components with multiple repositories which need to be merged into single authoritative repos
    - governance bodies for newly created repositories
    - transition plans for projects/applications under development utilizing a repository slated for re-location
- All repositories for Weather Forecast application created by September 2018
- Configuration file for manage_externals specific to the weather application by September 2018
- Inputs for build system for Weather Forecast application by October 2018
- Experiment configuration files for Weather Forecast application by December 2018
- Push Weather Forecast application to open-development site coincident with transition to full operational status

The UFS Seasonal Prediction App will add the following milestones:
- Seasonal Prediction application plans should take into account the common components with weather and adjust schedules accordingly
- Setup the coupled system to use the sea ice consortium repository by October 2018
- Exhibition of CMEPS coupling capability (replication of NEMS planned for September 2018, System Architecture Annex milestone) allows demonstration of the process by which one component is replaced by another within an umbrella repository.
- Create the open development umbrella repo with connection to atmosphere, ocean, ice and waves by January 2019

Major Resource Requirements *and* **Core Development Partners:**
Overall, we see the need for 13 FTEs to manage the interactions across the UFS repository suite. It should be emphasised that we are not identifying all these as new resources, and in many cases (e.g. MOM6, WW3) code managers have been identified as part of research and development. However, we felt the need to identify these resources here because these are job functions that are being carried out. Also note that institutional ownership is identified for roles and responsibilities to ensure that a) repository code management activities are adequately staffed and b) good governance principles as laid down in the spirit of open community development are followed. One caveat that we want to put down is that this estimate is based on what we think are areas/repositories that will have active development. It is feasible that one or more of these areas will have extensive development that the current allocated resources are not enough. Alternatively some areas may be over resourced. This resource allocation should be seen as a first estimate that may need to adjust to conditions on the ground.

UFS Weather Forecast Application
The weather application at its initial implementation will consist of the following repositories

NEMS Infrastructure -- 1 FTE (manages the coupling infrastructure across all applications including regular regression testing and porting in multiple platforms - repository management owned by EMC)

FMS Infrastructure -- 1 FTE (manages the parallelization as well as the coupling infrastructure for GFDL models. This is a resource shared across the GFDL modeling suite - repository management owned by GFDL)

FV3 Dycore -- 0.5 FTE (Seen as a relatively mature system with minimal changes in the near future. If dycore development becomes an active community interest and exercise then we will have to up the resources to a full FTE for code management across the different labs/agencies - repository management owned by EMC)

IPD Driver -- 0.5 FTE (Keeping this at 0.5 FTE for now as it still is not clear what the role of IPD will be with the evolution of CCPP. Will it have its own driver or will it use the IPD ? Will the IPD have to evolve with the CCPP ? Again if development activity becomes significant then this will be upgraded to a full FTE - repository management owned by EMC/GFDL)

Physics -- 1 FTE (This is key as collaborations across the agencies/groups/academia is expected to be driven primarily by this interaction - repository management owned by TBD)

Stochastic physics -- 1 FTE (A critical feature for ensemble development - repository management owned by ESRL)

NCEPlibs -- 1 FTE (Need resource for libraries that drive this modeling system- repository management owned by EMC)

FV3GFS driver system -- 0 FTE (This is nominally kept at 0 FTES because the person that maintains this driver system will be leveraged from the one who maintains the weather application - repository management owned by EMC)

Weather application -- 1 FTE (This is a critical resource as it ensures that all the individual repositories come together to make a weather scale operational model - repository management owned by EMC)

Total resources needed -- 7 FTEs

UFS Seasonal Prediction Application

Apart from the repositories needed for the weather application, the following repositories are needed for the seasonal application

MOM6 -- 1 FTE (coordinate development in the community ocean model - repository management owned by GFDL)

CICE -- 1 FTE (coordinate development in the community ice model - repository management owned by ice consortium. Is there an institution that this comes under?)

WW3 -- 1 FTE (coordinate development in the community wave model - repository management owned by EMC)

Seasonal Prediction app -- 1 FTE (Critical resource that ensures development in individual component repositories does not break the S2S model - repository management owned by EMC)

Total additional (over the weather application) resources needed -- 4 FTEs

UFS Chemistry Applications
FV3GFS-Chem -- 1 FTE (Weather forecast application plus GOCART aerosol package. Not clear at this point what the authoritative chemistry repository is - repository management shared between EMC/GSD)

FV3SAR-Chem -- 1 FTE (Air quality application utilizing the EPA CMAQ package - repository management shared between EMC/GSD)

EPA CB-VI/AERO-VI CMAQ -- 0 FTE (coordinate development with community in existing open-development authoritative repository)

GOCART -- FTE undetermined (there is no current open-development authoritative repository and there are various special purpose versions [GSD, GSFC, EMC, etc.] - this requires cooperation and partnerships between agencies)

Total additional (over the weather application) resources needed -- 2 FTEs

For more detailed information, please see the full report at:
https://docs.google.com/document/d/1aCGytKWK67xugHDGk3Igp92FY9jgJ_rPXAgU4xA1-bI/

<u>**Project 3.2:**</u> **Data Portal**

Project Overview: Access to the data used for retrospective evaluation is a requirement for the community to contribute. While the amount of data is unknown at this time, it is understood it will be at least the previous 3 years (4 cycles per day) and include ICs for select major events. The data is not limited to initial conditions and must include the climatological and other forcings.

Major Resource Requirements *and*
Major Risks and Issues: The Data Portal is unique in that it requires capital expenditures in hardware and manpower to achieve success. The best approach is for this to be addressed by the NOAA/NCAR MOA.

<u>Project 3.3:</u> **Community Workflow**

Project Overview: Ideally, the UFS workflow would have a number of key features: 1) satisfy operational requirements; 2) enable the research community to run and reconfigure the various UFS applications easily; and 3) share code as much as possible across applications. The Community Research and Operations Workflow (CROW) was initiated in FY17 to address these goals, but so far has focused on the operational aspects of the workflow. There is an effort in the Hurricane Supplemental to improve usability, portability, and hierarchical testing capabilities of the operational workflow by integrating elements of the Community Infrastructure for Modeling the Earth (CIME) tools used with NCAR and DOE models into the evolving CROW toolchain. The initial focus will be on the UFS Seasonal Prediction application and the Hurricane Advanced Forecast System (HAFS) that is currently being planned. First milestones include only the prognostic model; data assimilation, postprocessing, and other parts of the workflow will be addressed later.

Specific requirements are to ensure that “research-oriented aspects of the system should be usable in non-NCEP environments” and to ensure cross-platform portability. Since HAFS and UFS-Seasonal will require active coupling of FV3GFS to separate ocean and wave components, the workflow needs to support system as well as unit testing and also include the ability to isolate feedbacks in the coupled system. Basic verification capabilities are needed as well to validate porting of HAFS forecast components between systems, both within NCEP and external to it. The tasks proposed are to integrate elements of CIME that address these needs into CROW.

Major Milestones:

- Q2FY19: Make the UFS Earth system components anticipated for use in HAFS (FV3GFS, MOM6 or HYCOM, WW3) CIME compliant and demonstrate that these components can be run using CIME compsets on NCEP and non-NCEP platforms.
- Q3FY19: Demonstrate that CROW can invoke CIME for building and running simple configurations.
- Q4FY19: Generalize CIME data components for UFS to support grid resolutions and forecast periods used in the development of the coupled HAFS.
- Q2FY20: Demonstrate that a CIME workflow including HAFS test configurations of prognostic and data components produces physically realistic output.

- Q4FY20: Integrate the CIME testing infrastructure into CROW and demonstrate that a configuration with prognostic HAFS components validates between the original CROW workflow without CIME and the new CROW workflow that invokes CIME.

Appendix: Community Component Creation and Governance

Project Overview: Many of the components that make up the UFS are not yet open-development projects within a community. As the Infrastructure Repositories sub-group worked through the various elements for the repository management strategy, it was recognized the rules for repository governance could be utilized as a blueprint for transition and/or creation of open-development projects. The rules and categories from project 3.1 are duplicated here for convenience.

General repository practices:

- An authoritative central repository for the model component exists.
- The repository uses a code versioning and management system, typically git or SVN.
- A governing or management body that sets and enforces policies for the repository exists.
- There are clear terms of use and there is a way for credentialed users to request access.
- Reference versions which incorporate selected code changes are delivered at semi-regular intervals (generally less than two years).
    - Each reference version has a unique ID (e.g. tag, revision number).
    - Incremental changes made to the code between reference versions are documented.
    - Outdated and/or unsupported versions of the code are documented.
- The NUOPC cap for the component resides in the same authoritative repository as the model component code.

In addition, the following apply to “community” component models:

- Source code is either fully open or available through a registration process that takes less than a day.
- Policies are publicly documented, including:
    - A procedure for receiving, evaluating, reviewing and incorporating code changes.
    - A process for creating new branches/forks for development or implementation.
    - A process for making policy changes.
- Documentation related to the code is public.
- A support contact or mechanism (e.g. forum) for the code with some backup is provided - i.e., not a personal email.
- An issue tracking mechanism is provided.
- Initial response times for support and issue tracking are generally less than a week, though resolution may be longer.

UFS repositories:

- There is a well-defined, regression testing strategy, where applicable.

<u>ANNEX 4</u>: DYNAMICS AND NESTING

The Dynamics and Nesting (D&N) WG is established to explore incremental steps that can be taken over the next ~2-3 years to both improve the dynamics and related nesting capabilities for the currently planned NGGPS uncoupled atmospheric weather model, as well as to build upon that to also improve shared community capabilities for coupled models on S2S time scales, thereby improving the entire span of the future unified modeling system. The D&N WG is charged with recommending pathways and strategies for development nesting techniques for incorporating high-resolution convective allowing model (CAM) applications, and hurricane forecast capabilities that include moving nests (single, multiple, and telescopic) within the FV3 global (or regional) model. Other major area of emphasis for D&N WG is on vertical extension of the global model to provide forecast capabilities for the Whole Atmosphere Model (WAM) and coupling to Ionosphere - Plasmasphere - Electrodynamics (IPE) to address the Space Weather Prediction capabilities. It is expected that a combination of GFDL Flexible Modeling System (FMS) and NOAA Environmental Modeling System (NEMS) frameworks will be used to accomplish the objectives of D&N WG.

Critical dependencies identified by D&N WG are:

- Strategy for stand-alone FV3 regional development must take into consideration global-meso unification priorities along with physics and data assimilation strategies.
- Development of moving nests for FV3 is critically dependent on choice of framework, feasibility in operational settings, and computational efficiency.
- 3D physics development for space weather applications might need a separate strategy than that is pursued by Physics WG
- The current data assimilation does not support nested meshes, which needs to be accounted for in the JEDI development.
- Access to the model and model documentation/training needs to be easy in order to enable the community to participate. In addition, funding needs to be available to allow for community participation.
- Code (and configuration) management, governance, and decision making process need to be transparent.

<u>Project 4.1: Stand-Alone Regional FV3 and Static High-Resolution Nests for Global FV3</u>

As the NWS transitions to an FV3-based Unified Forecast System, the best method(s) must be found to replace the current operational models' generation of high resolution guidance. The ability to use a single enhanced resolution nest on a face of the global cube already exists. An option to use a standalone regional domain of FV3 that can be placed anywhere on the earth has now been added. The first version of this regional capability has been completed while further development continues. Side-by-side runs of 3 km resolution regional and nest domains over the CONUS are underway to help

assess the forecast skill and computational cost of each approach. To allow more precise targeting of forecast locations and resolutions a regional domain will be given the ability to first hold one and then multiple nests of its own. Data assimilation will be crucial for optimal use of regional forecasting and that work in the regional framework is beginning. Chemical/aerosol/emissions also should be considered in the regional/nesting approach given the potential impact on FV3-Chem, FV3-GOCART, and NAQFC. Use of the gnomonic projection to create the computational grid leads to an excessive range of grid cell sizes for large regional domains. This variation will be significantly reduced by transitioning to a rotated latitude/longitude projection.
(POC: Tom Black, NCEP/EMC)

Major Risks and Issues:

- Construction of a standalone regional FV3 domain that can contain nests will involve some significant modifications and additions to both the pre-processing and to the model code, and the underlying framework(s) (FMS for construction and ESMF for coupling to external models).
- Testing is underway to determine if the skill of the regional model and that of a nest on a global parent are approximately the same given the less frequent updating of the regional domain boundaries.
- Computational efficiency is a major determining factor for identifying the optimal strategy for FV3 nests

Major resource requirements:

- EMC: 2 FTE for development; additional 2 FTE for testing
- GFDL: 0.5 FTE for development and 0.5 FTE and support
- ESRL/GSD: 2 FTE to assist with regional stand-alone development and testing
- NSSL: 2 FTE to assist with regional stand-alone development and testing

Dependencies/linkages with other projects:

- CCPP; Refactored NCEP Advanced Physics options recommended by SIP Physics Working Group
- Post (UPP) and product generation for limited area domains
- NEMS/ESMF and FMS framework advances
- CAM and Ensemble WGs who need standalone/nested FV3 for developing REFS and HRGEFS; and for hurricane model development needs

Core development partners and their roles:

- NCEP/EMC: Ongoing improvement of standalone regional FV3 structure and capability.
- GFDL: Provide guidance and assistance to NCEP in adding nests to standalone regional domains. Provide the ability to run regional forecasts on a rotated latitude/longitude grid.
- ESRL/GSD: Add capability to generate initial and BC data for regional forecasts from RAP/HRRR; produce rocoto workflow; develop NCL visualization for native output.
- NSSL: Initial testing using the regional FV3 within data assimilation frameworks to determine strengths/weaknesses for storm-scale and ensemble cycled analysis systems.

- DTC/GMTB: Physics integration and T&E

Major Milestones:

- Q2FY19: Conduct evaluation of global parent w/nests compared to regional parent w/nests or regional domains with no parent for CAM applications, and report on the findings
- Q4FY19: Ability to run multiple static nests that can lie on edges/corners of the cube (from GFDL)
- Q2FY20: Allow regional forecasts to run on a rotated latitude/longitude grid.
- Q4FY20: Transition of static high resolution setup to operations (with inputs from CAM WG, potentially as a member of HREF)

<u>Project 4.1: Stand-Alone Regional FV3 and Static High-Resolution Nests for Global FV3 (FY19-21)</u>

Development of High-Resolution FV3 Global and Stand-Alone Regional Model with Multiple Static Nests

Timeline	FY19				FY20				FY21			
Component	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Evaluation of FV3 Stand-alone Regional Model for CAM applications	Report on evaluation of global parent w/nest compared to regional parent w/nest											
Development of Multiple Static Nests	Ability to run multiple static nests that can lie on edges/corners of the cube (w/support from GFDL)											
Static high-resolution setup for CAM WG support			Advancement of static and telescopic nests in support of FV3-CAM development needs									

<u>**Project 4.2: Hurricane moving nests**</u>

Background information

The Hurricane Analysis and Forecasting System (HAFS) is NOAA's next-generation multi-scale numerical model and data assimilation package which will provide an operational analysis and forecast out to seven days, with reliable and skillful guidance on TC track and intensity (including rapid intensification), storm size, genesis, storm surge, rainfall and tornadoes associated with Tropical Cyclones within the framework of the Unified Forecast System (UFS). Central to the development of HAFS will be the FV3 dynamical core with embedded moving nest capable of tracking the inner core region of the hurricane at 1-2 km resolution.

Although FV3 is fully tested in models at cloud-resolving resolutions, when compared to the existing operating capacity for hurricane forecasting in NOAA (e.g., HWRF and HMON) FV3 currently has a very basic static nesting capability. In addition, certain aspects of its nesting capability prevent its use for hurricanes. Apart from two way interactive grid nesting, hurricane application requires storm following, telescopic nests at about 1-2 km resolution that can be located anywhere in the globe. Such requirements cannot be fulfilled by the current nesting capability of FV3, and the nature of FV3's 'cubed sphere' domain may pose a significant technical challenge to unrestricted nest movement. AOML has been working with GFDL and EMC to explore approaches to address these issues and achieve the final goal. At the end of the exploratory phase (described in the SIP document, 2017), scientists at AOML have worked with EMC and GFDL to develop a blueprint for nest motion technique (Figure 1). The Hurricane supplemental effort is expected to provide an accelerated pathway for moving nest developments for the FV3 dynamical core: In Year 1, a moving nest framework (MNF) will be developed for one face of the cube covering the Atlantic basin, followed by extensive testing and evaluations in Year 2. In parallel, during Year 2, the nest motion algorithm will be extended across all faces of the cube. The eventual goal at the end of Year 3 of the supplemental effort will be to have multiple moving nests that can be placed across the globe for TC predictions

POCs: Gopal (AOML), Avichal Mehra (EMC) and Lucas Harris (GFDL).
Core development partners and their roles:

- AOML: Will be responsible for the moving nest code developments
- GFDL: Will support the key FMS utilities (parallel infrastructure in the FV3GFS dynamics and potential changes that may be required for telescopic nests and nest motion) and FV3 functionality needed for moving nests
- GFDL and EMC: Regional Nesting Project and Development of telescopic nests
- GSD/NESII: Leveraging developments on NEMS/ESMF based coupling of other Earth System components to FV3
- GMTB/DTC: Implementing Hurricane physics into FV3 via CCPP
- GSD: Pre-processing capability to initialize FV3 from HWRF initial conditions
- AOML and EMC: Data Assimilation in regional FV3 domains
- EMC and AOML: Vortex initialization and vortex modification for FV3

Major resources requirements:

- Personnel: 4 FTEs/CI employees (AOML), 2 FTE (GFDL), 3 FTE (EMC), 1 FTE (NESII), 1 FTE (GMTB), 0.5 FTE (GSD);
- HPC for development: Dedicated NOAA HPC for this R&D effort (about 2M hrs per month)

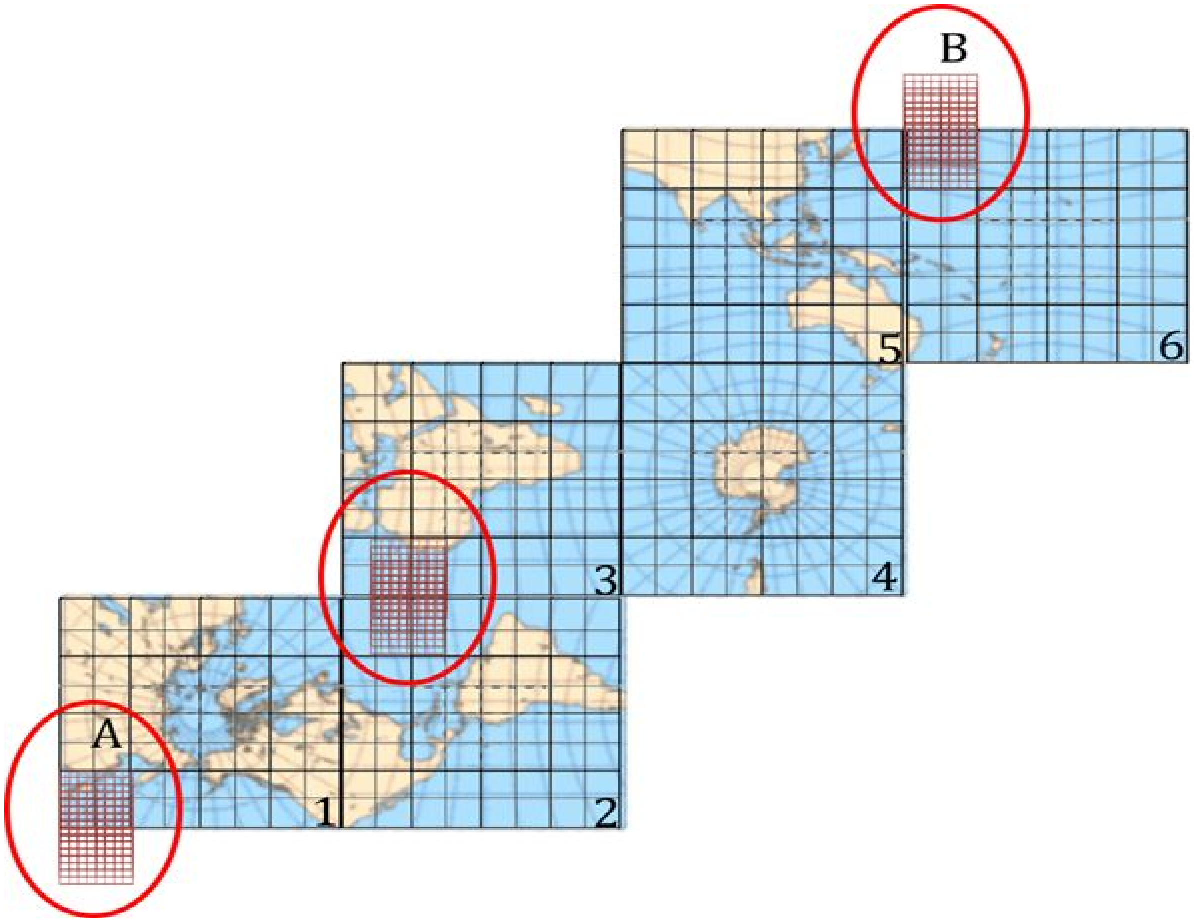

Figure 1: Cartoon from SIP presentations showing how high-resolution nests may be moved seamlessly within the 6 faces of the FV3 cube sphere grid. For example, nest in position A and B crosses the edge of face 1 and face 6. The nest will stay on one projection. The feedback and downscale at the leading edge of the moving nest will be on the interchangeable equivalent projections between face 1 and face 6 in this instance. The design will guarantee the physical equivalence in the finite volume framework on different cubic faces.

Major Risks and Issues:

- The progress of this project is dependent on availability of the hurricane supplemental funding in time (Oct 1, 2018).
- Although NOAA has the required expertise of seamlessly integrating high resolution nest in regional models, impacts of two-way interactive moving nest on global solutions is yet unknown.
- Exchange of data between parent and moving nested grids is critically dependent on the infrastructure. Since neither FMS nor NEMS utilities were originally developed with moving nest capability as an option, some significant time for building IT capacity may be required.
- Construction of moving nest in FV3 will involve some significant modifications and additions to both the pre-processing and to the model dynamics, and the underlying framework(s).

- Solving potential numerical stability issues in the FV3 dynamical core after introducing nest motion may require additional time.
- There maybe significant changes required to nests/model dynamics infrastructure for coupling other Earth System components to FV3. Similarly, there are other possible adjustments to nesting configurations based on regional data assimilation requirements.
- Annual review and adjustment on the timelines and deliverables based on our progress.

Dependencies/linkages with other projects:

- ANNEX 4: Regional model and Telescopic nest developments
- ANNEX 2: FMS and/or NEMS framework support is highly required.
- ANNEX 3: A developer's workshop for FV3 detailing the existing infrastructure and dynamics is recommended.
- ANNEX 2: Re-engineer coupling infrastructure developments for FV3 and other modeling components to support moving/telescopic nests and related model dynamics.
- ANNEX 6: Developments for data assimilation for FV3 regional domains with a potential extension for hurricane inner core data assimilation techniques

Major Milestones:

- Set up a stand-alone idealized version of FV3 (Q4FY17, completed)
- Start advancing the moving nest technique for FV3 within the idealized framework based on the prototype developed at AOML and EMC (Q1FY18, completed)
- AOML and EMC will work with GFDL and NESII and advise the SIP group on the further use of FMS and/or NEMS or a hybrid framework (similar to NGGNF) for developing moving nest. There will be only one approach at the end of this quarter (Q4FY18, completed)
- Build capacity within FV3 to set up the baseline static nested 3-km FV3GFS system for Hurricanes - (Jan 2019)
- Re-initializing the lower boundary, handling changes to the topography, and updating the two-way feedback (Jan, 2019)
- New code developments to implement moving nest framework in FV3GFS over one tile (AOML; June, 2019)
- Shifting the grid data (GFDL; June, 2019)
- Test, modify and extend parallel code infrastructure for nest motion and feedback within one tile (AOML; Oct 2019)
- Coupling capability for the regional stand-alone FV3 (Oct 2019)
- Code nest moving algorithm crossing the faces of the cubed sphere edges following the blueprint provided in Fig.1 (AOML, June 2020)
- Modify FMS code to implement the crossing edge algorithm (AOML, Oct, 2020)
- Start testing and evaluation of the global multi-nesting algorithm (EMC, AOML, GFDL, Jan 2021)
- Extend coupling to waves and multiple nests (June 2021)

Project 4.2: Hurricane Moving Nests

Development of Hurricane Moving Nests												
Timeline	FY19				FY20				FY21			
Component	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
High Resolution FV3 static nest	Set up baseline static nested 3-km FV3GFS system for Hurricanes											
SIngle Tile Developments		Moving nest infrastructure on a single tile of FV3 cubed sphere grid										
Multiple Tile Developments					Moving Nest infrastructure for crossing edges and corners of FV3 grid tiles							
Global multiple nests in FV3										Testing and evaluation of the global multi-nesting algorithm		

Project 4.3: Deep Atmospheric Dynamics (DAD) for FV3 Whole Atmosphere Model (WAM) and coupling to Ionosphere Plasmasphere and Electrodynamics Model (IPE)

Project overview: FV3 is a non-hydrostatic dynamics model, beyond non-hydrostatic dynamics is non-approximated deep-atmosphere dynamics. Developing deep-atmosphere dynamics (DAD) for FV3 is an essential step which is not only to move model dynamics into fully non-approximation to benefit all applications including weather and climate but also to support SWPC on whole atmosphere modeling to couple with SWPC IPE. The implementation of our DAD emphasizes on accuracy on top of non-approximation, especially starting from generalized multiple-constituent formulation for thermodynamics. Due to the consideration of accurate thermodynamics and DAD hydrostatic relation etc., the relation formulation used in model physics, data assimilation, pre-processing, and post-processing have to be modified for DAD ready, which leads to a DAD modeling in parallel development on WAM for SWPC IPE. In other words, while DAD works on model physics for WAM, DAD modeling benefit to improve accuracy of thermodynamics in model physics, the same for data assimilation and post processor etc. Thus, the DAD modeling will eventually provide non-approximated, accurate, and better dynamics for all other components on weather and climate modeling. For FY18, we have finished FV3WAM IC, extension of vertical to 500-600km (L150), and found the warm bias correction of the WAM IDEA physics coupling with GFS physics. We expect to finish implementation of multi gases and ideal physics option by the end of this year, then move to parallel project activities by working on DAD, DA, and coupling with IPE. **(POC: Henry Juang, EMC)**

Project accomplishment in 2018 and milestone modifications

During FY18, we have finished FV3WAM IC for 500-600 km atmosphere depth in global_chgres package for FV3, extension of vertical from 60 km(L64) to 500-600 km (L150) in FV3 with adiabatic mode and GFS physics mode, and found the warm bias correction of the WAM IDEA physics coupling with GFS physics. We have finished multi-constituent of R portion into FV3.

Due to time spent in debugging on the WAM IDEA physics coupling with GFS physics to correct the warm bias over low atmosphere and surface, we have to extend our milestone of some portion of multi-constituent of Cp portion and horizontal diffusion, and IDEA physics implementation into 2019.

Major Risks and Issues:

- Deep-atmosphere dynamics involves dynamical core modification, though the idea of scaled prognostic variable (the so-called smile space) minimizes the changes of the dynamical core, the stability of the deep-atmosphere dynamical core has to be examined and tested (e.g., tolerance to T>2000 K, V ~1000 m/s, W ~100 m/s; impact of non-hydrostatics on IPE). Further numerical techniques may be necessary.
- Vertical extension from 60 km to 600 km requires implementation of WAMGSM column physics, e.g., radiation, diffusion, ion drag, etc., and stability tests.
- Implement 3D diffusion in dynamical code (explicit may be an option of very small time steps ~1-10 s are tolerated).
- IPE couple issues ---Modify existing WAM-IPE ESMF mediator and 3D re-gridding, develop FV3WAM-CAP, implement one-way and possible two-way coupling.
- Data assimilation issues – implement IAU and existing 6-hr cycling. Extend GSI to 100 km, and implement 1-hr cycling window.

Major resources requirements:

- Personnel: EMC (1 FTE for development, 2 FTE for testing); SWPC (1 FTE for development, 2 FTE for testing); and GFDL (Xi Chen for discussion and unified code management)
- HPC for development: 250K CPU per month on Theia and 50 TB disk space

Dependencies/linkages with other projects:

- ANNEX 3 (system architecture): requires coupling techniques through NESII group with NEMS/NUOPC and ESMF modification of existing coupling scheme (mediator)
- ANNEX 5 (model physics): requires deep-atmosphere physics with physics project– import WAM column physics using IPD.
- ANNEX 6 (data assimilation): requires data assimilation project – higher cadence and extended altitude range.
- ANNEX 10 (aerosol and composition): requires to link to atmospheric composition on applying multiple- gases thermodynamics
- ANNEX 12 (post processing): requires to modify post-processor for deep-atmosphere dynamics.
- ANNEX 13 (verification): requires verification including deep-atmosphere dynamics, WAM, and IPE related capabilities.

Core development partners and their roles:

- Including multiple gases and deep-atmosphere dynamics
- Extension vertical domain with physics modification with implementation and tuning GW parameterization and others.
- Data assimilation – extend GSI to 100 km resolution, 1-hr cycling.
- Couple with IPE– one and possible two-way coupling through NESII NEMS.

Major Milestones:

- Q1FY18: Finish WAM initial condition for FV3
- Q2FY18: Extend vertical domain to WAM in FV3 with adiabatic mode
- Q3FY18: Fix warm bias of WAM physics
- Q4FY18: Finish vertical domain to WAM with gfs physics
- Q1FY19: Add multi_gases option of R and Cp into FV3WAM
- Q2FY19: Add idea_phys option into FV3WAM
- Q3FY19: Implement 3D molecular diffusion in FV3WAM
- Q4FY19: Validate standalone WAMFV3 against WAMGSM at similar resolution
- Q1FY20: Implement Data assimilation for FV3WAM using IAU
- Q2FY20: WAMFV3-IPE one-way coupling, validate against WAMGSM-IPE
- Q3FY20: implement deep-atmosphere dynamics into WAMFV3
- Q4FY20: WAMFV3-IPE two-way coupling
- Q4FY21: DA with 1-hr cycling and extended altitude range; implement space weather drivers; test.

<u>Project 4.3: Deep Atmosphere Dynamics for FV3WAM-IPE</u>

Development of Deep Atmosphere Dynamics for FV3WAM-IPE

Timeline	FY19				FY20				FY21			
Component	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Multi-gas option, 3D molecular diffusion and IDEA Physics	Include multi_gases option of R & Cp; 3D Molecular Diffusion and IDEA Physics into FV3WAM											
Validate FV3WAM compared to GSMWAM		T&E of FV3WAM in comparison to GSMWAM at same resolution										
Implement IAU based Data Assimilation			Develop and implement IAU based Data Assimilation for FV3WAM									
FV3WAM-IPE one-way coupling				FV3WAM-IPE coupled system validated against GSMWAM-IPE								
FV3WAM-IPE two-way coupling						Develop, test and evaluate FV3WAM-IPE two-way coupled system						
Space Weather Drivers and Real-Time Testing						DA with 1-hr cycling and extended altitude range; implement space weather drivers; test in real-time						

<u>ANNEX 5</u>: MODEL PHYSICS

Model physical parameterizations describe the grid-scale changes in forecast variables due to sub-grid scale diabatic processes, as well as resolved-scale physical processes. Physical parameterization development has been a critical driver of increased forecast accuracy of global and regional models, as more processes are accounted for with sophistication appropriate for the model resolution and vertical domain. Key atmospheric processes that are parameterized in current global models include subgrid turbulent mixing in and above the boundary layer, cloud microphysics and 'macrophysics' (subgrid cloud variability), cumulus convection, radiative heating, and gravity wave drag. Parameterizations of surface heat, moisture, and momentum fluxes over land, ocean, and other bodies of water/ice, subgrid mixing within the ocean due to top and bottom boundary layers, gravity waves and unresolved eddies, land surface and sea ice properties are also important on weather and seasonal time scales. Accurately yet efficiently incorporating this diversity of diabatic and transport effects in a global or regional forecast model is extremely demanding, requiring careful parameterization design that respects physical realism while supporting the range of model resolutions that will be used and a diagnosis of initialization and forecast errors that is tightly connected with the data assimilation system. Moreover, the interactions between various physical parameterizations play a major role in the prediction system forecast skill.

The ultimate goal of this SIP Physics WG is to support the development of a unified atmospheric physical parameterization suite that can be applied with minimal modification across convection-permitting to sub-seasonal to seasonal scales, to be used in all EMC operational atmospheric forecast models. We recognize that the physical parameterization needs for short range forecasts with regional convection allowing models (CAMs) with grids of 3 km or less pose different challenges than global weather forecast models with ~10 km resolution or seasonal forecast models with 50 km resolution. Thus, a priority must be to design, test (at multiple resolutions) and carefully tune scale-aware parameterizations for processes such as microphysics, convection, and gravity wave drag that are sensitive to this range of grid resolutions. This testing will involve metrics that are specifically designed to measure skill on different scales, including metrics recommended by stakeholders, users, and developers of a) global, coupled, seasonal to sub-seasonal modeling systems, b) emerging convection-allowing analysis and forecast systems, c) traditional global medium range numerical weather prediction models. The testing strategy, including assurance of an evidence-based decision process, will be developed in coordination with the SIP Verification Working Group and relevant testbeds, such as the Global Model Test Bed (GMTB), to provide guidance and recommendations on physics evaluation protocols and testing.

Another important issue this Physics WG will need to address in collaboration with the Ensembles WG is a strategy for advancing stochastic physics within this unified modeling framework. In particular, how strong a priority should be placed on making individual parameterizations stochastic vs. using an alternate strategy such as stochastically perturbed parameterization tendencies (SPPT) to develop reasonable ensemble spread.

A central strategic goal of EMC and the Unified Forecast System Steering Committee (UFS-SC) is to harness the ideas and expertise of the broader U. S. research community for physics development and testing. For this to be effective, the UFS community needs an efficient, easy to access, operationally-relevant physics development and testing environment that can help facilitate the R2O transition. The Common Community Physics Package (CCPP; a vetted, model-agnostic collection of physical parameterization and suites being developed for the UFS) is one possible way to more easily share and transition physics codes between the research community and operational centers. It is critical for the operational centers and community testbeds to have sufficient computational resources, including storage, ease of access, and documentation to meet the demands of full testing and evaluation of the physics in uncoupled and coupled applications, including CAM and global model configurations. Adequate funding resources are needed to foster collaborations between operations and research, and to leverage new research related to physical parameterizations emerging in the community at large.

Here we highlight three projects related physical parameterizations for the UFS.

- Project 5.1 focuses on new atmospheric physics parameterization development for the UFS over the next three years.
- Project 5.2 involves the design and implementation of unified metrics for weather, sub-seasonal and seasonal forecast model skill.
- Project 5.3 involves development and application of a collaborative framework for developing and testing physical parameterizations

Project 5.1: Selecting, Optimizing, and Implementing Advances in Model Physical Parameterization

Project overview: In planning for future forecasting systems NOAA/NCEP/EMC has embraced the idea of a multi-stage approach. The initial priority has been to implement the FV3 dynamical core in the GFS modeling framework, while keeping the physics largely intact. The major exception to the latter is a replacement of the outdated Zhao-Carr microphysics scheme with single-moment GFDL microphysics, while a notable addition is a parameterization from NRL that includes ozone photochemistry and associated databases as well as a new representation for stratospheric water vapor. Under the label FV3GFSv1 (GFSv15), Table 5.1 shows key components of the physics suite in this new modeling system. FV3GFSv1 performance is currently being evaluated in retrospective forecasts and in real-time testing, where it runs in parallel to all cycles of the operational GFS. Preliminary assessments have been quite favorable and FV3GFSv1 is scheduled to become GFSv15 in operations in early 2019.

An updated version of the modeling system (FV3GFSv2; GFSv16) is scheduled for implementation in early 2021, requiring that any upgrades must be selected and the code frozen by the end of CY2019. Given this rapidly approaching deadline, the near-term focus will be on assessing whether a nearly-wholesale replacement of the FV3GFSv1 physics suite might be justifiable on the basis of performance and potential for future growth. Specifically, the performance of two alternative parameterizations suites, listed separately in columns 3 and 4 of Table 5.1, will be evaluated across the range of scales and applications for which the UFS is intended, with special emphasis on the core functionality of the GFS – providing deterministic forecast guidance for the 3-10 day time frame. These suites include parameterizations of cloud microphysics, PBL/turbulent mixing, moist convection, and the land surface, with one suite having its roots in the mesoscale-modeling community (RAP/HRRR) and the other in the climate-modeling arena (Climate-Process Team - CPT). Some of FV3GFSv1 physics packages that will be evaluated for possible inclusion in FV3GFSv2 will be upgraded versions of those that are in FV3GFSv1. Regardless of whether the FV3GFSv1, RAP/HRRR, or CPT suite is selected in 2019, it is anticipated that other physics upgrades in FV3GFSv2 will include a) a unified gravity wave drag parameterization that includes orographic and non-orographic sources, b) the Noah MP land-surface model, c) a fresh-water lake model, and d) a multi-layer snow model. An upgrade of the RRTMG radiation package being developed by Robert Pincus and colleagues is expected to be available for implementation in 2019 as well. Furthermore, all model physics will be implemented using the CCPP starting with FV3GFSv2.

After the late 2019 code freeze for FV3GFSv2, development of physical parameterizations for UFS will become increasingly reliant on the hierarchical testing framework (HTF) connected to CCPP (see project 3). This framework will allow parameterizations to be tested across a hierarchy of modeling-system complexity, from fundamental process-level studies of individual parameterizations to multi-parameterization, one-dimensional single column models, to multi-dimensional, multi-component, and highly non-linear earth system models. **(POC: Jack Kain, EMC)**

Table 5.1. Prioritized candidates for the planned 2021 operational implementation of FV3GFS(v2)

Physical Process(es)	**CANDIDATE FV3GFSv2 (GFSv16) PHYSICS SUITES**		
	FV3-GFSv1	**RAP/HRRR**	**Climate Process Team EMC/CSU/Utah**
MICROPHYSICS	GFDL	Thompson	MG2/3
PBL/TURB	K-EDMF/SA-TKE-EDMF	MYNN/EDMF	SHOC
DEEP MOIST Cu	SA-SAS	GF	CS/AW
SHALLOW MOIST Cu	SA-MF	MYNN/EDMF	SHOC

Major Risks and Issues:
- The UFS workflow should be assessed for maturity and relevance for EMC decision making. It may require augmentation including additional computational resources and/or closer cooperation with EMC to establish, for example, workflows for FV3.
- Effective physical parameterization development demands sustained and adequately resourced close collaboration between EMC scientists and external collaborators, supported by a clear set of NCEP strategic priorities and goals focused on improving important aspects of unified forecast model skill.
- Access to adequate supercomputing resources (CPU and storage) has historically been quite a challenge for research and testing; this project cannot succeed without those resources.

Major resource requirements:
- Personnel: EMC (10 FTE); DTC/GMTB (3 FTE); GFDL (TBD); ESRL/PSD(1.5 FTE)

- HPC for development: 2M hours per month on RDHPCS.

Dependencies/linkages with other projects:

- Infrastructure WG: Community Research and Operations Workflow (CROW)
- Model Physics WG:
    - Project 2: Establishment of unified metrics covering synoptic to seasonal time scales;
    - Project 3: Collaborative framework for developing physical parameterizations
- Ensembles WG: Project 5: Develop, test, and implement codes for more physically based stochastic parameterizations
- Aerosols and Atmospheric Composition Project 10.1: Development of an atmospheric composition component
- Land Surface Models and Hydrology Project 9.2: NCEP Unified Land Data Assimilation System (NULDAS) Development

Core development partners and their roles:

- EMC: Collaborative development, testing and evaluation, integration into operational frameworks, tuning, and transition to operations of advances in parameterization of physical processes
- DTC/GMTB: Contribute to assessment of physics parameterizations and suites
- ESRL/GSD:Contribute to development and optimization of physical parameterizations and suites
- ESRL/PSD: Contribute to assessment of performance of physical parameterizations and suites
- GFDL: Contribute to development of physical parameterizations
- Navy: Collaboration on physical parameterization development and the collaborative framework for developing physical parameterizations

Major Milestones:

- Year 1 (FY19):
    - Evaluation, selection, and optimization of an advanced physics suite for FV3GFSv2 (GFSv16).
    - Scientist exchange between ESRL/GSD, ESRL/PSD, and EMC to discuss development, testing, and evaluation of physical parameterizations
- Year 2 (FY20):
    - Development, testing, and optimization of new/updated physical parameterizations for future operational implementations.
    - Results for funded projects (including NGGPS) to compare convection parameterizations and complete representations of clouds and boundary layers, evaluated using both weather and seasonal forecast metrics.
- Year 3 (FY21):
    - Development and End-to-end results of testing new/updated physics parameterizations for future operational implementations.

FY19				FY20				FY21			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Evaluation, selection, and optimization of an advanced physics suite for FV3GFSv2 using CCPP interface											
			Development, testing, and optimization of new/updated physical parameterizations for future operational implementations of the UFS								

<u>Project 5.2: Establishment of unified metrics covering weather to seasonal time scales</u>

Project overview: A key element of the UFS-SC/EMC vision is development of a unified modeling framework for all forecast scales (temporal and spatial) from high-resolution short-range regional to low-resolution long-range seasonal predictions. Here we focus on the more limited goal of a single global model that can be used for weather and, in ocean-coupled mode, for sub-seasonal and seasonal forecasting. To develop such a model and assess whether potential improvements are ready for operational implementation, we need a unified suite of metrics that covers all these scales. Here 'metrics' mean a small set of quantitative measures that can be reliably computed from observational analyses and which together encompass key aspects of the global model forecast performance. The metrics should be displayable in a simple 'dashboard' or 'scorecard' format that can easily be compared with other model versions including the baseline, and an attempt should be made to combine the metrics into one or two overall combined skill scores that summarize the overall model performance integrated over all the relevant forecast timescales. **(POCs: Jack Kain/Jason Levit; EMC)**

Unified model development will thrive only with an appropriate set of unified meso-synoptic-seasonal forecast metrics that reward model developments that improve performance across this entire range of timescales. Thus, an accelerated effort to define and implement unified metrics need to be a high priority for the UFS-SC and EMC.

1. A committee of EMC, NOAA/NWS stakeholders and external community members convened in late July/early August 2018 to discuss and propose a set of metrics and possible ways of combining them into a dashboard format and a summary skill score. This meeting included input from all SIP WGs, and as well as key personnel from NCEP. The development of seasonal forecast metrics involves specification of a 'test harness' of seasonal ocean-coupled hindcasts from which metrics (e. g. NINO3.4 SST anomaly, mean SST drift during months 1-3, CONUS T and precipitation anomalies) can be extracted, and should involve ensemble forecasts. A simple seasonal test harness was developed for CFSv2 by EMC that could serve as a prototype. Metrics and scorecards will need to reflect the different applications of the UFS and should be unified as much as possible across scales from CAM to medium range to sub-seasonal and seasonal applications.

Some specific metrics and diagnostics may need to be developed to guide physics development and evaluation.
2. The metrics approach must be implemented consistently at EMC and GMTB so that the metrics are computed as a routine step in model development and broadly shared across the UFS development community as a web page or similar readily accessible medium.
3. A key aspect is how to weight weather and seasonal forecast metrics to make an overall judgement as to whether a new model version should be adopted. Without an objective approach to this, it will be very hard for the outside community to contribute to a model development process that they do not 'own'. This will surely require experience with the new metrics suite and an iterative approach to refine to everyone's satisfaction.

Major Risks and Issues:

- Achieving consensus on a computationally reasonable seasonal 'test harness' that can be run at GMTB and on a small set of summary metrics may not be easy.
- There is a risk that the unified metrics will be ignored in favor of 'business as usual' in which the current weather forecast metrics are the sole basis for decisions about operationalizing new model versions.
- End-to-end workflow, coupled model, and relevant datasets need to be available outside of NOAA firewall or community involvement will be compromised.
- A strong connection to the Verification WG is needed, with eventual adoption of MET (or MET+) based software.

Major resources requirements:

- Personnel: Adequate personnel at EMC and GMTB to implement, test, document and refine broadly usable scripts for calculating and presenting metrics.
- HPC for development: Not a significant overhead except for METViewer or Web-based interface for demonstrating verification results. Need significant storage (disk) for staging the forecast and analysis datasets.

Dependencies/linkages with other projects: The SIP WG on Verification is also considering a similar project that will likely need to be coordinated and merged with this one.

Core development partners and their roles:

- EMC: Document and define operationally relevant metrics
- DTC/GMTB:

Major Milestones:

- See Gantt Chart below

Project 5.2: Establishment of unified metrics covering synoptic to seasonal time scales

Project 2											
FY19				FY20				FY21			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Select and define appropriate metrics and scorecard to evaluate the physics suite for FV3GFSv2 using CCPP interface (Q2) and continue to define metrics for physics evaluation across scales from CAM to Seasonal (Q4)											
Develop unified metrics within MET+ and apply for FY19 Q2 evaluation											
			Standardize and expand the evaluation metrics for use by research and operations								

Project 5.3: Collaborative framework for developing physical parameterizations

Project overview: Participants of the November 2016 NGGPS Physics workshop identified the need for putting in place an effective collaborative framework for physics development (link to workshop report). A key element of this framework is a community library of parameterizations (the Common Community Physics Package, or CCPP-Physics) with clearly defined interfaces for facilitating its use by the general community. A second key element is the CCPP Framework to connect the CCPP-compliant parameterizations to any model, therefore enabling a large number of scientist and institutions to run experiments with the same physics suites. **(POCs: Ligia Bernardet CIRES/GSD and Jack Kain EMC)**

Utilizing a collaborative framework, we would like to establish a new paradigm in which modeling experts (but not necessarily parameterization developers) develop and fully utilize a hierarchical test framework in order to "look under the hood" of the physical parameterizations to gain increased scientific understanding of the individual parameterizations AND their interactions. The vision is to:

- Develop additional diagnostic and visualization tools to be shared with the community.
- Bring in process-based observations for development of process-based metrics.
- Compare operational parameterizations from leading NWP centers with each other and with new innovations to make objective, independent decisions about best practices.
- Construct new parameterizations based on objective assessments of best practices for representing key physical processes.
- Develop insight for perturbation strategies for different parameterizations.
- Work collaboratively toward the improvement in physical parameterizations. break down the tribalism that has inhibited community efforts towards model development in the past.

With NGGPS support, GMTB (in collaboration with EMC and GFDL, and the NUOPC/ESPC Physics Interoperability Committee) has done the initial development of CCPP and its Framework leading to the CCPP v1 and v2 public releases, containing the GFDL microphysics plus the parameterizations of the current operational GFS, as well as the ability to connect with the GMTB Single Column Model (SCM). GMTB has also integrated the FV3GFS prognostic model with the CCPP, delivered the code to EMC and started a code review process for inclusion of the integration onto the FV3GFS authoritative repository. This project aims at continuing development of the CCPP so that it contains the current operational GFS physics, the candidates for the advanced physics suite, and new physics developments to be used in future operational implementations. GMTB is already supported to make CCPP-compliant several parameterizations that are candidates for the FY21 FV3GFS implementation. Non-GMTB community collaborators have committed in-kind support to make additional parameterizations CCPP-compliant for conducting experiments. As part of the NCAR-NOAA Memorandum of Agreement (MOA), which focuses on common infrastructure, NOAA and NCAR (WRF, MPAS, and CESM) models are moving forward to use the same framework for connecting physics and dynamics, and therefore being able to easily interchange physics between the two organizations. Likewise, the Navy Research Laboratory has expressed interest in implementing the CCPP to its next-generation model NEPTUNE and possibly its current operational global forecast system NAVGEM. Additional development of the CCPP Framework is expected to support emerging needs, and a unit and regression test for the CCPP Framework will be established under Hurricane Supplemental funding. The long-term vision is that the CCPP ecosystem will support many levels of engagement: users, developers, core partners, and operations.

To provide CCPP-compliant physics, the task of providing *caps* is primarily one of making explicit lists of all the physics arguments that are passed to and from the atmosphere driver and among the physics schemes. These lists are table-like text files documenting the names, meanings and units of the variables. The purpose of the CCPP Framework is to be a pass-through layer that can use these lists to generate calls to the physics during the running of the Atmosphere Driver (e.g. FV3). A few computations can be made by the CCPP Framework, such as automatically flipping the order of the arrays used by parameterizations whose order differs from the one used in the dycore, or changing units of variables when dycore and parameterizations are discrepant. Given the CCPP-specific lists (that depend on the physics suite), the linking of an Atmosphere Driver to the CCPP will be one of filling the necessary inputs and processing the outputs in a way that the atmospheric model requires. This matching of variables would occur in a specific Atmosphere Driver *cap* that calls the CCPP layer. The EMC FV3-based models use the Interoperable Physics Driver for a cap. Having individual *caps* for each parameterization, instead of calling groups of parameterizations together, will enable the ability of switching an individual scheme (e.g., the deep convection scheme), therefore enabling tests to be conducted.

In addition to the development of software, documentation, and training for the CCPP, this project also aims at the establishment of the CCPP governance. It is envisioned that there will be a small set of CCPP suites and parameterizations that will be supported to the general community, namely the operational suite and candidates for advancements. It is important to control the number of parameterizations in the supported CCPP such as not to overburden the CCPP users and funding agencies. Therefore, a governance structure must be established to determine programmatic, scientific, and technical criteria for inclusion in the supported CCPP. It is also anticipated that there will be parameterizations that are CCPP-compliant but not supported, for example those that are under development and testing by the general community.

Intrinsic to the CCPP is the concept of hierarchical development and testing. During testing, parameterizations should be assessed using several “tiers” of modeling configurations, arranged in a simple-to-complex hierarchy, as discussed by Oberkampf and Trucano (2002) and Rood (2017). Testing a physical parameterization innovation within such a structure allows one to objectively address how well it represents the physical processes it was designed to encompass in relative isolation from parameterizations for other processes. This capability is important because parameterization suites are often tuned/optimized as a package, such that better overall skill is achieved through compensating errors within different parameterizations in the suite, rather than optimal performance of each scheme. The sequential addition of model feedbacks adds levels of complexity to the interpretation of results as testing proceeds toward a potential operational configuration. Results of testing provide information for ongoing and iterative development.

This concept of hierarchical model testing has been partially implemented by GMTB, which has developed a SCM and made it available along with the CCPP and put in place a global workflow for conducting physics development. It has also been embraced by EMC, as reflected by the inclusion of a Hierarchical Model Development project in its FY2018-FY2020 Implementation Plan (NCEP 2018). Funding solicited as part of the Hurricane Supplemental provides us with a unique opportunity to build a world-leading capacity for accepting contributions from the broader research community, providing a comprehensive testing framework for developers, and a transparent, efficient, objective, and authoritative set of procedures for evaluating techniques and strategies for parameterization of physical processes. Results from these tests can inform the CCPP Governance process and determine inclusion of new parameterizations, and updates to existing ones, to the CCPP.

Major Risks and Issues:

- The CCPP Framework is not yet fully integrated onto the master code repositories of EMC and not all candidate parameterizations for the FY21 FV3GFS v2 operational implementation have been made CCPP compliant. Until these capabilities are established, tests should be conducted outside of the CCPP framework while its development progresses. This is being mitigated by focusing GMTB work on CCPP development. Additionally, a capability for using both CCPP-compliant and non-CCPP-compliant parameterizations in a single run has been developed.
- CCPP could be developed but not adopted by EMC due to perceived overhead of using a more general code whose functionality extends beyond FV3. This is being addressed by frequent meetings and exchange of planning information and materials between the core group (GMTB and EMC), as well as with a larger community (NUOPC Physics Interoperability Team and EMC SIP Physics Team).

Major resources requirements:

- Personnel: Adequate personnel at GMTB to document and train the community in the use of CCPP and the hierarchical model development framework, as well as to make the CPT/EMC/CSU/Utah CCPP-compliant (already funded).
- HPC: TBD

Dependencies/linkages with other projects:

- Software Architecture Working Group: also considering physics-dynamics interface
- Verification Working Group: involved in development of metrics for inclusion in the CCPP

Core development partners and their roles:
- GMTB and NCAR: evolve CCPP Framework
- GMTB: Coordinate the documentation and training of CCPP and hierarchical model development framework
- GMTB, EMC, PSD, NCAR: Develop hierarchical modeling development and testing framework
- EMC: Participate in CCPP Governance and use. Transition CCPP framework to operations.
- GMTB and Physics scientists: Contribute CCPP-compliant interfaces and documentation for parameterizations that are candidate for operationalization

Major Milestones:
- Year 1 (FY19)
    - Q1: CCPP capability working in FV3 with GFS operational physics and candidates for FY21 implementation, including FV3-GFSv1, RAP/HRRR, and CPT/EMC/CSU/Utah suites (all atmospheric parameterizations in Table 5.1; excludes FLake freshwater lake model and Noah-MP land surface model).
    - Q1: CCPP governance in place for assessment of which suites will become part of the NOAA-supported physics package.
    - Q2: CCPP public release with operational and developmental parameterizations. CCPP Tutorial.
    - Q3: Adoption of CCPP at EMC for tests toward FV3GFSv2 implementation.
    - Q4: Definition and implementation of additional set of hierarchical physics tests, building from existing efforts in GMTB and drawing on EMC experience
- Year 2 (FY20)
    - Q2: CCPP updated with operational and developmental parameterizations. Public release and training on CCPP and hierarchical model development framework.
    - Q2: CCPP Framework unit and regression test established
    - Q4: Enhanced hierarchical physics tests
- Year 3 (FY21)
    - Q2: CCPP updated with operational and developmental parameterizations. Public release and training on CCPP and hierarchical model development framework.
    - Q2: FV3GFS operational implementation using CCPP.
    - Q4: A comprehensive, robust testing framework with capabilities for the testing and development of physical parameterizations

Project 5.3: Collaborative framework for developing physical parameterizations

<table>
<tr><th colspan="4">FY19</th><th colspan="4">FY20</th><th colspan="4">FY21</th></tr>
<tr><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th></tr>
<tr><td colspan="4">Provide CCPP capabilities and governance for testing all candidate physical parameterizations for FV3GFSv2 (Q1), public release and tutorial (Q2), and definition and implementation of additional diagnostic capabilities from hierarchical testing framework (Q4)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="4">Augment CCPP framework and regression test procedures; transition CCPP to operations in FV3GFSv2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="9">Update CCPP with candidates for future operational implementation, execute periodic public releases and conduct training sessions with CCPP and hierarchical testing framework; deliver a comprehensive , robust testing framework with capabilities for the testing and development of physical parameterizations</td></tr>
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ANNEX 6: DATA ASSIMILATION

The NCAR/JCSDA 'Blueprints for Data Assimilation Workshop' in 2016 identified the following grand science challenges:

- Coupled data assimilation across the Earth System.
- Multi-scale data assimilation across temporal and spatial scales, from global to convective.
- Dealing with massive increases in the volume of obs, particularly hyperspectral sounders and radar.
- Representation of model uncertainty in ensemble systems.
- Dealing with non-linearity and non-Gaussianity in background and observation errors.

Efficiently transitioning research to address these challenges into operations requires a new object-oriented software framework that facilitates 'separation of concerns' and enables efficient collaboration. The 'Joint Effort for Data Assimilation Integration' (JEDI) project was initiated to develop this framework. A planning meeting was held in April 2017 to discuss the scope, priorities and requirements for JEDI. The initial milestones will focus on development of a Unified Forward Operator (UFO) library, and Interface for Observational Data Access (IODA), and implementation of these capabilities into the operational FV3-based atmospheric global data assimilation system. The first step for each of these milestones is to define high-level abstract interfaces between the components of the system (such as the UFO, IODA and the data assimilation solver). Once these interfaces have been defined, existing codes will be adapted to use these interfaces. The ultimate goal is to develop a community-oriented development model whereby contributions from the research community addressing the grand science challenges can be efficiently implemented and tested, and if the results warrant, transitioned into the operational system.

The projects listed below focus on addressing the science challenges listed above and on the development of the JEDI framework. JEDI is enabling technology that will allow the operational and research community to work together on addressing the long-term grand science challenges, but also will facilitate addressing more immediate operational challenges including .

- Improvement of forward models (including cloudy radiances and the development of operators for new instruments), GPS-RO operators, radar reflectivity and Doppler winds.
- Improvements to quality control and monitoring.
- Improvements in observation error representation (including the effects of correlated observation error and errors of representivity).
- Improvements in background-error modelling (including the treatment of sampling error in the estimation of ensemble-based covariances, i.e. localization).
- Data assimilation for the coupled state (land/ocean/atmosphere/chemistry/aerosols/sea ice).
- Improvements in observation and background bias correction techniques.
- Improvements to observation impact estimation techniques (e.g. EFSOI).
- Code optimization and improvements in scaling.
- Improved representation of model uncertainty in ensemble background forecasts.

Project 6.1: Observations

The accuracy of the analysis is strongly dependent on the observations that are available and the ability of the data assimilation system to effectively use these data. This project is therefore divided into three broad categories: new data types requiring significant development; addition of new instruments that are continuations of existing types; and development of new techniques for exploiting the information in the data

New data types

- **ADM-Aeolus**. Scheduled for launch in August 2018, ADM-Aeolus is a doppler lidar instrument that gives information on line-of-sight winds. Forward/adjoint models exist for this data type but will need to be tested in data assimilation systems. Strategies for determining error characteristics and possible bias-correction algorithms will need to be explored after data become available.
- **Geostationary hyperspectral sounders**. The MTG-IRS launch is currently scheduled for Q4 2021. Preparations are beginning in the NWP community to use high-spectral-resolution, high temporal-resolution data such as this. The potential for improving wind analyses through the use of temporally resolved radiances in a 4D DA system should be explored. Data volume is a significant issue with these data and the distribution of compressed data (through principal component analysis) is expected.
- **TAC-to-BUFR**: While not a new data type, this change in the method for distributing radiosonde data requires a re-writing of the data assimilation code that processes this type. Given the hundreds of vertical levels per sounding and the vertical correlations of errors, strategies for thinning and/or modifying observation errors based on data density need to be explored.
- **OMPS Nadir Profiler/Total Column/Limb Profiler.** The OMPS instruments on the JPSS satellite series continues the operational legacy of the SBUV series on the NOAA polar orbiters. The capability to monitor the nadir and total column components is included in the Q2FY19 FV3-GFS implementation and may potentially be switched on for operational assimilation in early 2019. The limb profiler is in the early testing period and is awaiting a stable real-time flow of BUFR data.
- **Satellite Sea-ice Data.** Development has commenced on a NOAA coupled ocean-atmosphere-sea ice model; consequently, new data types for assimilation include:
    - ***sea-ice thickness*** - radar altimeter (CryoSat), Vis/IR (JPSS), passive MW (SMOS, SMAP)2
    - ***ice-surface temperature*** - Vis/IR (JPSS)
    - ***sea-ice concentration*** - Vis/IR (JPSS), synthetic aperture radar (Sentinel-1a,b, Radarsat Constellation)
    - ***sea-ice vector motion*** (convergence/divergence) - Vis/IR (JPSS), synthetic aperture radar (Sentinel-1a,b, Radarsat Constellation)

- **Satellite Sea-surface Salinity**. Satellite sea-surface salinity (SSS), supports marine, coupled ocean-atmosphere, and coupled ocean-atmosphere-sea ice modeling. Satellite SSS is relevant to the ocean's thermohaline circulation and near-surface ocean stability, affecting heat and moisture fluxes between the ocean and atmosphere. SSS is relevant to the freezing temperature of sea ice and drives the salinity of the sea ice (particularly for new, thin (< 1m) sea ice), affecting the sea-ice emissivity, which is relevant to radiance assimilation for the UFS, particularly for coupled modeling.

Extension of existing series

- The following are expected to become available in the next three years:

  MetOp-C (IASI, AMSU-A, MHS, ASCAT); NOAA-21 (CrIS, ATMS, OMPS); GOES-17 (already launched but data not yet available); COSMIC-2; ISRO/ScatSat and OceanSat/OSCAT. In addition the move from the Legacy to Enterprise cloud mask for GOES products is expected to greatly improve their quality in this timeframe.

Currently available but not being (fully) used

- **Radar (reflectivity and radial wind)**: Essential for a storm-scale DA and forecasting system such as a future WoF system. The capabilities to assimilate full resolution observations in a hybrid EnVar framework have already been implemented in the GSI system. However, some modifications may be necessary to the forward operator to be implemented in the UFO framework. Errors associated with modification will need to be explored (especially for multi-moment microphysics schemes). Alternatively, UFO could be revised to readily accommodate non-conventional observations.
- **Reflectivity from GPM radar**: The assimilation of GPM radar data has the potential to improve high-resolution global forecasts. CRTM Community Active Sensor Module will enable direct assimilation of satellite-based radar reflectivities and path-integrated attenuation.
- **Lightning (GLM):** The assimilation of space-based lightning assimilation will be an area of focus, especially with the new GOES series of instruments (16 and 17) containing the Geostationary Lightning Mapper. While some operational applications convert lightning based observational data into proxy radar reflectivities, considerable work has been done over the past several years to evolve to newer observation operators to include lightning flash rate. This work should continue and be evolved into the UFO.

New methods for exploiting the data

- **Extension of cloudy radiance work**: There are significant opportunities for extending the use of radiances affected by cloud and precipitation including:
  - Extension to new hydrometeor types in the control vector
  - Validation and improvement of the CRTM
  - Evaluation of the information contained in the ensemble members
  - The introduction of cloud fraction

    - The extension from microwave to infrared radiance assimilation in cloudy regions.
- **Improved use of data over land:** Data usage over land is more difficult than over water as the surface emissivity is much less predictable, varying as it does both spatially and temporally. Land surface emissivity may be determined through one or a combination of 1) including the emissivity in the control vector – thereby determining directly from the observations or 2) greater use of information from the land surface model. Testing and utilization of the of the CRTM CSEM (Community Surface Emissivity Model) capability will be performed.
- **Improved Specification of model error:** The use of correlated observation error is becoming common in data assimilation systems. Further implementation and extension of the capability to use more complex error models (where appropriate) is desirable.

- **CRTM Improvements:**
    - Improvements to the specification of the hydrometeor particle size and shape distributions in order to be consistent with the treatment in the FV3 model.
    - New scattering and extinction properties based on the above specifications, providing a consistent, traceable path from observations to assimilation.
    - Implementation and testing of the CSEM surface emissivity module including specification of the BRDF over sea; salinity dependance of infrared surface emissivity over ocean and better utilization of radiances over land
    - Computational efficiency improvements.
- Development of IODA (Interface for Observation Data Access) and Unified Forward Operator (UFO) components of the Joint Effort for Data assimilation Integration (JEDI) project.

Major Milestones:

- Develop the capability to monitor ADM-Aeolus data and, if of sufficient quality, move towards operational assimilation of the data.
- Develop strategies for the assimilation of hyperspectral geostationary sounder radiances.
- Transition to high-resolution radiosonde BUFR data.
- Introduce new instruments as they become available.
- Extend the use of cloudy radiances to areas with precipitation and to the infrared.
- Improved use of data over land, snow and ice, through the use of improved emissivity atlases and the introduction of surface emissivity control variables.
- Wider implementation of spectrally correlated observation errors.
- Develop an initial capability for assimilating satellite sea-ice retrievals (thickness, concentration, ice-surface temperature, and vector motion).
- Develop the capability for assimilating satellite sea-surface salinity observations for both Level-2 retrievals data and Level-1 radiance data.

- Develop the capabilities to directly assimilate reflectivity and radial wind

Major resources requirements:

- Personnel: 7-10 FTE
- HPC for development: access to multiple platforms for testing

Core development partners:

- JCSDA, OAR/ESRL, NWS/EMC, NESDIS/STAR, NASA/GMAO, NRL

Dependencies/linkages with other projects:

- Annex 5 (Physics) - stochastic parameterizations to represent model uncertainty, microphysics changes needed to model all-sky radiances correctly.

Project 6.2: Data Assimilation Algorithms

Hybrid (ensemble + variational) data assimilation in its various forms is the current state-of-the-science for environmental prediction. This will remain the case over the next several years, implying that the JEDI framework will be required to support several current technologies for a variety of applications. It is envisions to utilize the JEDI framework to build out a project for global numerical weather prediction (FV3-GFS) inter-comparison between hybrid 4DEnVar (current technology) and Hybrid 4DVar (with adjoint). Additional sub-tasks will involve further exploitation of ensemble information, initialization strategies, multi-scale data assimilation, and research on use of data assimilation based initial perturbations for use ensemble prediction mode. Given the timescale for transition to operations of JEDI components, some of the components of this project may be tested and developed outside of JEDI.

Transitioning JEDI research into operations requires the ability to evaluate JEDI algorithms and compare results with the latest, established, (non-JEDI) operational implementation. Furthermore, the JEDI framework is expected to provide flexibility to test a variety of DA algorithms beyond those that running operationally.

At minimum the JEDI framework is expected to implement the GSI analysis algorithmic feature presently implemented in operations, namely:

1. Overall DA Strategy: Hybrid 4DEnVar.
2. Minimization Approach: B-preconditioner using a double conjugate gradient (DCG) algorithm.
3. Middle-loop minimization capability. This feature allows current system to account for nonlinearities in observation operators without need for integrating nonlinear model in each outer-loop.
4. First-guess at the appropriate time (FGAT) capability. This feature allows analysis system to calculate innovation (departure) vectors between observations and background fields without having to necessarily having to account for linear propagation of increments within minimization.

5. Nonlinear quality control: used as a means to adjust observation contributions to cost minimization following refinements to the underlying background fields.
6. Tangent linear normal mode constraint (TLNMC): used for initialization of analysis increments.
7. Spectrally-based ensemble error covariance localization.
8. Limited, but useful flexible control vector setting.
9. Variational bias correction (VarBC): presently implemented for aircraft and satellite radiances observations.

Additionally, since the operational hybrid GSI relies on an ensemble analysis system, namely, the Ensemble Square-Root Filter (EnSRF), JEDI is required to implement similar ensemble analysis capability. Indeed, and in all likelihood, by the time JEDI is ready to be compared with (fv3) GFS, the ensemble analysis strategy might have been upgraded to rely on the local ensemble transform Kalman filter (LETKF). In this regard it is recommended that JEDI supports similar ensemble analysis strategy. Among features relevant to the ensemble analysis and cycling, the following should be required by JEDI:

10) Availability of Ensemble analysis approaches: EnSRF and LETKF.

11) Ability to localize ensemble in both observation and physical space as desired by underlying application.

12) Removal of vertically integrated divergence from ensemble increments.

Furthermore, the JEDI framework is expected to provide support for alternative analysis algorithms currently available in GSI but only exercised under certain (research) environments. The following is a list of alternative features expected to be supported by JEDI:

A. 3DVar and Hybrid 3DVar. These are useful DA strategies especially for relatively quick testing. These are also useful when no tangent linear and adjoint models of the underlying nonlinear atmospheric (oceanic or coupled model) is available.
B. 4DVar and Hybrid 4DVar. These imply availability of tangent linear and adjoint models of the underlying nonlinear model.
C. Square-root-B preconditioning and corresponding control vector transform operations; this includes support for 3D and 4D hybrid applications.
D. Lanczos-based conjugate gradient minimization algorithm.

Beyond the features above, which are already largely support by the existing GSI-based system, the JEDI framework should also support:

I. Digital filter initialization of the nonlinear model.

II. 3D and 4D Incremental Analysis Update initialization of the nonlinear model.

III. Ability to allow development of multi-scale ensemble localization approaches in both variational and ensemble analysis contexts.

IV. Ability to allow development of time-dependent localization algorithms in both variational and ensemble analysis contexts.

In support of transition to operations, the JEDI frameworks are required to allow for head-to-head comparison of (fv3) GFS hybrid 4DEnVar with a JEDI-based: (i) hybrid 4DEnVar; and (ii) hybrid 4DVar. The JEDI-based framework is also required to support implementation of multi-incremental approaches to both these strategies, including variable resolution between inner- and outer- loops configurations with pertinent considerations to the underlying ensemble DA strategy.

Major Risks and Issues:

- Reliance of UFO and IODA and timeliness of their corresponding revelopments.
- Computational efficiency of variations configurations. JEDI-based system is required to perform either equality or better than its GSI-based operational counterpart.
- Flexibility in setting up various configuring .

Major resources requirements:

- Personnel: 5 FTE
- HPC for development: access to multiple platforms for testing

Core development partners:

- JCSDA, NASA/GMAO, NRL, OAR/ESRL, NWS/EMC

Major Milestones:

- Implementation of GSI-based Hybrid 4DEnVar for FV3GFS
- Testing of scale-dependent localization within FV3GFS
- Testing and implementation of incremental analysis update
- Intercomparison project for testing Hybrid 4DVar versus Hybrid 4DEnVar

Dependencies/linkages with other projects:

- Development of FV3 Hybrid 4DEnVar under GSI-based configuration as in Annex 1.
- Developments in this Project (Annex 6), sections 6.1 (UFO) and 6.2 (IODA).
- Some dependence on Annex 13, FV3 ensemble development.
- Dependency is also identified in regards to availability of verification tools as in Annex 13.

Project 6.3: Coupled Data Assimilation

The current atmospheric global data assimilation system updates the forecast model with partial coupling to sea surface temperature (SST) and interactive coupling with a land model. As NOAA transitions to a coupled modeling system, a coupled data assimilation capability is needed to initialize the fully coupled Earth system model to improve predictability from weather to S2S timescales.

1. ***Creating a consistent and balanced initial state***: As additional components of the Earth system are modeled and coupled to the atmosphere, this coupled Earth system begins to behave as an independent dynamical system. When each component of the earth system is analyzed

independently, these analyses have discrepancies at the model boundaries that can lead to 'shocks' in the assimilation system that have negative effects on predictive skill. As is already well understood, small perturbations to the model initial conditions can have significant impacts on a forecast.

2. ***Enhancing utilization of observations by extending their impact across domains***: The process of gathering Earth measurements is an expensive endeavor, and thus it is important to gain the most information from these measurements possible. A coupled data assimilation system provides the opportunity to have atmospheric observations constrain the ocean, land, and sea ice fields, and vice versa. Thus, the overall impacts of the existing observing system is amplified.
3. ***Enabling seamless prediction to extend forecast skill to weeks 3 and 4***: Due to the range of disparate temporal and spatial scales in the coupled Earth system model, multiscale DA methods are needed. The development of multiscale DA methods that produce initial conditions that can simultaneously improve both short and long term forecasts provide the opportunity to seamlessly extend the skill of weather scale forecasts into sub-seasonal and seasonal ranges.

This project will develop a strongly coupled data assimilation system (SCDA) for global analysis of the coupled Earth system. Some of the main scientific challenges that will need to be addressed are:

1. ***Data Latency of traditionally climate-oriented measurements***: Due to a traditional focus on climate scales by many of the non-atmospheric components of the observing system, for example snow cover on land, or Argo floats in the ocean, these have typically returned data on time intervals much longer than the 6-hour cycles that are used for atmospheric DA. This means that a large percentage of the global observing network may not be available at any given cycle. One approach for dealing with this situation is to use longer overlapping assimilation windows for the non-atmospheric components. This approach may also address the fact that the observations in the non-atmospheric components tend to be sparse in comparison to the atmosphere.
2. ***Addressing multiple analysis cycle timescales of the respective analysis systems***: The atmosphere has typically been analyzed at 6-hour intervals while the ocean has been analyzed at pentad or daily intervals. Similar time discrepancies exist with other Earth system components. It is not yet clear whether assimilating all data simultaneously at the shortest update time (i.e. based on the atmospheric analysis cycles, e.g. Sluka et al., 2016) or using some form of time-averaging (e.g. Lui et al, 2016) is preferable for operational prediction.
3. ***Multiscale DA***: Characteristics of sampling error in the estimation of ensemble-based background-error covariances will be different on different spatial and temporal scales. Analyzing the more slowly varying dynamics of the ocean, sea ice, and land together with the

more rapidly evolving atmospheric scales will require new more sophisticated methods, including upgrades to localization, hybridization, and multiscale modeling techniques.

4. ***Addressing model error at the component interfaces when developing cross-domain error covariance for a state-of-the-art Hybrid system***: While cross-domain error covariance is relatively easy to compute using ensemble methods, there are challenges that remain. First, the rapid timescales of the atmosphere relative to the ocean may make it difficult to compute accurate error covariance without going to larger ensembles and shorter analysis cycles. Even in simple models, climatological error covariances have produced poor analyses with sparsely observed systems due to ill-conditioning. Thus, multi-timescale analyses may be needed to replace climatological error covariance in hybrid applications.
5. ***I/O latency and in-core DA***: The current 6-h global assimilation system is already constrained by the cost of ensemble I/O. Increases in I/O speed have not been keeping pace with other improvements in HPC. As update frequency, ensemble size and resolution increase, it will become crucial to avoid I/O as much as possible. Strategies are needed for performing the forward integration of the model ensemble and the data assimilation in memory without writing out and reading in files from spinning disk.

Major Milestones:

- Develop and test a cycling global FV3/MOM6-based data assimilation workflow based on the current 6-h cycled FV3GFS workflow.
- Develop a strongly coupled atmosphere/land data assimilation capability using ensemble-estimated covariances of the atmosphere-land state vector and observations of soil moisture, near surface temperature, and humidity.
- Test strategies for dealing with time-lagged data delivery for non-atmospheric components (e.g. overlapping analysis windows)
- Test the inclusion of observational data from each component of the coupled Earth system independently to identify impacts on forecast skill of the coupled model.
- Test localization strategies that are appropriate across domains
- Test and evaluate the merging of all observational sources into the coupled Earth system model

Major resources requirements:

- Personnel: 5-7 FTE. In particular, the aggregate experience of the personnel should include experience in applying data assimilation to a variety of Earth system domains, ranging from research level algorithmic design to operational scale applications, expertise in domain

interfaces, and familiarity with applications at various prediction timescales (ranging from monitoring/nowcast to weather and S2S).
- HPC for development: Access to multiple platforms for testing. Significant resources will be needed and this must be acknowledged from the start.

Core development partners:

- JCSDA, OAR/ESRL, NWS/EMC, GFDL, Navy/NRL, NASA/GMAO

Dependencies/linkages with other projects:

- Annex 11 (Ensembles) - strategies for efficient in-core ensemble forecasts, representation of model uncertainty.
- Annex 8 (Marine Models) - DA for coupled atmosphere/ocean/wave states is needed
- Annex 10 (Aerosols) - DA for coupled atmosphere/chemistry/aerosol states is needed.
- Annex 3 (Infrastructure) - a community accessible code repository and flexible workflow that can execute applications in cycling DA mode.
- Annex 2 (System Architecture) - the ability to advance forecast models and integrate with DA with limited I/O is needed.
- Annex 5 (Physics) - stochastic parameterizations to represent model uncertainty; new methods need to be developed for ocean and other non-atmospheric components.

Project 6.4: JEDI Data Assimilation Framework

Project overview: Efficiently transitioning research into operations requires a new object-oriented software framework that facilitates 'separation of concerns' and enables efficient collaboration. The 'Joint Effort for Data Assimilation Integration' (JEDI) project was initiated to develop this framework. The main components of JEDI are

1. The 'Unified Forward Operator' (UFO): Observation operators (a.k.a. forward operators) simulate what an observation should be given a known state of a system. The UFO comprises two steps: an interpolation of the state values to the location of the observation and then the simulation of the observed quantity from those interpolated model variables. The first part (interpolation) is model dependent but the second is not. The goal of this task is to isolate the two aspects so that the scientific part of the observation operators can be shared between models. Quality control and bias correction algorithms that require simulated observations will be implemented and shared as part of the UFO.
2. The 'Interface of Observation Data Access' (IODA): The goal of the project is to create unified high level interfaces to access observation-related data so that scientific code can be written independently of data structures and technology used for the actual data handling. The benefits are that scientist can focus on scientific aspects of the code, while software specialists can

develop appropriate solution for data handling. This is especially important at a time when computer technology might change rapidly and achieving good scalability might require changes in data handling solutions.

3. JEDI Data Assimilation Solvers: This includes interfaces to algorithms for computing increments to a model forecast background using observations. Algorithms will include three and four-dimensional variational solvers and ensemble-Kalman filter based solvers. Methods for dealing with sampling error in the estimation of ensemble-based covariances are considered part of the solver component. All data assimilation algorithms will be written in model independent object-oriented framework, using the UFO/IODA interfaces and similar abstract interfaces developed for other model-dependent components of the data assimilation system. The solvers will be designed specifically with strongly coupled data assimilation in mind to enable updating a background that contains multiple model components. Operational constraints will be another strong driver for developments.

Major Risks and Issues:
- Observation operators are an area where many years of experience have accumulated in existing codes. Care will be taken not to lose existing knowledge or capability.
- The solver component depends on successful UFO/IODA implementation. Other components of the data assimilation system are comparatively easier to interface and carry less risk.
- Computational efficiency will be a constant topic of attention throughout the project.
- Complexity and variety of observation types used in modern DA systems.

Major resources requirements:
- Personnel: 7-9 FTE
- HPC for development: access to multiple platforms for testing

Core development partners:
- JCSDA, NASA/GMAO, NRL, OAR/ESRL, NWS/EMC

Major Milestones:
- Q4FY19: Connection of JEDI-UFO to GSI-EnKF
- Q4FY20: JEDI-UFO + JEDI-EnKF
- Q4FY21: JEDI-UFO connected to GSI-solver
- Q4FY22: JEDI-based solver replacement of GSI

Dependencies/linkages with other projects:
- The implementation of a FV3-based 4D-EnVar atmospheric data assimilation system is ongoing and included under ANNEX 1 (NGGPS GLOBAL MODEL SUITES PLANNED FOR NCEP/EMC OPERATIONS). This includes the implementation of the JEDI forward operator library in the operational FV3 GDAS in Q2FY19.
- Annex 13 (Verification) requires the use of the UFO for observation-space verification.
- Annexes 4, 8, 9 and 10: UFO must be flexible enough to deal with observation operators that span coupled state components, including radar operators, aerosol and chemistry operators, as

well ocean, land, hydrology, space-weather, sea-ice and wave observation operators. This includes interfacing with CRTM for such cases.

- Annex 13 (Verification) requires IODA to obtain observations for observation space verification.
- Annexes 4, 8, 9 and 10: IODA must be flexible enough to handle high-density radar observations, aerosol and chemistry observations, as well as ocean, land, hydrology, space-weather, sea-ice and wave observations.
- Annex 3 (Infrastructure) - a community accessible code repository and flexible workflow that can execute JEDI-based applications in cycling DA mode.
- Annex 2 (System Architecture) - the ability to advance forecast models from within JEDI is needed.
- Annex 4 (Dynamics and nesting) - the capability to calculate analysis increments on variable-resolution meshes and/or nested domains within JEDI is needed. Higher-cadence assimilation and incremental analysis update capabilities are needed for space weather applications.
- Annex 5 (Physics) - stochastic physics schemes that can represent uncertainty are needed for accurate background-error covariance estimates in JEDI-based ensemble DA solvers.
- Annex 8 (Marine Models) - DA for coupled atmosphere/ocean/sea ice/wave states is needed
- Annex 11 (Ensembles) - Ensemble DA solvers in JEDI are needed to initialize ensemble forecasts.
- Annex 7 (Convective Allowing Models/CAMs) - the capability to calculate analysis increments on variable-resolution meshes and/or nested domains on a rapid cadence is needed within JEDI. Multi-scale localization methods for dealing with sampling errors on convective and global scales is needed for initializing CAMs on continental and larger scale domains.
- Annex 10 (Aerosols) - DA for coupled atmosphere/chemistry/aerosol states is needed.

Project 6.5: Rapidly updating global data assimilation system

The current atmospheric global data assimilation system updates the forecast model with new observations that are collected over a 6-h time window. There are several reasons why updating more often would be desirable

1. ***Higher frequency phenomena resolved in both models and observations***: As model resolution increases, smaller-scale more rapidly varying features are resolved (such as convective outbreaks and rapidly intensifying hurricanes) whose predictability time-scale may be less than 6 hours. At the same time, more and more observations are becoming available on the global scale that can temporally and spatially resolve these phenomena. A more rapid update cycle is necessary to maximize the use of these observations.
2. ***Maintaining linearity and Gaussianity in the DA update***: Updating more frequently allows the linearity assumptions inherent in Kalman filter-based algorithms to remain valid even for

phenomena that are still predictable on a 6-h time scale, but have significantly non-gaussian error distribution. For example, non-gaussian error distributions can arise from large position displacements in forecasts of hurricanes and squall-lines.

3. ***Initializing regional convective-allowing ensembles***: Even though convective allowing models (CAM) on the global scale likely will not be feasible in the next three years, convective allowing regional domains for severe weather and hurricanes will continue to be an important part of the operational suite. A rapidly updating global analysis system could be used to provide initial and boundary conditions for these regional CAM forecasts, which will need to be run more frequently than every 6-h for the reasons mentioned in (1) and (2) above. Such a system will help simplify and streamline the NCEP suite, since frequently updating regional systems with resolutions similar to the global model (such as RAP and NAM) will no longer be needed to initialize the regional CAMs.

This project will develop a rapidly updating (O(1-h)) global analysis system for atmospheric applications. Some of the main scientific challenges that will need to be addressed are:

1. ***Dealing with data latency***: The observational data cutoff will need to be much shorter than the current 2.75-h cutoff used in the 6-h system. This means that a large percentage of the global observing network may not be available. The RAP/HRRR system (which currently uses at 26 minute data cutoff) addresses this with a 'catch-up' cycle which re-analyzes the previous six hours twice per day so that the impact of late arriving observations are at least included in the background forecast. An alternative approach is to use longer overlapping assimilation windows. For example, an hourly cycled system with overlapping 3-h assimilation windows can be used to include late-arriving observations (see e.g. Payne 2017).
2. ***Multi-scale DA***: Characteristics of sampling error in the estimation of ensemble-based background-error covariances will be different on different spatial and temporal scales. Analyzing more slowly varying synoptic and larger spatial scales together with more rapidly varying meso- and finer scales will require new more sophisticated localization methods. Multi-resolution ensembles may be the most efficient way to generate background ensembles that can accurately represent multi-scale background error statistics.
3. ***Dealing with high-frequency noise excited by analysis increments***: This noise is a consequence of sampling error in the estimation of the background-error covariances due to small ensemble sizes. In the 6-hourly cycled system currently undergoing pre-operational testing at NCEP, a four-dimensional incremental analysis update (4DIAU) approach (Lei and Whitaker 2016) is used to filter these oscillations in the background forecast. With a shorter assimilation window, the filtering effect of 4DIAU will be reduced and other strategies (such as the diabatic digital filter

currently used in the RAP) may be needed to control noise. Alternatively, the overlapping window approach may allow for the 4DIAU to be applied over a longer time window, improving its filtering properties.

4. ***More effective use of high temporal frequency observations***: In the RAP/HRRR system high frequency aircraft, radar and surface observations are the primary source of information on hourly time scales. On the global scale, the primary source of high-frequency observations are geostationary satellite observations, particularly GOES-16/17 and Himawari-8/9. Currently clear sky geostationary radiance observations have a relatively minor impact on forecast skill in global NWP systems as compared to radiances from polar-orbiting satellites. In order to fully realize the potential of a global hourly cycling system, all-sky information provided by geostationary radiances will have to be better utilized.
5. ***I/O latency and in-core DA***: The current 6-h global assimilation system is already constrained by the cost of ensemble I/O. Increases in I/O speed have not been keeping pace with other improvements in HPC. As update frequency, ensemble size and resolution increase, it will become crucial to avoid I/O as much as possible. Strategies for performing the forward integration of the model ensemble and the data assimilation in memory without writing out and reading in files from spinning disk will be needed.

Major Milestones:

- Develop and test an hourly cycling global FV3-based data assimilation workflow based on the current 6-h cycled FV3GFS workflow.
- Test strategies for dealing with data latency (‘catch-up’ cycles, overlapping assimilation windows)
- Once a preferred strategy for dealing with latency is selected, test strategies for filtering noise triggered by more frequent state updates (4DIAU, digital filters).
- Include more high-temporal frequency observations, including geostationary all-sky radiances and atmospheric motion vectors, hourly interpolated tropical cyclone position and intensity observations (‘tcvitals’), aircraft, radar and surface data.
- Develop an in-core DA integrated ensemble forecast and data assimilation update capability that minimizes I/O to/from spinning disk.

Major resources requirements:

- Personnel: 5-7 FTE
- HPC for development: access to multiple platforms for testing

Core development partners:

- JCSDA, OAR/ESRL, NWS/EMC

Dependencies/linkages with other projects:

- Annex 11 (Ensembles) - strategies for efficient in-core ensemble forecasts, representation of model uncertainty.
- Annex 7 (Convective Allowing Models/CAM) - initialization of CAM ensembles.
- Annex 4 (Dynamics and nesting) - initialization of high-resolution regional domains.
- Annex 5 (Physics) - stochastic parameterizations to represent model uncertainty, microphysics changes needed to model all-sky radiances correctly.

ANNEX 7: CONVECTION-ALLOWING MODELS (CAM)

This Annex lays out the broad program deliverables and schedule for replacement of NCEP's myriad mesoscale and convection-allowing-scale modeling systems with new systems based on the FV3 dynamical core. The NCEP meso/CAM scale modeling suite currently consists of the following components:

- North American Mesoscale (**NAM**) system: NAM runs on the Non-hydrostatic Multiscale Model on B-Grid (NMMB). The NAM consists of a North American 12-km parent domain run to 3.5 days and 4 non-moving nests run to 2.5 days at 3-km resolution over the CONUS, Alaska, Puerto Rico, and Hawaii. A “placeable” nest at 1.5-km resolution run inside the 3 km CONUS/Alaska nests, primarily for Fire Weather support, runs to 36 hr. The NAM features an hourly forecast and analysis cycle in its data assimilation system for the 12 km parent domain, the 3 km CONUS nest, and the 3 km AK nest.
- High-Resolution Window (**HiResW**): As of November 2017, the HiResW system consists of ~ 3-km runs of the NMMB model and two configurations of the Advanced Research Weather (ARW) model over the CONUS, Alaska, Hawaii, and Puerto Rico. For Guam, the HiResW consists of the NMMB model and a single ARW model configuration.
- High-Resolution Ensemble Forecast (**HREF**) system: Current and time-lagged HiResW and NAM CONUS nests combined to generate ensemble products. As of November 2017, version 2 of the HREF (HREFv2) became an 8-member ensemble for CONUS, and also run over Alaska, Hawaii, and Puerto Rico as a purely HiResW 6-member ensemble.
- Short-range Ensemble Forecast (**SREF**) system: SREF runs at 16 km over North America and currently consists of 26 members (13 NMMB, 13 ARW) with physics/initial condition diversity. The replacement of the SREF and deterministic NAM systems will be based on whether they can be replaced by improved forecast guidance from the FV3-GFS and FV3-GEFS.
- Rapid Refresh (**RAP**) and High-Resolution Rapid Refresh (**HRRR**): The RAP and HRRR are run hourly out to 21 hr and 18 hr, respectively. RAP is run at 13-km resolution over North America (identical to the NAM parent domain), while HRRR is run at 3 km over CONUS. With the upgrade to the RAPv4/HRRRv3 in July 2018, the 00/06/12/18z HRRR cycles were extended to 36-hr, and the 03/09/15/21z RAP cycles were extended to 39-hr. A HRRR-Alaska system was also added, running every 3 h.

Development of the NAM modeling system, including its high-resolution nests and the NMMB dynamical core, has been discontinued at NCEP. Similarly, the RAP, including its nested HRRR system and its ARW dynamical core, will be frozen at NCEP by the end of FY2019. However, operational execution of these modeling and associated DA systems will continue until comparable FV3-based systems are able to give similar performance. The transition of these deterministic modeling systems to FV3-based configurations is discussed in this Annex. Project 7.1 of this Annex will describe the implementation of the RAPv5/HRRRv4 system, scheduled for parallel testing in Q3 FY19. During the first year there will also be development of the FV3-based stand-alone regional model (SAR FV3) to bring its capabilities and performance up toward the current CAM systems. Project 7.2 will work toward developing the SAR FV3 to eventually be able to replace the ARW-based RAP and NAM mesoscale systems with equivalent FV3-based RAP and NAM. If this goes as planned, we would look to replace poorly performing members of the HREF with SAR FV3 equivalents FY21. Project 7.3 focuses on the ensemble data assimilation system for the SAR FV3 in combination with the new JEDI software. Project 7.3 will develop the science and technology needed for an RRFS system, which would is anticipated to be considered for operations sometime in the FY21 or FY22 timeframe.

Any decisions to sunset legacy modeling systems and/or implement new modeling systems will be based on the following criteria:

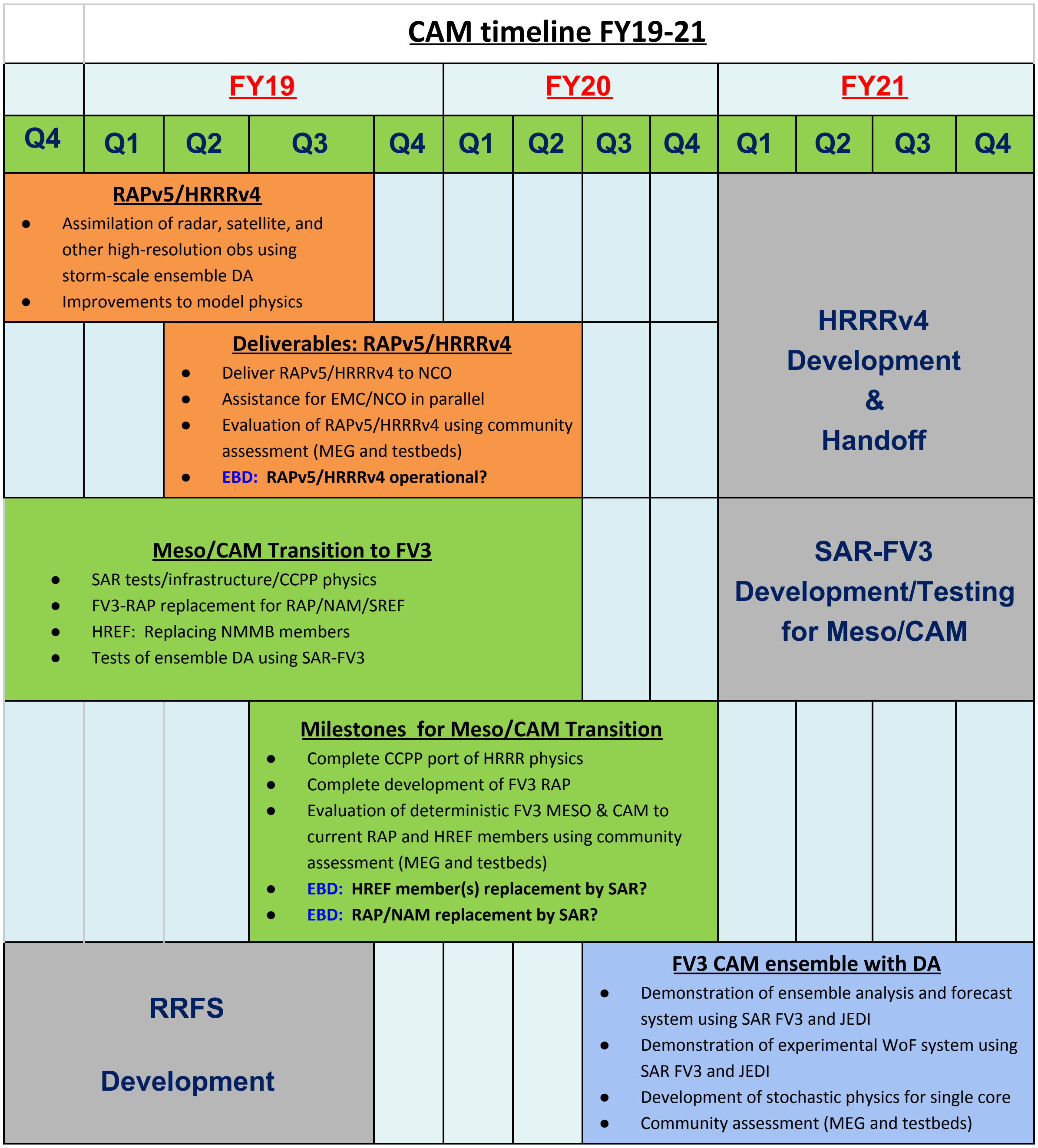
- Do they provide similar or improved forecast guidance relative to current operational products and contribute to a more unified production suite?
- Are they affordable and can they be implemented from available HPC resources? If they are more expensive, are the forecast benefit(s) worth the added cost?
- Can the forecast products meet operational delivery times?

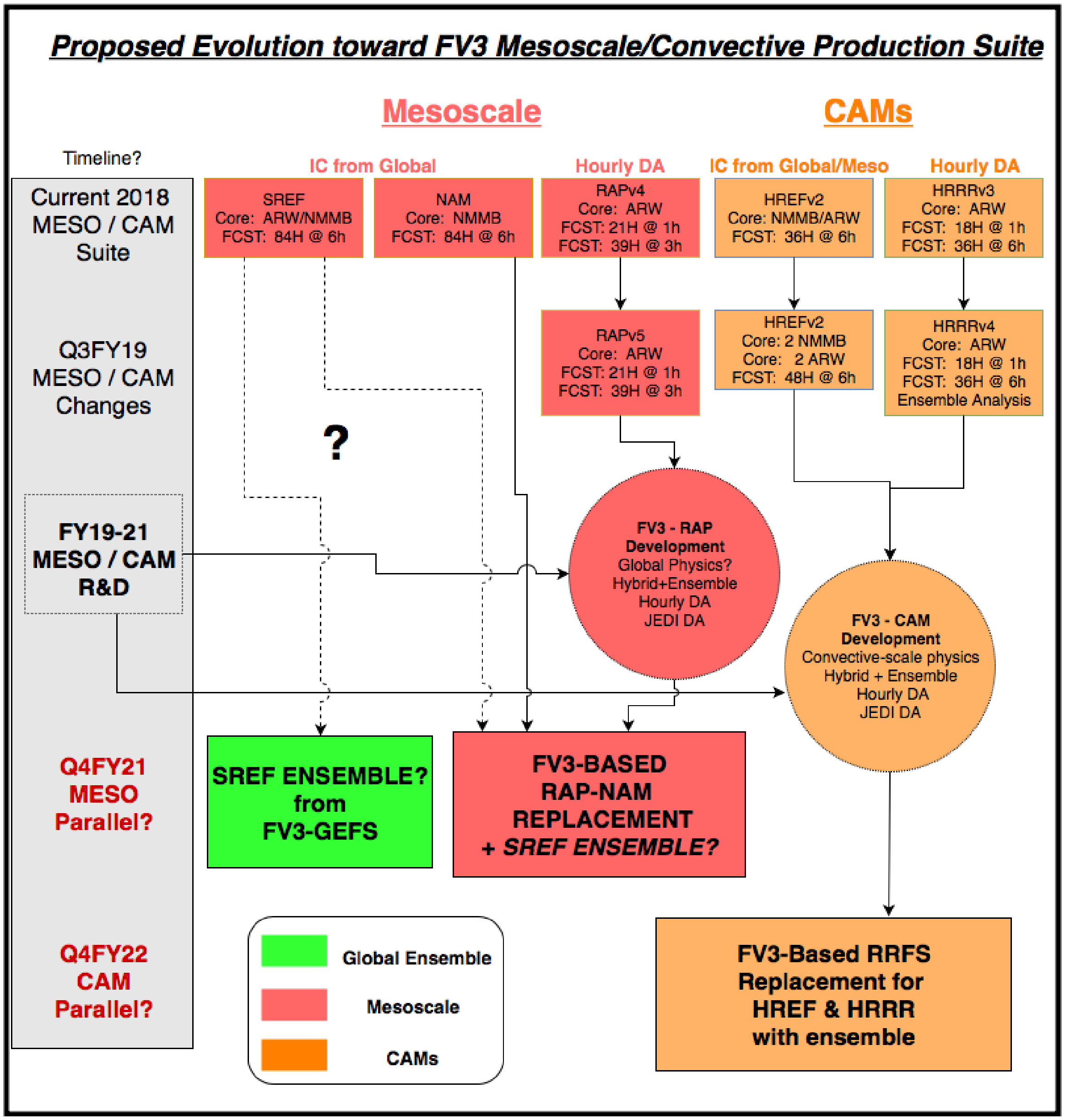
The determination of forecast improvements is itself an enormous effort that will involve objective verification, including probabilistic verification statistics of ensemble systems, as well as evaluation of novel probabilistic methods being developed between the OAR labs, NCAR, and EMC. Table 1 summarizes the verification metrics needed to make evidence-based decisions. It will require close collaboration with the Verification group (Annex #13). The MET verification system will serve as a common tool used by various groups. At the same time, experimental forecasts from each of the systems will also be evaluated through forecaster feedback in the various NCEP testbeds, EMC MEG reviews, and MEG-STI activities centered around these CAM systems through collaborations with several NCEP service centers (including EMC), NWS offices, and the model development groups at GFDL, ESRL, NSSL, and EMC. The NCEP testbeds include the Hazardous Weather Testbed (HWT) during the SPC/NSSL Spring Experiment, the Flash Flood and Intense Rainfall (FFaIR) experiment at WPC, the Winter Weather Experiment (WWE) at WPC, and the Aviation Weather Testbed (AWT) at AWC.

Table 1. CAM verification metrics

- Aspects unique to convection that include five categories of weather elements:
  - Mesoscale Environment (grid-to-point using METARs, RAOBs and aircraft obs)
  - Severe Convection (grid-to-grid using MRMS and surrogate severe obs)
  - Precipitation and Winter Weather (grid-to-grid using MRMS/Stage IV)
  - Aviation (grid-to-grid and grid-to-point using MRMS and METARs)
  - Air Quality (grid-to-point and grid-to-grid using METARs, RAOBS and ARM sites and CLAVR)
- Deterministic verification statistics
  - Continuous fields (RMSE, BIAS)
  - Dichotomous fields (CSI, BIAS, POD, FAR, FSS, AUC)
- Ensemble verification statistics
  - Continuous fields (spread-skill ratio, rank histograms)
  - Dichotomous fields (Brier score, Brier skill-score, reliability, sharpness, CRPS, CRPSS)
- Stratification of verification statistics
  - Forecast length (0-36 hrs)
  - Time-of-day (0-23Z)
  - Geographic domain (western and eastern US)
  - Neighborhood sizes in space (10-80 km) and time (instantaneous to 24 hrs)
  - Magnitude thresholds (varies by deterministic field and probabilities 0% to 100%)
- Summarize all of the information, as well as computational resource requirements, into a consolidated scorecard.

A detailed timeline for the three projects in the FY19-21 time frame is provided in the following Gantt chart. The second chart is an attempt to map out how the production suite might evolve over the next 3-5 years. After that, the three primary individual CAM project activities are described in more detail.





Project 7.1: Implementation of the RAPv5/HRRRv4 CAM ensemble analysis and hybrid deterministic HRRR forecast system

Project overview: As currently funded and described in the JTTI grant, *"Advancing Frequently-Updating Storm-Scale Ensemble Data Assimilation and Prediction Towards Operations"*, the last RAP-HRRR implementation is scheduled for code delivery to NCO in Q3FY19 for parallel testing in Q3-Q4 FY19. If successful, an operational implementation is planned for Q2 FY20. This system will provide an ensemble analysis system which can then be used for the reformulated 3DRTMA/3DURMA analysis. The 3 km ensemble analysis will be used by the GSI-based hybrid data assimilation to help generate the deterministic HRRR prediction forecast each hour.

As part of the transition to the UFS, the development of the NAM modeling system, including its high-resolution nests and the NMMB dynamical core, has been discontinued at NCEP. Similarly, the RAP/HRRR system and its ARW dynamical core will be frozen at NCEP by the end of FY2019. However, operational execution of these modeling and associated DA systems will continue until FV3-based systems are able to give equal or better performance. The final WRF-ARW implementation, RAPv5/HRRRv4, is scheduled for code delivery to EMC in Q3FY19 for an operational implementation in Q2FY20. This upgrade may include updates to the entire RAP/HRRR physics suite, use of new GOES-16/17 observations and MRMS dual-polarization radar mosaics, assimilation of VIIRS fire radiative power to initialize and predict wildfire-driven smoke plumes, and finally, adoption of an hourly-cycling storm-scale ensemble for data assimilation to improve HRRRv4 forecasts using the GSI-hybrid capability developed by Dr. Wang's group at the University of Oklahoma. The hybrid analysis system will be used to initialize the HRRR hourly deterministic forecasts.

Major Risks and Issues:
- Computational resources dedicated for model development and for operations
- Maintaining alignment with Unified Forecast System development strategy

Major resources requirements:
- EMC : 3 FTE
- ESRL/GSD : 3 FTE; GFDL : 2 FTE; NSSL : 1.5 FTE
- HPC for development:
- 10M CPU hours on WCOSS, NOAA R&D (Theia), Jet, Gaea;
- ~1000 TB scratch space and ~6 PB HPSS storage
- HPC for Operations:
- HRRRv4: ~700 TO4 nodes

Dependencies/linkages with other projects:
- MET-based Verification/Validation (Annex 13)

Core development partners and their roles:
- ESRL/GSD: Model development including physics and DA; retrospective and real-time experiments, testing and evaluation
- GFDL**:** Dynamics and grid configurations for regional domains; native support for CAM ICs and BCs; utilities for FV3 grid structure, diagnostics and I/O, including DA interfaces and interpolation tools; expertise and knowledge of FV3 dynamical core and related IPD and FMS software; model diagnostics and troubleshooting; advanced physics connections.
- NSSL: Daily real-time forecasting and evaluation based on applications for severe-weather prediction at SPC and across the NWS.

- EMC: Implementation, evaluation parallel testing, MEG.

Research and Development (R&D)/Testing and Evaluation (T&E) Milestones:

- Q1FY19 - Q4FY19 : Development of final WRF-ARW-based RAP/HRRR (RAPv5/HRRRv4) : ensemble data assimilation; model physics improvements and other changes to be decided
- Q1FY20 - Q4FY21 : Freeze deterministic WRF-ARW by Q1FY20 for RAPv5/HRRRv4 implementation

Project 7.2: Development of a SAR FV3 Meso/CAM replacement system for NAM/RAP/HREF-Member

Project overview: Currently, operational, deterministic, mesoscale and convection-allowing prediction capabilities at NCEP are enabled by the continental scale regional modeling systems (RAP and NAM). The RAP and NAM systems get their boundary conditions from the global model (i.e., the GFS) and leverage the GFS's atmospheric state for partial cycling. Both the RAP and NAM serve as the parent model for the operational CAMs. The NAM is updated at an hourly cadence with free-forecasts initialized every 6h and integrated forward 84h, enabling associated CAM forecasts (i.e., the NAM nest, Hi-res Window, and fire-weather nest) with potentially the same update frequency and forecast length. Meanwhile the RAP is updated hourly and integrated forward as far as 39h, depending on the initialization time, allowing corresponding CAM forecasts (i.e., the HRRR) with similar initialization frequency and forecast length.

As part of the NWS commitment to move towards a Unified Forecast System (UFS), NCEP's Regional/Mesoscale Modeling Suite will transition to use a high-resolution version of the FV3 dynamical core, both for the modeling and data assimilation components. A Stand Alone Regional (SAR) FV3 capability will be matured to facilitate low-observation-latency frequently-updating data assimilation cycles for components of the regional modeling suite.

A primary goal of the CAM-related strategy described in this SIP is to provide a pathway for achieving the functionality and performance of the RAP and NAM modeling systems and their respective CAM-scale nests – and to do so with a single, new (FV3) dynamical core. Specifically, this pathway should lead to the next generation (~2021) operational CAM prediction system at NCEP that is based on FV3, has an update cadence of no more than 1 hour, horizontal grid spacing of no more than 3 km, has a maximum forecast horizon of no greater than day 3-4, and analysis/integration domains covering CONUS in addition to those areas covered by current CAM prediction systems (e.g., Alaska, Hawaii, Guam, Puerto Rico, etc.).

This project has several components summarized below.

(a) Establish baseline CAM-ensemble performance (FY19 Q1-Q4)

Baseline performance will be assessed using a CAM scorecard developed using the MET verification software at DTC. Initial testing of a CAM scorecard occurred during SFE2018 and a comprehensive set of metrics for both deterministic and ensemble CAM systems has been developed by the CAM and V&V Working Groups that will be implemented into a more complete scorecard during FY19. This more comprehensive scorecard will be demonstrated during SFE2019, and by FY20 will be considered as one of the main evaluation tools for decision making on operationalizing future systems. The baseline ensemble against which newly developed systems will be evaluated is the current operational configuration of HREFv2.

b) Investigate and enhance the CAM-scale prediction capabilities of FV3-based models, including storm-scale processes and structures (FY19-20)

The ability of the FV3 dynamical core to support CAM-scale prediction capabilities has been an active area of exploration since 2016. Most of the testing has been done in a global configuration with a ~CONUS nest at ~3 km grid spacing. For the 2017 HWT Spring Forecasting Experiment (SFE), GFDL and OU/CAPS generated daily CAM-scale, ~36-h forecasts, using different microphysical parameterizations. A similar, but more expansive set of configurations were examined during the 2018 SFE. In general, results from subjective assessments and objective verification have suggested that, on average, the FV3-based forecasts are somewhat less skillful than those based on WRF-ARW and NMMB dynamical cores, but the latter have been optimized over a decade or more and the testing has not revealed any indication that the FV3 dynamical core is unsuitable for envisioned future CAM-scale modeling systems. Thus, we are confident that the development and implementation of FV3-based CAM systems will be successful. Since the skill of CAM-scale forecasts is known to be very sensitive to model physics, introduction of known meso- and CAM-appropriate physics packages will be tested first. The introduction of the Common Community Physics Package (CCPP) will enable a more rapid evaluation of current and improved physics packages.

c) Develop an FV3-based system with RAP/HRRR and NAM/NAM-nest-like capabilities (FY20-21)

The SAR FV3 will need to have the following characteristics in order to replace the current ARW-based RAP and HRRR systems:

- Must be capable of a cycling analysis of 1 hour frequency
- Horizontal grid spacing of no more than 3 km
- Forecast lengths of no more than 3-4 days
- Analysis/integration domains covering CONUS in addition to those areas covered by current RAP/NAM and HRRR/NAM-nest prediction systems (e.g., Alaska, Hawaii,, Puerto Rico, etc.)

In addition, the SAR FV3 will need a flexible and advanced nesting capability. This will be necessary for future generations of FV3-CAM. Thus, techniques for generating multiple nests and moving nests will be developed as part of this project and will also leverage the development supported by 2018-19 Hurricane supplemental funding.

While the eventual goal will be to replace the mesoscale (RAP/NAM) system with global ensemble system forecasts, the requirements from several of the operational centers (e.g., SPC, WPC) could delay this transition. *It is currently unclear whether the advanced physics package, slated for implementation in the global UFS Q2 2021? will be sufficient to meet all centers' operational requirements*. Therefore, it seems sensible, as a risk mitigation strategy, to develop an FV3-based RAP/NAM-scale replacement system to bridge any operational gaps downstream in the transition to the UFS. The current GSI-based approach, i.e., the advanced data assimilation (DA) capabilities (e.g., hourly cycle with radar/cloud assimilation as done in operational NCEP mesoscale DA systems), will be installed in the SAR FV3, starting in Q1FY19 to facilitate a transition to the FV3 core for deterministic mesoscale and CAM prediction after Q4FY20.

d) Develop an HREFv3 system with FV3 and ARW members (FY20-21)

The current operational CAM ensemble, HREFv2, uses a multi-core, multi-physics, and multi-IC/LBC configuration strategy, which emanated from the Storm Scale Ensemble of Opportunity (SSEO) developed at SPC in 2012. Since 2017, the NMMB has been frozen by EMC for development. As discussed previously, the SSEO system has proven to be difficulty to improve upon since its inception and development since 2012. The goal here is to improve the SAR FV3 performance sufficiently to match or exceed the NMMB/ARW performance.

Major Risks and Issues:

- Computational resources may not be available for making a comprehensive CAM scorecard by Q1FY20 for model development, validation testing, and parallel testing
- Engineering and infrastructure changes required for SAR: development with FV3 may be slower than anticipated
- Developing robust nesting capability within FV3
- Determination regarding whether hourly RAP-like mesoscale system will be needed while waiting on 13 km FV3-GEFS
- What do we do if skill of HREFv2 is never equaled or exceeded?

Major resources requirements:

- Personnel:
- EMC : 8 FTE
- ESRL/GSD : 6 FTE; GFDL; 2 FTE, NSSL (1 FTE)
- HPC for development : ~40M CPU hours on WCOSS, NOAA R&D (Theia), Jet, Gaea; ~1000 TB scratch space and ~6 PB HPSS storage

Dependencies/linkages with other projects:

- Standalone Regional (SAR) FV3 (Annex 4, Project 4.1)

- System Architecture/Nesting Requirements (Annex 2, Project 2.2)
- Infrastructure: Workflow, Documentation (Annex 3)
- Model Physics / CCPP (Annex 5)
- Data Assimilation (Annex 6)
- Unified Post-Processing (UPP) to support FV3 Standalone Regional (Annex 12)
- MET-based Verification/Validation (Annex 13)

Core development partners and their roles:

- **NCEP/EMC:** Model development including physics and data assimilation, evaluation of HREF members and implementation of SAR-FV3 into HREF, integration into NEMS framework and unified workflow, code management, retrospective and real-time experiments, testing and evaluation, transition to operations
- **ESRL/GSD:** Model development including physics; retrospective and real-time experiments, testing and evaluation
- **NSSL:** Daily real-time forecasting and evaluation based on applications for severe-weather prediction at SPC and elsewhere; HWT testing of various configurations.
- **GFDL:** Dynamics and grid configurations for regional domains; native support for CAM ICs and BCs; utilities for FV3 grid structure, diagnostics and I/O, including DA interfaces and interpolation tools; expertise and knowledge of FV3 dynamical core and related IPD and FMS software; model diagnostics and troubleshooting; advanced physics connections.
- **DTC:** Establish a user support framework that will include collaborating with and assisting NCEP/EMC to define a code management plan and repository testing protocols, code release procedures, a UFS-CAM Users' Guide, scientific documentation, and helpdesk support.

Major Milestones:

- **Q1 FY20:** Establish baseline CAM-ensemble performance using CAM scorecard in MET
- **Q4 FY20:**
    - Complete CCPP port of HRRR physics
    - Complete development of FV3 RAP
    - Develop hourly-updating DA cycle appropriate for CAM-scale prediction (with radar reflectivity assimilation, for example) with similar capabilities to current operational NCEP mesoscale DA with the FV3-based prediction system.
    - Evaluation of deterministic FV3 MESO & CAM to current RAP and HREF members using community assessment (MEG and testbeds)

- **Q2 FY21:**
    - Replacement of comparatively poor performing HREF member(s) by SAR
    - RAP/NAM replacement by SAR or global ensemble UFS?

Project 7.3: Developing a full CAM-scale ensemble DA and prediction system based on the SAR FV3 system

Project overview: This project describes the development, maturation, and eventual implementation of the Rapid Refresh Forecast System, the RRFS.

Use of storm-scale ensemble error covariance information during data assimilation for CAM applications will serve to improve both deterministic forecasts in project 7.1 and also serve to underpin future storm-scale ensemble forecasts discussed in project 7.2. Storm-scale ensemble data assimilation will be incorporated into the HRRRv4 operational implementation in Q2FY20. The ensemble analysis system will be used for the reformulated 3DRTMA/3DURMA analysis and HRRR deterministic system. Since the HRRRv4 system will then be frozen, this system can be used to assess the new SAR FV3 performance. In Q4FY19, the SAR FV3 infrastructure is planned to be mature enough to begin testing hybrid ensemble-variational data assimilation methods using case studies. Development and testing of hybrid and ensemble data assimilation techniques for hourly- and sub-hourly cycling using a wide variety of observations [e.g., satellite (GOES-16/17 and JPSS) cloud information, MRMS mosaics and radar radial velocity, lightning, upper-air and surface observations] should provide an initial benchmark for the FV3 performance by Q3FY19. By end of Q4FY20, an initial version of the SAR FV3 in the JEDI system should be available for real data experiments, but may not yet be fully mature for operational implementation.

The current operational CAM ensemble, HREFv2, uses a multi-core, multi-physics, and multi-IC/LBC configuration strategy, which emanated from the Storm Scale Ensemble of Opportunity (SSEO) developed at SPC in 2012. In multiple years of testing and evaluation during HWT SFEs by NSSL and SPC, as well as independent analyses performed at NCAR and GSD, HREFv2 has consistently outperformed CAM ensembles utilizing single model configuration strategies (e.g., the HRRRE, NCAR ensemble, CAPS SSEF ensemble, etc.). Thus, developing a single model, FV3-based CAM ensemble that provides equal or improved performance relative to HREFv2 will be a challenge for transitioning to the RRFS. Therefore, methods for providing appropriate representations of error/uncertainty applicable to the SAR FV3 system are of critical importance toward the successful realization of a single-core CAM ensemble system. Furthermore, reasonable representation of error is also a critical component of a successful ensemble data assimilation system since the ensemble is leveraged in generating the background error covariance which directly affects the quality of the analysis. Key components to account model the error distribution include: initial condition uncertainty, lateral boundary uncertainty, and model error.

- Initial condition uncertainty: Will be a natural byproduct of the ensemble-based data assimilation system. Tuning and adjustment, e.g. perturbation inflation, will be required to mitigate filter divergence.
- Lateral boundary uncertainty: It is anticipated that this will come from the GEFS, assuming it has sufficient spread characteristics.

- Model error: The addition of stochastic physics forcing. In a single-model, single-physics system, methods must be developed to account for model error, or the system will be under-dispersive. Several methods for introducing model error have already been tested in the HRRRE, and this testing will continue and expand in this development work for the SAR FV3. For example, lower boundary perturbations (e.g., soil moisture state) have or will be added and stochastic physics techniques such as SKEB, SPPT, and SPP will be added and expanded to the SAR FV3 system to account for as many model uncertainties as possible. Current work has focused on the development of the best configuration for the SPP to perturb variables and parameters in multiple physics scheme such as, PBL, surface layer, Land Surface Model (LSM), microphysics, and radiation. Changes within different schemes as well as a synergistic effect between various schemes needs to be evaluated and adjusted as needed. The employment of diversity in physics schemes may be introduced as a risk mitigation strategy.

Development of the hybrid EnVar data assimilation system will be informed by prior success and experience across collaborating organizations, which includes the HRRR and HRRRE, the NEWSe, and the NAM nests. Each of these systems currently employ a variant of the GSI data assimilation system for CAM DA. During the FY19-FY21 period we will be working within the JEDI project to ensure the incorporation of fundamental CAM DA capabilities of the aforementioned systems. However the JEDI system may not be sufficiently mature by the close of FY21 to support an operational RRFS. Therefore, as a risk mitigation strategy, developers may choose to perform a piecewise implementation of the core parts of the JEDI system along with GSI, e.g. the forward operators from JEDI with the solvers from GSI.

Major Risks and Issues:

- Computational, including disk and archive, resources dedicated for model development and for operations
- JEDI readiness - it is not likely the full JEDI system will be ready for SAR-FV3 by the close of the current SIP period (Q4FY21 years).
- Engineering and infrastructure changes required for SAR to run ensemble regional forecasts
- Implementation of convective-scale physics via the CCPP with FV3
- Ensemble-based high-frequency convective-scale DA requiring FV3 core tuning/improvements
- Sufficient funds, human resources, and subsequent slow onboarding procedures

Major resources requirements:

- Personnel:
    - EMC : 3 FTE
    - ESRL/GSD : 3 FTE; GFDL; 2 FTE, NSSL (1.5 FTE)
    - HPC for development:
        - 10M CPU hours on WCOSS, NOAA R&D (Theia), Jet, Gaea;
        - ~1000 TB scratch space and ~6 PB HPSS storage
- HPC for Operations:

    - RRFSv1 (~Q4FY21): ~3000 TO4 nodes?

Dependencies/linkages with other projects:

- Standalone Regional (SAR) FV3 (Annex 4, Project 4.1)
- System Architecture/Nesting Requirements (Annex 2, Project 2.2)
- Infrastructure : Workflow, Documentation (Annex 3)
- Model Physics / CCPP (Annex 5)
- Data Assimilation (Annex 6)
- Unified Post-Processing (UPP) to support FV3 Standalone Regional (Annex 12)
- MET-based Verification/Validation (Annex 13)

Core development partners and their roles:

- NCEP/EMC: Data assimilation development - including transitioning to JEDI, hybrid EnVar algorithm and observation operator development. Model/ensemble development (including physics), workflow, code management, retrospective and real-time experiments, testing and evaluation, transition to operations.
- ESRL/GSD: Model development including physics and storm-scale ensemble DA; retrospective and real-time experiments, testing and evaluation, SAR FV3-based system running under JEDI
- NSSL: High-frequency DA testing, development of JEDI UFO for radar observations.
- GFDL: Dynamics and grid configurations for regional domains; native support for CAM ICs and BCs; utilities for FV3 grid structure, diagnostics and I/O, including DA interfaces and interpolation tools; expertise and knowledge of FV3 dynamical core and related IPD and FMS software; model diagnostics and troubleshooting; advanced physics connections.
- ESRL/PSD and JCSDA: DA development support (JEDI)
- DTC: Establish a user support framework that will include collaborating with and assisting NCEP/EMC to define a code management plan and repository testing protocols, code release procedures, a UFS-CAM Users' Guide, scientific documentation, and helpdesk support.

Major Milestones:

- Q4FY20:
    - Development of stochastic physics for single core
    - Transition SAR FV3 DA to JEDI and complete initial testing.
    - Test SAR FV3 and JEDI for HRRR and WoF applications.
    - Complete *initial* testing of DA at CAM scales with an FV3-based system
- Q4FY21:
    - Demonstration of ensemble analysis and forecast system using SAR FV3 and JEDI
    - Demonstration of experimental WoF system using SAR FV3 and JEDI
    - Community assessment (MEG and testbeds)
    - Begin stakeholder evaluation process (e.g. NOAA testbeds) for possible implementation for RRFS.

<u>ANNEX 8</u>: MARINE MODELS

The Marine Modeling WG has outlined the following projects for this SIP document. These include projects which have a well-defined path for the next 3-5 years and those which are targeted towards delivering a long-term (5-10 years) strategy that will later result in new capabilities. The latter projects require further inputs and analysis from the community.

- Ocean Data Assimilation (NCODA) to support RTOFS (FY19-21)
- Marine Models coupling:
    - FV3 based Hurricane Model developments: Moving nests and coupling to other Earth System Components (FY19-21)
    - Development of Coupled Atmosphere-Ocean-Ice Wave System for sub-seasonal to seasonal (FY18-22)
    - Coupling wave models to Atmosphere systems (FY19)
    - Coupled Ice-Ocean System for weather time scales (FY18-20)
- Integrated Water Prediction (IWP) (next 3-7 years)
- Long-term strategy for NextGen Ocean Modeling and Data Assimilation (next 3-7 years)
- Ecosystems and Eco-Forecasting (next 3-7 years)

<u>Project 8.1: Ocean Data Assimilation (NCODA) to support RTOFS</u>

Project overview: In 2013, EMC signed a Memorandum of Understanding (MOU) with NRL to port NCODA to EMC. Having NCODA implemented at EMC will eliminate the need for a daily data feed from NRL to EMC, as well as the need for EMC to remain in lockstep with NAVO/NRL with respect to model development. The transfer of data assimilation (DA) approaches for real-time ocean analysis at NCEP will allow support of applications in the planned unified modeling framework.

The main goals for the first two years under R2O are twofold: 1) Implement NCODA at EMC, and 2) Provide ocean initialization/analysis fields for RTOFS/HYCOM based applications. As NCODA reaches implementation at EMC, development and research priorities will be addressed. The third year (FY20) will be spend on leveraging NCODA developments for marine JEDI based applications and including new observations.

POCs: Arun Chawla and Ilya Rivin (EMC)

Priority: High

Major Risks and Issues:

- System delivered from NRL was with missing documentation, test cases, operational protocols, scripts and supporting codes
- NCEP is under-resourced for marine observation processing

Major resources requirements:

- Personnel: EMC (2.5 FTE)

- HPC for development: 3 Million CPU-hours on WCOSS and RDHPCS; 50 TB of disc

Dependencies/linkages with other projects:
- ANNEX 6 (Data Assimilation) Processing and monitoring of marine/ocean observations
- ANNEX 6 (Data Assimilation) Marine JEDI development

Core development partners and their roles:
- JEDI and ObsProc team at EMC

Major Milestones:
- Develop and test interface between NCEP operational data tanks and NCODA QC. (FY18Q1, completed for SSH and SST)
- Implement global NCODA+HYCOM; test and cycle using canned data as input. (FY18Q3, completed)
- FY19Q1: Develop and test interface between NCEP operational data tanks and NCODA QC (for profiles and surface obs.)
- FY19Q2: Real time end-to-end NCODA parallel for RTOFS Global for evaluation
- FY19Q4: Pre-operational testing; transition to NCO
- FY20Q1+: Operation and maintenance of NCODA, including new and modifying data sources and QC procedures; evaluating downstream impacts

Project 8.1: Ocean Data Assimilation (NCODA) to support RTOFS

Implementation Plan for NCEP NCODA (FY19 - 21)										
NCODA	**FY19**				**FY20**				**FY21**	
	Q1	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**
NCODA QC	Develop and test interface between NCEP operational data tanks and NCODA QC.									
NCODA 3DVAR	Long-term global NCODA + HYCOM analysis using QCed data as input									
Real-time parallel	Real-time end-to-end NCODA+HYCOM parallel, testing, improving , and evaluation of downstream impacts.									
Transition to Ops			Transition to NCO							
NCODA O&M					Operation, maintenance, including new and modified data sources and improving QC.					

Project 8.2a: FV3 based Hurricane Moving nests

(Note: This project is cross-listed as 4.2 under the Dynamics and Nesting Annex of this SIP.)

Project 8.2b: Development of Coupled Atmosphere-Ocean-Ice Wave System for sub-seasonal to seasonal

(Note: This project is cross-listed under the Global Model Suites Annex of this draft SIP.)

Introduction The coupled atmosphere-ocean-ice-wave project will develop the next generation sub-seasonal to seasonal forecast system based on the FV3GFS atmospheric model, the MOM6 ocean model, CICE5 ice model, GOCART chemistry model and WAVEWATCH III wave model coupled via the NUOPC/NEMS framework. (Note: The GOCART and FV3GFS components are being coupled as a separate application initially while the coupled atmosphere - ocean-ice-wave system is being developed. Once the two applications reach a level of maturity the chemistry component will be added to the coupled application). The initial development is focused at the sub seasonal time scale (0 - 35 days forecast). The same framework will be extended to the seasonal time scales to provide model guidance out to 9 months. At this moment land is being considered as part of atmospheric physics. The decision to consider land as a separate component will be made by the physics and land working groups. The ensemble perturbations will be expanded to the ocean model to provide greater spread for the coupled system. The initialization of the other components (land, aerosol waves, ice) will also be developed.

POCs: Bin Li, Jessica Meixner, Jiande Wang, and Denise Worthen (EMC)

Major Risks and Issues:

- Computational resources for model development
- New physics algorithms for coupled systems require extensive testing
- Data assimilation techniques for ice is not at a mature stage
- Efficiency of fully-coupled high-resolution system has not been addressed
- Verification package for coupled system is not complete yet

Major resource requirements:

- Personnel: EMC (9 FTEs); ESRL/GSD/NESII (TBD); GFDL (TBD)
- HPC for development: TBD

Dependencies/linkages with other projects:

- Development for FV3-GEFS will feed into this system
- Annex 2 (SOFTWARE ARCHITECTURE): NEMS / NUOPC infrastructure for the component models needs to be ready; requirements need to be communicated
- Unified Workflow (CROW)
- Atmosphere - chemistry coupling
- Atmospheric physics development
- JEDI (JEDI is part of the Q2FY19 milestone for FV3-GDAS in Annex 1.)

Core development partners and their roles:

- NCEP/EMC: Partner with NESII to develop the coupled system in the NEMS framework including coupling the MOM6, WAVEWATCH III, CICE5 and GOCART components; developing the DA framework for each of the components; testing, tuning and verification of new physics algorithms for coupled systems
- GFDL: Partnering with EMC in developing wave and ocean coupled mixing parameterization. GFDL is also providing expertise in FV3 development and ocean modeling. The FV3-SFS development has numerous similarities with the CM4 model being developed by GFDL, and as such GFDL will provide their expertise knowledge in coupling FV3 with MOM6.

- ESRL/GSD (NESII): Partnering with EMC and GFDL on developing the coupled system in the NEMS framework. The NESII team led development of the NEMS mediator and previous coupling of atmosphere, MOM5, CICE5, and WAVEWATCH III.

Major Milestones:

- Prototype coupled system with FV3-MOM6-WAVEWATCHI-CICE5 (FY18Q3, completed)
- FY18Q4 - A coupled FV3-MOM6-CICE5-WW3 model available for science testing
- FY20Q1 - Testing of coupled system for week 3-4 using GEFS V12 configuration
- FY20Q1 - Marine DA system available for cycling coupled system
- FY21Q3 - Completion of R/R for coupled model
- FY21Q4 - Transition to operations of coupled model for week 3-4 forecasting

<u>Project Gantt Chart</u>

FY18				FY19				FY20				FY21				FY22			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Development of Coupled FV3 - MOM6 - CICE5 - WW3 model																			
			Test Coupled system out to week 3-4 using GEFS v12 configuration [Forecast only, full cycling when Marine DA is ready]																
		Adding GOCART (Aerosol) [Subject to FV3GFS - GOCART being ready]																	
			Add NOAH-MP																
					Enhance Atmospheric and Marine Perturbation techniques to improve skill														
					Explore alternative physics options and test balance across air - sea interface														

Development of DA capability for MOM6, CICE5, WW3, LAND, AEROSOL																			
									Reanalysis & Reforecast & Evaluation & Validation										
													T2O						

Project 8.2c: Coupling wave models to Atmosphere systems

Introduction Sea surface drag is modified by the waves. Right now GFS physics uses a constant Charnock coefficient which approximates wave effects indirectly through the wind speed. A detailed wave induced surface drag formulation has been developed in WAVEWATCH III. In this study, the FV3GFS atmospheric model and the WAVEWATCH III model will be coupled via NEMS connectors and the physics module will be changed in FV3GFS to accept the computed sea-state dependent drag formulation from the wave model. We expect impact limited to surface physics.

POCs: Jessica Meixner and Shrinivas Moorthi (EMC)

Major Risks and Issues:

- FV3 needs physics updates to accept z0 from wave model.
- Needs workflow development for cycling tests, including inclusion of wave validation into workflow.
- Efficiency in speed and memory usage in coupled FV3-WW3 system.
- Memory used in coupled FV3-WW3 runs for C768 is double for FV3 compared to standalone C768 FV3 run.
- Efficiency of FV3-WW3. The coupled app will benefit from improvements in standalone FV3 forecast (such as pre-computing route-handles and other planned improvements), however using 32 bit for FV3-WW3 does not give same improvement of speed as the standalone FV3 gets comparing 64 to 32 bit.

Major resource requirements:

- Personnel: 2 FTE per year
- HPC for development:

Dependencies/linkages with other projects:

- ANNEX 5 (PHYSICS): Developments for FV3-GEFS and FV3-GFS physics
- ANNEX 2 (SOFTWARE ARCHITECTURE): NEMS / NUOPC infrastructure for the component models needs to be ready; requirements need to be communicated

Core development partners and their roles:

- NCEP/EMC: Partner with ESRL/GSD (NESII) to develop the coupled system in NEMS framework including coupling the MOM6, WAVEWATCH III, CICE5 and GOCART components; testing new physics algorithms for coupled systems
- GSD/NESII: Partnering with EMC and GFDL on developing the coupled system in the NEMS framework. The NESII team led development of the NEMS mediator and previous coupling of atmosphere, MOM5, CICE5, and WAVEWATCH III.
- NRL: Further development of the NUOPC cap for multi-grid WW3 as well as coupled physics for wave - atmosphere and wave - ice interactions. NRL is also working in developing technical improvements to the wave model.

Major Milestones:

- Initial physics testing with cycled GFS coupled to WW3 (Q1FY18, completed)
- Coupled to FV3 cap with new physics (Q2FY18, completed)
- Add WW3 to FV3 based GEFS (Q3FY18, completed)
- Transition to WW3 Multi-grids (Q3FY18, completed)
- Sep 2018 -- Set up coupled FV3GFS - WW3 model for C768 FV3 and ½ deg WW3
- Nov 2018 -- Workflow for end to end run (initial conditions + forecast + post processing + validation)
- Dec 2018 - Jan 2019 -- First set of runs with validation
- Feb 2019 - March 2019 -- Alternative coupling scenarios

Project 8.2c Gantt Chart

FY19			
Q1	**Q2**	**Q3**	**Q4**
Set up high-res FV3GFS-WW3			
Workflow Updates for End-to-End System			
First experiments	First experiments		
		Alternative Coupling Scenarios	Alternative Coupling Scenarios

Project 8.2d: Coupled Ice-Ocean System for weather time scales

Introduction

NCEP currently runs a coupled ice-ocean model (RTOFS Global, with Hycom ocean and CICE4 sea ice) at high resolution and for short time scales (1/12th degree and 8 days maximum lead). This system, however, is not coupled through the NEMS/NUOPC framework and is not using the most recent sea ice component (CICE5), making it difficult to carry out community modeling with it, and to maintain it in an NCEP context. In this project, we are working with developing a coupled ocean - ice model that will use the NEMS/NUOPC framework to couple the HYCOM ocean model with the CICE5 ice model and using a data atmosphere NUOPC component to drive this system, analogous to current RTOFS operations, but also useful for development in other components which will couple with the atmosphere (e.g. wave-ocean-atmosphere and others). Then to develop metrics for sea ice component evaluation, and coupled system evaluation. This effort is the high resolution / short time scale end member of the efforts for coupled modeling, all of which will be using the CICE5 sea ice model from the Sea Ice Consortium.

POCs: Denise Worthen, Robert Grumbine, Avichal Mehra, Arun Chawla (EMC)

Major Risks and Issues:

- Computational resources for model development
- Data assimilation techniques for ice is not at a mature stage
- Efficiency of fully-coupled high-resolution system has not been addressed
- Verification package for coupled system is not complete yet
- No NWS Requirement yet articulated for coupled ice-ocean model guidance

Major resource requirements:
- Personnel: EMC (1.5 FTEs); ESRL/GSD (TBD); GFDL (TBD)
- HPC for development: TBD

Dependencies/linkages with other projects:
- Annex 2 (SOFTWARE ARCHITECTURE): NEMS / NUOPC infrastructure for the component models needs to be ready; requirements need to be communicated
- Unified Workflow (CROW)
- Atmospheric physics development (polar atmospheric physics, ice-atmosphere coupling)
- NCODA

Core development partners and their roles:
- NCEP/EMC: Partner with GFDL, Navy, ESRL, and Sea Ice Consortium in developing and testing sea ice component of coupled systems
- GFDL: Partnering with EMC coupled air/sea/ice modeling
- Navy: Partnering with EMC for community ice model development and HYCOM ocean model development
- ESRL/GSD (NESII): Partnering with EMC in developing/testing atmospheric physics in polar regions

Major Milestones:

- FY18Q4 - Data Atmosphere-Hycom-CICE5 model available for science testing
- FY19Q1 - Running routinely for forecast skill evaluation v. operations
- FY19Q2 - CaRDS requirement submitted
- FY19Q3 - NCODA ice/ocean DA handoff
- FY19Q4 - CaRDS requirement approved
- FY20Q1 - T2O of weather scale system
- Continual - Updates to and from Sea ice consortium
- Continual - Knowledge sharing to and from longer term, lower resolution configurations coupled to sea ice

Project 8.2d Gantt Chart

FY18				FY19				FY20			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Development of Coupled Data Atmosphere - Hycom - CICE5											
			Routine execution of coupled ice-ocean weather scale								
Pursuit of CaRDS requirements											
			NCODA (external)								
					T2O						
					Evaluation -- atmospheric physics in polar regions						
	Updates To/From Sea Ice Consortium										
	Sea ice observation and model knowledge sharing across time and space scales										

Project 8.3: Integrated Water Prediction (IWP) (3-5 years)

Project overview: NOAA has embarked on a comprehensive NOAA Water Initiative, designed to give people and governments better access to the water information they need for their unique circumstances, so that they may take appropriate actions to address water-related risks and manage their water resources more efficiently and effectively. NOAA is actively working with its partners in academic, non-governmental, and private sector organizations to develop and deliver services focused on next-generation water prediction, sustained decision support, and delivery of timely, accurate, and actionable water information services, based on a deep understanding of user needs.

The NOAA Water Initiative is guided by one overarching common goal - to transform water information service delivery to better meet and support evolving societal needs. This goal directly supports NOAA's mission to protect life and property from extreme events and to create and strengthen resilience in ecosystems, communities, and economies. A strategic implementation plan to revolutionize water modeling, forecasting and precipitation prediction is key to transforming NOAA's current water prediction services to provide integrated water modeling and prediction across a range of timescales and watershed sizes, with the appropriate timeliness, resolution, reliability, and accuracy required to help inform decision making. The pillars of this modeling work are:

- Transforming NOAA's inland and coastal hydrology prediction services through ongoing improvements to existing hydrologic services, including coastal mapping, the continued implementation and utilization of the Hydrologic Ensemble Forecast Service (HEFS), and the continued development of the National Water Model (NWM);
- Transforming NOAA's quantitative precipitation forecasting capabilities at time scales necessary to support water supply and water resource management —from daily to weekly to seasonal — through research into key underlying physical processes, including sources of predictability, and the development of subseasonal to seasonal forecasting tools;
- Recognizing water as habitat by integrating physical and ecological modeling of water quantity and water quality (e.g., temperature, salinity, ocean color, etc.) to inform effective management of riverine, estuarine, and marine ecological functions and processes in support of a wide variety of human uses and community needs; and
- Evolving NOAA's water modeling efforts in support of the longer range goal of integrated Earth system modeling in the context of a unified modeling approach, where best practices in process understanding, model development, data assimilation, post-processing, and product dissemination will be leveraged across disciplinary boundaries.

POCs: Pat Burke (NOS)

Major Risks and Issues:

- Sustained Federal appropriations are needed to fully realize the vision outlined above
- Decision on which storm surge model(s) will be supported is needed. A cross-NOAA Team led by NWS is drafting the Extra-Tropical Storm Surge Conops that will contain recommendations and requirements for improved Extratropical Storm Surge forecasts. The draft is due by the end of FY18. Recommendations from this report will be integrated into future versions of the SIP.

Major resources requirements:

- Personnel (TBD): NWS (OWP, NCEP, NHC), NOS (CO-OPS, OCS, IOOS), OAR (GLERL, GFDL)
- HPC for development and operations: a) Increased allocation needed for NWM and 2D/3D coastal models and b) seamless access to Federal systems to support advancements of external modeling communities

Dependencies/linkages with other projects:

- Land/Hydrology (ANNEX 9): Advancements are dependent on the continued development of the NWM
- NOS: Full buildout of NOS' Operational Forecast Systems
- NOS: COASTAL Act supporting coupling of ESTOFS (ADCIRC) with WaveWatch III. Note that coupling will take place within NEMS to facilitate the sharing of model parameters.
- OAR: Coordination with MOM6 development

- Coastal Ocean Modeling Testbed (COMT): NOS/IOOS grant mechanism to support multiple model coupling projects

Core development partners and their roles:

- NOAA (Lead)
- USGS
- USACE
- FEMA
- Navy
- Academia

Major Milestones:

- The Multi-Year Strategic Science and Services Plan is the proposed multi-year timeline to achieve the outcomes of this initiative. Dedicated funding through new appropriations from Congress will be needed to fully realize the goals of this plan.
- NOS will continue to expand coverage of its 3-D coastal operational forecast systems to support future integrated water prediction efforts over U.S. coastlines and the Great Lakes.
- Funding has been received through FY18 appropriations and through FEMA in support of the COASTAL Act. Initial work being supported is coupling of ADCIRC with WaveWatch III and coupling of ESTOFS with NWM using middleware called Deltares D-FLOW on a local, and then regional/national scale to support flash-flood and urban water prediction and total water levels during storm events. Note that more direct coupling approaches with NWM are also being advanced. Final coupling of NWM and ADCIRC will take place within NEMS.
- Investments are needed to improve quantitative precipitation forecasts from the short-time scale through seasonal prediction to improve precipitation forecasting products.
- Funded efforts to couple NWM with coastal OFS models are long-term goals of IWP to support total water level, drought and water quality objectives. Efforts to investigate approaches will begin in FY19.

Implementation Plan for Integrated Water Prediction (FY18-20)												
Integrated Water Prediction	FY18				FY19				FY20			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Future Models	Decision on future Storm Surge models											
Local coupling					Coupling of NWM and ESTOFS (ADCIRC) on a regional scale							
									Coupling of ESTOFS with WaveWatch III			

Implementation Plan for Integrated Water Prediction (FY21-23)												
Integrated Water Prediction	FY21				FY22				FY23			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
National Coupling	Coupling of NWM and ESTOFS on a national scale											
Precipitation Forecasts					Delivery of improved precipitation forecasting products							
Coupling to coast circulation models									Coupling of NWM and 3D coastal/lake models (ROMS, FVCOM) to support water quality and biogeochemical needs			

<u>Project 8.4: Long-term strategy for NextGen Ocean Modeling and Data Assimilation</u> (3-5 years)

Project 8.4a: NexGen Ocean Model

Project Overview: Recently, two community workshops have been held (October 2016, May 2017) to consider development of the NexGen ocean model based on Arbitrary Lagrangian Eulerian (ALE) coordinates along with the feasibility of a common ocean model framework for operations and research, suitable for both high-resolution, short time scale work as well as coarser resolution, longer time scale modeling. The first workshop in 2016 outlined a number of recommendations for future action. These recommendations fall into four broad categories: Code Sharing, Community Building, Code Merger and Performance and Future Development. Based on these initial recommendations, the 2017 workshop decided on a notional list of requirements for a common community ALE-based ocean modeling effort, which should:

- support as many agencies / modeling centers as possible, testable by each center's own metrics
- be an efficient, scalable code to permit high resolution modeling
- be a global multi-scale effort, capable of supporting nests for regional modeling
- consist of modular code so that ALE modeling groups in NASA GISS and DOE LANL could exchange modules, and thus enhance development
- allow many eyes throughout the community to look at the model, leading to model improvements

A key point that emerged from both these workshops is that ALE is versatile and permits general vertical coordinates including traditional z, isopycnal, and terrain-following coordinates, as well as hybrid combinations of the former and other creative treatments yet to be formulated and explored. The group agreed on the need to converge to a single, modular ocean modeling framework for all time scales. NWS/NCEP would benefit significantly from this approach by adopting this framework for all its ocean-based operational applications since they currently use both HYCOM- MOM-based systems.

POCs: Avichal Mehra (EMC)

Major resources requirements:

- Personnel: NRL (1 FTE), NOAA/GFDL (TBD), Univ. of Michigan (TBD), NOAA/NCEP (1 FTE Base)
- HPC for development: Allocations on research R&D resources (Theia, Gaea, S4)

Dependencies/linkages with other projects:

- Advancements are dependent on the continued development of the NexGen ocean model framework

Core development partners and their roles:

- NOAA/GFDL (Co-lead)
- US Navy (Co-lead)
- NOAA/NCEP
- University of Michigan

Project 8.4b: Marine DA

Introduction: EMC has begun the consolidation of marine data assimilation activities towards the JEDI paradigm. To this end, the individual data assimilation systems for ocean, sea-ice and waves have begun their refactoring within a single LETKF based ensemble data assimilation system. The second step is the replacement of the individual observation operators with the **U**nified **F**orward **O**perator (UFO) from JEDI. The next step is to replace the 3DVar from hybrid GODAS developed for the ocean DA system with the one from JEDI SOCA project. The final step is the replacement of stand-alone LETKF with the one from JEDI.

POCs: Daryl Kleist, Arun Chawla (EMC)

Major Risks and Issues:

- Generalized LETKF from CPC
- JEDI components [IODA, UFO, Model interfaces, 3DVar] from JCSDA
- EMC is under resourced for building JEDI interface and expertise

Major resource requirements:

- Personnel: EMC (4 FTE), CPC (1 FTE), JCSDA (1 FTE)
- HPC for development: 2 million CPU hours on Theia/WCOSS, 50 Tb of disk space

Dependencies/linkages with other projects:

- Annex 6 (Data Assimilation): Processing of Marine Observations [for IODA, UFO]
- Annex XX [where can I see the other Annexes?]

Core development partners and their roles:

- NCEP CPC [Development of generalized LETKF]
- NCEP EMC [Development of generalized workflow, Unified coupled FV3-MOM6-CICE5-WW3 model, WW3 Interface within JEDI, Observation pre-processing]
- JCSDA [Development of JEDI infrastructure and interface for MOM6-CICE5, Incorporation of IODA for handling ocean observations, Development of observation operators within UFO, 3DVar for MOM6]

Major Milestones:

- Q4FY2020: LETKF and workflow for MOM6-CICE5
- Q4FY2020: Replacement of observation operators with JEDI UFO

Project 8.5: Ecosystems and Eco-Forecasting (3-5 years)

Project Description: Ecological forecasts are used by NOAA to predict likely changes in ecosystem components in response to environmental drivers and resulting impacts on people, economies, and communities depending on corresponding ecosystem services. Ecological forecasts provide early warnings of the possible effects of ecosystem changes on coastal systems, human health, and/or regional economies, aiming to provide sufficient lead time for developing mitigation strategies and taking corrective actions. NOAA has adopted an Ecological Forecasting Roadmap (EFR), providing guidance for coordinating activities and leveraging resources amongst multiple activities for a multi-disciplinary capacity, including habitat/species ecological forecast models, supporting integrated habitat and living marine resource management. This Roadmap identifies NOAA priority ecological science needs, coupling data, models, and products to address ecological forecasting requirements and enable informed decision-making.

NWS/NCEP's role within the EFR: Amongst the outlined strategic priorities for Eco-Forecasting are core capabilities and cross-cuts that are essential for all ecological forecasts, including, but not limited to: ongoing observations and data collection from various platforms and *in situ* sensors; the integration and application of atmospheric, physical oceanographic, chemical, and ecological models; data management and analysis; computational capacity; test beds; capacity to develop and test new algorithms; and delivery mechanisms. A holistic view of national infrastructure requirements allows NOAA to be more effective in pursuing and applying its resources. NWS/NCEP, along with other core partners both within and outside NWS, can play a key role in providing this needed national infrastructure in support of the Eco-Forecasting roadmap objectives. The primary objective of a national infrastructure would be to enable NOAA's research, technology, people, processes, and systems to support ecological forecasting at a national scale, which then can be applied and delivered regionally. Some specific objectives of such an infrastructure could include:

- Establish a corporate ecological forecasting enterprise framework that builds on NWS/NCEP's existing infrastructure systems and capacities. These capacities include models, observations, data integration and analysis, product generation, dissemination, and archiving.
- Develop and advance a strategy to improve and operationalize observational and modeling capabilities for ecological forecasting, focusing on incorporating ecological forecasting requirements and time frames into existing products.
- Ensure ecological forecasting research and model development are aligned with service delivery needs and actively support the transition of new products and services into applications.
- Leverage and transition, as appropriate, partner regional ecological forecasting research and development into NOAA operations and applications.
- Incorporate NWS/NCEP and partner regional assets (e.g. IOOS Regional Associations) into the operational framework for forecasting to create an efficient business model for forecast development and delivery.

- Formalize agreements required for sustained operational ecological forecast production and delivery.
- Mobilize and sustain a highly skilled and motivated workforce across all Line Offices to meet EF mission objectives.
- Establish mechanisms for information technology (IT) support of cross-Line Office products and data streams, including data and product access and visualization.

POCs: Eric Bayler (NESDIS/STAR), Avichal Mehra (EMC)

Major resources requirements:

- Personnel/Funding (TBD): NOAA (NWS, NOS, OAR, NESDIS, NMFS), EPA, USGS
- HPC for development: Allocations on NOAA research R&D resources (Theia, Gaea, S4)

Dependencies/linkages with other projects:

- Advancements are dependent on the NOAA's overall strategy for Eco-Forecasting

Core development partners and their roles:

- NOAA (Lead agency) (NWS, NOS, OAR, NESDIS, NMFS)
- EPA
- USGS

Project 8.5: Eco-systems and Eco-forecasting

Implementation Plan for Ecosystems and Eco-forecasting												
Ecosystems and Eco-forecasting	**FY19**				**FY20**				**FY21**			
	Q1	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Collect requirements	**Collect User requirements and stakeholder feedback**											
Build Coupler and DA capability					**Construct a transition plan for regional quasi near-real-time forecasts, such as HAB and hypoxia**							
Quasi-operational testing						-			**Work on transitioning to operations a regional ecosystem forecast using NCEP infrastructure**			

<u>ANNEX 9</u>: LAND SURFACE MODELS (LSM) AND HYDROLOGY

The current NCEP production suite contains both uncoupled and coupled modeling systems that include several different land surface and hydrological models. There are three uncoupled systems: the North American Land Data Assimilation System (NLDAS) and the Global Land Data Assimilation System (GLDAS, part of CFS), both NLDAS and GLDAS utilize the Noah land surface model (LSM); and the National Water Model (NWM), which is based on WRF-Hydro and utilizes the Noah-MP LSM. The coupled systems include the CFS seasonal forecasting system, the GFS/GEFS, NAM, RAP/HRRR and HWRF/HMON, which again use the Noah LSM, and RUC LSM in the case of RAP/HRRR.

Modern land models simulate many quantities that potentially can be exploited to improve short- to medium-range weather forecasts and to expand the range of NCEP forecast products. With respect to forecast skill, predictability from the land comes from: (1) soil moisture, (2) snow pack/snow cover, and (3) vegetation phenology (the timing of leaf out and leaf senescence), all of which can significantly impact surface fluxes, boundary-layer development, and thus interaction with the atmosphere. Predictability is on short- to medium-range weather as well as longer-term (sub-seasonal to seasonal) time scales. Crop and irrigation modeling (as simple as regions identified from land-use maps) can capture the impact of intense land-use, which also has a significant impact on surface fluxes.

Modern land models are also making advances with respect to the representation of sub-grid land heterogeneity that, again, impact surface fluxes and the atmospheric boundary layer and convection. The ground hydrology and the lateral redistribution of water within and between model grid cells is also important in representing the hydrological cycle and must occur at the spatial and temporal scales necessary to resolve streamflow in small channels and water bodies. The latter occurs in the current operational NWM, and will be simulated by components of the NWM, which will be integrated into a more fully-coupled earth system model in a future iteration of this effort. Other examples of land model capabilities include (1) dust, Biogenic Volatile Organic Compounds (VOCs), and fire emissions, which have relevance for air quality forecasting, (2) urban modeling, which can capture differences in minimum and maximum diurnal temperatures in urban versus rural locations as well as the effect on the surface water budget/hydrological cycle, and (3) 1-D lake modeling. A need exists as well to develop an enhanced LSM that better integrates chemical surface-atmosphere exchange processes (emissions, deposition, canopy effects, etc.) that are relevant for Chem/Aerosol modeling.

Characterization of surface conditions is important for land-hydrology models, i.e. land-use and soil type, slope, surface radiation characteristics (albedo, emissivity), vegetation cover and density, soil moisture (including frozen), and snow pack/snow cover. Some of these quantities are state variables (e.g. soil moisture, snow), while others are specified as static (land-use and soil type) though may be time-varying (e.g. monthly surface albedo, and near-realtime weekly green vegetation fraction). Quantities that can be assimilated include snow cover (currently daily direct replacement is used), snow depth, streamflow, inundation, soil moisture (exploring the use of remotely-sensed soil moisture products), and vegetation (in a future version of the Noah LSM with prognostic vegetation phenology).

Finally, long-term data sets necessary for reanalysis (e.g. CFS) require that especially the multi-decade snow and vegetation products be re-evaluated.

There are about 304 million lakes (4.2 million km2 in area) on the earth. Lakes affect both weather and climate. Natural lakes are dominated in area by a large number of small to medium lakes. These small to medium lakes are indistinguishable as sub-grid scale features in most of NWP/NCP models, and their effects are either ignored or crudely parameterized. As the horizontal resolution increases, lakes are becoming resolved features, and their effects become apparent and will be taken into account.

Project 9.1: Land Data Assimilation in FV3GFS/UFS

Project overview: NOAA/NCEP Gridpoint Statistical Interpolation (GSI) is a unified variational data assimilation system utilized in operations for the Global Forecast System (GFS) in May 2007. However, the GSI lacks a land component and cannot assimilate land surface data such as soil moisture and snow. The current GFS-based hybrid ensemble-variational assimilation system opens up the opportunity to more closely integrate the ensemble-based land updates to the atmospheric component through the generation of a single ensemble of background states.

The land EnKF data assimilation technique is mature after more than a decade of study. Previous assimilation experiments with snow and soil moisture have demonstrated some improvements in land surface process simulations, which, in turn, also improve numerical weather predictions (such as precipitation forecasts). However, remotely-sensed estimates of land-surface states such as soil moisture and snowpack are not currently assimilated into any NWS operational systems, and we believe that assimilating satellite products will produce improved land surface states to better represent evolving conditions and contribute to the NWS Weather Ready Nation objectives.

NCEP receives snow cover data from NESDIS Interactive Multisensor Snow and Ice Mapping System (IMS) and snow depth data from Air Force 557th Weather Wing (557WW) in real time as part of NCEP operational data ingest. NESDIS SMOPS (Soil Moisture Operational Product System) developed the blended soil moisture from SMAP, AMSR-2, ASCAT, SMOS and GPM/GMI, and NESDIS operational SMOPS is ready to provide high resolution and high quality soil moisture data for NWS numerical weather prediction (NWP) models at every 6 hour matching GFS forecast cycles.

The offline NASA/LIS based land DA software package has matured through a decade of effort from NASA LIS team, NASA's GMAO (Global Modeling and Assimilation Office), and external land modeling communities. LIS DA toolkit provides an infrastructure to ingest various sources of remotely-sensed hydrologic observations to produce improved spatially- and temporally-consistent fields of land-surface states. The land DA system in LIS includes tools such as the Ensemble Kalman Filter (EnKF), which is widely accepted as an effective technique for sequential assimilation of hydrologic variables such as soil moisture, skin temperature, and snow. Therefore, at the first step, we propose to transition existing land data assimilation capabilities in LIS to NCEP and support assimilation of satellite-based snow depth and soil moisture products.

Most NWP centers outside the US constrain their model land soil states using 2-m atmospheric observations (usually of temperature and relative humidity), including at Deutscher Wetterdienst, ECMWF, Environment Canada, Meteo-France, and the UK Met Office. Therefore, NCEP's global systems propose to use T^{2m} and RH^{2m} to adjust soil moisture and soil temperature.

Major Risks and Issues:

- Dependencies on NOAA NESDIS for upgraded/higher-solution land data sets, e.g., realtime soil moisture, snowpack/snow cover, greenness vegetation fraction, etc.
- Availability and latency of observed air temperature and specific humidity.
- FV3GFS inclusion of NASA/LIS.
- JEDI inclusion of land DA capability

Major resources requirements:

- Personnel: NOAA/NCEP/EMC, NOAA/NESDIS, NASA/GSFC, NOAA/ESRL 8 FTEs (land data assimilation, land data sets, coupling into FV3GFS/GDAS).
- HPC for development: NCEP WCOSS, Theia and GFDL Gaea.

Dependencies/linkages with other projects:

- NEMS FV3GFS (LIS as an external land component), coupling LIS into FV3GFS CCPP inclusion for bit-by-bit reproducibility for external versus internal configurations.
- FV3DA (future unification under weakly vs strongly coupled DA).
- NULDAS
- JEDI (UFS SIP project 6.1)

Core development partners and their roles:

- NASA Goddard: LIS development and LIS-based land DA studies.
- NESDIS/STAR: development of land data sets for land data assimilation, e.g. snow, vegetation, soil moisture, green vegetation fraction.
- NOAA/ESRL: assimilation of 2m T and Td into NCEP GSI-based EnKF system to adjust soil moisture and temperature.
- JEDI core team: incorporate land DA capability into JEDI.

Major Milestones:

- FY19Q2: Merge NASA/LIS into GDAS for land DA
- FY19Q4: Test snow DA in GDAS/LIS
- FY20Q2: Test soil moisture DA in GDAS/LIS
- FY20Q3: Assimilation of 2m T and Td in a coupled system
- FY21Q1: Implement land DA into GDAS GSI-based Hybrid EnKF system
- FY21Q3: JEDI based land DA

Project 9.1: Land DA (FY19-21)

FY18	FY19				FY20				FY21			
Q4	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Merge NASA/LIS into FV3GFS/GDAS												
		Snow DA tests in GDAS										
			Soil moisture DA tests in GDAS									
Assimilation of 2m T and Td in GSI-based EnKF system												
					Implement land DA into GDAS GSI-based Hybrid EnKF system							
			JEDI based land DA									

Project 9.2: NCEP Unified Land Data Assimilation System (NULDAS) Development

Project overview: Merge the GLDAS and North American (CONUS) Land Data Assimilation System (e.g., ops real-time and research LIS-based NLDAS) into a "NULDAS" system at higher resolution (than the global model), e.g. on the order of 0.04-degree. NULDAS can then provide initial land conditions for all NCEP coupled weather and seasonal prediction systems, and provide support for e.g. CPC Drought Outlook and the water resources community more generally. Additionally, hydrologic components from the National Water Model will be leveraged in order to provide a global hydrology component and river-routing capability for fully-coupled earth system modeling. Generation of NULDAS 0.04-degree surface meteorological forcing is a critical step. The forcing will be produced by integrating community mature-data from various governmental agencies (e.g., NWC high-resolution forcing) and academia with NCEP and NESDIS operational product (e.g., blending, downscaling, bias-correction). The evaluation will be performed using independent gauge and tower observations and satellite retrievals when the downscaled operational GLDAS forcing is used as a benchmark.

Major Risks and Issues:

- Dependencies on NCEP Climate Prediction Center and NESDIS for upgraded/higher-solution land data sets, e.g. global precip (CPC), and static land-use/soils, near-realtime vegetation, snow pack/snow cover, etc., as well as multi-decadal land data sets (NESDIS).

- Dependencies on community mature-data and method for high-resolution surface meteorological forcing, downscaling techniques, and bias-correction methodologies, in particular for long-term retrospective period
- NULDAS offline “spin-up” multi-year runs can take a few months, several months for much longer 30+ year NULDAS “climate” spin-up runs.
- Adequate downscaling techniques needed to provide initial land conditions for higher-resolution nest/CAM-scale models, as well as for the atmospheric forcing for NULDAS.
- Collaboration with OWP (to leverage common hydrologic components where possible) on forcing data and extending the NWM hydrology and river-routing capability globally requires additional personnel, development and testing.
- Collaboration with NASA/Goddard on integrating LIS-based NLDAS into NULDAS

Major resources requirements:
- Personnel: 7 FTE (physics, land data assimilation, land data sets, coupling, NULDAS system infrastructure/LIS); ~3-5 FTE additional for downscaling work and NWM module integration.
- HPC for development: Could be significant depending on resolution. Gaea time under the “GLDAS” project may also be available in the future.

Dependencies/linkages with other projects:
- GFS/GEFS (NULDAS as upstream component), Coupling/infrastructure required to connect systems under NEMS, DA (future unification under weakly vs strongly coupled DA), SFS (NULDAS a future component).
- GLDAS forcing
- JEDI (UFS SIP project 6.1)

Core development partners and their roles:
- NASA Goddard: LIS developers, LIS-based NLDAS developer, LDAS partner
- NESDIS: land data sets for ingest and land data assimilation, e.g. snow, vegetation, soil moisture
- NCAR, NOAA ESRL & GFDL, and other partners: model physics development and related development issues.
- NWS/OWP: guidance on cross-pollination of forcing and hydrologic model components between NWM and NULDAS.
- Community mature-data and method from academia (e.g., Princeton U., U. Arizona, etc.)
- JEDI core team

Major Milestones:

- FY18Q4: Forcing data selection and generation
- FY19Q1: Benchmark creation and evaluation
- FY19Q3: Test upgrades to Noah LSM physics, new land data sets, land DA
- FY20Q1: Unification of NLDAS and GLDAS (into NULDAS), tests of river-routing scheme, leveraging of NWM hydrologic modules where appropriate

- FY20Q3: Optimize land physics and full NULDAS system test
- FY21Q1: Evaluation/Validation in FV3/NEMS

Project 9.2: NULDAS (FY19-21)

FY18	FY19				FY20				FY21			
Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Forcing data selection and generation												
	Benchmark creation and evaluation											
			Test upgrades to Noah LSM physics, new datasets, land DA									
					Unification of NLDAS and GLDAS, test of river-routing scheme							
							Optimize land physics and full NULDAS system test					
									Evaluation/validation in FV3/NEMS			

Project 9.3: Land surface model physics and system evaluation and selection

Project overview: Evaluate various land-hydrology model choices to address (and possibly select) the land-hydrology model system that yields the best performance, linking the atmosphere with the land-hydrology (to ocean) components. Evaluations should be relevant to regional and global systems as well as short-medium range (hours-weeks, e.g., HRRR/RAP, GFS) and longer term (weeks-months, e.g., CFS) scales with the goal to include modern physics and software design and support flexibility with respect to parameterizations, complexity, and spatial discretization.

Performance includes evaluating surface fluxes, land states (soil moisture, frozen soils possibly including permafrost, soil temperature, snow, vegetation), hydrology/water (rivers, lakes, reservoirs, groundwater), in offline land-hydrology-only testing with appropriate process-level and computational benchmarks for land-hydrology modeling, e.g. surface-layer exchanges (input to surface fluxes), surface energy partition, plant (including carbon and other biogeochemical cycles), and soil thermodynamic and hydraulic processes (heat and moisture movement in the soil), runoff, groundwater and stream-flow/river routing, freshwater discharge to oceans (water movement, including lateral movement). Tradeoffs in complexity and skill will be evaluated. NASA Land Information System (and Land Validation Toolkit), as well as GEWEX/GLASS PALS/PLUMBER, ESM-SnowMIP, OWP/NCAR, climate community ILAMB protocols to be used, along with other focus-area specific benchmarks from collaborators. Physics selections should be revisited and reevaluated on a regular basis.

Noah MP has been selected as LSM for the FV3GFS/UFS because of its flexibility with multi-physics options applying for different time scales. The incorporation of Noah MP into FV3GFS is undergoing via both inline and and external coupling. The extensive tests and evaluation will be carried out to select the optimal configuration of Noah MP physics options for all time scales application.

Fresh lake model FLake has been incorporated into FV3GFS. The tests have been undergoing to evaluate the impact on different time scale forecasts.

Major Risks and Issues:

- Sufficient alignment with land and hydrology research and model development communities, and associated FTEs.
- Sufficient data sets for testing all aspects of land-hydrology modeling at the process level, e.g. significant “data mining” will be necessary.

Major resources requirements:

- Personnel: 2-4 FTEs working on land-hydrology-related testing, evaluation, and benchmarking
- HPC for development: current levels from WCOSS, NOAA R&D, and other HPC systems should be sufficient.

Dependencies/linkages with other projects:

- Sufficient alignment with land and hydrology research and model development communities
- For fully-coupled earth system testing, see project 5.

Core development partners and their roles:

- See projects 9.1 and 9.2.

Major Milestones:

- FY18Q3: Agreed upon land-hydrology benchmarks for process-level study and associated data sets.
- FY18Q4: In line coupling of Noah MP and FLake to UFS
- FY18Q4: Land-hydrology models available, tested and evaluated in LIS and/or other testing platforms.
- FY19Q2: Land-hydrology models available for fully-coupled earth system testing.

- FY20Q1: Optimize land physics with other physics and a full system test
- FY20Q3: Operational implementation of selected land-hydrology model system in “LDAS” mode.
- FY21Q2: Operational implementation of selected land-hydrology model system in fully-coupled earth system mode (see project 9.5).

Project 9.3: Land Physics (FY19-21)

FY18	FY19				FY20				FY21			
Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
In-line coupling of Noah MP and Flake												
Uncoupled physics and model implementation and evaluation												
		Coupled physics and model implementation and evaluation										
					Optimize land physics performance and full system test							
							Operational implementation of land physics in LDAS model					
										Operational Implementation of land physics in UFS		

Project 9.4: Collaborative Development with National Water Model (NWM)

Project overview: As a significant step forward in transforming NOAA's water prediction capabilities, OWP, NCAR and NCEP implemented the first version of the National Water Model into operations in May 2016. The model will undergo its third upgrade to V2.0 in early 2019. The NWM represents NOAA's first foray into high performance computing for water prediction and expands NOAA's current water quantity forecasts from approximately 4,000 U.S. Geological Survey (USGS) stream gage sites across the country to forecasts of flow at 2.7 million stream reaches nationwide. The NWM provides hourly streamflow forecasts at those 2.7 million river reaches and other hydrologic information on $1km^2$ and $250m^2$ grids. Other NWM output includes high-resolution, spatially-continuous forecasts of soil moisture, evapotranspiration, runoff, snow water equivalent, and other parameters. These outputs are generated over the CONUS, but will soon include coverage for Hawaii. In addition, because land areas in Canada that drain into the Great Lakes are crucial for the overall water budget of the lakes, efforts are in progress to include these areas in the domain of the NWM.

Stakeholder needs within the water resource and emergency response communities along with congressionally mandated NWM enhancements for the FY18-20 SIP period necessitate the continued development of a NWM separate from the proposed regional and global unified systems. However, significant cross-pollination is essential to ensure that the global and regional coupled systems contain the hydrologic capabilities needed to accurately capture hydrologic-atmospheric feedbacks. In particular, NWM hydrologic components will be integrated into NULDAS and NGGPS where appropriate. Model component co-development activities will also proceed in instances where resources permit and use is possible across hydrologic scales, and validation and forcing generation techniques will be cross-leveraged as well. There exists the potential for state/information transfer between the high-resolution NWM and the 0.04-degree NULDAS system. This overall approach will ensure that stakeholder needs and congressional mandates are met while overlap and stove-piping are minimized wherever possible.

Over time, continued NWM enhancements will improve the NWS's ability to deliver impact-based decision support services nationwide through the provision of short through extended range, high fidelity "street level" water forecasts, and through linkages with other earth system modeling components. Many of these linkages are explicitly called out in **Annex 8** which includes a section on NOAA Integrated Water Prediction activities.

Major Risks and Issues:
- Congressional mandates are driving NWM enhancements at an extremely rapid pace. This may complicate cross-pollination efforts
- Uncertainty exists in terms of which hydrologic components are suitable for use across scales

Major resources requirements:
- Personnel: OWP and NCAR FTEs and contractors. Additional EMC and NASA GSFC staff TBD.
- HPC for development: NOAA WCOSS and NCAR Cheyenne development environments

Dependencies/linkages with other projects:

- NULDAS, GLDAS, NGGPS, Unified models, Ocean and estuary models, NEMS

Core development partners and their roles:

- OWP and NCAR: NWM governance, development, validation and R2O activities. Guidance on transfer of modules from NWM to NULDAS/NGGPS/UFS as appropriate
- NCEP EMC: Co-development and transfer of modules to/from NWM and NULDAS/NGGPS as appropriate
- NASA GSFC: Transfer of modules from NWM to NULDAS/NGGPS as appropriate

Major Milestones:

Planned out-year enhancements to the NWM are guided by a series of 5-year overlapping research to operations (R2O) OWP initiatives. These include:

- Centralized Water Forecasting (FY15-FY19)
- Flash Flood and Urban Hydrology (FY16-FY20)
- Total Water Level and Coastal Inundation (FY17-FY21)
- Drought and Post-Fire (FY18-FY22)
- Water Quality (FY19-FY23)

Highlights of these initiatives include the expanded assimilation of anthropogenic water management data, the incorporation of enhanced forcings, the provision of real-time flood forecast inundation maps, an operational nest to provide higher resolution forecasts needed to account for the built environment in urban areas, two-way coupling of the NWM with coastal estuary models for “total water level” forecasts in coastal zones, coupling with more advanced groundwater models to improve forecasts of low flow and drought, and tackling deeper challenges associated with water quality.

In order to accomplish these initiatives, OWP and NCAR have developed a strategic plan aimed at advancing NWM development in high priority development and improvement areas. This strategic plan, which builds on near-term NWM version 2.0 upgrades, advances development along a trajectory consistent with the R2O initiatives. It is anticipated that future versions of the NWM will include at a minimum:

- Implementation of hyper-resolution (~10 meter effective resolution), limited area nesting capabilities within the NWM for detailed flood inundation impacts predictions
- Enabling model physics linkages (i.e. coupling) to estuary and coastal models
- Enabling model physics linkages to 2D hydraulic models
- Building and improving model capabilities to represent the Great Lakes tributary hydrologic system within the NWM
- Developing operational prediction capabilities for Hawaii, Alaska and Puerto Rico
- Implementation of more complete groundwater representation
- Advancing data assimilation capabilities for the ingest of snow, vegetation, soil moisture and groundwater data
- Development of expanded and improved ensemble forecasting capabilities
- Improved and advanced calibration

This strategic plan will improve the 'total water accounting' capabilities within the NWM by improving representation of the spatial and temporal distribution of water in the terrestrial system and by improving the linkages between the NWM and other components of the Earth System (e.g. coasts and lakes). Inclusion of regions outside of the CONUS will ensure that the entire Nation is provided with equitable water forecasting services. Lastly, improving data assimilation and ensemble forecasting capabilities will help ensure that the NWM is incorporating several of the latest scientific advances in environmental forecasting methodologies.

<u>Project 9.4: NWM Collaboration (FY19-21)</u>

FY18	FY19				FY20				FY21			
Q4	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
NWM V2.0 Implementation (Hawaii domain, improved forcing downscaling, ensemble forecasts, improved calibration)												
NWM V2.1 Development (Great Lakes and Puerto Rico domain, improved, ensemble forecasts, reservoir module)				**NWM V2.1 Implementation**								
				NWM V2.2 Development (Improved ensembles, snow data assimilation, improved reservoirs)								
								NWM V2.2 Implementation				
								NWM V2.3 Development				

Project 9.5: Land-hydrology model system coupling with other earth-system model components

Project overview: Evaluate coupling of land-hydrology components with other earth-system model components, including atmosphere, ocean, and atmospheric chemistry. Land surface model (LSM) choices (e.g., NOAH, NOAH-MP, RUC, LM, CLM, CLSM) to address (and possibly select) the LSM that yields the best performance based on multiple criteria, linking the atmosphere with the land-hydrology (coupled to oceans). Tests include surface fluxes, BVOC and dust emissions, land states (soil moisture, frozen soils including permafrost, soil temperature, snow, vegetation), hydrology/water (rivers, lakes, reservoirs, groundwater, water quality), initially in offline land-only testing with appropriate process-level benchmarks, e.g. surface energy partition, river discharge, etc.; then progressively coupled in a hierarchical manner with relevant benchmarks (e.g. 500mb AC scores, regional circulation, seasonal snowpack, groundwater, ENSO indices, etc.) for a fully-coupled system, but also including process level benchmarks. Hierarchy: land-hydrology, land-atmosphere (with/without aerosols/chemistry), land-marine, land-hydrology-atmosphere, etc., up to fully-coupled earth system tests.

Major Risks and Issues:

- Sufficient alignment with land and hydrology communities.
- Sufficient connection with Model Physics, Marine, and Aerosols & Atmospheric Composition.
- In the operational GFS and CFS systems, the land surface component model is internal to the atmospheric component, where it is internal to the sub-grid physical parameterizations module. In some applications and for research purposes, it will be necessary for the land surface component to be a separate component. ESRL/GSD (NESII) and EMC have produced prototypes of a separate land component in NEMS, using the NOAH model accessed through the NASA Land Information System (LIS). A question is whether this project will continue the necessary changes to the coupled system architecture to enable a flexible land surface model (LSM) component that addresses the other issues listed below.
- Implicit vs. explicit coupling. The land surface has both fast and slow processes that interact with the atmosphere dynamically, thermodynamically and chemically. A choice must be made in implementing the LSM that represents those processes: it can be coupled to the atmosphere either tightly with an implicit scheme or loosely/asynchronously. There are pros and cons to both types of coupling. The SA should be flexible to support both types of coupling.
- Water sub-components of LSM. The land surface contains water in liquid and solid phases, and in many different landforms. The presence of water on the landscape in the form of soil moisture is commonly treated in LSMs. In addition, there are bodies of water with different characteristics: rivers that transport water mass and sediments over the landscape, thereby introducing a delayed hydrological effect complicating the relationship between precipitation, runoff and transport from the land surface to the ocean; lakes that provide reservoirs for storage of water and large surface area for evaporation; and estuaries that mingle fresh water from the land surface with saline water from the ocean. Often these water bodies occupy much less area than a grid box of the coupled model, so interactions between rivers, lakes, estuaries,

ocean and atmosphere must be treated as sub-grid physical processes. Furthermore, NOAA has launched a major initiative to predict river flow at millions of river reaches – the National Water Model (NWM) – this provides a framework that EMC could explore drawing from, potentially integrating components of the NWM into LDAS, NGGPS, UFS or other systems.

- Interaction with aerosols/dust/GHG emissions. The land surface acts as both a source and a sink for aerosols and dust as well as greenhouse gases, primarily carbon dioxide and methane. The vegetation on the land surface interacts with several of these constituents of atmospheric composition. The representation of the land surface, the vegetation, and the exchange of aerosols, dust and GHG with the atmosphere must be consistent across component models within the coupled system. If the land is tightly coupled, aerosol and chemistry may also need to be tightly coupled to keep the synergies for correctness. Transition to an integrated LSM with chemical surface-atmosphere exchange processes (deposition, emissions, canopy effects, etc.) should be considered.

Major resources requirements:
- Personnel: 2-4 FTEs from land-hydrology; 8-10+ FTEs to work on coupled physics to fully-coupled earth-system model testing.
- HPC for development: increasingly more resources required as more fully-coupled earth-system models are tested.

Dependencies/linkages with other projects:
- See projects 9.1 - 9.4.
- Model Physics: radiation, PBL, convection/microphysics, surface layer.
- System Architecture: land-atmosphere coupling, implicit/explicit, tiles, consistency, Interoperable Physics Driver development, etc.
- Aerosols and Atmospheric Composition: BVOC emissions, dust emissions, deposition, fire emissions, strategy for integrating atmospheric chemistry module into coupled applications.
- Marine: freshwater boundary conditions, NOAA Total Water Initiative (see Annex 8)
- Verification: Land process, and application-oriented verification metrics and benchmarks

Core development partners and their roles:
- See projects 9.1, 9.2, and 9.3.
- Members from other model physics projects (per project overview).

Major Milestones:
- FY18Q4: Agreed upon uncoupled and coupled benchmarks for process-level study and associated data sets.
- FY19Q2: Multiple models to be made available, tested and evaluated in LIS and/or other uncoupled testing platforms following Project 9.3 above.
- FY19Q4: Single coupled testing and evaluation (e.g., land-atmosphere, land-marine) - will need to address questions of implicit and/or explicit coupling options.
- FY20Q2: Multi-component testing (e.g. land-atmosphere-chemistry; land-atmosphere-marine)
- FY20Q4: Full system testing and evaluation

Project 9.5: Land-hydrology model system coupling with other Earth-system model components (FY19-21)

FY18	FY19				FY20				FY21			
Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Uncoupled and Coupled metrics and benchmarks												
		Uncoupled evaluation										
				Two-component coupled testing and evaluation								
						Multi-component coupled testing and evaluation						
								Full system testing and evaluation				
										Operational Implementation		

<u>ANNEX 10</u>: AEROSOLS AND ATMOSPHERIC COMPOSITION

This Strategic Implementation Plan identifies key capabilities, issues and a roadmap for expanding NGGPS from a global atmospheric composition model to a unified forecast system across spatial and temporal scales, and to establish the unified modeling system as a community model that meets the needs of operations as well as the R&D community. There are several reasons to include aerosol and gaseous composition in a system for Numerical Weather Prediction (NWP) applications:

- Improving weather forecasts and climate predictions by taking into account trace gas effects on radiation as well as aerosol effects on radiation, clouds and precipitation;
- Improving the handling of satellite observations by properly accounting for aerosol and trace gas effects during data assimilation;
- Providing aerosol and trace gas (lateral and upper) boundary conditions for regional air quality predictions; and
- Producing quality aerosol and trace gas information that addresses societal needs and stakeholder requirements, e.g., for air quality management, health applications, environmental policy making, climate science, and renewable energy planning.

The Unified Forecast System Atmospheric Composition Model (UFSACM) should address spatial scales from high-resolution, convection-resolving to global, and should be applicable to prediction needs from short-range forecasts (hours-days) to subseasonal and seasonal scales (weeks-months).

The UFSACM should provide all operational products/services provided by the current NWS operational atmospheric composition modeling suite with quality that matches or exceeds the quality of the current products:

1. Global Aerosols: NEMS Global Aerosol Capability: T126 2x/day to 5 days: GOCART aerosols (dust, smoke, sea salt, sulfate), Lu, et al. (2016); Bhattacharjee et al., (2018); Wang et al., (2018)
2. Global stratospheric ozone in GFS: T1534, 4x/day,
3. Ozone/PM: NAM-CMAQ: 12 km, 2x/day to 48 hrs, 155 species, Lee, et al. (2017)
4. Dispersion: NAM/GFS-HYSPLIT Smoke: 0.2°, 06z to 72 hrs, 1 species; Dust: 2x/day CONUS; Volcanic Ash, radiological Global; chemical emergencies, CONUS, Stein, et al. (2015)

The following identifies the key component projects for development of a unified atmospheric composition modeling system. These projects will evolve to account for current and anticipated future applications related to aerosols and atmospheric composition. Key projects include the development of a system architecture and a chemistry component that allows for coupling with model dynamics and physics, development of aerosol and atmospheric composition data assimilation capabilities, provision of anthropogenic and natural sources of emissions, verification and postprocessing. These projects would address the needs of aerosol and atmospheric composition modeling system development: from global to regional, high resolution air quality modeling and atmospheric dispersion modeling.

The development of the NEMS Global Aerosol Component (NGAC) model at NCEP has leveraged the expertise experiences from the ICAP (International Cooperative for Aerosol Prediction) and other atmospheric composition projects. The development of the aerosol component in the UFSACM should continue leveraging ICAP's and other project expertise in aerosol modeling/processes, aerosol data assimilation, global emission estimates, and verification.

Project 10.1: Atmospheric composition model component

Project overview: This is a project for development of a generic atmospheric composition component and its integration into the unified model system architecture for two-way interactive coupling with atmospheric physics and consistent coupling with dynamics. Some Aerosol and Atmospheric Composition (AAC) capabilities are already built in modular form and take advantage of ESMF infrastructure to couple with physics and dynamics (e.g., the comprehensive GEOS-Chem ESMF component from NASA GSFC which includes GOCART, MAM-7, CARMA, StratChem, GMI and Harvard's GEOS-Chem mechanisms). GEOS-Chem is the basis for the current mechanism of GOCART in the GFS operational NGAC. ESMF coupling would enable the atmospheric composition component to be self-contained (emissions, 1-D chemistry, deposition), allow ease of code maintenance and optimization as well as sharing of the code among users with different interests, including operations, development and research for either standalone applications or inclusion in the Earth System model with close interactions with other components. ESMF-based coupling provides a proven efficient mechanism for coupling chemical components to the FV3 dynamics and physics as evidenced by the GEOS-5 NASA system. In 2018, the AAC working group chose to develop a NUOPC cap and ESMF connectors for the first implementation of GOCART aerosols in the Unified Forecast System based on FV3GFS. This was chosen as the first version of an AAC component and this coupling will serve as a template for further chemistry coupling. In GFS, ozone is currently treated as a meteorological variable through the physics driver in the GFS physics, ozone should be unified with the final atmospheric composition approach. NOAA's Research Transition Acceleration Program (RTAP) supported the development of a reduced troposphere/stratosphere chemistry algorithm for NGGPS for one year. Further support is needed to complete this development. Besides ozone, there are other critical functionalities that require fine-scale features in order to predict high-impact weather and pollution events, such as extreme stagnation, cold pool, wildfires, dust storms, urban heat island and sea breeze. Dispersion and air chemistry driven by such fine resolution physics are important in regional FV3 and nested global FV3 implementations. Customized AAC verification is covered in the verification section of the SIP.

In FY18, NOAA/GSD developed a coupler to connect an atmospheric chemistry component with physics/dynamics through a NUOPC cap. In addition to consistent coupling, the following capabilities are recommended for physics, dynamics and AAC to allow full interaction among them:

Component	***Application****	***Importance***
Consistent chemical approaches across scales and regimes	R2X;T2O	Essential
Interactions with radiation RRTMGP/adv suites (aerosol properties; multi stream options for scattering vs operational constraint)	R2X;T2O	Essential
Aerosol aware microphysics (e.g., Morrison/Thompson); more cloud diagnostic fields	R2X;T2O	Desirable
Integrated Land Surface Model with chemical surface-atmosphere exchange processes (deposition, emissions, canopy chemical and physical interactions)	R2X	Desirable
Allow for inclusion of different physical processes important for AC (boundary layer physics, land surface, etc.), put in physical routines where possible	R2X	Desirable
Mass conservative, Positive definite dynamics	T2O	Essential
Mass flux convection scheme	T2O	Essential
Support backtracking backward dispersion applications; downstream model coupling	T2O	Essential
Shallow convection for tracer transport and/or boundary layer (like SHOC or TKE EDMF approaches)	T2O	Essential
Options for prescribing default gas and aerosol species	R2X	Essential
Inclusion of various aerosol approaches: aerosol size distribution, modal, sectional representation, mixing states	R2X	Desirable

* T2O: short term more mature development that could be Transitioned to Operations
* R2X: More research oriented long-term goal

Major Risks and Issues:

- Choice of architecture for coupling of advanced aerosols/composition components (ESMF/NEMS/NUOPC) and coordinated development using the chosen approach. *(NOTE: AAC WG met with SA WG and recommended that a separate AAC component with a NUOPC cap for coupling be pursued.)*
- Need for 2D diagnostics capability (e.g.: output hourly averaged species)

- Operational efficiency vs range of complexity necessary for research applications.
- Computational resources for higher resolution in-line global aerosol and regional air quality predictions
- Demonstration of superior performance compared to current operations
- Documentation, training, code management and code access by core partners and community
- Funding dependencies. For example, the NOAA/RTAP program provided only 1 year of support for reduced gas phase chemistry development. This capability has not been completed.
- For more complex EPA chemistry option (eg: CMAQ) is only coupled to EPA physics. Modifications will need to be made to use FV3GFS physics
- Not all fields required to drive off-line capabilities are output from physics (eg: sfc drag coef, conv. cloud…). More interactions with physics group is needed or POC needed to discuss how chemistry should react with physics...protocols
- Problems with including inline wet deposition processes has not been addressed.

Major resources requirements:

- Personnel (including existing): NCEP/EMC (2 FTEs); NOAA/ARL (2 FTEs); ESRL/GSD (2 FTEs); ESRL/CSD (1 FTE); GFDL (TBD); NOAA/NESDIS (1 FTE); NASA/GSFC: (TBD)
- HPC for development: TBD

Dependencies/linkages with other projects:

- System Architecture WG for continued NUOPC FV3 cap maintenance and development, 2d diagnostics and future maintenance
- Physics and Dynamics WG for defining coupler protocols esp with CCPP
- Physics WG for coupling chemistry with advanced physics options (e.g., aerosol-aware physics)
- GMTB & infrastructure WG for documentation and training
- Verification WG for including atmospheric composition variables in MET+ based verification
- Post-Processing WG for extending NCEP post for atmospheric composition parameters
- VLab and Code Management/Governance
- Land Surface Models WG (land-hydrology model system coupling)
- Dynamics and Nesting WG (nesting configurations)

Core development partners and their roles:

- NCEP/EMC to help test coupler for atmospheric composition component and transitioning chemistry modules in the AC component to operations
- NOAA/GFDL to transitioning their key chemistry modules into the AC component
- NASA/GSFC for transitioning their key chemistry modules into the AC component (eg: GEOS-Chem, MAM-7…) and guidance on best coupling practices from Architecture team
- NOAA/ESRL/GSD & NOAA/ARL & EPA for developing and transitioning the EPA CMAQ chemistry modules into the AAC component and for providing aerosol aware physics packages
- NOAA/ARL to develop and maintain HYSPLIT coupling
- NOAA/ARL, CSD, EMC to test coastal and/or complex terrain and/or pollution scenarios over selected air-sheds. NOAA/CSD for process studies and model evaluation

- NOAA/NESDIS for developing and transitioning reduced chemistry modules. This development is in jeopardy since RTAP follow-on funding was cut.
- NCAR & NASA for providing aerosol aware physics packages
- NCEP/EMC for transitioning key developments to operations.

Major Milestones:

- **Q2FY18: Develop common chemistry component coupler template for FV3-Chem (Completed)**
- Q4FY18: Move GFS ozone module into FV3-Chem (Note, has been moved into NESDIS version)
- Q2FY18: Identify any performance penalties with ESMF coupler **(Completed)**
- *Q4FY18: Develop chemistry based pre (emissions) and post-processing capabilities (on-going)*
- *Q4FY18: Move atmospheric composition verification to MET+; include revised GOCART with NASA updates, regional CMAQ and reduced chemistry in FV3- Chem component (on-going)*
- Q2FY19: Evaluate aerosol predictions; Test interactions with radiation and microphysics via chemical component coupler
- **Q2FY19: HYSPLIT off-line coupling with global FV3 (hybrid and P levels) and Regional FV3 (Completed for fv3gfs)**
- **Q2FY19: Initial coupling of CMAQ chemistry to FV3GFS**
- Q3FY19: Compare the decided regional-model driven air composition capability to that by NAQFC operational predictions
- **Q3FY19: Optimization, testing, retrospective and real time evaluation of global FV3-Chem at higher resolution (~ 25kmL64); Integrate final operational global FV3-Chem GOCART into FV3GFS**
- Q4FY19: Perform regional FV3Chem retrospective and real-time. Evaluate regional in-line carbon bond chemistry at ~10 kmL35; test regional aerosol interactions with radiation and microphysics.
- Q1FY20: Prepare FV3GFS-GOCART for T2O (C384, one member of GEFS)
- **Q2FY20: CMAQ chemistry connected and regression tested in both fv3gfs and fv3sar.**
- **FY21: Integrate regional atmospheric composition (CB-VI, AERO-VI), and advanced global (GEOS-Chem/RAQMS, depending on future funding) configurations into workflow; conduct pre-implementation T&E and prepare regional AC capabilities for transition to operations**

Project 10.1 Development of FV3-chem component and coupler (FY18-21)

<table>
<tr><td colspan="13">Implementation Plan for Global FV3-Chem (FY2018-2021)</td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">FV3Chem</td><td colspan="4">FY18</td><td colspan="4">FY19</td><td colspan="4">FY20</td><td colspan="4">FY21</td></tr>
<tr><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td></tr>
<tr><td>FV3GFS-Chem Development</td><td colspan="2">NEMS coupler and GOCART component</td><td></td><td></td><td></td><td colspan="4">Develop initial 2 way coupling to GFS physics; upd. emissions</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>FV3GFS-Chem Configuration</td><td colspan="4">Test FV3GFS-Chem, resolution, 1-way coupling,increase 25km</td><td></td><td></td><td></td><td colspan="4">Test various 2-way coupling/smoke emissions opts</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>FV3-Chem DA</td><td></td><td></td><td colspan="7">Test, eval; transition VIIRS, other AOD DA to Op GSI</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>FV3GFS-Chem Evaluation</td><td></td><td></td><td></td><td colspan="4">Final FV3GFS-Chem V1 configuration* & perform retros and real-time runs</td><td></td><td></td><td></td><td colspan="4">Final glbl config (2-way cpl to rad and/or microphys), fire plume rise</td><td></td><td></td></tr>
<tr><td>FV3GFS-Chem T2O</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="3">V1: Implem. FV3GFS-Chem</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">V2: AOD DA; 2-way coupling</td></tr>
<tr><td>FV3SAR-Chem</td><td></td><td></td><td></td><td colspan="3">Dev. new coupler for CB-VI chem</td><td colspan="4">Configure/test adv. chem (CB-VI, Aero) w/ FV3SAR</td><td colspan="2">Retros & RT runs</td><td colspan="2">Optimize FV3SAR Chem</td><td colspan="2">Implem. FV3SAR -Chem</td></tr>
<tr><td>Advance-ment of FV3-Chem</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="6">Develop, couple to adv. Physics, Transition to JEDI, Inline regional tests</td></tr>
<tr><td></td><td colspan="12">* Proposed changes for FV3GFS-Chem: 1) Couple with updated FV3-GFS physics/dynamics; 2) Increase horizontal resolution to 25 km; and 3) Assimilate VIIRS AOD
* Proposed changes for Reg FV3SAR-Chem(CB-VI): (1) Couple with advanced physics & reg. stand-alone FV3; (2) Test inline and offline approaches; (3) Update emissions to current year</td><td></td><td></td><td></td><td></td></tr>
</table>

Project 10.2: Data Assimilation for Atmospheric Composition

Project overview: An atmospheric composition data assimilation system is critical for constraining not only atmospheric composition species and aerosol size and number concentrations (chemical data assimilation or CDA), but also the emission (emission data assimilation or EDA), which are typically based on databases that can often be several years old. For example, satellite retrieved NOx and VOCs have been used to update regional anthropogenic emissions databases and satellite retrieved fire activities have been used to update global smoke emissions.

Furthermore, it was requested that the data assimilation system supports aerosol information from IR sensors. The AC-WG did identify other capabilities for data assimilation, but the most important for initial capability would be the ability to assimilate AOD from VIIRS and/or MODISby providing radiative properties of at least current operational species in the CRTM as well as allowing for atmospheric composition data ingest. Data assimilation for aerosols has been developed in research mode with 3D-Var using the GSI and the Ensemble Kalman Filter (EnKF, Whitaker et al.)The NGGPS DA plans for coupling low resolution aerosol to high resolution meteorological model assimilation should be tried here. Assimilation of gas tracers has not been attempted yet. We believe that currently, in addition to ozone (OMI) and …?, only CO from NUCAPS may be mature enough for data assimilation (regarding NUCAPS, C. Barnet, May, 2018, personal communication). Availability of retrievals of gases from new satellites (such as Sentinel 5P and its future descendants) needs to be assessed. For model verification using satellite data, coordination with the DA community will be essential so that model and observation products are spatially and temporally compatible. A strategy for matching satellite and model grids is needed for DA and verification.

Sub-setting of satellite data

Emission data assimilation or EDA will be developed to reduce uncertainties in emission inputs for both directly emitted aerosols (smoke particles, dust and marine) and key precursors (SO_2, NO_2, NH_3, and VOCs). Unlike CDA which alters chemical concentrations, EDA attempts to directly constrain model inputs with observations. Therefore, the impact of EDA will last much longer than CDA. In addition, EDA does not cancel off the biases caused by other model processes, such as transport and removing, allowing concurrent improvements. A prototype EDA package for NO_2 has been developed to represent rapid emission changes during the 2008 Great Recession (Tong et al., 2016). Similar capabilities can be developed for a number of species in partnership with the emission team and remote sensing communities. A number of EDA approaches are being developed and tested at several external projects (e.g., NASA HAQAST and NOAA JPSS PGRR).

Ultimately, the DA system should include the following essential capabilities as listed in the table below:

Component	**Application**	**Importance**
Ability to assimilate atmospheric composition concentrations to constrain both the current state and the emissions.	T2O	Essential
Ability to assimilate spatially (e.g. column) or temporally (e.g. deposition assimilate deposition? - is it for EDA?) integrated quantities.	T2O	Essential
Ability to handle model and observation biases.	R2X;T2O	Essential
Non-Gaussian error distributions.	R2X	Desirable
Conservation of mass and chemical balance.	R2X	Desirable
Ability to compute model background error without ensemble system outputs (is that for 3D-Var? Some explanation needed)	T2O	Essential
For aerosols ability to assimilate AOD, PM, and lidar backscatter: -- development of CRTM for new sensors -- data ingest -- specification of obs errors	T2O	Essential
Consistency in the specification of aerosol optical properties (e.g., refractive index) in model physics, data assimilation and post-processing (Recommend using parameters defined in the CRTM)	R2X;T2O	Essential
Coupling of assimilation of aerosol and gaseous composition with meteorological data assimilation	R2X	Desirable
Ability to assimilate trace gas (NO2, O3, CO, N2O, CH4) retrievals -- Development of observation operators -- Specification of observation errors -- Data ingest -- Background Error Covariances	R2X;T2O	Essential
CRTM updates to incorporate aerosol and trace gas information into IR radiance assimilation	R2X	Desirable

Major Risks and Issues:

- Simple GOCART type aerosol properties have been included in the Community Radiative Transfer Model (CRTM). LUTs for CMAQ chemistry do exist but only in a research version of CRTM.

- Timely availability of input datasets through operational data flow
- Major differences between MODIS and VIIRS AOD should be addressed in DA codes.
- No clear plan for aerosol DA. Recommend AAC representation on DA team.
- Better coordination with research community and NCEP DA team
- There are significant differences in terms of observation processing (no CRTM but NASA's CARMA) and methodology (solely EnKF approach), and possibly also different version of GOCART to support in CRTM/DA.

Major resources requirements:
- Personnel: NWS/NCEP/EMC (1 FTE); NESDIS (1 FTE); NOAA/ARL (1 FTE); NOAA/ESRL/GSD (1 FTE)
- HPC for development: TBD CPU hours per month; 200 TB

Dependencies/linkages with other projects:
- JEDI
- JPSS and Sentinel-5P data products
- Readiness and availability of data from GOES-16/17
- DTC/GMTB CCPP
- Advanced physics options recommended by SIP Physics Working Group
- MET based verification
- Transition to VLab and Code Management/Governance
- Data Assimilation team

Core development partners and their roles:
- NWS/NCEP/EMC: Transfer/integration of DA capabilities into NCEP, code management, retrospective and real-time experiment testing and evaluation, transition to operations
- NESDIS: Development of trace gas DA capabilities, incorporation of averaging kernels in JPSS trace gas products, satellite data distribution and QC in BUFR
- OAR: Development of emission DA capabilities; evaluate and choose proper satellite products for EDA

Major Milestones:
- *Q4FY18: Capabilities for aerosol AOD with Kalman Filter and total column ozone global data assimilation developed in GSI and CRTM and JEDI (ongoing)*
- *Q3FY19: Evaluate assimilation of JPSS aerosol properties (ongoing)*
- *Q4FY19: Evaluate effects of emission data assimilation for NO2 in regional FV3-chem (ongoing)*
- Q2FY20: Implement Total Column O3 DA into FV3GFS operational run
- FY20: Integrate AC data assimilation capability into JEDI framework
- FY21: Develop aerosol/O3 DA with regional FV3-Chem
- FY21: Develop NO2 DA, OMI/TROPOMI with FV3-Chem
- FY21: Begin to develop aerosol reanalysis using EnKF and NASA NNR observations and pre-processing. some leveraging possible with MAPP/CPO grant (mid 2018-mid 2022).

Project 10.2: Data Assimilation for Atmospheric Composition (FY/18-21)

Implementation Plan for FV3-Chem Assimilation (FY2018-2021)

FV3CDAS	FY18				FY19				FY20				FY21			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4				
Preliminary GSI/EnKF DA for FV3GFS-Chem	Develop global Aerosol AOD and NO2 DA for FV3GFS-Chem															
GOES-16, JPSS DA		Testing, Evaluation of assimilation aerosol properties from JPSS products														
JEDI Infrastructure					Incorporate JEDI Unified Forward Operator and Modular GSI infrastructure											
Initial Operational Capability					Retros testing and implementation of Global AOD DA											
Regional DA	Develop Regional AOD DA & NO2 EDA					Include EPA chem in CRTM; Testing/Evaluation of regional DA; retro testing										
Advancement of FV3Chem DA											Further advancements of FV3GDAS;Unified DA Development; Implement regional DA					

Project 10.3: Atmospheric composition emissions capability

Project overview: A unified emission system with the capability of providing model-ready, global anthropogenic and natural source emissions inputs for aerosol and gas phase atmospheric composition across scales is needed. A key capability of the emissions system is the "forecasting" of emissions based on existing emissions inventories, FV3-predicted meteorology, assimilation of near-real-time satellite and in-situ data (emission data assimilation, in conjunction with Project 2 efforts), and economic and energy use projections. The emissions modeling system will provide the best available estimate of emissions of gases and particles, or "forecast-ready emissions", suitable for forecasting applications. The system should be capable of three key capabilities, including: (1) ingestion of anthropogenic emission inventories; (2) prediction of natural source emissions not included in emission inventories; and (3) timely update of emission data through emission data assimilation or other approaches. Table 10.3.1

lists the details for each component of the emissions system in the current implementation of, or in planned updates to, FV3-Chem.

Table 10.3.1. List of emission components for FV3-Chem

. Anthropogenic emission modeling		
Emission Sector	Global approach	Regional approach
agricultural	CEDS-2014	NEI2014+ECCC2012+MEX2014
Anthro fugitive dust	None	NEI2014+ECCC2012+MEX2014
aircraft	CEDS-2014	NEI2014+ECCC2012+MEX2014
train	CEDS-2014	NEI2014+ECCC2012+MEX2014
Anthropo marine	CEDS-2014	NEI2014+ECCC2012+MEX2014
nonroad	CEDS-2014	NEI2014+ECCC2012+MEX2014
onroad	CEDS-2014	NEI2014+ECCC2012+MEX2014
oil_gas	CEDS-2014	NEI2014+ECCC2012+MEX2014
EGU	CEDS-2014	NEI2014+ECCC2012+MEX2014
non-EGU points	CEDS-2014	NEI2014+ECCC2012+MEX2014
Residential wood burning	CEDS-2014	NEI2014+ECCC2012+MEX2014
Other area sources	CEDS-2014	NEI2014+ECCC2012+MEX2014
2. Natural emission modeling		
Wildfires/Prescribed burning	3BEM real-time (MODIS/VIIRS)	HMS+Bluesky
Windblown dust	GOCART	FEGNSHA
Biogenic	MEGAN (Guenther et al., 2000)	BEIS
Marine (VOCs, DMS, Organic aerosols, sea-salt, halogens)	DMS from GOCART Sea-salt from GOCART No VOCs, OA or halogens.	JPSS isoprene, DMS, Organic aerosols;
Lightning NOx	None	CMAQ, but not implemented due to large uncertainty

Volcanic SO2 and ash	Stauffer et al. (2013)	OMI/OPMS based emission estimates (tested over Hawaii)
3. Emission rapid refresh with emission data assimilation (EDA)		
NO2		OMI-based process aware emission data assimilation
SO2		
Anthropogenic Dust		NEI adjusted with met data
Windblown Dust		VIIRS/MODIS based EDA
NH3		
4. Emissions Processor		
	prep_chem_sources	SMOKE

The first capability is to ingest data for anthropogenic emission sources characterized as either points (e.g., large power generation and industrial facilities), mobile (including transportation sources on roads, rails, seas, and in the air), or area (generally distributed smaller sources such as residences, agriculture, etc). Initial FV3-GOCART/Chem aerosol treatments will require information about anthropogenic sources of sulfate, nitrate, ammonia, fugitive dust, black carbon and organic carbon. Future FV3-Chem versions will incorporate fuller treatments of gas- and aerosol-phase chemistry and will require a broader speciation of emissions. Gas phase emissions will need to be compatible with and easily convertible between multiple chemical mechanisms and aerosol modules and would include nitrogen oxides, sulfur dioxide, ammonia, carbon monoxide, speciated volatile organic compounds (anthropogenic and biogenic), and carbon dioxide (and other compounds, depending on particular applications). Anthropogenic emissions inputs to FV3-Chem can be provided by the Community Emissions Data System (CEDS, http://www.globalchange.umd.edu/CEDS/), a flexible and regularly updated framework developed at the U. Maryland/PNNL's Joint Global Change Research Institute that generates global anthropogenic emission estimates in near-model-ready format. Regional emission datasets will be synchronized with CEDS when necessary. These regional datasets will be based on official inventory data generally provided by regulatory agencies, including the US Environmental Protection Agency's (EPA's) National Emission Inventory (NEI), Environment and Climate Change Canada, and the Mexico's National Institute for Ecology.

The system will apply various emission models/datasets to represent natural source emissions. Emissions of windblown dust will be predicted by algorithms within FV3-GOCART/Chem, incorporating near-real-time surface properties (NDVI, soil moisture, etc.) derived from satellite data and coupled to FV3-predicted meteorology. Particles and gas-phase compounds in wildfire smoke will be derived from near-real-time satellite detections of fire locations and fire radiative power, along with off-line information about fuel loading and emissions speciation, and coupled to algorithms using FV3-predicted meteorology to model fire plume rise. The NESDIS GBBEPx emission product that combines NASA QFED approach with geostationary and polar orbiting satellites is currently used operationally at NCEP. Any new approach should be tested against or leverage the operational biomass emissions. Emissions from biomass burning have much room for improvement. This includes the development of a quality control system for biomass burning emissions, implementing time consistency when clouds prohibit satellites from seeing the fires, implementing dependencies on the impact of rain, and developing ensembles for fire emissions in sub-seasonal forecasting. Volcanic emissions derived from satellite data should be compatible as input to FV3-GOCART/Chem. Biogenic emissions from land vegetation will be predicted by algorithms driven by FV3 meteorology constrained by the NGGPS land surface model processes and satellite-derived vegetation phenology. Examples of possible biogenic emissions models for implementation include the Model of Emissions of Gases and Aerosols from Nature (MEGAN, http://lar.wsu.edu/megan/index.html), and the Biogenic Emission Inventory System (BEIS, https://www.epa.gov/air-emissions-modeling/biogenic-emission-inventory-system-beis). Marine emissions of sea salt, organic aerosols, volatile organic compounds (e.g., isoprene), halogens and biogenic sulfur (DMS, MSA) will be predicted by algorithms driven by FV3-predicted meteorology, ocean color data from S-NPP and future JPSS satellites, and other marine data sources. Estimates of marine emissions also require spatial and temporal distribution of phytoplankton species that may be made available from the ecosystem forecasting (using a ten-year climatology from satellite detection now).

The third capability, timely emission updates, ensures that the system is capable of projecting anthropogenic emissions from the year of a reference inventory to near-real-time, based on updated information from remotely-sensed measurements (e.g. satellite trend data), in situ measurements or other validated emission information.

Future versions of the emissions modeling system would ideally be intimately linked with an integrated LSM with chemical surface-atmosphere exchange processes (emissions, deposition, canopy effects, etc.) to provide chemical, physical and biological consistency among these processes for forecasting and earth-system model applications.

Finally, it is important to establish reliable QA/QC procedures for new emission dataset to be implemented in the system. Methods to blend high fidelity regional emission inventories (e.g., North American) and country-based global emission data will be critical. The development of FV3 emissions should accommodate multiple chemistry modules and flexible chemical speciation for VOCs, NOx, and aerosols. Hence the emissions system should be able to provide merged emissions as well as sector-based emission inputs to allow accurate speciation. Information of spatial and temporal allocation is essential to properly distribute country-level emissions into individual model grids in order to resolve fine-scale features such as urban ozone plumes and secondary aerosol formation.

Important emission systems capabilities are summarized in the following table:

Capability	**Application**	**Importance**
Easily accessible, regularly updated, global anthropogenic emission databases in model-ready format	Global; T2O Regional; R2X	Essential Desirable
Near-real-time biomass burning emissions	Global, Regional; T2O	Essential
Natural and anthropogenic dust emission algorithms with coupling to FV3 dynamics/physics suites	Global, Regional; T2O	Essential
Volcanic, radioactive tracer capability	Global, Regional; T2O	Desirable
Coupling NGGPS land surface and ecosystem model processes with dynamic emission processes (biogenic, dust, ocean, etc.)	Regional; Global; R2X	Essential
Rapid emission update capability through assimilating near-real-time observations (in-situ, surface and satellite) for aerosols and key precursors (NO2, SO2 and NH3)	Regional; Global; R2X	Essential
Marine emissions (sea salt and organic aerosols, isoprene, halogens, biogenic sulfur) with coupling to FV3 meteorology and satellite-derived data	Global; T2O Regional: R2X	Essential Desirable
Option for climatological smoke, dust, marine emissions	Regional; Global; T2O	Desirable
Compatibility/synchronization of global inventory with info. from detailed regional inventories (e.g., U.S. EPA NEI)	Global;Regional; R2X	Desirable

Major Risks and Issues:

- The CEDS emissions system is relatively new and not extensively tested as a source of emissions data for global or regional forecasting operations
- Development of emission data assimilation packages for aerosols, NO2, SO2, and NH3
- Improved methods for inclusion of wildfire smoke emissions and injection heights, and crop residual burning emissions over agricultural regions. Better understanding of diurnal variations of biomass burning and transition into models.
- Detailed accounting of aerosols and reactive gases emissions from the oceans (OC, DMS, halogen, etc.); split sea salt into inorganic and organic components to better predict CCN and ice nucleation in FV3
- Methods to account for agricultural emissions besides NH3 (trace gases and aerosols);
- Tools to quickly incorporate new/high-impacting emission sources (volcano eruption, radiative leaking, oil spill, etc.)
- Impact of various natural forcing terms on sub-seasonal to seasonal prediction (wildfire smoke, dust, marine)

- Methods for incorporating elevated point sources
- Methods for incorporating diurnal profiles of global anthropogenic emissions
- More near-real-time anthropogenic emissions using *in situ* and remotely sensed data for adjustment to forecast-ready emissions
- Compatibility/synchronization of global inventory with information from detailed regional inventories.

Major resources requirements:
- Personnel: ESRL/CSD (1 FTE); ESRL/GSD (1.0 FTE); NOAA/ARL (2 FTE); GFDL (TBD); NCEP/EMC (0.5 FTE); NESDIS (1 FTE)
- HPC for development: CPU hours per month (TBD); Storage (~200 TB)

Dependencies/linkages with other projects:
- All emission data assimilation packages (aerosols, NO2, SO2, and NH3) require data supply by NOAA satellite programs (JPSS and GOES-R) or other agencies;
- GMTB/CCPP & infrastructure for documentation, training and providing a data portal
- MET based verification development for atmospheric composition variables
- Transition to VLab and Code Management/Governance
- NUOPC FV3 cap
- UMD/PNNL JGCRI for Community Emissions Data System
- Regional emissions for NWS/NAQFC.
- Emission measurements from NOAA/NESDIS, NASA, EPA etc.

Core development partners and their roles:
- NCEP/EMC: Emission capability transition to and implementation in the operational environment
- NOAA/ESRL/CSD: Process CEDS anthropogenic emissions and provide model-ready gridded inputs
- NOAA/ESRL/GSD: Assist in anthropogenic emissions processing. Predict fire emissions.
- NOAA/ARL: Project anthropogenic emissions to near-real-time using satellite and in situ data; process-based emission models to estimate natural source emissions; regional emission forecasting for NAQFC.

Major Milestones:
- **Q3FY18: Develop CEDS anthropogenic emissions inputs compatible with FV3-Global Chem (completed)**
- Q4FY18: Develop CEDS anthropogenic emissions inputs for more complex chemistry scheme at global scale (completed)
- Q1FY19: Implement NESDIS GBBEPx biomass burning into FV3GFS-GOCART system
- Q4FY18: Update the FV3-GOCART anthropogenic emissions inputs with 2016 CEDS data
- Q1FY19: Update biomass burning emissions inputs to FV3-GOCART - add plume-rise module
- Q1FY19: Couple one or two top performing dust emission schemes into FV3-GOCART.

- Q2FY19: Extend base year emissions from the CEDS inventory to near real time using satellite adjustments
- Q4FY19: Evaluate CEDS emissions with NAQFC benchmark dataset over CONUS.
- Q4FY19: Develop CEDS anthropogenic gas-phase emissions inputs for FV3-Reg Chem.
- Q4FY19: Develop emission rapid updating capability for NO2;
- Q3FY19: Develop and test final wild-fire smoke emissions for FV3-Global Chem
- Q4FY20: Develop forecast-ready emission dataset, with emission rapid refreshing capability, for regional FV3-Reg Chem.
- Q2FY19: Develop and test marine emissions (isoprene, DMS, and primary organic aerosols) for FV3-Global Chem
- Q2FY20: Implement global emissions in FV3-global Chem into Operations
- Q2FY20: Develop and test wild-fire smoke emissions for FV3-Reg Chem
- FY21: Unify emissions, increase resolution, more frequent emission update with satellite retrievals

<u>Project 3 Atmospheric Composition Emissions Capability (18-21)</u>

Implementation Plan for FV3-Chem Emissions (FY 2018-2021)

FV3CHEM	**FY18**				**FY19**				**FY20**				**FY21**			
	Q1	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**				
Global anthro emissions	**Develop; evaluate Global CEDS emissions**															
Regional anthropogenic emissions				**Develop, evaluate regional CEDS emission for NAQFC**												
Global natural emissions		**Couple global wild-fire smoke, dust emissions systems (eg: GBBEPx, QFED..)**														
Regional natural emissions							**Couple regional wild-fire smoke, dust emissions systems (e.g., FRP, USFS Blue Sky)**									
FV3-Chem Implementation							**FV3GFS-Chem ops**								**FV3SAR-Chem ops**	
Advancement of FV3Chem emissions											**Further advancements of FV3-Chem emissions: real-time updates from satellites; higher resolution; unification of global-regional where possible**					

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<u>ANNEX 11</u>: ENSEMBLES

The intent of improved ensemble predictions are to directly provide sharp (specific) forecasts that are reliable (i.e., the event occurs 80% of the time when an 80% probability is forecast) and that provide situation-dependent estimates of the forecast uncertainty. These can be used to provide improved decision support for a large variety of customers. Ensembles are now also commonly used to provide improved estimates of forecast-error covariances in data assimilation methods, thereby improving the quality of the initial condition and subsequent deterministic and ensemble forecast accuracy.

There are two sources of forecast uncertainty that should be modeled accurately in ensemble prediction systems. The first is initial-condition uncertainty. An ensemble should be initialized with samples from the distribution of plausible analysis states. The second is model uncertainty, which can bias the mean forecast and limit the spread of simulations, resulting in an overconfident ensemble, especially for surface-related variables (e.g., surface temperature and precipitation) and tropical forecasts such as hurricane tracks. These contributions to forecast error can be attributed to model deficiencies as well as from deterministic assumptions built into the forecast models' components, such as parameterizations. As NOAA moves to more fully utilize coupled forecast models (atmosphere/ocean/land/ice, and perhaps more), the challenges of estimating forecast uncertainty will extend to estimating the coupled initial-state uncertainty and sources of model uncertainty in the coupled prediction system.

Addressing the atmospheric initial-condition uncertainty has progressed in recent years more than the model uncertainty. With ensemble Kalman filters and hybrid data assimilation methods, there is now a direct method for producing ensembles of initial conditions that represent samples from the distribution of analysis uncertainty. The accuracy of such methods, however, depends critically on ensemble size, the treatment of model uncertainty in the data assimilation cycle, the extent of non-linearity and non-Gaussianity of error statistics, and the chosen methods for dealing with position errors of coherent features. While intimately related to ensemble prediction, NGGPS development activities related to improving atmospheric ensemble initial conditions are primarily managed through the Data Assimilation working group (see Annex 6).

The second source of forecast uncertainty is model uncertainty. This can be manifested as forecast bias and a lack of spread in ensembles, leading to unreliable, over-confident forecasts. General forecast biases such as consistently biased forecasts of land-surface temperatures or consistent misrepresentations of tropical deep convection and its associated circulations should and will be addressed directly, such as through model improvements; see the Model Physics portion of the SIP (Annex 5) and the land-surface plan (Annex 9) for implementation plans to address these.

Even if a parameterization produces unbiased simulations, its formulation can still contribute to a lack of spread in ensemble predictions. For example, convective parameterizations as currently formulated are deterministic. The amount of convective rainfall and the tendencies of temperature, humidity, and winds are completely determined by the column's vertical profile of temperature, humidity, and wind components, taking no account of possible sub-gridscale variability. In reality, the convective response may depend on the unresolved detail; two grid cells with identical vertical profiles but differing sub-grid detail may have completely different realizations of deep convection. Hence, deep convection and many other parameterizations that are currently treated deterministically need to be reformulated in ensembles to be stochastic rather than deterministic, in ways that are physically based, i.e., consistent with our knowledge of the sources of uncertainty.

The state of current research into stochastic parameterization to address model uncertainty is less advanced than research into initial-condition uncertainty. There are first-generation techniques under development that are scheduled for implementation (with NGGPS funding). Ultimately, we want to address the uncertainty at the process level, with physically based stochastic processes introduced into each parameterization.

A new challenge will also occur as we migrate to the use of coupled models. Imperfections in the interactions of the coupled state components will also need to be simulated properly.

Ensemble predictions are increasingly being used for providing situational awareness of high-impact weather forecast events, informing the forecaster of the range of possible weather scenarios, especially after statistical postprocessing (Annex 12). Ensembles are now also commonly used to provide estimates of forecast-error covariances in data assimilation methods.

Project 11.1: FV3-GEFS implementation

This is the highest-priority project for the next few years, the development of the next-generation global ensemble forecast system using the FV3 dynamical core. This project is described now in ANNEX 1 (Global Systems); the reader is referred to this section for details, including dependencies.

Project 11.2: High-resolution global ensemble forecast system (HRGEFS)

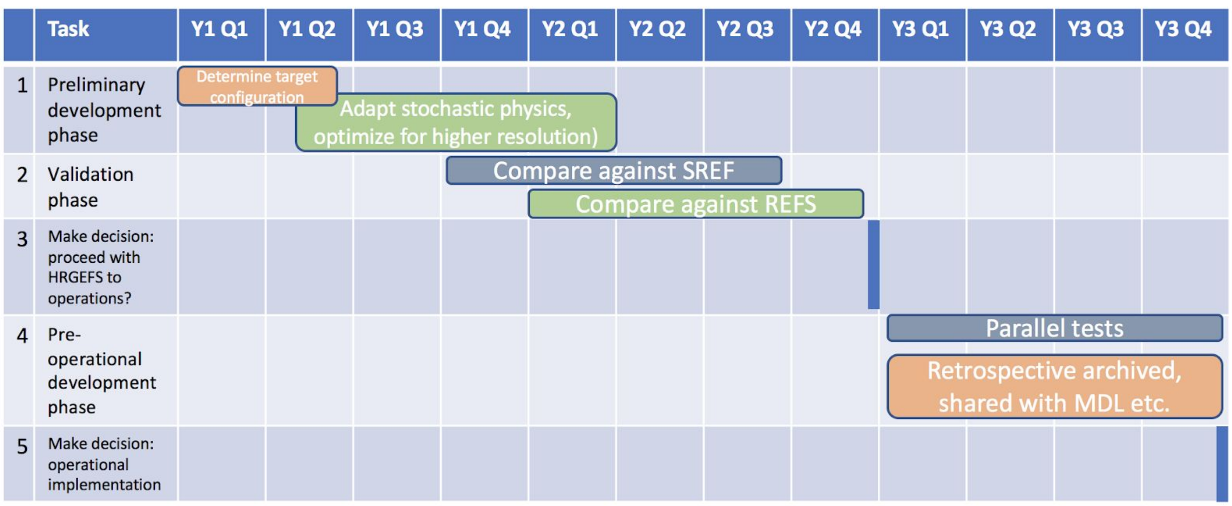
Project Overview: *(Note: this project is planning stages, so not yet authorized by NGGPS to commence).* The desired intent, if possible, is to deploy a higher-resolution global ensemble system that produces output to several days, with the intent of producing guidance of such quality that it can supplant regional multi-day ensembles. This system is being planned for because the UMAC recommends that NCEP reduced the complexity of its production suite. "*The large number of modeling systems maintained by NCEP is overwhelming NCEP personnel, computer resources and stakeholders. It greatly reduces the ability of individual NCEP modeling systems to achieve excellence. A strategy for the phasing out of redundant or obsolescent models needs to be put in place*." A key recommendation by UMAC (2015) for ensemble and post-processing states specifically the following: "*Ensemble product generation from the SREF should be moved over to the GEFS, and the SREF should be discontinued after careful evaluation of GEFS for providing useful shorter range regional ensemble information*."

This desire for production suite simplification around global models is in tension with user desire for higher-resolution regional ensemble guidance to several days. Prototypes of multi-day regional ensembles at convection permitting grid spacing have been generally well received by the community.

Accordingly, under this project the HRGEFS system will be developed and evaluated for replacement of the legacy SREF system. Likewise, the prototype of a convection-permitting regional ensemble forecast system (i.e., the FV3-based Regional Ensemble Forecast System, or REFS), will be developed and evaluated for replacement of the legacy HREF system. The ultimate decision about whether to operationally deploy a HRGEFS, the REFS, both, or neither, will be made after both systems have been developed and compared. See annex 7, Convection-Allowing Models, project 2, for more on the REFS.

Plans and milestones for potential deployment of a HRGEFS: We envision a three-year project with three phases (preliminary development, validation, and pre-operational development. There would be two major decision points. The first would come following a comparative evaluation against the SREF system in development. The decision would be whether to proceed with pre-operational testing of a HRGEFS presuming an eventual implementation. The third phase, conditioned upon a decision to go forward, consists of formal pre-implementation parallel runs, including the archive of these current and any retrospective simulations as training data for statistical postprocessing.

Ideally, development would start soon, e.g., Q1 of FY2018. To be flexible, the Gantt chart below simply provides milestones relative to whatever start date is chosen.



After a successful operational implementation, it is possible that the deterministic GFS system may be decommissioned, and future implementations would be with the HRGEFS system at decreasing grid spacing. The specific details of this are omitted, as they are in the more distant future.

Challenges and critical issues:

HPC resources:

- For short term plan (0-3 years), the HPC pool will be known, though whether available resources are used for a HRGEFS and/or REFS (see Annex 7 on CAMs) is TBD.
- For mid- to long-term planning (3-10 years), pending resolution increases to provide greater accuracy, we will need to estimate required HPC and storage resources and make sure these are reflected in HPC purchases.

Workforce:

- Much would be similar between the HRGEFS and GEFS systems, so GEFS developmental talent can largely be leveraged. There may be some system differences, however, such as the use of an uncoupled prediction for the HRGEFS vs. coupled for GEFS that will require 1-2 staff beyond those currently developing the GEFS. These might potentially be staff working on the SREF and/or CAMs, pending the decision on the REFS.

Science and implementation issues:

- Is coupling required and justified given the increased computational expense. Coupling may include coupled ocean, sea-ice, wave and aerosol states.
- The production suite is typically more crowded around and just after synoptic times (00, 06, 12, 18 UTC). When are the appropriate periods for HRGEFS computations? Should they be run 4x/day, 8x/day, or other? At certain times of day (e.g., 12, 00 UTC) should ensembles be run to a longer lead time?
- To what extent are reforecasts and associated reanalyses needed for this system? Will those users requiring extensive reforecasts be requested to use the GEFS system, such that a HRGEFS is more "nimble" and implementations can happen on a quicker pace with fewer retrospective simulations required? Or are product requirements such that extensive retrospectives are needed for the HRGEFS system as well.

<u>Project 11.3: Ensuring consistency between global and regional ensemble systems</u>

Project Overview: *(Note: this project is planning stages, so not yet authorized by NGGPS to commence).* NWS is expected to provide a "seamless suite" of forecasts, i.e., ones where the forecast quality and character does not change with forecast lead time. Such abrupt changes are possible if products depend on both regional and global ensemble systems -- unless they are carefully co-developed. To provide this seamlessness in the future, for example, the ideal suite of ensemble systems would have characteristics such as (1) lateral boundary conditions for a regional ensemble system would be provided by the global ensemble system; (2) the regional and global system would share dynamical cores and suites of scale-aware parameterizations, so that biases were similar; (3) methods for dealing with model uncertainty in the ensemble systems would be treated in very similar ways.

At this point, development of a regional, high-resolution, rapidly updating ensemble system is occurring without extensive coordination with global system development. This new project would ensure that the regional and global ensemble development is well coordinated, and is meant as a potential complement to ensembles project 2, as discussed above. That project is intended to determine whether a regional ensemble system is needed for forecast lead times of several days. This project is intended to make sure that any regional ensemble system, including a convection-permitting ensemble for leads of 1 day, are as consistent as possible with the global ensemble systems in development.

Major Risks and Issues:

- Major changes to regional ensemble systems are likely needed to achieve consistency. There is a different paradigm in current high-res regional ensembles, where multiple dynamical cores and physical parameterizations are used to increase ensemble diversity. This is different from the approach used with global models, where the same model and parameterization suite is used for all members, and reliability is more generally achieved with statistical postprocessing. This was done to lessen the amount of prediction software to maintain, and to ensure that error characteristics were similar for all members to make downstream product development easier. Unification of regional and global ensemble systems will be difficult unless regional systems adapt to the paradigm of the global system, using a single dycore and parameterization suite.

- Regional, very-high resolution ensemble systems can be computationally expensive, especially if updated and run hourly. Computational resources may not be adequate unless compromises are made, such as the use of few ensemble members or small domains. Such compromises may to limit the quality of products generated from the regional ensemble system.

Major resources requirements:

- Personnel: TBD pending agreement that the project should be undertaken. As this project involves mostly coordination, it is anticipated that personnel resources are minimal.
- HPC for development: Minimal, presuming the actual HPC requirements are already reflected in other projects such as the REFS development.

Dependencies/linkages with other projects:

- Dependency upon successful development of the FV3 GEFS and perhaps the HRGEFS, previously discussed.

Core development partners and their roles:

- Global ensemble system developers (ESRL/PSD, EMC) will need to partner with the developers of regional ensembles, including NSSL, ESRL/GSD, and perhaps NCAR, Navy, and universities.
- We will also need the input of major product users such as the NCEP Storm Prediction Center.

Major Milestones: This is a coordination function only, and so the milestones should be reflected instead in the actual development of other projects.

Project 11.4: Improve uncertainty treatments in the ensemble system to make them suitable for sub-seasonal forecasts and for a full spectrum of environmental prediction needs (mostly in planning).

Project Overview: *(Note: this project is planning stages).* The current GEFS system provides forecasts to only +16 days. To extend the useful skill of forecasts to leads up to +35 days, improvements to the GEFS system will be necessary; what skill may be realized in weeks +3 and +4 may depend on physically realistic coupling to the more slowly varying ocean, land, and sea-ice states, and modeling the uncertainty in that coupling. Future requirements may extend to providing sub-seasonal forecasts including the upper atmosphere, and full coupling to other environmental states such as ocean waves. This project envisions four sub-projects, described separately below. These include: (a) providing improved estimates of the uncertainty related to the imperfections in the dynamical core; (b) providing improved and more physically based stochastic parameterizations; (c) modeling the uncertainty of the coupled state, which may include ocean, sea-ice, and land (for +30 day applications), upper atmosphere (for space-weather forecast applications), and ocean waves and storm surge (for marine and coastal inundation applications).

Sub-project 1: Dry dynamical core uncertainty. The finite resolution of the dynamical core and the necessity of numerical diffusion for model computational stability reduce the spread in ensemble forecasts. We seek in this project to realistically model the uncertainty due to these causes, increasing spread in the ensemble prediction system in a manner that is physically realistic. Project activities will include: (a) determine the extent to which finite resolution and imperfections in the dynamical core formulation are contributing to a lack of spread in ensemble prediction systems; (b) develop and test methods for increasing the ensemble spread in physically realistic ways that account for the finite resolution and dycore imperfections; and (c) pending improvement in spread with no increase in error, publish results and implement.

Major risks and issues: Given success at ESRL/PSD with early software versions, the risk is minimal.

Major resources requirements:

- Personnel: ~0.5 FTE x 2 years.
- HPC for development: TBD, but moderate.

Dependencies/linkages with other projects: Dependency upon successful development of the NEMS version of the FV3 GEFS, which will be the standard for comparison.

Core development partners and their roles: Global ensemble system developers (ESRL/PSD, EMC). Jeff Whitaker (ESRL/PSD) has already done some advanced development.

Major Milestones: Milestones and GANTT chart TBD pending interest in the project.

Sub-project 2: Develop, test, and implement codes for more physically based stochastic parameterizations. The current GEFS system is being upgraded for version 12 with a suite of stochastic parameterizations that improve system performance, including spread. However, these new methods are less physically based than desirable and represent an interim step toward stochastic procedures that are more physically realistic and potentially more accurate. Accordingly, this task proposes to add stochastic elements within the advanced physics suite being developed by EMC and collaborators in order to increase ensemble spread and decrease mean error in physically realistic ways. Improved parameterizations to which stochastic elements may be added include the Simplified Higher Order Closure (SHOC) scheme for boundary-layer turbulence and shallow convection and the scale-aware Chikira-Sugiyama and Grell-Freitas deep convection schemes). This overall project is envisioned as likely two or more funded projects. One project has begun, a shorter-term development and implementation to add stochastic elements to deep convective parameterizations and one or more that addresses some more fundamental issues in stochastic parameterization of the boundary layer, microphysics, or other key parameterizations.

Major resources requirements:

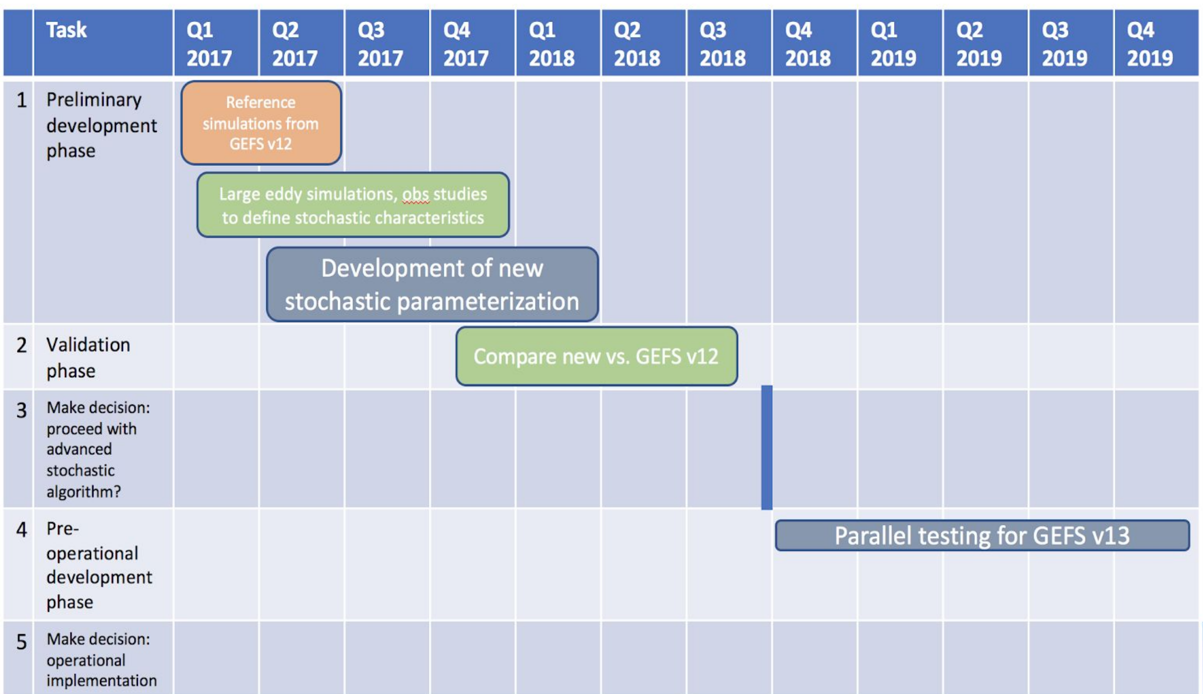
- Personnel: For the first project, we anticipate 1 FTE x 3 years. $173K was allocated in FY17, and follow-on funding will be solicited in FY18 for advanced testing and implementation pending improved performance. Similar personnel resources should be anticipated for secondary, tertiary projects. POC: Jian-Wen Bao, ESRL/PSD
- HPC for development: TBD, but moderate.

Dependencies/linkages with other projects: Dependency upon successful development of the FV3 GEFS, discussed above. This system will provide a benchmark for performance.

Core development partners and their roles: Global ensemble system developers (ESRL/PSD, EMC). Perhaps universities or NCAR for secondary, tertiary projects. There is a project in progress at ESRL/PSD addressing the stochastification of deep convective parameterizations.

Major Milestones: Initial milestones for preliminary development and validation phases for the project in progress are shown below. A Gantt chart is shown below; milestones include:

- Q3FY17: Establish a baseline in the NEMS/FV3 framework using first-generation stochastic parameterizations (see task 5.4.1 above).
- Q1FY18: Conduct analysis of observations and large-eddy-simulation data sets to define probability density functions of sub-grid variability in convection and PBL mixing.
- Q3FY18: Demonstrate an initial stochastic physics capability in the advanced physics suite and provide comparisons against the baseline simulations previously generated. Pending a successful demonstration during the research phase, there would be a subsequent pre-operational development phase requiring resources.



__**Sub-project 3: Develop and implement methodologies for a future coupled FV3-based GEFS system to make its forecasts suitable for the full 0-30 day prediction period**__ __(in planning, not yet authorized)__. Several activities are possible under this task. They could include: (a) development and implementation of a methodology for a estimation of coupled state ensemble of *initial perturbations,* suitable for coupled forecast model initial condition (land/atmosphere, ocean/atmosphere, ice/ocean/atmosphere) [possibly under the DA component of the plan] (b) Development and implementation of advanced methodologies for estimation of coupled state model uncertainties, such as how model uncertainty in the ocean model can be estimated in such a way as to have realistic effects on atmospheric uncertainty estimated from ensembles.

Major resources requirements:

- Personnel: Unknown, but probably best handled through a grant process to labs or universities; this topic is at a lower TRL. If such a project demonstrated potential, subsequent funding including EMC and OAR for advanced development and implementation would be solicited.
- HPC for development: TBD, but large, given that many simulations will be necessary to monthly time scales.

Dependencies/linkages with other projects: Coupled DA would presumably occur through the JEDI DA infrastructure, hence a dependency on this.

Core development partners and their roles: ESRL/PSD, other government labs, universities, EMC.

Major Milestones: TBD, based on success of grant proposals.

Sub-project 4: Develop and implement a comprehensive extended ensemble prediction system addressing a wider range of environmental prediction needs (e.g., ocean waves, space weather). [in planning, not yet authorized]**.** These may include activities such as: (a) development of modifications to the basic GEFS system to make the prediction system suitable for space-weather applications, (b) development of modifications to the GEFS system to provide coupled wave and coastal inundation forecasts. (c) other modifications as needed for extension to other high-priority needs.

Major resources requirements:

- Personnel: Unknown, but substantial.
- HPC for development: TBD.

Dependencies/linkages with other projects: TBD.

Core development partners and their roles: TBD.

Major Milestones: TBD, based on grant proposals.

<u>ANNEX 12</u>: POST-PROCESSING

This annex to the NGGPS SIP will guide the development and implementation of the post-processing portions of Unified Forecast System (UFS). As with the other components of UFS, NOAA seeks to engage with the public, private, and academic sectors of the weather enterprise to develop and advance a world-class post-processing system. To this end, NOAA has recruited a team of experts from throughout the weather enterprise to provide feedback on this plan.

In operational meteorology, the term post-processing refers to one or more scientific software processes that capture the output from a Numerical Weather Prediction (NWP) system and enhance its value in some way. For UFS, the NWP model will be NOAA's operational Global Forecast System (GFS) based on the Finite-Volume Cubed-Sphere Dynamical Core (FV3; GFSFV3).

Post-processing algorithms can be used to generate traditional meteorological variables (e.g., temperature, visibility, precipitation amount) and/or weather-dependent variables that are either not forecast or are poorly forecast by NWP models (e.g., road conditions, optimal evacuation path, crop disease susceptibility, renewable energy production). Often, these techniques generate or improve expressions of uncertainty (e.g., event probabilities, probability distributions).

Post-processing can be said to include the following three broad areas: (Please note, we consider these categories to be informative rather than restrictive. Techniques exist that clearly span the boundaries suggested by these definitions.)

Model Post-processing (ModPP)--A post-processing step that interprets NWP output in native model coordinates (e.g. sigma levels, spherical harmonic coefficients) and produces output in coordinates more familiar to human meteorologists (e.g., isobaric levels and regularly-spaced grids)

Diagnostic Post-processing (DiagPP)--A post-processing step that applies interpretive algorithms without training (e.g., the BUFKIT application, ensemble relative frequency) to NWP output

Statistical Post-processing (StatPP)--A post-processing step that uses statistical inference based on current NWP output, past forecasts, observations/analyses, and other data sets to create new or improved forecast quantities. Examples include Model Output Statistics (MOS) and multi-model blending such as the National Blend of Models (NBM).

NOAA's operations are currently supported by a number of post-processing techniques that are distributed across a broad swath of organizations and computing platforms. They employ a variety of techniques, software infrastructures, and purpose-built data formats. The exchange of information among research, development, and operational entities is generally problematic because of these disparities. The process of migrating research to operations and vice versa often suffers unnecessarily because of these disparities.

NGGPS provides an opportunity for seminal change. This annex to the SIP outlines steps that NOAA will follow to evolve operational post-processing towards a community approach.

Project 12.1: Transition all NOAA Operational Post Processing packages (ModPP, DiagPP, and StatPP) to support FV3 (FY19-21)

Project overview: NOAA is required to support existing operational products during each model upgrade and that includes the transition to FV3 (currently planned in January 2019). EMC is building new Model Post-processing **(ModPP)** interfaces to efficiently interpolate FV3 model output from cube-sphere grid to regular orthogonal grids. This will facilitate a smoother transition from spectral GFS to FV3 GFS for users throughout the weather enterprise. Downstream applications, however, will likely need adjustment to accommodate FV3's bias characteristics.

The FV3GFS model output will include native model output in netCDF and nemsio binary formats as well as post processed output in GRIB2 to improve conformance with community standards and to facilitate data exchanges with the rest of the weather enterprize. There will also be a regional version with FV3 dynamical core that will be developed at roughly 3 km resolution and will serve as the eventually replacement for systems like HRRR, RAP, HREF, NAM, and SREF. Development to add compatibility with this stand-alone regional (SAR) capability will eventually be needed, but it is unclear if this will happen before FY22.

Priority: This project impacts NWS operations. It will have the highest priority.

Major Risks and Issues:

- Risk of degraded efficiency when creating or ingesting netCDF output.
- Level of effort required to generate and test new datasets.
- Some organizations may need to change their StatPP techniques significantly.

Major resource requirements:

- Personnel: various from EMC, MDL, AWC, CPC, SPC, WPC, and DTC.
- HPC for development: NOAA's WCOSS for EMC and other local platforms for MDL, AWC, CPC, SPC, and WPC. DTC will test UPP on various platforms.

Dependencies/linkages with other projects:

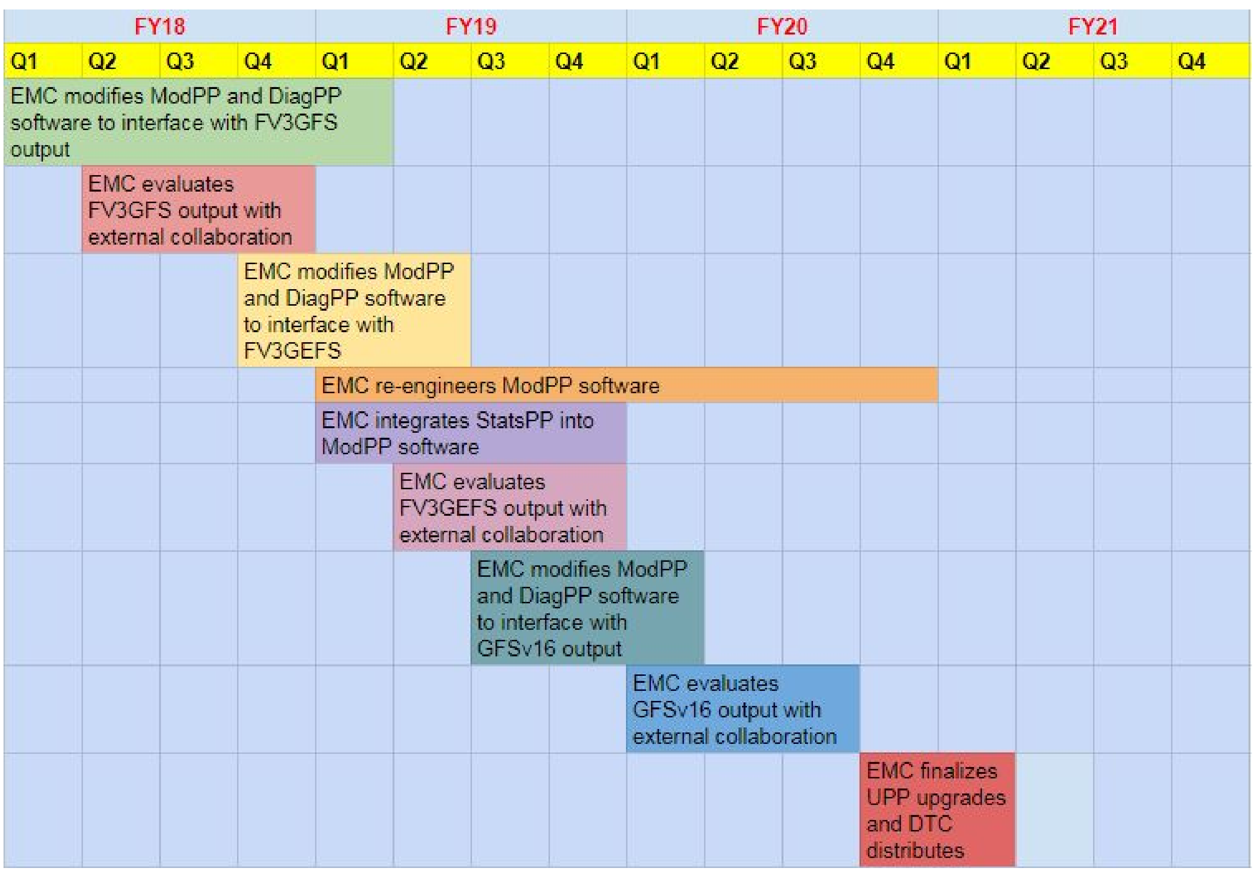
- Annex 1, Projects 1.1, 1.2, 1.3
- Annex 4, Projects 4.1, 4.3
- Annex 7, Project 7.2
- Annex 8, Project 8.2
- Annex 10, Project 10.1
- Annex 12, Project 12.5
- Annex 13, Projects 13.4, 13.5

Core development partners and their roles:

- EMC will update ModPP to interface with FV3 output in netcdf format**.**
- EMC will provide FV3 output to NOAA organization for testing in their downstream applications as soon as possible.
- MDL, AWC, CPC, SPC, and WPC will test FV3 output provided by EMC in their downstream applications and adjust their algorithms if necessary.
- DTC will support the enhanced UPP (ModPP) on multiple platforms to community users so they can post process new FV3 output pending funding.

Major Milestones:

- MDL, AWC, CPC, SPC, and WPC provide feedback about their evaluation results on FV3 GFS (Q3 FY18 - Q1 FY19)
- Q1FY19: EMC updates UPP to support post processing of regional high resolution FV3
- Q2FY19: EMC updates UPP to support FV3 GEFS post processing
- Q3FY20: EMC improves UPP efficiency to support FV3 GFS with higher vertical resolution (GFSv16)
- Q1FY21: DTC distributes new UPP that reads FV3 output, pending funding



Project 12.2: Develop an ensemble visualization capability

Project overview: A rich set of ensemble visualization tools have been developed by NCAR, NWS Western Region, and other groups. These are some of the most popular DiagPP capabilities in NWS. These tools provide forecasters information about what is significant in the forecast, the range of possible solutions, and the potential impacts in terms of sensible weather. This project will focus on transitioning that research into operations to provide visualization of ensemble uncertainty information to NWS field operations. Improved access to uncertainty information will benefit forecaster awareness of high-impact weather events, which is crucial to allowing the NWS to expand its Impact-based Decision Support Services (IDSS). EMC has investigated using the prototype software, and is looking towards a fully functioning system to use as a main post-processing display system for experimental model data and for use during Model Evaluation Group (MEG) presentations.

Priority: Important

Major Risks and Issues:

- Few since most of the exploratory development is complete.

Major resource requirements:

- 1 full-time lead developer. This has been funded by STI.

Dependencies/linkages with other projects:

- Few.

Core development partners and their roles:

- Originating organizations.

Major Milestones:

- Additional ensemble visualization tools
- Incorporation of new derived fields from Environmental Modeling Center (EMC)
- Implementation of Ensemble Viewer at EMC to display experimental model data (FY19Q2)
- Version 2.0 of prototype Ensemble Viewer with NCEP ensemble data (FY19Q3)

Project 12.3: Develop/implement National Blend of Models (NBM) v3.2

Project overview: NBM is the NWS's premier multi-model ensemble (StatPP). It uses a number of techniques to weight members, including expert weights, decaying average weighting, and sophisticated quantile mapping. The primary purpose of NBM v3.2 is to fill additional gaps from 9 National Service Programs.

In FY 2019, emphasis will be on Winter Weather, Climate, Marine, Fire Weather, and Aviation services. Some of the higher priority additions will include freezing spray, icing, turbulence, and solar radiation. Ceiling and visibility will be added to the OCONUS sectors. Basic elements for a new NBM sector in Guam will also be added. Quantile Mapping will also be added to the PoP/QPF post-processing for Alaska and Puerto Rico. Initial support for probabilistic Winter Weather, probabilistic QPF, and probabilistic temperature is also planned for the CONUS.

Additional activities are planned for the Numerical Weather Prediction (NWP), such as adding the ECMWF to the Oceanic Domain (including significant wave heights), adding the BoM ACCESS-G, and improving the resolution of some of the global ensemble datasets from 1.0 deg to 0.5 deg. We also plan on integrating the wind forecasts from HWRF and HMON.

Looking ahead for FY 2020 and 2021, the NBM v4.0 and v5.0 will expand from the traditional deterministic forecast parameters to increasingly calibrated probabilistic forecasts to better support Impact Based Decision Support Services (IDSS). Better quantification of forecast confidence, timing, storm intensity, and alternative scenarios is the expected outcome of providing these probabilistic forecasts.

The NBM has the current deficiency of not being a system where developers can perform experimentation (ie download current code and test data sets) and to test improved versions. The infrastructure to run retrospective forecasts is also not available to make evidenced-based decisions prior to implementation.

Priority: Important

Major Risks and Issues:

- Aggressive development schedule
- Challenges with operational implementation
- Evolution from deterministic to probabilistic forecast databases is not clear
- Need to narrow current StatPP operational product suite to become more streamlined and easier to maintain

Major resource requirements:

- Several full-time development staff, generally funded by STI.

Dependencies/linkages with other projects:

- Blended MOS (BMOS) and WISPS development

Core development partners and their roles:

- ESRL/PSD

Major Milestones:

- FY19 Q1: NBM V3.2 parallel running on WCOSS development

- FY19 Q2: NBM V3.2 Science Briefing: code frozen and handed to NCO
- FY19 Q3: NBM V3.2 30 Day IT Stability test at NCO/WCOSS
- FY19 Q4: NBM V3.2 operational on WCOSS production
- FY20 Q1: NBM V4.0 parallel running on WCOSS development
- FY20 Q2: NBM V4.0 Science Briefing: code frozen and handed to NCO
- FY20 Q3: NBM V4.0 30 Day IT Stability test at NCO/WCOSS
- FY20 Q4: NBM V4.0 operational on WCOSS production
- FY21 Q1: NBM V5.0 parallel running on WCOSS development
- FY21 Q2: NBM V5.0 Science Briefing: code frozen and handed to NCO
- FY21 Q3: NBM V5.0 30 Day IT Stability test at NCO/WCOSS
- FY21 Q4: NBM V5.0 operational on WCOSS production

Project 12.4: Develop station-based StatPP techniques for multi-model ensemble forecasts

Project overview: Many of the techniques used within the NBM can be fruitfully applied to point forecasts that use station observations as the proxy for truth. This work is in the early stages of development as of this writing.

Priority: Important

Major Risks and Issues:

- Attempting to maintain both station based and gridded based forecast systems
- Forecaster and user acceptance of station forecasts based on multiple inputs

Major resource requirements:

- Migrating to new software and data format platforms like WISP (Python, netCDF, git)
- Need for extensive NWP and data archives that exceed those of single model systems

Dependencies/linkages with other projects:

- NBM (to avoid duplication of efforts)

Core development partners and their roles:

- EMC, OAR, MDL

Major Milestones:

- FY19 Q4: Discontinue GMOS and EKDMOS as stand alone products
- FY20 Q4: Beginning running V1.0 of BMOS station forecasts
- FY21 Q4: Sunset individual MOS station products like GFS MOS

Project 12.5: Integrate Weather Information Statistical Post-processing System (WISPS) into NCEP Production Suite

Project overview: Statistical Post-processing (StatPP) techniques are playing a pivotal role in the generation of probabilistic forecasts that support Impact-Based Decision Support Services (IDSS) and the

Weather-Ready Nation (WRN). The NWP post-processing infrastructure used by MDL and EMC must be modernized and enhanced as a community code. The Weather Information Statistical Post-processing System (WISPS) embodies the software and standards that will facilitate collaborative efforts both within NOAA and between NOAA and the broader weather enterprise.

Priority: Important

Major Risks and Issues:

- Challenges of developing and using a new software framework while maintaining development in the old framework.

Major resource requirements:

- Two full-time developers, one each at MDL and EMC (funded by STI).

Dependencies/linkages with other projects:

- TBD

Core development partners and their roles:

- UK MetOffice, Australian Bureau of Meteorology, ESRL/PSD.

Major Milestones:

- Blended MOS (BMOS) and precipitation portions of National Blend of Models (NBM) implemented in WISPS (FY2019Q4)
- Community-based Unified Post Processor software that integrates WISPS and associated metadata standards (FY2019Q4)
- WISPS available to the weather enterprise as community code (FY2019Q2)

<u>Project 12.6</u>: Improve the accuracy of post-processed guidance through better science and better data

Project overview: Many of the algorithms that form the mainstay of NOAA's post-processed guidance may be sub-optimal. Existing algorithms such as multiple linear regression may not provide the highest quality guidance. Existing algorithm may be geared for weather applications, but may not be extensible to needed, longer-lead, sub-seasonal forecast products. Also, somewhat specialized post-processing methods may provide higher-quality guidance for certain products such as severe-weather probabilities, precipitation typing, or aviation hazards.

The underlying data sources are evolving. Previous algorithms may have been developed with short training data sets and station data. Now, with longer training data sets and improved quality analyses, alternative techniques may provide improved guidance if they leverage these.

This project, then, covers future scientific and data improvements to post-processed guidance in NOAA. We envision many possible sub-projects that may concentrate on various weather and climate elements of interest, such as one project for extended-range severe weather, another for hurricane intensity, and so forth. Such projects might be solicited under future requests for proposals through programs like

NGGPS, CPO/MAPP, or JTTI. An expectation is that as potential new methods are developed, they will be compared against the current most skillful reference standard.

Priority: Important

Major Risks and Issues:

- A lack of a community post-processing software infrastructure mentioned in previous projects, if not developed, will slow development efforts here, as each project scientist will have to build their own infrastructure to read in data, validate forecasts, and so forth.

Major resource requirements:

- Personnel: TBD. We anticipate future funding opportunities will allow investigators to scope out the particular personnel requirements for the project they propose.
- HPC for development: For conventional postprocessing (i.e., not machine learning), requirements are moderate. Some machine learning projects, if proposed, may have higher HPC requirements.

Dependencies/linkages with other projects:

- Potentially upon existence of retrospective forecast training data sets such as the reforecast data set for the GEFS system (see Annex 1).
- PP Testbed project in Annex 12.

Core development partners and their roles:

- These projects may be especially suitable for lab and university partners. NWS can provide the training data, and these partners can then develop algorithms to a state of maturity where they are ready for technology transfer.

Major Milestones:

- TBD, will depend on each funded project.

<u>Project 12.7</u>: Comparison and Validation of Post-Processing Techniques; Testbed for Post-Processing

Project overview: Numerous post-processing approaches exist within NOAA and the broader community, but there has been no organized way to test the various approaches. This will require testing new techniques, selecting appropriate proxies for truth, selecting appropriate metrics for evaluation, and actually conducting the comparison and validation. This is a challenging problem, since testing post-processing approaches requires relatively large model datasets over at least a year or two as well as the various observational and or (re)analysis datasets. There is currently no easy way for the community to share such large datasets. Therefore, we need a “walk before we can run” approach by using existing infrastructure to start (phase 1), and then hopefully expand to a more efficient system (phase2: perhaps using cloud computing) that will allow outside users to plug and play (host data, workflow and test techniques). We need a group to own the effort to start, so the Developmental

Testbed Center (DTC) should be the organization to lead the testbed effort in collaboration with relevant NOAA laboratories (e.g., MDL, EMC,...).

Priority: Not urgent, but greater than most people realize.

Major Risks and Issues:

- Comparisons/Validation of this nature can be resource-intensive. Need to likely use existing infrastructure, which is not adequate for a plug and play approach, for various groups to test their post-processing. HPC access to others outside of NCEP to help test is limited.
- Testing of various post-processing approaches typically require a year or two of model data (e.g., FV3-GFS), from a model that is relatively static, available to the community.
- Requires coordination between groups, such as DTC, NOAA (MDL, EMC, …) and other groups (universities and private sector).
- NOAA organizations may not have a clear path to implement the various post-processing techniques. One important metric of success is whether the post-processing approaches are transitioned to NOAA operations.
- It may be difficult to forge a small number of reference “truths” and verification metrics.

Major resource requirements:

- Personnel: Would require at least one person at DTC dedicated to getting the data, gathering post-processing approaches, and establishing a testing framework that is open to the community.
- Funding: Would benefit by having an active visiting scholar program at DTC or NOAA operations around this issue.
- HPC resources: Requires disk space for the models and observations. Cloud computing may be helpful for phase 2.

Dependencies/linkages with other projects:

- Verification and Ensemble WGs
- There is a strong linkage to Annex 12, projects 2 and 3, since data formats, data dissemination, and new post-processing approaches will come from these other efforts.

Core development partners and their roles:

- DTC should host the initial testbed effort provided adequate resources (e.g., funding, personnel, compute, storage)
- DTC collaborates with NOAA post-processing organizations
- NCAR/RAL and other non-NOAA entities contribute as opportunities arise

Major Milestones:

- TBD

<u>ANNEX 13</u>: VERIFICATION

As NGGPS works toward replacing much of the numerical weather prediction suite, an evidence-based evaluation of all components will be needed to ensure the new modeling systems are better than those being replaced. There will be a need to construct optimal verification methods and tools to evaluate the performance of the NGGPS model at both global and meso scales and consider the spectrum of user needs including applications in aviation, severe storms, space weather, tropical cyclones, and precipitation forecasting. Ultimately, it is intended that this system will unify verification across the user community and create common metrics for multiple applications with the intent to provide consistent verification approaches. In this case, verification relates to the weather prediction context of using observations to assess skill.

Under the auspices of the Next Generation Global Predictions System (NGGPS) program, a unification of the verification system is based on the community Model Evaluation Tools (MET), originally developed at NCAR/Research Applications Laboratory (RAL) through the Developmental Testbed Center (DTC). It has been expanded to include a database and display system, called METviewer, and python scripts for low-level workflows to demonstrate use-cases (examples), and is now called METplus. METplus is a flexible suite of verification tools developed by the community led by NCAR/RAL, NOAA/ESRL and NOAA/EMC, and supported to the community through the Developmental Testbed Center (DTC).

METplus is envisioned to expand verification capability over the next 3 years to develop of a forecast capability for the fully-coupled unified verification system that will encompass a variety of spatial scales (from convective to global) and temporal scales (from minutes to seasonal predictions), as well as provide a basis for evaluation of individual earth system component models (including atmosphere, atmospheric composition, land, ocean, ice and waves, and space) and the partially and fully coupled system as dictated by the given UFS system architecture configuration. In order to enable more efficient use of operational prediction systems in research environments and more efficient transition of promising research into NWS operations, the unified verification system will incorporate community input in its design and development.

To drive the requirements for the initial NGGPS unification project, a group of scientists and engineers from NCAR/RAL, NOAA/ESRL through the DTC met with NCEP staff, including EMC, WPC, OPC, CPC and NCO to assess current capabilities as well as near-term and long-term needs. A requirements document was written and made available to EMC management in September 2016. It can be found on a Google Drive in this NGGPS_V&V_Reqs_Status directory:
https://github.com/NCAR/METplus/wiki/NGGPS-Verification-Unification-Requirements ---Status-Reports

and provides the foundation for the FY19-FY21 unification activities. Additional requirements have been gathered from the UFS SIP V&V members and interactions with other working groups. These will be used to augment the requirements for the system.

Project 13.1: T&E for demonstration of operational readiness of prediction systems

Project overview: This project will entail continuing to engage the community both independently and through the Governance and Communications WG to determine a set of methods and common metrics that can be used in all verification efforts. Ultimately, there will be an established and well-documented T&E testing procedure that may be executed using the METplus system.

With the recent paradigm shift to model evaluations occurring much earlier in the implementation schedule, EMC's Model Evaluation Group (MEG) has taken on the role of leading evaluations of major model upgrades. Evaluations had previously been performed by NCEP and NWS stakeholders over a short 30-day period immediately prior to NCEP director approval immediately prior to the operational implementation, but this was found to be an insufficient time period and also allowed for the possibility of NCO building their parallel system only to have the evaluators reject the proposed upgrade.

The new paradigm has the developers running an early parallel system and the MEG leading the evaluation with frequent updates given to developers, researchers and forecasters at the group's weekly webinars. The evaluations consist of a combination of statistical evidence as well as case studies and reviews of daily inspections of critical forecast parameters. Statistical evidence and forecast examples from retrospective runs are also presented. As part of an STI initiative, three MEG sub-teams, consisting of members from the NCEP and NWS SOO community were established to assist with evaluations of global and high-resolution FV3 runs and to assist with the challenge of disseminating parallel data to the field. It is planned for the global and dissemination teams to merge in late FY17, with the single group focused both on evaluation of FV3GFS and FV3GEFS and getting test data to the field. This MEG-STI global team will play a critical role in providing neutrality and forecast expertise in assessing the day-to-day forecast utility of the new systems.

The MEG will lead the writing of the test plan for the FV3-based systems with input from the community and organizations such as the Developmental Testbed Center (DTC) and the Community Earth System Modeling (CESM) group. The test plan will not only be based on statistics and metrics but also on subjective evaluations by the EMC MEG, the MEG-STI global group, NWS Regions, NCEP Centers, and other customers and stakeholders. The metrics will not be unified across all scales, and engagement with the forecaster and verification community will be critical in identifying scale-appropriate metrics for each system. Once written, the test plan will be used to conduct the formal evaluations by the MEG, the listed organizations and the community.

Major Risks and Issues:

- Reaching consensus on the correct fields, measures and display methods as well as the minimum sample size for effective T&E will be challenging to achieve.
- There is potential for evaluations of multiple major modeling systems to be needed simultaneously, which will severely tax limited MEG resources.

Major resources requirements (per year):

- Personnel: EMC (2 FTE + STI SOO-based team); DTC (1.25 FTE)
- HPC: There is minimal HPC requirement.

Dependencies/linkages with other projects:

- Governance and Communication WGs to gather community input on metrics
- All WGs for metrics that are meaningful within their specific groups
- Evaluation of the FV3-GFS needed.
- Evaluation of the FV3-GEFS needed.
- Evaluation of CAM ensemble system needed.

Core development partners and their roles:

- NOAA/EMC: Model Evaluation Group will lead the evaluations/validations of major modeling systems.
- DTC: Provide METplus development and enhancement, based on needs of the verification community.
- NCAR/RAL: Provide METplus development and enhancements through various projects focused on evaluation of critical UFS applications.
- NOAA/ESRL: Provide METplus development and enhancements through various projects focused on evaluation of critical UFS applications.
- General research community to help establish standardized metrics including coupling metrics
- Continue to promote the MEG e-mail lists and VLab page through social media and other marketing techniques to involve the broader community as much as possible, especially to the academic community

Major Milestones:

- Q4FY18: Hold a Test Plan and Metrics Workshop
- Q2FY19: Complete FV3-GFS evaluation as part of transition to operations

- Q4FY19: Complete FV3-GEFS evaluation as part of transition to operations
- Q4FY20: Complete FV3 evaluation as part of transition to operations

<u>Project 13.1: T&E to Demonstrate Operational Readiness (FY19-21)</u>

Project 1: T&E to Demonstrate Operational Readiness

	FY18	FY19				FY20				FY21			
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	Hold a Test Plan and Metrics Workshop												
	Complete FV3-GFS evaluation as part of transition to operations												
			Complete FV3-GEFS evaluation as part of transition to operations										
						Complete FV3 evaluation as part of transition to operations							

Project 13.2: Unified verification and validation system

The unified verification capability will need to leverage capability from other NGGPS community packages so redundancy is eliminated. At the core is the Model Evaluation Tools (MET), its database and display packages, METviewer and METexpress, and the umbrella framework/repository called METplus. This section describes to efforts to establish the METplus authoritative V&V repository framework that relies on components developed under 13.3 Metplus Statistics (MET) and 13.4 METplus Database and Display (METviewer and METexpress). 13.5 Outlines the use of these tools, and others, to establish a testing and evaluation (T&E) framework to inform an evidence-based decision. The Joint Effort for Data assimilation Integration (JEDI), Unified Post-Processor (UPP), Statistical Post-Processing System and Community Research to Operations Workflow (CROW)) are examples of community packages that may provide beneficial capabilities to METplus. The observation database and forward operators envisioned for JEDI will be crucial for computing appropriate observation and analysis fields for verification purposes. Coupling with the Unified Post-Processor will allow for derivation of complex parameters (e.g. visibility, CAPE, PBL height) as well as an initial capability of verifying model native grids without generating a new file. Finally, integrating with the Unified Workflow is crucial for verification in an operational setting.

Major Risks and Issues:

- Other tools may not develop on a complementary timeline

- Interface between tools may be complicated
- Compilation of verification system may become very complex
- Ensuring compatibility and ability to be incorporated into FV3 CROW Unified Workflow but also stand alone for community code releases

Major resources requirements:

- Personnel: DTC 1.25 FTE, NCAR/RAL 1 FTE; EMC (0.25 FTE)
- HPC for development: Nominal resources required

Dependencies/linkages with other projects:

- System Architecture WG plans for Coupled System
- Refactored NCEP POST (UPP) and product generation
- Unified Workflow (CROW)
- DA (JEDI IODA and UFO)
- NWS/MDL Weather Information Statistical Processing System (WISPS)

Core development partners and their roles:

- DTC: Provide METplus development and enhancement, based on needs of the verification community.
- NCAR/RAL: Provide additional METplus development and enhancement through various projects focused on evaluation of critical UFS applications.
- NOAA/ESRL: Provide additional METplus development and enhancement through various projects focused on evaluation of critical UFS applications.
- NOAA/EMC: Primary developer of UPP and CROW
- JSCDA: Primary developer of JEDI IODA and UFO

Major Milestones:

- Q1FY19: Develop METplus dependency on UPP for deriving fields from observations reported in PrepBUFR files
- Q2FY19: METplus workflow management requirements identified for efficient coupling with CROW Unified Workflow
- Q1FY20: Expand use of UPP for deriving fields
- Q1FY20: METplus available to be called by CROW Unified Workflow
- Q1FY20: Identify development needed to interface with JEDI IODA and UFO, Post Processing packages
- Q3FY20: METplus ready to couple with IODA and UFO and Post Processing packages
- Q4FY20: METplus enhanced to fully leverage CROW, IODA, UFO and UPP

Project 13.2: **Unified verification and validation system** (FY19-21)

Project 2: Unified verification and validation system

	FY18	FY19				FY20				FY21			
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	Develop METplus dependency on UPP for deriving fields from observations reported in PrepBUFR files												
	METplus requirements identified for efficient coupling with CROW Unified Workflow												
		Expand use of UPP for deriving fields											
			METplus available to be called by CROW Unified Workflow										
			Identify development needed to interface with JEDI IODA and UFO, Post Processing packages										
					METplus ready to couple with IODA and UFO and Post Processing packages								
						METplus enhanced to fully leverage CROW, IODA, UFO and UPP							

Project 13.3: Development of METplus and core component MET

Project overview: The transition of the EMC Verification, Post-Processing and Product Generation Branch to a METplus-based system is ongoing. Critical functionality has been added to the core component, MET and the METplus Python layer but more is still required. Verification procedures addressed with this project include those for global to meso- to storm scale phenomena, cyclones (both tropical and extra-tropical), and atmospheric composition and air quality, and others represented by the other 12 SIP working groups. This process began in FY17 and requires additional development to meet the expected timelines. The transition is needed to establish a unified system and free up resources to define the optimal verification methods and tools to enact the critical evaluation of the NGGPS. Several of the components (e.g. Marine, Hydrology, Land Surface Model, Sub-Seasonal to Seasonal) have well established packages that need to be integrated into METplus. If the method is not currently available in METplus, enhancements to the system will be made to ensure that the capability exists. This effort will also expand to validation of the fully coupled system, including visual inspection of high-frequency data (i.e. fluxes) through process oriented methods. Effort will be made to include these capabilities in the next 3 years but this will likely require additional effort beyond FY21.

Major Risks and Issues:

- MET, and hence METplus, may become difficult to compile/configure and hence unwieldy
- Lengthy list of development tasks – sufficient resources are needed for expedited development and training
- Several components already have well established packages

Major resources requirements (per year):

- Personnel: EMC (2 FTE); DTC (1.3 FTE);NCAR/RAL (1.5 FTE); NOAA/ESRL (0.1 FTE)
- Community Resources: Funding needs to be made available to bring university researchers and other organizations into the unification effort (great opportunity to be had - make sure coding standards are upheld)
- HPC for development: MET is designed to run on a single processor and be “parallelized” through a workflow manager such as Rocoto or ECFlow. It has become increasingly apparent that evaluation of a global high-resolution model will require better memory handling to speed up computations. MET may need to be parallelized.

Dependencies/linkages with other projects:

- METplus-based verification and validation for the FV3-GFS
- METplus-based verification and validation for the FV3-GEFS with process-oriented metrics for ensemble evaluation
- METplus-based verification and validation for convection-allowing ensembles
- METplus-based verification and validation for aerosols and atmospheric composition models
- METplus-based verification and validation for marine models
- METplus-based verification and validation for land-surface models and hydrology
- METplus-based verification for Space-Weather
- METplus-based verification for S2S Prediction
- METplus-based verification for Seasonal Prediction

Core development partners and their roles:

- NOAA/EMC: Verification Branch will lead verification and evaluation efforts for the FV3 applications. The Model Evaluation Group (MEG) will lead evaluations of individual modeling systems.
- DTC: Support METplus to the community and provide development and enhancements based on needs of the verification community.

- NCAR/RAL: Enhance METplus through various projects focused on evaluation of critical UFS applications.
- NOAA/ESRL: Support development of MET
- NOAA/NCEP Centers and NOAA Labs: Provide additional METplus tools and visualization capability
- Community of researchers: Provide innovative methods for use in future UFS testing.

Major Milestones:
- Q1FY19: METplus accepted for FV3 aerosol, atmospheric composition and air quality verification
- Q3FY19: METplus accepted for FV3 CAM verification and linked to Marine, Land Surface Model, Hydrology and Sub-Seasonal packages
- Q1FY20: METplus released with expanded support for TCs, large scale diagnostics, sea ice, and process-based metrics for looking at physics
- Q4FY20: METplus major release with coupled system requirements met, including basic evaluation capability for space weather

<u>Project 13.3: **Development of METplus core component – MET (FY19-21)**</u>

Project 3: Development of METplus and Core Component MET													
	FY18	FY19				FY20				FY21			
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	METplus accepted for FV3 aerosol, atmospheric composition and air quality verification												
		METplus accepted for FV3 CAM verification and linked to Marine, Land Surface Model, Hydrology and Sub-Seasonal packages											
			METplus releasedexpanded support for TCs, large scale diagnostics, sea ice, and process-based metrics for looking at physics										
						METplus major release with coupled system requirements met, including basic evaluation capability for space weather							

<u>Project 13.4: Robust METplus statistical database and display systems for UFS applications</u>

Project overview: METviewer is the companion database and display system to the MET verification package. It reads in both MET statistics files as well as legacy EMC Verification Statistics Database

(VSDB) files. The system is designed for flexibility to provide the users with a great deal of control over what is plotted. Scorecards for model comparison are generated using the METviewer batch engine capability. Additionally, the community has expressed a desire to have the unified system provide access to the UFS statistics to compare directly with other models. Developers are working on a system, called METexpress, to satisfy this need. It will use the same database as METviewer and provide a simplified interface with predefined queries. , Fixed-assets, either at NCWCP or in the cloud, are also needed to address the community's requirements. A prototype system has been established by NCO on the Interactive Data Protocol (IDP) development framework but EMC's need for METviewer has grown beyond the disk space available in the IDP. Several attempts to obtain sufficient storage and server resources have been made with no success.

This project will focus on continuing to develop METplus database and display systems to address the UFS community needs through continue enhancement to METviewer, the development METexpress, and the exploration of new technology to improve the speed queries and breadth of data available for analysis.

Major Risks and Issues:

- The current EMC METviewer server is filled to capacity. More storage and potentially a new database design is required.
- Software solutions outside the realm of what is hosted on the current RedHat Linux OS version, an enterprise support solution must also be provided (with an additional cost)
- EMC has stated that there is a requirement to keep decades of data on disk for plotting of historical performance, an efficient solution must be found to achieve this goal
- As with all relational databases, once a schema and indexing is established, additional work will need to be performed to load non-standard output (e.g. from verification software that has not yet been coupled with METplus). Moving to newer database technologies would address some of the continued cost of updating the database.
- Enhancement requests may overwhelm current staff – sufficient resources need to be available
- Developers would benefit greatly from METviewer batch engine capability on HPCs such as WCOSS/Theia – need to figure out how

Major resources requirements:

- Personnel: DTC (0.5 FTE); NCAR/RAL (1.0 FTE); NOAA/ESRL (1.4 FTE); EMC (1 FTE)
- HPC for development: Use of container technology on the HPC is desirable
- Disk space: ~5-10 TB per year for storage

- Dedicated server to host METviewer using appropriate database technology so it's available for use by UFS developers as well as accessed by the community
- Fast, easily deployable database and display tool

Dependencies/linkages with other projects:

- JEDI IODA
- Text output from other verification components

Core development partners and their roles:

- DTC: Support METviewer to community and perform nominal enhancements based on needs of the verification community.
- NCAR/RAL: Provide METviewer development and enhancements through various projects focused on evaluation of critical UFS applications.
- NOAA/ESRL: Provide METexpress development and exploring other database options
- NOAA/EMC: The VPPPG Branch will lead verification and evaluation efforts for FV3 applications. The Model Evaluation Group (MEG) will lead evaluations of individual modeling systems.

Major Milestones:

- Q2FY19: Obtain resources to host more data and explore new database technologies
- Q2FY19: Less complex UI (METviewer-lite) to provide quicker selection of plots available for testing
- Q4FY19: New database server set-up and available for testing and development
- Q4FY19: Use of container technology either on HPC or in the cloud tested
- Q1FY20: METviewer-lite available for UFS community to use
- Q2FY20: EMC verification moved to new server

Project 13.4: **METplus statistical database and display systems for UFS applications** (FY19-21)

	FY18	FY19				FY20				FY21			
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	Obtain resources to host more data and explore new database technologies												
	Less complex UI (METexpress) to provide quicker selection of plots available for testing												
		New database server set-up and available for testing and development											
		Use of container technology either on HPC or in the cloud tested											
			METexpress available for UFS community to use										
				EMC verification moved to new server									

Project 13.5: Develop protocol for community contribution to authoritative code repository

Project overview: The Infrastructure WG has specified the initial requirements to participate as an authoritative repository for the NGGPS system include having an established code base with help desk, open to the community, governance, documentation, and regression testing. METplus has three components to the codebase. MET is currently available to the community via download from the DTC website and help desk is provided through DTC. METviewer and the METplus python framework are available via a closed repository on Github. All three come with documentation, with MET being the most comprehensive. Regression testing has already been established for MET and will be established soon for METviewer and METplus python. Work that still needs to be done is moving MET to Github and making the entire repository open via some controlled mechanism to meet ITAR and FISMA mandates. Governance and guidelines for community contribution need to also be established.

Major Risks and Issues:

- Making sure International Traffic in Arms Regulation (ITAR) and Federal Information and Security Management Act (FISMA) requirements are met for the community repository

- Identifying governance that needs to be in place to successfully manage the maintenance and growth of METplus
- Balance between GitHub and VLab

Major resources requirements:

- Personnel: DTC (0.35 FTE); EMC (0.15 FTE)
- HPC for development: TBD
- Way to gather community input on future needs for metrics development, possibly through a google form, and prioritize through community input

Dependencies/linkages with other projects:

- Infrastructure project: Establish authoritative community repository
- JEDI: To remain consistent with their governance
- CROW: To remain consistent with their governance
- UPP: To remain consistent with their governance

Core development partners and their roles:

- DTC: Establish and maintain METplus repository and maintain help desk
- EMC: Help define governance and maintain help desk
- ESRL: As part of DTC establish and maintain METplus repository and maintain help desk

Major Milestones:

- Q1FY19: Move MET codebase to Github repository
- Q2FY19: Governance and community contribution procedures established and METplus repository open
- Q3FY19: Establish committee to develop governance of repository
- Q4FY19: Publish METplus governance and community contribution procedures on NGGPS website
- Q2FY20: Review governance and community contribution procedures and adjust as necessary

Project 13.5: METplus Community Repository Governance (FY19-21)

<table>
<tr><th colspan="14">Project 5: Develop Protocol for Community Contribution to Authoritative Code Repository</th></tr>
<tr><th></th><th>FY18</th><th colspan="4">FY19</th><th colspan="4">FY20</th><th colspan="4">FY21</th></tr>
<tr><th></th><th>Q4</th><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th></tr>
<tr><td></td><td colspan="2">Move MET codebase to Github repository</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="3">Governance and community contribution procedures established and METplus repository open</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="4">Establish committee to develop governance of repository</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="4">Publish METplus governance and community contribution procedures on NGGPS website</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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