Project Plan and Charter for Global Forecast System (GFS) v17.0.0

by

NCEP/Environmental Modeling Center

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1 Introduction

The National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) has the responsibility to provide weather, water, and climate information to protect life and property, and enhance the national economy. The NWS mission is to provide the best possible guidance to a wide variety of customers, including emergency managers, forecasters, and the aviation community. The Environmental Modeling Center (EMC) of the National Centers for Environmental Prediction (NCEP)'s fundamental mission to is to, in close collaboration with our partners and stakeholders, maintain, enhance, and transition to operations advanced numerical guidance systems for the Nation's weather/water/climate enterprise and the global community for the protection of life and property and the enhancement of the economy. The mission objectives include being one of the world's best and most trusted providers of deterministic and probabilistic forecast guidance across all spatial and temporal scales.

In 2015, the UCAR Community Advisory Committee for NCEP (UCACN) Modeling Advisory Committee (UMAC) performed an external review of the NCEP production suite. Their report contained several key recommendations for different organizational and application areas of production suite development (https://www.ncep.noaa.gov/director/ucar_reports/ucacn_20151207/UMAC_Final_Report_20151207-v14.pdf). The key recommendation driving the strategy for EMC's future model development is to "**Reduce the complexity of the NCEP Production Suite**". EMC has since committed itself to unifying the production suite under the umbrella of the Unified Forecast System (UFS), consisting of a shared set of community developed components. Using the UFS as a basis, 10 application areas were identified for the future modeling systems, spanning a variety of spatial and temporal scales as well as Earth system components, from the atmosphere to lakes and hydrology to space weather:

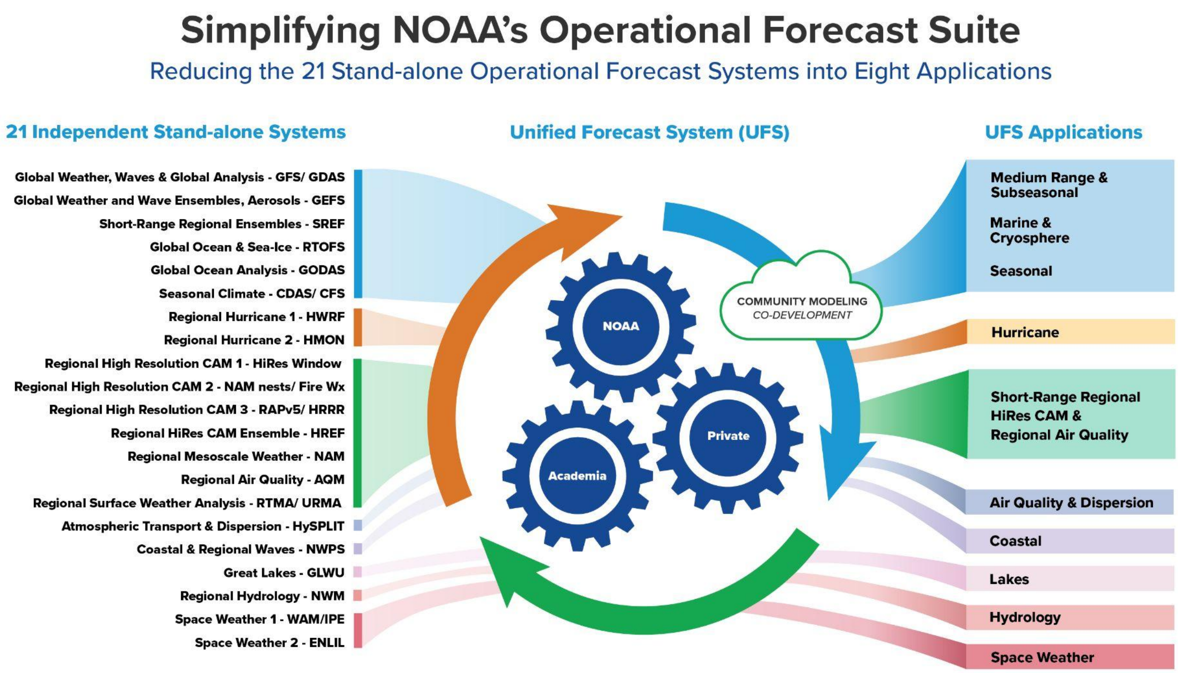

Figure 1: Schematic representation of the simplification of the NCEP Production Suite. The Global Forecast System and Medium Range Weather application are depicted in blue. (Uccellini et al, in review for BAMS)

As of January 2023, the production suite consists of 21 separate modeling systems, with each system containing individualized components, i.e. each system contains its own workflow infrastructure, verification tools, and post processing software. The new UFS applications will pull from a shared set of tools and components, many of which are community developed. This drastically reduces the amount of software that will need to be maintained moving forward. Different models will be brought more into alignment with each other, not just in a code management or graphical sense, but also in a scientific one, bringing more consistency between the products that NCEP distributes. One of the ten identified application areas is Medium Range Weather (MRW), the first application released to the UFS community. This application will be the target for future Global Forecast System (GFS) implementations, subsuming other global modeling systems, such as RTOFS and GODAS, as components are merged and coupled.

This paradigm shift in development addresses another UMAC recommendation: "**NOAA needs to better leverage the capabilities of the external community**." Contributions in the development of the UFS are coming from many types of members of the community, including other labs and centers within NOAA (e.g., GSL, PSL, GFDL, AOML, ARL, CSL, SWPC), NCAR, the private sector, and academia. Public releases and user workshops will accelerate the ability of community members to get acquainted with various UFS components, allowing them to contribute to development more rapidly.

While there have and will continue to be many community contributions to the UFS MRW, EMC ultimately has the responsibility to prepare and evaluate implementation packages for the GFS, continually upgrading the system on a periodic basis to meet customer requirements. The frequency of implementation upgrades is limited by both computational and human resource constraints for testing, evaluation, and impact on downstream models and applications.

This project plan fulfills another recommendation from the UMAC report: "**Execute strategic and implementation plans based on stakeholder requirements**." Section 2 contains details on requirements gathering along with an overview of the GFS and its recent implementations. Descriptions of potential upgrades for each model component (model, data assimilation, workflow, and CONOPS) as well as potential upgrades to products are discussed in Sections 3 and 4, respectively. Implementation timelines, including development phases and milestones, are covered in Section 5 with computational estimates being provided in Section 6. The document closes with a discussion of Roles and Responsibilities in Section 7 and Project Risks and Management in Section 8. This document does not cover the planning for other connected projects directly, such as the Global Ensemble Forecast System (GEFS), but it notes where overlap between these projects occur.

2 GFSv17

2.1 GFS Overview

The GFS is NOAA's premier global numerical weather prediction system and provides initial and boundary conditions for many other models in NCEP's production suite, including atmospheric models for different scales (HRRR, HMON) and models for other components of the Earth system (NWM, WAM). Originally based on the Global Spectral Model, the GFS incorporated the Finite-Volume Cubed-Sphere (FV3) dynamic core in 2019, developed by Princeton's Geophysical Fluid Dynamics Laboratory (GFDL) under NOAA's Office of Atmospheric Research (OAR). With the adoption of the FV3, GFS became the first of NCEP's applications to move towards the UFS-community paradigm. Since then, the system continues to pave the way for new UFS capabilities and collaboration, from the use of github and public releases to prototype evaluation.

The deterministic atmospheric component of the GFS runs at ~13 km horizontal resolution (C768) out to 16 days with a cycling cadence of every 6 hours. There is also a data assimilation (DA) ensemble of 80 members at ~25 km resolution (C384) that runs out to 9 hours. This ensemble is utilized by the hybrid 4DEnVar deterministic analysis, computed at the same resolution as the ensemble. A subset of the DA ensemble is used to initialize the Global Ensemble Forecast System (GEFS), albeit after some additional processing and interpolation. In 2021, the vertical resolution was nearly doubled, increasing the number of vertical layers from 64 to 127. The same vertical resolution is used in both the deterministic and DA ensemble forecasts. The atmospheric component is also one-way coupled to the Global Wave Model (WAVEWATCHIII), which is unified with the formerly separate multi_1 system, producing a 16 day forecast. The GFS also contains the Global Land DA System (GLDAS) which uses CPC gauge precipitation data to spin up the land states for the 00z GDAS cycle each day.

2.2 Requirements

The targeted scientific advancements for GFSv17 include interactive coupling of atmospheric model with ocean, sea-ice, and waves, advanced physics, improved data assimilation with potential transition from GSI to JEDI, and consolidation of NCEP production suite through combining GODAS with GFS, the retirement of NAM and RAP and to streamline UFS based coupled model development for MRW applications. In addition to general system improvements, specific focus will be to improve on the known issues with GFSv16.

2.3 Known Strengths and Deficiencies of GFSv16

A major upgrade to the Global Forecast System and Global Data Assimilation System was implemented operationally on March 22, 2021 as version 16.0. The main feature of this upgrade was the increase in vertical resolution, from 64 layers to 127 layers, and a raising of the model top, from ~54 km to ~80 km. Along with advancements in the model physics as well as the data assimilation and initialization, the atmospheric model exercised one-way coupling to the Global Wave Model for the first time (additional details can be found at https://www.emc.ncep.noaa.gov/users/meg/gfsv16/pptx/CCB_9-30-20_GFSv16_Full.pdf). Almost two years of retrospective and real-time experiments, including three hurricane seasons, were run at full resolution and evaluated to provide a comprehensive statistical analysis of the upgrade's performance as compared to the existing operational model. The Model Evaluation Group (MEG), as part of EMC's Verification, Post-Processing and Product Generation (VPPPG) Branch, led an independent evaluation effort, including a rigorous examination of numerous case studies throughout the retrospective period. Details of the MEG's evaluation can be found at https://www.emc.ncep.noaa.gov/users/meg/gfsv16/.

As summarized by the MEG, several areas of improvement were found in the v16 atmospheric forecasts compared to v15:

- Notable improvements in synoptic-scale performance in the medium-range
  - Progressive bias in GFSv15 appears mitigated with better consistency catching correct solutions earlier
  - Improved frontal positions and QPF
- Improvement in low-level temperature forecasts (mitigation of the winter low-level cold bias)
- Better ability to resolve shallow, cold air masses and some associated cold air damming events
- Improvements to TC intensity and increased lead time for genesis
- With stronger TCs, GFSv16 has overall better track, size, and intensity

However, the MEG also highlighted deficiencies in the atmospheric forecasts compared to v15:

- Increased right-of-track bias at longer lead times for North Atlantic TCs
- Larger TC False Alarm Rate (FAR) in the western North Atlantic (70°W–50°W)
- Tendency to strengthen all TCs in the long range (pre-formation, not in stats)
- Exacerbation of low instability (i.e., CAPE) bias that already existed in GFSv15, driven largely by dry soil moisture (Note, a joint mitigation plan was developed by EMC and SPC to 'identify, ameliorate, and re-evaluate the low bias of CAPE in GFSv16').
- Lack of considerable improvement in forecasting radiation inversions

The wave model component of GFSv16 showed improvements over the previous deterministic operational wave model multi_1:

- Globally GFSv16 has lower bias and RMSE for significant wave height compared to multi_1.

The evaluation and subsequent feedback revealed a few concerns in the performance of the wave model component of GFSv16:

- Low bias in large-amplitude wave heights. (Note, a joint mitigation plan was developed by EMC and OPC to 'identify, ameliorate, and re-evaluate' this issue.)
- Ice coverage in the ice analysis where no ice is present has caused downstream wave model performance issues where the wave heights are too low in multiple cases.
- Consistently low swell fields have been observed in the Pacific, which also has had downstream impacts in NWPS.
- The removal of the 4 arcmin grids caused gaps in downstream model coverage areas for NBM and was the source of forecaster concern. Additionally, it is suspected that some degradation compared to multi_1 can be attributed to the high resolution grid removal.

2.4 Expected Benefits from GFSv17

The ultimate goal of this project is to implement upgraded GFSv17 into operations that will provide improved forecast guidance, demonstrated through evaluation of multi-year retrospective and real-time experiments compared against GFSv16. The evaluation will be based on objective and subjective metrics that will document maintaining or improving on existing strengths, while attempting to address known deficiencies noted in the GFSv16 configuration listed below.

Atmosphere and land:

- Removal of the negative tracer values that occurred from the PBL and convection schemes
- Improvement of forecasts of low-level inversions
- Enhancement of the underestimated surface-based convective available potential energy (CAPE)
- Reduction of the nighttime cold 2m temperature biases over CONUS forested regions
- Reduction of the CONUS 10m wind speed biases
- Improved representation of land physics and its interaction with the atmosphere

- Improved forecast of cloud hydrometers especially for mixed-phase clouds and supercooled liquid clouds
- Improvement of the Madden-Julian Oscillation (MJO) intensity and propagation

Wave:
- Address low bias in high amplitude wave events
- Improved swell forecasts in the Pacific which have been observed to be too low and have a negative impact on the downstream boundary conditions to NWPS.
- Will consider increasing the global resolution or adding high resolution coastal nests as resources are deemed scientifically beneficial and computational resources allow.

GFSv17 is planned to be a coupled model including ocean and ice components. In addition to continuing to streamline the production suite this will provide a more consistent deterministic forecast for all included components. Based on the implementation of coupled models at ECMWF[1,2,3], UKMet[4] and ECCC[5] for medium range weather forecast systems, we expect the impact of coupling to improve air-sea interaction, atmospheric dominant modes especially atmospheric waves in the tropics, general medium-range weather forecast large-scale flow patterns and to have positive impacts on forecasts of tropical cyclones.

3 System Upgrades

3.1 Coupled Model and Component Upgrades

In GFSv17, we will have a coupled model consisting of the atmosphere, land, ocean, ice and wave components. If resources allow and results support its inclusion, the GOCART aerosol component can also be included in the coupled model, computing prognostic aerosols and potentially feedback to the atmospheric radiation. In the subsections below, potential upgrades for the atmosphere, land and wave components are given, followed by descriptions of the new ocean and ice component, and lastly a description of the full coupled model. Infrastructure details for the model can be found in Section 3.3.1.

3.1.1 Atmospheric Component (Dynamics and Physics)

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[1] Buizza, R., et al. "IFS upgrade brings more seamless coupled forecasts." *ECMWF Newsletter* 156.10 (2018).
[2] Mogensen, K., et al. "Effects of ocean coupling on weather forecasts." *ECMWF newsletter* 156 (2018).
[3] Mogensen, K., L. Magnusson, J.-R. Bidlot & F. Prates. Ocean coupling in tropical cyclone forecasts. *ECMWF Newsletter* No. 154 (2018).
[4] Vellinga, M., et al. (2020). Evaluating Benefits of Two-Way Ocean–Atmosphere Coupling for Global NWP Forecasts, *Weather and Forecasting*, *35*(5), 2127-2144. Retrieved Nov 3, 2022, from https://journals.ametsoc.org/view/journals/wefo/35/5/wafD200035.xml
[5] Smith, G. C., et al. (2018). Impact of Coupling with an Ice–Ocean Model on Global Medium-Range NWP Forecast Skill, *Monthly Weather Review*, *146*(4), 1157-1180. Retrieved Nov 3, 2022, from https://journals.ametsoc.org/view/journals/mwre/146/4/mwr-d-17-0157.1.xml

There is no planned significant atmospheric dynamics upgrade. An increase of model resolution from C768 (~13km) to C1152 (~9km) could be possible. Some changes to the damping scheme are being tested to improve ensemble forecast spread in the upper atmosphere, but this update may take more time and not be ready for GFSv17.

The current Interoperable Physics Driver (IPD) framework is replaced by the Common Community Physics Package (CCPP) framework. The CCPP is “designed to facilitate the implementation of physics innovations in state-of-the-art atmospheric models, the use of various models to develop physics, and the acceleration of transition of physics innovations to operational NOAA models”[6].

Most components of the GFSv17/GEFSv13 physics package plan to be either updated or upgraded with more advanced physics parameterizations. In particular, GFDL cloud microphysics (MP) scheme and Noah Land Surface Model (LSM) will likely be replaced by the Thompson MP scheme and Noah-multiparameterization (Noah-MP) LSM, respectively. New small-scale gravity wave drag and turbulence form drag will also likely be included. Details about the potential upgrades are described below.

- Planetary boundary layer (PBL: sa-TKE-EDMF):
    - Implementation of a positive definite mass-flux (MF) transport scheme and a method for removing negative tracer mixing ratio values
    - Suppression of PBL overgrowth
    - Improvement of surface inversion forecast
    - Reduction of excessive vertical turbulence mixing in stronger wind shear environment

- Surface layer:
    - Implementation of a new sea spray parameterization
    - Implementation of a new stability limit as a function of background diffusivity
    - Calling the surface layer scheme within the Noah-MP land surface model.

- Cumulus (Cu) convection (Deep Cu: sa-SAS; Shallow Cu: sa-MF):
    - Implementation of a positive definite MF transport scheme and a method for removing negative tracer mixing ratio values
    - Enhancement of the underestimated convective available potential energy (CAPE) with more strict convection trigger
    - Reduction of the tropospheric cold temperature biases with reduced rain evaporation
    - Enhanced downdraft detrainments starting from 60 hPa above the ground surface
    - Modification of cloud depth separating shallow convection from deep convection

[6] https://dtcenter.org/community-code/common-community-physics-package-ccpp

    - Implementation of a stochastic convective initiation and organization based on cellular automata (CA)

- Microphysics:
    - Replacing GFDL MP scheme with Thompson MP scheme
    - An innerloop is added in the Thompson MP to improve the stability of the scheme when a relatively large time step is used.
    - A Semi-Lagrangian sedimentation technique is added in Thompson MP and applied to rain and graupel to reduce computational cost and improve computational instability.
    - The ice to snow conversion threshold is modified to increase ice and improve the radiative fluxes at the top of the atmosphere.
    - Updated diagnostic cloud fraction scheme to improve cloud cover and radiative fluxes.

- Gravity wave drag (GWD):
    - Implementation of a new small-scale gravity wave drag parameterization
    - Implementation of a new turbulent orographic form drag scheme
    - Code unification and updates of orographic GWD, mountain blocking, and non-stationary GWD

- Radiation:
    - The current RRTMG will possibly be replaced by RRTMGP, which is written with modern Fortran language and has more spectral bands and improved accuracy. RRTMGP has a much higher computational cost and may not be implemented until the next upgrade unless sufficient optimization is realized.
    - Streamlined and unified the coupling of radiation with clouds from different cloud microphysics schemes.

- Aerosol:
    - The old coarse resolution 5° x 5° Optical Properties of Aerosols and Clouds (OPAC) data is replaced by 0.5° x 0.625° MERRA-2 aerosol climatology.

- Miscellaneous:
    - Developed new approaches for computing surface flux exchange coefficient, albedo and emissivity over fractional grid covered by fractional land, ice, and/or water bodies.
    - Replaced CFSR ice climatology with high-res (0.05°) climatology for ocean and lakes merging 4-km NIC Northern Hemisphere IMS climatology and 10-km NIC Southern Ocean Ice Climatology
    - Updated momentum roughness over ice
    - Updated surface cycle for fractional grid

3.1.2 Land Model

The land surface model (LSM) is changed from the Noah LSM to the Noah-MP LSM. Noah-MP is a community-based model that was developed specifically to address known limitations of the Noah LSM (used in GFSv16) and to allow multiple options for key land-atmosphere interactions. It improves upon Noah in multiple ways. For example, it uses

(1) a tiled approach to separate vegetation and bare soil,
(2) improved stomatal resistance/photosynthesis treatments,
(3) a dynamic vegetation scheme,
(4) a multi-component, separate vegetation canopy,
(5) a two-stream canopy radiative transfer approach along with shading effects and under-canopy snow processes,
(6) a multi-layer snow pack with liquid water storage and melt/refreeze capability and a snow-interception model describing loading/unloading, melt/refreeze capability, and sublimation of canopy-intercepted snow,
(7) groundwater transfer and storage including water table depth to an unconfined aquifer.
These additional features have the potential to significantly improve the realism of the land surface, hydrology, and atmosphere interactions.

In addition, vegetation type in both GFSv17 and GEFSv13 was updated from MODIS to VIIRS, and land-sea mask was created using the VIIRS dataset. Fractional land-sea masks were introduced to GFSv17 and GEFSv13.

3.1.3 Wave Component

With the inclusion of coupled ocean/ice models, there will be changing sea-ice concentrations in the wave model input and the current inputs will come from the coupled ocean component instead of RTOFS. The resolution of the ocean current input could impact wave model results. The initial conditions for the GFS forecast will remain unchanged from v16 where initial conditions are generated from the self cycled GDAS forecasts. Additionally, higher resolution grids along the coastlines and a possible global increase in model resolution will be explored for this upgrade. The limitations will be to show improved skill and not exceed available computational resources.

The action plan for the wave component upgrades for GFSv17 can be found here. In broad terms the major actions are as follows:

- Determine which choices of grids are technically feasible given development timelines and computational resources.
- Create a model validation package to be used for grid choice and model development.
- Determine which grid configuration scientifically is the best choice within the constraints of human and computational resources.

- Optimize the physics parameters for the chosen grid (or top candidates).
- Complete any model development required for GFSv17 (some items can be completed in parallel to the above three items) including making sure the wave component is in compliance with EE2.

3.1.4 Introducing Ocean Component

The ocean component is the Modular Ocean Model (MOM6). MOM6 is a community-based model which is developed jointly by GFDL, NCAR, NCEP, FSU and several other developers. Major features in MOM6 consist of (1) using C-grid which is preferred for simulations of mesoscale eddy field, (2) using the Arbitrary Lagrangian Eulerian (ALE) algorithm which allows the usage of a variety of vertical coordinators, and (3) the implementation of vertical ALE makes the model unconditionally stable in thin layers removing the CFL restriction on time step and thus allowing the use of vertical high-resolution coordinates with reasonable computation cost. A 0.25° tripolar grid is employed with 75 vertical layers. The physics package for MOM6 in GFSv17 will follow GFDL MOM6-examples OM4.0 settings which have been tested extensively among the MOM6 community.

3.1.5 Introducing Sea-Ice Component

The sea ice model is CICE version 6, CICE6. CICE is developed and maintained by the CICE consortium, which is a group of the main stakeholders and developers of the model. The CICE model uses the same 0.25° tripolar grid as the ocean model. In GFSv17, we plan to use 5 thickness categories and Mushy thermodynamics. Possible updates include using the C-grid version.

3.1.6 Model Coupling

In GFSv17 coupled model configuration, the wave model and the atmospheric model each have their own grids and the ocean and ice components are on the same tripolar grid. The atmospheric model uses the ocean land/sea mask by allowing grid cells to contain partial land (land fraction must be greater than 0.01%). Internal atmospheric fluxes on a grid cell are calculated on the surface by weighted averages of fluxes over land, open water, and sea ice. In this coupled model, atmosphere/ice fluxes are computed by the ice model and the atmosphere/ocean fluxes are computed by the atmospheric model after the foundation SST is received from the ocean model.

In GFSv16, the wave model received the 10-meter wind components from the atmospheric model and surface currents from RTOFS and used a persistent ice concentration analysis. In GFSv17, winds will continue to come via coupling and the surface currents will come from the coupled ocean model and ice concentration will come from the ice model. The wave model can provide feedback to other components in GFSv17. The wave model can send Stokes drift to the ocean model for calculation of sea-state dependent Langmuir mixing and z_0 roughness length to the atmosphere model. The land/sea mask between the atmosphere and the wave model currently do not match, which requires the atmospheric model to then determine where values of the surface roughness are not valid values from the wave model and calculate its own value.

While the atmosphere and ice models communicate on a “fast” time step that is the same as the atmospheric and ice internal model time steps, the ocean and wave models are planned to be coupled at a “slow” time step. Turning on feedback from the wave model in this paradigm is being tested and will be turned on or off based on results of additional tests.

More details of the coupling infrastructure can be found in section 3.3.1. A basic schematic of the coupled model is included in the figure below.

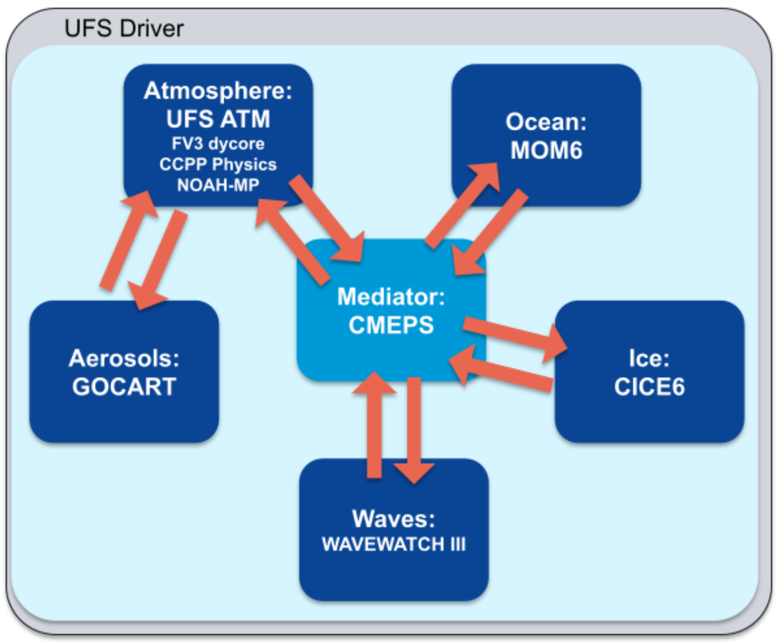

Figure 2: Schematic diagram of the coupled model, driven by the UFS driver. In the figure the mediator is shown in blue, the model components are shown in dark blue and the NUOPC connectors are represented by red arrows.

3.2 Data Assimilation Upgrades in GFSv17

The Global Data Assimilation System (GDAS) provides initial conditions for the GFS. With the increased incorporation of coupled modeling components, the initialization of each new component will need to be defined, with the exception of waves which will contain no data assimilation system in GFSv17. Historically, data assimilation (DA) within the GFS focused on the atmospheric component only, which utilizes the Gridpoint Statistical Interpolation (GSI) framework. Due to the need to incorporate new DA components along with computational bottlenecks and a renewed focus on community modeling, the decision was made to replace much of the existing DA infrastructure with components of the Joint Effort for Data assimilation

Integration (JEDI) framework. Developed by a consortium of operational centers and research partners and managed by the Joint Center for Satellite Data Assimilation (JCSDA), JEDI is a modular and flexible environment using modern coding practices that can provide the basis for NCEP's UFS DA system. Code from JCSDA's JEDI repositories will be connected to EMC's global-workflow through the GDASApp NOAA-EMC repository. This repository contains many scripts and YAML configuration files for both cycling and standalone testing, enabling easier validation of all of the JEDI components.

Details specific to the JEDI transition will be documented in the JEDI transition plan (link to come). The following sections provide an overview of the other potential upgrades to the data assimilation components of the system. Additional details will be provided and continually updated in the GDAS Action Plan.

3.2.1 Atmospheric DA

While the goal is to replace the deterministic GSI-based hybrid 4DEnVar, the ensemble GSI-based LETKF, and the GSI observer with JEDI-based counterparts, unless the timeline for implementation slips significantly, the current set of GSI-based algorithms will remain in operations for v17. The move of the atmospheric DA components to JEDI will likely be incorporated into v18 instead, with significant transition work ongoing.

With the deterministic analysis likely remaining with the GSI, there is an opportunity to transition some mature research to operations. Options include upgrading the hybrid 4DEnVar algorithm to include scale-dependent localization (SDL) as well as an expansion of the ensemble using a valid time shifting (VTS) method. Additional modifications to the atmospheric DA will be made in response to changes in the atmospheric model. The change in the microphysics scheme from GFDL to Thomspon requires accompanying changes in the GSI to ingest the new number concentration variables. Additional optimizations for all sky assimilation under the new scheme will also be needed.

In current operations for GEFSv12 and GFSv16, the GEFS initializes its ensemble using 6 hour forecast ensemble perturbations from the previous cycle of GDAS rather than the analysis perturbations from the current cycle due to the late arriving nature of the ensemble analysis. To foster a more direct connection between the systems, v17 plans to provide an additional set of analysis ensemble perturbations in the early cycle instead of only in the late cycle, contingent on the availability of computational resources. It would also provide more consistency within the GEFS between its ensemble and its control member, which is initialized using the current cycle's early deterministic analysis. This early cycle update could be of a reduced ensemble size, utilize fewer observations, and/or be run at coarser resolution to decrease costs but still provide the GEFS with adequate initial conditions. The current late cycle EnKF will remain generally unchanged. Configuration and evaluation will be closely coordinated with the GEFS team.

Additional observations will be pursued for inclusion in v17. These potential data sets include:

- NOAA-20 OMPS-NP
- NOAA-21 VIIRS, OMPS-NP, OMPS-TC, ATMS, CrIS
- MetOp-C GOME
- GOES-18 ABI
- Himawari-9 AHI, AMVs
- Sentinel-6
- MetOp Second Generation, Meteosat Third Generation
- GMI
- Saildrones

It is likely that many of these observations will be included in operations through minor implementations before v17. In addition, evaluation of new observations could potentially result in code changes in elements not directly involved in the ingestion of new observation types, such as quality control and bias correction.

3.2.2 Marine DA

The marine DA component of v17 will initialize the ocean (MOM6) and sea-ice (CICE6) component of the coupled UFS. The DA system, entirely JEDI based, will be released as GODASv3 as part of GFSv17. GODASv3 will consist of an engineering and scientifically sound application of a hybrid-EnVar in the global-workflow, capable of assimilating all common ocean and sea-ice observations at the same frequency as the atmosphere, i.e., using 6 hour DA cycles.

Both the ocean and sea-ice DA system in GODASv3 make use of SOCA, a model interface to JEDI, co-developed and maintained by the JCSDA and EMC. While primarily developed for MOM6, SOCA can handle other domains such as sea-ice, waves, and biogeochemistry.

Similarly to the atmosphere, the deterministic analysis will be using a hybrid-EnVAR algorithm available in JEDI with the slight difference that the ensemble background error model will not be time dependent. The ensemble perturbations will be generated by a SOCA implementation of the JEDI LETKF. Depending on available resources, a lower vertical resolution for the ocean is being considered for the analysis and ensemble.

Options for the handling of sea surface temperature (SST) and the atmospheric DA derived near-surface sea temperature (NSST) are still being explored. These options generally fall into two categories: 1) moving the NSST into the ocean system and assimilating ocean surface sensitive radiances in SOCA or 2) merging the GSI NSST analysis with the SOCA analysis offline.

The observations ingested in GODASv3 will consist the following:

- In situ temperature and salinity
- Sea surface temperature and salinity retrieved from IR and MW instruments
- Absolute dynamic topography

- Sea ice concentration and thickness

3.2.3 Land DA

Land DA in GFSv17 concerns two components of the system: snow and soil. The long term goal for both components is to utilize JEDI-based data assimilation systems, though initial development has been done with GSI-based software. Since the land model runs on the same FV3 grid as the atmosphere, land DA will leverage the progress made with atmospheric FV3-JEDI DA.

Snow DA in GFSv17 will include replacing the GFSv16 snow depth update with a 2D Optimal Interpolation-based analysis using GTS station snow depth and IMS satellite snow cover. The snow DA system will be a JEDI-based system running on the native model grid, in contrast to the current system, which involves interpolation from existing snow depth products.

The long term goal for soil DA is to produce screen level temperature and moisture analyses with a JEDI LETKF system, replacing the existing Global Land Data Assimilation System (GLDAS) that was introduced in GFSv16. Alternatively, a GSI-based soil DA system is possible for GFSv17 if the JEDI system is not ready. It is also possible that this analysis will not be cycled initially to reduce the risk of implementing a new land model and new land DA system at the same time and be unable to separate impacts. If the LETKF system is not ready to go for GFSv17, GLDAS will likely still be discontinued.

Additional land DA infrastructure will be added to support parameter perturbations consistent with the Noah-MP land model including identifying appropriate parameters for perturbation.

3.2.4 Aerosol DA

The coupled GFS forecast will very likely not include an aerosol component. However, the GDAS forecast could be coupled to GOCART if resources allow and the GEFSv13 implementation plans to couple at least a control member forecast. Since GEFSv13 will be using initial conditions provided by the GFSv17 DA ensemble, the GDAS will also provide a means to prescribe the aerosol initial conditions for the GEFS. See Section 3.4 for more details about potential workflow placement for the aerosol DA steps.

The aerosol DA target for v17 is a JEDI-based 3DVar-FGAT system run at C384 (~25 km) or C192 (~50 km) horizontal resolution and 127 layers in the vertical. The observations constraining the analysis will come from VIIRS AOD aboard NOAA-20 and NOAA-21 with an analysis being computed at a 6-hourly cadence. If a GEFS aerosol ensemble is required, it will be recentered about the 3DVar-FGAT analysis. Potential aerosol ensemble perturbations would require additional treatment such as rescaling or additional perturbation generation such as varying emissions since an ensemble analysis is not planned for v17.

3.3 Infrastructure

3.3.1 Model Infrastructure

Model infrastructure will be significantly upgraded in GFSv17. GFSv16 has two model components with the atmosphere model (FV3ATM) one way coupled to the wave model (WW3) through ESMF connectors. Four new model components including ocean (MOM6), sea ice (CICE6), aerosol (GOCART) and data model (CDEPS) are integrated into GFSv17/GEFSv13. The NEMS mediator is upgraded to the Community Mediator for Earth Prediction Systems (CMEPS). The NUOPC caps for the model components have been adopted/upgraded or developed from their authoritative repositories. The FV3ATM NUOPC cap is updated to couple with those components. The WW3 NUOPC cap is transitioned from the one used in GFSv16 to a NUOPC cap that allows the WW3 to couple through CMEPS. Each of the model components communicates with other model components under the earth model driver either through CMEPS or through ESMF connector directly.

A common field dictionary is composed with all the coupling fields shared among the model components. The coupling fields are set up for each model component defined on its own grid using the field dictionary as an ESMF data container. CMEPS, a NUOPC-compliant Mediator component replacing the NEMS mediator, is integrated into the GFS/GEFS earth system model to transfer coupling fields from one model component to another. The transfer includes mapping the coupling fields between different model grids, merging fields between different model components and time averaging fields over the coupling periods. A direct coupling field transfer without using CMEPS is also available for simple data mapping between two model components through the ESMF connector. In GFSv17, all the model components will communicate through CMEPS. It is the same in GEFSv13 except that the additional aerosol component communicates with the atmosphere model through the ESMF connectors.

An advertising, hand-shaking and realizing initialization step is set up for all the model components to verify that proper fields have been requested by a component and provided to other components. Multiple time scale coupling can be enabled in the coupling framework. The GFSv17/GEFSv13 currently supports two time scale coupling steps during an integration period. Model components decide the coupling frequencies according to their scientific coupling features. At this time the ocean is coupled to the atmosphere, sea ice and wave model through the slow time loop, while the atmosphere, aerosol and ice are coupled through the fast loop. The run sequence of coupling time and model running steps are specified in a configuration file that can be tuned for best scientific performance.

The model build system is updated to support multiple configurations with different model components for the weakly coupled DA capability in GFSv17/GEFSv13. Code quality testing including a debug mode test and reproducibility tests for threading, MPI tasks and restart will continuously run to ensure that the model runs in operations consistently. Stability analysis and code optimization will be conducted. Initial tests have identified a bottleneck and therefore a new option will be added to write the restart files on the write grid component in the atmospheric model FV3ATM to allow asynchronous IO to speed up the coupled model. Unstructured grids should improve the scalability of WW3, therefore the mesh cap will be updated to use an unstructured grid. However, WW3 scalability will still likely need further investigation and poses a risk in the project.

The coupling framework developed in GFSv17/GEFSv13 provides capabilities to support scientific coupling developments. In the case of GFSv17 being not sufficiently skillful with current coupling configuration, as a risk mitigation, coupling strategies that include coupling only for certain regions or times are being considered. This development is non-trivial and dependent on available resources.

3.3.2 Workflow Infrastructure

The workflow infrastructure will include updates such as:

- Updating workflow to work for coupled model for cycled, atm-only, ocean-only, atm+aerosol as well as their ensemble counterparts
- Updating workflow to accommodate DA for coupled model using GSI for the atmospheric component
- Add workflow components for JEDI-based DA for land, ocean, ice and aerosol components
- Unification of file naming and folder structure conventions between GFS and GEFS
- Unification of product generation workflow infrastructure between GFS and GEFS
- Unification of GEFS and GFS workflow infrastructure where possible
- Addressing bugzilla issues

3.4 CONOPS

The cycling cadence of the GFS and GDAS will remain as it is in operations: a cycling interval of every six hours (00, 06, 12, and 18z). The GFS will continue to run with two batches of observations each cycle: the early cutoff and the late cutoff, sometimes referred to as the early and late cycles or the GFS and GDAS cycles (Figure 3). The early cutoff produces the long forecast that is most utilized by forecasters and is therefore run at an earlier wall clock time for a quicker delivery. The late cutoff waits longer to initiate, allowing for more observations to be ingested and a more accurate analysis to be produced. The forecast generated from this analysis is much shorter and used to initialize the next cycle. In current operations, an ensemble is also run in the late cutoff in order to estimate the flow dependent background error for the next cycle's data assimilation.

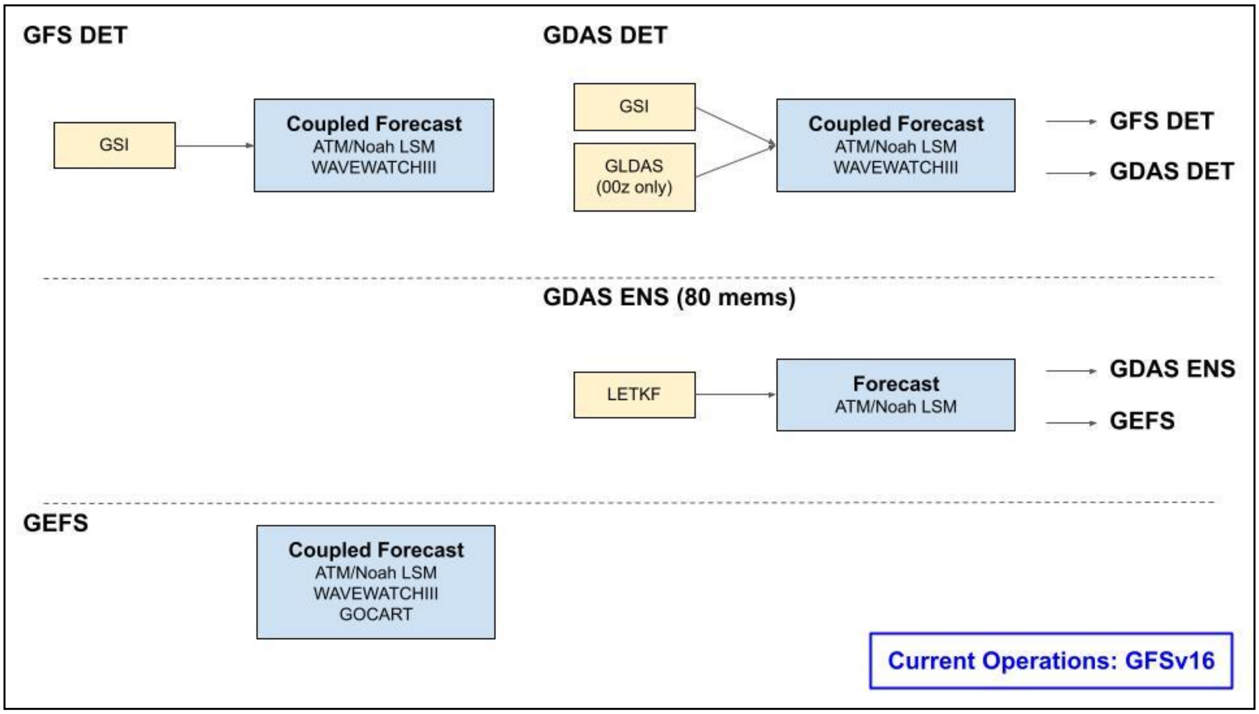

Figure 3: Flowchart for the GFS/GDASv16 and GEFSv12 in operations. The early cutoff runs have a deterministic component only, while the late cutoff runs have both deterministic and ensemble components.

For version 17, there are two major changes in the structure of the early and late cutoff runs (Figure 4). Firstly, an ensemble analysis step will be added to the early cutoff workflow as resources allow. This ensemble analysis will be used to initialize the GEFS only (Section 3.2.1). A set of GFS ensemble forecasts will not be run from these analyses. Secondly, the data assimilation for the non-atmospheric components will be added to both the early and late cutoffs. Marine DA will compute analyses in both the deterministic and ensemble portions of the early and late cutoff runs (Section 3.2.2). Land DA will compute a deterministic analysis and will separately produce the needed land ensemble perturbations (Section 3.2.3).

Aerosol DA will be added to initialize the GEFS control member (Section 3.2.4). At the time of writing, it is unknown whether aerosols will be included in the deterministic forecast, which impacts the infrastructure design of the aerosol DA steps. If aerosols are included in the deterministic forecast, the aerosol DA steps can be run alongside the other component DA tasks within the GFS application. If aerosols will not be included in the deterministic forecast, one option is to keep the aerosol DA in the GFS application since including aerosols in the GFS is a long term goal. However, this creates an additional GFS dependency on the GEFS as the DA is operating on the GEFS aerosol control member. Another option is to have the aerosol DA function as a preprocessing step within the GEFS application.

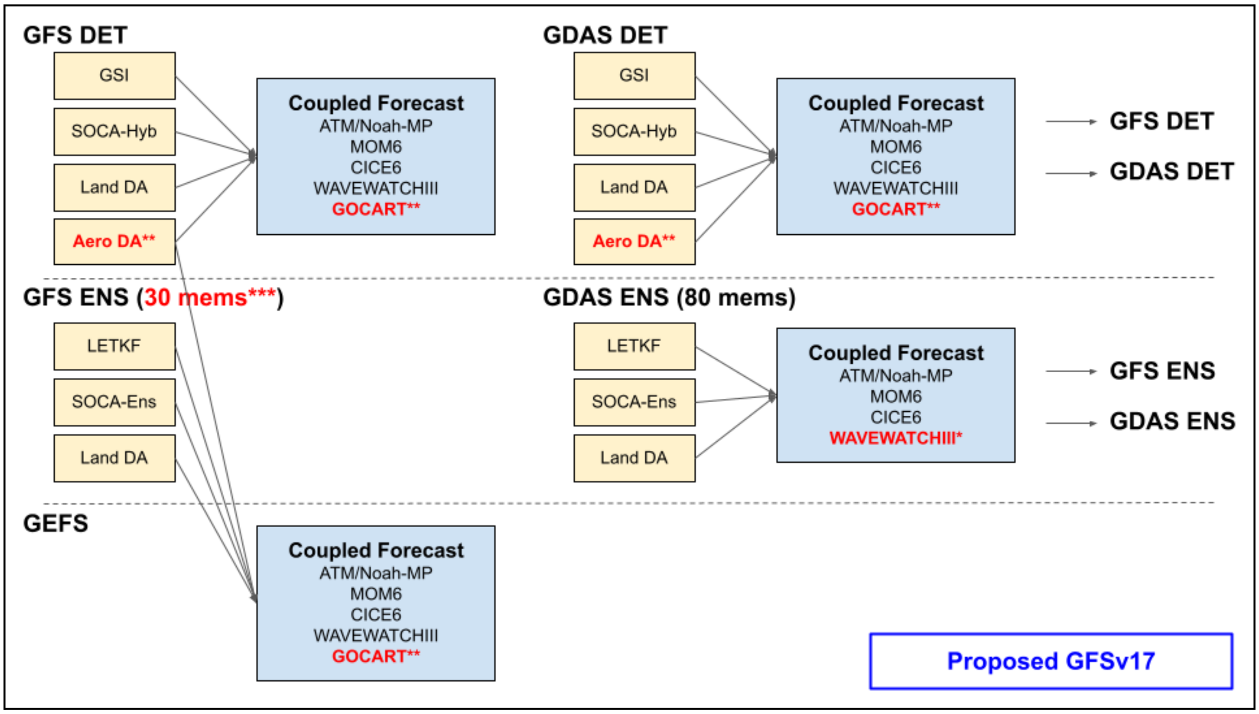

*Figure 4: Flowchart for the proposed GFS/GDASv17 and GEFSv13 workflows. The early cutoff adds an ensemble component to initialize the GEFS in the current cycle. *Undecided at the time of writing whether the GDAS ensemble will run with the wave component. **Undecided at the time of writing which forecasts (GFS/GDAS/GEFS) will couple to GOCART. ***Undecided at the time of writing how many members will be computed in the early cycle EnKF.*

The atmospheric model forecast in operations will be replaced with the coupled model described in Section 3.1. The length of the deterministic and ensemble forecasts will remain unchanged (384 hours for the early deterministic and 9 hours for the others) as will the frequency of the atmospheric output (hourly out to 120 hours, 3-hourly afterwards). The atmospheric component will also continue to use 4DIAU for initialization. The ocean component will utilize 3DIAU over the same window as the atmosphere and the sea ice and wave components will not use IAU initialization.

4 Products

The product changes associated with GFSv17 will be significant, as the model will both subsume products from legacy systems that GFSv17 is meant to replace, as well as potentially add new products that are derived from new capabilities and components. Additionally, algorithms to compute RH, visibility, and winter precipitation variables will be updated significantly in an effort to unify post processing variables across NOAA operational models. This unification will be applied to both gridded products generated by UPP and Station sounding products generated by the GFS BUFR sounding package. Significant updates will need to be made to the GFS BUFR sounding package to add unified GSL precipitation type and winter variables.

4.1 Consistency in Products Across Components

Ensure that all components gridded files are coordinated and consistent. For example in GFSv16 a user noted that the Max East Longitude is 179.75° and the Pixel Size for Longitude is 0.25° while for GFSv16 the wave component products the Max East Longitude is 179.74999998888117° and the Pixel Size for Longitude is 0.2500000111188325°.

4.2 Atmospheric Component Product Changes

To provide consistency between regional and global applications and address user requests, precipitation products will include explicit types (freezing rain, sleet, snow) for accumulations. This will require model, post processing, and product changes.

In addition, product changes are expected to include 1) bug fixes to a handful of products, 2) unification of RH, visibility, gust wind and ceiling algorithms as well as potentially winter variables as mentioned above, 3) addition of variables, and 4) removal of legacy variables. Further details are included below.

- Product updated and changes:
    - Changes in RH, visibility, gust wind, ceiling, and potentially winter variable algorithms as part of algorithm unification effort within UPP. Upon implementations of HAFSv1, RRFSv1, GFSv17, and GEFSv13, the post processing algorithms used to compute above mentioned variables will be unified.
        - The GSL visibility and ceiling algorithms will be used as the unified algorithms going forward.
        - The computation of RH will be unified to be computed with respect to water only in the UPP. However, inside the model RH will still be computed with respect to both water and ice depending on ambient temperature.
    - Updated version of In flight icing 2.0 adjusted to and tuned to GFSv17 physics
    - Turbulence algorithm adjusted to and tuned to new physics
    - Change in Grib phenomic name of cloud water mixing ratio (CLWMR->CLMR). => **Significant impacts to all applications that use GFS output are anticipated**
    - Bug fixes to a few known product issues:
        - Spotty PVU fields, that started occurring occasionally after GFS V16 implementation, will be fixed by increasing the depth over which PVU thresholds have to be met.
        - Occasional issues with ceiling heights due to an uninitialized input variable.

- Product addition:
  - New snow/liquid ratio (SLR) product
  - Probabilistic GTG to meet 2026 ICAO milestones
  - 0-1000 m helicity
  - Several Land Surface variables including land fraction, soil surface evaporation, and precipitation advected heat flux.
  - New MERRA climatological aerosol products
  - Six winter weather variables
  - Snow density
  - Foundation sea surface temperature

- Product removal:
  - Synthetic GOES upon successful PNS process

4.3 Wave Component Product Changes

The NWS field requests changes to products in GFSv17 to assist with the NWS Impact-based Decision Support Services (IDSS) mission. The list of NWS requests follows for the wave component:

- The National Hurricane Center (NHC) requests additional output points from the GFS-Wave component to extend their northern boundary from 32.0N to 35.5N in order to provide enhanced IDSS to the US Coast Guard. A list of the required new points exists on the TAFB Additional Boundary Points spreadsheet. The POC for this request is Jeffrey Lewitsky at NHC.
- The Ocean Prediction Center requests that new boundary condition points be added to GFSv17 to meet the requirement to produce gridded forecasts for the OPC ocean domains and provide similar information in scale as NHC TAFB and HFO. These points and capability of the GFSv17 will be the basis for transitioning to full basin grid production for the north Atlantic (ONA) and Pacific (ONP) domains for the Nearshore Wave Prediction System. The file of points exists in the OPC Requested NWPS Domain Boundary Condition file, which includes the names of the domains as the WW3 spectral files will need to include reference to the specific domain. This request is a requirement to be implemented via CaRDS requirement 17-005.

The following list product changes in consideration for the wave component:

- Consider redesigning AWIPS grids to reflect the increase in global resolution that occurred in v16 but was not reflected in the regional 10m grids due to space constraints, which might still be an issue.
- OPC has informally requested that AWIPS products for waves be generated for GDAS.
- Consider creating an extra regional grid for Alaska similar to the multi_1 Alaska 10m grid.
- Fix wave grib products grib and process IDs. (Document)

- Reduce the number of parm files for wave products which could be templated instead of repeated when only the forecast hour changed. (See https://github.com/NOAA-EMC/global-workflow/tree/develop/parm/parm_wave)
- Consider unifying the output parameters for GFS wave and GEFS wave, including adding output of input fields for ice and current. Alternatively, if NetCDF output is produced instead of binary, these could just be available in NetCDF instead of Grib.
- Update ww3_gint program so that interpolation of input fields are not masked by active sea-points. (See github issue for more information).
- Wave post point jobs need to be refactored and parallelized to be efficiently used with the per-time-step point output. Additionally, NetCDF could replace the binary output. One place for further efficiency would be to find a parallel tar program as the tarring of the files can take up to 5 minutes.
- Confirm with downstream models for any boundary points that should be revised, including removing boundary points that are no longer needed.
- If 48 directions are used instead of 36, spectral output products will change and notification is needed.
- Add point output for the following places, based on a request from Tim Garner to support the National Weather Service Spaceflight Meteorology Group, which have been grouped into two priorities:
  Highest priority:

Latitude	**Longitude**	**Station Name**	**Description**
32.333	-117.8	SITE3	NASA Orion
32.8	-117.8	SITEX	NASA Tophatc
28.61461388	-80.5947827	CAPC	1km offshore Cape Canaveral NASA (this may be too close to the shore for the model to resolve)
32.51558564	-75.7584389	ATX1	650km NE Cape Canaveral NASA
32.67131851	-75.5696493	ATX2	675km NE Cape Canaveral NASA
28.25	-80.25	CAP1	Cape Canaveral Atlantic NASA
28.85	-80.23	CAPN	North Cape Canaveral Atlantic NASA
28.8	-80.6	DAB	Daytona Atlantic NASA
30.9167	-80.25	JAX	Jacksonville Atlantic NASA
28.5	-83.75	TPA	Tampa GoM NASA
29.25	-84.2	TLH	Tallahassee GoM NASA
29.766	-86.028	PAN	Panama City GoM NASA
29.8	-87.5	PEN	Pensacola GoM NASA

Secondary Priority:

Latitude	Longitude	Station Name	Description
42.0543	-64.9688	ECALE	ECAL Early NASA
45.8746	-54.2504	ECALL	ECAL Late NASA
51.2262	-9.2532	SHAN	Offshore Shannon Ireland NASA
46.3497	-53.0046	STJO	Offshore St Johns Canada NASA
33.5012	-75.0457	CMFS	Atlantic CMFS NASA
-21.9419	-143.6375	TAHI	South Pacific NASA

4.4 Products for New Components

The following items and tasks are required:

- Determine which products and at what resolutions will be provided for new components.
- If the format will be netcdf or grib for ocean and ice files.
- If conversion from tripolar to regular lat/lon is required for products becomes a requirement, utilities will need to be generated using WCOSS2 approved software (current capabilities require NCL which is not allowed).
- Any specific products from the aerosol component DA.

4.5 Replacement of NAM and RAP

The VPPPG Branch has been coordinating with all FAA vendors on finding them replacement products upon retirement of NAM and RAP. These FAA vendors use RAP and NAM based aviation products in their domestic flight planning and routing softwares and thus are considered our high impact customers. Most FAA vendors stated they will switch to RRFS 13 km products because of its hourly updated cycle capability. Only one vendor will switch to GFS and confirm current GFS 0.5 degree pressure Grib files on NOMADS have all the variables they need.
To ensure other NAM and RAP product users can use GFS products as their replacement, the team has cataloged a list of RAP products disseminated to NOMADS and SBN. The same effort will be made for NAM and will be included in this spreadsheet.

4.6 NOMADS, AWIPS, Dissemination Coordination

The update in the Grib phenomic name of cloud water mixing ratio is expected to have a major impact on GFS users. A PNS will be sent out early to notify users of this change. This change will also soon be coordinated with the AWIPS program office. The decision to remove GFS synthetic GOES products will also be noted in PNS and will be made based on users' feedback. This product is not disseminated to AWIPS. The data volume is not expected to change much. However, the final product volume estimate will be presented to the Dataflow team.

5 Timeline

The pathway to operations involves several important steps designed to ensure the integrity[7] and the quality of the complete package.

5.1 Project Phases

The GFSv17 project consists of the following phases, which are not necessarily sequential and may be iterative:

1. Planning
2. Research and Development
3. System Integration and Configuration Test Phase
4. Science Freeze
5. Pre-Implementation Test Phase
6. NCO IT Stability Test
7. Implementation

Results from the configuration test phase meeting requirements will result in the milestone of the science freeze. Maintaining the iterative process in the test phase increases the likelihood of meeting requirements and reduces the probability of discovered bugs in the public-facing phases of 5-6. Bugs discovered during later stages are exponentially more costly[8] to address and risk undermining stakeholder confidence, the latter of which is difficult to measure but perhaps most impactful.

The GFSv17 timeline depicted below.

	FY22			FY23				FY24				FY25				FY26			
TASKS	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Project Planning																	MORATORIUM		
Research and Development																			
System Integration and Configuration Test Phase																			
Science Freeze																			

[7] e.g., NOAA Administrative Order 202-735D-2: Scientific Integrity. https://www.noaa.gov/organization/administration/nao-202-735d-2-scientific-integrity

[8] 2002 NIST Planning Report 02-3, "The Economic Impacts of Inadequate Infrastructure for Software Testing". https://www.nist.gov/system/files/documents/director/planning/report02-3.pdf

Pre-implementation Test Phase (Retrospective Experiments for GFSv17)																			
Pre-implementation Test Phase (Science Evaluation including downstream T&E completed)																			
Realtime Parallel																			
NCO IT Stability Test																			
Implementation																			

5.1.1 Planning

The planning phase is the first portion of the entire project and sets the overall scope of the project based upon mission requirements. For GFS, this involves the following steps:

- Gathering requirements
- Creating the project plan (this document)
- Creating the Work Breakdown Structure
- Creating the project management materials necessary to support the project for its entire duration
    - Risk management plan and risk register
    - Communications plan
    - Change management plan

5.1.2 Research and Development Phase

This phase pertains to the research, development, and preliminary testing of all scientific, engineering, and product components of GFS. Development priorities are informed by requirements identified during the Planning phase and are guided by the priorities provided by stakeholders. Most importantly, this phase is iterative and when successful will ultimately lead to the Science freeze and subsequent Pre-implementation finalization and evaluation phase.

All major potential upgrades to the GFS components need to be incorporated into the GFS framework at least three months prior to the start of the pre-implementation test phase to allow for fine-tuning of the entire end-to-end system.

This phase of development and tests can be performed on RDHPCS and/or WCOSS2.

The following criteria is used to make decisions on upgrade component selection for inclusion into GFSv17:

- Individual changes to the model are tested separately and independently.
- Developers start with a branch from the develop branch of GFS (or component repository) and conduct scientific experiments either on RDHPCS or WCOSS2.
- For coupled model upgrades, developers follow the test plan by MDAB Physics and Coupled Modeling Group Leads. Typically, the test plan consists of “forecast only” experiments over a predetermined period of time using v16 or other analysis as initial conditions and comparing to GFSv16 (for atmosphere and waves). Note while some component specific standalone tests will be required, fully coupled tests are also required for testing. Additionally, AMIP-type climate experiments running at lower resolutions are also needed for testing, for instance, the unified gravity-wave drag parameterization, to understand its impact on certain atmospheric modes that can be assessed only in extended climate runs.
- For DA and Observing System upgrades, developers follow the test plan designed by MDAB Data Assimilation Group Lead. Usually the plan consists of running low-resolution cycled experiments for one summer month and one winter month, and using GFSv16 configuration as the control.
- For resolution upgrades, developers will make necessary changes to the model and conduct full resolution “forecast only” experiments using ECMWF analysis or GFSv16 analysis over a long period (for instance, every 10th day for two years), and use GFSv16 configuration as the control.
- For bug fixes and addressing other “known” issues within GFSv16, developers will make necessary changes to the model and conduct full resolution “forecast only” experiments using GFSv16 analysis over a long period (for instance, every 10th day for two years), and use GFSv16 configuration as the control.
- Results from each of the experiments in the development phase will be evaluated against respective control experiments, and presented at the GFSv17 coordination meetings or other venues of opportunity.
- Model Evaluation Group (MEG) will provide necessary support for evaluating the development phase experiments, and the developers will make a proposal for inclusion of model changes into the develop branch.
- A configuration review committee consisting of EMC management (Director and/or Deputy Director), Project Managers, Project Leads, and Code Manager(s) will evaluate the proposal and provide recommendations for acceptance (or rejection) of the science changes.
- If accepted, the developers will follow the code management procedures defined by each repository for committing the codes to the develop branch and ensure the full inclusion of the change in the entire end-to-end system.

All changes needed for inclusion of approved scientific upgrades must be committed to the develop branch of the respective repositories before the integrated Configuration Test phase. Upgrade candidates not selected for inclusion or not ready before the next phase will be returned to the pool of potential upgrades for the next version of GFS (or other applications as appropriate). There will be no exceptions for inclusion of new science changes after the development phase is completed.

5.1.3 System Integration and Configuration Test Phase

This phase pertains to integrating and testing all candidate upgrades for all components with a model configuration intended for implementation of GFSv17 into operations. This phase includes assembling all approved science changes, conducting tests for technical and scientific integrity and robustness, fine tuning of model parameters, addressing dependencies for pre- and post-processing tools and libraries, and conducting full resolution cycled experiments for one summer month and one winter month (and selected case studies recommended by MEG) and evaluated comparing with GFSv16 as control to confirm intended benefits from individual component testing in the development phase are retained. The same metrics used in the development phase will be used for evaluation in the configuration test phase.

If the results are not favorable to proceed with, developers of the respective upgrade components will work with the Project Managers to develop alternate strategies, which may result in re-tuning the model configuration and repeat the system integration tests as needed.

The configuration test will be performed on the NCEP WCOSS2.

All necessary changes to the workflow, scripts, build system, production suite libraries, pre- and post-processing utilities, model evaluation tools, and process automation aspects will be finalized in this phase.

5.1.4 Science Freeze

Once the system integration and configuration test phase shows that the GFS system is meeting requirements, the scientific package for GFS is frozen and the implementation candidate is declared. This is the official scientific package that will be put forth for full consideration in operations. A pre-implementation tag will be created for retrospective and real-time experiments.

All changes needed for inclusion of approved scientific upgrades must be committed to the authoritative repositories. Upgrade candidates not selected for inclusion or not ready before the next phase will be returned to the pool of potential upgrades for the next version of GFS (or other applications as appropriate).

5.1.5 Pre-Implementation Test Phase

GFS is the flagship model of NCEP for medium range weather forecast guidance, and influences a significant portion of the NCEP production suite through downstream and upstream dependencies. Apart from primary customers and stakeholders of the National Weather

Service, GFS analysis and forecasts are used by the larger weather enterprise across the globe. Apart from real-time operational forecasts, retrospective experiments will provide valuable information for calibration and validation of statistical post-processing and dynamical downscaling applications. Documenting the model performance over a sufficiently long period of time will enable the weather enterprise to adapt to the characteristics of the model behavior and biases. Pre-implementation testing and evaluation with a frozen configuration of the GFSv17 modeling system intended for transition to operations is the most crucial phase of this project.

Typical pre-implementation test includes retrospective and real time experiments covering parts of a three year period, primarily to capture three seasonally varying hurricane conditions and a large sample of severe weather events where the forecasts matter the most. Three hurricane seasons will be covered in addition to two full years of combined retrospective and real time experiments.

Increased complexity of the modeling system with cycled data assimilation, demand for more computational resources to accommodate expensive model upgrades, and severe constraints on the available resources on WCOSS2 and NOAA RDHPCS, it is impractical to conduct continuously cycled experiments for the entire test period. It is imperative that the pre-implementation tests are divided into multiple streams and use all available resources for conducting, monitoring, trouble-shooting, and evaluating retrospective and real-time experiments in a rapid response mode. It is also important to keep in mind the data assimilation system requirements for providing consistent analyses. Usually it takes a minimum of a 2 weeks of spin-up for generating model initial conditions that provide balanced model consistent analyses for each stream of experiments, which needs to be taken into account while dividing the test period into multiple chunks.

A detailed test plan will be developed prior to the start of the pre-implementation phase that maximizes the throughput of pre-implementation tests, addresses the stakeholder requirements, and optimizes testing to the available resources provided for this project.

The two last weeks of this phase are focused on summarizing all the evaluations and endorsements from the stakeholders. The EMC Configuration Change Board (CCB) meeting is conducted during this phase to review and assess the result from the proposed GFS configuration, the EMC director approval is granted during this meeting if the upgrade is deemed beneficial. The NCEP director approval is conducted subsequently.

The real-time tests will be performed on the NCEP WCOSS2 computers. Other streams can be run on WCOSS2 or RDHPCS or potentially cloud computing (if available). Project leads will submit a request to HPCRAC to obtain necessary resources to conduct the real-time and retrospective experiments.

5.1.5.1 Accepting Mid-stream Changes Once Pre-Implementation T&E has Started

Once the configuration for GFSv17 is finalized and codes are frozen, a pre-implementation tag will be created and used for real-time and retrospective experiments. In the event of any change required to be included in the pre-implementation configuration after the code freeze, the following guidelines will be used:

- **Code/Workflow changes that will not alter results:** For modifications that are non-answer changing, the code manager will make a decision to include them into the GFSv17 pre-implementation branch at an appropriate time determined by the project leads. These changes are generally required to improve the efficiency of the system or fix any issues with the workflow. There will be no impact on scientific evaluation aspects due to these changes.
- **Code/Workflow changes that will alter results:** Every effort will be made to not to make any changes that will impact the scientific integrity of GFSv17 pre-implementation package. Invariably, there will be discoveries from real-time and retrospective model evaluation that might reveal scientific issues negatively impacting model performance, and potential scientific changes may be required to address any degradation of results that could put the implementation at risk. Another situation is uncovering any bugs present in the pre-implementation tag that require fixing in a timely manner to make the system scientifically accurate and robust. The following guidelines will be used to make a decision when such situations arise:
    - An internal EMC Implementation Review Committee (EIRC) consisting of the management team (Deputy Director, three Branch Chiefs and three Group Chiefs) will be responsible for making decisions.
    - Project leads, in consultation with the model evaluation team and corresponding model developer, will make a proposal to the EIRC for either a science change or bug fix that will alter the results (thereby invalidate all experiments conducted till then), providing justification for such a change, and pros and cons for including the change.
    - EIRC will review the proposal and make recommendations to accept or reject or conditionally accept the change(s) based on the impact to schedule and resources. If it is early in the process, it may be advisable to restart the real-time and retrospective experiments. Output products and downstream related changes can be considered for acceptance as long as they don't impact scientific outcome.
    - In case of a conflict, EIRC will consult with the EMC Director for a final resolution.

5.1.5.2 Finalization

5.1.5.2.1 Environmental Equivalence

The transition to operations follows the Environment Equivalence standards (referred to as the EE2 process)[9]. A brief overview is provided here with details laid out in the EE2 documentation.

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[9]https://docs.google.com/document/d/1zR6-MfLDIuAoMNv7J35XO8DCfpkc3MwePHcAPOWJS04/edit?usp=sharing

After experimental testing has reached an advanced enough stage, the first interaction with NCO on the project is established via the initial coordination Environmental Equivalence (EE) or “kickoff” meeting. It is expected that by the time of the EE meeting, development testing of the system should have reached an advanced enough stage for specific resource details to be known. For new systems an existing system upgrade that requires a >=3x increase in computing resources, approval must be obtained from the NCEP High Performance Computing Resource Allocation Committee (HPCRAC), which in EMC is coordinated through the Engineering and Implementation Branch head. The brief to HPCRAC should be done as early as possible but not later than the time of the EE Kickoff meeting with NCO.

Attending the EE kickoff meeting will be the project development team, NCO SPA team, Dataflow team and (if applicable) a member of the EMC Engineering and Implementation Branch[10] who has been assigned to the project team for EE2 compliance. In this meeting, the developers present to NCO the following information:

1. A brief overview of the new project or the upgrades planned for an existing production system.
2. For new systems, the expected computing resources to be needed; for existing systems, the changes in resources needed compared to the current production system. The resource information provided should include:
    a. Node usage and expected run end-to-end time on the production machine
    b. Total disk space usage per day or per cycle required on the production machine
    c. Total disk space usage for HPSS archive per day or per cycle
    d. Total disk space usage per day or per cycle on the operational NCEP FTP/NOMADS server
    e. Any changes to model products that are processed for distribution to customers (inc. AWIPS).
    f. Anticipated changes to output grids (either in GRIB2 or GEMPAK format).

The NCO team at the EE meeting will list all outstanding Bugzilla tickets for the modeling system, with the developers providing information on the extent to which the planned upgrade addresses these issues. All Bugzilla items need to be addressed by developers by the time of the handoff of the system to NCO. All actions done by developers on Bugzilla tickets (either resolving them or reasons why they could not be addressed) must be documented in the online Bugzilla database. The development organization is encouraged to discuss code conformity issues with SPAs well in advance of the code hand-off date, including giving NCO an early look at the codes so the SPAs can comment on adherence to standards. On or around the time of the EE kickoff meeting, a Public Information Statement (PNS) that outlines the major changes being introduced in the implementation is written by the developers and sent to NWS Headquarters for dissemination per National Weather Service Instruction 10-102 for comments from stakeholders.

[10] Note: this will only apply to the implementations that EMC is responsible for. Other DevOrg’s will decide what their representation at this meeting will be.

After the EE meeting, major development is ended and the final version is frozen for the science evaluation test of the system, which is run by the developers. Ideally, this test should include both real-time and retrospective forecasts which are to be evaluated by stakeholders inside and outside of NWS. If multiple full season retrospectives are not possible due to resource constraints, stakeholders should be given every opportunity to request specific cases of interest to be rerun. Prior to the start of the science evaluation, the developers write a Request for Evaluation letter for distribution to stakeholders. The evaluation letter describes details of the system changes, what impact these changes should have on analysis / forecast performance. Those who agree to evaluate the package are then notified by the developers when the evaluation starts and ends. The length of the science evaluation period is at least 30 days, but may be considerably longer for major high-profile system upgrades (like the replacement of the NCEP Spectral Model with the FV3 model in the GFS).

Once the science test is completed and evaluations are collected, the Configuration Change Board (CCB) meeting for the project will be held, which is essentially a briefing on the project to the EMC management team. At this meeting, the project leads will brief the EMC Director on the project with an emphasis on the scientific results and the system evaluation by stakeholders during the science test. If the EMC Director signs off on the project, the immediate next step is to give the Science briefing to the NCEP Director (referred to as the OD brief), during which the PI gives an overview of the planned changes, and the stakeholders discuss their evaluations. If the NCEP Director approves the planned science changes for implementation, the project leads finalize the Service Change Notice (SCN), submits to NCO along with code hand-off, and NCO sends it to NWS Headquarters for dissemination. At the CCB and NCEP Director Briefings, developers must get approval from the EMC and NCEP Directors for any changes in product delivery times. If during their IT testing (see next section) NCO determines that product delivery times are > 5 minutes from the current operational systems, NCEP Director approval is required for them to proceed with the implementation.

5.1.5.2.2 Products

Products will also be finalized during this period. This includes checking and confirming the availability and fidelity of products for stakeholders and any downstream applications in the production suite (e.g. the Real Time Mesoscale Analysis). The team will also contact the AWIPS Data Management & Activation Committee (ADMAC) to coordinate any changes/updates to AWIPS/SBN products at least nine months prior to implementation.

5.1.5.3 Final Evaluation

In addition to verification and validation of the model, field evaluation and downstream model and product evaluation which are each discussed in detail below, a risk/benefit analysis will also be considered. This analysis will consider the computational expense of the upgrade including timings, memory usage and disk space, the difficulty of implementation, reliability and robustness, and the unification and consolidation of the production suite.

5.1.5.3.1 Verification and Validation

The verification, validation, and evaluation of GFS v17 is a critical step in ensuring operational readiness prior to implementation. The Verification, Post-Processing, and Product Generation Branch (VPPPGB) will help plan and coordinate these steps with the rest of the GFS team. Before the NWS field evaluation can begin, GFS retrospective data will need to be completed and quality controlled, and a set of case study dates developed that will be used in the evaluation process (case studies are typically a subset of the retrospective data). VPPPGB will assist with quality control of the retrospective data using the new EMC Quality Control Software System (QCSS). Once the retrospective data is completed and assured to be free of errors, VPPPGB and the Model Evaluation Group (MEG) will begin preparing the evaluation package and placing graphics and other necessary materials on the EMC website for the NWS field and partners to use in the evaluation period. In addition, the MEG will also evaluate real-time parallel runs of the GFS as they are performed, and this component will be an integral part of the field evaluation.

The metrics used for the field evaluation are derived from the 2021 DTC UFS Metrics Workshop and are listed in Appendix 9.5. Additional metrics and diagnostics for the evaluation of individual components include but are not limited to the following:

- Mean calculations of
    - 2-m temperature, relative humidity, dew point, and specific humidity
    - 10-m U and V wind components
    - Surface and sea-level pressure
    - PBL height
    - Accumulated Snow Water Equivalent
    - Top-layer soil moisture and temperature
    - Surface-based CAPE
    - Cloud Water and Precipitable Water
    - Total-column ozone
    - Height, temperature, and pressure of tropopause
- Total and low/mid/high cloud covers against monthly-mean CERES observations (or ISCCP climatology of no CERES obs)
- Global mean column-integrated water and ice clouds, including temporal trends
- Global mean column-integrated water vapor compared with NASA's VAP climatology
- Global mean surface and TOA radiative fluxes compared with NASA SRD or CERES database
- Temporal stability in global-mean trends - test for model drift in global mean fields like clouds/precip/evap/temperature/PW
- Significant wave heights and 10m wind speeds compared to satellite-computed RMSE, bias, and 95th percentile for all lead times. Additionally, separately calculate RMSE and bias for high seas conditions. This is dependent upon the capability to read in the validation data being added to MET prior to the evaluation period.
- Statistical significance of differences with respect to the control (scorecard)

5.1.5.3.2 Field Evaluation

The EMC Model Evaluation Group (MEG) will coordinate the field evaluation for GFS customers and stakeholders during the pre-implementation test during a six month period prior to the NCEP OD briefing. The MEG recommends a six month NWS field evaluation as the GFS is replacing important legacy systems that the NWS and partners rely heavily on for life-saving forecasts, and it will be extremely important for a thorough and comprehensive evaluation prior to recommending for implementation. The field evaluation phase not only assists the NCEP Director with making a decision to implement, but it also builds trust on the new system with the NWS and partners, which takes time and will require additional effort in this case to ensure the GFS is ready to replace legacy systems.

The MEG will assess retrospective runs and the real-time parallel from the final implementation candidate, generating graphics to compare operational and parallel/retrospective forecast fields. The MEG will assess relevant verification statistics and will confirm that the statistics are consistent with the daily forecast maps. The subjective component of the evaluation will also assess the GFSv17 candidate with respect to known strengths of the GFS to confirm that degradation is not seen, and it will also assess the candidate with respect to known weaknesses to look for improvements in the new version.

The MEG will communicate model evaluation results to all stakeholders and model evaluation participants through regularly scheduled MEG webinars. It is also expected that a team of National Weather Service Science and Operations Officers (SOOs) will be organized by the MEG, in conjunction with OSTI, to give extra scrutiny to the parallel and retrospective forecasts and provide forma numerical ratings.

5.1.5.3.3 Downstream Model and Product Evaluation

As part of GFSv17 evaluation, all GFS downstream products need to be evaluated by the downstream products developers prior to the CCB.

5.1.5.3.3.1 Evaluation and Impact Assessment from Hurricane, GEFS, AQ and Regional Wave Models

The GFS analysis and forecasts provide initial and boundary conditions for the HWRF/HMON and future HAFS hurricane models and the GDAS/GFS EnKF ensemble forecasts provide initial perturbations for GEFS. It is critical that GFS upgrades do not inadvertently degrade the forecast performance of these important downstream applications. Special attention is given to these two applications (HWRF/HMON/HAFS and GEFS) by including a test plan that documents the impacts of GFS changes to them. Usually NHC provides a list of high priority storms for testing of HWRF/HMON/HAFS with new GFS upgrades. The same will be applied for GFSv17 downstream evaluation.

GFSv17 and GEFSv13 are currently planned to be implemented together. In this case, the retrospective experiments for GFSv17 will provide the initial conditions for the GEFSv13 retrospectives. In the event that the GFS and the GEFS are not implemented simultaneously, the GEFS will use one summer and one winter period to test the impact of GFS upgrades as has been done in previous GFS implementations.

Air Quality (AQ) models also depend on native model output from GFS, and the EMC AQ team will conduct the testing required to demonstrate non-negative impacts of GFS upgrades to CMAQ model.

The wave component provides initial and boundary conditions for downstream regional and hurricane wave models. EMC will conduct proper testing and evaluation to demonstrate non-negative impacts of the GFS upgrade to downstream wave models.

In addition, several downstream products generated from GFSv17 should be validated, see the references section for a comprehensive list of downstream products to be validated.

5.1.5.3.3.2 Evaluation of MDL MOS and NHC TC Genesis

In addition to the downstream models mentioned in Section 5.1.5.3.3.1, two additional applications will need to be extensively tested and evaluated. One of them is the Model Output Statistics (MOS) maintained by Meteorological Development Laboratory (MDL), which requires specific input data from large-scale retrospective runs with GFSv17 configuration. The workflow for retrospective experiments will include scripts for generating the data required for MOS evaluation, which should be included in the real-time parallel and retrospective workflows. MDL is responsible for providing assessment of impact of GFSv17 data on MOS skills using a subset of data (three summer months and three winter months) and inform whether there is a need for collecting data from retrospectives for multiple seasons. If the impact of changes to the GFS to MOS is deemed to be significant, MDL will need to conduct a full recalibration of MOS and deliver a new version to NCO prior to implementation. MDL will likely require at least one, but perhaps up to three, years of retrospective data, and nine months to a full calendar year of work time, to complete this task if needed. A new version of GFS MOS might not have to be implemented at the same time as GFSv17, if MDL deems the skill of GFS MOS is still sufficient enough to keep the system executing using the new GFS data.

The National Hurricane Center (NHC) requires evaluating tropical cyclogenesis forecasts from multi-season retrospectives from GFSv17. EMC will provide a specific subset of model output consisting of variables needed for computing TC genesis parameters. NHC is responsible for doing the TC genesis evaluation and providing a report on the findings.

5.1.5.3.3.3 EMC Verification System

The EMC Verification System (EVS) will become a downstream system from the GFS when implemented prior to GFSv17. Therefore, the EVS will need to potentially be upgraded and reconfigured if any modifications are required due to scientific or technical changes, especially if the verification of legacy systems needs to be removed. A new version of the EVS will need to be delivered with the GFSv17 system, if needed.

5.1.6 NCO IT Stability Test Phase

Once the system is handed off to NCO, the SPA team will examine the package to see if it conforms to WCOSS Implementation Standards and fill out the implementation checklist. They will perform IT testing, the scope of which will vary based on the complexity of the system. The IT testing consists of checking the capabilities of the code, including capacity management, failure mode, restart, cold start, code stability and scalability, dependency checkout, bug verification, standards enforcement and output product technical verification. This IT testing will usually include both source code checks (warning messages during code compiles, arrays out-of-bounds, memory leaks) and the impact of missing upstream data on the system. After the IT testing, NCO informs the developer of any issues found that should be addressed. If NCO deems the package acceptable, it will proceed with setup of the parallel production system. If there are sufficient deficiencies in the system, NCO will send it back to the developer with instructions on what issues need to be addressed. During IT testing, NCO determines whether product delivery times are within 5 minutes of the current operational version of the system. If delivery times are > 5 minutes later with the new version, the NCEP Director needs to be informed for approval for the implementation to proceed.

Once the package is fully compliant with NCO Implementation standards and is set up to run in its production configuration, NCO will run a 30-day stability test. If there are any problems during this 30-day test (system code failures, system bugs, issues with downstream products and downstream modeling systems) these problems are addressed by the developer or the SPA, and the 30-day test is restarted. If NCO determines that product delivery times will be > 5 minutes later than the current ops system then the NCEP Director needs to be informed for approval for the implementation to proceed.

After a successful 30-day stability test, NCO gives the Technical Briefing on the system to the NCEP Director, whose approval will allow the system to be implemented into operations about 1 week later.

5.2 Key Milestones and Deliverables for GFSv17

The key milestones and deliverables for typical implementations are listed in the table below, these are estimated dates and will be refined as needed and based on available resources (support staff and Computer/IT), readiness of the GFS components, and management direction. Timeline for GFSv17 is provided as an example.

Milestone	Timeframe	Notes	Actual Date of Accomplishment
GFSv17 Project Implementation Plan	2 years prior to ops implementation	This document.	
T2O quad chart	Approximately 18 months prior to ops implementation	Update this project plan, if required, for additional details for the upcoming GFS upgrade.	

Complete science freeze and finalize codes	1 month prior to pre-implementation test	Begins only when evaluation criteria from individual components indicate performance requirements have been met.	
Finalize test plan for pre-implementation test (field valuation)	1 month prior to pre-implementation test		
Initial coordination with NCO (EE)	No later than 1 year prior to ops implementation		
Brief HPC Resource Allocation Committee	No later than 1 year prior to ops implementation	Secure pre-implementation resources and potential operational resources.	
Products frozen, share data volume info with NCO and AWIPS team	10 months prior to ops implementation	● Provide data timing and data volume forms for NOMADS and SBN 6 months before code delivery to NCO. ● Inform AWIPS team of frozen product status, provide samples if necessary. LDM testing is likely required.	
EMC issues Public Information Statement (PNS)	10 months prior to ops implementation	EMC issues PNS approximately 1 month prior to pre-implementations testing and evaluation. PNS describes the upgrade and solicits feedback.	
Start EMC pre-implementation test	9 months prior to ops implementation	Includes retro and real-time runs.	
Contact AWIPS Data Management and Activation Committee to coordinate any changes/updates to AWIPS/SBN products	9 months prior to ops implementation		
Complete retrospective runs prior to start of field evaluation	8 months prior to code handover to NCO		

Start six month field evaluation	7 months prior to code handover to NCO		
Complete pre-implementation test	2 weeks prior to code handover to NCO		
Complete EMC & stakeholders evaluation	2 weeks prior to CCB and OD brief; 20 weeks prior to ops implementation		
EMC CCB	18 weeks prior to ops implementation	Brief the EMC CCB on the GFS package and evaluation	
NCEP Office of Director (OD) brief	18 weeks prior to ops implementation	Brief the NCEP Director on the GFSv17 package and evaluation. Invite stakeholders.	
Deliver full code to NCO	17 weeks prior to ops implementation	This includes GFS and all downstream codes.	
Submit Service Change Notice (SCN)	5 weeks prior to ops implementation	EMC to generate and submit the SCN to NCO.	
Start IT test	5 weeks prior to ops implementation		
Implementation	Day “0”		

6 Computing

6.1 Estimate of Pre-Op Real-Time and Retrospectives

The estimated pre-implementation IT Resources needed for each implementation is shown in the table below. Note that more core hours may be required to rerun some of the streams in case major issues are uncovered during pre-implementation tests.

The computing times using 148 nodes on Hera for the GFS 24-hour forecast with C768L127 resolution are:

1) Uncoupled atmosphere-only: about 25 min
2) Coupled with 0.25 degree ocean and ice (no coupling with the wave model): about 25.5 min

Additional timing tests and resource estimates for real-time and retrospectives will be obtained at a later date and tracked in the spreadsheet here.

7 Roles and Responsibilities

Project Managers	Daryl Kleist Fanglin Yang
Project Leads	Jessica Meixner Cathy Thomas
Infrastructure	Jun Wang Rahul Mahajan
Physics	Jongil Han
Ocean/Sea Ice/Waves	Avichal Mehra
Data Assimilation	Cathy Thomas Guillaume Vernieres Cory Martin
Observation Pre-Processing	Iliana Genkova
Post Processing & Products	Huiya Chuang Andrew Benjamin Gwen Chen Bo Cui Wen Meng
Verification and Validation, Field Evaluation	Geoff Manikin Alicia Bentley Mallory Row Shannon Shields Jiayi Peng Ocean Verif 1 (TBD) Ocean Verif 2 (TBD) New global verif hire (TBD) 2 FTE from MDAB-P
EE2/NCO coordination	Rahul Mahajan

7.1 Each Developer’s Responsibility

Each developer working on GFSv17 is expected to follow EMC code management best practices, which includes submitting issues to report problems in appropriate repositories, following each repository's guidelines for testing and submitting pull requests for their contributions. Additionally, developers are also expected to comment their code, document their updates and ensure all new features are properly regression tested and working in the global-workflow.   It is expected that everyone can run the workflow, ensure that their updates make it to the final global-workflow and can test their own updates. Developers should plan accordingly for the time required to document, test and follow proper procedures for their contributions. Developers are expected to make their updates available to use from the workflow if at all possible and be written in a way to be easily ported to new machines (i.e. no hard coded paths). Lastly, developers are expected to report on the status of their tasks and to always follow the NOAA Scientific Integrity Policy[11].

7.2 Collaboration and Organization Interactions

As part of the UFS community, the EMC GFS team collaborates and coordinates the development activities with most of the UFS working groups and UFS-R2O Project to effectively transition new innovations to the GFS components and transition the GFS application to operations. In particular, collaborations with the following UFS-R2O groups are essential:

- MRW/S2S Application Team
- Marine Components Development Team
- Atmospheric Physics and Dynamics (including stochastic physics and land) Development Team
- Data Assimilation, Reanalysis & Reforecast Development Team
- Modeling Infrastructure Development Team
- Verification & Post-Processing Infrastructure Development Team

Additionally, coordination with downstream product developers is vital to ensure that the GFS upgrades do not affect the GFS downstream products negatively, the list of the anticipated downstream products for GFSv16 can be found in the references section.

7.3 Support Staff / Resources

The following table is a first estimate of the support staff/resources for the GFSv17 project and will be updated to align with the holistic EMC T2O resources planning when available.

Role	Number of Dev FTEs	Number of T2O FTEs
Physics development, testing and evaluation	8	3
I&T including tuning		
Pre-implementation testing		
Atmospheric DA	0.5	0.5
Atmospheric Obs	2	0.5
Marine DA	2.5	2
Land DA	1.5	0.5
Aerosol DA	1.5	1

[11] e.g., NOAA Administrative Order 202-735D-2: Scientific Integrity. https://www.noaa.gov/organization/administration/nao-202-735d-2-scientific-integrity

Observation Pre-Processing	0.5	0.5
Wave model development I&T	0.4	0.4
Ice model development I&T	0.4	0.4
Ocean model development I&T	0.6	0.6
Post processing	5	5
Verification	7	7
Field evaluation (MEG)	3	3
Workflow development, monitoring of retro and real-time parallels	2	2
Model Infrastructure development	4	4
Code management (GFS & GDAS)	5	5
T2O/NCO Coordination/EE2		
Total		

8 Project Risks and Management

Project status will be reported to the EMC director at least on a quarterly basis during the EMC Project Management Review (PMR). Development progress related to all GFS components will be presented during the regular GFS technical meetings. Regular coordination meetings to monitor and coordinate all activities related to GFSv17 development and transition to operations will start about two years prior to operational implementation. In addition, all activities related to GFSv17 will be tracked in smartsheets. Project risks will be managed via a smartsheets page here and a subset of these risks are listed below.

RISK AND MANAGEMENT PROFILE

Risk	Level	Management
Mid-stream changes once pre-implementation T&E has commenced	**Medium**	Code/Workflow changes that will not alter results: For modifications that are non-answer changing, the code manager will make a decision to include them into the pre-implementation branch at an appropriate time determined by the project leads. These changes are generally required to improve the efficiency of the system or fix any issues with the workflow. There will be no impact on scientific evaluation aspects due to these changes. Code/Workflow changes that will alter results: Should such a scenario arise, the Risk and Change Management Plan drafted during the Planning phase will contain guidelines for handling such a situation, which may be highly specific/nuanced.
Collaborators and funding	**Medium**	Some scientific upgrades in GFSv17 depend upon external collaboration. Successful integration into GFS requires that funding and associated resources are sufficient for collaborators to meet GFS deadlines. Should funds be lacking or collaborators be unable to meet deadlines GFS

		may need to (1) have its scope adjusted accordingly or (2) undergo delays.
AWIPS/SBN Readiness	**Medium**	Eliminate/limit forecast hours or fields from files provided to SBN, particularly for new components. Work with dissemination and stakeholders.
Code is too slow or expensive to run	**Medium**	Regular testing should identify issues with code efficiency in such a way that they may be addressed in a proactive manner. However, if such issues are not addressable under the context of present methods (i.e. deficiency in algorithms), then project management should be engaged for discussion and mitigation strategy. Mitigation may involve consulting with a high performance computing analyst, adjusted timeline/scope, etc.
GFSv17 is not sufficiently skillful	**Medium**	Specific efforts need to be made to ensure that issues with GFSv16 (e.g. low bias for high seas for waves, CAPE, inversions, hurricanes) are addressed. Moreover, to mitigate the risk of a scenario where the coupling is not skillful, we will pursue infrastructure updates that will allow for coupling to be turned on after a set time period or to be turned off based on geographic limits. In general, if the results are not favorable to proceed with, developers of the respective upgrade components will work with the Project Manager to develop alternate strategies, which may result in re-tuning the model configuration and repeat the system integration tests as needed.
WW3 Scalability	**High**	The WW3 code using structured grids has been found to be very slow. To mitigate this, we are employing unstructured grids and outer-loop coupling.
WW3 Unstructured Grids	**High**	The implementation of unstructured grids in WW3 requires the replacement of a library, which is dependent on work outside of EMC, updates to the mesh-cap for unstructured grids, and many other updates. There is a significant amount of work to implement unstructured grids. A single tripolar grid will be pursued as a back-up plan to mitigate the risk with pursuing unstructured grids.
Insufficient staffing	**Medium**	Proper staffing will be essential to complete this project. Should staffing be expected to become insufficient, proactive steps should be taken to engage with managers to assess if the issue may be ameliorated through the addition of new, or re-assignment of existing, staff. If an increase in staffing is not possible, project descoping or adjustments to the timeline should be considered.
HPSS storage limitations for additional components	**Medium**	Consult with HPCRAC prior to implementation. Consider limiting the new amount of storage via removal of fields, number of levels, or frequency in addition to considering adding netCDF compression.
Existing workflow infrastructure is not capable of handling the proposed upgrades	**High**	The various branches in EMC will have to work together towards defining requirements, identifying resources, and helping implement the needed workflow infrastructure updates for the proposed GFSv17 upgrades.
JEDI and its dependencies are	**High**	Marine and aerosol DA cannot run without JEDI software. Until NCO approves and installs the packages, R&D machines can be leveraged for development, but system

not approved for WCOSS2		integration and operational-like runs will be delayed and the pool of available computing resources will be greatly reduced.
JEDI development for component DA may not meet schedule	Medium	Acceleration of JEDI/SOCA development.
Replacing NAM/RAP with GFS	Medium	Need additional coordination with the field, including addressing implicit and explicit dependencies.
MOM6 at 1/12 deg resolution yet to match HYCOM skill	Low	Continue to work with GFDL and FSU for improving MOM6. RTOFS inclusion in GFS will be delayed to GFSv18.
Evaluation period is only one month after retrospectives have been run.	Medium	If the evaluation period starts before all retrospectives are complete, VPPPG must generate images and stats during the time that should have been spent doing the actual evaluation work, including scrutinizing the forecasts and stats and making presentations for MEG webinars. Evaluators, including SOO teams, struggle to work with incomplete evaluation materials, as they typically have limited time to examine the materials.The formal evaluation period should not start until all materials are in place. Mitigation will include asking for additional time in the schedule, descoping or finding additional resources.
Meteorological Development Laboratory (MDL) evaluation of Model Output Statistics (MOS)	Medium	If MDL finds that the new version of GFS significantly degrades MOS beyond their acceptable thresholds, then MDL will need to perform a recalibration of MOS prior to implementation. MDL will require at least one, and up to three, years of retrospectives and nine months to a year of time to perform the recalibration. The last time a MOS calibration has been performed was with GFS v14.

9 Appendices

9.1 Upstream/Downstream Dependencies and Retrospective Requests

9.1.1 Downstream of Atmosphere Component

As the global deterministic model, GFS/GDAS serve as boundary and initial conditions for many other systems such as the GEFS, regional hurricane models (ie HAFS), and as forcing for other models. A list of downstream dependencies will be maintained here.

9.1.2 Downstream of Wave Component

If NetCDF spectral files are provided in addition to ASCII for wave point output, downstream wave models which use these files for boundary conditions could update their models to use the NetCDF files, which would likely benefit them as the output would be available sooner.

HWRF (and future HAFS) model uses the initial conditions of GFS wave model and must be updated to read the new initial conditions and interpolate them to its new grid.

If grids are changed, HWRF, URMA, RTMA and NBM will all need downstream model changes.

If 48 directions are used instead of 36, ww3_bound/ww3_bounc needs to be updated to accommodate interpolation of frequencies and downstream models will require to be updated with these new capabilities. A list of downstream dependencies will be maintained here.

9.2 Libraries, Utilities and Repositories

Repositories are managed through GitHub unless otherwise stated. The following repositories make up GFS:

- Authoritative workflow
    - https://github.com/noaa-emc/global-workflow
- Data assimilation software
    - Gridpoint Statistical Interpolation data assimilation system
        - https://github.com/NOAA-EMC/GSI
    - GDASApp: driver for JEDI-based DA applications in the global workflow
        - https://github.com/NOAA-EMC/GDASApp
    - Sea-ice Ocean Coupled Assimilation (SOCA)
        - https://github.com/JCSDA-internal/soca
    - FV3-JEDI interface
        - https://github.com/JCSDA-internal/fv3-jedi
- Unified Forecast System Utilities
    - https://github.com/ufs-community/UFS_UTILS
- Unified Forecast System Weather Model
    - https://github.com/ufs-community/ufs-weather-model
    - Atmospheric Model
        - https://github.com/NOAA-EMC/fv3atm
        - The FV3 cubed sphere dynamical Core
            - https://github.com/NOAA-GFDL/GFDL_atmos_cubed_sphere
        - The Unified Post Processor
            - https://github.com/NOAA-EMC/EMC_post
        - Includes Common Community Physics Package (CCPP)
            - https://github.com/NCAR/ccpp-physics
            - https://github.com/NCAR/ccpp-framework
    - MOM6
        - https://github.com/NOAA-EMC/MOM6

- CICE6
    - https://github.com/noaa-emc/cice
- WW3
    - https://github.com/NOAA-EMC/WW3
- Stochastic physics
    - https://github.com/noaa-psd/stochastic_physics

- HPC Stack - Unified build system to set up and install necessary libraries
    - https://github.com/NOAA-EMC/hpc-stack

The links to the aforementioned repositories may change, be merged, etc. during the course of development. The list above is simply for descriptive purposes at the time of writing and serves to underscore that established version control protocols will be an integral part of GFS development.

Several codes, which will be required for operations, may not yet exist in a formal repository structure at the time of writing (e.g. reside within an older operational model's workflow repository). This list of software is not to be considered exhaustive.

9.3 References

Development and implementation plans

- The UFS Strategic Plan (link)
- GFSv17 Project Plan and Charter (link) this document
- Action Plans for Individual Components
    - Wave Action Plan
    - GDAS Action Plan
- The METViewer web site can be accessed at: https://metviewer.nws.noaa.gov/metviewer, and METExpress can be accessed at: https://metexpress.nws.noaa.gov/

EMC Quad charts

- GFSv17 T2O quad chart (link)
- Physics development quad (link)
- Land modeling quad (link)
- DA development quad (DA Legacy Systems, JEDI, Marine DA, Observations)
- Pre-processing (link)
- Infrastructure development quad (UFS, General)
- Global Workflow quad (link)
- UFS MRW/S2S App quad (link)
- Wave modeling development quad (link)
- Post Processing and Products development quad (link)
- Verification and evaluation quad (link)
- EMC Verification System quad (link)

Smartsheets

- Dashboard
- Work Breakdown Structure
- Risk Register

9.4 Acronyms

Acronyms	Description
4DEnVar	4 Dimensional Ensemble Variational
4DIAU	4 Dimensional Incremental Analysis Update
ABI	Advanced Baseline Imager
ACC	Anomaly Correlation Coefficient
ADMAC	AWIPS Data Management and Activation Committee
AHI	Advanced Himawari Imager
ALE	Arbitrary Lagrangian Eulerian
AMIP	Atmospheric Model Intercomparison Project
AMV	Atmospheric Motion Vector
AOD	Aerosol Optical Depth
AOML	Atlantic Oceanographic and Meteorological Laboratory
AQ	Air Quality
ARL	Air Resources Laboratory
ASCII	American Standard Code for Information Interchange
ATMS	Advanced Technology Microwave Sounder
AWIPS	Advanced Weather Interactive Processing System
BUFR	Binary Universal Form for the Representation of meteorological data
CA	Cellular Automata
CAPE	Convective Available Potential Energy
CaRDS	Capabilities and Requirements Decision Support
CCB	Configuration Change Board
CCPP	Common Community Physics Package
CDEPS	Community Data Models for Earth Prediction Systems
CERES	Clouds and the Earth's Radiant Energy System

CFL	Courant-Friedrichs-Lewy
CFSR	Climate Forecast System Reanalysis
CICE	Community Ice CodE
CMAQ	Community Multiscale Air Quality
CMEMS	Copernicus Marine Environment Monitoring Service
CMEPS	Community Mediator for Earth Prediction Systems
CONOPS	Concept of Operations
CONUS	Continental United States
CrIS	Cross-track Infrared Sounder
CSL	Chemical Sciences Laboratory
DA	Data Assimilation
DTC	Developmental Testbed Center
ECCC	Environment and Climate Change Canada
ECMWF	European Centre for Medium-Range Weather Forecasts.
EE2	Equivalent Environmental 2
EIB	Engineering and Implementation Branch
EIRC	EMC Implementation Review Committee
EMC	Environmental Modeling Center
EnKF	Ensemble Kalman Filter
ESMF	Earth System Modeling Framework
ETS	Equitable Threat Score
EVS	EMC Verification System
FAA	Federal Aviation Administration
FAR	False Alarm Rate
FGAT	First Guess at Appropriate Time
FSU	Florida State University
FV3	Finite-Volume Cubed-Sphere
GDAS	Global Data Assimilation System
GEFS	Global Ensemble Forecast System
GEMPAK	GEneral Meteorology PAcKage
GFDL	Geophysical Fluid Dynamics Laboratory
GFS	Global Forecast System

GIOMAS	Global Ice-Ocean Modeling and Assimilation System
GHRSST	Group for High Resolution Sea Surface Temperature
GLDAS	Global Land Data Assimilation System
GMI	Global Precipitation Measurement Microwave Imager
GOCART	GOddard Chemistry Aerosol Radiation and Transport
GODAS	Global Ocean Data Assimilation System
GOES	Geostationary Operational Environmental Satellites
GOME	Global Ozone Monitoring Experiment
GRIB2	GRIdded Binary - 2
GSI	Gridpoint Statistical Interpolation
GSL	Global Systems Laboratory
GTS	Global Telecommunication System
GWD	Gravity Wave Drag
HAFS	Hurricane Analysis and Forecast System
HMON	Hurricanes in a Multi-scale Ocean-coupled Non-hydrostatic model
HPC	High Performance Computing
HPCRAC	HPC Resource Allocation Council
HRRR	High-Resolution Rapid Refresh
HWRF	Hurricane Weather Research and Forecasting
ICAO	International Civil Aviation Organization
IDSS	Impact-based Decision Support Services
IMS	Interactive Multisensor Snow and Ice Mapping System
IPD	Interoperable Physics Driver
JCSDA	Joint Center for Satellite Data Assimilation
JEDI	Joint Effort for Data assimilation Integration
LETKF	Local Ensemble Transform Kalman Filter
LSM	Land Surface Model
MDAB	Modeling and Data Assimilation Branch
MDL	Meteorological Development Laboratory
MEG	Model Evaluation Group
MERRA-2	Modern-Era Retrospective analysis for Research and Applications, Version 2
MET	Model Evaluation Tools

MF	Mass-Flux
MJO	Madden-Julian Oscillation
MODIS	MODerate resolution Imaging Spectroradiometer
MOM6	Modular Ocean Model
MOS	Model Output Statistics
MP	Microphysics
MRW	Medium Range Weather
NAM	North American Mesoscale
NASA	National Aeronautics and Space Administration
NBM	National Blend of Models
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCL	NCAR Command Language
NCO	NCEP Center Operations
NEMS	NOAA Environmental Modeling System
netCDF	Network Common Data Form
NHC	National Hurricane Center
NIC	National Ice Center
NOAA	National Oceanic and Atmospheric Administration
NOAH	Noah Land Surface Model
NOAH-MP	Noah Multiparameterization Land Surface Model
NOMADS	NOAA Operational Model Archive and Distribution System
NSST	Near-Surface Sea Temperature
NUOPC	National Unified Operational Prediction Capability
NWM	National Water Model
NWPS	Nearshore Wave Prediction System
NWS	National Weather Service
OAR	Oceanic and Atmospheric Research
OD	Office of the Director
OMPS	Ozone Mapping and Profiler Suite
OMPS-NP	OMPS Nadir Profiler
OMPS-TC	OMPS Total Column

OPAC	Optical Properties of Aerosols and Clouds
OPC	Ocean Prediction Center
OSI SAF	Ocean and Sea Ice Satellite Application Facility
OSTIA	Operational Sea surface Temperature and Ice Analysis
OSPO	Office of Satellite and Product Operations
PBL	Planetary Boundary Layer
PMR	Project Management Review
PNS	Public Information Statement
POD	Probability of Detection
PSL	Physical Science Laboratory
QPF	Quantitative Precipitation Forecast
R2O	Research to Operations
RAOBS	Radiosonde observations
RAP	Rapid Refresh
RDHPCS	Research & Development High Performance Computing System
RH	Relative Humidity
RMSE	Root Mean Square Error
RRFS	Rapid Refresh Forecast System
RRTMG	Rapid Radiative Transfer Model for GCMs (General Circulation Models)
RRTMGP	RRTMG-Parallel
RTMA	Real-Time Mesoscale Analysis
RTOFS	Real-Time Ocean Forecast System
S2S	Subseasonal 2 Seasonal
SAS	Simplified Arakawa-Schubert
SBN	Satellite Broadcast Network
SCN	Service Change Notice
SDL	Scale-Dependent Localization
SLR	Snow/Liquid Ratio
SOCA	Sea-ice Ocean and Coupled Analysis
SOO	Science Operations Officer
SPA	Senior Production Analyst
SST	Sea Surface Temperature

STI	Science and Technology Integration
SWPC	Space Weather Prediction Center
T2m	Two meter Temperature
TC	Tropical cyclone
TKE	Turbulent Kinetic Energy
TKE-EDMF	TKE-based Moist Eddy-Diffusivity Mass-flux
TOA	Top of Atmosphere
UCACN	UCAR Community Advisory Committee for NCEP
UCAR	University Corporation for Atmospheric Research
UFS	Unified Forecast System
UMAC	UCACN Modeling Advisory Committee
UPP	Unified Post Processing
URMA	UnRestricted Mesoscale Analysis
V&V	Verification & Validation
VIIRS	Visible Infrared Imaging Radiometer Suite
VPPPGB	Verification, Post Processing, and Product Generation Branch
WAM	Whole Atmosphere Model
WCOSS2	NOAA's Weather and Climate Operational Supercomputing System Phase 2
WW3	WAVEWATCH III

9.5 Evaluation Metrics

[1]G2O=grid-to-obs G2G=grid-to-grid
[2]E/W/C/S CONUS=East, West, Central, and South CONUS regions (separately)
[3]CTC=Contingency Table Counts

Variable	Spatial	Metric	Temporal	Regions	Verf Source	Type[1]
Geo. Height (atmos)	250-hPa, 500-hPa, 700-hPa 1000-hPa	ACC	0-384h/6h	Global, NH, SH, Tropics	Model's own analysis	G2G
Geo. Height (atmos)	500-hPa	ACC Fourier Decomp. for Wave # 0–3, 4–9, 10–20, and 0–20	0-384h/6h	Global, NH, SH, Tropics	Model's own analysis	G2G

Temperature (atmos)	250-hPa, 500-hPa 850-hPa	ACC	0-384h/6h	Global, NH, SH, Tropics	Model's own analysis	G2G
U, V Winds (atmos)	250-hPa, 500-hPa 850-hPa	ACC	0-384h/6h	Global, NH, SH, Tropics	Model's own analysis	G2G
Vector Wind (atmos)	250-hPa, 500-hPa 850-hPa	ACC	0-384h/6h	Global, NH, SH, Tropics	Model's own analysis	G2G
Pressure (atmos)	Sea Level	ACC, RMSE, Bias	0-384h/6h	Global, NH, SH, Tropics	Model's own analysis	G2G
Pressure (atmos)	Sea Level	RMSE, Bias	0-384h/6h	CONUS, E/W/C/S CONUS[2], U.S. Subregions	METARS	G2O
U, V Winds (atmos)	10-m	RMSE, Bias	0-384h/3h	CONUS, E/W/C/S CONUS[2], U.S. Subregions, Alaska	METARS	G2O
Vector Wind (atmos)	10-m	RMSE, Bias	0-384h/3h	CONUS, E/W/C/S CONUS[2], U.S. Subregions, Alaska	METARS	G2O
Wind Gust (atmos)	Surface	RMSE, Bias	0-384h/3h	CONUS, E/W/C/S CONUS[2], U.S. Subregions, Alaska	METARS	G2O
Temperature (atmos)	2-m	RMSE, Bias	0-384h/3h	CONUS, E/W/C/S CONUS[2], U.S. Subregions, Alaska	METARS	G2O
Dew Point (atmos)	2-m	RMSE/Bias, Freq. Bias (50,60,70F)	0-384h/3h	CONUS, E/W/C/S CONUS[2], U.S. Subregions, Alaska	METARS	G2O

Relative Humidity (atmos)	2-m	RMSE, Bias	0-384h/3h	CONUS, E/W/C/S CONUS[2], U.S. Subregions, Alaska	METARS	G2O
CAPE (atmos)	Surface-based	RMSE, Bias, Perfor. Diagram	0-384h/6h	CONUS, E/W/C/S, CONUS[2], U.S. Subregions, Alaska	RAOBS	G2O
CAPE (atmos)	Mixed Layer	RMSE, Bias, Perfor. Diagram	0-384h/6h	CONUS, E/W/C/S CONUS[2], U.S. Subregions, Alaska	RAOBS	G2O
PBL Height (atmos)	-	RMSE, Bias	0-384h/6h	CONUS, E/W/C/S CONUS[2], U.S. Subregions, Alaska	RAOBS + Aircraft	G2O
Visibility (atmos)	Surface	RMSE, Freq Bias (<0.5, <1, <3, <5, <10, >=5 miles (Flight Rules)	0-384h/6h	CONUS, E/W/C/S CONUS[2], U.S. Subregions	METARS	G2O
Ceiling (atmos)	Surface	RMSE, Freq Bias (<0.5, <1, <3, <5, <10, >=3 kft (Flight Rules))	0-384h/6h	CONUS, E/W/C/S CONUS[2], U.S. Subregions, Alaska	METARS	G2O
Total Cloud Cover (atmos)	Surface	CTC, RMSE, Bias (<10%, >10%, >50%, >90%)	0-384h/3h	CONUS, E/W/C/S CONUS[2], U.S. Subregions, Alaska	METARS	G2O
Sea Surface Temperature (atmos)	Sea Surface	RMSE, Bias	0-384h/24h	Global, NH, SH, Tropics	GHRSST OSPO	G2G
Snowfall (WEASD and	Surface	FSS, CTC[3] (includes	0-384h/24h (12Z–12Z)	CONUS, E/W/C/S	NOHRSC	G2G

SNOD) (atmos)		ETS, FBias) (1”, 4”, 8”, 12” in 24h)		CONUS[2]		
Snow Depth (atmos)	Surface	RMSE, Bias	0-384h/24h (12Z–12Z)	CONUS, E/W/C/S CONUS[2]	NOHRSC	G2G
Precipitation (atmos)	Surface	FSS, ETS, FBias, POD, FAR (0.1, 0.5, 1, 5, 10, 25, 50, 75 mm/24 h and 0.01", 0.1", 0.25",0.5",1", 2", 3”/24 h)	0-384h/24h (12Z–12Z)	CONUS, E/W/C/S CONUS[2]	CCPA	G2G
Precip Type	Surface	Multi-category contingency table, Individual CTC[3] , Freq Bias	0-60/6h	CONUS, E/C/W/S CONUS[2], Alaska	METARS	G2O
Geo. Height (atmos)	Vertical Profile (1, 5, 10, 20, 50, 100, 150, 200, 250, 300, 400, 500, 700, 850, 925, 1000-hPa)	RMSE, Bias	0-384h/6h	Global, NH, SH, Tropics, CONUS	RAOBS	G2O
U, V Winds (atmos)	Vertical Profile	RMSE, Bias	0-384h/6h	Global, NH, SH, Tropics, CONUS, Alaska	RAOBS	G2O
Vector Wind (atmos)	Vertical Profile	RMSE, Bias	0-384h/6h	Global, NH, SH, Tropics, CONUS, Alaska	RAOBS	G2O
Temperature (atmos)	Vertical Profile	RMSE, Bias	0-384h/6h	Global, NH, SH, Tropics, CONUS, Alaska	RAOBS	G2O
Specific	Vertical	RMSE, Bias	0-384h/6h	Global, NH, SH,	RAOBS	G2O

Humidity (atmos)	Profile			Tropics, CONUS, Alaska		
Relative Humidity (atmos)	Vertical Profile	RMSE, Bias	0-384h/6h	Global, NH, SH, Tropics, CONUS, Alaska	RAOBS	G2O
TC Track Error (tropcyc)	Surface	Mean Absolute Error (NM)	0-384h/6h (For “early” and “late” cycles)	North Atlantic, East Pacific, West Pacific Basins	Best Track	G2O
TC Along Track Error (tropcyc)	Surface	Bias (NM)	0-384h/6h (For “early” and “late” cycles)	North Atlantic, East Pacific, West Pacific Basins	Best Track	G2O
TC Across Track Error (tropcyc)	Surface	Bias (NM)	0-384h/6h (For “early” and “late” cycles)	North Atlantic, East Pacific, West Pacific Basins	Best Track	G2O
TC Intensity Error (tropcyc)	Surface	Mean Absolute Error (kt), Bias (kt)	0-384h/6h (For “early” and “late” cycles)	North Atlantic, East Pacific, West Pacific Basins	Best Track	G2O
TC Genesis (tropcyc)	Surface	Hits, Misses, False Alarms, POD, FAR	0-384h/6h	North Atlantic, East Pacific, West PacificBasins	Best Track	G2O
Wind Shear (tropcyc)	850–200-hPa	RMSE, Bias	0-384h/6h	Atlantic and East Pac MDRs	GFS Analysis	G2G
Sea Ice Concen. (atmos)	Surface	Perf. Diag. (15, 40, 80%), , CSI, RMSE, Bias	Daily average (0-384h)	Arctic and Antarctic	OSI-SAF 10 km Analysis	G2G
Sea Ice Extent (atmos)	Surface	RMSE/Bias, Std. Dev., Correlation	Daily/ Weekly average (0-384h)	Arctic and Antarctic	OSTIA, GIOMAS	G2G
Geo. Height Anomalies (atmos)	500-hPa	RMSE, Bias	Daily avg. (0-384h)	NH, SH, Tropics	Model’s own analysis	G2G

Temperature Anomalies (atmos)	2-m	HSS, RMSE, Bias	Daily avg. (0-384h)	CONUS, E/W/C/S CONUS[2], AK	METARS	G2O
Latent Heat Flux (atmos)	Surface	RMSE, Bias	0-384h/6h	Global, CONUS	ALEXI	G2G
Sensible Heat Flux (atmos)	Surface	RMSE, Bias	0-384h/6h	Global, CONUS	ALEXI	G2G
Ozone (atmos)	1, 5, 10, 20, 30, 50, 70, 100. 925-hPa	RMSE, Bias	0-384h/12h	NH, SH, Tropics, Global	Model's Own Analysis	G2G
Pressure (atmos)	Sea Level	S1 Score	0-240h/24h	NH, SH	Model's own analysis	G2G
Geo. Height (atmos)	250-hPa	S1 Score	0-240h/24h	NH, SH	Model's own analysis	G2G
Geo. Height (atmos)	500-hPa	S1 Score	0-240h/24h	NH, SH	Model's own analysis	G2G
Significant Wave Height (wave)	Surface	RMSE, Bias	5-Day Avg. (0-384h)	Global	CMEMS (Daily Satellite Product)	G2G
Significant Wave Height (wave)	Surface	RMSE/Bias, Corr. Coeff., Std. Dev., Scatter Ind., Mean, 95th percentile	0-384h/6h	Individual buoys, Global, U.S. Coastal Water Regions	Buoys, C-MAN, ships	G2O
Peak Period (wave)	Surface	RMSE/Bias, Corr. Coeff., Std. Dev., Scatter Ind., Mean, 95th percentile	0-384h/6h	Individual buoys, Global, U.S. Coastal Water Regions	Buoys, C-MAN, ships	G2O

Wind Speed (wave)	10-m	RMSE/Bias, Corr. Coeff., Std. Dev., Scatter Ind., Mean, 95th percentile	0-384h/6h	Individual buoys, Global, U.S. Coastal Water Regions	Buoys, C-MAN, ships	G2O
Temperature (aviation)	850, 700, 600, 500, 400, 300, 250, 200, 150, 100 hPa	RMSE	6-36h/6h	Global, NH, SH, tropics, N Atlantic, N Pacific, Asia, Australia, Middle East, N America	GFS (WAFS) Analysis	G2G
Wind Speed (aviation)	850, 700, 600, 500, 400, 300, 250, 200, 150, 100 hPa	RMSE (full and ≥80 kts)	6-36h/6h	Global, NH, SH, tropics, N Atlantic, N Pacific, Asia, Australia, Middle East, N America	GFS (WAFS) Analysis	G2G
Icing Potential (aviation)	800, 700, 600, 500, 400 hPa	Hit Rate; False Alarm Rate; Bias (thresholds 0.1-0.9"/0.1")	6-36h/3h	Global, NH, SH, tropics, N Atlantic, N Pacific, Asia, Australia, Middle East, N America	GFS (WAFS) Analysis	G2G
Icing Severity (aviation)	800, 700, 600, 500, 400, 300hPa	Hit Rate; False Alarm Rate; Bias (thresholds 0.1-0.9/0.1)	6-36h/3h	Global, NH, SH, tropics, N Atlantic, N Pacific, Asia, Australia, Middle East, N America	GFS (WAFS) Analysis	G2G