Development and Evaluation of NCEP's Global Forecast System Version 16

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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

GFSv16 Acknowledgements

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<th>Major components upgrade</th>
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<td>64</td>
<td>T254 (55km)</td>
<td>Sigma Eulerian</td>
<td>SSI to GSI</td>
</tr>
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<td>T382 (35km)</td>
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<td>Jul 2010</td>
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<td>T574 (23km)</td>
<td>Hybrid Eulerian</td>
<td>4-D Hybrid En-Var DA</td>
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<td>Jan 2015</td>
<td>64</td>
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<td>Finite-Volume</td>
<td>NGGPS FV3 dycore</td>
</tr>
</tbody>
</table>
GFS Historical Performance

NH 500-hPa HGT Day-5 ACC Frequency Distribution
Day at which forecast loses useful skill (AC=0.6)
N. Hemisphere 500hPa height calendar year means

Forecast day
GFS.v15 Transition to Operation

*Finite-Volume Cubed-Sphere Dynamical Core (FV3)*

*Microphysics Scheme with Multiple Prognostic Cloud Hydrometers*

In Operation: June 12, 2019

**Configuration:**
- High-res: C768 (~13km)
- Data Assimilation: C384 (~25km, 80 member ensemble)
- 64 layer, top at 0.2 hPa
- Uniform resolution for all 16 days of forecast
- Dycore: FV3, non-hydrostatic, single precision
- Physics: GFS Physics + GFDL Cloud Microphysics, double precision
A gain of 0.011

Increase is significant up to day 10
GFS.v15 - Improved Precipitation Forecast

Precip ETS and BIAS SCORES over the Continental US
00Z Cycle, verified against gauge data, 20150601~20180912

- Improved ETS scores for almost all thresholds and at all forecast length
- Reduced wet bias for light rains
- Slightly worsened dry bias for moderate rainfall categories

Summer 2018 CONUS Domain-Avg PCP

Improved Precipitation Diurnal Cycle
GFS.v15 shows a much better wind-pressure relation than GFS.v14 (GSM) for strong storms.

Graph made by HWRF group.
Excessive cold bias in the winter season

Progressive bias for synoptic scale systems

Less skillful TC track forecasts, especially for stronger storms

Temperature cold bias in the stratosphere

Poor representation of boundary layer inversions
# Change History of GFS Configuration

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<tr>
<td>Feb 2021</td>
<td>127</td>
<td><strong>FV3 (13km)</strong></td>
<td>Finite-Volume</td>
<td>IAU, LETKF, TKE-EDMF, uGWD</td>
</tr>
</tbody>
</table>

18 years !
GFSv16: Major Changes to the Forecast Model

Model resolution:
Increased vertical layers from 64 to 127 & raised model top from 54 km to 80 km

Physics updates:
- **PBL/turbulence:** Replaced K-EDMF with sa-TKE-EDMF (Revised background diffusivity as a stability dependent function)
- **GWD:** Added a parameterization for subgrid scale nonstationary gravity-wave drag
- **Radiation:** Updated calculation of solar radiation absorption by water clouds; Updated cloud overlap assumptions.
- **Microphysics:** Updated GFDL microphysics scheme for computing ice cloud effective radius
- **Noah LSM:** Revised ground heat flux calculation over snow covered surface; Introduced vegetation impact on surface energy budget over urban area

Coupling to Wave Model:
One-way coupling of atmospheric model with Global Wave Model (WaveWatch III, Multi_1)
GFSv16: Major Changes to the Forecast Model

New TKE-EDMF PBL:

- Higher-order accuracy in turbulence representation, less diffusive than K-EDMF
- Advection of turbulence by the grid-mean flows
- Inclusion of moist processes
- Mass-flux representation for the nonlocal momentum mixing
- EDMF parameterization for the stratocumulus-top-driven turbulence mixing
- Scale awareness
- Interaction of TKE with cumulus convection
GFSv16: Major Changes to the Forecast Model

Non-Stationary GWD: Impact on QBO/SAO

In collaboration with CIRES, UCB

- Current operational model cannot simulate the QBO
- A QBO-like feature is captured in GFS.v16 “climate” run with the non-stationary GWD physics included; However, the periodicity is too short, appears to be a downward propagating SAO.
Forecast improvements in the Stratosphere

Improved 1-hPa Temperatures:
60N-90N  Dec 2019 – Jan 2020

Captured water vapor seasonal cycle in the stratosphere, compares well with UARS HALOE observations (Sept. 2019-May 2020)

Figures courtesy: Craig Long, CPC
Improved ice cloud – radiation interactions

Use Wyser (1998) formula to calculate $r_{\text{eff-ice}}$ as a function of $q_i$ and $T$ for $q_i > q_{\text{min}}$ instead of using a constant $r_{\text{eff-ice}}$

In collaboration with GFDL

reduced tropospheric cold bias
Addressing Model Stability Issues

- The GFS.v16 had a few model crashes in early September when a strong typhoon passed over a small island over southern Japan. EMC worked with GFDL to diagnose the cause of the crashes and tested a few options to stabilize the model. All crashed cycles had excessive vertical velocities (>300 m/s) and delp becoming negative.
- The model failures have close resemblance to similar failed cases for GEFSv12, which was addressed by applying the 2dz filter to 100hPa and above (n_sponge=23 instead of 4). However, GFSv16 with similar settings (n_sponge=40) did not recover the failures.
- After several trials, a solution was implemented by extending the delta-z filter in the vertical from the model top down to the tropopause and increasing the value of a minimum layer thickness parameter which enforces height monotonicity.

In collaboration with GFDL

- All crashed cases were recovered.
- This solution was tested in both forecast-only experiments and a cycled experiment. It has a very small impact on the forecast skills and proved to be efficient in removing the model instability issues.
One-Way Coupling to Wave Model

Operational Multi_1 (GWMv3)
- Arctic Polar Stereographic
  - 18 km resolution
  - 50°N to 90°N
- Global grid: 30 arc min
- Regional grids: 10 arc min
  - ak_10m; wc_10m; at_10m; ep_10m
- Coastal grids: 4 arc min
  - ak_4m; wc_4m; at_4m
- No ocean current interactions

GFSv16-Wave Component
- Arctic Polar Stereographic: 9 km resolution
  - 50°N to 90°N
- Global grid: 16 km (10 arcmin)
  - 15°S to 52.5°N
- Southern Ocean: 25 km (15 arcmin)
  - 10.5°S to 79.5°S
- Removal of regional and coastal grids
- New RTOFS ocean surface current forcing up to 192h
- Forecasts will be extended from 180 hr to 384 hr.
- Improved Wave Physics
Major Upgrades to GDAS

- **Local Ensemble Kalman Filter (LETKF)** with model space localization and linearized observation operator to replace the Ensemble Square Root Filter (EnSRF)
- **4-Dimensional Incremental Analysis Update (4D-IAU)**
  - Turn on SKEB in EnKF forecasts
  - New variational QC
  - Apply Hilbert curve to aircraft data
  - **Correlated observation error** for CrIS over sea surfaces and IASI over sea and land
  - Update temperature aircraft bias correction with safeguard
  - Assimilate AMSU-A channel 14 and ATMS channel 15 w/o bias correction

- Assimilate CSR data from ABI_G16, AHI_Himawari8, and SEVIRI_M08; AVHRR from NOAA-19 and Metop-B for NSST
- **Assimilate additional GPSRO** (add Metop-C GRAS, More Cosmic-2)
- **Assimilate** high-density flight-level wind, temperature, and moisture observations (HDOBS) in tropical storm environment (first time in operations for GFS)
- Reduce the distance threshold for inner core dropsonde data to 55km (from 111km or 3*RMW) and add a wind threshold of 32 m/s to allow more dropsonde data being assimilated
- Use CRTM v2.3.0
RMS O-F (2019112400-2019122306)

All Insitu V: GL

All Insitu T: GL

All Insitu RH: GL

In collaboration with OAR/PSL
A new variational quality control is applied to conventional observations.

Previous variational quality control could not be applied in the first iterations of minimization due to the possibility of multiple minima in the cost function.

New probability density function formulation greatly reduces the possibility of multiple minima.

Greatest impact in wind RMSE and in the northern hemisphere.
New Assimilation of HDOBS

Significant improvements in track forecast errors, especially for strong storms.
Infrastructure changes

• **Change the model output format from nemsio to compressed netCDF**
  • A new parallel I/O was developed with updated netCDF and HDF libraries
  • 3D Atmospheric fields will have 5x compression (33.6 GB to 6.7 GB, lossy compression)
  • Surface 2D fields will have 2.5x compression (2.8 GB to 1.1 GB, lossless compression)

• **Pre-Processing Changes**
  • obsproc_global and obsproc_prep was updated to process new satellite observations, high density aircraft observations, and to work with model history files in netCDF format.

• **Inline Post-Processing**
  ◦ Inline post makes use of forecast data saved in memory for post processing, reduces I/O activity, and speeds up the entire forecast system.
  ◦ A Post library was created using the offline post Fortran programs. It can be called by the Write Grid Component within the forecast model.
  ◦ Since lossy compression is applied for writing out forecast history files, inline post generates more accurate products than the standalone offline post.
  ◦ Simulated satellite radiance and WAFS files are still made by the offline post.
Impact on Computational Resources

<table>
<thead>
<tr>
<th>Model</th>
<th>GFS v15</th>
<th>GFS v16</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>time (min)</td>
<td>nodes</td>
</tr>
<tr>
<td>gfs_analysis</td>
<td>28.0 - 28.7</td>
<td>240</td>
</tr>
<tr>
<td>gdas_analysis_high</td>
<td>32.2 - 33.0</td>
<td>240</td>
</tr>
<tr>
<td>gfs_forecast_high</td>
<td>100.8 - 103.4</td>
<td>148</td>
</tr>
<tr>
<td></td>
<td>(6.38 min/day)</td>
<td></td>
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<tr>
<td>wave_fcst</td>
<td>53.8 - 54</td>
<td>18</td>
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<tr>
<td>gdas_forecast_high</td>
<td>11.5 - 11.7</td>
<td>28</td>
</tr>
<tr>
<td>enkf_update</td>
<td>6.5 - 6.8</td>
<td>90</td>
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<tr>
<td>enkf_fcst_X</td>
<td>19.7 - 19.8</td>
<td>14 x 20 = 280</td>
</tr>
<tr>
<td>Machine &amp; Throughput</td>
<td>Period to be covered (total days)</td>
<td>Wave starting Cycle</td>
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<tr>
<td>----------------------</td>
<td>----------------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>v16retro0e Mars Dell 3.5 7 cycles/day</td>
<td>05/10/19~05/31/19 (26)</td>
<td>No WAVE</td>
</tr>
<tr>
<td>v16retro1e Mars Dell 3.5 7 cycles/day</td>
<td>06/1/19~08/31/19 (92)</td>
<td>2019060712</td>
</tr>
<tr>
<td>v16retro2e Mars Dell 3.0 4 cycles/day</td>
<td>09/1/19~11/30/19 (91)</td>
<td>2019090918</td>
</tr>
<tr>
<td>v16retro3e HERA 7 cycles/day</td>
<td>12/01/19 ~ 05/19/20 (169)</td>
<td>2020013106</td>
</tr>
<tr>
<td>v16retro5e Venus Dell 3.5 4 cycles/day</td>
<td>08/31/18~10/12/18 (43)</td>
<td>No Wave</td>
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<tr>
<td>v16rt2 Mars Dell 3.0</td>
<td>05/19/20 ~</td>
<td>2020051900</td>
</tr>
</tbody>
</table>
Carried out by EMC Model Evaluation Group with contributions from GFS.v16 model developers, NWS STI Science Operations Officers (SOO), and community collaborators.

https://www.emc.ncep.noaa.gov/users/meg/gfsv16/

- The GFSv16 official evaluation included analyses of:
  - Retrospectives (5/5/19–5/18/20; added 8/31/18–10/12/18)
    - Statistics
    - 50 Case Studies
  - Real-time Parallel (5/19/20–09/16/20)
    - Statistics
    - Representative examples

Evaluation of WAVE forecasts is skipped in this presentation.
Common Strengths From All Evaluations

- Notable improvements in synoptic-scale performance in the medium-range
  - Progressive bias in GFSv15 appears mitigated with better consistency catching correct solutions earlier
  - Improved frontal positions and QPF

- Improvement in low-level temperature forecasts (mitigation of the winter low-level cold bias)

- Better ability to resolve shallow, cold air masses and some associated cold air damming events

- Improvements to TC intensity and increased lead time for genesis
  - With stronger TCs, GFSv16 has overall better track, size, and intensity
Strengths: 500-hPa AC Scores (Global)

Valid: 6/12/19–9/16/20 (Day 5)

GFSv15 = .888
GFSv16 = .895

GFSv15 = .891
GFSv16 = .896

GFSv15 = .882
GFSv16 = .890

Statistically Significant
### GFSv16 AC Scores (NH 500-hPa Z at Day 5)

<table>
<thead>
<tr>
<th></th>
<th>GFSv15 (OPS)</th>
<th>GFSv16 (RETRO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall 2018</td>
<td>0.916</td>
<td>0.916</td>
</tr>
<tr>
<td>May 2019</td>
<td>0.880</td>
<td>0.897</td>
</tr>
<tr>
<td>Summer 2019</td>
<td>0.880</td>
<td>0.888</td>
</tr>
<tr>
<td>Fall 2019</td>
<td>0.897</td>
<td>0.901</td>
</tr>
<tr>
<td>Winter/Spring 2020</td>
<td>0.909</td>
<td>0.913</td>
</tr>
<tr>
<td>Real-Time Parallel</td>
<td>0.864</td>
<td>0.871</td>
</tr>
<tr>
<td>Full Retro Period</td>
<td>0.890</td>
<td>0.896</td>
</tr>
</tbody>
</table>
GFSv16 forecasted the location of this and other cutoff lows earlier and more consistently than GFSv15, with some mitigation of the progressive issue noted in the GFSv15 evaluation.

Several evaluators noted that GFSv16 showed more run-to-run continuity than GFSv15.

TC Olga Case
Fcnt: 00z 10/20/20 (F144)
Valid: 00Z 10/26/20
Strengths: Improved QPF ETS and Bias

Valid: 6/12/19–9/23/20 (F120)

Equitable Threat Score (ETS)

- 24-h QPF improvements appear most pronounced in the medium range, which is consistent with improved 500-hPa AC scores
  - **F120**: Statistically significant improvement at 0.2–35 mm thresholds

24-h QPF ETS
Strengths: Improved QPF ETS and Bias

Valid: 6/12/19–9/23/20 (F120)

- 24-h QPF bias improvements also most pronounced in the medium range
- Reduction of the high bias at lower QPF thresholds is statistically significant
- Reduction of the low bias at medium-to-high QPF thresholds is statistically significant
- Overall bias improvement is seen in the short range as well
Strengths: Improved QPF ETS and Bias

West Coast Bomb Cyclone Case
Fcst: 00z 11/22/19 (F132)
Valid: 12Z 11/27/19

- GFSv16 consistently had (correctly) higher QPF amounts inland over N California and Oregon for this case
Common Strengths From All Evaluations

- Notable improvements in synoptic-scale performance in the medium-range
  - Progressive bias in GFSv15 appears mitigated with better consistency catching correct solutions earlier
  - Improved frontal positions and QPF

- Improvement in low-level temperature forecasts (mitigation of the winter low-level cold bias)

- Better ability to resolve shallow, cold air masses and some associated cold air damming events

- Improvements to TC intensity and increased lead time for genesis
  - With stronger TCs, GFSv16 has overall better track, size, and intensity
GFSv15 has a known low-level cold bias that gets worse with lead time.

GFSv16 has less of a cold bias at longer lead times.

GFSv16 has lower RMSE at and after F036.
Strengths: Mitigated Low-Level Cold Bias

Western US – Winter/Spr. 2020

GFSv16 has less of a cold bias at longer lead times for 00z valid times

GFSv15
GFSv16
2-m T Bias

Eastern US – Winter/Spr. 2020

GFSv16 has less of a cold bias at longer lead times

GFSv15
GFSv16
2-m T Bias

Grid-to-Obs
Common Strengths From All Evaluations

- Notable improvements in synoptic-scale performance in the medium-range
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- Improvements to TC intensity and increased lead time for genesis
  - With stronger TCs, GFSv16 has overall better track, size, and intensity
Strengths: Temps in Shallow, Cold Air Masses

- GFSv16 was correctly colder than GFSv15 over VA/MD area, where cold air damming is occurring along the eastern Appalachians.

- Improved 2-m T forecasts in shallow, cold air masses may be tied to a better handling of low-level clouds.

- This is a long-standing GFS issue for which there seems to be some v16 improvement.
**Strengths: Resolved Low-level Warming Issue**

- An odd GFSv15 low-level warming issue that was seen a few cases last winter in GFSv15 appears to be resolved in GFSv16. In this example, GFSv15 forecasts rain over IA/IL/WI/MO where snow occurred; GFSv16 forecast is much improved.

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**Midwest Ptype Event**

Fct: 12z 01/20/20 (F084)

Valid: 00Z 01/24/20

Thanks to Ray Wolf (WFO DVN)
Common Strengths From All Evaluations

- Notable improvements in synoptic-scale performance in the medium-range
  - Progressive bias in GFSv15 appears mitigated with better consistency catching correct solutions earlier
  - Improved frontal positions and QPF

- Improvement in low-level temperature forecasts (mitigation of the winter low-level cold bias)

- Better ability to resolve shallow, cold air masses and some associated cold air damming events

- Improvements to TC intensity and increased lead time for genesis
  - With stronger TCs, GFSv16 has overall better track, size, and intensity
Strengths: Identifies TCs More Often & Earlier

- **Legend:**
  - x-axis: Success Ratio (1−FAR)
  - y-axis: Probability Of Detection (POD)
  - dashed lines: Frequency Bias
  - solid lines: Critical Success Index (CSI)

- All values would equal 1 in a perfectly performing model

- On average, GFSv16 exhibits:
  - Larger POD and CSI (closer to 1)
  - Frequency Bias is closer to 1
  - Smaller Success Ratio (FAR too high)

- GFSv16 is more cyclogenetic than GFSv15, and it identifies genesis with more lead time.

Thanks to Dan Halperin (ERAU)
GFSv16 has lower track error than GFSv15 for strong TCs (≥65 kt) during most of the medium range in both the North Atlantic and East Pacific.
**Strengths: Improved Medium-Range Track Error**

TC Dorian
Fcst: 00z 08/30/19 (F132)
Valid: 12Z 09/04/19

- GFSv16 forecasted Dorian to track north of Puerto Rico more than 24 h earlier than GFSv15 (not shown)

- Shown here, GFSv16 forecasted Dorian to turn right and skim the Florida coast 36 h earlier than GFSv15
GFSv16 has lower intensity error than GFSv15 at almost all lead times in the N Atlantic.

GFSv16 has less of a weak bias than GFSv15 at longer lead times.
Strengths: Improved TC Intensity in N Atlantic

TC Michael
Fcst: 12z 10/08/18 (F048)
Valid: 12Z 10/10/18

- Michael: GFSv16 consistently (and correctly) forecasted a stronger TC than GFSv15
• Increased right-of-track bias at longer lead times for North Atlantic TCs

• Larger TC False Alarm Rate (FAR) in the western North Atlantic (70°W–50°W)

• Exacerbation of low instability (i.e., CAPE) bias that already existed in GFSv15, driven largely by dry soil moisture

• Lack of considerable improvement in forecasting radiation inversions
Concerns: Increased Right-of-Track Bias

**MODEL FORECAST – ALONG TRACK BIAS (NM) STATISTICS**
GFS V16/V15 Atlantic 2018–2020

**MODEL FORECAST – CROSS TRACK BIAS (NM) STATISTICS**
GFS V16/V15 Atlantic 2018–2020

- **N Atlantic Along-Track Bias**
  - GFSv15
  - GFSv16

- **N Atlantic Across-Track Bias**
  - GFSv16
  - GFSv15

A slower and right-of-track bias at longer lead times suggests that GFSv16 may be recurving TCs earlier than GFSv15.

GFSv16 has a larger slow bias than GFSv15 that grows with forecast length in the N Atlantic.

GFSv16 has a larger right-of-track bias than GFSv15 that is largest at longer lead times.
• Increased right-of-track bias at longer lead times for North Atlantic TCs

• Larger TC False Alarm Rate (FAR) in the western North Atlantic (70°W–50°W)

• Exacerbation of low instability (i.e., CAPE) bias that already existed in GFSv15, driven largely by dry soil moisture

• Lack of considerable improvement in forecasting radiation inversions
Larger TC False Alarm Rate

Large number of false alarms in GFSv16, relative to v15, between 50° and 70° W

From Dan Halperin, ERAU
Common Concerns Across the Evaluations

- Increased right-of-track bias at longer lead times for North Atlantic TCs
- Larger TC False Alarm Rate (FAR) in the western North Atlantic (70°W–50°W)
- Worsened low instability (i.e., CAPE) bias that already existed in GFSv15
- Lack of considerable improvement in forecasting radiation inversions
Operational GFSv15 CAPE analyses/forecasts are consistently lower than obs.

CAPE magnitudes in GFSv16 analyses/forecasts are consistently lower than those from GFSv15.
CAPE Magnitudes Are Reduced in GFSv16

- GFSv16 CAPE was notably lower across the Northern and Central Plains, as well as over the Gulf Coast region and southeast; smaller reductions over the northeast, Ohio Valley, and Mexico.
Tendency to Overmix the Boundary Layer

GFSv15  GFSv16  Obs

- **GFSv16** PBL was drier/warmer/deeper than **GFSv15** and **obs** in the unstable air
• Increased right-of-track bias at longer lead times for North Atlantic TCs

• Larger TC False Alarm Rate (FAR) in the western North Atlantic (70°W–50°W)

• Exacerbation of low instability (i.e., CAPE) bias that already existed in GFSv15, driven largely by dry soil moisture

• Lack of considerable improvement in forecasting radiation inversions
Inversions - BIS soundings

Bismarck, ND (BIS)

Fcst: 12Z 04/29/20 (F024)
Valid: 12Z 04/30/20

- GFSv15 and v16 both fail to capture the strength of the low-level inversion and end up way too warm at the lowest levels
- GFSv16 shows very modest improvement over v15
- Note how the observed winds are weak at the lowest level; both GFS versions have winds that are too strong
Summary of GFSv16 Objectives

➢ Science Changes: Increase the vertical resolution (from 64 to 127 levels), implementation of advanced physics; Advanced 4D-IAU data assimilation with LETKF, new Variational QC and use of additional satellite and aircraft (HDOBS) data; One-way coupling to deterministic Global Wave Model (WaveWatch III) within the UFS framework towards simplifying the production suite.

➢ Performance Evaluation
- Excessive cold bias in the winter season – mitigated
- Progressive bias for synoptic scale systems - improved
- Less skillful TC track forecasts, especially for stronger storms - improved, especially with HDOBS assimilation
- Low bias for stratospheric temperature forecasts - improved
- Precipitation dry bias for moderate rainfall - improved
- Poor representation of boundary layer inversions – Not much improvement.
GFSv16 Development and T2O Timeline

- Development started after GFS.v15 implementation – 6/12/2019
- Project Plan and Charter drafted and approved – 9/5/2019
- Freeze GFSv16 configuration (including waves) for retrospectives – 5/19/2020
- Produce full retrospective and real-time experiments: 8/31/2020
- Deliver PNS to HQ:
  - Complete field evaluation: 9/25/2020
  - EMC CCB: 9/30/2020
  - MEG final briefing: 10/1/2020
  - Science briefing to NCEP OD: 10/05/2020
  - Final IT and EE2 compliance – 10/08/2020
  - Deliver final package to NCO: 10/09/2020
- Transition to Operations: 02/03/2021 (Planned)
Fully coupled atm-ocn-ice-wave model for MRW/S2S operation in 2024
thanks you