Project Plan and Charter for

Global Forecast System (GFS) V16.0.0

Development and Transition to Operation

VERSION 1.0

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U.S. Department of Commerce (DOC)
National Oceanic and Atmospheric Administration (NOAA)
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National Centers for Environmental Prediction (NCEP)
Environmental Modeling Center (EMC) &
NCEP Central Operations (NCO)

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NCEP Project Plan and Charter	
Implementation of Global Forecast System Upgrades (GFSv16), Q2FY2021	
Effective Date: Date of last signature **Responsible Organizations: NWS/NCEP/EMC & NCO**	**GFS V16.0.0 Plan v1.0**

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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) is primarily responsible for working with several partners in developing, maintaining, enhancing and transitioning-to-operations numerical forecast systems for weather, ocean, climate, land surface and hydrology, hurricanes, and air quality for the Nation and the global community and for the protection of life and property and the enhancement of the economy. The mission objectives include being the world's best and most trusted provider of deterministic and probabilistic forecast guidance across all spatial and temporal scales. Fundamental and central to this mission is the global numerical weather prediction system developed and maintained by the Modeling and Data Assimilation Branch (MDAB) of EMC with support from Verification, Post-Processing, Product Generation Branch (VPPGB) and Engineering and Implementation Branch (EIB). Major applications of the global modeling system include the high resolution deterministic medium range Global Forecast System (GFS), the Global Ensemble Forecast System (GEFS), and the atmosphere-ocean-ice coupled Climate Forecast System (CFS). Apart from providing forecast guidance over different time scales, the global model also provides data for initial conditions and boundary conditions driving various downstream applications including high-resolution regional atmosphere, hurricane, ocean, wave, space weather, and air quality models, and a wide range of products to various service centers, Weather Forecast Offices (WFOs) and other stakeholders. To properly serve the customers, the forecasts must be made available reliably and at the appropriate time within available resources.

As part of the Next Generation Global Prediction System (NGGPS) program initiative and broad support from the community, NCEP/EMC replaced the spectral semi-lagrangian reduced Gaussian-grid hydrostatic dynamic core of the current operational GFS with the non-hydrostatic Finite Volume Cubed-Sphere (FV3) dynamic core developed at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) for its scientific integrity and computational performance. Another major change to GFS is the implementation of a new microphysics scheme developed at GFDL, which is expected to improve the modeling of clouds and precipitation. GFS v15.1, to be implemented operationally in Q3 of FY19 (planned for June 12, 2019 at the time of writing this document), will be the first operational configuration of the model with the FV3 dynamic core and GFDL Microphysics. This modeling system will provide a fundamental early building block for the emerging Unified Forecast System (UFS) that is envisioned as a full community-based Earth-System model. The NOAA Environmental Modeling System (NEMS) framework is providing the infrastructure for unifying and coupling the global system to various components to create the UFS. As such, GFS v15.1 is the first instantiation of UFS in operations, and will form the basis for migrating and unifying NCEP Production Suite (NPS) with different UFS configurations, allowing the same code base to be used for community research and operations.

EMC is responsible for continuous upgrades of the operational GFS with enhanced components such as horizontal and vertical resolution, global physics, atmospheric Global Data Assimilation System (GDAS) consisting of 4D Hybrid Ensemble Variational (4D-EnVar) techniques within the Gridpoint Statistical Interpolation (GSI) framework, the Noah Land Surface model, and the FV3 dynamic core. It is important to note that in order to meet the customer requirements, the operational GFS is upgraded periodically, and each upgrade includes enhanced components that are ready to be incorporated into the operational system during the upgrade cycle. Ideally, GFS upgrade cycle should happen at least once every year, however, due to several constraints (e.g., computational resources) and complexities associated with testing, evaluation and validation of GFS and its downstream applications, EMC is striving to conduct GFS upgrades on a biennial basis.

The next major upgrade of the GFS (GFS v16) is expected to be in the area of model physics along with increased vertical (and possibly horizontal) resolution with a higher model top, and coupling the atmospheric model with the current operational Global Wave Model (GWM) based on WAVEWATCH III for improved representation of the marine boundary layer of the atmosphere through modification of the surface roughness and low-level winds. The atmosphere-wave coupling enabled by the NEMS infrastructure will also address the objectives of simplifying the NPS by reducing the number of independent modeling systems in operations.

This project plan documents the requirements, procedures, milestones and timelines for the upgrade cycle of GFS v16.0.0 leading to the operational implementation scheduled for Q2FY2021. This project describes utilizing NEMS based UFS infrastructure towards unifying the NCEP deterministic global atmospheric model and global wave model. In addition, this project describes selection of upgrades to the physics and data assimilation components of the GDAS/GFS. This plan does not include upgrade strategies for other global model applications (e.g., GEFS v12.0, SFS v1.0) or other NPS applications not directly connected to GFS upgrades, but provides basis for developing separate project plans for these components.

This project plan and charter between EMC and NCO was created to address communication and expectation between EMC and NCO in preparation for the GFS v16 implementation.

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1.1 NGGPS Program Description

Information of the Next Generation Global Prediction System (NGGPS program at the National Weather Service (NWS) can be found at: https://www.weather.gov/sti/stimodeling_nggps

1.2 Global Forecast System Description

On June 12, 2019, GFS v15.1 replaced GFS v14 into operations, incorporating major upgrades through implementation of the non-hydrostatic FV3 dynamic core and GFDL microphysics along with many other changes. The new GFS 15.1 operates at a horizontal resolution of GFS v14, C768 (~13 km) and 64 vertical levels with model top at 0.2 hPa, and provides uniform resolution forecasts out to 384 hours, four times a day with hourly output for the first 120 hours and then three-hourly output up to 384 hours. Documentation of GFS v15.1 is available from the FV3GFS community webpage. Data assimilation is provided by 4-dimensional Ensemble Variational (En-Var) hybrid Global Data Assimilation System (GDAS).

2. Objective and Scope

The main objective of this project Plan and Charter is to describe the process for upgrade cycle of GDAS/GFS components leading to implementation of GFS v16.0 in operations by Q2FY2021 (before WCOSS moratorium is in place). The project plan is divided into several sub-projects, each comprising requirements and procedures for development, testing and evaluation, and transition to operations for implementation of a specific configuration of GDAS/GFS. The scope also includes modifications needed for various downstream applications of NPS dependent on GFS upgrades, and validation of the outcome. The plan includes a detailed list of tasks, milestones, deliverables, and stakeholders, and specifies roles and responsibilities of each member of the project team. The criteria for inclusion/exclusion of different components of the modeling system is determined by their maturity and readiness levels, and is governed by evidence based decision making process at each stage of the project. In general, prior knowledge of possible improvements in forecast skill and/or computational efficiency guides the selection of potential candidates for inclusion in the final configuration for full-scale evaluation.

2.1 Known Strengths and Deficiencies of GFS V15.1

An upgrade to the Global Forecast System (GFSv15.1), a key part of the UFS, will soon be in NCEP operations (scheduled for June 12, 2019 at the time of writing this document). The Model Evaluation Group (MEG), part of EMC's Verification, Post-Processing and Product Generation Branch (VPPPG) led a rigorous, independent evaluation (GFS v15 official evaluation site)of the performance of GFS V15.1 compared against the current operational GFS v14. The evaluation involved comprehensive statistical verification of about three years of retrospective (May 2015 - May 2018) and real-time experiments (May 2018 - May 2019).

The upgraded GFS v15.1 showed improvements over the current operational GFS v14 in many different areas, summarized based on both objective and subjective assessment:

- (significantly) Improved 500-hpa anomaly correlation (NH and SH)
- Intense tropical cyclone deepening in GFS v14 not observed in GFS v15.1
- GFS v15.1 tropical cyclone track forecasts improved (within 5 days)
- Warm season diurnal cycle of precipitation improved
- Multiple tropical cyclone centers generated by GFS v14 not seen in GFS v15.1 forecasts or analyses
- General improvement in HWRF and HMON runs
- New simulated composite reflectivity output is a nice addition
- Some indication that fv3gfs can generate modest surface cold pools from significant convection
- GFS v15.1 with advanced GFDL MP provides better initial and boundary conditions for driving stand alone FV3 regional model, and for running downstream models that use advanced MP.
- FV3 based GEFS V12 showed significant improvements when initialized with GFS v15.1
- Improved ozone and water vapor physics and products
- Improved extratropical cyclone tracks
- Improved precipitation ETS score (hit/miss/false alarm)
- Overall reduced T2m biases over CONUS

However, the evaluation also revealed some concerns in the performance of GFS v15.1 compared to GFS v14:

- GFS v15.1 can be too progressive with synoptic pattern
- Precipitation dry bias for moderate rainfall
- Extremely hot 2-m temperatures observed in mid-west based on some case studies
- Spurious secondary (non-tropical) lows show up occasionally in GFS v15.1 since the advection scheme change was made
- NHC reported that GFS v15.1 degraded track forecast of hurricanes (initial wind > 65 kts) in the Atlantic basin
- Both GFS v14 and GFS v15.1 struggle with inversions
- Both GFS v14 and GFS v15.1 often has too little precip on the northwest side of east coast cyclones
- GFS v15.1 exhibits a pronounced cold bias and may produce excessive snow in the medium range.

2.2 Expected Benefits from GFS v16.0

The ultimate goal of this project is to implement upgraded GFS v16 into operations that will provide improved forecast guidance, demonstrated through evaluation of multi-year retrospective and real-time experiments compared against GFS V15.1. 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 GFS V15.1 configuration. It is expected that, with the model top being extended to the mesopause and with doubled vertical layers, forecasts in the upper atmosphere will be more accurate. More satellite observations in the upper atmosphere will be assimilated. The model can better capture the phonema in the stratosphere and mesosphere such as sudden stratospheric warming, the QBO, NAO and AO that have impact on tropospheric circulation, and hence has the potential to improve medium-range weather forecasts and seasonal-to-subseasonal predictions. Inversions near the surface is likely to be improved with higher vertical resolution.

2.3 Metrics for evaluation

Metrics for evaluation of individual components include but are not limited to the following:

- Global, NH and SH 500-hPa (and other level) HGT ACC, verified against ECMWF or it's own analysis
- Global, NH and SH TEMP biases on standard pressures, verified against ECMWF or it's own analysis
- Global, NH, SH, and Tropical wind and T RMSE and BIAS, verified against RAOBS
- surface 10-m wind, T2m and Td over CONUS West and East, verified against Sfc Obs
  - include mean diurnal cycle
  - include analysis of model-forecast soundings at selected sites
- precipitation ETS and BIAS scores over CONUS for warm/cold season
  - include mean diurnal cycle for warm season
- Tropical cyclone track and intensity, TC Genesis, Wind-Pressure relationship
- Extra tropical storm tracks
- Column integrated ozone
- 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 verified against NASA's VAP climatology
- Global mean surface and TOA radiative fluxes verified against 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 other wave model verification metrics for wave coupling tests
- Statistical significance of differences with respect to the control (score card)
- Computational expense
- Risk/Benefit analysis:
  - Difficulty of implementation
  - Reliability and robustness
- Subjective evaluation of selected case studies from MEG

- Anecdotal evidence from experiments with other modeling systems or other model configurations

Additional criteria include addressing known concerns from GFS v15.1 evaluation (see Section 2.1) or statistically significant improvements in known strengths. Note that while it is not practical for each individual component to satisfy all criteria for evaluation, the Configuration Review Committee will take into consideration other criteria as appropriate, and makes the final recommendations.

Computational costs also determine the ability to accept new developments into GFSv16 configuration. EMC Review Committee will assess the cost/benefit aspects if the innovations require substantially more resources than those currently used in operations.
EMC's VSDB software will be used in the development phase, and will migrate to MET+ based verification system when it becomes available for use within the global_workflow.

2.4 Potential scientific upgrades for GFS v16.0

Potential upgrades for the GFS V16.0 include the following science changes for the atmospheric model, wave model and data assimilation systems.

Science changes for the atmospheric model component
1. Model resolution: ● Increased vertical resolution from 64 to 127 vertical Levels ● Increased model top from 54 km to 80 km ● Increased horizontal resolution from 13 km to 10 km (depending on operational resources) 2. Dynamics: ● New advection algorithms developed at GFDL 3. Advanced physics chosen from Physics Test Plan: ● Planetary Boundary Layer/turbulence: K-EDMF => sa-TKE-EDMF ● Land surface: Noah => Noah-MP ● Gravity Wave Drag: separate orographic/non-orographic => unified gravity-wave-drag ● Radiation: updates to cloud-overlap assumptions, empirical coefficients, etc. in RRTMG ● Microphysics: Further improvements to GFDL microphysics ● Fine tuning of advanced physics suite consistent with increased vertical resolution
4. Coupling to WAVEWATCH III
● Two-way interactive coupling of atmospheric model with Global Wave Model (GWM) ● Modifications to surface physics to account for wave interactions
5. Science changes for the Global Data Assimilation

• Local Ensemble Kalman Filter (LETKF), linearized observation operator for LETKF, and including early cycle updates in support of GEFS • 4-Dimensional Incremental Analysis Update (4DIAU) • Add Stochastic Kinetic Energy Backscatter for atmosphere (SKEB) and introduce procedures for land/surface flux perturbations to be consistent with Stochastically Perturbed Physics Tendencies (SPPT) • Modified stratospheric humidity increments • Improved Near Surface Sea Temperature (NSST) analysis • Semi-Coupled Land Analysis as forced by observed precipitation • Improve cloud analysis by using cloud fraction in the forward model and properly treating super-cooled water clouds
6. Observation changes for the Global Data Assimilation System
• ObsProc changes (independent upgrades) • New observations (satellite and conventional) • Land Data (TBD) • Others (TBD)

2.4.1 Resolution Upgrades

The original plan for NGGPS implementation was expected to have increased horizontal and vertical resolution, advanced physics and data assimilation, and improved scalability. That scope was reduced in GFS v15.1 to match the current operational configuration with minimum changes except for the dynamic core and GFDL microphysics to accelerate the transition of FV3 based global model applications into operations. Model forecast skill is significantly influenced by the horizontal and vertical resolution, and other major global modeling centers are operating their global prediction systems at a much higher resolution, leaving a gap between NCEP and other centers. ECMWF, the world leader in the global NWP, operates the Integrated Forecast System (IFS) with about ~9km horizontal resolution and 137 vertical levels. UK Met Office operates their Unified Model with ~10km horizontal resolution and 70 vertical levels.

The current operational GFS operates at a resolution of ~13km in the horizontal and 64 levels in the vertical, with model top extending to 0.34 hPa (~54km). GFS has not increased its vertical resolution (64 levels) since 2002, and horizontal resolution (13 km) since 2015. It is imperative that GFS v16 should have higher vertical and horizontal resolution commensurate with available computational resources. This project plan aims at increasing the vertical resolution to 127 levels and raising the model top to 80 km, with higher resolution in the middle to lower troposphere for resolving the boundary layer and convection. Computational costs are the biggest inhibitors for increasing the model resolution. Preliminary testing of GFS with 127 vertical levels (C768L127) with 80-member C384L127 GDAS configuration showed that the forecast model itself scales well (see table below), and it is possible to achieve the same run times with twice the resources used for GFSv15.1. However, the data assimilation cycle requires three times more computing nodes to fit within the current operational window (with a 5-minute margin of error). Disk space for both online computation and HPSS archive will be doubled compared to the current operation.

Timing test of FV3GFS forecast on Dell, based on a single 10-day forecast

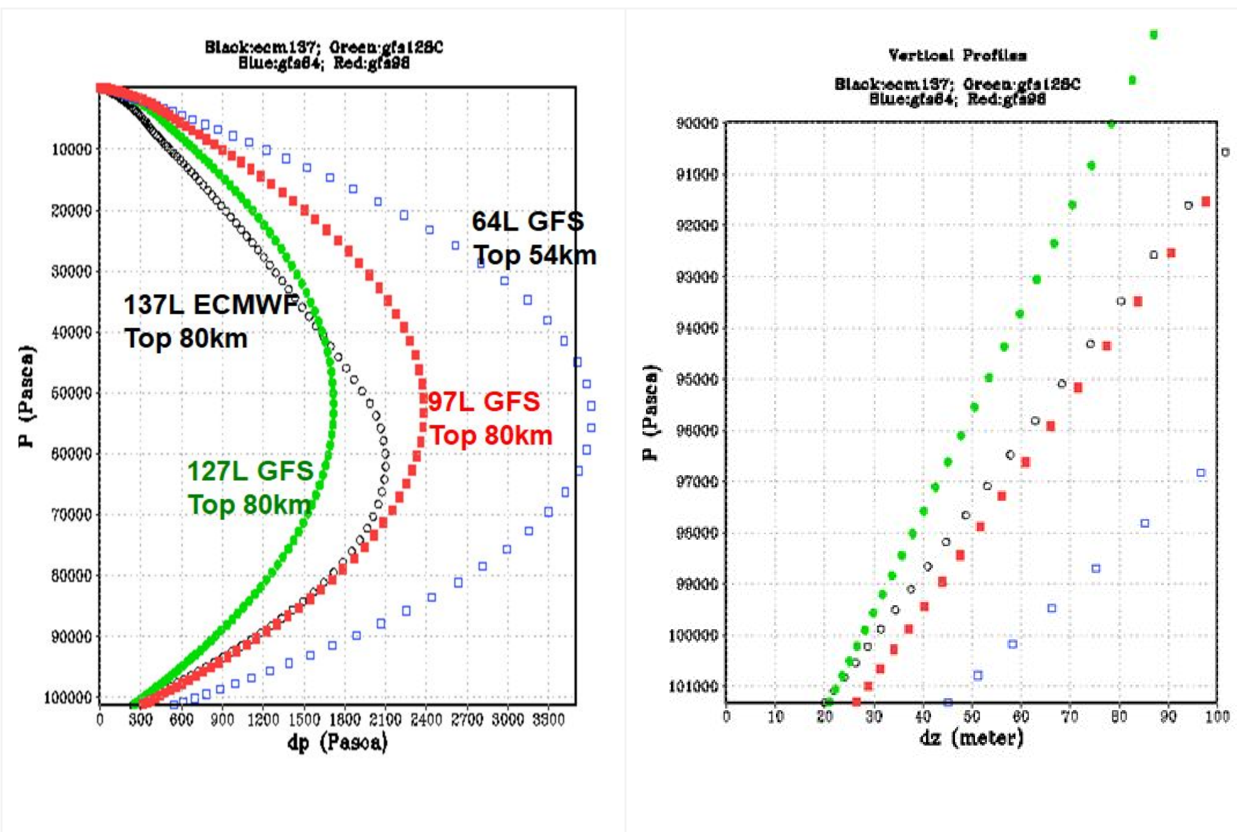
	C768L64	**C768L97**	**C768L127**
Layout	8x24	6x24	8x24
Tasks per node	12	6	6
threads	2	4	4
Output frequency	Hourly	3 hourly	3 hourly
I/O groups and total nodes	4, 20	3, 12	3, 24
Total #nodes	116	156	216
CPU	7.2 min/day	8.0 min/day	7.9 min/day
Atm nemsio	16.9 GB	25.7 GB	33.6 GB
Sfc nemsio	2.83 GB	2.83 GB	2.83 GB

	C384L64	**C384L97**	**C384L127**
Layout	4x6	4x8	4x12
Tasks per node	12	12	12
threads	2	2	2
Output frequency	3 hourly	3 hourly	3 hourly
I/O groups and total nodes	1, 2	1, 2	1,2
Total #nodes	14	18	26
CPU	12 min/day	11.2 min/day	10.4 min/day

Atm nemsio	3.94 GB	6.4 GB	8.41 GB
Sfc nemsio	0.71 GB	0.71 GB	0.71 GB

Timing Analysis for GSI = GSI wall time (m)

avg 27.4
min 27.1
max 28
max-min 0.83
stdev 0.32



127L GFS has higher resolution than 137L IFS in the middle to lower troposphere, but coarser resolution above 400 hPa. 127L GFS 1st layer is 20m thick; 64L GFS 1st layer is 40m thick.

An alternate configuration consisting of 97 vertical levels (80 km model top) is also being considered for GFS v16 to optimize the model run times fit into operational window of generating one-day forecast in about 8 minutes of wall clock time. Depending on the available computational resources and further efforts to optimize the model performance, the specifications of model resolution will be finalized at the early stage of model development (Q3FY19).

2.4.2 Model Dynamics Upgrades

NOAA's GFDL is the primary developer of the FV3 dynamic core and Flexible Modeling System (FMS) framework. Advancements to the dynamic core continued after the initial delivery and integration of it into the NEMS framework. Apart from tuning the dynamic core for higher vertical resolution, possible upgrades to the dynamic core include a new positive-definite scalar advection algorithm, and further changes to in-line microphysics consistent with the model dynamics. GFDL maintains code repositories for the FV3 dynamic core at GFDL, outside of the main GFS repositories managed by EMC on VLab Git. Any new changes made to the dynamic core have to be manually integrated into the GFS code repository with assistance from GFDL collaborators. EMC will coordinate with GFDL colleagues to obtain the latest version of the FV3 dynamic core for possible inclusion into GFS v16 configuration (Q3FY19).

2.4.3 Model Physics Upgrades

GFSv16 is expected to include significantly advanced model physics. Multiple candidates for deep and shallow moist convection (CP), cloud microphysics (MP), and planetary boundary layer (PBLP)/turbulence were recently considered by designing an experiment to assess whether advances in GFS physics could be accelerated by introducing already-tuned CP-MP-PBLP sub-suites instead of evaluating CP, MP, and/or PBLP components separately.

Two sub-suites of CP-MP-PBLP parameterizations were identified as possible replacements for the current GFSv15 sub-suite: (a) Chikira-Sugiyama and Arakawa-Wu scale aware convection; aerosol-aware Morrison Gettleman Microphysics; and (b) scale and aerosol aware Grell-Freitas convection; MYNN-EDMF PBL; scale and aerosol aware Thompson Microphysics. Based on objective and subjective assessment, as well as a recommendation from an independent panel, neither candidate CP-MP-PBLP sub-suite performed as well as the current (GFSv15.1) CP-MP-PBLP combination.

On the basis of this assessment, the CP-MP-PBLP sub-suite targeted for GFSv16 implementation is very similar to that in GFSv15, with the exception of a significant upgrade to the PBLP in GFSv15. In addition, 3 other major upgrades/replacements are being targeted for GFSv16 development:

- PBLP: Add a prognostic TKE component and canopy heat storage GFSv15's K-EDMF scheme
- Land surface: Replace Noah with Noah-MP LSM
- GWD: Replace separate orographic/non-orographic components with a unified gravity-wave-drag scheme

- Radiation:
    1. Upgrade the sw cloud optical coefficients for liquid clouds
    2. Add a new type of cloud overlap scheme
    3. Improve the spectral band interpolation algorithm
    4. Update the computations of cloud quantities for model output products to be more consistent with what is used by radiation computations preliminary testing of each of these new/upgraded parameterizations has been conducted with favorable results, using the framework developed for the CP-MP-PBLP sub-suite evaluation and the suite configurations shown below. With confidence inspired by these favorable results, the 4 new/upgraded parameterizations have been combined in a GFSv16 prototype configuration and testing of the full system is underway.

Proposed PHYSICS OPTIONS for Preliminary GFSv16 Physics Testing

	P1: GFSv15+ sa-TKE-EDMF (control)	P2 Radiation change	P3 LSM change	P4 GWD change
Deep Cu:	sa-SAS	sa-SAS	sa-SAS	sa-SAS
Shallow Cu:	sa-MF	sa-MF	sa-MF	sa-MF
Microphysics:	GFDL	GFDL	GFDL	GFDL
PBL/TURB:	sa-TKE-EDMF + canopy heat storage	sa-TKE-EDMF + canopy heat storage	sa-TKE-EDMF + canopy heat storage	sa-TKE-EDMF + canopy heat storage
Radiation:	RRTMG	Modified RRTMG	RRTMG	RRTMG
Land:	Noah	Noah	NOAH-MP	Noah
O-GWD:	GFS Orog. GWD and Mtn Blocking	GFS Orog. GWD and Mtn Blocking	GFS Orog. GWD and Mtn Blocking	UGWD
C-GWD:	C-GWD	C-GWD	C-GWD	
O3/H2O:	NRL	NRL	NRL	NRL

2.4.4 Coupling to WAVEWATCH III Wave Model

The current operational multigrid Global Wave Model (GWM) based on WAVEWATCH III is planned to be integrated with GFS v16 for improved representation of the marine boundary layer of the atmosphere through modification of the surface roughness and low-level winds. The atmosphere-wave coupling enabled by the NEMS infrastructure will also address the objectives of simplifying the NPS by reducing the number of independent modeling systems in operations. The FV3GFS-WW3 coupled system was developed and tested primarily for technical compatibility, and is a potential candidate for GFS v16.

The multigrid wave model will be coupled to GFS v16 with one-way interaction (no feedback from wave model to the atmosphere), allowing for simplification of NPS. All operational multigrid wave model products will be absorbed by GFS v16.

2.4.4.1 Upgrades to Wave Model

Potential upgrades to the wave model are listed below:

- Global grid mosaic redesign to
  - Increase global core resolution from ½ degree to ⅙ degree
  - Remove current 10 min grids
  - Increase north polar stereo grid resolution from 18 km to 9 km
  - Remove Alaska grids,
  - Add south polar-stereo 9 km grid
  - Keep Conus, Hawaii, Puerto Rico 4 min grids
- Inclusion of RTOFS surface currents
- Physics tune-up: objective optimization
- Redesign AWIPS products
- Removal of legacy grid products
- Redesign of operational workflow for being unified with global-workflow (see workflow section)

For the wave modeling initial conditions, the following two options are currently being considered:

- Option A: Use GEFS/wave ensemble as input for running analysis to generate IC for waves, or
- Option B: Use output of GDAS and run a 9 hour hindcast as a separate pre-run step before the forecast to mimic what is currently being done in operations for the wave model.

A final decision on which option to use will be made primarily based on the availability of a waves DA framework that could be tested and implemented on time given the current implementation GFSv16 schedule. Both options would be tested and verified against the current operational framework, results of V&V would allow that an evidence-based decision be made on which strategy to adopt.

The resolution increase and inclusion of wave-current interactions proposed for the wave model component in GFSv16 will require increasing the /com disk space requirements relative to the current operational model from about 100Gb/day to 300Gb/day. Changes to the wave model configuration relative to the current stand-alone wave model in operations will require doubling the computational resource footprint from 30 to 60 nodes.

2.4.5 Upgrades to Global Data Assimilation System

Continuous advancements to the Global Data Assimilation System (GDAS) are essential for providing improved analysis and more accurate initial conditions for model forecasts. Several new changes are considered for GFS v16. Some of these proposed changes have been developed in close collaboration with partners from NOAA PSD, NASA GMAO and JCSDA.

- Tuning for increased vertical resolution and higher model top; including modifications to Tangent Linear Normal Mode Constraint (TLNMC), satellite channel selection and bias correction
- Local Ensemble Kalman Filter (LETKF) with model space localization to replace Ensemble Serial Square Root Filter (EnSRF), including early cycle updates in support of GEFS
- 4-Dimensional Incremental Analysis Update (4DIAU)
- Add Stochastic Kinetic Energy Backscatter for atmosphere (SKEB) based and introduce procedure for land/surface flux perturbations to be consistent with Stochastically Perturbed Physics Tendencies (SPPT)
- Improve cloud analysis by using cloud fraction in the forward model and properly treating super-cooled water clouds
- Use linearized observation operators in EnKF (LETKF) to speed up workflow
- Switch from binary to netCDF diagnostic files
- Modified stratospheric humidity increments
- Improvements to NSST
- Semi-coupled land analysis forced by observed precipitation

A comprehensive test plan for each of the above mentioned components is developed and executed by the Data Assimilation Group at EMC.

Of the possible changes listed above the first, running the GDAS with increased vertical resolution, is the highest priority for GFS v16. Considerable effort is required to optimize DA codes and workflow in order to run the increase vertical resolution GDAS within the operational run time window. Time and resource limitations, plus the short development timeline, may result in other changes listed above not being in the final GFS v16 package.

The test plan generally includes running low-resolution cycled experiments for individual as well as combinations of possible candidates for inclusion into GFS v16. The DA algorithm changes will be finalized in Q4FY19 before full scale retrospective and real-time testing begins in Q1FY20.

2.4.6 Upgrades to Observation Systems

Observing systems continually evolve with new data becoming available operationally. Data assimilation systems need to take into account various format changes, and QA/QC of the data apart from ingesting new data as it becomes available (or remove old data that is no longer available or usable). The following data are tentatively targeted for inclusion in GFS v16:

- Assimilate NOAA-20 VIIRS winds
- Assimilate MetOp-C ASCAT winds
- Assimilate MetOp-C and MetOp-B AVHRR data
- Assimilate KOMPSAT-5 GPSRO observations
- Assimilate COSMIC-2 data when it becomes available
- Assimilate MetOp-C GRAS data
- Assimilate TAMDAR and Canadian AMDAR Temperature and Winds
- ObsProc change to prevent loss of sonde data and surface pressure buoy data due to TAC2BUFR transition

As with DA algorithm changes time and resource limitations, data availability issues, and the short development timeline may result in some of the changes listed above not being in the final GFS v16 package.

Similar to DA algorithm test plan, observation changes are also tested running low-resolution cycled experiments for individual as well as combinations of possible candidates for inclusion into GFS v16. The observation changes will be finalized before full scale retrospective and real-time testing begins in Q1FY20.

2.5 Potential Upgrades to infrastructure and products

2.5.1 In-line Post with write-grid component

Potential upgrades to the post processing component for GFS v16 will include the following:

- Post processing will run on write grid component to generate POST high resolution master files
- POST processing in workflow will only contain downscale jobs to generate low resolution POST products.
- FV3 history files can be removed if downstream jobs can directly read in POST files. or high resolution history files can be reduced to the first couple of days to provide boundary conditions for regional FV3.
- If required, low resolution history file can be output without pushing too much pressure on system I/O.

2.5.2 NEMS/ESMF

GFS v16 will include the following potential upgrades to the ESMF and NEMS coupling infrastructure:

- New ESMF public release 8.0.0 to support flexible run sequence in coupled system.

- New NEMS build system using GNU Make to support systems with multiple components

2.5.3 CCPP

All physics development and testing for GFS v16 were performed through the IPD, the CCPP infrastructure was not available GFS v16 physics testing.

- CCPP framework that can support multiple configurations.
- Currently static link is used for operational implementation since the configuration is chosen and fixed.

2.5.4 Workflow

The following changes are being made to the workflow

- It is being upgraded to allow EMC real-time parallels to run using ECFLOW. Retrospective runs will still use ROCOTO.
- It is being updated make porting to different platforms easier.
- A cmake based build system is being developed
- A broader unification between the FV3 global and regional workflows is occurring and toolsets that are shared across these two are being merged and managed in a common ufs_utils repository
- The workflow is being upgraded to work for coupled systems
- The ability to handle IAUs for Data Assimilation
- Updating the verification to use MET based verification scripts
- Clean up of all the scripts, including standardized inline documentation and transitioning to using bash environment for all

2.5.5 METplus

METplus 2.1 and MET 8.1 are expected to be installed into WCOSS operations in summer 2019. This software will be used to perform all verification and validation for GFS v16, and will be incorporated into the GFSv16 workflow.

2.5.6 Libraries/Utilities

- New NCEP libraries is installed to support CCPP framework and portability
- Utilities chgres needs to be updated to support L127 layers initial conditions.

2.5.7 Repositories

- NEMSfv3gfs repository is consolidated with EMC_FV3-WW3 repository to form new GFSv16 code base.
- NEMSfv3gfs repository has capability to run in both coupled mode (FV3-WW3) and standalone mode.

- Regression test will be updated for coupled system to create baseline automatically.
- Besides standalone atmosphere and wave regression tests, another group of regression tests with same atmosphere configuration standalone FV3, one-way coupling and two way coupling will be set up in RT suite to test scientific ATM-Wave coupling impact and performance.
- Same code management procedure will be extended to WW3 to maintain consistency on code management.

2.5.8 System Integration for GFS v16

GFSv16 will be tested using incremental integration testing approach to confirm the system compliance with implementation requirements:

- Scientific performance test
    - Potential new feature coming into GFSv16 will be tested separately and independently.
    - GFSv16 final configuration will pick those features showing positive impact.
    - Once the final configuration is fixed, integration test will be conducted to check if the improvement remain true.
- Technical performance test:
    - Scalability test (increasing # of computer tasks speeds up model integration),
    - Tests for IO and coupling (to address any bottlenecks)
    - Meet EE2 standards: correct data flow and control flow; timing and memory usage satisfies requirement (high watermark test) , restart capability, harness test, debug mode test
    - Exception handling
- All the test procedures and results will be documented.
- Transition to operations

2.5.9 Product Changes for GFS v16

Potential upgrades to products for GFS v16 will include the following:

- WAFS products, including turbulence and icing
- Discontinuation of 3-hourly precipitation buckets, replaced by continuous accumulation
- Discontinuation of omega (pascal/s), replaced by vertical velocity (m/s)
- Grib1 discontinuation - removal no earlier than 2022 via agreement with FAA, unless special approval
- Other changes requested by the field
- New station data and bufr soundings (on native levels vs. pressure levels)

2.5.10 Downstream changes for GFS v16

GFSv16 downstream jobs need to be updated to use POST processing files if it's decided to not output high resolution history files.

- GFS downstream codes
- NPS GFS v16 downstream dependencies
- Downstream models that use GFS forecasts data in nemsio format on Gaussian grid as initial and boundary conditions need to switch to grib2 products on lat-lon grid produced by the planned inline UPP. Sample data will be provided as early as possible to all downstream model developers for extensively testing and evaluation. Individual downstream application leads will ensure necessary changes are made to their modeling systems and make code deliveries along with GFSv16 code hand-off to NCO. The application leads need to look at the current operational products being generated by UPP and identify the fields that they will need for their downstream models.

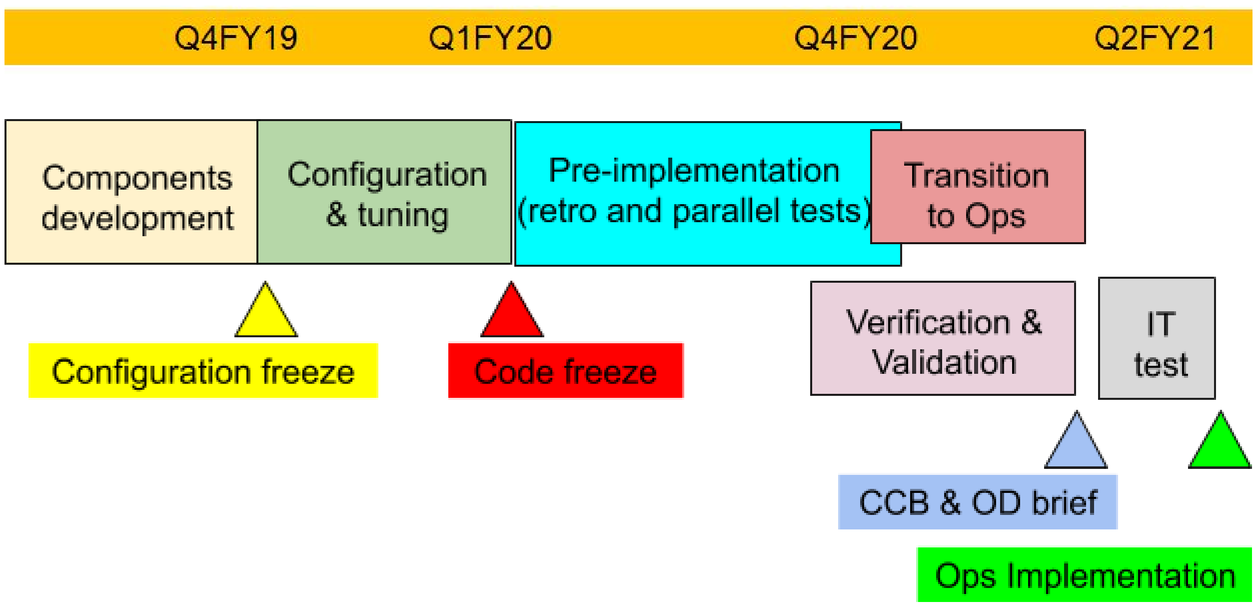
3. Project Description

3.1 Project Phases

The figure below illustrates a schematic describing the development and operational implementation cycle for the GFS v16. The choice of scientific upgrades is dependent on various factors, including:

- Recommendations from the field to address known issues
- Research readiness and maturity of advanced scientific innovations
- Favorable results from extensive pre-implementation tests
- Availability of operational computational resources
- Favorable endorsements from the stakeholders.

Typical developmental phases of GFS are described in the diagram below.



3.1.1 Development Phase

This phase pertains to the development and testing of all potential upgrades, it can include activities such as code/algorithm assessment, test and evaluation, and interface with the operational code. Detailed information about this phase can be found in the project and test plans for each component described in Section 3.

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 NOAA R&D computers such as Jet, Theia, Gaea, or on the NCEP WCOSS computer.

The following criteria is used to make decisions on upgrade component selection for inclusion into GFS v16:

- Individual changes to the model are tested separately and independently.

- Developers start with a branch from the master version of GFS (currently based on GFS v15.1) and conduct scientific experiments either on R&D HPC or WCOSS.
- For physics upgrades, developers follow the test plan designed by MDAB Physics Group Lead. Usually the plan consists of "forecast only" experiments over a long period (for instance, every 10th day for two years) either using ECMWF analysis or GFS v15.1 analysis, and use GFS v15.1 configuration as the control. 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 use GFS v15.1 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 GFS v15.1 analysis over a long period (for instance, every 10th day for two years), and use GFS v15.1 configuration as the control.
- For bug fixes and addressing other "known" issues within GFS v15.1, developers will make necessary changes to the model and conduct full resolution "forecast only" experiments using GFS v15.1 analysis over a long period (for instance, every 10th day for two years), and use GFS v15.1 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 GFS v16 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 Master.
- A configuration review committee consisting of EMC management (Director and/or Deputy Director), Project Manager, Project Leads, and Code Manager 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 documented in Section 1.3.10 and commit the codes to the Master.

All changes needed for inclusion of approved scientific upgrades must be committed to the Master 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 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.

3.1.2 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 GFS v16 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 GFS v15.1 as control to confirm intended benefits from individual component testing in the development phase are retained. The same metrics used in the development phase described in section 4.1.1 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 Manager 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 WCOSS computers

At the end of this phase, the appropriate configuration is selected and frozen in preparation for the subsequent pre-implementation test phase. 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. A pre-implementation tag will be created for retrospective and real-time experiments.

3.1.3 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 GFS v16 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 about a three year period, primarily to capture the seasonally varying hurricane conditions and large sample of severe weather events where the forecasts matter the most.

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 WCOSS and NOAA RDHPC, 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 analysis. Usually it takes about 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.

To maximize the throughput of pre-implementation tests, and to address the stakeholder requirements, the retrospective and real-time experimental setup for GFS v16 will be divided into multiple streams and will be optimized to the available resources provided for this project.

Detailed test plan will be developed prior to the start of the pre-implementation phase

The two last weeks of this phase is 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 WCOSS computers. Other streams can be run on WCOSS or RDHPC 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.

3.1.3.1 Accepting Mid-stream changes once pre-implementation T&E is commenced

Once the configuration for GFSv16 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 GFSv16 pre-implementation branch at an appropriate time determined by the project lead. 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 GFSv16 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 lead, 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 EMC Director for final resolution.

3.1.4 Verification and Validation

The EMC Verification, Post-Processing, and Production Generation Branch will play an important role in the assessment of the GFS v16 upgrade and will be responsible for coordination and summarizing the stakeholders' evaluation during the pre-implementation test as described in the project plan. The Branch will assist with the EMC internal scientific evaluation, downstream products validation, post-processed products and data formats evaluation, and coordinating the NWS field evaluation. Additionally, the Branch will communicate model evaluation results to all stakeholders and model evaluation participants, through regularly scheduled briefings.

The V&V group at EMC has created a GFS verification website that will contain all operational, parallel, and experimental verification static graphics for the GFS, and can be accessed at: https://www.emc.ncep.noaa.gov/gmb/mpr/gfs_verif/ops/. All metrics used in the prior evaluation of GFS v15 will be used for GFS v16 evaluation. In addition, the web-based tools for verification data visualization, METViewer and METExpress, can be used by EMC staff and collaborators to generate custom graphics plots using output from MET. The EMC V&V team will make available all GFS v16 retrospective and parallel run data available via these web-based tools, so that both internal and external users can visualize specific metrics within custom temporal windows.

3.1.5 Field Evaluation

EMC's Model Evaluation Group (MEG) will coordinate the National Weather Service field evaluation of GFS v16, working with NWS HQ, Regions, and National Centers to collect their evaluation information on GFS v16 performance. The field evaluation is one of the last steps prior to briefing the NCEP Director for operational implementation approval, and will be conducted once the scientific component of the code is complete (i.e., "frozen" code) and all retrospective runs are complete. Results from the MEG evaluation, both internal and external, will be assessed and examined by the GFS project manager, and any significant findings will be addressed by the modeling team prior to implementation.

As with GFS v15, the MEG will provide a comprehensive web page that links to all aspects of the model evaluation for GFS v16. The GFS v15 page can be found at: https://www.emc.ncep.noaa.gov/users/meg/fv3gfs/. A similar page will be created for GFS v16.

Another major component of the GFS v16 field evaluation will include coordinating a test of GFS v16 output data with the GFS Model Output Statistics (GFSMOS), in a partnership with the Meteorological Development Laboratory (MDL). The test will determine if GFS v16 output degrades or alters, in a statistically significant way, the current GFSMOS output. If MDL concludes that GFSMOS needs to be redeveloped using GFS v16 data, then MDL will need to obtain two full years of GFS v16 retrospective data and re-develop the static equations that create GFSMOS, prior to implementation. A GFSMOS redevelopment effort could alter the implementation schedule significantly, due to the effort needed via MDL personnel to redevelop the GFSMOS equation suite, and additional work needed by NCO to implement a new GFSMOS version concurrently with GFS v16.

3.1.6 Downstream Model and Product Evaluation

As part of GFS v16 evaluation, all GFS downstream products need to be evaluated by the downstream products developers prior to the CCB.

3.1.6.1 Evaluation and impact assessment from HWRF/HMON, GEFS, AQ and wave models

The NCEP Global Forecast System (GFS) analysis and forecasts provide initial and boundary conditions for the HWRF/HMON 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/HOMN 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 with new GFS upgrades, and GEFS uses one summer and one winter period to test the impact of GFS upgrades. The same will be applied for GFSv16 downstream evaluation.

Since the wave model is being subsumed by GFSv16, there will not be a need for separate evaluation of Global Wave Modeling System.

Air Quality 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.

In addition, several downstream products generated from GFSv16 should be validated, see the references section for a comprehensive list of downstream products to be validated.

3.1.6.2 Evaluation of MDL MOS and NHC TC Genesis

In addition to the downstream models mentioned in Section 3.1.6.1, 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 GFSv16 configuration. The workflow for retrospective experiments will include scripts for generating the data required for MOS evaluation. MDL is responsible for providing assessment of impact of GFSv16 data on MOS skills using a subset of data (one summer month and one winter month) and inform whether there is a need for collecting data from retrospectives for multiple seasons.

The National Hurricane Center (NHC) requires evaluating tropical cyclogenesis forecasts from multi-season retrospectives from GFSv16. 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 provide a report on the findings.

3.1.7 Transition to Operation

The transition to operations follows the Environment Equivalence standards (referred to as the EE2 process)[1]. A brief overview is provided here with details laid out in the EE2 documentation.

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

[1] https://docs.google.com/document/d/1zR6-MfLDluAoMNv7J35XO8DCfpkc3MwePHcAPOWJS04/edit?usp=sharing

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[2] 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 per day or per cycle on the operational NCEP FTP/NOMADS server
    d. Any changes to model products that are processed for distribution to customers (inc. AWIPS).
    e. 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 either 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.

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

[2] 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.

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 evaluation 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 Change Control 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 PI 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 PI finalizes 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.

3.1.8 NCO IT 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 then 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 setup 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.

3.2 Key Milestones and Deliverables for GFS v16

The key milestones and deliverables for typical Q2 implementation 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 GSF components, and management direction. Timeline for GFS v16 is provided as example.

Milestone	Timeframe	v16	Notes
Charter	18 months prior to ops implementation	Q3FY19	
T2O quad chart	18 months prior to ops implementation	Q3FY19	Update this project plan for add details for the upcoming GFS upgrade
Select potential physics upgrades		Q3FY19	This correspond to start of configuration test
Select potential DA upgrades		Q3FY19	
Select potential configuration		Q4FY19	Estimate compute requirements
Complete initial testing and tuning		Q4FY19	Testing and tuning will include examination of results from a suite of case studies provided by the Model Evaluation Group. Any significant findings or errors will be addressed, and signed off by the GFS v16 project manager, prior to selecting final configuration and creating retrospective simulations.
Select final configuration	1 week prior to pre-implementation test	Q1FY20	

Finalize test plan for pre-implementation test	1 week prior to pre-implementation test	Q1FY20	including test cases and HPC requirements
Initial coordination with NCO (EE)	1 year prior to ops implementation	Q1FY20	Secure pre-implementation resources and potential operational resources
Start EMC pre-implementation test	9 months prior to ops implementation	Q2FY20	Includes retro and //
PNS			
Complete pre-implementation test	2 weeks prior to code handover to NCO	Q4FY20	
Complete EMC & stakeholders evaluation	2 weeks prior to CCB and OD brief; 20 weeks prior to ops implementation	Q4FY20	All retrospective simulations are to be completed prior to start of NWS field evaluation.
EMC CCB	18 weeks prior to ops implementation	Q1FY21	
NCEP Office of Director (OD) brief	18 weeks prior to ops implementation	Q1FY21	
Deliver full code to NCO	17 weeks prior to ops implementation	Q1FY21	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”	Q2FY21	

3.3 Project Assumption and Risks

Assumptions and risks associated with the GFS v16 development and transition to operations are summarized below:

- Scientific assumptions and risks

The key assumption for this project is that the planned scientific upgrades for GFS does not degrade the scientific performance of the model. In particular the planned upgrades to the physics, vertical resolution (127 level), higher top (80 km), and integrating the land DA into GDAS, all need to show no degradation to current operational model (GFS v15) for the primary metrics identified in Section 2.3. In addition, field evaluation & concurrence and approval from the NCEP director are required to transition the model into operation, without that, the model will not be upgraded.

- Technical assumptions and risks

Technical performance (CPU, I/O footprint,...etc.) of the model is crucial to the operational implementation of the GFS v16; unsatisfactory technical performance will require additional code optimization and may lead to delay in transitioning GFS upgrades to operation.

- Resources

Personnel and compute resource needs listed in tables 8.1 and 8.2 are critical to the success of this project; inadequate resources may lead to reducing the scope of this upgrade and/or delaying the operational implementation of the GFS v16.

3.4 Collaboration – Organization Interactions

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

- **Physics SIP WG including GMTB**: The Physics development strategy and plan is described in the Physics project plan (SIP Annex 5)
- **Data Assimilation SIP WG**: The Data Assimilation development strategy and plan are described in the Data Assimilation project plan (SIP Annex 6)
- **Infrastructure and System Architecture SIP WGs**: The strategies for NEMS infrastructure development, code management, workflow and system libraries and utilities are described in the project plan (SIP Annex 2 and Annex 3)
- **Dynamic & Nesting SIP WG**: The dynamic core development strategy is described in the project plan (SIP Annex 4)
- **Coupled System teams**: Development of coupling to WAVEWATCH III is coordinated through Coupled System development team as described in the project plan (SIP annex 2 and Annex 8)
- **Land surface models SIP WG**: Development of the land surface models strategy is documented in the UFS SIP annex 8.
- **EMC Model Evaluation Group**: (MEG website)
- **Downstream products developers:** Coordination with all the GFS downstream products 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 GFS v16 can be found in the references section .

4. Roles and Responsibilities

Role	Name	Responsibilities
Project Sponsor	Brian Gross	Provides the budget and funding, and sets the strategic goals and objectives.
Project Manager	Vijay Tallapragada	Responsible for the overall success of the project, including project team, milestones and deliverables.
Project Manager Support	Farida Adimi	Provides support to the project manager and project area leads; ensures all components are coordinating with each other.
Project Area	**Lead**	**Responsibilities**
Project Leads	Fanglin Yang (model) Russ Treadon (DA)	Responsible for coordinating activities related to all components and integrating them into the GFS framework.
Code Managers	Jun Wang (GFS) Cathy Thomas (GDAS) Kate Friedman (Workflow)	Responsible for the overall success of the project area including providing status reports, issues, concerns, and risks to the project lead and project manager. The project area lead is also responsible for meeting all milestones and deliverables associated with their projects.
Verification tools	Mallory Row	
GSI/GDAS	Russ Treadon	
Physics	Jack Kain	
Waves	Henrique Alves	
Verification & validation	Mallory Row	
Field evaluation	Geoff Manikin	
Documentation	Valbona Kunkel	
Post processing/Products	Huiya Chuang	
Pre Processing/Obs	Shelley Melchoir	
Code Optimization	Jun Wang (GFS) Jim Abeles (GSI)	Need additional support from IBM specialists
T2O and EE2 compliance	Eric Rogers	

5. Resources

5.1 Support staff

Role	Number of FTEs	duration from	to
Physics development, testing and evaluation	8	present	through implementation date
I&T including tuning	4	present	through implementation date

Pre-implementation testing	2	present	
DA development and testing	4	present	through implementation date
DA Observation	4	present	through implementation date
GLADS for land spin-up	1.5	present	through implementation date
Wave model development I&T	1.5	present	through implementation date
Pre-Processing	2	present	through implementation date
Post processing	2	present	through implementation date
Verification tools (MET)	2	present	through implementation data
Field evaluation (MEG)	2	when retrospective runs are finished	through implementation date
Workflow development, monitoring of retro and real-time parallels	4	present	through implementation date
Code management (GFS & GDAS)	2	present	through implementation date
T2O/NCO Coordination/EE2	1	freeze code/workflow	through code delivery
Total	40		

5.2 Compute and IT

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

Configuration (High-res/Ensemble)	Parallel Streams	Period of Testing	Platform and Computing Nodes	Core Hours (million)	Online ptmp disk (TB)	HPSS storage (TB) per cycle
C768/C384 L127	real-time	March 1, 2020 - implementation	WCOSS 700 nodes	30	120 TB	2300 TB

C768/C384 L127	Retrospectives	May 1, 2017 - Feb. 29, 2020	WCOSS 700 nodes	150	600 TB	2300 TB

6. Appendices

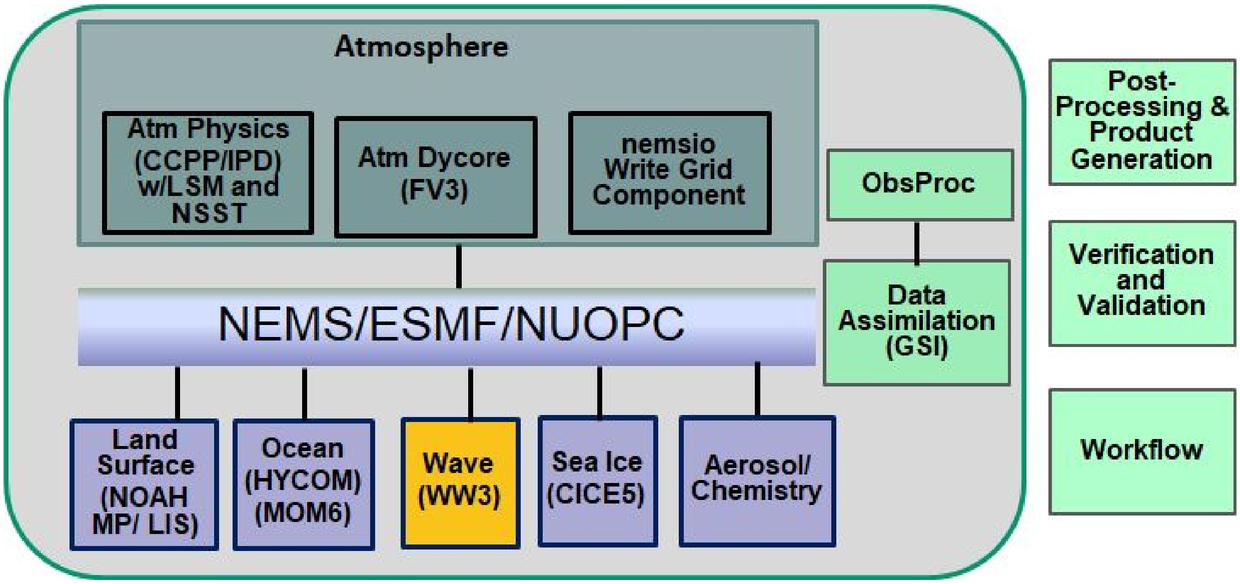
6.1 GFS Components

GFS encompasses several components pertaining to the forecast model such as atmospheric dynamics, parameterizations of various physical processes including land surface processes and sea surface temperature, coupled earth system components (land, ocean, waves, sea ice, aerosols and chemistry), data assimilation system, post processing system, verification and validation system, and infrastructure components including workflow necessary to operate and sustain the model components. Several utilities including system libraries, interpolation algorithms for processing the observations and forecast data, projecting the output to various grids, and databases for verification and validation are also considered part of the end-to-end system.

Each component goes through a development and testing phase. Upgrades that are ready for GFS implementation will be incorporated into the GFS framework to be tested and evaluated in conjunction with all other GFS components. The diagram below illustrates the eventual GFS components; the current GFS configuration does not include the Aerosols/Chemistry, Ocean, Wave, and Ice components. Land surface processes are included as part of the physics package.

GFS is continuously cycled in the data assimilation system where new observations are ingested into the model at every six-hour interval, generating high-quality analysis and initial conditions required for generating the forecasts. A separate Observations Processing (ObsProc) system takes care of quality control and quality assessment (QC/QA) aspects of billions of observations from various sources (e.g., satellites, aircraft, rawinsondes, ships, buoys, AWS etc.) in real-time, and format them into BUFR for ingesting them into data assimilation systems.

Components of the Global Forecast System



6.1.1 Dynamic Core

The NCEP GFS is transitioned to using the GFDL FV3 non-hydrostatic dynamic core as the main engine of the atmospheric model. Code documentation can be found here, Additional documentation of FV3 dynamic core is available from the FV3GFS vlab community page

6.1.2 Atmospheric Physics

The physics package is one of the core components of GFS, which defines the physical parameterization schemes used in GFS. These are related to processes such as deep and shallow convection, boundary layer and turbulence, cloud microphysics, radiation, gravity wave drag, and Earth System surface fluxes and state (land surface processes and sea surface temperatures). Detailed information about the GFS Physics is documented here and also as part of CCPP documentation.

6.1.3 Interoperable Physics Driver (IPD) and Common Community Physics Package (CCPP)

The Interoperable Physics Driver (IPD) is a software infrastructure developed to facilitate the research, development, and transition to operations of innovations in atmospheric physical parameterizations. The IPD enables coupling the FV3 dynamic core and GFS physics suite with a modular infrastructure that is computationally efficient and easy to implement new physical parameterization schemes or physics suites. Details of the latest version of IPD v4 are documented here.

More recently, NGGPS has initiated development of the Common Community Physics Package (CCPP), which 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. The CCPP consists of two separate software packages, the pool of CCPP-compliant physics schemes (CCPP-Physics) and the framework that connects the physics schemes with a host model (CCPP-Framework). At the time of writing this document, CCPP is not accepted yet for operational considerations. Implementation of CCPP into operations depend on successful acceptance of CCPP and integration of advanced physics options selected for GFS v16. In addition, GFS v16 with CCPP should be compatible with atmosphere-wave coupled system configuration and interactions between wave physics and atmospheric physics should be included in CCPP before freezing the codes. Computational efficiency is another issue that need to be addressed. EIB will oversee the implementation of CCPP into GFSv16 working closely with GMTB. More details on CCPP can be found at the GMTB site.

6.1.4 Write Grid Component

The output and IO related downstream processes are implemented into NEMS framework as a write grid component that releases forecast tasks from IO tasks, and to process forecast data and to write out results. The output data are represented as ESMF fields with meta data and data values, these fields are stored in forecast grid component export state. ESMF regridding is used to transfer the data from forecast grid component to write grid component on a desired grid in various data formats including nemsio and netcdf. Downstream jobs such as post-processing and verification can be conducted on write grid component where all the output data are available. More details are at: https://vlab.ncep.noaa.gov/group/fv3gfs/ or https://vlab.ncep.noaa.gov/web/fv3gfs

6.1.5 Observation Processing System (ObsProc)

Most of the observational data at NCEP are stored in WMO BUFR format. This format is an international standard and provides an efficient means for transferring data. In addition it allows for great flexibility for adding new observation elements. A separate Observations Processing (ObsProc) system takes care of quality control and quality assessment (QA/QC) aspects of billions of observations from various sources (e.g., satellites, aircraft, rawinsondes, ships, buoys, AWS etc.) in real-time, and format them into BUFR for ingesting them into data assimilation systems and for verification and validation as well . ObsProc upgrades are generally done independent of GFS model upgrades and are handled by a separate project. More details on ObsProc are documented here

The following observation changes are included in GFS v15.1:

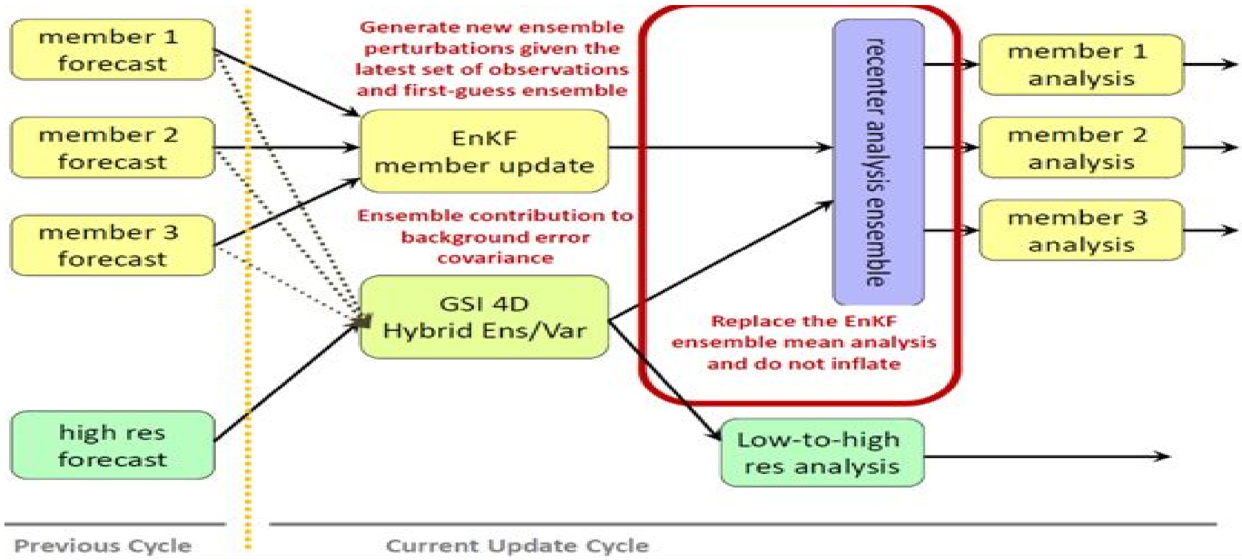
- Monitor NOAA-19 SBUV/2 (previously assimilated)
- Assimilate NPP OMPS layer and total column ozone
- Assimilate M11 SEVIRI channels 5 & 6
- Add Metop-C to satinfo but keep all sensors in monitor mode.
- Add ECMWF AMV quality control for GOES-16 and GOES-17
- Add ability to read and process buoyb sst data

In addition, the following changes will become available in July 2019 pending successful validation:

- Assimilate GOES-17 AMVs
- Assimilate Metop-C AMSU-A and MHS
- Assimilate KOMPSAT-5 (GPS-RO)
- Assimilate buoyb sst data

6.1.6 Global Data Assimilation System (GDAS)

The Global Data Assimilation System (GDAS) used by GFS is a community based Gridpoint Statistical Interpolation (GSI) that includes hybrid ensemble and variational data assimilation algorithms, designed to be flexible, state-of-art, and run efficiently on various parallel computing platforms. The current operational GDAS is based on 4D Hybrid EnVAR that includes 80 members of atmospheric model with Ensemble Kalman Filter (EnKF) and stochastic perturbations provide the flow-dependent background error covariances for generating analysis and initial conditions for the forecast model. The initial conditions for the global forecasts are obtained through the Global Data Assimilation System (GDAS). The GDAS ingests all available global satellite, conventional (rawinsonde, aircraft, surface) and radar observations with a plus or minus 3:00 hour window of the analysis time. A 9-hour C768L64 forecast from the previous GDAS cycle is used as a first guess for the assimilation. The GDAS runs with a late (6:00) data cutoff to provide the next 6 hourly cycle background using the largest amount of available observations. In the 4DEnVar formulation, the propagation of the background error covariances in time is approximated by an hourly ensemble of forecasts, rather than by a tangent linear and adjoint model as in 4DVar formulations. The 4DEnVar method is more scalable and computationally inexpensive with respect to 4DVar and is also more easily applied to other models. Within a variational framework, the hourly ensemble covariances are combined with a time-invariant estimate of the background error derived from the model's 24-48 hour forecast climatology. The ensemble covariance comprises 87.5% of the total background error covariance while the climatology portion comprises 12.5%. Additional features of the analysis formulation include a reduction of the horizontal localization length scales in the troposphere as well as the inclusion of multivariate ozone covariances. Due to the inclusion of hourly background covariances, it is now possible to extract time information from a portion of the observations. 4D thinning has been applied to the atmospheric motion vectors and the time component of the data selection procedure for all observations has been removed, no longer giving preference to observations at the center of the observing window. Another major recent addition to the GDAS is the implementation of a variational bias correction for the aircraft temperature data, reducing the warm bias in the upper troposphere. Also, the GDAS is now able to assimilate AMSU-A microwave radiances that are affected by non-precipitating clouds. The Community Radiative Transfer Model (CRTM) has also been updated to better process these cloudy radiances. More details on GSI and GDAS are at: https://www.emc.ncep.noaa.gov/gmb/gdas/



6.1.7 Coupled System Components (Land Surface, Ocean, Sea-Ice, Waves, Aerosols & Chemistry)

Current operational GFS is still uncoupled to other earth system components such as ocean, sea-ice, waves, aerosols, and chemistry. Land surface processes are considered part of the physics package along with near surface sea temperatures (NSST) providing oceanic boundary conditions. The future goals of NPS is to move towards coupled modeling using UFS infrastructure. These component models are developed in a community modeling framework and will be included in future GFS upgrades as they become mature and ready for transition to operations. As such, description of these components in the project will be limited to the ones that will be considered for operational implementation (e.g., wave model for GFS v16). Details on UFS components are published at the UFS portal.

6.1.8 Unified Post Processing, Product Generation, Tropical Cyclone Tracking, Aviation Products, Wave Model output etc.

The GFS utilizes NCEP's Unified Post Processor (UPP) system to generate forecast products in the required Grib2 format for dissemination. Using a common post processor for all NCEP weather models allows NCEP to compare and verify all model output fairly. GFS post processing system continues to add new variables with each GFS upgrades. These new variables include simulated satellite imagery, radar reflectivity, global aviation products etc., along with bufr sounding data. A separate tropical cyclone tracker is used to produce ATCF formatted tropical cyclone track, intensity, structure, and phase information. Similarly, an extra tropical tracking software is employed to generate information on non-tropical systems. GFS started to distribute higher resolution 0.25 degree data to users with its 2015 upgrade. GFS began distributing hourly 0.25 degree data up to F120 in May 2016. Potential changes to the tracker software include more flexible frequency of output and extended forecast length, and fixing known bugs.

In addition to model forecast output on regular lat-lon projection in Grib2 format, several downstream products are generated using the post-processed output to cater to various users and stakeholders. A detailed list of all products generated by GFS in operations is available at:
https://www.nco.ncep.noaa.gov/pmb/products/gfs/.

Operational wave products are currently generated independently from the UPP, and will continue to be produced this way within the GFSv16 upgrade. Wave model output data consists of gridded fields of relevant wave parameters, as well as detailed station data at relevant locations such as weather buoys and areas of interest to marine forecasters. The GFS-wave model component outputs also include boundary conditions for downstream forecast systems such as the HWRF and NWPS. The implementation of the GEFS-wave component will entail changes to grid resolutions (see section 1.4.5 below) which will allow redesigning data distribution grids in accordance to marine forecaster requests. A description of the current operational wave products is available at:
https://www.nco.ncep.noaa.gov/pmb/products/wave/.

Proposed changes to wave model products are described in:
https://docs.google.com/spreadsheets/d/1BZnHE22DBsADvg-sg_hH32Ml4VglR0vJ-Jf3etfMVU4.

6.1.9 Verification, Validation, Visualization and Model Diagnostics

Verification, validation and diagnostics are critical for supporting model development efforts and generating objective evidence for demonstrating model improvements during the upgrade cycles. A comprehensive Verification System Data Base (VSDB) developed at EMC is currently used for generating statistical verification metrics to support model evaluation efforts. Various standard verification metrics comparing model output with analysis, observations, and climatology are developed and used for both real-time and retrospective experiments. In addition, several tools including grid-to-grid verification, gird-to-obs surface verification, upper-air fit-to-observations, station-based precipitation verification, and a detailed “scorecard” showing statistical significance of model differences are used for model evaluation. Routine evaluation of global models from various global operational centers are also managed by VSDB. More details on VSDB and its functionality are documented at: https://www.emc.ncep.noaa.gov/gmb/STATS_vsdb/

The UFS community have chosen to use the community based Model Evaluation Tools (MET) developed at NCAR, and EMC is in the process of transitioning all V&V software to use MET. Transition of VSDB to MET for global model verification is expected to happen in summer 2019, ready for use in GFS v16 evaluation, and for use by the modeling team in efforts within the GFS v16 development workflow. More information on MET, METplus, and associated functionality are documented at: https://ral.ucar.edu/solutions/products/model-evaluation-tools-met

In addition to objective evaluation of model performance, several diagnostic capabilities along with visualization tools are developed to support subjective evaluation of selected case studies recommended by the field (usually associated with high impact weather events). These efforts are managed by the Model Evaluation Group (MEG) of EMC's Verification, Post-Processing, and Product Generation Branch. MEG coordinates all evaluation aspects of the model upgrades, and for the first time, led an unprecedented official evaluation of GFSv15.1 with a one-stop-shop website https://www.emc.ncep.noaa.gov/users/meg/fv3gfs/ documenting each stage of the evaluation leading to operational implementation.

The V&V team will also assist in developing a comprehensive test and evaluation plan for the GFS, an early version of which will be available for limited use and guidance during the development phase of GFS v16, with a more comprehensive version available for GFS v17. This test plan will include additional involvement of the V&V team throughout the development process, through the creation of V&V tools for use by the modeling team, identification of a standard suite of case studies to use during routine development and testing, and the use of MEG expertise to examine the result of GFS algorithm introductions and adjustments during the development process. These activities will occur prior to scientific code completion and retrospective run creation (i.e., "frozen" code).

6.1.10 Workflow, NCEP Libraries, Utilities, System Engineering and Code Management

Robust software infrastructure is required for supporting system architecture design and execution of complex modeling systems for research and operations. It is equally important to have reliable and reproducible workflow components with sophisticated exception handling for building and porting the codes to various HPC architectures. These include various software libraries, tools for system integration, configuration management, code repository management, and flexibility to operate in multiple environments. A robust global_workflow was developed and implemented for use with GFS v15.1 upgrade using rocoto workflow manager for research and development, and ecFlow for operations.

The system is designed based on principles that will allow the requirements and constraints to be met; minimize risks and impacts of the assumptions; and advance NCEP in the direction of the key drivers. A set of shared scientific libraries (NCEP Libraries) are developed to provide support of NCEP models development, management, and operations. Additional community based libraries include ESMF, CRTM, NUOPC Mediator, NetCDF etc.

Robust code management is another crucial element of system integration. Currently, all GFS codes are managed using Git, Gerrit and redmine based collaboration and development services offered by NOAA's VLab. VLab facilities are also used to support general project management aspects including issue tracking, risk management, and inter-dependencies of tasks. The following code management procedure is used for making changes to the GFS codes:

- Proposal of changes, including expected code and science impacts submitted by the developer through ticket system
- Evidence-based review of science impacts before final code review
- Review committee evaluates proposal and provides feedback
- If okayed, branch is created and software work completed
- Run regression tests in the branch to evaluate impacts on science and computational performance
- Master branch development merged into the branch, submit for code review
- Code review done by review committee and code manager
- Code is committed to repository

More details on access to the codes and code management procedure (including rigorous regression tests) are available at: https://vlab.ncep.noaa.gov/redmine/projects/nemsfv3gfs/wiki

A more robust code management using the GITFLOW model (see https://docs.google.com/document/d/1H5McooP-ZmDIOhcy4zJwdFVk3DyjbJt_Nyqj4QGBRBU/edit?usp=sharing) and repository plan is being developed for community based UFS development efforts on Github.com. Until that becomes available, GFS v15.1 and GFS v16 implementations will continue using VLab Git for code management. Three categories of branches will be made available in github:

1. **pre-dev** (light testing, fast commit, broad options, serving community),
2. **dev** (tested for all the FV3 related applications, only contains options having potential for implementation),
3. **master** (implementation branches, FV3GFS, SAR, HAFS, etc. relatively fixed configuration, tested through parallel runs, targeted for implementa
4. tion)

6.2 Project Status and Reporting

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 GFS weekly technical meetings (link). Regular coordination meetings to monitor and coordinate all activities related to GFV v16 development and transition to operations will start about two years priorior to operational implementation (link)

In addition, all activities related GFS v16 are tracked in the EMC PM projects through Vlab redmine (link).

6.3 References

Development and iImplementation plans

- The UFS Strategic Implementation plan (link)
- GFS v16 project plan and charter; this document (link)
- The physics plans (GFS v16 suite selection report, Independent panel report for GFS physics, GFS v16 supplementary test plan, GMTB)
- Data Assimilation plan for GFS v16 (link)
- Data Assimilation Observations plan (link)
- Verification and Validation plan for GFS v16 (link)
- Wave modeling plan (link)
- GFS v16 forecast timing test (link)
- GFS v16 DA timing test (link)
- Unified FV3-base weather and climate at GFDL (link)
- NPS GFS v16 downstream dependencies (link)
- 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

- GFS v16 T2O quad chart (link)
- FV3 Global development quad (link)
- DA development quad (DA Infrastructure, DA Observations)
- Physics development quad (link)
- Infrastructure development quad (link)
- Couple system development quad (link)
- Wave modeling development quad (link)
- Post Processing and Products development quad (link)
- Model evaluation quad (link)
- Verification quad (link)
- ObsProcessing quad (link)
-

More details about the tasks and activities can be found in Vlab Redmine EMC projects (restricted to EMC members only)

- EMC projects (link)

STI AOP Milestones related to GFS development and implementation:

- Q1FY20: Integrate METplus into GFS workflow for internal GFS v16 testing and development
- Q4FY20: Update WAFS icing and turbulence algorithms to work with GFS V16
- Q4FY20: Complete development, testing and evaluation of GFS v16

6.4 Acronyms

List of related acronyms can be found here