UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service

Office of Science and Technology Integration
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2017-2018 Roadmap for the Production Suite at NCEP

Developed 2017-2018, signed 2020
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1 Introduction

1.1 Purpose

A Strategic Vision (SV) for NOAA's Physical Environmental Modeling Enterprise is described in a companion paper. This enterprise supports the forecast, analysis, and assessment missions of NOAA and its governmental, academic, private and commercial partners, both with respect to operations and research. The goal is to make this enterprise the best in the world.

A core element of this enterprise is the suite of operational computer models[3] that are run every day by the National Centers for Environmental Prediction (NCEP). This manuscript provides a Roadmap for evolving this suite of models to become the best in the world in the next 5 to 10 years. It addresses other elements of the enterprise as far as they directly influence modeling, as discussed in the SV. It does not address most details of its implementation, nor does it discuss the transition to a new layout of this model suite. The latter will be addressed in the Strategic Implementation Plan (SIP), which is a companion to the SV and this Roadmap. By nature, the SV, Roadmap and SIP are living documents. The Production Suite is heavy on weather applications, but is evolving into a more holistic environmental modeling approach.

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[1] NOAA, National Weather Service, Office of Science and Technology Integration
[2] NOAA, Atmospheric and Oceanographic Research, Office of Weather and Air Quality
[3] Including data assimilation, processing of observations, post-processing etc.

1.2 Background

Numerical modeling guidance has been the cornerstone of most[4] weather forecasting for decades, and covers scales from minutes for severe weather to up to a year for seasonal outlooks. The models used by the NWS for operational weather forecasting are generally denoted as "operational" models, and are run on a fixed schedule by NCEP Central Operations (NCO). The set of models run in this way is referred to as the Production Suite at NCEP (PSN), and also includes many other environmental applications, such as ice, ocean and wave models. Several organizations other than NCEP contribute to the PSN, in particular the NWS Meteorological Development Laboratory (MDL), the NWS Office of Water Prediction (OWP), all Laboratories and Program Offices of NOAA's Oceanic and Atmospheric Research (OAR), and the National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS).

External reviews of NCEP (UCACN, 2009; UCACN, 2011-2015) have long observed that the PSN is too complicated and needs to be simplified. In response to this, the NCEP director charged the UCAR Community Advisory Committee for NCEP (UCACN) in 2015 to stand up the UCACN Model Advisory Committee (UMAC). The charge of UMAC was to review the entire PSN. This review was performed in August of 2015, and the UMAC provided its report back to NCEP on December 7, 2015 (UMAC, 2015). Additional annual reviews were performed in 2016 and 2017. Key findings of the UMAC were the need for simplifying the PSN, and the need to have a detailed strategic plan to do so. The SV, Roadmap and SIP are being developed in direct response to these recommendations.

Figure 1 shows (a simplified view of) the production suite as it existed in August 2016. This production suite evolved over decades as a set of solutions (models) for individual problems, rather than through a systematic approach of providing products to satisfy technical requirements, which in turn result from service and mission requirements. This resulted in a quilt of models, with multiple model approaches with overlapping functions and products. The end goal is to move from this quilt of models to a unified modeling approach. A Unified system focuses limited resources on a smaller number of models, allowing a faster improvement of the elements of the PSN, as well as the PSN as a whole, consistent with principles of Unified Modeling as outlined in the whitepaper of the NOAA Unified Modeling Task Force[5] (UMTF, 2017).

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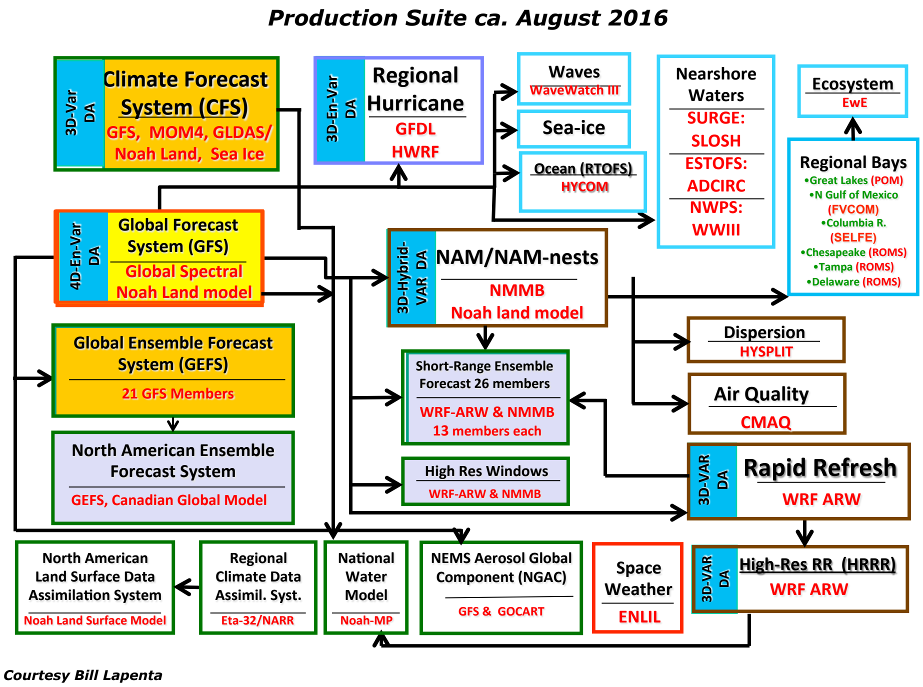
[4] Observations are still the primary input for nowcasts and forecasts with very short lead time.
[5] Now the Unified Modeling Committee (UMC) of the NOAA Research Council.



Courtesy Bill Lapenta

Figure 1: Production Suite ca. August 2016

2 Basic Concepts

2.1 Introduction

This section of the Roadmap addresses basic concepts used to develop a new strategic design for a Unified PSN, following basic concepts as outlined in the SV for the Physical Environmental Modeling Enterprise. These basic concepts were developed in internal discussions mostly within the NWS and OAR, and were both confirmed and expanded upon by UMTF, representing the larger NOAA community. It has been socialized and discussed at many public fora during its development.

2.2 Unified Modeling and Data Assimilation

The ultimate vision for a Unified PSN is to create the world's best integrated modeling system that unifies scales from convection-resolving (sub-hour scale) to seasonal prediction (1 year scale), and integrates environmental subcomponents for atmosphere, oceans, land, ice, hydrology, and aerosols, in a scientifically sound, and economically justifiable way to most efficiently support NOAA's operational mission. NOAA's mission in turn supports the mission of its governmental, commercial, and academic partners. Reaching the goal of the SV requires us to simplify the present quilt of operational models as illustrated in Figure 1.

2.2.1 Product and requirement based

The disparate quilt of models that represent the present PSN (Figure 1) developed over decades as new solutions (models) were added to the suite, typically as "stovepipes", serving selected user groups and championed by developers, sometimes in competition with other elements of the PSN. This has resulted in many models with overlapping products based on disparate modeling approaches. This is particularly true for mesoscale models, where as many as seven different models have been used (often side-by-side) in the last two decades.

Moving to a simplified production suite requires a ***product-focused*** design, where ***requirements*** drive technical development foci, using models that are adopted to provide the required products. These products in turn are based on vetted service requirements.

Having a product-oriented PSN requires a corresponding strategic design (the SV and Roadmap), a plan to implement such a design (the SIP), but most importantly, a governance structure that strongly enforces a product-based approach and avoids one-off model implementations unless there is a solid science/business case to do the latter.

2.2.2 Unified Modeling Approach

A product-oriented PSN naturally leads itself to a unified modeling approach. At the least, one modeling system supports each set of consistent products, and is adopted and developed to satisfy documented requirements. However, following the approach of leading weather centers, in particular the UK Met Office (UKMO), a unified approach across scales is considered preferable, using a single unified modeling system from Convection Allowing[6] Models (CAM, hour time scale) to seasonal models (year time scale). Unified modeling principles are described in a whitepaper of the NOAA Unified Modeling Task Force (NUMTF, 2017), and imply that modeling efforts are focused on a minimum set of models, driven by scientific and business principles. It ***does not*** imply unitary modeling, where the goal is to focus on a single model

2.2.3 Key elements of the PSN

Traditionally, the main focus of the PSN has been on atmospheric weather and sub-seasonal to seasonal (S2S) elements. Other environmental sub-components are present in the PSN, and satisfy specific mission requirements of NOAA. The PSN is continually evolving, and three key elements of the PSN beyond traditional weather applications need to be considered strategically. These three elements are

Environmental sub-components and coupling

The present PSN contains products and models for land/hydrology, oceans (coasts), sea ice, waves, aerosols, marine ecosystems[7] and (space) weather. Historically, these systems have been treated as stand-alone environmental sub-systems. Starting with seasonal applications (and decadal and centennial applications outside of the PSN), these systems are considered more and more as coupled holistic environmental systems, both to provide required products for sub-systems, and to improve the overall quality of all products. With this in mind, a Unified PSN will be inherently coupled across environmental sub-components. The sub-components (including their justification / legal authority for being included in the PSN) are reviewed in more detail in Appendix A.

Ensembles

Uncertainty is a fundamental characteristic of physical environmental prediction, and no forecast is complete without a description of its uncertainty (US NRC Report -

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[6] Soon to evolve to Convection Resolving Models.

[7] Presently only water quality-related models such as Harmful Algae Bloom (HAB) models are part of the PSN, and only such ecological models that can provide a direct feedback to the physical environment are considered in this plan. Coupling to, e.g., fish stock models is not considered here.

Completing the Forecast, 2006). Ensembles of possible model solutions are used for providing assessments of forecast uncertainty on weather, sub-seasonal and seasonal forecast ranges, tentatively across all environmental subsystems. Given the greater value of probabilistic forecasts compared to the traditional single deterministic forecast, all future guidance products will be ensemble based. Control runs of an ensemble are ideally of the same resolution as the ensemble itself. This avoids the historical tendency to consider the control run as the deterministic model of choice (mostly because of the higher quality of the higher-resolution model). It will help move forecasters and other users away from a "model of the day" approach, and focus more on model uncertainty***. In a unified modeling approach an ensemble ideally is based on a single-core, stochastic physics / forcing approach***, while creating multi-model ensembles by combining products of different institutes (see Appendix C.9). The decisions on actual transitioning to such an ensemble system, including running a control run at the same resolution as the ensemble, need to be evidence based (see Section 2.4).

Reforecast and reanalysis

Another recently added element of the PSN is the use of Reforecasts and Reanalysis (RRs) of ensemble products. Such RRs provide a clear benefit as they are used to calibrate ensemble outlook products. More recently, RRs are used for Impact-based Decision Support Services (IDSS) as part of the NWS' Weather Ready Nation (WRN) strategic focus (Weather Ready Nation Roadmap, 2013). Once the entire PSN is ensemble-based, the traditional retrospective testing of new model implementations will naturally obtain the characteristics of RRs.

2.3 Community approach

The new PSN will use a community modeling approach that involves NOAA, other federal partners (e.g., NASA, JCSDA, DoD, etc.[8]), and the research and academic community at large. Only with appropriate contributions from the entire U.S. modeling community will we be able to build the best ***national*** modeling system possible[9].

The ***definition*** of "community" is important, and not all community efforts are identical. Prior community modeling efforts (ECMWF, WRF, CESM, WW3, etc.) show both strengths and weaknesses of different approaches, and that one size does not fit all. The community approach will include training and support (e.g., help desks and/or support

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[8] Initial community modeling efforts for the PSN such as WAVEWATCH III also include international partners such as the UK Met Office (UKMO) and foreign universities.

[9] Not necessarily "the" national modeling system, but at least a key element of a national MME as mentioned throughout this Roadmap.

groups), and may be formalized in approaches and organizations such as the Developmental Testbed Center (DTC).

The unified modeling system will be built to support the needs of both ***operations*** and ***research***, with a well-defined path for transitioning research to operations (R2O) that is rooted in using operational systems for research (O2R). Without that linkage, the incentives for the research community to participate will be sub-optimal.

Best practices have shown that different levels of community partners should be established, with specific roles/responsibilities for each. For example:

- ***Trusted super-users*** may be established that have different access than occasional research users, so that they can conduct beta testing, test early prototyping, etc.
- ***Core development partners*** that regularly make substantial contributions to development of the system have different roles than casual "users" that run the model but not contribute to development.
- ***Users*** and ***stakeholders***, while not contributing to the code in general, contribute requirements and needs, and drive the direction of development, resource allocations and prioritization (within the NOAA mission). 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.

The goal for the unified modeling system is a national system where all core partners have true ***ownership***[10]. As such, each core partner has to treat their role on the national team as a ***fundamental*** and ***enduring*** priority for their respective organization, supported where appropriate with ***internal base resources***. This unified modeling system will form part of NOAA's modeling contribution to the National Earth System Prediction Capability (National ESPC), which extends from near-real-time to decadal scales, and will be able to leverage interagency partnerships coordinated by National ESPC. The community approach is presently defined in more detail as part of the SIP development process.

2.4 Evidence driven approach

One of the key findings of UMAC is that "*The NOAA environmental modeling community requires a rational, evidence-driven approach towards decision-making and modeling system development.*" Key decisions on architecture, scientific selection (e.g., dynamics, physics, data assimilation), etc. will therefore be based on ***objective validation***

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[10] This may include super-users from the core partners, but trusted super users can also be targeted collaborators outside core partner organizations, typically funded on explicit development projects.

and verification, and not on assertion. This requires the establishment of ***requirements***, agreement on ***validation metrics***, and a unified approach to computing such metrics, as well as an assessment of the benefit relative to the cost (resource needs, maintenance, and future development).

In the community context described above, an effective and transparent testing process needs to be established, which can be carried out effectively with the engagement of (or independently by) key partners. Formal Testbeds, as already established for many service areas, are playing an increasingly important role in evidence-driven decision making.

2.5 Governance

With the community approach to modeling the elements of the PSN, all core partners will have a voice in making strategic decisions, not just the operational center(s). This section will mainly focus on the governance structure covering NOAA and its community partners, while recognizing that service (operational) requirements in the NWS are driven by internal NWS governance processes,

In order to effectively coordinate the activities of the community partners, as well as to manage the collaborative projects of those partners, a robust community governance structure is being put in place, which is based on several core principles and values:

- **Commitment by core development partners**: The community-based unified modeling system is being designed to be a national system where all core partners are truly invested and empowered. This implies that each core partner will need to consider their role on the national team as a *fundamental and enduring priority* for their respective organization, and that each core partner will have a voice in making strategic decisions, not just the operational center(s).
- **Informed practices**: The governance structure will leverage successful practices from “tried and true” structures from prior and existing community modeling systems.
- **Community Values:**
    - Promotes an environment for individuals to succeed by recognizing talent in diverse communities, by assuring that efforts are credited and rewarded, by providing opportunities for career advancement, and by providing incentives to make decisions in context of community and system requirements (collaborative rather than individual decision making).
    - Evidence-based decision making that is requirements driven and that considers the balance of cost, requirements, scientific credibility, and user experience.
    - Supports a Scientific Organization (rather than an Organization of Scientists).

  - Committed to process improvement (verification, validation, documentation, reduced redundant systems, optimization of human and computational resources).
  - Trust and transparency.

While still under development as part of the SIP process, the proposed governance structure is intended to be led by a high-level executive Steering Committee and a set of subordinate Working Groups that will represent the essential science, technical, and design aspects of the unified modeling system that is to become the foundation of the PSN. The Working Groups span the community of expertise needed to support the unified system. While still in development as part of the SIP process, there are a several types of groups with specific areas of focus and functionality:

- **Science Working Groups**, for example land modeling, where focus might be on a component model, with scientific development a high priority.
- **Systems Working Groups**, for example, Systems Architecture, Verification and Validation, Ensembles, Communications, End-user, where the focus is on the system as a whole, the community as a whole, and meeting an optimization of technical and scientific requirements, as well as cost.
- **Applications Working Groups**, for example, Medium-range Global, Seasonal, Space Weather, where the components are brought together as a configuration to address the requirements of a particular application.

This governance structure has to work in lockstep with the internal governance of the Line Offices. For instance, for the NWS applications that dominate the PSN, the NWS governance (NWS, 2016) identifies three key steps:

1. Establish service requirements and associated products, using the CaRDS process (Capabilities and Requirements Decision Support, CaRDS, 2016), through the Analysis Forecast and Services (AFS) office.
2. Determine scientific requirements and solutions, primarily through the Office of Science and Technology Integration (OSTI) and EMC. Note OSTI and EMC will use the community governance structure outlined above to achieve this.
3. Requirements are validated and prioritized within the NWS by the Mission Delivery Council (MDC, NWS 2016). A process for dealing with prioritizing non-NWS work in the PSN is not yet in place.

2.6 High Performance Computing

The PSN is critically dependent on High Performance Computing (HPC). In this context, NOAA needs to aggressively pursue HPC capacity in a holistic way, balancing computing power (including memory), storage, and data access. Rather than being reactive, the NOAA Office of the Central Information Officer (OCIO) has developed a 100% requirement document for all NOAA HPC, part of which is reproduced here in Section 4. HPC resources need to be addressed holistically in two ways. First, computing power needs to be balanced with memory, internal (computing) and external (dissemination) bandwidth, and storage. Presently, effective usage of operational NOAA computers is limited by IO interferences between applications (IO of one model slowing down another model), as well as storage and raw computing power. Secondly, resources for operations, transitions to operations, research and RR need to be balanced.

With the expectation that Moore's law may no longer be applicable, and that we can therefore no longer expect to see rapidly increasing computing power with flat funding profiles, and considering that present codes have systematically become less efficient relative to the processor capabilities, optimization of models on new hardware is of paramount importance. Unified modeling using a small (reduced) number of models will make the optimization process more efficient. With the efficiency of typical codes having dropped from 20-40% of peak Floating Point Operations in the 1990's to typically 3-5% presently, there is both a need and an opportunity for increasing performance of codes on modern processor architectures (including IO optimization). Note that this is potentially in conflict with improving portability of models in the context of community modeling. NOAA is addressing optimization of models in the Software Enhancement for Novel Architectures (SENA) project, and in collaboration with external partners.

The Production Suite is designed to support NOAA's mission and the timely dissemination of all pertinent post-processed output within the NWS (and to other NOAA LOs and external stakeholders) is essential. Internal to NOAA, dissemination capacity has typically lagged NCEP/EMC data production and forecasters have not been able to access (via AWIPS workstations) complete datasets. Dissemination of PSN data to the field and other customers has to be considered as part of every implementation. Moreover, the NWS needs to re-assess the basic design of data dissemination using modern "Big Data" and "Cloud" approaches. Central to Big Data practices is how data are accessed and disseminated to the community. Centralized, redundant, and sequenced storage capabilities will need to be taken into consideration as we evolve into this new paradigm. How this involves tools like AWIPS, is out of the scope of the present Roadmap.

3 The Big Picture

3.1 Introduction

Section 3 steps through the key elements of a high-level roadmap plan based on the basic concepts laid out in Section 2. Section 3.2 starts with looking at ranges of forecast products in the (present) PSN, as required by our main stakeholders. Section 3.3 discusses the resulting high-level design of a new unified PSN. Section 3.4 discusses the underlying system architecture, with a focus on coupling subcomponents in a holistic physical environmental modeling approach. Unification of the sub-components is discussed in Section 3.5, and Section 3.6 addresses unification of the PSN elements complementing the actual running of models.

3.2 Products

The first step to move from the quilt of Figure 1 to a unified PSN is to start with products rather than solutions. Traditionally, the PSN is mostly focused on atmospheric weather and outlook products and is expected to remain so in the future.

An analysis of present products in the PSN, along with a discussion with the main stakeholders at the December 2015 NCEP Production Suite Review identified 6 temporal product ranges as presented in Table 1. The first five ranges consist of analyses / Data Assimilation (DA) and models initialized by DA. The "Now" (nowcast) products are focused on analyses that represent observations in the most accurate way, and are not intended to initialize models. Whereas the same tools may be used for DA for model initialization and nowcasts, these two products are nevertheless systematically different, and hence are separate applications within the PSN. Cadences (times between running forecast systems) and forecast ranges are driven by requirements, and are therefore subject to continuous review and adjustments.

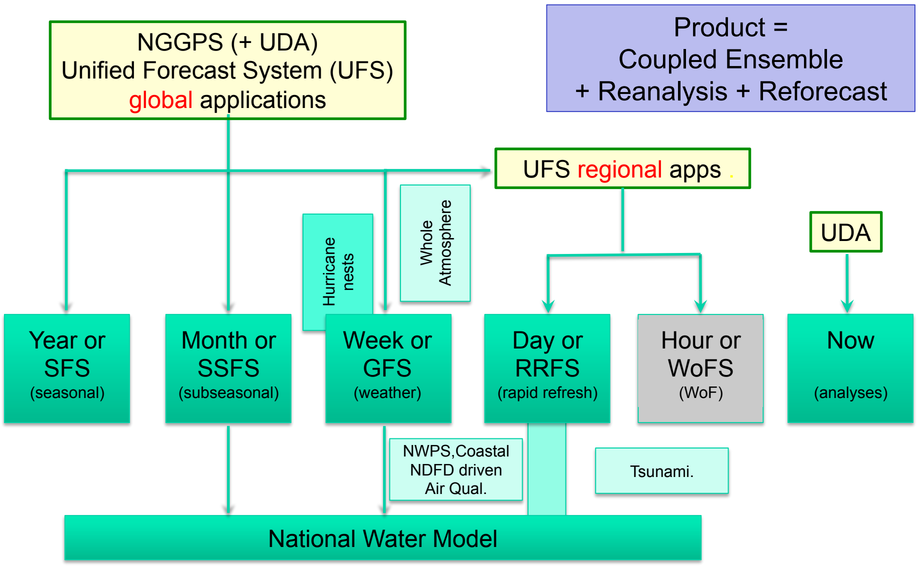
Table 1: Product ranges for a new PSN (atmospheric focus)

Range	Target	Cadence	Forecast
Year	Seasonal (months)	7 days	9-15 mo.
Month	Subseasonal (weeks)	24 h	35-45 d
Week	Days 1-7, Actionable Weather	6 h	5-8 d
Day	Days 1-3, Mesoscale / Stormscale Hazardous Weather Prediction	1 h	18 h
Hour	Hours 1-4, Stormscale Hazardous Weather Warning	5-15 min	2-4 h
Now	Analysis	5-15 min	---

Table 1 is focusing on weather products in the PSN. As discussed in the Section 2 and in Appendix A other ***coupled*** components, ***ensembles***, and ***reforecasts and reanalysis*** are an integral part of the unified PSN. Note that other components of the environmental modeling enterprise may need other cadences and forecast ranges. Note that the Year+ range identified in the SV document is not part of the PSN.

3.3 High-level design

The above considerations result in a high-level layout of a new PSN as presented in Figure 2, which can tentatively be achieved in 5-10 years. From the global perspective, development moving to this design has already started with the Next Generation Global Prediction System (NGGPS) project (Toepfer et. al., 2014). All systems are denoted as *guidance* rather than *forecast* systems, as (using NWS terminology) models provide guidance to forecasters, and forecasts are created by forecasters, not by models. Below, terms guidance and forecasts are used interchangeably, with all modeling systems called forecast systems to minimize impacts on existing product nomenclature.



UDA: Unified Data assimilation
SFS: Seasonal Forecast System
SSFS: Subseasonal Forecast System
GFS: Weather Forecast System
RRFS: Rapid Refresh Forecast System
WoFS; Warn on Forecast System

Figure 2: High-level Unified PSN design

The Seasonal, Subseasonal and Global Forecast Systems (SFS, SSFS and GFS) are inherently global. These three applications will all be based on a single Unified Global Coupled Model (UGCM), and a Unified Data Assimilation (UDA) approach, which is expected to evolve into a Unified Forecast System (UFS) across all scales. A global approach may include variable resolutions with a focus on the mission areas for NOAA, e.g., CONUS, Alaska, Hawaii, Guam, Puerto Rice, and American Samoa, or relocatable nests as presently used for fire weather and hurricanes.

The convection allowing Rapid Refresh and Warn on Forecast Systems (RRFS and WoFS) are inherently regional, and should cover all mission areas of the NWS as identified in the previous paragraph.

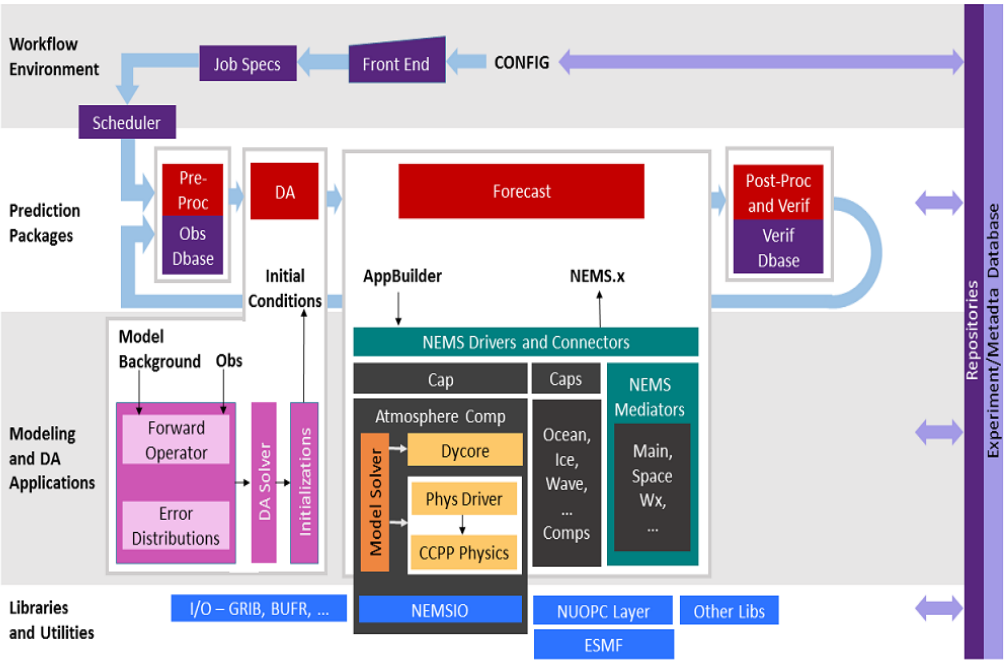
The SFS, SSFS, GFS, RRFS, WoFS and analyses (nowcasts) form the core of the unified PSN in Figure 2. A review of the present PSN shows that not all present products in the PSN fit into this structure. Elements that are not included are hurricane models, space weather, the National Water Model (NWM), the Nearshore Wave Prediction System (NWPS), coastal and estuarine models (including storm surge models), on-demand air quality models, models driven by data from the National Digital Forecast Database (NDFD), and Tsunami models. These elements are identified individually in Figure 2, and are discussed in more detail in Appendix B.

The ensemble approach in Figure 2 implies the use of single-core ensembles with stochastic physics and perturbed initial conditions (or forcing for non-chaotic components such as wave and estuarine models). For long-term development, this provides a strong business model where all resources for development can be concentrated on a unified modeling system. However, presently much of the value in some ensemble systems (e.g., regional Short Range Ensemble Forecast (SREF) and hurricane forecasting) comes from a multi-model ensemble approach. This implies that developing competitive unified model ensembles represents a critical research need (see Section 5 and Appendix C). The transition to such ensembles needs to be evidence driven (Section 2.4) and based on a holistic cost-benefit assessment. Note that forecasters have access to models and ensembles from other centers. This implies that effectively a Multi Model Ensemble (MME) approach can still be used by forecasters even if the ensembles in the PSN are based on a unified approach (Appendix C.9).

3.4 Architecture (coupling)

A critical element of a unified approach is its overall system architecture, particularly for coupling. An essential feature of a coupled modeling strategy is that it allows for efficient coupling of environmental subcomponents, while minimizing the additional burden that coupling places on development of the individual subcomponents. This naturally leads to a modular approach, where each component has a clear interface and can be built separately, and where subcomponents are generally linked through an external coupler / mediator. An additional benefit of a modular approach for an operational environment is that different levels of coupling (including phasing in as the forecast time progresses) can be used for different applications of a single unified modeling system by manipulating the coupler / mediator only.

This modular approach is generally identified as “loose” coupling. Its major disadvantage is that short time scales of interactions or large volumes of data exchanges associated with interactions between subcomponents may make a modular approach less suitable and efficient than a single, integrated code for multiple sub-systems (e.g., Dietrich et al. 2011). Conversely, it is not yet clear if modularity will enable or limit code optimization on emerging computer architectures. For the period covered by this roadmap, where coupling approaches in general are not yet mature, the benefits of a modular approach far outweigh its potential disadvantages.



Courtesy NOAA NCEP System Architecture Working Group

Figure 3: Modular NEMS design for coupled modeling

US government agencies (e.g. NASA, the Department of Defense, NOAA, the National Science Foundation, etc.) have invested in the development of the Earth System Modeling Framework (ESMF, Theurich, et al., 2016), which provides an architecture and tool set for modular coupled modeling. The National Unified Operational Prediction Capability effort (NUOPC, Sandgathe, et al., 2011) standardized component interfaces in

ESMF in the so-called NUOPC layer, to facilitate “plug-and-play” coupling approaches where different models for a given environmental sub-component can be exchanged relatively easily. NCEP (with financial support from STI and CPO) has invested in the NCEP Environmental Modeling System (NEMS) as a general coupler / mediator environment based on ESMF and the NUOPC layer, in close collaboration with ESRL. The ESMF-NUOPC-NEMS approach to unified modular coupled modeling was endorsed by UMAC and its general layout is illustrated in Figure 3. ESMF and NUOPC are mature inter-agency approaches, and are increasingly adopted by academia (e.g., NCAR’s CESM), and are consistent with the National ESPC approach (Carman, et. al., 2017). NEMS is less mature, and its approaches may need to be revisited periodically. The separation of the dynamic core and physics for the atmosphere as introduced in Figure 3 will be discussed in Section 3.5.

3.5 Component models

A key element needed to make the architecture of Figure 3 successful is to limit the number of models used for subcomponents, i.e., to use a unified approach per subcomponent (consistent with NUMFT, 2017). It should also be noted that not all elements of the unified modeling systems need to be used for every individual application, and that the selection of components in a coupled system should be based on both requirements and evidence.

3.5.1 Atmospheric Weather and Outlook models

The global atmospheric models have traditionally been unified to a high degree around the Global Spectral Model (GSM), with a single physics package identified as the “GFS physics”. The Climate Forecast System[11] (CFS) and Global Ensemble Forecast System (GEFS) traditionally have been based on older versions of the GFS, and the core model development has been focused on the high-resolution deterministic GFS model. As part of the NGGPS project, a new dynamic core has been selected to replace the spectral core of the GSM (Ji, et. al., 2016). The new core will be adopted from the GFDL Finite Volume version 3 (FV3) model (Putman and Lin 2007; Harris and Lin 2013; Harris and Lin 2014; Harris, Lin, and Tu 2016). In the new PSN, the following changes compared to the present PSN will be implemented with respect to global modeling:

- Full integration in the unified architecture (NEMS).

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[11] The CFS will be renamed to Seasonal Forecast System (SFS) to properly describe its function.

- One software package with three main applications (SFS, SSFS, GFS)[12]. NCEP will need to consider if the SFS and SSFS products could be provided with a single model application, as will be discussed in Section 4.
- Unified development and parallel testing of all applications (SFS, SSFS, GFS)[12], rather than "trickle down" approach from shorter to longer time scales (similar to UKMO approach).
- Separation of the dynamic core and the physics in the underlying architecture.

The present mesoscale modeling effort is not well unified, using four different models (WRF-ARW, NMM-B, HWRF, and GFDL hurricane), and a plethora of physics approaches in the SREF. The FV3 core will become the core for the RRFS and WoFS regional application, unifying all atmospheric models on a single dynamic core.

As observed by UMAC, it is essential to rapidly move to a unified Convection Allowing Model (CAM) approach for the RRFS and WoFS. Key elements in building such a capability are operationalizing proven multi-model ensemble approaches, while moving toward a single-core (FV3) ensemble approach. More detailed strategies to achieve this will be developed as part of the SIP, and will be evidence-driven.

To facilitate both development and unification of physics packages, the dynamic core and physics are modularly separated in Figure 3, using an Interoperable Physics Driver (IPD) based on Common Community Physics Packages (CCPP, Auligne at al., 2016). The success of the modular physics approach will depend on its unification. To be avoided are the large number of physics approaches presently used in the PSN, or the unbridled proliferation of physics approaches presently available in, for instance, the SREF system or WRF model. Whereas diversity enables scientific research, unbridled diversity has arguably stunted true progress in convection-allowing modeling (Mass, 2015).

A short-term transition to a unified physics approach applies the IPD / CCPP as defined in Figure 3 initially (less than 3 years) to a small number of successful operational physics packages (selected from, e.g., GFS, HRRR, NMMB, HWRF, GFDL, CESM). The long-term target is to move to the most optimal unification of physics approaches across scales, utilizing both scale awareness and stochasticity. Work along the two development tracks will overlap. This will require a well-defined and strong governance approach with respect to developing physics approaches.

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[12] With the likely addition of a space-weather application as shown in Figure 2, and the possible merging of SSFS and SFS applications, see Section 4.3.

3.5.2 Other environmental subcomponents

Figure 3 identifies additional models for environmental subcomponents as presently used in the PSN. In general, a reasonably unified approach is used for these subcomponents. As mentioned above Unified modeling as defined by the NUMTF implies the smallest number of models that makes scientific and economical sense. For instance, for oceans the Hybrid Coordinate Ocean Model (HYCOM) and the Modular Ocean Model (MOM) are used side-by-side, as they (and their communities) have been identified as more appropriate for weather and climate time scales, respectively.

Strategically, a unified approach for subcomponent models will continue for the next 5-10 years, but focal models for individual subcomponents may change, for instance:

- It is not clear if GOCART will have long-term support from its main developer (NASA), and in the community; WRF-Chem is becoming more capable and popular, but has been used regionally only. Alternative community-supported chemical mechanisms for aerosols (e.g. the Modal Aerosol Model) are being evaluated in WRF-Chem experiments to assess reliability and performance for use in a unified modeling approach.
- Results from an October 2016 and May 2017 workshops with participants from NOAA, DoD and academia, suggest that the HYCOM and MOM community efforts might be combined in a single MOM6 (or similar) approach.
- Several recent workshops on sea ice modeling have resulted in the development of a consortium to further develop the LANL CICE ice model as a true community model, and to explore if CICE, SIS2, and KISS elements can be included in a single community modeling framework.
- NOS is working with the community on focusing coastal ocean applications on a smaller set of models, embedded in their unified Coastal Ocean Modeling Framework (COMF).
- SWPC is working with academia on community modeling efforts for space weather applications.

3.5.3 Data Assimilation

Data assimilation for the (global) atmosphere is specifically mentioned in Figure 3. Global atmospheric data assimilation (Global Data Assimilation System, GDAS) has transitioned rapidly to a hybrid ensemble 4D variational (4dENVAR) approach, built around the Gridpoint Statistical Interpolation (GSI) software. A traditional 4D approach relies on adjoints of the model for which the DA is applied. The ensemble hybrid approach does not require an adjoint, but extracts the needed information from the ensemble. This makes the ensemble hybrid approach up to an order of magnitude cheaper in computing costs, and eliminates the need for developing and maintaining adjoints of models (roughly half the cost in human resources). This approach therefore represents a balance between economy and accuracy, and is expected to remain the mainstay approach for DA in the period covered by this strategic plan. The DTC has supported this approach to the community for several, including cheaper 3dENVAR approaches. The GSI software is used by partners such as NASA.

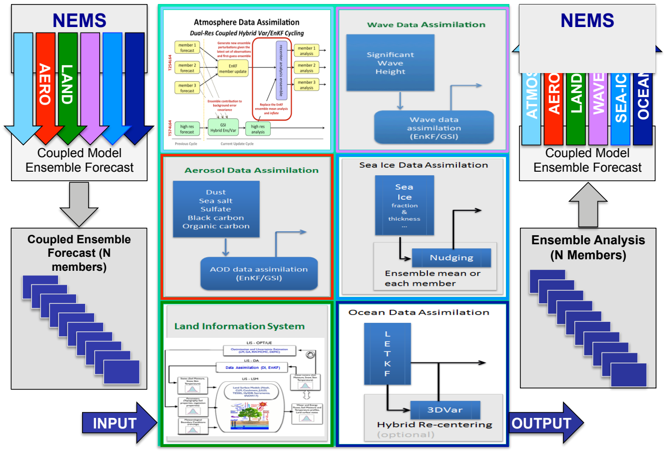
The strategically important Joint Effort for Data assimilation Integration (JEDI) project of the Joint Center for Satellite Data Assimilation (JCSDA) will shape the DA efforts for the next 5-10 years. JEDI aims to provide a community environment for data assimilation, and a re-factoring of the GSI code. A key strategic goal for the simplification and unification of the PSN is to align the PSN with JEDI and vice versa, and to use this project to apply a 4dENVAR DA approach to all subcomponents of a full environmental modeling system. JEDI is also expected to provide the diversity needed where research on full 4DVAR approaches can continue consistent with the operational DA approaches, even if the full 4DVAR is not used in operations. The JEDI framework is presently used to develop DA approaches for wind waves and ice, and to convert OI and variational DA approaches for oceans to a unified approach in preparation for coupled DA as described below.

A second strategic goal is to move to coupled DA. Generally, several levels of coupling in DA can be identified.

0. Uncoupled DA (present GDAS approach).
1. Weakly coupled
    a. Through first guesses from coupled models, but with independent DA per subsystem (present CFS approach).
    b. Through first guesses from coupled models, and in iteration loops in 4dENVAR, but with independent DA per subsystems (in preparation at ECMWF in a full 4DVAR approach).
2. Stronger coupled by addressing cross-correlations of errors between subsystems, but with independent DA per subsystems.
3. Fully coupled DA, including coupled (simultaneous) assimilation in all subsystems.

Coupled DA at level 1.a has proven its value in the CFSRR (Saha et al. 2010) and is similar to the coupled DA approach targeted by ECMWF (1.b). Level 2 represents the cutting edge of coupled DA, and a potential layout for such a system with six subcomponents is illustrated in Figure 4. Considering the lack of maturity of such an approach, the strategic goal for the PSN in the next 5-10 years should be to move toward such a coupled DA system, but without a strong commitment for implementation.

Similarly, coupling at level 3 has not been tried at any level yet, and should be considered out of strategic scope in the next 5-10 years.



Courtesy Suru Saha

Figure 4: Potential prototype layout for a more coupled data assimilation approach using existing DA approaches for subcomponents (pre-JEDI)

3.6 Full Unification

Sections 3.2 through 3.5 deal with traditional forecast systems in the PSN. Full unification of the PSN requires additional unification of functional areas that are shared across modeling systems.

3.6.1 Unifying data processing

Most components of the PSN depend critically on input from observations. For a truly unified PSN, it is critical that data ingest and quality control is done centrally for as far as different data sources (including data for different sub-component models) allow this. Particularly, mixing of data ingest with generation of specialized products (e.g., MRMS and MODIS) needs to be avoided, as it leads to stove-piped rather than unified generation of products. Data QC of individual observations is an essential part of data processing and DA. This is also associated with the monitoring of the "health" of observation systems. The latter may be naturally addressed in model validation and verification below.

Similarly, post-processing should be unified across modeling systems. This approach has been started with the establishment of the Unified Post Processor (UPP). The unified approach to post-processing needs to be expanded to all post-processing, including use of RRs and community-based software. Common file formats and software that is extensible and shareable to enable collaboration are needed to support the advancement of the development and implementation of statistically post-processed products derived from the suite of operational models. MDL leads an effort to develop the suite of statistically post-processed guidance providing calibrated products in the form of Model Output Statistics (MOS), specialized aviation products known as the Localized Aviation MOS Program (LAMP), and the National Blend of Models (NBM). They are partnering in their efforts with OAR, as well as with partners in NCEP Centers focused on calibrated probabilistic guidance.

3.6.2 Validation and Verification

A special case of data processing is model validation and verification (V&V). Unification of V&V within the PSN is sensible from a business perspective. Unification needs to address both standard metrics and scorecards. The latter are critical because of the increasing complexity of (competing) requirements, and the reality that model upgrades provide incremental improvements, where not all metrics will be improved upon with any implementation.

More important is to unify V&V between operations and research. Using unified V&V is one of the key approaches needed for operations to adopt test results from the research community without the need to redo much of the testing. Hence, unified V&V will accelerate Transition to Operations (T2O), which is a high-level goal of NOAA (NOAA Administrative Order, NOA 216-105, 2015).

EMC has started to move its V&V to the Model Evaluation Tools (MET) of NCAR. This requires a close collaboration between NCAR and the NWS, because unification of V&V at the NWS / PSN requires that MET includes all present V&V techniques and tools as used for the PSN. Conversely, the PSN benefits from new validation techniques already available in MET, such as object oriented validation metrics (MODE, Method for Object-Based Diagnostics Evaluation). For true unification, a long-term goal is to add key parameters of other environmental subcomponents to MET. For long term sustained model improvement, and for understanding of underlying strengths and weaknesses of models, process-based metrics are essential, and are starting to find their way into MET.

3.6.3 Access to results

Numerical model results from the PSN can be assessed in a unified way through centralized data sites on the www. However, data formats mandated by the World Meteorological Organization (WMO) such as BUFR and GRIB are not self-contained with respect to its metadata, and are therefore not fully discoverable on the web. NOAA has started to move into more modern data dissemination methods with the development of the NOAA National Operational Model Archive & Distribution System (NOMADS), which uses OPeNDAP and is looking into THREDDS protocols for easier data access, and which includes some datasets in the fully discoverable NetCDF or HDF formats.

Many (external) users access PSN products/data in graphical form from web sites, open access policies for which should be retained wherever possible. NCO's Models Analysis and Guidance website (MAG, http://mag.ncep.noaa.gov) attempts to provide a one-stop shop, but presents only a small fraction of the PSN data. This web site is augmented with a plethora of disparate web sites, which can be difficult to discover. A unified PSN needs to be presented to its users in a modern, one-stop web site, linked to a one-stop data distribution channel. Whereas these data access and archive considerations could be considered outside the core functionality of the PSN, they are essential for public access to the PSN products, and therefore should be considered part of an integrated SP and Roadmap. As outlined in Section 2.6, emerging best practices for Big Data and Cloud approaches should be adopted in the PSN.

4 End State

4.1 Introduction

The previous section presents basic elements of the Unified PSN in terms of forecast ranges of key elements of the PSN, but does not address other details of their implementation. A target layout of the PSN is needed to make the Roadmap actionable, and to address resource needs and limitations. This section will consider two possible configurations. The first is a minimum configuration needed to consolidate and unify the PSN (Section 4.2). Ideally, the transition to such a configuration should target the first five years. The second is a "moonshot" vision for the PSN to become the best in the world (Section 4.3). This latter presents a target for the PSN in 10 years, as well as targets for research to be started immediately. Moving to the consolidation and to the development of the moonshot are not sequential but overlap, and the progress of both will depend on progress of research and availability of resources for both operations and research. The details of the implementation of these PSN configurations in the next 3 years are the subject of the SIP.

Table 2: Tentative consolidation-state for key elements of the PSN in 5 years focusing on atmospheric components. Resolutions of other coupled environmental component models may be different.

Element	Cadence	Range	Resol.	Ens.	Update	RR
SFS	7 d	9-15 mo	50 km (g)	28	4 y	1979-present
SSFS	24 h	35-45 d	35 km (g)	31	2 y	20-25 y
GFS	6 h	7-10 d	13 km (g)	26	1 y	3 y
RRFS	1 h	18 h	3 km (r)	26	1 y	TBD
	6-12 h	30 h				
	6-12 h	60 h				
WoFS	5-15 min	2-4h	1 km (r)	26	1 y	TBD
Analyses						
Trad.	6-24 h	---	Var. (g)	---	6 mo	N/A
RUA	15 min	---	TBD (r)	---	6 mo	

(g) Global
(r) regional
Red: uncharted territory

4.2 Consolidation and Unification

Table 2 represents a possible consolidation state of the PSN to be achieved in 5 years. A detailed review of the key modeling elements of the Unified PSN in this Table is presented in Sections C.2 through C.7 of Appendix C.

As before, the focus is on the atmospheric components, with the understanding that other coupled environmental components may require different resolutions and other details as presented in this table. This layout of the PSN was developed using the following design principles:

- All present products of the production suite are represented in the new PSN, including product resolutions and ensemble sizes.
- All PSN elements will be ensemble based with appropriate RR.
    - The SFS and SSFS are already ensemble based, and therefore additional resources are used to increase spatial resolutions (evidence-based).
    - The GFS and RRFS need to move from deterministic to ensemble systems. As this requires a significant increase in computational costs, spatial resolutions for these systems remain largely unchanged while introducing ensemble approaches.
- The layout of the RRFS is based on a consensus proposal from all six regional NWS headquarters.
- All weather elements of the PSN move to coupling with other environmental sub-systems from the present production suite. At least one-way coupling will be considered, consolidating the complexity of the PSN, providing increased resolution of input of "downstream models", and reducing reliance on file systems and I/O on forcing the latter models.
- The WoFS will still be in a development stage as this consolidation is executed.

Items in red in Table 2 cannot be established accurately due to a lack of scientific evidence or of established requirements. Note that the table does not address vertical resolution and number of levels for atmospheric models. To simplify nesting strategies in the atmosphere, and following evidence-based development at leading operational centers, the PSN should move toward using the same vertical resolution for all Forecast Systems (with the exception of Space Weather), and the number of vertical levels should be increased to typically 100-150.

With the tentative layout of the key elements of the Unified PSN as summarized in Table 2, it is possible to estimate the computational cost of each element. This has been done by Tolman (2016) in support of the NOAA 100% requirement exercise mentioned in Section 2.6, and is summarized in Table 3. The need for computing resources in PFlop are based on extending the present models run on the Weather and Climate Operational Supercomputing System (WCOSS) for configurations outlined in Table 2, including costs of coupling and DA, and represent raw computing needs. The corresponding nominal peak performance of the operational super computer is estimated at 37 PFlop, and for efficient use of such an operational computer will need to be supported by a much larger computing resource for NOAA R&D (see Appendix D). As a reference the peak performance of the operational half of the present WCOSS in early 2017 was approximately 2.8 PFlop.

Table 3: Computing cost estimates for consolidation-state PSN elements

	SFS	SSFS	GFS	RRFS	WoFS
PFlop	0.19	0.33	4.98	9.17	89.1[a] 8.91[b]
Fraction [c]	1.3%	2.2%	34%	63%	---

[a] Assuming same spatial coverage as RRFS
[b] Assuming 10% of spatial coverage as RRFS
[c] State before implementation of WoFS

Table 3 shows that the SFS through RRFS all require resources that will tentatively fit on realistic future operational computers (one order of magnitude increase in computing resources in 5 years). However the WoFS if applied uniformly over the RRFS domain (option [a]) does not. Considering this, the vision for a WoFS is a frequently updated, regional-scale on-demand convection-resolving prediction system (option [b]) that will be invoked as needed by a national center (e.g. SPC) to support warning operations within NOAA, and will not be developed to run over the entire CONUS.

The RUA element is not included in the estimates, but is likely to represent a sub-set of the cost of the DA part of the RRFS. The bottom line in Table 3 shows the corresponding distribution of computing resources. Considering that historically half the computing resources have been used for global applications, this identifies a shift toward resource allocation to CAM modeling for IDSS, resulting from requirement-based resource allocation.

4.3 Moonshot

The layout of a Unified PSN as presented in the previous section is essential for efficient operation and development of the PSN. It will not, however, bring us to the goal of creating the best Physical Environmental Modeling Enterprise in the world. A target "moonshot" layout of the PSN to become the best, and to be reached in 10 years is presented in Table 4. The aggressive nature of this layout implies extrapolation of proven concepts, and its layout will be adjusted based on evidenced-based decision protocols and resource availability.

The inherently large computational requirements needed to implement a moonshot configuration may limit its practical feasibility. Nevertheless, setting such ambitious goals is essential for the US to produce the best Physical Environmental Modeling Enterprise in the world for two reasons. First, it sets a direction for research and development that needs to start ***today***, in order to reach the goal of being the ***best enterprise in 10 years***. Second, it allows us to address resource needs ***proactively***, as it starts providing a cost-benefit analysis for necessary investments in computing and research.

Table 4: Like Table 2 for moonshot configuration in 10 years.

Element	Cadence	Range	Resol.	Ens.	Update	RR
S3FS	7 d	12 mo	15 km (g)	200	TBD	1979-present
	24 h	45 d		100		
GFS	1? - 6 h	7-10 d	5 km (g)	50	1 y	3 y
RRFS	1 h	24 h	1.5 km (r)	50	1 y	TBD
	3 h	48 h				
	6 h	72 h				
WoFS	5 min	2h	0.5 km (r)	50	1 y	TBD
Analyses						
Trad.	6-24 h	---	Var. (g)	---	1 y	N/A
RUA	5 min	---	TBD (r)	---		

The SFS and SSFS ***products*** in Table 4 at approximately 15km atmospheric resolution will be generated using a single coupled Seasonal and Sub-Seasonal Forecasts Systems (S3FS) ***model application***, where the high spatial resolution is expected to improve shorter SSFS forecasts, whereas the larger ensemble size is expected to be critical for the longer term SFS forecasts[13]. The additional cost of running higher resolution for the SFS is expected to be offset by the consolidation of development and maintenance costs, but mostly by combining two RRs into a single RR.

The GFS resolution of approximately 5 km and ensemble sizes (50) are moving NOAA to the forefront of resolution and ensemble sizes in the world (e.g., ECMWF, 2016a,b). Accepting lower resolutions and smaller ensemble sizes will hamstring NOAA to do so. Part of the GFS may run on a 1h cadence to support the RRFS. This also may result in modeling configuration where the RRFS is run directly coupled to the GFS.

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[13] ECMWF presentation at NCEP bilateral meeting, July 2017.

The RRFS resolution (1.5 km) and ensemble sizes (50) are set to fully utilize the GFS data used to drive this model, and the moonshot configuration includes a first full operational implementation of the WoFS at 0.5km resolution for 10% of the US.

Computing cost estimates for this PSN configuration are presented in Table 5. Compared to the costs of the conversion configuration, it is assumed that Data Assimilation for the RRFS and WoFS have become more efficient, and that optimization of codes for new hardware will give a significant improvement in efficiency (factor 2). All atmospheric models are assumed to have 128 vertical levels. The total operational computer resources needed for this configuration are estimated as approximately 730 PFlop (see Appendix D), or a 20 times increase compared to resources needed for the consolidation configuration.

Table 5: Computing cost estimates for moonshot PSN elements.

	SFS	SSFS	GFS	RRFS	WoFS
PFlop	29	3.0	102	70	87[a]
Fraction	10%	1.0%	35%	24%	30%

[a] Assuming 10% of spatial coverage as RRFS

5 Research Needs

To achieve the SV and Roadmap ongoing research will be required to continuously improve NOAA's environmental modeling enterprise feeding into the PSN. This research will fully support the community modeling paradigm to ensure that the entire modeling enterprise can contribute and can be contributed to, and will be conducted by NOAA and its partners in academia, the federal government, and the private sector working together to ensure resources are applied to critical research needs to meet the goals described in this Roadmap.

Given the current state of technology and modeling capabilities, many gaps exist that will require ongoing research that systematically will be transitioned into the operational modeling system following the principals described in NOAA's Administrative Order (NAO) 216-115A, Research and Development in NOAA[14]. NOAA's modeling enterprise will require research in areas that are applicable to many time scales. The details of the key science questions/issues that need to be addressed with additional research by time scale are described in Appendix C. The main areas of research that are needed initially are:

- predictability studies,
- model physics,
- full coupling of the earth system,
- data assimilation of all available in-situ and remotely sensed data,
- ensemble design,
- postprocessing,
- validation and verification,
- configuration management,
- and social science.

Predictability studies are particularly important for the seasonal and subseasonal timescales as well as storm-scale timescales. Current operational ensemble modeling has historically focused on seasonal timescales, with an emphasis on ENSO. Increased information beyond traditional temperature and precipitation anomalies products are needed by decision makers for subseasonal and seasonal timescales. Research will identify those aspects of the Earth System that show predictability and which model improvements will maximize this predictability. Predictability studies are also needed for convective storms to determine the predictability time limit of storm-scale models that are expected to provide accurate forecasts beyond one hour.

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[14] http://www.corporateservices.noaa.gov/ames/administrative_orders/chapter_216/216-115A.html

Research to improve model physics associated with all time scales, will focus on the development and use of scale-aware and stochastic physics to support a seamless unified probabilistic product suite. Research in model physics will also include interactions across boundaries associated with the atmosphere, ocean, ice, ground, and space. Understanding the interaction across boundaries and the importance of such interactions are critical to determining the degree to which coupling of the Earth system elements is required to improve predictions at all time scales.

Driving the improvement in predictions will be research in data assimilation techniques for various data types, including coupled data assimilation, that have not traditionally been considered in modeling periods from several weeks to months, as well as very short time scales from minutes to hours. Research will examine how to improve model predictions using data assimilation of observations from *in situ* and remote sensing instruments from minutes to months as well as techniques for generating ensemble forecasts that span the uncertainty of observations within data assimilation schemes. Other research in ensemble design will identify how to generate and interpret appropriate ensembles to ensure the span the uncertainty of the system for short and long timescales and to ensure that the resulting probabilities from the ensemble are reliable. A critical and immediate need for research is to bring the level of sophistication of global atmospheric DA (ensemble hybrid 4DVAR, full 4dVAR) to CAM applications and to other environmental components, preferably though a unified JEDI approach.

Ensemble design needs to be addressed both in the context of probabilistic forecasting, and in the context of DA, with a focus on scale-aware stochastic physics as described above. A critical and immediate need for research is to focus on ensemble design (and DA) for CAM models (RRFS and WoFS), where such systems are still in their infancy, and for development of ensembles of GFS scales (order of 10 km), where regional experiences with the SREF show that realistic ensemble spreads presently require MME approaches. For all these scales, ensemble designs with realistic model spread based on single-model approaches are essential for efficient unification of the PSN.

In addition to research to improve the components of the modeling system, research in configuration design is necessary to bring these components together. This research will ensure a flexible, modular system that is amenable to frequent community updates to modeling system modules and runs efficiently within strict runtime constraints and can be upgraded easily to ever-evolving computer technologies.

So far, the assessment of research needs has focused on the modeling at the core of the PSN. Just as important is further development of techniques to post-process raw model results. This is essential to maximize the quality and accuracy of model guidance provided to the forecast at all spatial and temporal scales. Moreover, it is essential to develop unified post-processing techniques to move towards a unified PSN. With this, unification of Verification and Validation (V&V) around the MET package is essential. This goes beyond the technical aspects of MET centric V&V unification, as understanding of model behavior represents a cyclic process where understanding of the physical behavior of models goes hand-in-hand with the development of metrics and V&V techniques. To make MET a toolbox that can be used both for forecaster / forecast-relevant V&V, and for a more in-depth assessment of models behavior, MET will have to incorporate an increasing set of process based metrics, rather than model output based metrics. Similarly, MET needs to be extended from being weather-centric to cover the whole environmental modeling effort (including interactions between modeling components), and needs to address V&V in a holistic way through holistic error assessment such as Taylor and Target diagrams and scorecards.

Finally, research in the social sciences will focus on understanding human behavior to identify how to maximize the interaction of forecasters with model data and how NOAA's operational products and forecasters can provide more value to decision makers.

6 Timeline

To move from the quilt of models making up the present PSN (Figure 1) to a unified and consolidated production suite (Figure 3), while moving from a consolidated configuration (Table 1) to a moonshot configuration (Table 4) to become the best modeling system in the world represents a complex scientific and engineering effort. This effort is complicated by the fact that operations have to continue while the PSN is rebuilt. NCEP has started this process as outlined in the SIP document covering Fiscal Year 2018 (FY18) through 2020 (FY20). In this section, a high-level time line with deliverables is presented, where the first three years are taken from the initial SIP plan, and where the later years represent key milestones needed to achieve the moonshot configuration in 10 years. Resource availability (human and computing) determines the feasibility reaching the moonshot configuration, and conversely, the plan as outlined in Section 4 identifies computing resources needed to get there.

The Tables below identify key deliverables, generally based on the 13 focal areas identified in the SIP plan. However, in this Roadmap, the focus is on the bigger picture, not presenting the level of detail of the SIP. For the first three years, more detailed Gantt charts are available in the SIP report. In the tables, green shading identifies elements set forth in the SIP. Elements with grey background identify elements outside of the scope of the initial SIP.

Figure 5 presents the time line for the general governance. Other than the necessity to get governance in place early, this table presents little detail, other than that governance needs to be actively executed, and regularly reviewed.

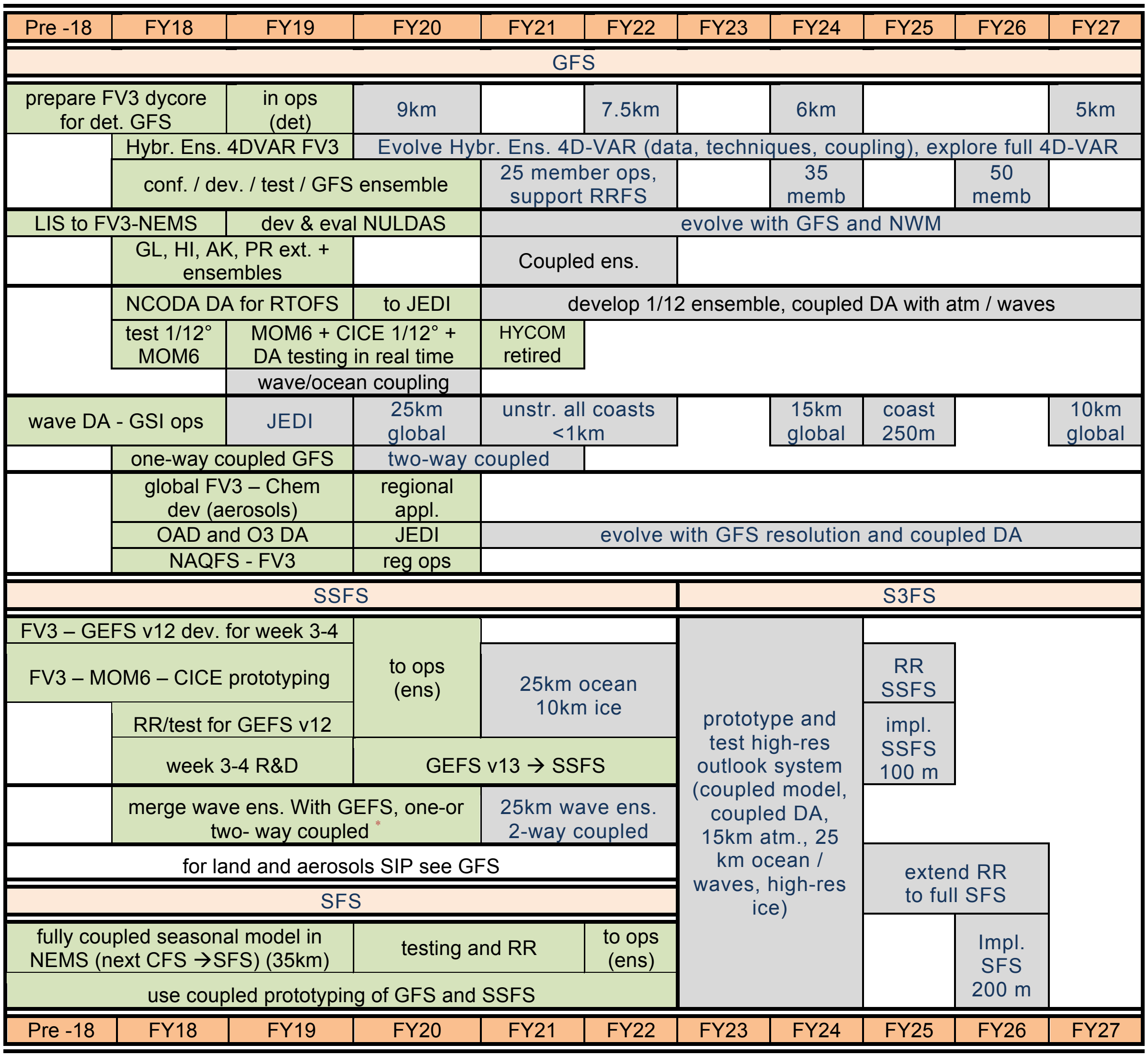
Figure 5: General Governance

Pre -18	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27
design oversight and work group structures										
	implement	execute, review and adjust as needed								

The bread and butter of the PSN are the global and regional models and analyses. A high-level time line for these models is presented in Figure 6 through Figure 8.

The time line for global models (Figure 6) includes SIP elements from SIP annexes for global modeling, data assimilation, ensembles, marine, land and aerosols. As component models are coupled to the weather models, stand-alone versions of these models are retired, as is indicated by * in the Tables. Ice modeling will be linked closely to the ocean model development. Note that starting in FY22, the SFS and SSFS products are tentatively produced from a single global coupled model application (S3FS).

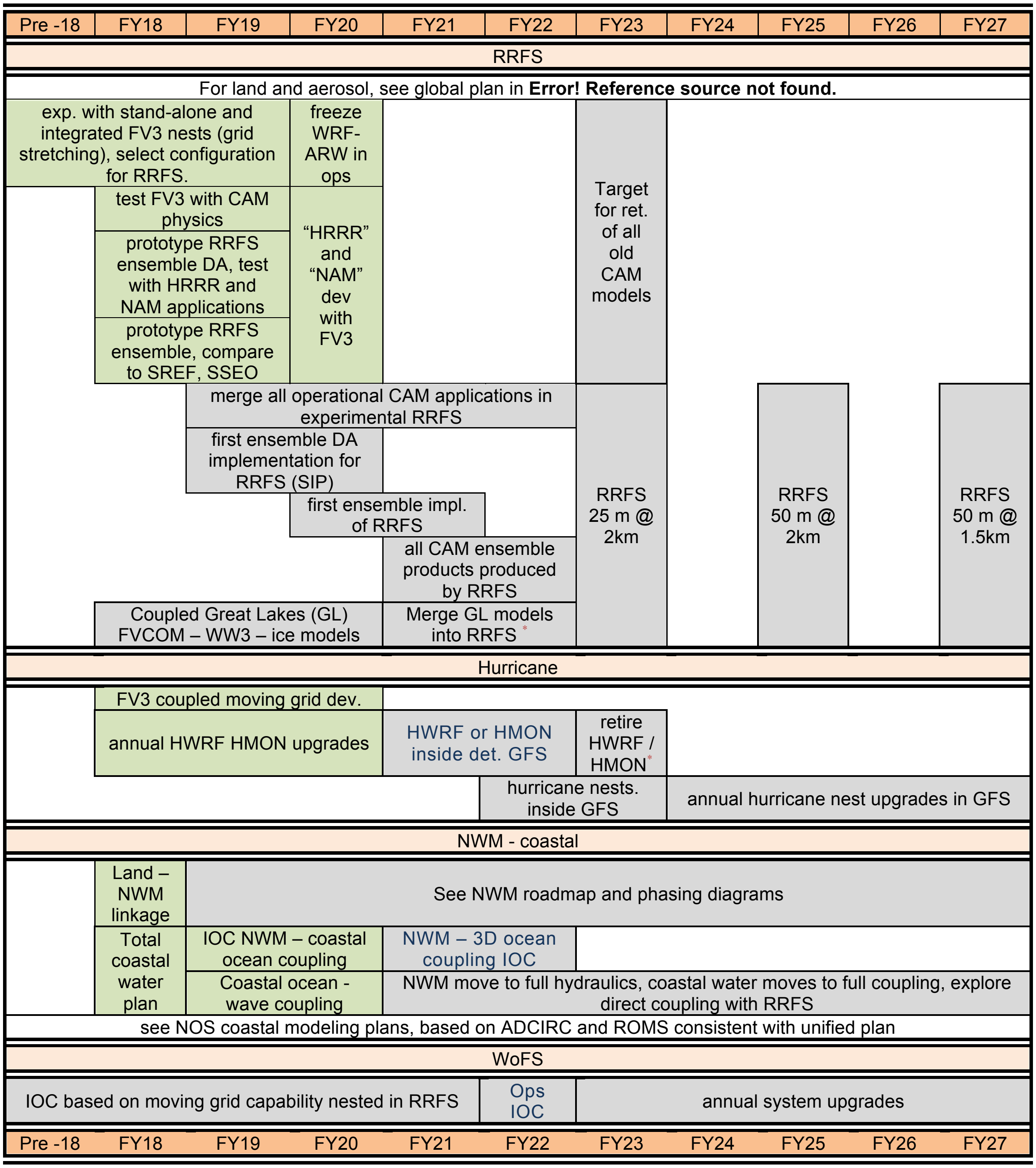
Figure 6: Global models * _identifies retirement of stand-alone model_



<table>
<tr><th>Pre -18</th><th>FY18</th><th>FY19</th><th>FY20</th><th>FY21</th><th>FY22</th><th>FY23</th><th>FY24</th><th>FY25</th><th>FY26</th><th>FY27</th></tr>
<tr><td colspan="11">GFS</td></tr>
<tr><td colspan="2">prepare FV3 dycore for det. GFS</td><td>in ops (det)</td><td>9km</td><td></td><td>7.5km</td><td></td><td>6km</td><td colspan="2"></td><td>5km</td></tr>
<tr><td></td><td colspan="2">Hybr. Ens. 4DVAR FV3</td><td colspan="8">Evolve Hybr. Ens. 4D-VAR (data, techniques, coupling), explore full 4D-VAR</td></tr>
<tr><td></td><td colspan="3">conf. / dev. / test / GFS ensemble</td><td colspan="2">25 member ops, support RRFS</td><td></td><td>35 memb</td><td></td><td>50 memb</td><td></td></tr>
<tr><td colspan="2">LIS to FV3-NEMS</td><td colspan="2">dev & eval NULDAS</td><td colspan="7">evolve with GFS and NWM</td></tr>
<tr><td></td><td colspan="2">GL, HI, AK, PR ext. + ensembles</td><td></td><td colspan="2">Coupled ens.</td><td colspan="5"></td></tr>
<tr><td></td><td colspan="2">NCODA DA for RTOFS</td><td>to JEDI</td><td colspan="7">develop 1/12 ensemble, coupled DA with atm / waves</td></tr>
<tr><td></td><td>test 1/12° MOM6</td><td colspan="2">MOM6 + CICE 1/12° + DA testing in real time</td><td>HYCOM retired</td><td colspan="6"></td></tr>
<tr><td colspan="2"></td><td colspan="2">wave/ocean coupling</td><td colspan="7"></td></tr>
<tr><td colspan="2">wave DA - GSI ops</td><td>JEDI</td><td>25km global</td><td colspan="2">unstr. all coasts <1km</td><td></td><td>15km global</td><td>coast 250m</td><td></td><td>10km global</td></tr>
<tr><td></td><td colspan="2">one-way coupled GFS</td><td colspan="2">two-way coupled</td><td colspan="6"></td></tr>
<tr><td></td><td colspan="2">global FV3 – Chem dev (aerosols)</td><td>regional appl.</td><td colspan="7"></td></tr>
<tr><td></td><td colspan="2">OAD and O3 DA</td><td>JEDI</td><td colspan="7">evolve with GFS resolution and coupled DA</td></tr>
<tr><td></td><td colspan="2">NAQFS - FV3</td><td>reg ops</td><td colspan="7"></td></tr>
<tr><td colspan="6">SSFS</td><td colspan="5">S3FS</td></tr>
<tr><td colspan="3">FV3 – GEFS v12 dev. for week 3-4</td><td rowspan="3">to ops (ens)</td><td colspan="2"></td><td colspan="2" rowspan="9">prototype and test high-res outlook system (coupled model, coupled DA, 15km atm., 25 km ocean / waves, high-res ice)</td><td></td><td rowspan="5"></td><td rowspan="9"></td></tr>
<tr><td colspan="3">FV3 – MOM6 – CICE prototyping</td><td colspan="2" rowspan="2">25km ocean 10km ice</td><td>RR SSFS</td></tr>
<tr><td rowspan="2"></td><td colspan="2">RR/test for GEFS v12</td><td rowspan="2">impl. SSFS 100 m</td></tr>
<tr><td colspan="2">week 3-4 R&D</td><td colspan="3">GEFS v13 → SSFS</td></tr>
<tr><td></td><td colspan="3">merge wave ens. With GEFS, one-or two- way coupled *</td><td colspan="2">25km wave ens. 2-way coupled</td><td></td></tr>
<tr><td colspan="6">for land and aerosols SIP see GFS</td><td colspan="2" rowspan="2">extend RR to full SFS</td></tr>
<tr><td colspan="6">SFS</td></tr>
<tr><td colspan="3">fully coupled seasonal model in NEMS (next CFS →SFS) (35km)</td><td colspan="2">testing and RR</td><td>to ops (ens)</td><td rowspan="2"></td><td rowspan="2">Impl. SFS 200 m</td></tr>
<tr><td colspan="6">use coupled prototyping of GFS and SSFS</td></tr>
<tr><td>Pre -18</td><td>FY18</td><td>FY19</td><td>FY20</td><td>FY21</td><td>FY22</td><td>FY23</td><td>FY24</td><td>FY25</td><td>FY26</td><td>FY27</td></tr>
</table>

A time line for regional models is given in Figure 7. This table covers the regional CAM models that are to be consolidated in the RRFS, as well as the convection resolving models that will comprise the WoFS. The figure also addresses hurricane models and the NWM. The hurricane models will initially be run as stand-alone moving nest models, but around FY22 or FY23 become fully integrated with the GFS (deterministic first, full ensemble later). A major gap in the present NPS capabilities is that of total coastal water prediction. A plan for integrated coastal water (wave and wind surge + river flow + local rain) is presently being developed, and will tentatively first see a coupling between the NWM and the 2D coastal surge models.

Figure 7: Regional modeling



Pre -18 | FY18 | FY19 | FY20 | FY21 | FY22 | FY23 | FY24 | FY25 | FY26 | FY27

RRFS

For land and aerosol, see global plan in **Error! Reference source not found.**

exp. with stand-alone and integrated FV3 nests (grid stretching), select configuration for RRFS.

freeze WRF-ARW in ops

Target for ret. of all old CAM models

test FV3 with CAM physics

prototype RRFS ensemble DA, test with HRRR and NAM applications

"HRRR" and "NAM" dev with FV3

prototype RRFS ensemble, compare to SREF, SSEO

merge all operational CAM applications in experimental RRFS

first ensemble DA implementation for RRFS (SIP)

first ensemble impl. of RRFS

all CAM ensemble products produced by RRFS

Coupled Great Lakes (GL) FVCOM – WW3 – ice models

Merge GL models into RRFS

RRFS 25 m @ 2km

RRFS 50 m @ 2km

RRFS 50 m @ 1.5km

Hurricane

FV3 coupled moving grid dev.

annual HWRF HMON upgrades

HWRF or HMON inside det. GFS

retire HWRF / HMON

hurricane nests. inside GFS

annual hurricane nest upgrades in GFS

NWM - coastal

Land – NWM linkage

See NWM roadmap and phasing diagrams

Total coastal water plan

IOC NWM – coastal ocean coupling

NWM – 3D ocean coupling IOC

Coastal ocean - wave coupling

NWM move to full hydraulics, coastal water moves to full coupling, explore direct coupling with RRFS

see NOS coastal modeling plans, based on ADCIRC and ROMS consistent with unified plan

WoFS

IOC based on moving grid capability nested in RRFS

Ops IOC

annual system upgrades

Pre -18 | FY18 | FY19 | FY20 | FY21 | FY22 | FY23 | FY24 | FY25 | FY26 | FY27

Figure 6 and Figure 7 include Data Assimilation development as needed for model initialization. They do not address Data Assimilation for analysis products. A time line for the latter products is presented in Figure 8. Note that model initialization and analyses generally use the same tools, although the latter may be ensemble-based, but are essentially deterministic products.

Figure 8: Analysis products

Pre -18	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27
	RTMA-URMA → RUA IOC (NBM focus)		Hybrid Ens 4DVAR RUA from CAM ensemble		maintain and evolve based on user requirements					
			merge MRMS etc. into RUA			all reg. analysis through RUA				
	review and consolidate global, slow cycling analysis products			maintain and evolve based on user requirements						

A unified NPS requires development of various tools, including elements of a unified systems architecture in infrastructure. Time lines for tool development are gathered in Figure 9.

Figure 9: System architecture, infrastructure and tools

Pre -18	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27
Develop community res & ops workflow (CROW)		CROW in GFS ops								
		CROW in GEFS (SSFS)	CROW in CFS (SFS)	CROW to regional						
				CROW maintenance						
NEMS – NUOPC layer for all components		ESMF / NUOPC / NEMS maintenance								
		recurring exploration of novel software architectures (exascale, fault tolarance)								
develop framework and req. deep atmosphere		GFS/GSI – WAM with one-way IPE	two-way IPE	explore "vertical nesting" for integration with GFS						
Develop framework and req. moving nests										
	Moving nest development and testing (FV3-based, in NEMS)			maintenance and development based on requirements						
	JEDI Unified Forward Operator (UFO) in GSI - GDAS									
JEDI IODA (Interface for Obs. Data Access) development and optimization				maintenance, development for new data types and models						
	JEDI non-UFO component treatment		moving toward fully coupled and 4D-VAR approaches							
CCPP in FV3-GFS with GFS physics		evolve and maintain CCPP		evolve and maintain CCPP, assure unified approach across scales and applications						
	MET github / governance		MET+ coupled, space wx							
	MET+ at WCOSS global and CAM, in CROW, JEDI, UPP			Maintain and evolve, requirements based, annual planning						
	METviewer new DB	METviewer at EMC, major release								
Pre -18	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27

Initial unification efforts through NGGPS have focused on the adoption and unification of the atmospheric dynamic core, resulting in the adoption of the FV3 core. The dynamic core selection is essential to unify the basic atmospheric model architecture, and effectively use new computer hardware architectures. The next step is to unify and develop improved physics schemes to improve forecast quality. The importance of physics development is acknowledge here by isolating key deliverables for improved and unified physics in Figure 10, although a significant part of the development could be considered as part of Figure 9 (CCPP, MET).

Figure 10: Physics

Pre -18	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27
CCPP in GFS + gov.	gov. for adding to CCPP	CCPP used as basis for community dev.								
	hierarchical testing defined	move selected physics packages to CCP suites								
		Intermediate physics suite development		cyclical development and testing of advanced physics packages annual review of typically three-year plans						
develop metrics for physics across scales, move to MET		expand MET to for research use (process based metrics)		continue standardization and expansion of MET physics assessment for both research and operations						

Similarly, effective and modern post processing is an essential element driving the quality of outlook forecast products, particularly the SSFS and SFS. This ranges from conventional product generation using a Unified Post Processor (UPP), to state-of-the-art post processing focusing on error correction of raw model output (Figure 11).

Figure 11: Post processing

Pre -18	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27
	ModPP - FV3		UPP for FV3 at DTC	Test simple PP while refactoring UPP						
NGGPS post workgroup established		Establish post testbed at DTC		R&D and requirement driven evolution of postprocessing						

7 Vetting and Approval

This documents has contributions of, and is vetted by all Centers, Regional Headquarters and Program Offices of the NOAA's National Weather Service (NWS), all Laboratories and Program Offices of NOAA's Oceanic And Atmospheric Research (OAR), NOAA's Office of the Chief Information Officer (OCIO), all other NOAA Line Offices through their representatives in the NOAA Unified Modeling Committee (UMC), and has been socialized and discussed at many public fora during it's development.

This document is approved by:

Louis W. Uccellini
April 23, 2020

Dr. Louis W. Uccellini
Date
NOAA Assistant Administrator for Weather Services,
Director, National Weather Service

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Appendices

Appendix A Coupled Environmental Modeling

The PSN of Figure 1 contains many products other than weather products, all of which are mandated products for the NWS. The following product types are part of the present (2017) production suite.

Land / Hydro: Land models are typically integrated in weather models, but are also used in stand-alone mode. Land-surface models provide the bottom boundary conditions as surface fluxes for parent atmospheric models, accounting for heat, moisture and momentum exchanges between the atmosphere and the surface. Land models also determine the evolution of the soil moisture, ice and temperature, and the snow pack, where all depend on the land-use/vegetation type and cover, and soil texture. Hydrology models account for the movement of soil moisture to the water table and subsequent flow of water to rivers and streams, ultimately connecting with the ocean. Some stand-alone products are mandated by the National Integrated Drought Information System (NIDIS, authorized by Congress in 2006 as Public Law 109-430, with NOAA the lead NIDIS agency). Advances in Land and Hydrology models include carrying carbon budgets and other biogeochemical cycles necessary to more completely model plant growth, and transport of different constituents such as sediment, oxygen and nutrients by water in the soil, groundwater, and in streams and rivers to the coastal ocean.

Ocean / Coast: NOS has traditionally provided coastal ocean products, directed by the Organic Act of February 10, 1807 founding the Survey of the Coasts, the Coast and Geodetic Survey Act of August 6, 1947, and the Hydrographic Services Improvement Act (HSIA) of 1998. Short-term ocean forecasts became an official part of the PSN after a recommendation of the Science Advisory Board (SAB) on ocean modeling, and the NOAA Administrator's subsequent response (SAB, 2004, 2005). NCEP's Ocean Prediction Center (OPC) and National Hurricane Center (NHC), as well as the Central Pacific Hurricane Center (CPHC) rely on short-term ocean surface and mixed layer products to provide accurate forecasts of hazardous marine winds and waves to meet requirements of the International Maritime Organization's Global Maritime Distress and Safety Subsystem (GMDSS) as governed by SOLAS 1974. This is particularly critical near major ocean currents such as the Gulf Stream. Ocean data are also vital inputs to coastal ocean models, as well as coastal inundation maps and storm surge watches and warnings, as mandated by NOAA's Storm Surge Roadmap. NCEP's Climate Prediction Center (CPC) relies heavily on ocean models for seasonal outlooks products (National Climate Act, Public Law 95-367).

Ice: Analyses, forecasts, and outlooks for sea and lake ice are produced by the National Ice Center (NIC) to meet requirements of the International Maritime Organization's Global Maritime Distress and Safety Subsystem (GMDSS) as governed by SOLAS 1974, and to meet U.S. Navy operational requirements. The NIC is a Navy-NOAA-Coast Guard tri-agency activity operated in accordance with Annex V to the umbrella Navy-NOAA Memorandum of Agreement. Snow and ice analyses over the northern hemisphere provided by the NIC provide critical lower boundary conditions for the mesoscale weather prediction models. Additionally, the Alaska Sea Ice Program of the NWS Alaska Region provides sea ice-related decision support products for emergency managers and other state and local activities in Alaska.

Waves: Forecasts of hazardous marine winds and waves are produced four times daily by OPC, NHC, and WFO Honolulu. They are disseminated via the World Meteorological Organization (WMO) Marine Broadcast System to meet requirements of the International Maritime Organization's Global Maritime Distress and Safety Subsystem (GMDSS) as governed by SOLAS 1974.

Aerosols: In 2003, the U.S. Congress mandated that NOAA establish a program "To provide operational air quality forecast and warnings for specific regions of the US." Regionally fine aerosol particulate matter, smoke and dust are provided twice per day out to 48 hours to the public and state air quality forecasters to support their air quality advisory products. They are disseminated via the NWS National Digital Guidance Database (NDGD) web site. Global aerosols are predicted to 5 days and provide boundary conditions to regional models, to improve retrievals of sea surface temperature and UV indices as well as to eventually incorporate aerosol effects on weather in NWS operational NWP models. Advanced modeling is shifting toward a more complete prediction of atmospheric composition, in particular for climate and regulatory purposes.

Space Weather: Space Weather Authority, 15 U.S.C. § 1532 authorizes the Secretary of Commerce to conduct research on all telecommunications sciences, including wave propagation and reception and conditions which affect electromagnetic wave propagation and reception; preparation and issuance of predictions of electromagnetic wave propagation conditions and warnings of disturbances in such conditions; research and analysis in the general field of telecommunications sciences in support of other Federal agencies; investigation of ionizing electromagnetic radiation and its uses; as well as compilation, evaluation and dissemination of general scientific and technical data when such data are important to science, engineering, industry or the general public and are not available elsewhere (15 U.S.C. § 1532(1)-(7)).

Additionally, NOAA is starting operational ecosystems products in response to the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998. Presently, these products are downstream products produced by post processing marine model output. In the future, some of these models, particularly ecosystems processes associated with ocean color, may become part of an integrated operational environmental modeling system (e.g., internal EMC workshop on ocean modeling, 2007).

Table 6: Non-weather environmental subsystems in PSN.

Subsystem	Year	Month	Week	Day	Hour
Land / Hydro	Y	Y	Y	Y	?
Ocean / Coast	Y	Y	Y/R	S/R	?
Ice	Y	Y	S	?	?
Waves	S	Y	Y	Y	?
Aerosols	S	S	Y	Y	?
Space Weather	?	?	Y	Y	Y

Y: *Present product.* S: *Science benefit for coupling.* R: *Unmet requirement.* ?: *TBD*

Table 6 identifies which environmental subsystems that are already part of the PSN (Y in the Table), or which represent unmet requirements (R in the Table). Furthermore, with respect to coupling, literature shows benefits for some component models not yet in the PSN (S in the Table).

For the subsystems that are already in the PSN or those that should be there (Y and R in Table 6), there are benefits for the initial creation of a one-way coupled system, that is, information in the coupling flowing only from the atmospheric component to the traditional downstream component. There are four benefits for such a one-way coupled approach:

1. It generally increases the time resolution (and reduces errors) of the forcing for the downstream models while reducing I/O needed to force models.
2. It creates a more integrated test environment for holistic evaluation of model upgrades throughout the PSN. Presently, impacts on downstream models are not always assessed adequately in an implementation.
3. It reduces the number of implementations.
4. It creates a natural environment for investigating and implementing benefits of two-way coupling.

For many of the environmental subsystems (Y in Table 6), the costs of coupling will be limited, as the resources needed to run the sub-components are already expended in the PSN (assuming a limited overhead for load balancing between components). For coupled subsystems representing unmet requirements, or with science benefits which are not yet represented in the PSN (R and S in Table 6), adding the new environmental subsystem to the PSN will increase computational costs as they represent new products from new model applications.

There are also negative aspects to coupling, for instance:

1. Individual implementations of coupled systems are more complex than those of traditionally isolated subsystems.
2. There will be less flexibility in tailoring products of subsystems, particularly with respect to run-cadence and forecast range.
3. Development of subsystems needs to be much more rigorously tested in a coupled environment, instead of in a "stand-alone" environment (avoiding unintended consequences of coupling).

In particular with respect to the last point, it is essential to use a modeling architecture that allows for effective development of coupled systems, as well as a capability to use different coupling strategies in different applications of a unified modeling system (see Section 3.4).

Appendix B Other elements in the PSN

When reviewing the present PSN, several products and their applications do not fit seamlessly in the overarching PSN layout of Figure 2.

Hurricane models: The present HWRF and HNMMB hurricane models utilize relocatable telescoping nests to provide the best balance between accuracy of intensity guidance with economy of computation (Zhang et al., 2016, Goldberg et al., 2015, Trahan et al., 2013). Tentatively, these individual telescoping nests for individual tropical storms should be integrated in a global high-resolution model, as is depicted in Figure 2 with the overlapping GFS and Hurricane Nest boxes. Such an approach is under development as part of the Hurricane Forecast Improvement Project (HFIP) and NGGPS (Gopalakrishnan et al., 2016, Gall et al., 2014). It is expected that the WoFS will have similar characteristics as the present hurricane models, and that the technology developed for hurricane models can be leveraged for the WoFS.

Space Weather: Space Weather applications are a relatively recent requirement from the Space Weather Prediction Center (SWPC). The atmospheric components of such models consider model tops well into the ionosphere, where prevalent temperatures and wind speeds result in either very small time steps, or much lower horizontal resolutions than attainable in conventional weather models with lower model tops (Akmaev, 2011). Combining this with a faster model cadence desired for space weather applications (Toth et al., 2012), it becomes prudent to treat the space weather applications for the foreseeable future as a separate application, sharing the weather models with the other global guidance systems in Figure 2. Whereas there may be benefits for integrating space weather applications more fully with the more traditional global applications in Figure 2 (Wang et al, 2014), this should be treated as a potential unification of opportunity, but not as a fundamental goal of the unification of the PSN in the next 10 years. The whole atmosphere / space weather box in Figure 2 is therefore a separate, non-overlapping application.

National Water Model: The National Water Model (NWM), based on the WRF-Hydro hydrologic modeling framework, is a recent addition to the PSN. It has been designed to be compatible with the existing PSN, and with the developing unification of the PSN) (Cosgrove et al., 2016; Givati et al., 2016; Gochis et al., 2015; Lin et al., 2016; Senatore et al., 2015; Xiang et al., 2016; Yucel et al., 2015). The first Initial Operational Capability (IOC) of the NWM was implemented in August 2016. The NWM is inherently regional, but is (intended to be) driven by many global products in the PSN. This makes the initial implementation of the NWM naturally a downstream rather than integrated and coupled element of the PSN. A possible exception is the integration of the relevant parts of the NWM in the RRFS. Considering the developmental status of the NWM, this should be considered a unification of opportunity rather than a fundamental goal in this roadmap. Even with the downstream nature of this model, linkages with NOS coastal models, NWS and NOS storm surge models, and the NWPS with respect to coastal inundation will require continuous coordination to avoid duplication of products and inconsistent products in the PSN. Furthermore, linkage of land model errors with limited hydrological capabilities in present weather models (e.g., presentations at CAWCR, 2015[15]) make the full integration of the NWS in coupled PSN a long-term goal.

Nearshore Wave Prediction System: The Nearshore Wave Prediction System (NWPS) represents a unique on-demand model for guidance for high-impact coastal issues such as waves, inundation (still to be implemented) and rip currents (Van der Westhuysen et al., 2013; Stockdon et al., 2006; Dusek and Seim, 2013). This application is integrated with the PSN through use of upstream products and shared software. While developing a unified PSN, overlap between NWPS, NWM, and NOS/MDL coastal models will need to be addressed continuously via the NOAA Storm Surge Roadmap. Due to its on-demand nature, it is represented as a separate box in Figure 2. Note that the on-demand nature may also need to be re-considered in the context of an efficient unified PSN.

Coastal models: The coastal and port models of NOS similarly have a highly localized nature. Until the initial unification of the PSN is achieved, it is prudent to keep such models as separate downstream models in the PSN, and treat these model as targets of opportunity for coupling / unification where appropriate and feasible, with the exception of unifying all water aspects Coastal Inundation as mentioned above

On-demand Dispersion models: The Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT), developed by NOAA's Air Resources Laboratory, is one of the most widely used models for atmospheric trajectory and dispersion calculations. HYSPLIT is used at NCEP for on-demand response for radionuclide and hazardous material release, volcanic ash as well as for smoke originated from and wind-blown dust, (Stein, et al., 2015). The on-demand nature of these models results in a separate box in Figure 2. Due to international commitments, these models are expected to remain as stand-alone applications in the PSN

NDFD driven downstream models: Starting with the Great Lakes wave models, some traditional "downstream" models in the PSN are alternatively driven by forecaster-

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[15] http://cawcr.gov.au/events/AWS9/CAWCR-workshop-2015-Program1.pdf

produced National Digital Forecast Database (NDFD) winds (Alves et al., 2014). The benefit of such an approach is that downstream models have the maximum consistency with the official weather forecast, and are potentially more accurate. However, the approach becomes more cumbersome in an inherently coupled PSN, and is leading to a proliferation of specialized applications in the PSN. It is not clear what the position of such models will be in a unified coupled PSN (see also NWPS).

Tsunami models: The *Tsunami Warning and Education Act* (P.L, 109-479 Title VIII, January 2007), recently updated as the *Tsunami Warning, Education, and Research Act of 2017* (P.L. 115-25 Title V, 2017) directs and authorizes NOAA to provide tsunami forecasts and warnings. The operational tsunami model used as guidance at the Tsunami Warning Centers is the Method of Splitting Tsunamis (MOST), and is part of the Short-term Inundation and Forecasting for Tsunamis (SIFT) system. This system is presently run completely independent of all other elements of the PSN. The codes have been transitioned to the IPD platform at NCO, but are generally still run operationally at workstations at the Tsunami Warning Centers.

Appendix C PSN Core Elements

C.1. Introduction

Sections C.2 through C.7 describe the six main elements of the consolidation layout of the PSN as outlined in Figure 2 and Table 2. Discussed are the tentative layout, the present status (including mature science finding that drive near-term expansions), and key science questions that need to be addressed in order to implement the element in the consolidated PSN as discussed in Section 4.2.Section C.8 discusses Reforecasts and Reanalyses (RRs), and Section C.9 discusses combined (multi-model) ensembles. Note that (in particular for the GFS and RRFS) the resolution and ensemble membership and subsequent resources needed as discussed in Section 4.2 represent the minimum requirement to simplify the production suite without degrading resolutions and ensemble memberships of existing products in the PSN. Note that the "Year+" range (decadal, centennial etc.) identified in the Strategic Vision document are not run on fixed daily schedules and are therefore not part of the PSN.

C.2. Year range (SFS, seasonal)

Tentative layout: A fully coupled atmosphere, land, ocean, wave, ice and aerosol ensemble model with a typical resolution of approximately 50 km and a forecast range of 9 months, or up to 15 months if evidence proves the value of the extension in forecast range, with an extended ensemble size updating weekly. The weather component will be FV3-based The DA system will move to a more strongly coupled approach. The targeted update cycle for the SFS is four years.

Present status: in the present PSN, the Climate Forecast System (CFS) provides this element. In terms of applications, this part of the PSN is already unified. The CFS typically uses previous generation technology from the Global Forecast System (GFS) and the Global ensemble Forecast System (GEFS). In the PSN layout of Figure 2, development of the various global applications will become a more parallel approach, with the SFS tentatively leading the way with respect to advanced coupling techniques. Mature science indicates that wave coupling needs to be added to improve ocean mixed layer prediction though Langmuir mixing (e.g., Belchar et al. 2012; Sallee et al. 2013; Fan and Griffies 2014).

Key science questions / issues: The following key science questions need to be addressed to guide the development of the SFS:

- *Predictability*; which products have a societal benefit, and scientifically proven value with respect to predictability. The present CFS historically focused on ENSO prediction.
- *Advanced coupling*; the present CFS couples atmosphere, land, ocean and ice. A plethora of potential benefits for more detailed coupling can be found in literature, and need to be assessed in the operational environment, both with respect to the forecast model and with respect to DA.
- *Physics*; include features of physics packages presently used in the mesoscale models in global PSN elements such as the SFS. The benefits to be addressed are improved forecasts in general, and better severe weather outlook products in particular (boundary layer representation, CAPE, Lifted Index, etc.). Additional attention needs to be given to stochastic physics approaches, enabling (together with coupling) realistic spreads of ensemble products.
- *DA*: Quantify the impact of stronger coupled DA.
- *DA*: Does the SFS need it's own DA system, or will it use the SSFS or GFS DA system.
- *Optimum ensemble sizes*. For operations, ensemble sizes have been determined more by available resources than by scientific evidence.

Implementation issues: The new SFS represents a subset of the present CFS products (9 month runs only), and as such is easy to implement. Issues to be addressed with users are reducing the update rate of the products from daily in the CFS to weekly in the SFS. Technical issues to be addressed are where to run this system (i.e., does this need to run on the operational computer if the update cycle is weekly?), and how to deal with the substantial RRs requirements.

C.3. Month range (SSFS, subseasonal / weeks 3 and 4)

Tentative layout: A fully coupled atmosphere, land, ocean, wave, ice (and possibly aerosol) model with a typical resolution of approximately 35 km and a forecast range of 35 to 45 days, with an extended ensemble size updating daily. The DA system will also move to a more strongly coupled approach. The targeted update cycle for the SSFS is two years. The weather component will be FV3-based.

Present status: in the present PSN, the 45-day runs of the CFS provide this element. In the new PSN layout, targeting a coupled extended GEFS to become the starting point for the OFS is preferred as the SFS and SSFS target different model resolutions. The present Global Wave Ensemble System (GWES) will naturally be absorbed in the SSFS, initially in a one-way coupled approach, enabling more strongly coupled future approaches. Ocean and ice components can be taken from the present CFS, but do not yet exist in the extended GEFS environment. Evidence of predictability in this forecast range is scant, with a focus on MJO predictability with coupled models. (Saha et al, 2014). Note that the Office of Science and Technology Policy (OSTP) recently mandated this product range, and its implementation is therefore less evidence-driven than the implementation of most PSN elements.

Key science questions / issues: The key science questions that need to be addressed for the development of the SSFS are similar to those posed for the CFS.

- *Predictability*; Some predictability exists in this forecast range with respect to MJO as mentioned above. For key forecast parameters addressed by CPC (US temperature and precipitation outlooks for weeks 3 and 4) no present predictability is obtained from models. To get to predictability of these parameters is a major science issue.
- *Advanced coupling*; see comments on SFS. Coupled approaches are essential for predictability (e.g., MJO), but maturity of coupled modeling for these time scales may require an IOC with limited coupling. Note that coupling at short forecast ranges might require a hybrid approach where coupling is introduced slowly as the forecast proceeds) (e.g., ECMWF coupling strategy[16]).
- *Physics*; see comments on SFS.
- *DA*: Quantify the impact of stronger coupled DA.
- *DA*: Does the SSFS need it's own DA system, or will it use the GFS DA system.
- *Optimum ensemble sizes*; see comments on SFS.

Implementation issues: The OGS of the unified PSN will be filled by extending the GEFS, while replacing the 45 day runs of the present CFS, and as such is relatively trivial to implement. Technical implementation issues to be addressed are to phase in coupling rapidly but reasonably, and how to deal with substantial RR requirements.

C.4. Week range (GFS, actionable weather)

Tentative layout: The WFS will consist of a global FV3-based 10-13 km resolution ensemble weather model with 21-26 members running a 5-8 day forecast every 6 hours. All other environmental subsystems are at least one-way coupled, and two-way coupled where the scientific benefit is proven. The WFS will become the focal point for global DA efforts. The targeted update cycle for the WFS is annually.

Present status: There is presently no global ensemble at this resolution and forecast range in the PSN. However, there are many weather components in the PSN at these spatial scales and forecast ranges that will be absorbed in the WFS. These are the

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[16] E.g., 2016 Annual Seminar, http://www.emetsoc.org/wp-content/uploads/2016/10/report_ecmwf2016_ruggieri.pdf

deterministic Global Forecast System (GFS), deterministic North American Mesoscale (NAM) parent model, deterministic RAP, and the regional Short Range Ensemble Forecast (SREF) systems, as well as elements of the nested HWRF model. All other environmental subsystems already have components in the PSN, with land models embedded in the weather models, the global Real Time Ocean Forecast System (RTOFS-Global, run daily), the global multi-scale wave model, and an ice model embedded in RTOFS-Global. Aerosols are coupled within the NEMS Global Aerosol Capability (NGAC) with dust predictions provided since 2012 and other aerosols (smoke, sulfates, sea salt) experimentally since 2016 (Lu, et al., 2016). Regional ozone and fine particulate matter predictions are produced from the National Air Quality Forecast Capability, EPA Community Model for Air Quality (CMAQ, Lee, et al., 2016).

Key science questions / issues: The key science questions that need to be addressed for the development of the GFS are somewhat different from those that need to be addressed for the SFS and the SSFS.

- *Ensemble design*; the GFS will consist of a single-core ensemble. At these space scales, it is not yet clear how to develop an ensemble with a reasonable spread. Sensible paths of research include stochastic physics and variability in boundary data obtained by the weather models from other environmental subcomponents. Note that the tentative ensemble size is taken from the SREF, but should be considered systematically.
- *Physics*; see comments on mesoscale physics features for SFS and SSFS, and need for stochastic physics mentioned in the previous bullet. Another issue to be addressed at this scale is the need for scale-aware physics, particularly if unified physics are used throughout the PSN, and if the GFS eventually moves into "grey zone" spatial scales (see also Section 5). Various projects within NOAA are presently addressing scale-aware physics options.
- DA; is there a need / benefit for running DA at slower or faster cadences than 6h. Quantify the impact of coupled DA.
- How will space weather and hurricane science and engineering issues be addressed to possibly merge these two applications with the GFS.

Implementation issues: The new GFS element of the PSN will replace many components of the present PSN. This will be complicated with respect to many aspects of the PSN, and will require a detailed transition plan.

- Users need to transitions from present products to equivalent products from the new GFS. Providing "look-alike" products should be avoided, or provided with limited shelf-life only, because such products have proliferated in the past, and even now represent a significant part of the products provided by the PSN

- The present models with 13km resolution have many downstream dependencies, for instance to provide input data for the NWPS and the High Resolution Rapid Refresh (HRRR) models. While the PSN transitions to its new layout, all these dependencies need to be addressed, either permanently, or for transition purposed only.

Whereas moving from deterministic individual environmental subcomponent to an at least one-way coupled approach is mostly cost-neutral, the introduction of a full ensemble approach is not. This is only partially offset by re-using resources no longer used by the SREF ensemble.

C.5. Day range (RRFS, rapid refresh regional)

Tentative layout: The RRFS will consist of a regional 3 km resolution ensemble weather model with approximately 20 members running an 18h forecast every hour. This creates a Convection Allowing Model (CAM) model ensemble. Two to four times per day, the forecast will be extended to 30h, and two to four times per day, the forecast range will be extended to 60h. This configuration covers all present deterministic mesoscale model products in the PSN, and was suggested by the NWS regional representatives. The RRFS will have its own regional data assimilation scheme, consistent with global DA, and will cover all areas for which the NWS presently has regional products and responsibilities (CONUS, Alaska, Hawaii, Guam, Puerto Rico, and American Samoa). One way coupling to waves, ice and circulation for the Great Lakes will be included, and will be expanded to two-way coupling in the time frame of this strategic plan. The latter is based on the clear benefit of such coupling for “Lake Effect Weather”, as has been demonstrated operationally by Environment Canada for the Saint Laurence Seaway regional coupled model, Smith et al., 2012). The targeted update cycle for the RRFS is annually.

Present status: Presently, the PSN only has deterministic components that are consistent with the envisioned RRFS, These are (i) the High Resolution Rapid Refresh (HRRR) model, running a 3km resolution18h CONUS WRF-ARW forecast every hour, (ii) the NAM nest, running a 3-6km resolution 60h NMMB forecast every 6h for CONUS, Alaska, Hawaii and Puerto Rico, (iii) the HighResWindow model, running a 3-4km resolution 48h NMMB and WRF-ARW forecast every 12h for CONUS, Alaska, Hawaii, Puerto Rico, and Guam, and finally (iv) the FireWXNest, running a 1.5km resolution 36h NMMB forecast every 6h for a placeable 500 km^2 grid. There is presently no ensemble at this scale yet, and the DA approach is significantly less advanced than for the global models with respect to the underlying approaches. Land models are embedded in the above weather models, lake circulation, waves and ice for models are run for the Great Lakes as part of the present PSN as downstream models. EMC, NOS and the Great Lakes Environmental Research Laboratory

(GLERL) are presently developing a coupled circulation-wave-ice model, intended to replace the corresponding uncoupled subsystems in the PSN.

Key science questions / issues: The RRFS largely represents a new ensemble system with many science and engineering questions to be addressed.

- *Ensemble design*; see corresponding issued for GFS ensemble. For the RRFS, the selection of the dynamic core is additional issue. The new dycore selected for the UGCM needs to be tested for applicability of the RRFS scales. As this core is not yet available, the present research is most efficiently done with the WRF-ARW as is the foundation of the HRRR model.
- *Physics*; see corresponding issues for GFS physics.
- *DA*; DA at this resolution is innovative with respect to using radar data, but is in its infancy with respect to basic approaches as used. Approaches for global models, HRRR and NAM models need to me leveraged and merged, resulting in an ensemble hybrid 4dENVAR approach. Much work needs to be done in this field, and uncertainty in the size of the ensembles needed for such a hybrid convection allowing DA approach make costs estimates somewhat uncertain.

Implementation issues: The RRFS aims to replace a set of deterministic CAM products with a full (new) ensemble set of products, as well as with a much more advanced DA approach. This implies a massive increase of required computing resources, tentatively 20 times the resources used by the present HRRR model. Where the RRFS combines a disparate set of previous models, the same transition issues will occur with respect to changing products as was discussed for the GFS. An implementation issue unique to the RGS is the need for unifying the dynamic core, either by going to a single meso scale model (WRF-ARW), or in adopting the new global FV3 dynamic core directly in the meso applications. Note that as long as the underlying model has not been selected, it is prudent to focus development on model-agnostic research topics.

C.6. Hour range (WoFS, Warn on Forecast regional)

Tentative layout: 1 km resolution 5-15’ cadence ensemble forecasts of 3-6 hours with a placeable and possibly moving nest (see Section 4), with initial and boundary conditions from the RRFS, and additional assimilation of in particular radar data.

Present status: Research and development is in progress through the Warn of Forecast Program.

Key science questions / issues: See present status. Some of the key science questions being addressed include:

- Determine whether a variational, ensemble-based, hybrid, or other data assimilation method yields the best convective-scale analyses and forecasts.
- Evaluate sensitivities to model resolution and how to optimize capabilities for predicting specific convective hazards given the resolution that resources will allow.
- Reduce model error by improving parameterizations of the cloud microphysical processes.

Implementation issues: Not to be considered until the end of the period addressed by this strategic plan due to maturity of science and technology, as well as required computer resources. Nevertheless, the strong requirement for these products justify a strong emphasis on developing these products, as an economical relocatable on-demand application.

C.7. Now range (analyses)

Tentative layout: traditional, usually global analyses such as the Real Time Global Sea Surface Temperature (RTGSST) and ice concentration analyses used as model input and for model validation, For the focus are of the NWS, the Rapidly Updated Analysis will provide a three-dimensional CAM resolution atmospheric analysis at time intervals as short as 5-15 min (i.e. analysis is perform as soon as new Doppler Radar observations are available).

Present status: RTGSST and ice products are produced once per day, and do not include diurnal information. The Real Time Mesoscale Analysis (RTMA) and UnRestricted Mesoscale Analysis (URMA) provide high-resolution (sensible weather) analyses for CONUS, Alaska, Puerto Rico, Hawaii and Guam every hour. The Multi-Radar Multi-Sensor (MRMS) system processes and maps 88D Doppler radar data into CONUS domain mosaics every 2 minutes. NCEP's SPC produces its own mesoscale analyses during severe weather season while NCEP's WPC continues the long tradition of producing analysis "charts". Aviation threat conditions are now diagnosed & 'analyzed' by algorithms running regularly at NCEP's AWC and on NCEP's WCOSS by EMC [WAFS] & MDL [LAMP] and producing gridded fields of icing, turbulent and convective conditions for domestic and international domains. AWC runs Helicopter and Emergency Medical Support (HEMS) which seeks to provide the best depiction of atmospheric conditions (especially cloud ceiling and visibility) for these critical flights. NCEP/EMC's Rapid Update-RTMA (RU-RTMA) will soon provide HEMS with 15 minute updates and has the goal of making 5 minute updates by 2019.

Key science questions / issues: The global, slow cadence products are well established. The RUA represents a new technology that is not yet in the PSN, with the following science and engineering question:

- Should the RTMA evolve into a RUA, or should the RUA be developed in parallel. The focus is presently on the former.
- The RUA will present unique engineering challenges due to the need for a very short latency to make a 15 min or faster update useful.
- There is a social science challenge associated with all analyses as forecasters want to see analyses that fit observations exactly, whereas scientists acknowledge unavoidable errors in both observations and analyses, and hence expect analyses ***not*** to represent data exactly.

Implementation issues: The RUA represents a new capability that will need to be resourced properly. A challenge for unifying the PSN is that systems like MODIS provide both data processing and analysis. In a Unified PSN, data processing and analyses should be separated, with the analyses products gathered into a single RUA (or unified global) approach.

C.8. Reforecast and reanalysis

Tentative layout: RRs are made for all key elements of the Unified PSN, with a focus on model calibration and correction for the longer time scale, and on model validation and interpretation for shorter time scales. For longer time scales, a distinction needs to be made for RRs for calibration, which can be done with relatively small RRS (Hamill et al., 2014), and reforecasts for validation and IDSS support, which require much larger RRs (Brown, 2015).

Present status: the CFS comes with a complete RR (Saha et al. 2010), and the GEFS has a "one-off" reforecast (Hamill et al., 2013). Other components have extensive retrospective testing, but this is presently done in a deterministic way, not as a RR ensemble.

Key science questions / issues: The RRs still largely represents a new element of the PSN with many science and engineering questions to be addressed.

- Should /can RRs be done in real time ("on the fly") or should they be completed off-line before implementation of the corresponding element in the PSN?
- General ensemble generation with proper spread based on single core components with stochastic physics in the atmosphere and perturbed coupled NEMS components is preferable, but still need massive scientific development work/

- Presently IDSS reanalyses requirements are associated with brute force reanalyses, i.e., using a high and constant temporal sampling rate. Experience with other fields of sampling and optimization suggests that smart, dynamic sampling can massively reduce the size of ensembles. Initiating research into dynamic sampling for RRs is essential for economic feasibility.

Implementation issues: The RRs are not a traditional ***operational*** element of the real-time operational PSN. It should be run on dedicated computing resources, that can be significantly cheaper than the WCOSS and its successors, since the availability requires for RRs are much more lenient than for the conventional PSN. For the longer time scale forecasts, RRs are essential for model validation and correction, and the associated resources need to be planned rigorously to assure minimal and predictable impact on the implementation schedules. Due to their size, it may not be able to do IDSS reforecasts for every model upgrade. It is essential, however, to do smaller calibration RRs for each implementation.

C.9. Combined ensembles

Tentative layout: The present PSN includes multi-model ensembles built from contributions of different organizations, and blended model products. In the PSN, maintaining multi-model ensembles such as the SREF can only be justified from a business perspective if the scientific evidence does not support single-model ensembles. Multi-model ensembles where multiple organizations combine the single-model ensembles in a cross-organizational multi-model ensemble, however, do provide a viable long-term business model for high fidelity, large membership ensembles. The latter is particularly true if this approach is implemented with shared modular modeling components as is envisioned in the National ESPC.

Present status: The present PSN contain the North American Ensemble Forecast System (NAEFS) and the NCEP FNMOC Wave Ensemble System (NFWES). Both systems either have, or are intended to have contributions from NCEP, Navy and Environment Canada (operational) model. Since 2006, the NAEFS combines state of the art weather forecast tools, called ensemble forecasts, developed at the US National Weather Service (NWS) and the Meteorological Service of Canada (MSC). When combined, these tools (a) provide weather forecast guidance for the 1-14 day period that is of higher quality than the currently available operational guidance based on either of the two sets of tools separately; and (b) make a set of forecasts that are seamless across the national boundaries over North America, between Mexico and the US, and between the US and Canada. The National Blend of Models is developing a complete set of post-processed guidance for NDFD weather elements by leveraging evolving state of the science data assimilation analyses, ensemble systems and statistical post-processing techniques to remove bias, produce reliable probabilistic output and make the forecast guidance more useful.

Key science questions / issues: Design have, and optimal merging of multi-model ensembles.

Implementation issues: The existing ensembles represent a small commitment in CPU time as it represents post-processing only of existing model output, but does require a significant disk-space commitment, dedicated connectivity and bandwidth between collaborating organizations, and human resources. With the focus of the NWS on reliable, timely and on-time delivery, reliable connectivity and delivery times from external contributors is and will be critical.

Appendix D Holistic Computing Needs

Table 2 on page 22 presents a layout of major elements in the consolidated PSN to be achieved in 5 years, with computing costs per element presented in Table 3. Using estimates presented in the latter Table, computer resources needed for the full Unified PSN can be estimated and are presented in Table 7. This Table accounts for PSN elements other than the elements represented in Table 2 (e.g., the NWM) and accounts for the fact that only a fraction of peak performance can be used for sustained computing. These values are based on current application performance and assume no performance improvements in the models' software. PSN models may not be able to leverage anticipated performance improvements in future HPC architectures without a significant code revision.

Table 7: Total computing needs in peak PFLOP for NOAA for full support of PSN

Ops	Backup	T2O	R&D	RR	Total
37	37	73	245	28	419

In Table 7 "**ops**" represents the operational supercomputer and "**backup**" the full operational backup as mandated by the Department of Homeland Security (Department of Homeland Security, Federal Continuity Directive 1: Federal Executive Branch National Continuity Program and Requirements, Annex G, October 2012). To fully support "**ops**", Transition to Operations (T2O) requires 3 times the computing resources of the operational machine, of which "**backup**" provides 1 factor and the "**T2O**" column represent the remaining 2 factors. Additional columns in Table 7 represent Research and Development ("**R&D**") preparatory to T2O, and the emerging need for dedicated resources for the RR requirements ("**RR**").

Table 7 provides a unique holistic view of computing needs for NOAA with respect to the PSN. Note that it is essential to balance these computing needs with sufficient storage (real-time and archiving) and bandwidth to move the resulting data[17].

Similar estimates of computational requirements have been performed for the moonshot configuration, but have not been reproduced here. It suffices to say that the moonshot configuration will require 8-10 times more computing than is required for the configuration analyzed in more detail here.

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[17] Note that on the present NOAA high performance computers (HPC), I/O interference between models run side-by-side, disk storage and bandwidth are clearly limiting the full use of the HPC.

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Appendix F Glossary

3dENVAR	Hybrid Ensemble 3-D Variational data assimilation
4dENVAR	Hybrid Ensemble 4-D Variational data assimilation
AFSO	Analysis, Forecast and Support Office (NWS)
ARL	Air Resources Laboratory (OAR)
AWC	Aviation Weather Center (NWS/NCEP)
BUFR	Binary Universal Form for the Representation of meteorological data
CaRDS	Capabilities and Requirements Decision Support
CAM	Convection Allowing Model
CAPE	Column Available Potential Energy
CCPP	Community Common Physics Package (DTC)
CESM	Community Earth System Model (UCAR)
CFS	Climate Forecast System
CFSRR	Climate Forecast System Reforecast and Reanalysis
CICE	Los Alamos Sea Ice Model
CLUE	Community Leverages Unified Ensemble
CONUS	Continental United States (lower 48 states)
CO-OPS	Center for Operational Oceanographic Products and Services (NOS)
CPC	Climate Prediction Center
DA	Data Assimilation
DHS	Department of Homeland Security
DTC	Developmental Testbed Center (NCAR)
DoD	Department of Defense
DoE	Department of Energy
ECMWF	European Centre for Medium Range Weather Forecasting
ENSO	El Niño Southern Oscillation
ESMF	Earth System Modeling Framework
ESRL	Earth Systems Research Laboratory (OAR)
FNMOC	Fleet Numerical Meteorological and Oceanographic Center
GDAS	Global Data Assimilation System for the atmosphere
GEFS	Global Ensemble Forecast System
GFS	Global Forecast System
GFDL	Geophysical Fluid Dynamics Laboratory (OAR)
GOCART	Goddard Chemistry Aerosol Radiation and Transport air quality model
GRIB	GRIdded Binary (WMO data format)
GSI	Gridpoint Statistical Interpolation DA software
GWES	Global Wave Ensemble System
HDF	Hierarchical Data Format
HFIP	Hurricane Forecast Improvement Project
HNMMB	Hurricane NMMB model

HRRR	High Resolution Rapid Refresh deterministic mesoscale weather model
HWRF	Hurricane WRF model
HWT	Hazardous Weather Testbed
HYCOM	Hybrid Coordinate Ocean Model
IDSS	Impact-based Decision Support Services
IOC	Initial Operational Capability
IPD	Interoperable Physics Driver
JCSDA	Joint Center of Satellite Data Assimilation
JEDI	Joint Effort for Data assimilation Integration (JCSDA)
KISS	Keep Ice’S Simplicity ice model
LAMP	Localized Aviation MOS Program
LANL	Los Alamos National Laboratory (DoE)
MAG	Models Analysis and Guidance website (NCO)
MDL	Meteorological Development Laboratory (NWS)
MET	Model Evaluation Tool (NCAR)
MODE	Method for Object-Based Diagnostics Evaluation
MOST	Method of Splitting
MJO	Madden-Julian Oscillation
MOM	Modular Ocean Model
NASA	National Aeronautics and Space Administration
NDFD	National Digital Forecast Database
NIDIS	National Integrated Drought Information System
NOAA	National Oceanic and Atmospheric Administration
NAM	North American Mesoscale regional model
NAEFS	North American Ensemble Forecast System
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCO	NCEP Central Operations
NDFD	National Digital Forecast DAtabase
NEMS	NCEP Environmental Modeling System
NESPC	National Erath System Prediction Capability
NetCDF	Network Common Data Form
NFWES	NCEP FNMOC Wave Ensemble System
NGGPS	Next Generation Global Prediction System
NHC	National Hurricane Center
NOMADS	NOAA National Operational Model Archive & Distribution System
NOS	National Ocean Services (NOAA Line Office)
PSN	NCEP Production Suite
NUOPC	National Unified Operational Prediction Capability
NWM	National Water Model
NWPS	Nearshore Wave Prediction System
NWS	National Weather Service (NOAA Line Office)
NUMTF	NOAA Unified Modeling Task Force (NOAA RC)

NUOPC	National Unified Operational Prediction Capability
OAR	Oceanic an Atmospheric Research (NOAA line office)
OPC	Ocean Prediction Center
OPeNDAP	Open-source Project for a Network Data Access Protocol
OSTI	Office of Science and Technology Integration (NWS)
OSTP	Office of Science and Technology Policy (White House)
OWP	Office of Water Prediction (NWS)
PSN	Production Suite at NCEP
R&D	Research and Development
RAP	Rapid updating low-resolution mesoscale model providing boundary data for the HRRR.
RC	NOAA's Research Council
RRFS	Rapid Refresh Forecast System
RRs	Reforecasts and Reanalyses
RTGSST	Real Time Global Sea Surface Temperature
RTMA	Real Time Mesoscale Analysis
RTOFS	Real-Time Ocean Forecast System
RUA	Rapidly Updated Analysis
S3FS	Seasonal and Sub-Seasonal Forecast System
SIFT	Short-term Inundation and Forecasting for Tsunamis
SIP	Strategic Implementation Plan
SIS2	Sea ice Simulator 2 ice model
SFS	Seasonal Forecast System
SOLAS	Safety of Life at Sea.
SV	Strategic Vision
SPC	Storm Prediction Center (NWS/NCEP)
SREF	Short Range Ensemble Forecast regional model system
SSFS	Subseasonal Forecast System (week 3-4)
SST	Sea Surface Temperature
SWAN	Simulating Waves Nearshore wind wave model
SWPC	Space Weather Prediction Center (NWS/NCEP)
T2O	Transition to Operations
THREDDS	Thematic Realtime Environmental Distributed Data Services
UCACN	UCAR Community Advisory Committee for NCEP
UCAR	University Corporation for Atmospheric Research
UDA	Unified Data Assimilation
UFS	Unified Forecast System
UGCM	Unified Global Coupled Model
UMAC	UCACN Model Advisory Committee
UPP	Unified Post Processor
URMA	UnRestricted Mesoscale Analysis
V&V	Validation and Verification
WAFS	World Area Forecast System
WCOSS	Weather and Climate Operational Supercomputing System
WMO	World Meteorological Organization
WoFS	Warn on Forecast System

WRF	Weather Research and Forecasting mesoscale atmospheric model	WW3	WAVEWATCH III wind wave model

Appendix G Revision History

Date	Ver.	Author/Editor	Comment
Aug. 2018	1.0.3	Hendrik Tolman John Cortinas	Final version 1.0
Oct. 2018	1.0.4	Hendrik Tolman	Updated signature page
Feb. 2020	1.0.5	Hendrik Tolman	Minor updates for additional signatures