Descriptions of the Major Modeling Systems Operated at NOAA/NWS/NCEP

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ABSTRACT

Both Nationally within the U.S. and internationally there is a growing awareness of the requirement to develop and deploy significantly enhanced numerical earth system prediction capabilities necessary to address evolving societal needs for natural disaster preparedness, adaptation to climate change, ensuring food security for growing planetary population, national security and defense as well as future economic prosperity. Internationally, consortia of interested scientists are bringing the science and technology needs and challenges of earth-system prediction into focus.

NOAA's Models provide information on the future state of weather, short-term and long-term climate, ecosystems, the ocean, and thus significantly contribute to the decision making process for individuals through policy makers, and for sectors ranging from water resources to financial markets. The modeling projects proposed are designed to advance the foundational NOAA operational numerical guidance system and directly support the goals set forth in the NOAA Next Generation Strategic Plan (NGSP): 1) Climate Adaptation and Mitigation; 2) Weather-Ready Nation; 3) Healthy Oceans; and 4) Resilient Coastal Communities and Economies. In addition, the numerical guidance systems directly support the NWS mission to provide weather, water, and climate data, forecasts and warnings for the protection of life and property and enhancement of the national economy. Specific NWS goals supported include: 1) Deliver a broad suite of improved water forecasting services to support management of the Nation's water supply; 2) Enhance climate services to help communities, businesses, and governments understand and adapt to climate related risks; 3) Improve sector relevant information in support of economic productivity, and; 4) Enable integrated environmental forecast services supporting healthy communities and ecosystems.

This document provides descriptions and near-future plans for the major components of the NCEP production suite. Additional details can be obtained for each system upon request.

1.0 The NCEP Global Forecast System (GFS)

(Updated 1 June 2012, Shrinivas* Moorthi Shrinivas.Moorthi@noaa.gov *)

The NCEP's Global Forecast System (GFS) is the cornerstone of NCEP's operational production suite of numerical guidance. NCEP's global forecasts provide deterministic and probabilistic guidance out to 16 days. The GFS provides initial and/or boundary conditions for NCEP's other models for regional, ocean and wave prediction systems. The Global Data Assimilation System (GDAS) utilizes maximum amounts of satellite and conventional observations from global sources and generates initial conditions for the global forecasts. The global data assimilation and forecasts are made four times daily at 0000, 0600, 1200 and 1800 UTC.

1.1 Forecast model:

The atmospheric forecast model used in the GFS is a global spectral model (GSM) with spherical harmonic basis function. In response to increased computing resources and changing computer architecture at NCEP, the GFS has evolved to higher resolution, both horizontally and vertically, and a more modular code structure. The current horizontal resolution is T574 (T190), or approximately 27 km (80km) for the week one (two) forecasts, and vertically there are 64 layers in a domain from the surface to 0.27 hPa (approximately 55 km). The GFS adiabatic dynamics and physics require application of Fourier and Legendre transforms to convert between spectral and grid-point spaces. Advective processes are computed on the transform grid from spectral coefficients. A hybrid sigma-pressure vertical coordinate option is used. A leap-frog with semi-implicit time integration scheme is used along with Asselin time filter. Physical parameterizations and non-linear dynamics computations are applied on a reduced (quadratic) Gaussian grid for computational economy. A positive-definite tracer transport scheme (Yang et al., 2009) is used in the vertical.

It is important to note that the same physical parameterization package is used across all horizontal and vertical resolutions (with slightly different tunable parameter). Upgrades to the physical parameterizations are ongoing and occur on the average of every other year.

1.2 Changes to physical parameterization since 2007 include:

1.2.1 Radiation:

The longwave (LW) and the shortwave (SW) radiation parameterizations in NCEP's operational GFS are both modified and optimized versions of the Rapid Radiative Transfer Models (RRTMG_LW v2.3 and RRTMG_SW v2.3, respectively) developed at AER Inc. (Mlawer et al. 1997, Iacono et al., 2000, Clough et al., 2005). The LW algorithm contains 140 unevenly distributed g-points in 16 broad spectral bands, while the SW algorithm includes 112 g-points in 14 bands. In addition to the major atmospheric absorbing gases of ozone, water vapor, and carbon dioxide, the algorithm also includes various minor absorbing species such as methane, nitrous oxide, oxygen, and up to four types of halocarbons (CFCs). A maximum-random cloud overlapping method is used in both LW and SW radiation calculations. Cloud condensate path and effective radius for water and ice are used for calculation of cloud-radiative properties. Hu and Stamnes' method (1993) is used to treat water clouds in both LW and SW parameterizations. For ice clouds, Ebert and Curry's method (1992) is used in the LW while Fu's scheme (1996) is used for the SW.

In the operational GFS, a climatological tropospheric aerosol with a 5-degree horizontal resolution is used in both LW and SW radiations. A generalized spectral mapping scheme was developed to compute radiative properties of various aerosol components for each of the radiation spectral bands. A separate stratospheric volcanic aerosol scheme was added that is capable of handling volcanic events. In SW, incoming solar constant is held constant at 1366 W/m2 in the operational GFS. However, an option to use an eleven-year solar cycle was also added for long term simulation (or climate) purpose. SW albedo scheme uses surface vegetation type based seasonal climatology similar to that described in the NCEP Office Note 441 (Hou et. Al, 2002) but with a modification in the treatment of solar zenith angle dependency over snow-free land surface (Yang et al. 2008). Black-body surface emissivity is assumed for the LW radiation. Concentrations of atmospheric greenhouse gases are either obtained from global network measurements, such as carbon dioxide (CO2), or taking the climatological constants, such as methane, nitrous oxide, oxygen, and CFCs, etc. In the operational GFS, the actual CO2 value for the forecast time is an estimation based on the most recent five-year observations.

1.2.2 Boundary layer:

The boundary layer scheme is upgraded by including stratocumulus-top driven turbulence mixing and by enhancing stratocumulus-top driven diffusion when the condition for cloud top entrainment instability is met. A local diffusion scheme for the nighttime stable boundary layer is used. The background diffusivity in the lower inversion layers is reduced to 30% of that at the surface to avoid excessive erosion of stratocumulus along coastal areas.

1.2.3 Gravity wave drag and mountain blocking:

The gravity wave drag and mountain blocking parameterizations are modified to automatically scale with model resolution (T382L64 -> T574L64). Compared to the T382L64 version of GFS, the T574L64 version uses four times stronger mountain blocking and one half the strength of gravity wave drag.

1.2.4 Shallow convection:

A new mass flux shallow convection scheme is developed based on the bulk mass-flux parameterization of deep convection. Separation of deep and shallow convection is determined by cloud depth (currently 150 hPa). Entrainment rate is given to be inversely proportional to height and much larger than that in the deep convection scheme. Mass flux at cloud base is given as a function of the surface buoyancy flux.

1.2.5 Deep convection:

The Simplified Arakawa-Schubert (SAS) deep convection scheme is revised to make cumulus convection stronger and deeper to reduce excessive grid-scale precipitation. Random cloud-top selection is replaced by an entrainment rate approach with an environmental moisture dependent entrainment rate. The convective overshooting as well as the effects of convection-induced pressure gradient force (which reduces convective momentum transport) are included. The cloud condensate is detrained from upper cloud layers above downdraft initiating level.

1.2.6 The Noah Land Surface Model (LSM):

In early 2005 the land surface model (LSM) of GFS was upgraded from two soil layer (10, 190 cm thick) Oregon State University model to four soil layer (10, 30, 60, 100 cm thick) Noah model. The Noah LSM includes addition of frozen soil physics, new formulations for infiltration and runoff (giving more runoff for unsaturated soils), revised physics of the snowpack and its influence on surface heat flux and albedo, tuning and addition of canopy resistance parameters, spatially varying root depth, revised treatment of ground heat flux and soil thermal conductivity, reformulation for dependence of direct surface evaporation on first layer soil moisture, and improved seasonality of green vegetation cover. The frozen soil physics includes soil heat sinks/sources from freezing/thawing and influences vertical transport of soil moisture, soil thermal conductivity and heat capacity, and surface infiltration. The prognostic states of snowpack depth and liquid soil moisture were added to the already present prognostic states of snowpack water-equivalent (SWE), total soil moisture (liquid plus frozen), soil temperature, canopy water, and skin temperature. SWE divided by the snowpack depth gives the snowpack density. Total soil moisture minus liquid soil moisture gives the frozen soil moisture.

The addition of Noah LSM greatly reduced the two prominent biases in land-surface processes: 1) an early depletion of snowpack; and 2) a high bias in both surface evaporation and precipitation in the warm season in non-arid mid-latitudes. However, a lower tropospheric warm bias as well as increased surface sensible heat flux emerged, particularly, over the arid areas during the daytime. Extensive tests attributed this bias mainly to improper treatment of the thermal roughness length. In May 2011, a new thermal roughness length scheme, which assigned a smaller value for the thermal roughness length compared to the momentum roughness length, was implemented. This greatly reduced the warm surface air temperature bias and the cold skin temperature bias over the arid areas during the daytime.

1.3 The Global Data Assimilation System (GDAS):

The initial conditions for the global forecasts are obtained through the Global Data Assimilation System (GDAS). 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 GSM forecast (T574) from the previous GDAS analysis is used as the 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. A three-dimensional hybrid variational-Ensemble Kalman Filter

(EnKF) system is used. The EnKF provides one background error estimate derived from a current ensemble (T254) run of 80 members (A schematic of this procedure is shown in Figure 1.1). The other background error estimate is derived from the model's 24-48 hour forecast climatology. Satellite data provide information in the form of selected channel radiances.

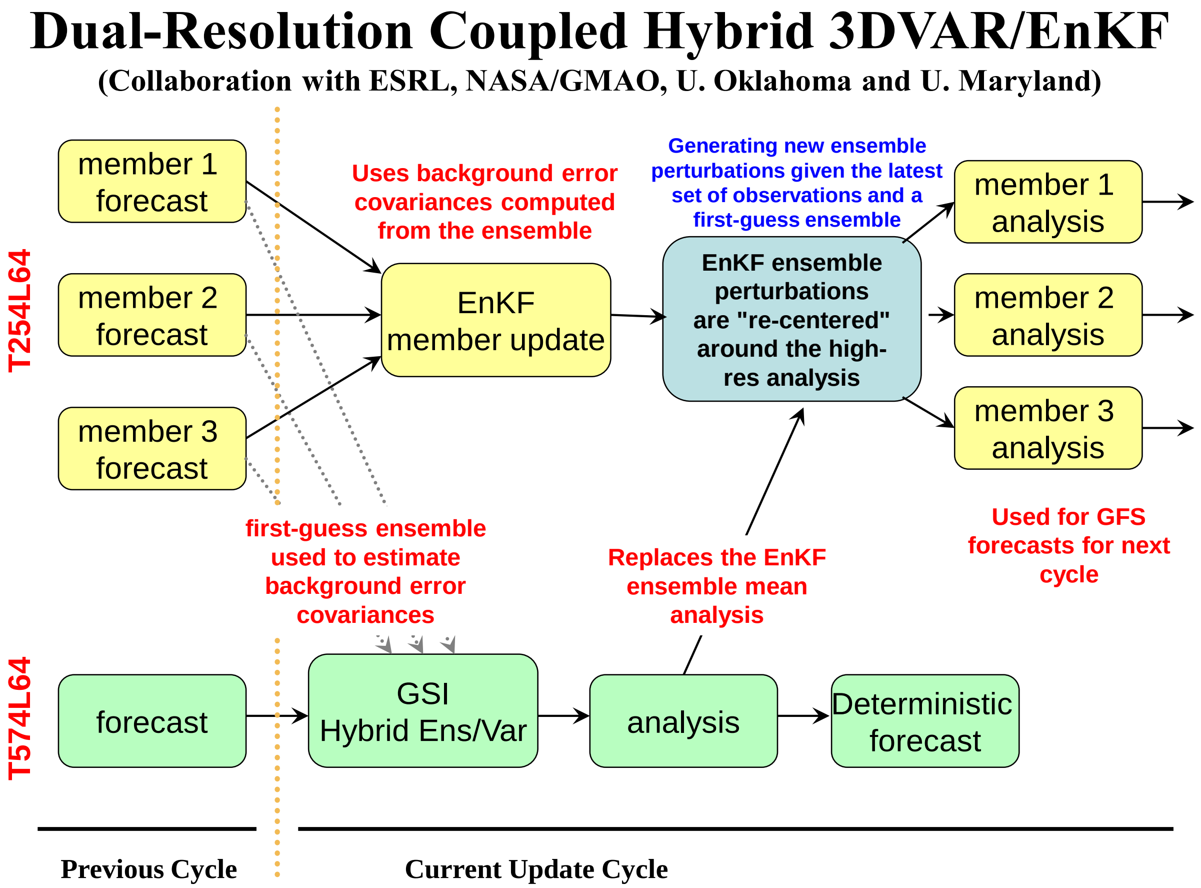

Figure 1.1: A Schematic of the dual- resolution coupled hybrid 3DVAR/EnKF assimilation system that became operational on 22 May 2012.

Additional analysis changes include the use of GPS RO bending angle rather than refractivity, inclusion of compressibility factors for atmosphere, retuning of SBUV observational errors, fixing a bug at the top, updating radiance usage flags, preparing for monitoring NPP and Metop-B satellite data, adding NPP ATMS satellite data,GOES-13/15 radiance data, SEVERI CSBT radiance product. The changes also include satellite monitoring statistics code in operations, a new satellite wind data and quality control and update to current version of analysis trunk for optimization and preparation for future updates.

1.4 The post processing system:

The GFS replaced its post processing system with NCEP Unified Post Processor in 2007. Using a common post processor for all NCEP weather models allows NCEP to compare and verify all model output fairly. The NCEP Unified Post Processor computes most variables in the same way as previous GFS post processor. The largest difference is that the NCEP Unified Post does not filter its output.

The operational GFS post processing currently outputs 685 variables on native high resolution grid. However, only a subset of these variables on global 0.5 degree and 1 degree lat/lon grid are distributed to users due to bandwidth. Among the new variables which we output for GFS recently are simulated GOES, membrane sea level pressure, and fire weather variables. A complete list of output is available upon request.

1.5 Future plans:

The next major GFS upgrade is expected to me made sometime in 2013 after the transition of NCEP operational suite to the Weather and Climate Operational Supercomputing System (WCOSS). In this upgrade we plan to include:

- Increased horizontal and/or vertical resolution of the GSM – to either Eulerian T878 or to semi-Lagrangian T1148. Along with the resolution and/or dynamics change, we also plan to improve the physics package to include Monte-Carlo Independent Column Approximation (McICA), surface vegetation based emissivity, and other upgrades in RRTM, upgrades to boundary layer and moist/precipitation physics to address surface cold bias near the winter pole and the precipitation bull's eyes etc. Coupling with an ocean model may also be considered.

- The next major Noah LSM upgrade is planned for the unification among different NCEP models. The Noah LSM in the current GFS will be upgraded from version 2.7.1 to version 3.3, which includes many physics upgrades and new land datasets.
- Major changes to the analysis system will include increased resolution, updating to the head of the GSI trunk, using new satellite data (e.g. CrIS), analyzing the near-surface sea temperature (NST) etc.

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2.0 Global Ensemble Forecast System (GEFS)

***(Updated October 2014 by Dingchen Hou* Dingchen.Hou@noaa.gov *and Yuejian Zhu* Yuejian.Zhu@noaa.gov **)**

2.1 Historic Review

NCEP's Global Ensemble Forecast System (GEFS) has been in operation since December 1992, using the NCEP Global Forecast System (GFS) model for integration and Breeding Vector (BV) technique to generate perturbations in the initial conditions. After the Aug. 25, 2005 implementation, GEFS runs four times per day (0000, 0600, 1200 and 1800 GMT) out to 16 days. At each time, 10 (5 pairs) perturbed members are initialized using BV method with 6 hours cycling. Meanwhile, a “relocation” technique is applied in the initial condition of each run to adjust the initial central location of tropical storms to the actual location (see: Liu and et al., 2006). Since 2006, extended BV method with Ensemble Transform and Rescaling (BV-ETR; Wei and et al., 2008) was applied in operation. In early 2010, GEFS was upgraded by introducing model uncertainty which names “Stochastic Total Tendency Perturbation (STTP)” (see: Hou and et al., 2011)

2.2 Recent Changes in Configuration (Feb. 2010, Feb. 2012)

See details of implementation log:
http://www.emc.ncep.noaa.gov/gmb/ens/ens_imp_news.html

2.2.1 Horizontal and Vertical Resolutions:

In the coming implementation to be finished in Feb 2012, the horizontal resolution will be increased to T254 (about 55km on equator) for 0-192 hours and the same for 192-384 hours (T190), the vertical resolution will be increased to 42 hybrid levels from 28 levels.

2.2.2 Membership:

The number of perturbed members was the same as before (20 members), and ensemble control forecast for all four forecast cycles.

2.2.3 Generation of the Initial Perturbations:

Breeding Vector (BV) technique is modified by applying Ensemble Transformation (ET) to the ensemble perturbations in 6-hr forecasts. The resulted initial perturbations are then rescaled, leading to ET with Rescaling (ETR) method. ETR was introduced to the Breeding Vector technique (BV-ETR) in May 2006 (see: Wei and et al., 2008).

2.2.4 Representation of Model Related Uncertainty:

In Feb. 2010, a Stochastic Total Tendency Perturbation (STTP) scheme was implemented to represent uncertainties associated with the NWP model used for the integration. STTP is based on the hypothesis that tendencies of the ensemble perturbations provide a representative sample of the random total model errors (see: Hou and et al. 2011).

2.3 Post Processing Products

2.3.1 Global products at 1x1 degree resolution:

A set of probabilistic forecasts of 10%, 50%, 90%, ensemble mean, mode and spread have been generated daily for 48 bias corrected variables.

2.3.2 CONUS products at 5x5km resolution

A set of probabilistic forecast of 10%, 50%, 90%, ensemble mean, mode and spread have been generated daily for 4 surface variables.

2.3.3 Alaska Region products at 6x6km resolution

A set of probabilistic forecast of 10%, 50%, 90%, ensemble mean, mode and spread have been generated daily for 8 surface variables.

2.4 Future Plan

NCEP GEFS will be upgraded in earlier 2015 (March 2015) that will have new GFS model version (semi-Lagrangian with many upgraded model physics).

2.4.1 Horizontal and Vertical Resolutions:

In the coming GEFS upgrade, the horizontal resolution will be increased to T574 (about 34km on equator) for 0-192 hours and T382 (about 55km on equator) for 192-384 hours, the vertical resolution will be increased to 64 hybrid levels from 42 levels.

2.4.2 Membership:

The number of perturbed members was the same as before (20 members), and ensemble control forecast for all four forecast cycles.

2.4.3 Generation of the Initial Perturbations:

GEFS initial perturbations will be from 6-hour forecasts of EnKF (80 members) data assimilation with additional processes. Additional processes are tropical storm relocation and centralization of new selected 20 EnKF forecasts.

2.4.4 Representation of Model Related Uncertainty:

In Feb. 2010, a Stochastic Total Tendency Perturbation (STTP) scheme was implemented to represent uncertainties associated with the NWP model used for the integration. STTP is based on the hypothesis that tendencies of the ensemble perturbations provide a representative sample of the random total model errors (see: Hou and et al. 2011).

Version	Date	Initial Uncertainty	TS Relocation	Model Uncertainty	Resolution	Fcst length	Ensemble members	Daily Frequency
V1.0	1992.12	Breeding vector (BV)			T62L18	12	2	00UTC
V2.0	1994.3				T62L28	16	10(00UTC) 4(12UTC)	00, 12UTC
V3.0	2000.6				T126L28(0-2.5) T62L28(2.5-16)		10	
V4.0	2001.1				T126L28(0-3.5) T62L28(3.5-16)			
V5.0	2004.3				T126L28(0-7.5) T62L28(7.5-16)			00, 06, 12, 18UTC
V6.0	2005.8		Relocation		T126L28			
V7.0	2006.5	BV + Ensemble transform with rescaling (BV-ETR)					14	
V8.0	2007.3						20	
V9.0	2010.2			Stochastic total tendency perturbation (STTP)	T190L28			
V10.0	2012.2				T254L42(0-8) T190L42(8-16)			
V11.0	2015.3(?)	EnKF F06			T574L64(0-8) T254L64(8-16)			

Table 2.1: The changes of NCEP Global Ensemble Forecast System (GEFS)

2.5 Reference(s) for GEFS, NAEFS and post process:

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Ma, J., Y. Zhu, D. Wobus and P. Wang, 2012: "An Effective Configuration of Ensemble Size and Horizontal Resolution for the NCEP GEFS" Advance in Atmospheric Sciences, Vol. 29, No. 4, 782-794

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3.0 North American Ensemble Forecast System (NAEFS)

(Updated October 2014 By Bo Cui Bo.Cui@noaa.gov *and Yuejian Zhu* Yuejian.Zhu@noaa.gov *)*

3.1 General description:

The Canadian (Meteorological Service of Canada, MSC), the Mexican (National Meteorological Service of Mexico, NMSM), and the US (National Weather Service, NWS) NMS established the North American Ensemble Forecast System (NAEFS) which was inaugurated in November 2004, and the first operational implementation of NAEFS products occurred in May 2006. In December 2007, down-scaling products for Continental United States (CONUS) have been implemented in NWS/US operation. In December 2010, down-scaling products for Alaska region have been implemented in NCEP operation. Latest NAEFS upgrade was April 2014 in NCEP operation that includes surface dew-point temperature and surface relative humidity of CONUS and Alaska region.

Within the NAEFS, ensemble producing centers (currently MSC and NWS):
(1) Exchange in real-time their raw forecast data (operational since September 2004) and bias corrected forecast (operational since March 2011);
(2) Statistically post-process (include down-scaling) all ensemble members; and
(3) Jointly with other members (currently NMSM) develop and produce end products based on the combined ensemble of forecasts;
(4) NAEFS workshop was held every other year. 5th workshop was in May 2010 at Cuernavaca, Mexico. The 6th NAEFS workshop was in May 2012 at Monterey CA, USA. The latest (7th) NAEFS workshop was in June 2014 at Montreal, Canada

This Operational data exchange is providing strong basis for the development of contingency plans in case of major production disruption at any of the producing centers.

3.2 Basic products:

Statistical post-processing involves
(a) The correction of all ensemble members for biases (first and higher moments),
(b) The establishment of weights for the combination of all members which include bias corrected high resolution deterministic forecast (named hybrid), and
(c) The expression of each bias-corrected forecast member in terms of percentile values within a long-term climatological distribution of the NCEP-NCAR reanalysis.

The participating centers collaborate in the development of post-processing algorithms and software and share a common procedure to generate the basic products of bias-corrected forecasts, the corresponding weights and climatological percentile values. The products for probabilistic forecast (10%, 90%, 50%, mean, mode and spread) have been generated after statistical bias correction for all ensemble members. These basic products were operationally implemented in May 2006, December 2007 and December 2010. The products are freely accessed through NOMADS (http://nomads.ncdc.noaa.gov/) worldwide.

3.3 End products.

The final goal of the NAEFS is the generation of end products for the use of the participating and other NMS, including those used for severe weather warnings. Down-scaling probabilistic products for CONUS and Alaska region are generated in NDGD (National Digital Guidance Database) grid by using Real Time Meso-scale Analysis (RTMA) as proxy truth. Some of the end products are developed jointly (such as the North American week-2 temperature and precipitation anomaly forecast) with NCEP service centers, while others will be provided by individual participating centers. In all cases, end-products will be based on the common set of basic products described above, ensuring the consistency of all NAEFS end products. NAEFS participants actively seek input from potential users in the immediate Region IV neighborhood: Central America and Caribbean, as well as other developing countries worldwide regarding desired end products for these areas.

3.4 Potential Expansion of NAEFS:

The current NAEFS could be considered as a prototype for a multi-center, multi-model ensemble forecast system, envisaged by the THORPEX research program. The US Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC) ensemble is planned to be next one to joint NAEFS, while the US Air Force Weather Agency (AFWA) as a user. These possible expansions will broaden the scope of the NAEFS and may lead to the development of a Global Ensemble Forecast System (GEFS), as the ensemble forecast component of the Global Interactive Forecast System (GIFS), foreseen by the THORPEX program and other international collaboration. The NAEFS, and a possible future GEFS would well represent the spirit of the enhanced international collaboration sought by the THORPEX research program. In particular, the NAEFS would provide a framework of operational requirements and constraints within which new research initiatives must be conceived on, and will offer a receiving end for any new methods developed based on the THORPEX Interactive Grand Global Ensemble (TIGGE) data archive, or related to other THORPEX initiatives.

4.0 The NCEP Climate Forecast System Version 2

(Updated Octobor 2014 by Suranjana Saha** Suranjana.Saha@noaa.gov **)

4.1 Introduction

The second version of the NCEP Climate Forecast System (CFSv2) was made operational at the National Centers for Environmental Prediction (NCEP) in March 2011. This version has upgrades to nearly all aspects of the data assimilation and forecast model components of the system. A coupled Reanalysis (Climate Forecast System Reanalysis CFSR, Saha et al, 2010) was made over a 32 year period (1979-2011), which provided the initial conditions to carry out a comprehensive Reforecast over 29 years (1982-2011). This was done to obtain a consistent and stable calibration, as well as, skill estimates for the operational sub seasonal and seasonal predictions at NCEP with CFSv2. The operational implementation of the full system ensures a continuity of the climate record and provides a valuable dataset to study many aspects of predictability on the seasonal and sub seasonal scales. Evaluation of the reforecasts show that the CFSv2 increases the length of skillful forecasts of the Madden-Julian Oscillation (MJO) from 6 to 17 days (dramatically improving sub-seasonal forecasts), nearly doubles the skill of seasonal forecasts of 2 meter temperatures over the U.S. and significantly improves global sea surface temperature (SST) forecasts over its predecessor. The CFSv2 not only provides greatly improved guidance at these time scales, it also creates many more products for sub-seasonal and seasonal forecasting with an extensive set of retrospective forecasts for users to calibrate their forecast products. These retrospective and real time operational forecasts will be used by a wide community of users in their decision making processes in areas such as water management for rivers and agriculture, transportation, energy use by utilities, wind and other sustainable energy, and seasonal prediction of the hurricane season.

Obviously CFSv2 has improvements in all the four components mentioned above, namely the two forecast models and the two data assimilation systems. CFSv2 also has a few novelties: an upgraded four level soil model, an interactive three layer sea-ice model, and historical prescribed (i.e. rising) CO_2 concentrations.

The coupled forecast model used for the seasonal retrospective and operational forecasts is different from the model used for obtaining the first guess forecast for CFSR and for its operational implementation as the Climate Data Assimilation System (CDAS). The ocean and sea-ice models are identical to those used in CFSR. The atmospheric and the land surface components, however, are different and these differences are briefly described below.

The atmospheric model has a spectral triangular truncation of 126 waves (T126) in the horizontal (equivalent to nearly a 100 Km grid resolution) and a finite differencing in the vertical with 64 sigma-pressure hybrid layers. The vertical coordinate is the same as that in the operational CDAS. Major differences between the model used here and in CFSR are mainly in the physical parameterizations of the atmospheric model and some tuning parameters in the land surface model, which is described in detail in the CFSv2 paper, Saha et al, 2012.

4.2 **Reforecast Configuration of the CFSv2**

9-month retrospective forecasts were initiated from every 5th day and run from all 4 cycles of that day, beginning from Jan 1 of each year, over a 29 year period from 1982-2010 This is required to calibrate the operational CPC longer-term seasonal predictions (ENSO, etc)

There was also a single 1 season (123-day) hindcast run, initiated from every 0 UTC cycle between these five days, over the 12 year period from 1999-2010. This is required to calibrate the operational CPC first season predictions for hydrological forecasts (precip, evaporation, runoff, streamflow, etc)

In addition, there were three 45-day (1-month) hindcast runs from every 6, 12 and 18 UTC cycles, over the 12-year period from 1999-2010. This is required for the operational CPC week3-week6 predictions of tropical circulations (MJO, PNA, etc). The total number of years of integration is near 10,000 years.

Selected data from the retrospective forecasts may be downloaded from the NCDC web servers at: (http://nomads.ncdc.noaa.gov/data.php?name=access#cfs)

Smoothed calibration climatologies have been prepared for monthly means and time series of selected variables and are available for download from the CFS website (http://cfs.ncep.noaa.gov)

Having a robust calibration for each cycle, each day and each calendar month, allows CPC to use ensemble members very close to release time.

4.3 Operational Configuration of the CFSv2

There are a total of 16 CFS runs every day, of which 4 runs go out to 9 months, 3 runs go out to 1 season and 9 runs go out to 45 days. There are 4 control runs per day from the 0, 6, 12 and 18 UTC cycles of the CFSv2 real-time data assimilation system, out to 9 months. In addition to the control run of 9 months at the 0 UTC cycle, there are 3 additional runs, out to one season. These 3 runs per cycle are initialized as in current operations.

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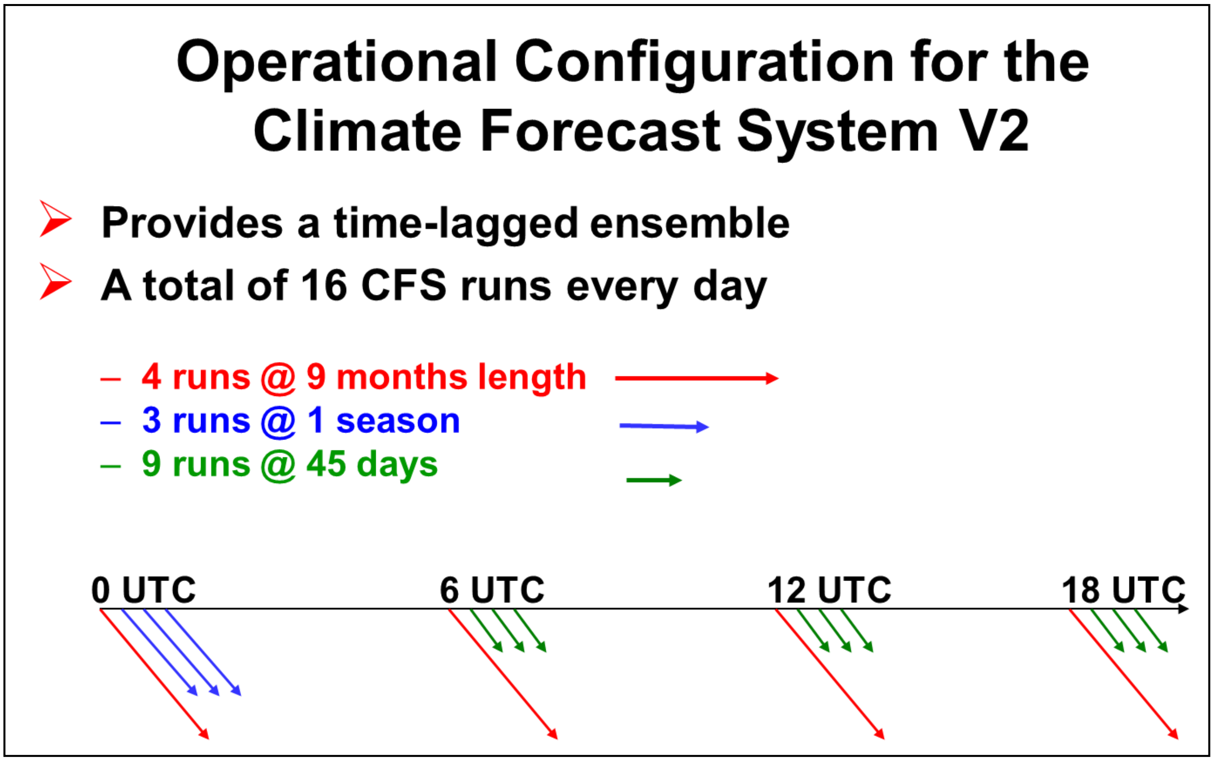
In addition to the control run of 9 months at the 6, 12 and 18 UTC cycles, there are 3 additional runs, out to 45 days. These 3 runs per cycle will be initialized as in current operations.



Operational Configuration for the Climate Forecast System V2

- **Provides a time-lagged ensemble**
- **A total of 16 CFS runs every day**
  - **4 runs @ 9 months length** →
  - **3 runs @ 1 season** →
  - **9 runs @ 45 days** →

Data from the operational CDAS and CFSv2 real time forecasts may be downloaded from a 7-day rotating archive at the official NWS site: http://nomads.ncep.noaa.gov/pub/data/nccf/com/cfs/prod/

4.4 Decadal Prediction with CFSv2

Participating in the CMIP5 protocol, 60 decadal prediction were made with the CFSv2 from initial conditions on Nov 1, 0Z, 6Z, 12Z and 18Z cycles (i.e. 4 'members'), for these start years: 1980, 1981, 1983, 1985, 1990, 1993, 1995, 1996, 1998, 2000, 2003, 2005, 2006, 2009, 2010. Each run is subject to the appropriate increase of GHG and is 122 months long (the first Nov/Dec months are not used to avoid spin-up issues). These decadal runs bring in an element of initial condition in terms of land, ocean and atmosphere. And perhaps this might add information for the first 10 years in addition to the general warming that most models will predict when GHG increases. Data from these runs are available at the PCMDI gateway: http://pcmdi3.llnl.gov/esgcet/home.htm

4.5 Long free running CMIP runs (multi-decadal and centennial) with CFSv2

On the very longest time-scales, three single coupled runs lasting from 43 to 100 years (sometimes designated as CMIP runs) were made with the CFSv2. There is nothing that reminds these runs of the calendar years they are in, except the GHG level, which, in equivalent CO2 terms, is projected to increase by 2ppm in future years. Here we are interested in behavioral aspects, including a test as to whether the system is even stable or drifting due to technical issues. The initial conditions were chosen in late 1987, 1995, and 2001 respectively. Some limited amount of data from these 3 runs, for 1988-2030 (43 years), 1996-2047 (52 years) and 2002-2101 (100years) can be downloaded from the CFS website at: http://cfs.ncep.noaa.gov/pub/raid0/cfsv2/cmipruns/

None of these runs went off the deep-end. A common undesirable feature is a slow cooling of the upper ocean for the first 15-20 years. Only after this decline stabilizes, does a global warming of SST set in 25-35 years after initial time. In contrast, the water at the bottom of the oceans shows a small warming from beginning to end, a very slow drift.

4.6 Some results from the 45-day retrospective forecasts of CFSv2

Figure 4.1 shows the skill, as per the bivariate anomaly correlation (BAC, see equation 1 of Lin et al, 2008) of the CFSv2 in predicting the MJO, as expressed by the Wheeler and Hendon (2004) (WH) index (using 2 EOFs of combined zonal wind and OLR). The period is 1999-2009. On the left is CFSv2, on the right CFSv1. Both are subjected to systematic error correction (SEC). It is quite clear that CFSv2 has much higher skill than CFSv1 throughout the year, and out to 30 days. In fact, this is the improvement of half a generation (~15 years of work by many), taking into account that CFSv1 has rather old R2 (NCEP/DOE Reanalysis, Kanamitsu et al, 2002) atmospheric initial conditions as its weakest component. The BAC stays above 0.5 (the black line) for two to three weeks in the new system, while this was only one week previously. Both systems show a similar seasonal cycle in forecast skill with maxima in May-June and Nov-Dec respectively, and minima in between. Note that we verify v1 and v2 both against R2 based observations of RMM1 and RMM2 (using an observed climatology (1981-2004) from R2 winds) and satellite OLR.

One rarely sees such a demonstration of improvement. This is because atmospheric NWP models are normally abandoned when a new model comes in. But in the application to seasonal climate forecasting, systems tend to have a longer lifetime. This gave us a rare opportunity to compare two models that are about 15 years apart in vintage. The causes for the enormous improvement seen in Fig.A are probably very many, but especially the improved initial states in the tropical atmosphere and the consistency of the initial state and the model used to make the forecasts play a role. Further research should bring out the importance of coupling to the ocean and its quantitative contribution to skill.

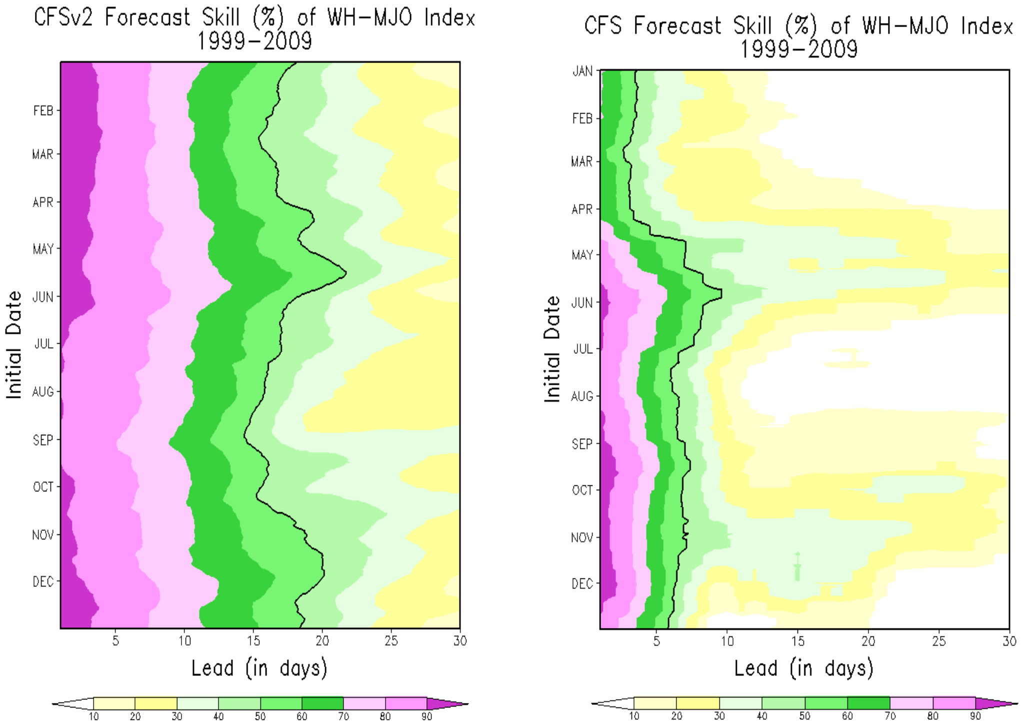


Fig.4.1: The bivariate anomaly correlation (BAC)x100 of CFS in predicting the MJO for period 1999-2009, as expressed by the Wheeler and Hendon (WH) index (two EOFs of combined zonal wind and OLR). On the left is CFSv2 and on the right is CFSv1. Both are subjected to Systematic Error Correction. The black lines indicate the 0.5 of BAC.

4.7 Development of CFSv3

In 2018, CFSv3 will replace CFSv2 (implemented in 2011). CFSv3 will offer many improvements over CFSv2. Some of these improvements are coupled hybrid ensemble Kalman filtering data assimilation, multi-model ensemble forecasting, regional climate forecasting, and seamless weather to climate forecasting including calibration on all scales.

4.7.1 NEMS

The NOAA Environmental Modeling System will be the vehicle used to make seasonal forecasts. The NEMS superstructure allows the coupling of multiple-model geophysical components for both weather and climate prediction.

4.7.2 Multi-model Ensemble

The ensemble coupling strategy in NEMS is wrapped around the full Earth system components. That is, each member is a fully coupled geophysical component. The NEMS ensemble coupler supports stochastic state forcing among its full geophysical components, allowing controlled ensemble spread with consistent physical members.

4.7.3 Testing for Atmosphere, Ocean, Land, Ice and Biosphere:

Atmospheric Dynamics

All capable of non-hydrostatic, global semi-lagrangian spectral, NMM-B, FIM (ESRL), MPAS (NCAR), MCUBED (GFDL) and others

4.7.4 Atmospheric Physics

GFS physics, MYJ boundary layer, RAS convection, Aerosol and chemistry capable, cloud resolving and others

4.7.5 Ocean

Navy/NCEP HYCOM, GFDL GOLD, Near-surface SST diurnal model and others

4.7.6 Land

Full biosphere, land use, migration, emissions, volcanism and others

4.7.7 Ice

Sea ice, shelf ice, sheet ice, glacial ice and others

4.7.8 Chemistry and Aerosols

Dust, carbon dioxide, methane, nox, ozone, sulfates, black carbon

4.8 Regional climate

A major advantage of a unified modeling system is the capability of supporting regional weather and climate models within the global system. The regional climate models will effectively downscale the global seasonal and climate predictions. The regional capability can also be seamless from daily to seasonal forecasting.

4.9 Data assimilation

The coupled hybrid ensemble Kalman filter data assimilation system will not only support consistent ocean and atmosphere observation analysis, it will also naturally support self-consistent ensemble initial conditions for both the weather and climate prediction capability.

4.10 Reanalysis and Reforecast

Like CFSv2, a complete reanalysis and reforecast has to be done to obtain the full calibration at both weather and climate timescales, as well as at both global and regional spatial scales.

4.11 Seamless daily to seasonal forecasts

A major advantage to CFSv3 will be the seamless daily to seasonal forecasts. The seasonal forecasts will start with the high resolution NWP coupled forecasts, drop to a medium resolution for the week-3 to week-6 prediction, and likely lower resolution for the year-1 prediction. All prediction lengths will have a coupled regional component attached for the best possible downscaling available. There will be a consistent calibration on all prediction scales for bias-free products.

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5.0 Global Real-time Ocean Forecast System (RTOFS)

(Updated June 2012 by Avichal Mehra avichal.mehra@noaa.gov)

A global **R**eal-**T**ime **O**cean **F**orecast **S**ystem (RTOFS) was implemented in operations at NCEP/NWS/NOAA on 10/25/2011. This system is based on an eddy resolving 1/12 degree global HYCOM (**HY**brid **C**oordinates **O**cean **M**odel) and is part of a larger national backbone capability of ocean modeling at NWS in strong partnership with US Navy.

5.1 Introduction

In the July 2004 report of the NOAA Science Advisory Board on Ocean Modeling, NWS/NCEP was charged to become the “computational backbone” for operational physical ocean modeling within NOAA. In particular the response to the report states that the charge is

“*to develop a national backbone capability for ocean, coastal ocean and Great Lakes modeling as part of an integrated operational Earth System Model … [to] serve as the foundation for operational environmental prediction for a diverse array of customers and partners*.“

Within NOAA, the primary responsibility for (weather- and) basin-scale physical modeling resides with NWS/NCEP, whereas the responsibility for regional and coastal scales is shared by partners inside and outside NOAA (NOS, OAR, IOOS Regional Associations, etc.), with relevant modeling efforts to be transferred to NCEP operational supercomputing facilities. The primary responsibility for the integrated Ecosystem modeling resides within NOS, with individual responsibilities mainly residing within NOS and NMFS. These efforts can only succeed as a part of a national effort, with strong partnerships with the Navy, NASA, USCG, USACE, academia and industry.

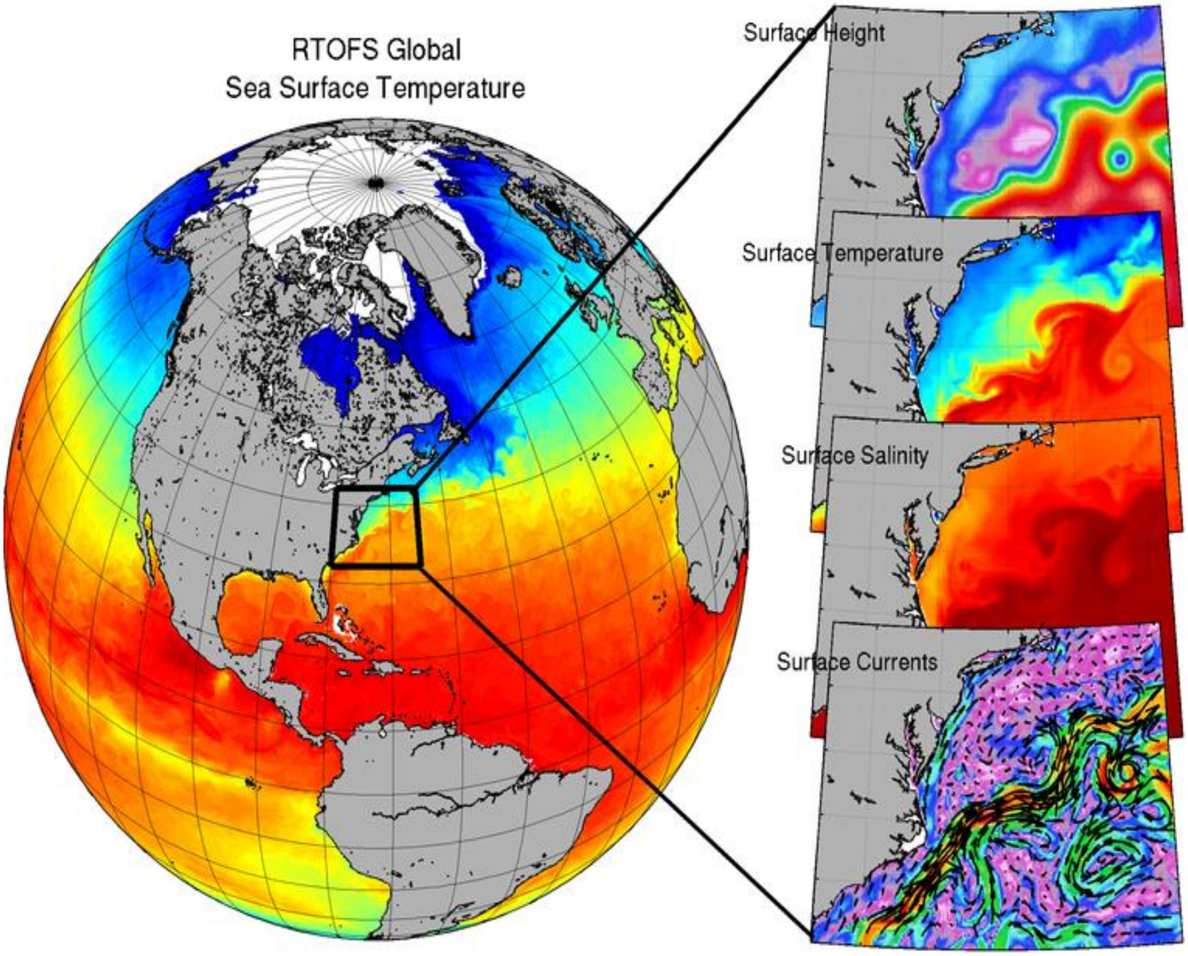
As a response to this charge and to build adequate ocean forecasting capability at NCEP, an operational global eddy resolving system was needed to provide initial and boundary conditions for other operational basin-wide, regional and coupled forecast systems. Such a real-time global ocean forecast system was implemented in operations at NCEP/NWS/NOAA. This system is based on an eddy resolving 1/12 degree global HYCOM model (Bleck, 2002; Chassignet et al., 2009) and serves as part of a larger national backbone capability of ocean modeling at NWS in strong partnership with US Navy.

5.2 System Description

Based on the successful design of the existing operational RTOFS-Atlantic system (Mehra and Rivin, 2010), the global ocean forecast system will run once a day and produce a 8 day long forecast using the daily initialization fields produced at NAVOCEANO using NCODA, a 3D multi-variate data assimilation methodology (Cummings, 2005). The data types assimilated include in situ profiles of temperature and salinity from a variety of sources and remotely sensed SST, SSH and sea-ice concentrations. The operational ocean model configuration has 32 hybrid layers and a horizontal grid size of (4500 x 3298) . The grid has an Arctic bi-polar patch north of 47 deg N and a Mercator projection south of 47 N through 78.6 S. The coastline is fixed at 10 m isobath with open Bering Straits. The potential temperature is referenced to 2000 m depth (sigma-2) and the first level is fixed at 3 m depth. The dynamic ocean model is coupled to a thermodynamic energy loan ice model and uses the KPP mixed layer formulation (Large et al., 1994). The forecast system is forced with 3-hourly momentum, radiation and precipitation fluxes from the operational Global Forecast System (GFS) fields.

Results include daily volume and 3 hourly surface fields in netCDF format with CF conventions. Some surface fields in GRIB format are also generated for internal use at NWS. More details on the configuration and data distribution portals are available at http://polar.ncep.noaa.gov/global/.

Figure 5.1: NCEP's Global RTOFS (Real Time Ocean Forecast System)



5.3 Applications

The global surface currents and temperature fields from the Global-RTOFS are used by the U.S. Coast Guard (USCG) for planning for their Search and Rescue Operations, and by NOAA Office of Response and Restoration (ORR) for response to hazard materials spill emergencies in the maritime environment. Prior to the model becoming operational, the Ocean Prediction Center (OPC) began to deliver near real time model data to USCG and ORR in late summer 2011 to enable both organizations to prepare for the arrival of the new model data. OPC also built parallel data delivery of the Global RTOFS data, along with the Navy operational global model, known as global NCOM, to users that rely on those near real time data. OPC is working with NCOM data users to update their applications to adopt the real time Global RTOFS model data, as the Navy is expected to discontinue the global NCOM in favor of the Global HYCOM as the operational global ocean model.

Real time ocean model guidance for surface ocean currents enables OPC to provide enhanced navigation safety information. For example, in areas where strong ocean surface currents flow against strong surface winds, the condition creates strong surface wave conditions that could be hazardous to ships. The unusually strong wave conditions under this circumstance are not accounted for by the present operational wave forecast model. The new global RTOFS provides improved simulation of the Gulf Stream conditions, better resolves fine structures of ocean surface currents, and provides OPC a more powerful tool to identify the wind-against-current hazards, thus enables OPC to better serve mariners navigation safety needs when traveling in the gulf stream area.

5.4 Radionuclide Tracers in the North West Pacific

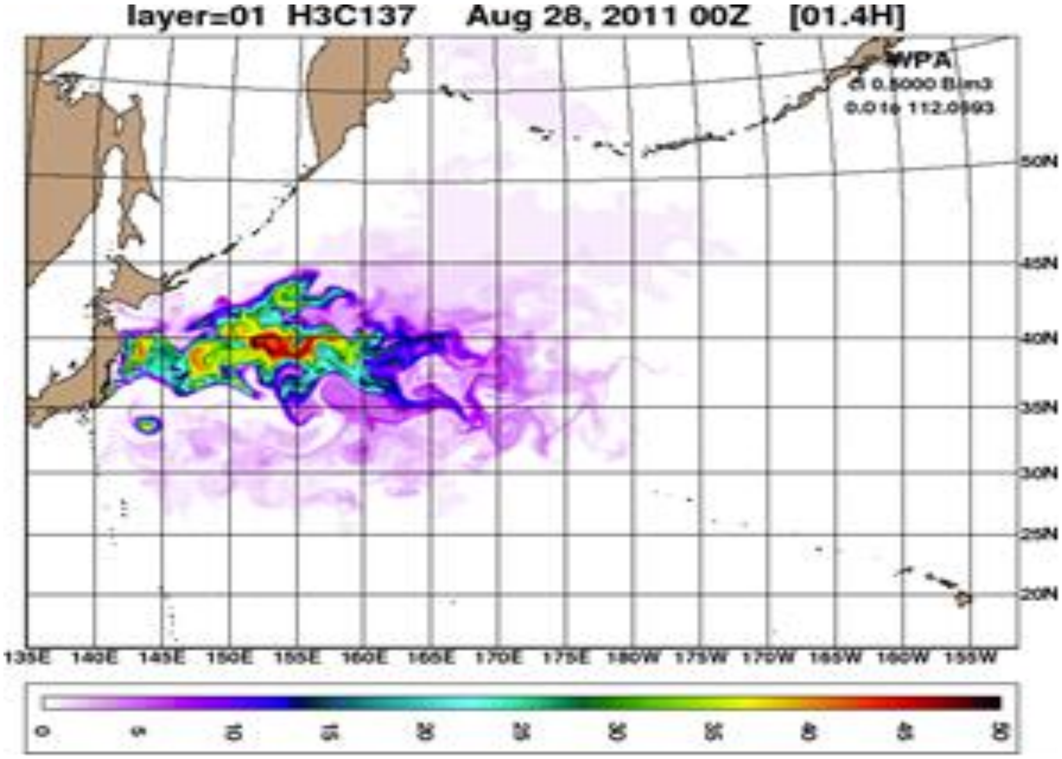
Immediately after the Fukushima-Daiichi nuclear plant accident on March 11 2011 in the aftermath of a disastrous earthquake/tsunami off the east coast of Japan, simulations were begun for idealized synthetic floats and drifters originating near the Fukushima-Daiichi nuclear plant. Synthetic particles were advected by the 3-meter depth velocities of the RTOFS-GLOBAL 1/12° simulation produced at NOAA-EMC. The aim of this approach was to identify regions where surface particles originally at the Fukushima location migrate as a function of time. This was done before any estimates of the radionuclide sources in the atmosphere or ocean became available (Tolman et al., 2012).

Soon after the accident, and as estimations of atmospheric deposition became available, a full three-dimensional passive tracer model was set up to model the evolution of Cs-137. This procedure allowed real-time simulation of the spatial location and concentration of Cs-137 tracers over the North-West Pacific Ocean. A regional model was built for the region of the North Western Pacific extending from 133.75°E to 150°W, and from 15.3°N to 58°N, at 1/12° resolution. This regional simulation was nested in the 1/12° global RTOFS model. The regional model was initialized with the nowcast state of RTOFS-Global for March 11, 2011. The model horizontal grid, a subset of the global model, has 1/12° resolution, is a Mercator grid except north of 47°N. The vertical structure has 32 vertical layers which are the same as the layers of RTOFS-Global with 1m and 2m depth for the top two layers away from the coasts. The regional model is run in forecast mode in the interior, with no data assimilation. The lateral boundary conditions are provided by the daily nowcast states of the RTOFS-Global results.

Starting on March 11, 2011, simulations for Cs-137 focused on the tracer deposited on the ocean surface through the atmosphere. To these, direct ocean discharge from contaminated waters from the plant was added after 45 days as predicted from a high resolution coastal domain model by NOAA/NOS. The objective of the particle and the tracer simulations was to obtain results for quick guidance on environmental contamination, which was provided as actionable prompt information to managers and decision makers in real-time (see Figure 5.2). In addition, the tracer simulations at EMC aim to advance practical methods for biological tracking with realistic currents (Garaffo et al., 2012).

This tracer forecast system will be implemented in EMC operations in CY 2012.

Figure 5.2: Simulated surface Cs-137 concentrations (in Bq/m^3) showing the eastward extent of propagation as of 28th August, 2011.



5.5 Future Work

In-house analysis and initialization of this system at NCEP using a 3DVAR data assimilation will be developed in time for the next machine (hardware) upgrade expected in 2014. Long term plans also include providing initial and boundary conditions to existing operational regional and coupled hurricane forecast systems at NCEP.

A coarser version of RTOFS Global (1/4th degree) will also serve as the ocean component of a future climate forecast system via NEMS (NCEP's Environmental Modeling System) using ESMF libraries for dynamic coupling of various earth components. A series of global runs are planned using NCEP's Climate Forecast System Reanalysis (CFSR). The first simulations will be done with a global 1/4th degree domain. These simulations will be examined and corrections will be applied for drifts and other factors. After the completion of 1/4th degree simulations, higher resolution (at 1/12th degree) will be considered. These experiments will be used to analyze seasonal to inter-annual signals associated with ENSO, NAO etc.

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6.0 The North American Mesoscale (NAM) Analysis and Forecast System

(Updated October 2014 by Geoff DiMego (*Geoff.dimego@noaa.gov*) and Eric Rogers (*eric.rogers@noaa.gov*))

6.1 Forecast Model Description

The North American Mesoscale Forecast System (NAM) provides high resolution forecasts over North America out to 84 hours at 0000, 0600, 1200 and 1800 UTC.

The forecast component of the NAM is the Non-hydrostatic Multiscale Model on B-grid (NMMB). The model is based on precise dynamics and numerics, using a hybrid sigma-pressure vertical coordinate. The NMMB includes a full set of parameterizations for physical processes, including the Janjic-modified Betts-Miller convection and Mellor-Yamada-Janjic turbulent exchange, RRTM longwave and shortwave radiation, the Noah land surface scheme with 4 soil layers and the Ferrier-Aligo predictive cloud scheme. The NMMB has an extended capability beyond earlier NAM prediction models to run either regionally or globally with embedded nests. The lateral boundary conditions for NAM are derived from the prior (6-h old) NCEP global model forecast at a 3 hour frequency. The modeling infrastructure used by the prediction model is based on the NOAA Environmental Modeling System (NEMS) which, in turn, is based on the tenets put forth by the Earth System Modeling Framework.

The NAM forecast consists of 1) an 84-h forecast at 12 km resolution over the full North American domain; 2) four high-resolution one-way interactive nests run to 60-h [4 km over the continental United States (CONUS), 6 km over Alaska, and 3 km over Hawaii and Puerto Rico]; and 3) an innermost nest at 1.333 km resolution (if over CONUS) or 1.5 km resolution (if over Alaska) which runs to 36-h (see Figure 6.1). This innermost nest is can be centered over different locations over the CONUS or Alaska each NAM cycle. Its primary function is for use by Fire Weather / IMET [Incident METeorologist] Support (FWIS) meteorologists during the U.S. fire season. When not required for IMET support, this innermost nest is placed over areas of interest as determined by the NCEP Service Centers and the NCEP Senior Duty Meteorologist. All domains (parent 12-km and nests) use 60 vertical levels with the model top at 2 mb. All nests except the 6 km Alaska domain run with explicit convection.

6.2: NAM Data Assimilation System (NDAS)

Initial conditions for the NAM runs are produced by the regional Grid-point Statistical Interpolation (GSI) hybrid ensemble analysis, which is a multivariate 3-dimensional variational analysis which uses as its first guess a 3-hour 12-km NMMB forecast from the NAM Data Assimilation System (NDAS). As of August 2014 the NAM GSI uses the NCEP global EnKF members to improve the background error covariances. The data cutoff time for the NAM initial conditions is 1 hour and 10 minutes past the nominal NAM analysis time. The data time window radius is 1.5 hours about the center of the data cutoff time.

The NDAS is a partial cycled, intermittently updated system of 3-hourly 12-km NMMB forecasts over the full North American domain and regional GSI analyses, using global atmospheric fields only at the beginning of the 12-h NDAS period and for lateral boundary conditions. An NDAS cycle runs prior to each NAM forecast, assimilating all available observations within the 12-h period preceding the NAM initialization time, with a data cut-off time up to 9-10-h past the nominal NDAS analysis times. The data time window radius is 1.5 hours about the centre of the data dump cycle times. For the NDAS forecasts a diabatic digital filer initialization is applied prior to the 3-h integration. To initialize the NAM nests, the 12-km NDAS first guess valid at the nominal NAM analysis time is interpolated to the each nest domain, and a GSI analysis is performed for each nest. No cycling for the nests is performed at this time.

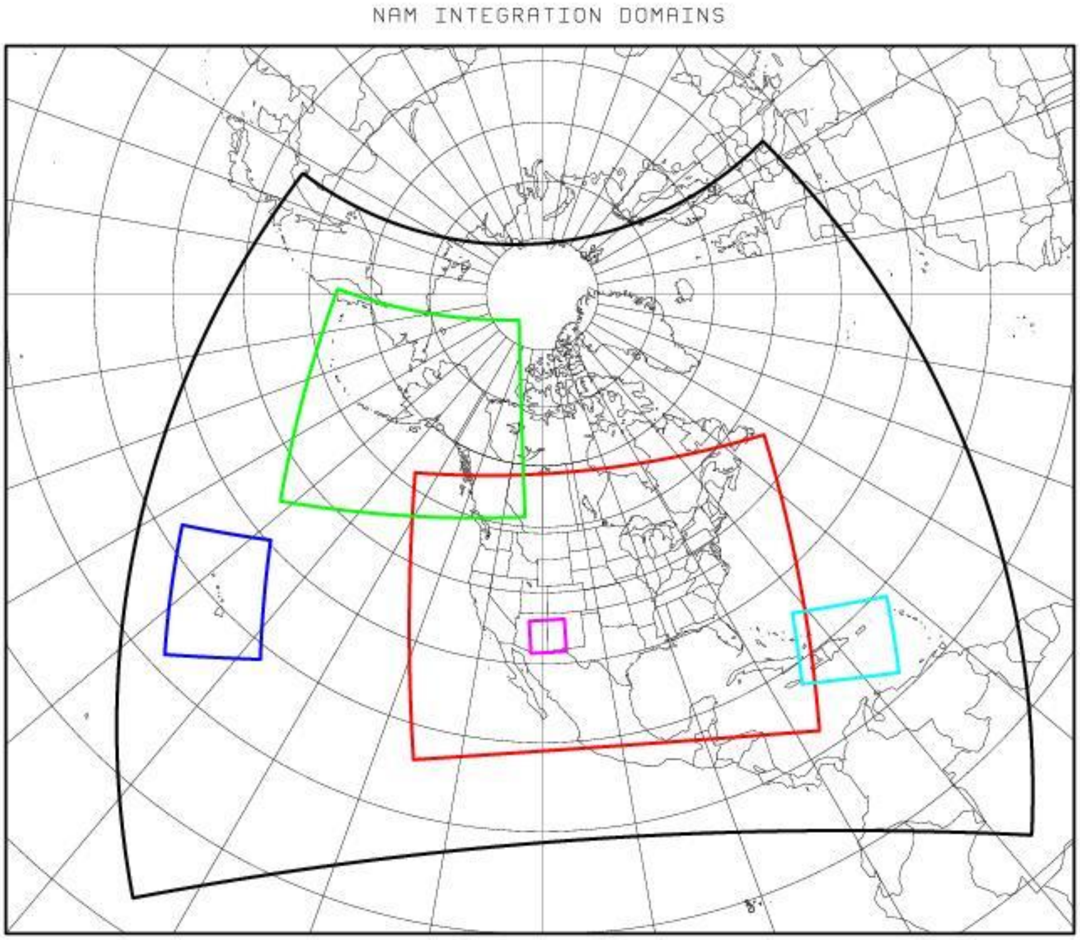


Figure 6.1 : The integration domains of the 12-km NAM North American region (black), the 4 km CONUS nest (red), the 6 km Alaska nest (green), the 3 km Puerto Rico nest (light blue), and the 3 km Hawaii nest (dark blue). An example of the 1.333 km FWIS nest inside the CONUS nest is also shown in magenta

6.3 Future plans

The next major NDAS/NAM upgrade is tentatively planned for the fall/winter of 2015. Planned/possible changes in this upgrade include:

- Increase in resolution of the NAM CONUS and Alaska nests to 3 km

- Replace the 3-hourly NDAS with an hourly-updated NAM Rapid Refresh (NAMRR) with assimilation or radar reflectivity. The hourly cycle will be done on the 120km parent domain and possibly on the 3 km CONUS nest domain

- Improvements to the microphysics/convection to address model biases in QPF, ceiling height, 2-m temperature

- MODIS-based midday albedo

7.0 The High Resolution Window (HiResW) Forecast System

(Updated October 2014 by Matthew Pyle (**matt.pyle@noaa.gov**) and Geoff DiMego (**Geoff.dimego@noaa.gov**))

7.1 System Description

The High-Resolution Window (HiResW) makes nonhydrostatic regional forecasts to 48 h over different regions at different times of day. This model guidance is used for basic weather forecasting purposes, in general, but is focused on severe weather forecasting in particular. The modeling system consists of two different dynamical cores. One is the Weather Research and Forecasting (WRF) Advanced Research WRF (ARW) utilizing the WRF v3.5 release, but includes minor local modifications. In 2014 the WRF Nonhydrostatic Mesoscale Model (WRF-NMM) core was replaced by the Nonhydrostatic Multiscale Model on the B grid (NMMB). Horizontal grid scale varies slightly by domain, but now is 3.5-4.2 km for the WRF-ARW and 3.0-3.6 km for the NMMB. Both dynamical cores utilize 40 vertical levels on mass-based vertical coordinates with model tops of 50 hPa.

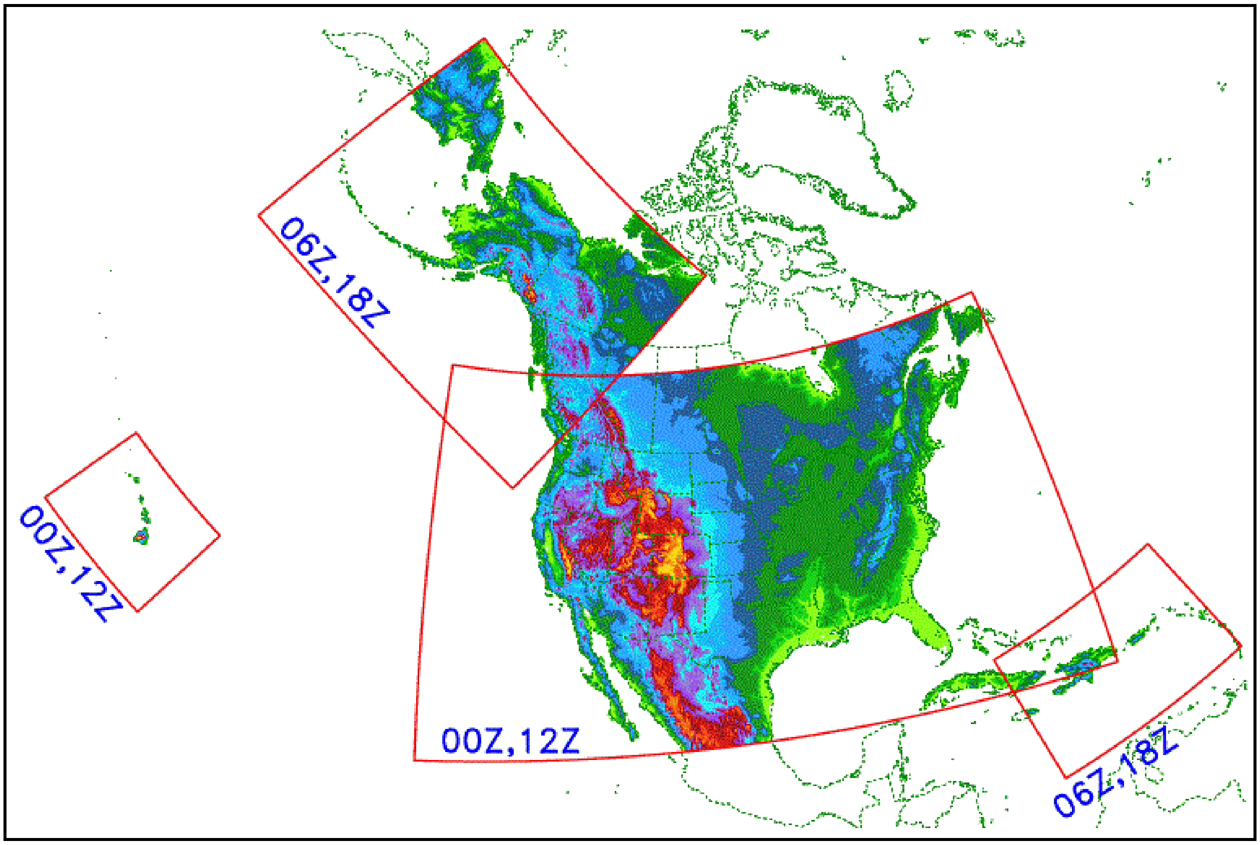


Figure 1. The regions covered by the current HiResW system and the time(s) at which each region is run. Not shown is the Guam domain, which is run at 00Z and 12Z.

There are two larger domains: Alaska and continental United States (CONUS), and three smaller domains covering Hawaii, Puerto Rico/Hispaniola, and Guam. All domains but Guam are shown in Figure 1, along with the times of day at which they are run. For each of the major cycle times (00Z, 06Z, 12Z, and 18Z), one large and one or two small regions are run with both the WRF-ARW and NMMB models. The HiResW runs within the operational computer allocation (aka runslot) designated for hurricanes, so the HiResW is subject to preemption during model cycles when hurricane models are being run over several tropical storms.

The two dynamical cores utilize different physics configurations, but have commonality in generally running without parameterized convection. The various parameterizations used with each dynamical model are listed in Table 1.

	WRF-ARW	**NMMB**
Microphysics	WRF Single-Moment, 6-class (WSM6)	Ferrier
PBL	Yonsei University (YSU)	Mellor-Yamada-Janjic (MYJ)
Radiation (shortwave / longwave)	Dudhia / Rapid Radiative Transfer Model (RRTM)	RRTM / RRTM
Land Surface	Noah	Noah
Convection	-none-	-none-*

* Except for Puerto Rico and Guam, where a tunable version of Betts-Miller-Janjic (BMJ) is used to provide a weakly adjusting convective parameterization.

Table 1. Summary of the physics parameterizations used with the 2014 version of the HiResW

HiResW initial conditions are derived from direct interpolation of the GFS (for non-CONUS domains) or Rapid Refresh (RAP, CONUS only) analysis, and lateral boundaries for all domains are computed from GFS forecast files. The HiResW contains no data analysis component of its own. Use of NAM analyses were eliminated with the 2014 upgrade in the interest of providing a greater diversity of solutions across the NCEP mesoscale modeling suite (as the NAM nests at 3-6 km horizontal scale also are based on the NMMB forecast model). The RAP analysis utilizes radar reflectivity data, which provides the CONUS domain runs with a more accurate initial representation of precipitation systems.

7.2 Future plans

In 2015 there are plans for a minor upgrade to the HiResW system which will include:

- Implementation of a time-lagged National Convection Allowing Scale Ensemble (NCASE) made up of convection-allowing model runs available from NCEP operations (HiResWindow, NAM nests, and the High Resolution Rapid Refresh (HRRR)) to generate ensemble products and prepare the user community for a more coherent multi-model convective scale ensemble that will be coming in the second half of this decade.

- A possible increase in the number of vertical levels from 40 to 45 or 50 if the expected increase in computing power allows for it.

- Addition of new productions to enhance utility for aviation and severe weather forecasting applications.

- Elimination of the internal use of GRIB1 data as NCEP moves toward being purely GRIB2 in production.

8.0 The Real-Time Mesoscale Analysis (RTMA) and Unrestricted Mesoscale Analysis (URMA)

(Updated October 2014 by Manuel Pondeca (Manuel.Pondeca@noaa.gov) and Geoff DiMego (Geoff.dimego@noaa.gov))

8.1 System Description:

The Real-Time Mesoscale Analysis (RTMA) is a high (2.5- to 6 km) resolution analysis system for surface and near surface parameters, and sky cover. It was implemented for the first time in 2006 for a domain matching the 5-km resolution Contiguous United States (CONUS) grid of the National Digital Forecast Database (NDFD). Between 2008 and 2010, it was also implemented for the 6-km Alaska NDFD grid, and the 2.5-km Hawaii, Puerto Rico, and Guam NDFD grids. A higher (2.5km) resolution RTMA-CONUS was implemented in 2010, and a higher (3km) resolution RTMA-Alaska was implemented in 2014. Also, in 2014, a 2.5km resolution RTMA-NWRFC was implemented for the Northwest River Forecast Center area of interest. The RTMA analysis is performed hourly in all applications, except for RTMA-Guam, where the analysis is performed 3-hourly.

The RTMA is used to support NDFD operations, situational awareness, and routine forecast preparations at the NWS Weather Forecast Offices. It also provides reference fields to correct model biases in the NCEP Global Ensemble Forecast System, and is used by the research community to support climate modeling studies.

The main component of the RTMA is the NCEP Grid-point Statistical Interpolation (GSI) run in 2DVar mode to analyze observations of surface pressure, temperature, moisture, and wind. The observations originate from synoptic, METAR, Mesonet, ship, buoy, tide gauge, and C-MAN (Coastal-Marine Automated Network) stations. The system also assimilates satellite low-level cloud-drift winds and ocean surface scaterometer (ASCAT & WindSat) winds. The first guess for the 2DVar is a short-range forecast from the Rapid Refresh (RAP) or the North American Mesoscale (NAM) downscaled to the resolution of the RTMA domain. The gridded analyses of the RTMA are for surface pressure, 2m- temperature, 2m- specific humidity, 2m-dew point, and 10-m winds. The RTMA also provides gridded fields of the analysis uncertainty for each analyzed parameter, representing enhanced estimates of the 2DVar analysis error. The RTMA precipitation and sky cover represent a re-mapping of the NCEP Stage-II quantitative precipitation amount and the NESDIS GOES sounder effective cloud amount, respectively, to the RTMA domain.

Some of the RTMA products can be viewed or downloaded from the following websites:

ftp://tgftp.nws.noaa.gov/SL.us008001/ST.opnl/DF.gr2/DC.ndgd/GT.rtma/AR.conus/
ftp://tgftp.nws.noaa.gov/SL.us008001/ST.opnl/DF.gr2/DC.ndgd/GT.rtma/
http://www.nco.ncep.noaa.gov/pmb/products/rtma/

In 2014, the Unrestricted Mesoscale Analysis (URMA) was implemented for CONUS and NWRFC at 2.5km resolution. URMA is similar to the RTMA, except is runs six-hours later to incorporate observations that arrive too late to be used by the RTMA. The URMA analysis is therefore more accurate than the RTMA analysis and as such more suited for forecast and model verification.

8.2 Description of important system updates during 2010

NCEP/RTMA upgrade (October 2010)

- Resolution doubling to 2.5 km for RTMA-CONUS
- RTMA-GUAM implemented at 2.5 km resolution
- Add bias correction for the first guess temperature
- Add the technique of the First Guess at the Appropriate Time to improve the time interpolation for the first guess
- Add the assimilation of satellite low-level cloud-drift winds and ocean surface ASCAT and WindSat winds

8.3 Description of important system updates during 2014

NCEP/RTMA and URMA upgrade (January 2014)

- Resolution doubling to 3 km for RTMA-Alaska
- Implement 2.5km resolution RTMA-NWRFC
- Implement URMA-CONUS and URMA-NWRFC at 2.5km resolution
- Implement routine cross validation for RTMA CONUS-2.5km and URMA CONUS-2.5km
- Improve the observation quality control by adding diurnal blacklists for temperature and moisture, and direction-stratified accept-lists for wind
- Use cross-validation to re-tune the parameters of the background error models used with the 2DVar

8.4 Future plans (2015)

- Replace the 13km-RAP model forecast with a blend of the 3km HRRR and 4km NAM-nest forecasts as the background for RTMA-CONUS and URMA-CONUS
- Implement a mass conservation-based wind downscaling for the background.
- Add a buddy-check observation quality control
- Add a new variational observation quality control

- Analyze total cloud amount
- Analysis cloud ceiling height
- Analyze minimum temperature and maximum temperature
- Analysis significant wave height
- Analysis pressure at mean sea level
- Set up an RTMA system for Juneau at 1.5 km resolution

9.0 Short Range Ensemble Forecast (SREF) System

(updated October 2014 by Jun Du (jun.du@noaa.gov), Geoff Dimego (Geoff.dimego@noaa.gov) and Yuejian Zhu (yuejian.zhu@noaa.gov))

9.1 History:

NCEP Short Range Ensemble Forecast (SREF) system was first implemented in 2000 and officially declared as operational system in May 2001 (the first operational LAM-EPS in the world at that time) as a 10-member Eta (with BMJ convective scheme)/RSM based multi-model regional ensemble prediction system (Du and Tracton 2001). A different version of Eta and two versions (NMM and ARW) of WRF (Weather Research and Forecasting) model are added into the system in 2003 (Du et al. 2003) and 2005 (Du et al. 2006), respectively. Currently (Du et al. 2009; 2014), SREF has 21 members based on two models NEMS_NMMB and WRF_ARW. Model related uncertainty is represented by multi-model and multi-physics approach, i.e. using different numerical core structures and different physics schemes within each model core. The perturbations in the initial conditions are generated by regional breeding as well as blended by global ETR perturbations. All member forecasts are integrated four times daily at horizontal resolution of 16km, up to 87 hours with output every hour to 39hr and every 3 hour to 87hr. It covers the continental U.S., Alaska and Hawaii regions.

9.2: Planned Changes in Configuration (Spring 2015)

The configuration of SREF will be changed in the coming implementation in spring 2015.

9.2.1 Model Change:

- 3-model system becomes 2-model system (getting rid of non-evolving model WRF_NMM)
- Ensemble membership increases from 21 to 26

9.2.2 Initial Condition Diversity

- Initiate each model core with three different control analyses
- Improve IC perturbation by blending larger-scale ETR (Wei et al. 2008) and smaller-scale BV (Toth and Kalnay 1997) for all 26 members

9.2.3 Physics Diversity

- More diversity by adding wide range of various physics schemes as well as stochastic physical parameters

9.2.4 Ensemble Products

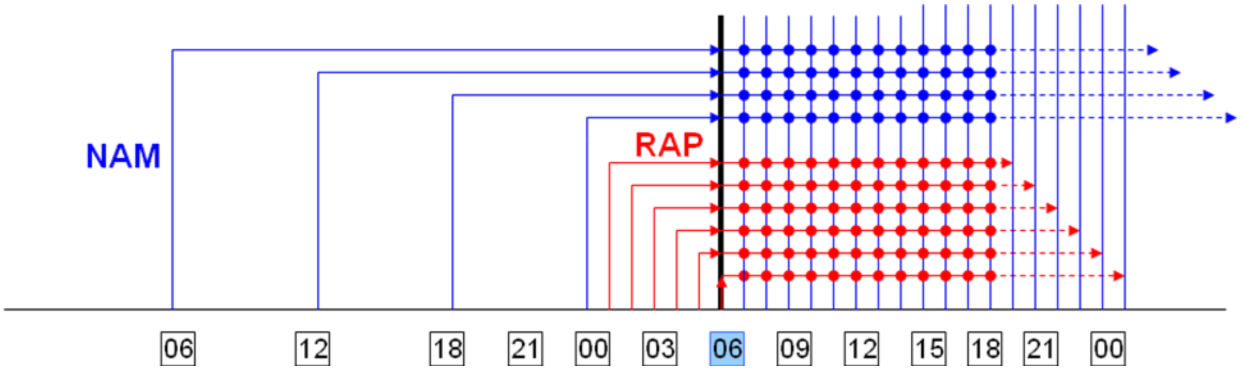
- Anomaly forecasts and related new products (Randy et al. 2013; Du et al. 2014)

10 The North America Rapid Refresh Ensemble (NARRE) forecast system

(Updated June 2012 by Geoff DiMego (geoff.dimego@noaa.gov))

10.1 System Description

A North America Rapid Refresh Ensemble (NARRE) forecast system was implemented on 1 May 2012. NARRE's members are based on NCEP operational runs of the North American Mesoscale (NAM) and Rapid Refresh (RAP) and, until computer resources increase to the point where multiple runs of NAM and RAP can be made each cycle, NARRE's membership comes mostly from time-lagged members. NARRE members consists of the most recent 6 RAP and most recent 4 NAM forecasts. It is updated every hour and extends to 12 hours in forecast length. NARRE domains covering the contiguous United States (CONUS) and Alaska are extracted from the NAM & RAP runs on grids with 13 km grid-spacing in the horizontal and on 50 levels in the vertical.



The figure above depicts the contents of a NARRE assembled for 06z. It is made up of the 6 RAP cycles: the 6z plus the previous 5z, 4z, 3z, 2z, and 1z runs with progressively longer forecast range, and the 4 NAM cycles: the6z plus the previous 0z, 18z and 12z. Member weights are inversely proportional to forecast range according to: Weight = 1 - forecast range (hr) / 30.

The NARRE product generator then produces ensemble mean, spread and probabilities which, at present, are mostly aviation weather related. The NARRE output suite includes icing and clear air turbulence at various flight levels; ceiling and surface visibility for different thresholds; flight restriction categories; fog and dense fog; radar reflectivity and echo top for different dBZ thresholds; low level wind shear; jetstreams height and freezing level; precipitation (rain, snow and freezing rain) and accumulated precipitation.

The real time NARRE icing (and all other) products can be viewed at this web site www.emc.ncep.noaa.gov/mmb/SREF_avia/FCST/NARRE/web_site/html/icing.html . The NARRE gridded product data files are available in GRIB2 from the NCEP NOMADS site at nomads.ncep.noaa.gov/pub/data/nccf/com/rap/prod/narre.YYYYMMDD/ensprod/ where YYYY is year, MM is month, DD is date.

10.2 Description of important system updates during 2011-2012

NARRE was first implemented on 1 May 2012 as part of the RAP implementation into NCEP operations.

10.3 Future plans

Add more variables upon request, particularly those non-aviation weather variables. Work towards hourly updated NAM and the addition of perturbed real-time runs of NAM & RAP to reduce dependency on time-lagged members.

11.0 Ensembles of Opportunity

(Updated June 2012 by Geoff DiMego (**Geoff.dimego@noaa.gov**))

11.1 High-Resolution Ensemble Forecast (HREF)

The High-Resolution Ensemble Forecast (HREF) for high-impact weather is a dynamically downscaled 5km 44-member ensemble for high-impact weather forecasts such as heavy precipitation, which was operationally implemented in April 2011. It is based on the dual-resolution hybrid ensemble approach (Du 2004) by applying forecast variance from 32km SREF to two 5km WRF-based single forecasts. The ensemble products derived from the HREF are listed in the following two tables for 7 surface and 7 upper air variables, respectively. It covers continental U.S. and Alaska regions and has hourly output to 48 hours.

11.2 North American Rapid Refresh Ensemble–Time Lagged (NARRE-TL)

This is a 10-member time-lagged ensemble (Hoffman and Kalnay, 1983) based on two 12km-regional models (Rapid Refresh/RR and North American Meso/NAM). It’s updated every hour (24 cycles per day) to a forecast length of 12 hours tailed to aviation weather forecasts. It is planned to be operationally implemented later this year (December 2011). Aviation ensemble products derived from the NARRE-TL are listed in the following table. It covers the continental U.S. and Alaska regions.

HREF Ensemble products (7 upper air variables)

	Mean	Spread	Probability
850T	x	x	x(<0C)
850RH	x	x	
850U	x	x	
850V	x	x	
850Wind	x	x	
500T	x	x	
500H	x	x	
250T	x	x	
250U	x	x	
250V	x	x	
250Wind	x	x	

NARRE-TL ensemble-based aviation weather products

Products	Description
Icing	Occurrence prob on 8 FL
Turbulence (CAT)	3 severity occurrence Prob on 9 FL
Ceiling (cloud base)	Mean/spread/prob of 4 ranges
Visibility	Mean/spread/prob of 4 ranges
Low level Wind shear	Mean/spread/occurrence prob
Jet stream	Prob on 3 levels
Fog (light/dense)	Mean/spread/prob
Convection	Prob of occurrence
Reflectivity	Prob of 4 thresholds
Freezing height	Mean/spread
Precipitation type	Prob of rain and snow types
Accumulate Precip	Prob of 3 and 6hr acc. precip
Lightning	Prob of occurrence
Severe thunderstorm	Prob of occurrence

HREF Ensemble products (7 surface variables)

	Mean	Spread	Probability
01h-, 03h-, 06h-, 12h-, 24h-apcp	x	x	x(>0.01”,0.05”,0.1”,0.25”,0.5”,1.0” ,1.5”,2”,4”,6”)
2m-T	x	x	x(<0C, >25.5C)
10m-U	x	x	
10m-V	x	x	
10m-Wind	x	x	x(>25kt, 34kt, 50kt)
2m-RH	x	x	
CAPE	x	x	x(>500, 1000, 2000, 3000, 4000)
CIN	x	x	x(<-50, -100, -200, -300, -400)
SLP	x	x	

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12.0 Developments in Post-Processing and Calibration

(Updated October 2014 by Bo Cui Bo.Cui@noaa.gov and Yuejian Zhu Yuejian.Zhu@noaa.gov***)***

12.1 Bias Correction (Statistic):

Bias correction to the GEFS products has been conducted operationally since May 30, 2006, and the number of bias corrected variables was increased in Dec. 2007, and in Feb. 2010. The bias correction is done for each variable, each lead time and each forecast cycle on point wise basis. The bias is estimated using an adaptive (Kalman Filter type) algorithm and taking the weighted average (with decaying weights) of forecast errors in the most recent forecast cases (about 50 days) (see: Cui and et al., 2011)

12.2 Statistical Downscaling:

Statistical downscaling was implemented in Dec. 2007 to present GEFS products on high resolution meshes and to provide forecast guidance at local scale. Real Time Mesoscale Analysis (RTMA), which generates real time hourly analysis at NDFD (5km for CONUS) resolution, is used as the reference for downscaling. The procedure is applied to the bias corrected GEFS forecasts (interpolated to NDFD resolution) and the algorithm is the same as bias correction except that the difference between high resolution and low resolution analyses is used to estimate the bias (see: Cui and et al., 2011).

In late 2010, Alaska regional downscaling probabilistic product was implemented. The variables include surface pressure, temperature, max/min temperature, winds, wind direction/speed. The resolution is about 6km (NDGD format).
Statistical downscaling product will extend to dew-point temperature and relative humidity in April 2014.

12.3 Frequency Matching Calibration:

For precipitation calibration, NCEP introduced “frequency-matching method” for operational implementation in 2004 (Zhu and Toth, 2004). An adaptive (Kalman Filter type) algorithm has been used to accumulate past information for calibration. The product resolution is 2.5 * 2.5 degree for CONUS.

Recently, “frequency-matching method” has been extended to use high resolution precipitation calibration (at 1*1 degree) and downscaling (to 5*5km) which applied to each RFC (river forecast center) region over United States (see: Zhu and Luo, 2014).

12.4 2nd moment justification (MDL – John Wager and Bruce Veenhuis - 2011)

Ensemble Kernel Density MOS (EKDMOS) method has been applied to NAEFS global ensemble system to improve second moment calibration by using spread-skill relationship.

12.5 References

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13.0 Real Time Ocean Forecast System (Atlantic)

(Updated June 2012 by Avichal Mehra (**avichal.mehra@noaa.gov)**)

13.1 Introduction

RTOFS (Atlantic) is the first of a series of ocean forecast systems based on HYCOM. Part of the development of this system was done under a multi-national HYCOM Consortium funded by NOPP. HYCOM is the result of collaborative efforts among the University of Miami, the Naval Research Laboratory (NRL), and the Los Alamos National Laboratory (LANL), as part of the multi-institutional HYCOM Consortium for Data-Assimilative Ocean Modeling funded by the National Ocean Partnership Program (NOPP) to develop and evaluate a data-assimilative hybrid isopycnal-sigma-pressure (generalized) coordinate ocean model.

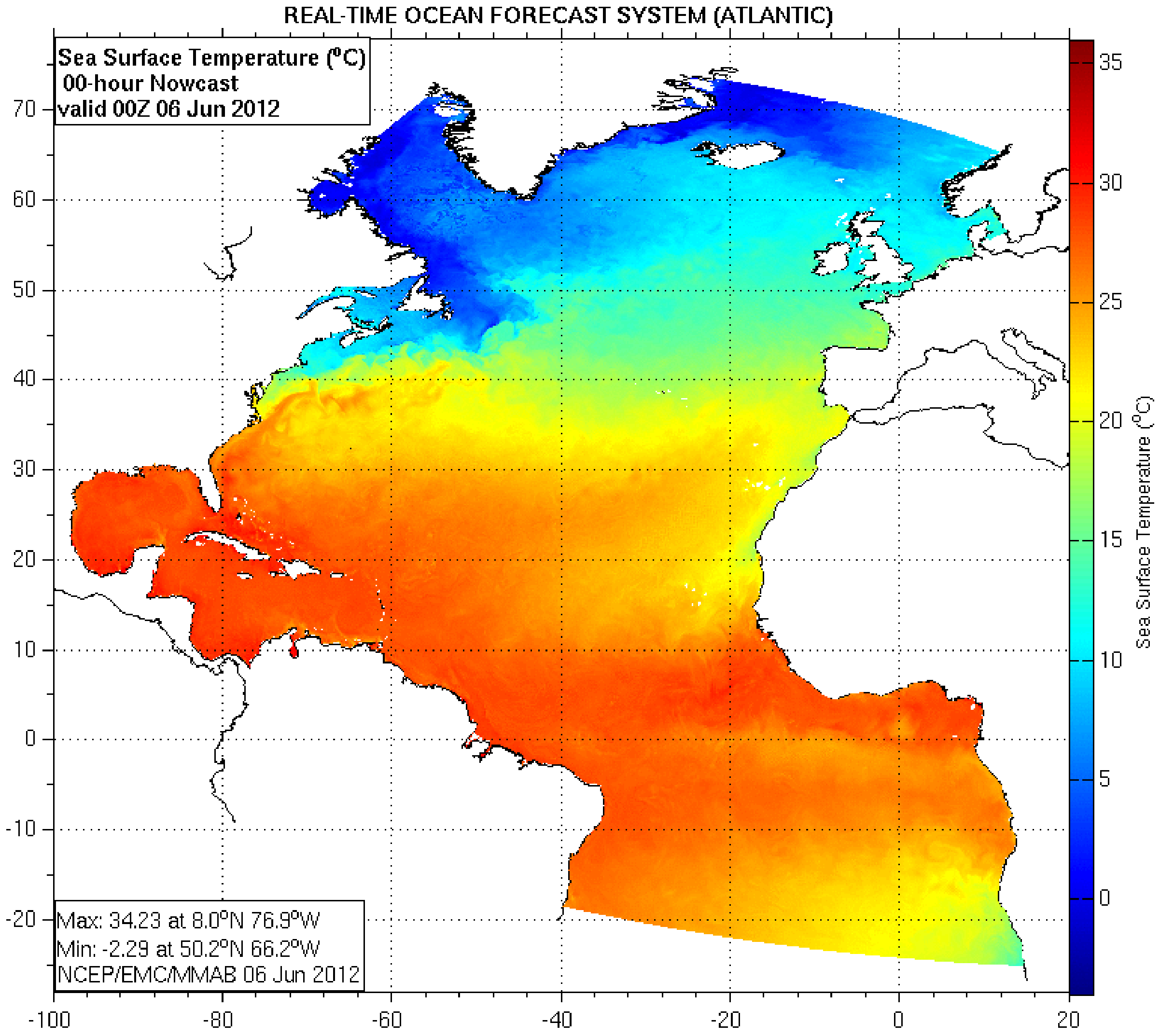
RTOFS (Atlantic) is a basin-scale ocean forecast system based on the HYbrid Coordinate Ocean Model (HYCOM). RTOFS (Atlantic) is described in the following paper (PDF): "A Real Time Ocean Forecast System for the North Atlantic Ocean" by Mehra and Rivin, Terr. Atmos. Ocean. Sci., Vol. 21, No. 1, 211-228, February 2010
The model is run once a day, completing at about 1400Z. Each run starts with a 24 hour assimiliation hindcast and produces ocean surface forecasts every hour and full volume forecasts every 24 hours from the 0000Z nowcast out to 120 hours.
RTOFS (Atlantic) model data and results are available daily at:
http://polar.ncep.noaa.gov/ofs/index.shtml

13.2 Goals

- Establish operational high resolution (eddy resolving) ocean forecast system for short-term forecasts (approximately 1-week) of the Atlantic ocean with US deep and coastal waters well resolved.
- Nowcasts and forecasts of sea levels, currents, temperatures, and salinity. Emphasis on the coastal ocean, the Loop Current and the Gulf Stream regions.
- Provide seamless boundary and initial conditions to regional ocean physical and biogeochemical models.
- Coupled circulation-wave ocean models with one-way and two-way interactions.
- Coupled atmosphere-ocean hurricane forecast

13.3 Model Configuration

- The dynamical model is HYCOM.
    - The model uses curvilinear coordinates in the horizontal and hybrid vertical coordinates in the vertical.
    - Runs one day nowcast and 6 days forecast dailyOrthogonal grid (1200 x 1684 points)
    - 26 vertical coordinates (21 isopycnal, 5 z-level)



- Surface Forcing
    - forcing fields from 3-hour NCEP (GDAS/GFS) model
    - Open Boundaries
    - Relaxed to NCEP climatology. Also relaxed to climatology in the Straits of Gibraltar region
- Tides
    - M2, S2, N2, K1, P1, O1, K2, Q1 tidal modes
    - Body and boundary tides
- Rivers
    - From daily USGS data and RIVDIS climatology
- Data Assimilation
    - SST: from GOES AVHRR and in-situ
    - SSH, T, S: using SLA from JASON GFO
    - T,S: from ARGOS, XBT, CTD
- Model Parameters
    - Time step: split-explicit 150 sec baroclinic, 5 sec barotropic
    - Advection scheme: 2nd order Flux Corrected Transport (FCT) with density and salinity as the advected scalars
    - Horizontal momentum viscosity: additive laplacian with biharmonic operators
    - Laplacian: deformation factor = 0.1, diffusion velocity = 0.0075 m/s
    - Biharmonic: deformation factor = 0.0, diffusion velocity = 0.01 m/s
    - Laplacian scalar diffusion (diffusion velocity: 0.005 m/s)
    - Vertical viscosity and mixing: GISS
    - Quadratic bottom friction coefficient: 0.003
    - Bottom boundary layer thickness: 10 m

14.0 The GFDL Operational Hurricane Prediction System

(*Updated June 11, 2012 by Morris Bender (Morris.Bender@noaa.gov)*)

Since 1995 the GFDL hurricane prediction system has been part of NCEP's operational production suite on NOAA's Central Computer System, providing forecast track and intensity guidance to the National Hurricane Center for Atlantic and Eastern Pacific tropical cyclone activity. This forecast system was developed by the hurricane modeling group at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) who continue to assist with support for the forecast system. A version of the GFDL model (GFDN) was transferred to the U.S. Navy in 1996 (Rennick 1999) where it provides forecast guidance to the Joint Typhoon Warning Center (JTWC), for the western Pacific and all other ocean basins in their area of responsibility.

The GFDL model is run for all storms requested by the National Hurricane Center (NHC) for the North Atlantic and North Eastern Pacific basins (maximum of five storms each cycle), and provides 5-day forecast guidance for hurricane track and intensity at every 6-hr interval. The approximate running time for a 5-day forecast is 65 minutes, using 37 CPUs. The NCEP Global Forecast System (GFS) analysis and forecasts provide initial and boundary conditions. The tropical cyclone is initialized using information provided from the National Hurricane Center (e.g. storm location, intensity and structure) using a vortex spin-up technique developed at GFDL (Kurihara et al, 1993 and 1995).

After being frozen since 2006, the model was officially unfrozen in 2011, and the model physics were upgraded that year with the new GFS Simplified Arakawa Scheme, improved surface flux computation, and numerous bug fixes.

14.1 Atmospheric model:

The GFDL hurricane model is a triply nested and movable two-way interactive grid system with the inner grids of highest resolution centered on the storm. The present model consists of 42 sigma levels in the vertical with relatively high vertical resolution (~5 levels) in the planetary boundary layer. The outer domain, which spans 75 degrees in the latitude and longitude direction, has resolution of .5 degrees telescoping to a 1/12 degree resolution in the innermost nest, which covers a five degree square area. Currently, the model domain spans from 15^{o}S to 60^{o}N with the longitudinal boundaries determined from the current and 72h forecasted storm positions. Finite differencing of the governing equations is based on the box method (Kurihara and Holloway 1967). When a mesh moves, coarse boxes at the leading edge zone become fine boxes and fine boxes at the trailing edge zone become coarse boxes.

The model utilizes a two-step iterative time integration scheme that utilizes frequency-selective damping characteristics, to minimize the impacts of noise related to mesh movement (Kurihara and Tripoli 1976). Finally, a wind direction-dependent open lateral boundary condition is employed, where the strength of forcing of the predicted values toward the reference values is dependent on the direction angle of the predicted wind at the boundary grid point (Kurihara et al. 1989). The wind direction-dependent lateral boundary scheme was specifically designed for the hurricane model to minimize the amount of boundary noise, and distortion of propagating waves into the limited area. Details of the hurricane model are summarized in Kurihara et al. (1998) and more recently in Bender et al. (2007).

14.2 Ocean Model:

In 2001, the operational GFDL model was coupled to the Princeton Ocean Model (POM), for the North Atlantic basin with coupling extended to the Eastern Pacific in 2004. POM is a three-dimensional, primitive-equation model with complete thermohaline dynamics, a sigma vertical coordinate system, and a free surface (Blumberg and Mellor 1987). The specific ocean model details and description of the ocean initialization have been outlined extensively in Bender and Ginis (2000). For computational efficiency, in the current operational ocean model configuration, the POM is divided into two overlapping domains for the Atlantic basin- one for the eastern Atlantic the other for the western Atlantic- which are selected automatically, depending on the location of the forecast storm. The horizontal grid resolution of each ocean domain is 1/6th degree, with 23 sigma levels in the vertical. The current ocean model and configuration is presently operational in the HWRF modeling system.

In 2004, ocean coupling was introduced in the eastern Pacific in the operational version of the model, where, for computational efficiency, the GFDL model was coupled to a one-dimensional ocean model derived from the three-dimensional POM. In 2013, the one-dimensional coupling in the eastern Pacific will be extended to full three dimensional ocean coupling, similar to the Atlantic.

14.3 Deep convection:

In the 2003 GFDL physics model upgrade, the Kurihara (1973) convective parameterization was replaced by a simplified Arakawa-Schubert (SAS) cumulus parameterization. This scheme, which is based on Arakawa and Schubert (1974) and simplified by Grell (1993), was made operational in NCEP's GFS in 1995. A major simplification was made to the original AS by considering a random cloud top at a specified time increment (4 minutes for the GFDL hurricane model), and not the spectrum of cloud sizes, as in the computationally expensive original Arakawa and Schubert (1974). The SAS scheme was upgraded in 2011, with the improved version that was made operational in the GFS the previous year, where the random cloud top specification is eliminated and only deepest clouds are considered.

14.4 Shallow convection:

In the 2012 GFDL model upgrade, the mass flux shallow convection scheme implemented in the GFS model in 2010, was implemented into the GFDL hurricane forecast system. Separation of deep and shallow convection is determined by cloud depth, currently 150hPa. Entrainment rate is given to be inversely proportional to height and is much larger than that in the deep convection scheme. Mass flux at cloud base is given as a function of the surface buoyancy flux.

14.5 Microphysics:

In 2006 the Ferrier microphysics package, operational in the NCEP regional Eta Model, was implemented into the GFDL hurricane model, replacing the simple large-scale condensation. The scheme predicts four classes of hydrometeors: suspended cloud liquid water droplets, rain water, large ice particles, which include snow and graupel, and small ice particles. A simplification is made (Ferrier 2005) for optimization, by treating only the sum of the four hydrometeor classes (referred to as the total condensate) in the advection of the cloud species in both the horizontal and vertical directions. In the 2013 model physics upgrades, this simplification is planned to be replaced with advection of each of the individual micro-physics species (cloud water, rain water, and ice). Tests indicate this change will increase computational time less than 6% but leads to more realistic storm structure in sheared situations, improving the prediction of storm intensity.

One of the novel aspects of the Ferrier (2005) scheme is inclusion of a rime factor that allows for a continuum of rimed ice growth from snow to graupel and sleet. The scheme allows for the coexistence and interaction of all forms of liquid and frozen cloud and precipitation particles under certain conditions. During the original evaluation of the Ferrier package in the GFDL hurricane, it was found that a value of .25 g m^{-3} gave the best results for the auto conversion threshold.

14.6 Horizontal and Vertical Diffusion processes:

Effects of horizontal diffusion are estimated by the nonlinear viscosity scheme (Smagorinsky 1963) from the strain due to the resolvable winds for momentum and from the horizontal gradient of the temperature and wind for heat. The diffusion coefficients are determined from the deformation and the scale length.

In the 2003 physics model upgrade, the Mellor and Yamada level-2.5 vertical diffusion scheme was replaced with a nonlocal boundary layer parameterization based on the Troen and Mahrt (1986) concept implemented into the NCEP GFS in October 1995 (Hong and Pan 1996). In this parameterization, the boundary layer height is determined from the critical bulk Richardson number. The vertical profiles of the eddy diffusivities are determined as a cubic function of the boundary layer height.

In the 2012 GFDL model upgrade the critical Richardson number was changed from .5 to .25, which is the same as the value used presently in the GFS. This modification lead to a significantly improved PBL height and structure and was also made operational in 2012 HWRF.

14.7 Surface Physics:

The air-sea flux calculations in the GFDL model are based on the Monin-Obukhov similarity theory, with roughness height (zo) modified in 2006 with a formulation based on output from a coupled wind-wave model simulations in hurricane conditions (Moon et al. 2007). In the original Monin-Obukhov formulation the surface drag coefficient (Cd) and enthalpy exchange coefficient (Ch) increase linearly at all wind speeds. However recent observations clearly indicate the surface drag levels off in high wind conditions. This tendency is captured in the revised formulation. In the 2012 implementation the enthalpy exchange coefficient was modified to more closely fit observed values, while being restrained not to exceed the value of the surface drag coefficient (Cd) in higher wind conditions.

14.8 Radiation:

Radiation effects are evaluated by the Schwarzkopf and Fels (1991) infrared and Lacis and Hansen (1974) solar radiation parameterizations, including diurnal variation and interactive effects of clouds. Calculated radiative fluxes are updated every 10 minutes. Clouds are specified where the model condensation takes place either from initiation of convection from the SAS scheme, or the presence of combined condensate from the micro-physics.

14.9 Vortex Initialization:

The initial condition relies on the global analysis and information on the tropical cyclone structure obtained from the storm message file prepared by forecasters at NHC. The vortex initialization is formulated using a vortex replacement strategy in which the vortex in the global analysis is removed through application of two filters developed by the hurricane group at GFDL (Kurihara et al. 1993 and 1995) and a new specified vortex is inserted based on the observed structure. A unique aspect of this strategy is the separation of the global analysis into a basic and disturbance field and a second separation of the disturbance field into a hurricane and non-hurricane component. It is assumed that the analyzed vortex is confined within a finite filter domain, beyond which the disturbance field is entirely non-hurricane. Within the filter domain the disturbance field is assumed to be a combination of a hurricane and non-hurricane component with only the hurricane disturbance component removed, through application of the second filter.

A specified hurricane vortex is obtained through a controlled spin-up using an axi-symmetric version of the hurricane model. The axi-symmetric model uses the identical physics and resolution of the full 3 dimension model. The tangential wind at the 850 hPa level is gradually nudged toward a target wind filed obtain from information from the NHC storm message file. The axi-symmetric integration proceeds for 60h, with strongest nudging near the storm center and lower free atmosphere, very weak nudging at the higher levels, and no nudging in the planetary boundary layer, enabling the model to produce a model consistent structure. No nudging is applied to the other atmospheric variables, which are free to evolve into a model consistent and balanced state. Finally, the axi-symmetirc vortex is added back into the global analysis (where the global vortex has been removed), at the observed position. Previously, an asymmetric vortex component was also added, derived from the 12h forecasted storm obtained from the previous 12 hour forecast. However, this step was removed in the 2012 model implementation, after tests over the 2010 and 2011 hurricane seasons indicated that this additional initialization step no longer had any impact on either track or intensity skill.

14.10 Future plans:

During discussion of the present model configuration, some of the plans for model upgrades were briefly mentioned. Details and summary of these upgrades are detailed below.

- The one-dimension ocean coupling in the eastern Pacific will be extended to a full three dimension ocean coupling in 2013. This version is now operational in GFDN.
- Advection of the individual micro-physics species (cloud water, rain water, and ice) will replace the advection of the total condensate, in the 2013 upgrade. Tests indicate this will increase computational time less then 6% but lead to much more realistic storm structure in sheared situations and reduce the errors in prediction of storm intensity.
- The GFDL hurricane model resolution is constrained since it is a hydrostatic model. However testing has indicated significant improvements in intensity prediction and hurricane structure are attainable for intense hurricanes by increase of the model resolution in the inner nest from the present 1/12th degree to 1/18th degree. This is the limit in resolution that can be realistically utilized with hydrostatic dynamics. The increase in computational requirements for this upgrade is about 45%, which can be realized with more allocation of CPUs. This model is being further tested in 2012.
- The current radiation package operational in the GFDL hurricane model has not been upgraded in over 20 years. An effort is underway at GFDL to test the model with some of the upgraded radiation physics developed at GFDL. The radiation upgrade is planned for 2013 or 2014.
- With the upgraded radiation package, the hurricane model can be tested with increased vertical resolution. The transmission functions in the current package are hardwired to the current 42 levels.
- A version of the current GFDL hurricane model has been successfully coupled to the WaveWatch III model developed at NCEP. With wave model coupling, the spatial distribution of the surface roughness can be more accurately obtained, resulting in improved model forecasted surface wind fields. Tests indicate this positively impacts both track and intensity. Sea-spray in hurricane conditions may play an increasing role in the hurricane intensity as the surface winds

increase. However, realistic parameterization of sea-spray is dependent on correct prediction of the sea state and wave heights, which require full wave coupling. Wave dependent sea-spray parameterizations are currently being developed and tested in the version of the GFDL model with full wave coupling. Further development of this coupled system will be continue with possible future implementation as resources permit. This improved coupled system will also be transferable to HWRF.

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15.0 Hurricane Weather Research and Forecast (HWRF) Modeling system (*Updated Oct., 2014, Vijay Tallapragada (Vijay.Tallapragada@noaa.gov)*)

15.1. Introduction:

The Environmental Modeling Center (EMC) at the National Centers for Environmental Prediction (NCEP) provides high-resolution deterministic tropical cyclone forecast guidance in real-time to the National Hurricane Center (NHC) for the North Atlantic (NATL) and Eastern North Pacific (EPAC) basins; to the Central Pacific Hurricane Center (CPHC) for the Central North Pacific (CPAC) basin; and to the United States (US) Navy's Joint Typhoon Warning Center (JTWC) for all other tropical ocean basins including Western North Pacific (WPAC), North Indian (NIO), South Indian (SI) and South Pacific (SP). The Hurricane Weather Research and Forecast (HWRF) system became operational at NCEP starting with the 2007 hurricane season for the NATL and EPAC basins, and has grown ever since in its applications for tropical cyclone forecast for all ocean basins by 2014. Figure 1 shows the regions where HWRF model is currently operated in real-time.

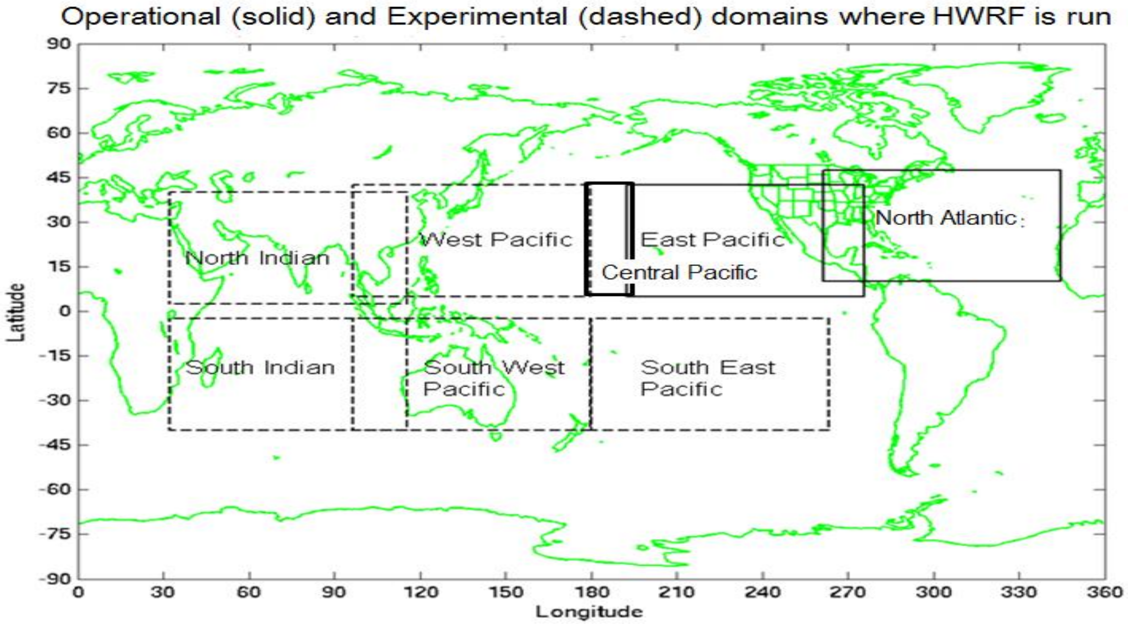


Figure 1: Tropical oceanic basins covered by the HWRF model for providing real-time TC forecasts. Solid lines represent operational HWRF domains at NCEP. Dashed lines show the areas where experimental forecasts are provided by HWRF in real-time.

Development of the HWRF began in 2002 at EMC in collaboration with the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanic and Atmospheric

Administration (NOAA) and the University of Rhode Island (URI). To meet operational implementation requirements, it was necessary that the skill of the track forecasts from the HWRF and GFDL hurricane models be comparable. Since the GFDL model evolved as primary guidance for track prediction used by NHC, CPHC, and JTWC after becoming operational in 1994, the strategy for HWRF development was to take advantage of the advancements made to improve tropical cyclone track, intensity, structure and rainfall predictions through a focused collaboration between EMC, GFDL, and URI and transition those modeling advancements to the HWRF. This strategy ensured comparable track and intensity forecast skill to the GFDL for initial implementation in 2007. Additionally, features of the GFDL hurricane model that led to demonstrated skill for intensity forecasts, such as ocean coupling, upgraded air-sea physics, and improvements to microphysics, were also captured in the newly developed HWRF system.

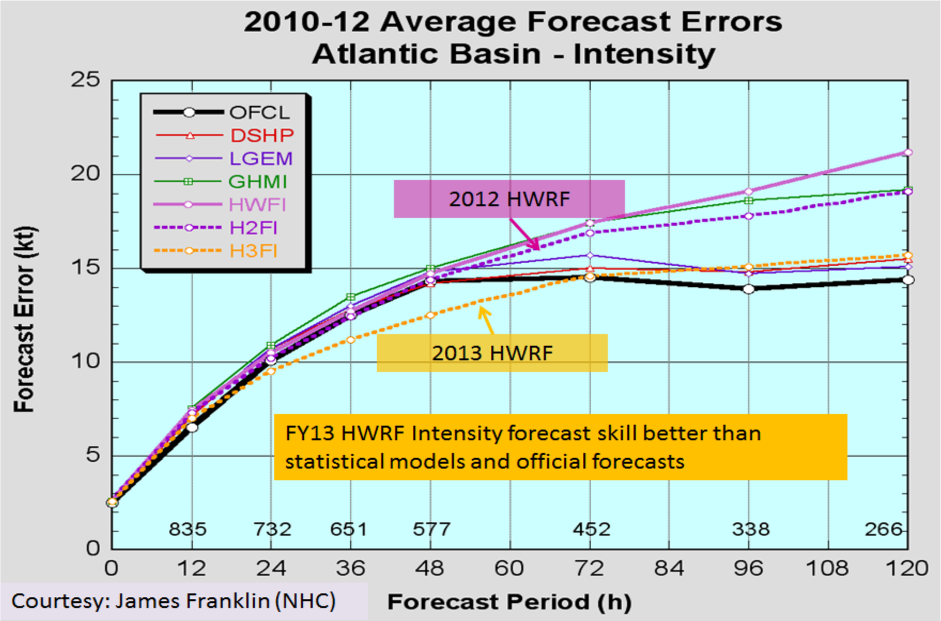
Upgrades to the HWRF system are performed on an annual cycle that is dependent on the hurricane season and on upgrades to the Global Data Assimilation System (GDAS) and the Global Forecast System (GFS) that both provide initial and boundary conditions for HWRF. Every year, prior to the start of the Eastern North Pacific and Atlantic hurricane seasons (15 May and 1 June, respectively), HWRF upgrades are provided to NHC by EMC so that NHC forecasters have improved hurricane guidance at the start of each new hurricane season. These upgrades are chosen based on extensive testing and evaluation (T&E) of model forecasts for at least two recent past hurricane seasons. There are basically two phases of development. The first is developmental testing that occurs prior to and during the hurricane season (roughly 1 April to 30 October) where potential upgrades to the system are tested individually in a systematic and coordinated manner. The pre-implementation testing starts in November and is designed to test the most promising developments assessed in the development phase to define the HWRF configuration for the upcoming hurricane season. The results of the pre-implementation testing must be completed and the final HWRF configuration locked down by 15 March for each annual upgrade. Once frozen, the system is handed off to NCEP Central Operations (NCO) for implementation by about 1 June. The cycle is then repeated for the next set of proposed upgrades to the HWRF system. During the hurricane season (1 June to 30 November) changes are not made to the operational HWRF in order to provide forecasters with consistent and documented numerical guidance performance characteristics.

Since its initial implementation in 2007, HWRF has been upgraded every year to meet specific scientific goals addressed through the aforementioned pre-implementation T&E. Changes to the vortex initialization and convective parameterization were the focal areas for the 2008 HWRF implementation. Infrastructure upgrades and transitioning to the new IBM machine were dominant for the 2009 HWRF implementation. For 2010 upgrades, the HWRF team at EMC worked on further improving the vortex initialization, including gravity wave drag parameterization and modifying the surface physics based on observations. Limiting rapid growth of initial intensity errors was one of the focal areas for the 2011 HWRF implementation, along with major upgrades to model dynamical core from WRF v2.0 to community-based WRF v3.2, bridging the gap between the operational and community versions of the WRF model. Other significant developments in year 2011 were to make the operational HWRF model available to the research community through the Developmental Testbed Center (DTC), and to draw the codes from the community repository maintained and supported by DTC, ensuring that the operational and research HWRF codes remain synchronized.

To significantly improve hurricane forecast skill, the hurricane modeling team at NCEP/EMC, with support from NOAA's Hurricane Forecast Improvement Project (HFIP) and in collaboration with the Hurricane Research Division (HRD) of the NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) and several partners within NOAA as well as academia, implemented major changes to the 2012 version of operational HWRF. The biggest improvement was the triple-nest capability that included a cloud-resolving innermost grid operating at 3 km horizontal resolution. Other major HWRF upgrades implemented for the 2012 hurricane season include a centroid-based nest movement algorithm; explicit representation of moist processes in the innermost grid; inclusion of shallow convection in the Simplified Arakawa Schubert (SAS) convective parameterization; observation-based modifications to the convective, microphysics, Planetary Boundary Layer (PBL) and surface parameterizations, making them suitable for higher resolution; re-design of the vortex initialization for 3-km resolution with improved interpolation algorithms and better representation of the composite storm; improved Princeton Ocean Model for TCs (POM-TC) initialization in the Atlantic domain and new 1-D ocean coupling for the Eastern North Pacific basin; upgrade of the Gridpoint Statistical Interpolator (GSI) data assimilation system; improved HWRF Unified Post Processor (UPP) to generate simulated microwave satellite imagery products; and very high-resolution (every 5 s) storm tracker output to support NHC operations. The HWRF codes were optimized to ensure that the 2012 model ran in the time slot allotted for operational products at NCEP and with few additional computer resources.

Apart from obtaining significant improvements in the track forecast skill compared to previous versions, 2012 version of the operational HWRF has conclusively demonstrated the positive impact of resolution on storm size and structure forecasts (Tallapragada et al. 2014a). Such large reduction of the strong wind radii indicates that the high-resolution HWRF model forecasts were able to capture the inner-core region of the storms more realistically. This is expected as storm structure and fine-scale processes are believed to be better resolved with higher resolution.

The 2013 version of the operational HWRF made additional huge improvement in track, intensity and structural prediction of TCs by taking further advantage of the high-resolution capability built in the 2012 HWRF. Major upgrades for the 2013 HWRF include changes in model configuration, such as use of a larger innermost 3-km domain and higher frequency of physics calls; an advanced parent-nest interpolation method; a more sophisticated vortex following algorithm based on nine different parameters as in GFDL vortex tracker; upgrades to the PBL parameterization to fit observed structures of both the hurricane area and the outer environmental region; modifications of the vortex initialization method with adjusted filter size, storm size correction, and weak storm treatment; and for the first time, implementation of the Hurricane Data Assimilation System (HDAS), a GSI-based one-way hybrid ensemble-variational data assimilation scheme to assimilate inner core observations from the NOAA P3 aircraft Tail Doppler Radar (TDR) data, when available; improved ocean model; and further improvements to the forecast products.

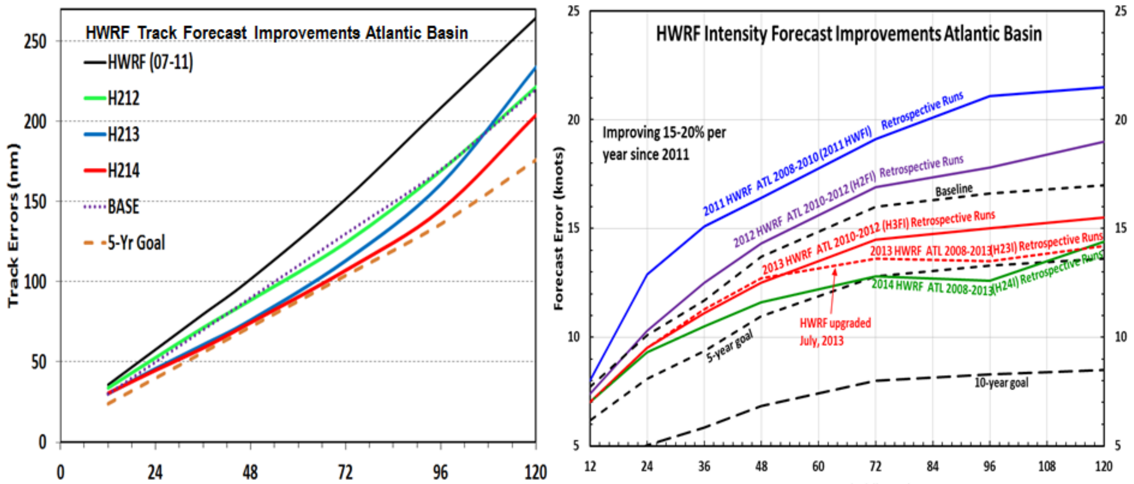


Courtesy: James Franklin (NHC)

Figure 2: Average intensity forecast errors for 2010-2012 hurricane seasons from 2013 version of HWRF model (H3FI) compared to 2012 version (H2FI), operational HWRF (HWFI), GFDL model (GHMI), statistical models LGEM (Linear Growth Equation Model) and DSHP (Decay Statistical Hurricane Intensity Prediction System). Dark black line represents NHC Official Forecast errors as a function of time, and the number of cases verified at each forecast period is shown along the x-axis.

One of the highlights of the 2013 HWRF configuration retrospective T&E, performed on a vast sample of three hurricane seasons (2010-2012), was the remarkable intensity forecast skill. Results shown in Fig. 2 indicated that the HWRF model outperformed the statistical models for intensity prediction in the 2 to 3-day forecast period. Historically, statistical models have been more skillful than dynamical models for hurricane intensity prediction. These HWRF results demonstrate, for the first time, the potential of an operational dynamical model as a viable hurricane intensity prediction tool. Track forecast skills from the 2013 HWRF have also been significantly improved compared to the 2012 HWRF, and are now comparable to the best-performing GFS model.

Major upgrades for the 2014 version of the operational HWRF include increased vertical resolution (61 levels) and higher model top (2 hPa), inclusion of aircraft reconnaissance dropsonde data in the inner core, implementation of a new, high-resolution version of POM-TC (MPIPOM-TC), with a single, transatlantic ocean domain for NATL and 3-D coupling for the EPAC basins. Evaluation of 2014 HWRF upgrades have shown further improvements in track and intensity forecasts, with the track errors now comparable to the best performing GFS model and intensity errors better than NHC official forecasts at all forecast lead times. Figure 3 shows the cumulative improvements obtained from the operational HWRF during the last four years (2011-2014), highlighting the role of HWRF in providing more accurate track and intensity forecast guidance for NHC. HWRF model's progress towards accomplishing 5-year goals of HFIP is also highlighted in this figure.



Significant improvements in the Hurricane Track Forecasts for the Atlantic Basin: Approaching the NOAA HFIP 5-year Goals

Accelerated progress in improving the Hurricane Intensity Forecasts for the Atlantic Basin: Approaching the NOAA HFIP 5-year Goals

Figure 3: Cumulative forecast improvements in the NATL basin from operational HWRF over the years since 2011. Each configuration of HWRF was evaluated for multiple hurricane seasons. The dashed lines show HFIP baseline (BASE) and 5-year goal for track and intensity errors.

The list of upgrades to the HWRF from 2008 through 2014 is available on EMC's HWRF website (http://www.emc.ncep.noaa.gov/index.php?branch=HWRF). These details will also be made available on the WRF for Hurricanes website hosted by DTC (http://www.dtcenter.org/HurrWRF/users).

The HWRF system is composed of the WRF model software infrastructure, the Non-Hydrostatic Mesoscale Model (NMM) dynamic core, the MPIPOM-TC, and the NCEP coupler. HWRF employs a suite of advanced physics developed for tropical cyclone applications. These include GFDL surface physics to account for air-sea interaction over warm water and under high wind conditions, GFDL land surface model and radiation, Ferrier Microphysics, NCEP GFS boundary layer, and GFS SAS deep and shallow convection. Figure 4 illustrates all components of HWRF supported by the DTC, which also include the WRF Pre-Processor System (WPS), prep_hybrid (used to process spectral coefficients of GDAS and GFS in their native vertical coordinates), a sophisticated vortex initialization package designed for HWRF, the regional hybrid Ensemble Kalman Filter (EnKF) - three-dimensional variational data assimilation system (3D-VAR) GSI, UPP, and the GFDL vortex tracker.

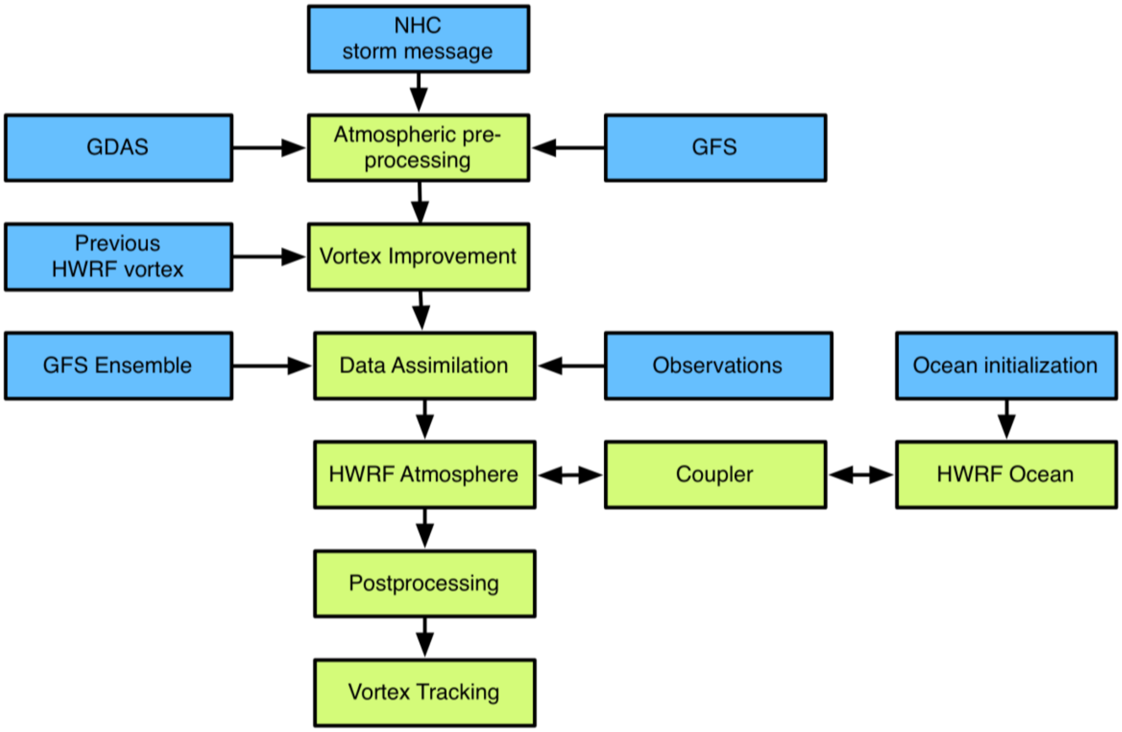


Figure 4: A simplified overview of the HWRF system. Components include the atmospheric initialization, the vortex improvement, the GSI data assimilation, the HWRF atmospheric model, the atmosphere-ocean coupler, the ocean initialization, the MPIPOM-TC, the post processor, and the vortex tracker.

It should be noted that, although the HWRF uses the same dynamic core as the NMM in the Arakawa E-staggered grid (NMM-E) developed at NCEP, HWRF was customized for hurricane/tropical forecast applications, and is very different from other operational models that employ NMM-E, such as the High-Resolution Windows (HRW) and the Short-Range Ensemble Forecast (SREF) System. HWRF also differs substantially from the North American Mesoscale (NAM) model, which now employs the NMM dynamic core in the Arakawa-B grid (NMM-B). The HWRF is an atmosphere-ocean model configured with a parent grid and two telescopic, high-resolution, movable 2-way nested grids that follow the storm, using a unique physics suite and diffusion treatment. The HWRF also contains a sophisticated initialization of both the ocean- and the storm-scale circulation. Additionally, unlike other NCEP forecast systems which run continuously throughout the year, the HWRF and GFDL hurricane models are launched for operational use only when NHC or JTWC determines that a disturbed area of weather has the potential to evolve into a depression anywhere over their area of responsibility. After an initial HWRF run is triggered, new runs are launched in cycled mode at 6-h intervals, until either the storm dissipates after making landfall, becomes extra-tropical, or degenerates into a remnant low, typically identified when convection becomes disorganized around the center of circulation. Currently, the HWRF model is run in NCEP Central Operations (NCO) for the NATL, EPAC and CPAC basins, and experimentally on HFIP computational resources for all other basins, four times daily producing 126-h forecasts of TC track, intensity, structure, and rainfall to meet the operational forecast and warning process objectives.

Unlike other NCEP forecast systems which run continuously throughout the year, the hurricane models, e.g. both the HWRF and the GFDL models, are launched for operational use only when NHC determines that a disturbed area of weather has the potential to evolve into a depression anywhere over NHC's area of responsibility (covering the North Atlantic and Eastern North Pacific ocean basins, from approximately 0 – 140^{o}W). After an initial HWRF or GFDL run is triggered, new runs are launched in cycled mode until the storm either dissipates, becomes extratropical, or degenerates into a remnant low. Currently, the HWRF runs in NCEP operations four times daily (00, 06, 12 and 18 UTC) producing 5-day forecasts of hurricane track and intensity for as many as 5 storms to meet NHC operational forecast and warning process objectives.

The HWRF modeling system is composed of several key components for providing accurate hurricane track intensity forecast guidance to NHC forecasters - the WRF model software infrastructure, the Non-Hydrostatic Mesoscale Model (NMM) dynamic core, the three-dimensional Princeton Ocean Model (POM), the NCEP coupler, and a physics suite tailored to the tropics, including air-sea interactions over warm water and under high wind conditions, and boundary layer and cloud physics developed for hurricane forecasts. HWRF model employs an advanced hurricane vortex initialization and cycling technique coupled to NCEP's Grid Point Statistical Interpolation (GSI) data assimilation system for representing initial vortex structure. Forecast products from HWRF model are generated using NCEP's Unified Post Processing (UPP) system and GFDL's storm tracking algorithm.

15.2. Atmospheric model:

The atmospheric component of HWRF modeling system is composed of the Non-Hydrostatic Mesoscale Model (NMM) dynamic core of the community WRF model software infrastructure (Janjic, 2010). The HWRF is configured with a parent grid and high-resolution movable telescopic 2-way nested grids that follow the storm Tallapragada et al., 2014). The current HWRF configuration used in operations contains three domains: a parent domain with 27-km horizontal grid spacing and two vortex-following intermediate and inner-most domains operating at a resolution of 9-km and 3-km respectively, to capture multi-scale interactions. The nested domains have two-way feedback with their respective parent grids. The parent domain at 27km resolution covers roughly 80^o X 80^o on a rotated latitude/longitude staggered Arakawa E-grid. The intermediate domain (9km) spans approximately 11^o x 10^o and the innermost domain (3km) covers an area of about 6^o x 6^o. All three domains have same vertical structure with 42 hybrid levels and model top at 50 hPa. When more than one storm becomes active over the NHC's area of responsibility, a separate HWRF run is launched with its unique storm following nested grids.

HWRF uses a combination of WRF Pre-Processing System (WPS) and spectral data processing software to initialize atmospheric model variables from GFS spectral analysis and forecast datasets. All variables of the fine grid, except terrain, are initialized from the parent grid. Initialization of the other land variables, such as land-sea mask, soil temperature and vegetation type is done through a nearest-neighbor approach. To obtain the temperature, geopotential, and moisture fields for the nest initialization, pseudo hydrostatic mass balance is applied. The two-way interactive feedback procedure uses 13-points averaging with a weighting factor is 0.5, indicating that a coarse grid point retains half of its original value.

15.3. Ocean Model:

The oceanic component of HWRF modeling system is identical to the one used by the operational GFDL hurricane model, the Princeton Ocean Model (POM). The primary purpose of coupling the POM-TC to the HWRF is to create an accurate SST field that subsequently used to calculate the surface heat and moisture fluxes from the ocean to the atmosphere. POM is a three-dimensional, primitive-equation model with complete thermohaline dynamics, a sigma vertical coordinate system, and a free surface (Blumberg and Mellor 1987). The specific ocean model details and description of the ocean initialization have been outlined extensively in Bender and Ginis (2000). For computational efficiency, in the current operational ocean model configuration, the POM is divided into two overlapping domains for the Atlantic basin- one for the eastern

Atlantic and the other for the western Atlantic- which are selected automatically, depending on the location of the forecast storm. The horizontal grid resolution of each ocean domain is 1/6th degree, with 23 sigma levels in the vertical. Starting with 2012 implementation, HWRF model is coupled in the Eastern Pacific basin with a simplified 1-D POM model. Starting with the 2014 hurricane season, the operational HWRF is now coupled to the 3-D MPIPOM-TC in both the North Atlantic and eastern North Pacific basins. HWRF/MPIPOM-TC coupling also exists in other worldwide ocean basins, with a variety of potential ocean initialization options, but these other basins are not being released to the community until the developers have completed sufficient testing and evaluation.

Much research is currently underway in the atmospheric/oceanic hurricane community to prioritize and determine the model complexity needed to simulate realistic air-sea interactions. This complexity may include coupling to an adaptable multi-grid wave model (WAVEWATCH III – WW3) and simulating wave-current interactions that may prove important to address coastal inundation problems for landfalling hurricanes. The NCEP operational hurricane wave model driven by HWRF forcing has shown significant improvements in forecasting the signficant wave heights. Starting with 2014 hurricane season, NCEP Hurricane WW3 model will become a downstream model for HWRF, replacing the wind forcing from GFDL model forecasts with high-resolution HWRF hourly wind forecasts.

15.4. NCEP Coupler:

HWRF modeling system uses advanced air-sea interface software, known as the NCEP coupler. The coupler performs two major roles - transferring the required model variables between atmospheric and oceanic models, and interpolating those variables onto the grid points of target model. Currently, the HWRF atmospheric model provides the ocean model (POM) with momentum fluxes, latent and sensible heat fluxes and radiative fluxes at the surface as external forcings for the ocean model. In return, POM transfers the forecasted Sea Surface Temperature (SST), important for hurricane evolution, back to the atmospheric model. Through this process, atmosphere and ocean are fully coupled (for each atmospheric domain) and they communicate regularly at coupler time step (set to 540 sec. in the current HWRF configuration). The coupler in HWRF is also capable of three-way coupling among atmosphere, ocean and wave models to enable further enhancements to the operational HWRF modeling system.

15.5. HWRF Physics Suite:

Some of the physics in the HWRF evolved from a significant amount of development work carried out over the past 15 years in advancing model prediction of hurricane track with global models, such as the NCEP GFS, the Navy Operational Global Atmospheric Prediction System (NOGAPS), the United Kingdom Met Office (UKMO) model, and subsequently with the higher resolution GFDL hurricane model that had demonstrated improvement in hurricane intensity forecasts. These physics include representations of the surface layer, planetary boundary layer, microphysics, deep convection, radiative processes, and land surface. Commensurate with increasing interest in the ocean impact on hurricanes in the late 1990's and the operational implementation of the coupled GFDL model in 2001, collaboration increased between the atmospheric/oceanic research and operational communities that culminated in the Navy's field experiment, the Coupled Boundary Layer Air-Sea Transfer (CBLAST), carried out in the Eastern Atlantic in 2004. During CBLAST, important observations were taken that helped confirm that drag coefficients used in hurricane models were incorrect under high wind regimes. Since then, surface fluxes of both momentum and enthalpy under hurricanes remain an active area of hurricane scientific/modeling interest and are being examined in simple air-sea coupled systems and three-dimensional air-sea coupled systems with increasing complexity, including coupling of air-sea to wave models. Surface physics parameterization schemes used in the GFDL and HWRF models have continuously been calibrated to match the air-sea exchange coefficients based on findings from various observational campaigns and laboratory experiments. Recent research findings based on extensive dropsonde data collected from NOAA P3 aircraft and analyzed by scientists at NOAA/AOML have led to the improved representation of the vertical mixing in the hurricane planetary boundary layer (PBL) formulation in HWRF (Gopalakrishnan et al., 2012). Further improvements to the PBL scheme include formulation of variable critical Richardson number based on surface wind speed and calibration of PBL height and inflow angle to match the analysis provided by the observations from various field campaigns. The moist physics (convection and microphysics) used in the HWRF model has also been constantly improved to obtain improved hurricane intensity forecast skill. Dependency of convection scheme on model resolution requires adopting more sophisticated scale-aware physics; however, convection is explicitly resolved in the inner core region covered by the 3km nest. While there have been lot of efforts evaluating the impact of advanced microphysics schemes like the double-moment Thompson scheme, the results so far did not yield the desired benefits in improving hurricane intensity forecasts, and hence HWRF still employs the most successful Ferrier scheme modified for hurricane applications. Accurate representation of cloud-radiative feedback and land surface processes, improved interactions between various components of the physics and dynamics, and testing of next generation scale-aware and stochastic physics continue to be of high priority area of research for the HWRF model improvements.

15.5.1. Radiation:

Long-wave radiation in HWRF model is parameterized using a simplified exchange method (Fels and Schwarzkopf, 1975 and Schwarzkopf and Fels, 1991), with calculation over spectral bands associated with carbon dioxide, water vapor, and ozone. The Rodgers (1968) formulation is adopted for ozone absorption. Clouds are randomly overlapped. The HWRF shortwave radiation scheme is a GFDL version of the Lacis and Hansen (1974) parameterization. Effects of atmospheric water vapor, ozone and carbon dioxide (Sasamori et al. 1972) are included in this parameterization. Shortwave calculations are made using a daylight-mean cosine solar zenith angle for the specific time and grid location averaged over the time interval given by the radiation call frequency (one hour in the current operational setup).

15.5.2. Planetary Boundary layer:

The HWRF PBL scheme is based on the GFS PBL scheme which is a non-local mixing scheme originated by Troen and Mahrt (1986) and modified by Hong and Pan (1996). This scheme has a first-order vertical diffusion parameterization that uses the bulk-Richardson approach to iteratively estimate the PBL height starting from the ground upward. Once the PBL height is determined, the profile of the coefficient of momentum and heat diffusivity is specified as a cubic function of the PBL height. The GFS non-local scheme is, however, known for producing too high PBL height in hurricane area compared to the observation, so the vertical mixing becomes too strong. As a result, HWRF simulated hurricane tends to have large, diffusive structure. In order to alleviate this problem, critical Richardson number is reduced from 0.5 to 0.25 and momentum diffusivity is reduced to half of the original values in the 2012 version of HWRF model.

15.5.3. Deep convection:

Deep convection scheme for the HWRF model is a modified version of Simplified Arakawa-Schubert scheme (SAS) from NCEP GFS model based on Arakawa and Schubert (1974) and simplified by Grell (1993). This original GFS SAS scheme is revised to make cumulus convection stronger and deeper, and to reduce excessive grid-scale precipitation. In the current version of HWRF, convection parameterization is not used in the finest nest domain. Also, the convective momentum mixing coefficient is reduced from 0.55 to 0.2 to produce improved hurricane track and intensity forecasts.

15.5.4. Shallow convection:

The mass flux shallow convection scheme from GFS model is adopted in the current version of operational HWRF. Separation of deep and shallow convection is determined by cloud depth, currently set to 150hPa. Entrainment rate is inversely proportional to height and much larger than that in the deep convection scheme. Mass flux at cloud base is determined as a function of the surface buoyancy flux. A few other changes specific to HWRF model include no precipitation when the thickness of shallow convection is less than 50hPa and the top of shallow convection is below PBL top.

15.5.5. Microphysics:

HWRF uses a bulk microphysics scheme based on the Eta Grid-scale Cloud and Precipitation scheme developed in 2001 and known as the EGCP01 scheme (Ferrier 2005). This scheme predicts changes in water vapor and condensate in the forms of cloud water, rain, cloud ice, and precipitation ice (snow/graupel/sleet). For computational expediency, the individual hydrometeor fields are combined into total condensate which is advected along with the water variable. Several parameters such as NLImax, NCW and snow fall speed are modified for hurricane environment in the HWRF model.

15.5.6. Surface layer:

The surface layer scheme in HWRF is originated from the GFDL surface layer scheme, based on Monin-Obukhov similarity theory, with a formulation based on output from a coupled wind-wave model simulations in hurricane conditions (Moon et al. 2007). In the original Monin-Obukhov formulation the surface drag coefficient (Cd) and enthalpy exchange coefficient (Ch) increase linearly at all wind speeds. However recent observations clearly indicate the surface drag levels off in high wind conditions. This tendency is captured in the revised formulation. In the 2012 implementation the enthalpy exchange coefficient was modified to more closely fit observed values (constant at all wind speeds), while the surface drag coefficient (Cd) levels off in higher wind conditions.

15.5.7. Land Surface Model:

HWRF uses such a simple one-level land model following GFDL slab model developed by Tuleya (1994) based on Deardorff (1978). The surface wetness is assumed to be constant during the model forecast, with initial values based on the host model GFS analysis. This simple model is able to realistically simulate the development of the 'cool pool' land temperature under landfalling tropical storms, thereby drastically reducing the surface evaporation over land leading to rapid decay over land.

15.6. The vortex initialization system:

Tropical cyclones simulated by GFS can be very different from the observed position, initial intensity and structure. These initial errors grow larger with time and can lead to inaccurate hurricane track and intensity forecasts. In order to provide realistic representation of initial position, intensity and structure, an advanced vortex initialization system is designed for the HWRF model. The HWRF vortex initialization consists of several major steps: definition of the HWRF domain based on the observed storm center position; interpolation of the analyzed NCEP global model fields onto the HWRF parent domain, removal of the global model vortex and insertion of a mesoscale vortex obtained from the previous cycle's HWRF 6-hr forecast (if available) or from a synthetic vortex (cold start). Modification to the vortex structure includes corrections to the storm size, intensity and to the three-dimensional fields near the hurricane core and rebalancing between the model winds, temperature, pressure and moisture fields. The HWRF vortex initialization system matches the initial 10m wind speed of the initial vortex reported from NHC by combining previous 6hr forecasted vortex and a pre-generated composite vortex. In addition to the 10m winds, the location of the initial vortex is adjusted to the observed position using the relocation method.

15.7. The data assimilation system:

In addition to the vortex initialization system, the operational HWRF utilizes the NCEP Gridpoint Statistical Interpolation (GSI) based 3D-VAR data assimilation system where the conventional observations and clear-sky radiance datasets from several geostationary and polar orbiting satellites are assimilated in the hurricane environment. At present, inner-core conventional observations (within 150 km from the storm center) are excluded from the data assimilation procedure due to presumed ambiguity in observations. Further advancements to the data assimilation system include capability to ingest inner core observations from aircraft reconnaissance data (dropspondes, Tail Doppler Radar winds and flight level data) and cloudy and rain-affected satellite radiance datasets. The operational HWRF data assimilation system (HDAS) implemented in 2013 now includes the community GSI with a regional hybrid EnKF-3DVAR data assimilation procedure that consists, for the first time, assimilation of TDR data from the NOAA P3 aircraft, when available. The NCEP operational GFS 80-member ensemble forecast provides the ensemble background error covariances for HDAS. Apart from the NOAA P3 TDR, dropsonde data from aircraft reconnaissance missions, conventional observations, and clear-sky radiance datasets from several geostationary and polar orbiting satellites are also assimilated in the hurricane environment using GSI. In addition, a more advanced self-consistent EnKF-3DVAR hybrid regional data assimilation system is being developed for future HWRF applications.

15.8. The post-processing system:

HWRF model uses NCEP Unified Post Processing (UPP) system which provides model output in standard GRIB format projected on to regular lan/lon grid on standard pressure levels for all 3-D variables and a suite of 2-D variables at the surface. Using the capabilities of UPP Community Radiative Transfer Model (CRTM), several hurricane specific diagnostic products including synthetic satellite imagery from geostationary (GOES) and polar orbiting (SSM/I-S) sensors and radar reflectivities are generated at the request of NHC forecasters.

15.9. Vortex Tracker:

HWRF model uses standard NCEP tracker software developed by GFDL for providing the storm forecast position, intensity and various other parameters in ATCF format. A modified version of GFDL tracker is implemented in the current version of HWRF that enables providing additional tracking parameters that describe the thermodynamic state of the storm at every forecast interval. Starting with 2012 implementation, a very high temporal resolution (every 5 sec) tracker output is also made available to NHC forecasters on an experimental basis.

15.10. HWRF as a community model:

The HWRF model is an important component of the numerical guidance used at the National Hurricane Center, making it critical that HWRF be continuously improved. For that reason, NCEP/EMC has partnered with NOAA’s Developmental Testbed Center

(DTC) to accelerate the transfer of new developments onto HWRF and made all components of operational HWRF available to the research community through a code repository maintained and supported by DTC. More details on accessing the operational model codes is available at http://www.dtcenter.org/HurrWRF

15.11. Future plans:

Continuous advancements to the operational HWRF system are made possible through extensive support from NOAA's Hurricane Forecast Improvement Project (HFIP) and collaboration with several partners from government labs and academia. Future plans include:

a) Comprehensive three-way atmosphere-ocean-wave coupled system that includes affects of sea-spray and wave state for improved intensity predictions

b) Development of basin scale HWRF modeling system with multiple moveable nests and hybrid EnKF/3DVAR data assimilation system

c) Coupling to NCEP operational HYCOM ocean model

d) Advanced physics options based on observational findings

e) Higher model top and increased vertical resolution

f) Transitioning to the NOAA's Environmental Modeling System (NEMS) framework that provides global-to-local scale modeling infrastructure

g) Coupling to NOAH land surface model, dynamic storm surge model and hydrological model for advanced prediction of coastal impact of landfalling storms, inland flooding and inundation

Figure 5 shows the fully coupled proposed operational hurricane system, with 2-way interaction between the atmosphere-land-ocean-wave models, providing feedback to high-resolution bay and estuary hydrodynamic models that predict storm surge inundation.

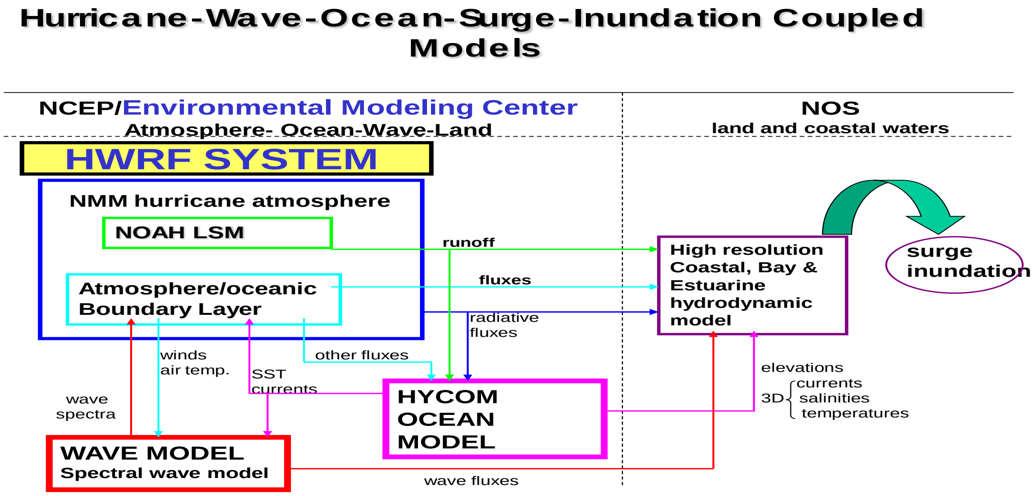


Figure 5. Proposed future operational coupled hurricane forecast system.

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16.0 The North American Land Data Assimilation System (NLDAS)

(Updated: June 2012 by MiMichael Ek (Michael.Ek@noaa.gov))

16.1. Description of NLDAS

Currently NLDAS is a quasi-operational system to support U.S. operational drought monitoring and seasonal hydraulic prediction, in particular for the National Integrated Information System including U.S. Drought Monitor and Monthly Drought Briefing. Detailed information about NLDAS can be found at NOAA (http://www.emc.ncep.noaa.gov/mmb/nldas) and NASA (http://ldas.gsfc.nasa.gov/nldas/) websites. The system consists of a retrospective 29-year (1979-2008) historical execution and a near real-time daily update execution using four land surface models (NCEP/Noah, NASA/Mosaic, NWS/OHD/SAC, and VIC developed by Princeton University and University of Washington) on a common 1/8th degree grid using common hourly land surface forcing. The non-precipitation surface forcing is derived from the NCEP retrospective and real-time North American Regional Reanalysis (NARR), and now the NCEP operational Regional Climate Data Assimilation System (RCDAS). The precipitation forcing is anchored to daily gauge-only precipitation over Continental United Sates (CONUS) that applies Parameter-elevation Regressions on Independent Slopes Model (PRISM) corrections. This daily precipitation analysis is then temporally disaggregated to hourly precipitation amounts using radar products. The NARR-based surface downward solar radiation is bias-corrected using seven years (1997-2204) of satellite-derived solar radiation retrievals.

The 29-year NLDAS retrospective run is used to derive the climatology of each of the four land models. Then current near real-time (past week, past month) land states (e.g. soil moisture, snowpack), and water fluxes (e.g. evaporation, total runoff, streamflow) of each of the four models from daily executions are depicted as anomalies and percentiles with respect to their own model climatology. The simulated streamflow, soil moisture, snowpack, and evapotranspiration from the four models are well evaluated and validated using in-situ observations from the U.S. Geological Survey, Illinois, Oklahoma, and CONUS soil moisture, and evapotranspiration form U.S. surface flux measurement sites. This evaluation provides a basis to apply NLDAS products. One key application of the near real-time updates is drought monitoing over CONUS, shown at the “NLDAS Drought” tab of the NLDAS website. NLDAS products are directly provided to the U.S. Drought Monitor author group through a daily cron job.

16.2. Future plans

NLDAS has become mature enough for NCEP operational implementation, and will be implemented in NCEP operations in the near future. At the same time, we recognize that the current NLDAS is not an “actual” land data assimilation system because remotely-sensed estimates of land-surface states such as soil moisture and snowpack, and in-situ observations such as streamflow and soil moisture, are not yet assimilated into current version of NLDAS. The NCEP/EMC NLDAS team is collaborating with the NASA Goddard Hydrological Sciences Branch to add their Land Information System (LIS) to the current NLDAS system which would allow assimilation of remotely-sensed data and in-situ observations, e.g. via an ensemble Kalman filter approach.

17.0 Rapid Refresh (RAP) Analysis and Forecast System and High-Resolution (HRRR) Rapid Refresh Analysis and Forecast System

(Updated December 2014 by Stan Benjamin (Stan.benjamin@noaa.gov) and Geoff DiMego (Geoff.dimego@noaa.gov))

17.1 Forecast Model Description

The Rapid Refresh (RAP) analysis and forecast system provides hourly updated 13km forecasts over North America out to 18 hours, with a new data assimilation forecast cycle using latest hourly observations to run new forecasts every hour. The High-Resolution Rapid Refresh (HRRR) provides hourly updated 3km forecasts over CONUS and adjacent areas of Canada, Mexico (Fig. 17.1), and oceanic areas out to 15-h duration. The HRRR 3-km model is nested within the RAP model (domain over lower 48 United States shown in Fig. 17.1) as described below under Sections 17.2 and 17.3. The domains of the hourly updated RAP and HRRR models are shown in the figure below.

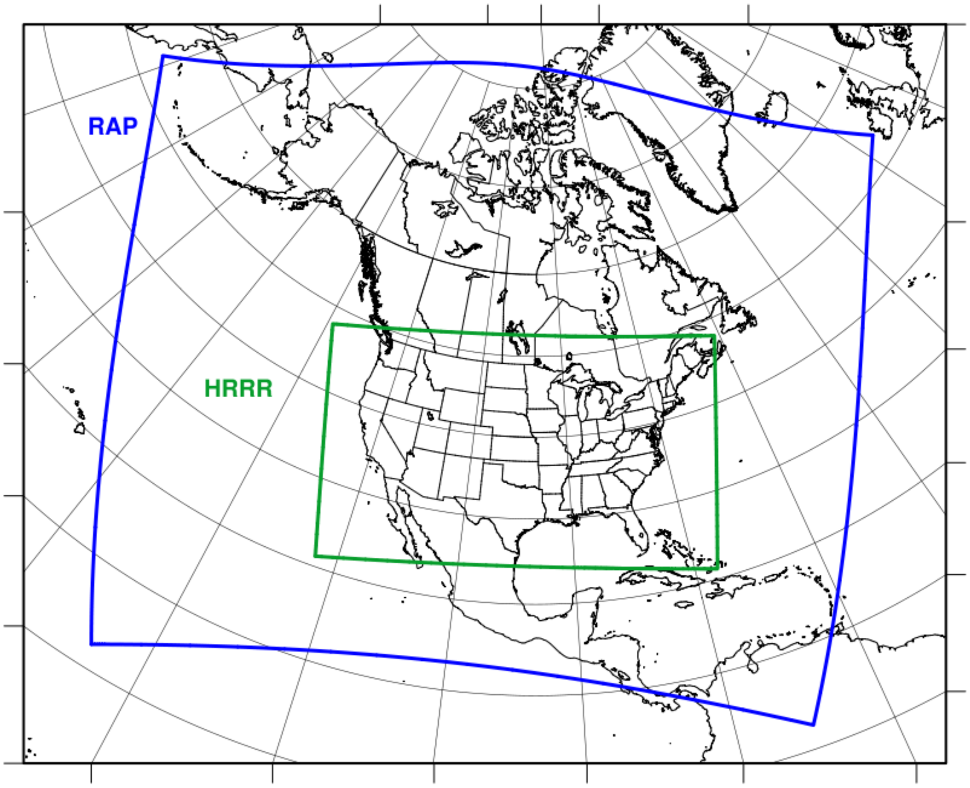
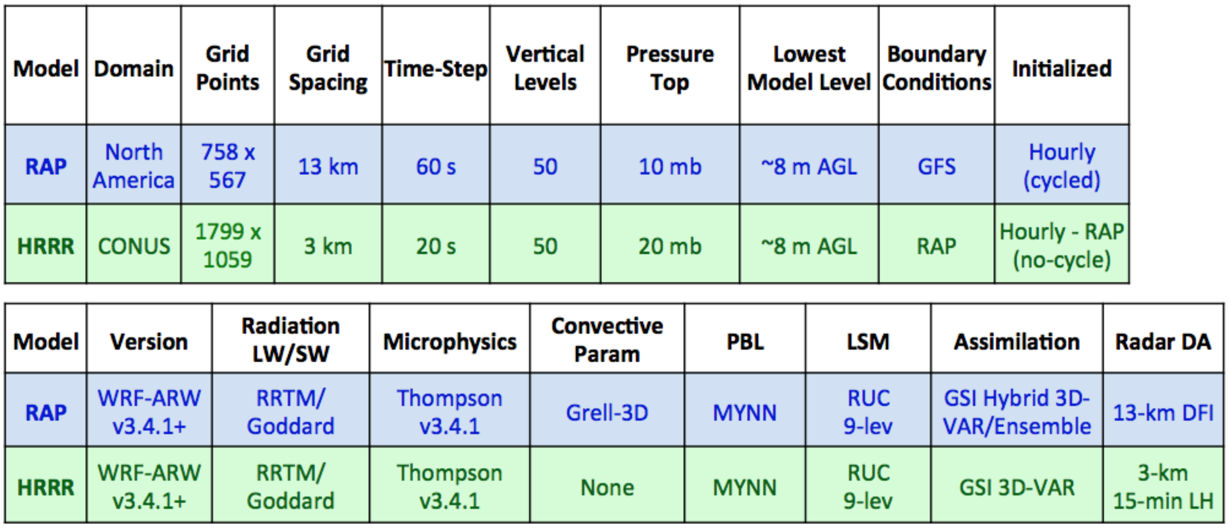


Figure 17.1. Model forecast domains for the hourly updated NCEP models, for the 13-km RAP in blue, covering North America, for for the 3-km HRRR in green, covering the lower 48 United States.

The forecast component for both the RAP-13km and HRRR-3km systems uses closely related versions of the WRF model using ARW dynamic core. The RAP/HRRR version of WRF-ARW uses an advanced set of parameterizations for physical processes with only one exception, use of a convective parameterization for RAP-13km but fully explicit convection in the HRRR-3km model with no convective parameterization. The advanced set of parameterizations for RAP/HRRR (see Fig. 17.2) is designed for accuracy in cloud processes and near-surface boundary-layer and land-surface processes for aviation, energy, and severe weather applications. The RAP/HRRR specifically use the Thompson 5-species bulk cloud microphysical scheme, the MYNN turbulent (primarily boundary layer) scheme, the RUC land-surface scheme with 9 soil levels and 2 snow levels, and the RRTM longwave and Goddard shortwave radiation (both sensitive to each of the full 5 hydrometeor prognostic variables). The RAP-13km model uses the Grell 3-D convective parameterization. Versions of all of these physical parameterizations are available within the WRF community model, and RAP/HRRR development of these parameterizations then become available for other WRF community users. All of these parameterizations currently used in the NCEP RAP and HRRR as of October 2014 were included in WRF version 3.4.1 issued in late 2013. Lateral boundary conditions for the RAP-13km model are specified from the most recent NCEP GFS global model (run every 6h). Lateral boundary conditions for the HRRR-

3km model are specified from the most recent RAP forecast, usually that from the previous hourly RAP run (e.g., 13z RAP forecast used for the 14z HRRR forecast).



Model	Domain	Grid Points	Grid Spacing	Time-Step	Vertical Levels	Pressure Top	Lowest Model Level	Boundary Conditions	Initialized
RAP	North America	758 x 567	13 km	60 s	50	10 mb	~8 m AGL	GFS	Hourly (cycled)
HRRR	CONUS	1799 x 1059	3 km	20 s	50	20 mb	~8 m AGL	RAP	Hourly - RAP (no-cycle)

Model	Version	Radiation LW/SW	Microphysics	Convective Param	PBL	LSM	Assimilation	Radar DA
RAP	WRF-ARW v3.4.1+	RRTM/ Goddard	Thompson v3.4.1	Grell-3D	MYNN	RUC 9-lev	GSI Hybrid 3D-VAR/Ensemble	13-km DFI
HRRR	WRF-ARW v3.4.1+	RRTM/ Goddard	Thompson v3.4.1	None	MYNN	RUC 9-lev	GSI 3D-VAR	3-km 15-min LH

Figure 17.2. Model/assimilation characteristics for the hourly updated NCEP models, for the 13-km RAP in blue and for the 3-km HRRR in green.

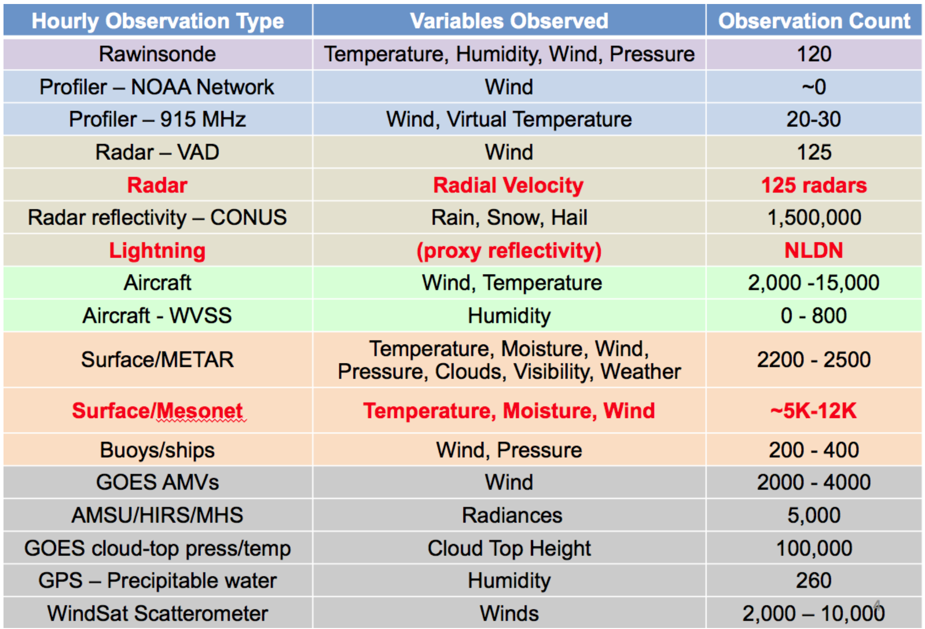
The RAP-13km forecast model runs out to 18-h each hour with 50 vertical levels and with a 10-hPa model top. The HRRR-3km forecast model currently runs out to 15-h, also rerun each hour with latest observations assimilated, also with 50 vertical levels and with a 20-hPa model top. The RAP and HRRR model configurations use a sigma vertical coordinate with the lowest level set quite close to the surface with σ=0.998, about 8m above ground level allowing less vertical interpolation necessary for 10m winds and 2m temperature and moisture values.

The RAP-13km was most recently updated to RAPv2 at NCEP in February 2014, and the HRRR-3km model was introduced at NCEP in September 2014.

17.2: RAP Data Assimilation

Initial conditions for the RAP forecasts are produced hourly by assimilation with the regional Gridpoint Statistical Interpolation (GSI). The RAP application of GSI uses a hybrid ensemble/variational option with the ensemble-based background error covariance (BEC) component specified from the most recent 80-member NCEP GFS assimilation ensemble. Observations used in the hourly updated RAP are listed in Fig. 17.3. (Those listed in red will be added in the 2015 update at NCEP.) The hybrid assimilation for RAP is to use 0.5-weighted BEC from the ensemble component and half from the fixed covariance. In addition to those observations shown in Fig. 17,3, pseudo-observations are created from surface observations through 1h forecast boundary-layer depth to increase retention, when appropriate, with surface information.
Cloud/hydrometeor fields (3-d fields of cloud water, ice, rain, snow, graupel with two

moments for rain and snow) are updated in GSI through a non-variational assimilation of satellite cloud-top data and METAR ceiling and visibility observations. Radar reflectivity is assimilated in the RAP by specifying latent heating from 3-d radar data, where available within the forward step of a backward-forward 20-min-duration digital filter initialization (DFI) step to produce balanced divergence increments consistent with current radar data.



Hourly Observation Type	Variables Observed	Observation Count
Rawinsonde	Temperature, Humidity, Wind, Pressure	120
Profiler – NOAA Network	Wind	~0
Profiler – 915 MHz	Wind, Virtual Temperature	20-30
Radar – VAD	Wind	125
Radar	**Radial Velocity**	**125 radars**
Radar reflectivity – CONUS	Rain, Snow, Hail	1,500,000
Lightning	**(proxy reflectivity)**	**NLDN**
Aircraft	Wind, Temperature	2,000 -15,000
Aircraft - WVSS	Humidity	0 - 800
Surface/METAR	Temperature, Moisture, Wind, Pressure, Clouds, Visibility, Weather	2200 - 2500
Surface/Mesonet	**Temperature, Moisture, Wind**	**~5K-12K**
Buoys/ships	Wind, Pressure	200 - 400
GOES AMVs	Wind	2000 - 4000
AMSU/HIRS/MHS	Radiances	5,000
GOES cloud-top press/temp	Cloud Top Height	100,000
GPS – Precipitable water	Humidity	260
WindSat Scatterometer	Winds	2,000 – 10,000

Figure 17.3. Observations assimilated for the hourly updated RAP and HRRR models.

The RAP data assimilation is an intermittent, forward, hourly updated cycle with previous 1h RAP forecasts used as background, including for the 3-d 5-species hydrometeor species. Partial cycling is applied twice daily with 6h parallel spin-up cycles started with GFS initial conditions, replacing 1h background fields at 09z and 21z instead of the main cycle, to introduce better long-wave information. Land-surface fields are full cycled within the RAP cycle for the 9 soil levels and 2 snow levels (within the RUC LSM).

17.3: HRRR Data Assimilation

The HRRR model is partially initialized by downscaling a post-radar-DFI-assimilation field from the 13km RAP to the 3km HRRR domain, but then followed by a 1h spin-up cycle on the HRRR grid at 3km. During this 1h period, radar reflectivity data is applied every 15-min by specifying latent release from observed 3-d data over respective 15-min windows. At the end of this 1-h period, GSI is applied at 3km using the same observations shown in Fig. 17.3, including a 3-d cloud/hydrometeor assimilation step. Hydrometeors are specified directly during this same 60-min 3km period every 15 min from shortened application of GSI for radar only. An example of the HRRR initial conditions radar reflectivity diagnosed from 3-d hydrometeor 0-h fields compared with that observed is shown in Fig. 17.4. The light reflectivity over Texas, Louisiana, and Mississippi in the HRRR initial conditions but not in the observed reflectivity is due to low-level cloud below the lowest radar elevation in these regions.

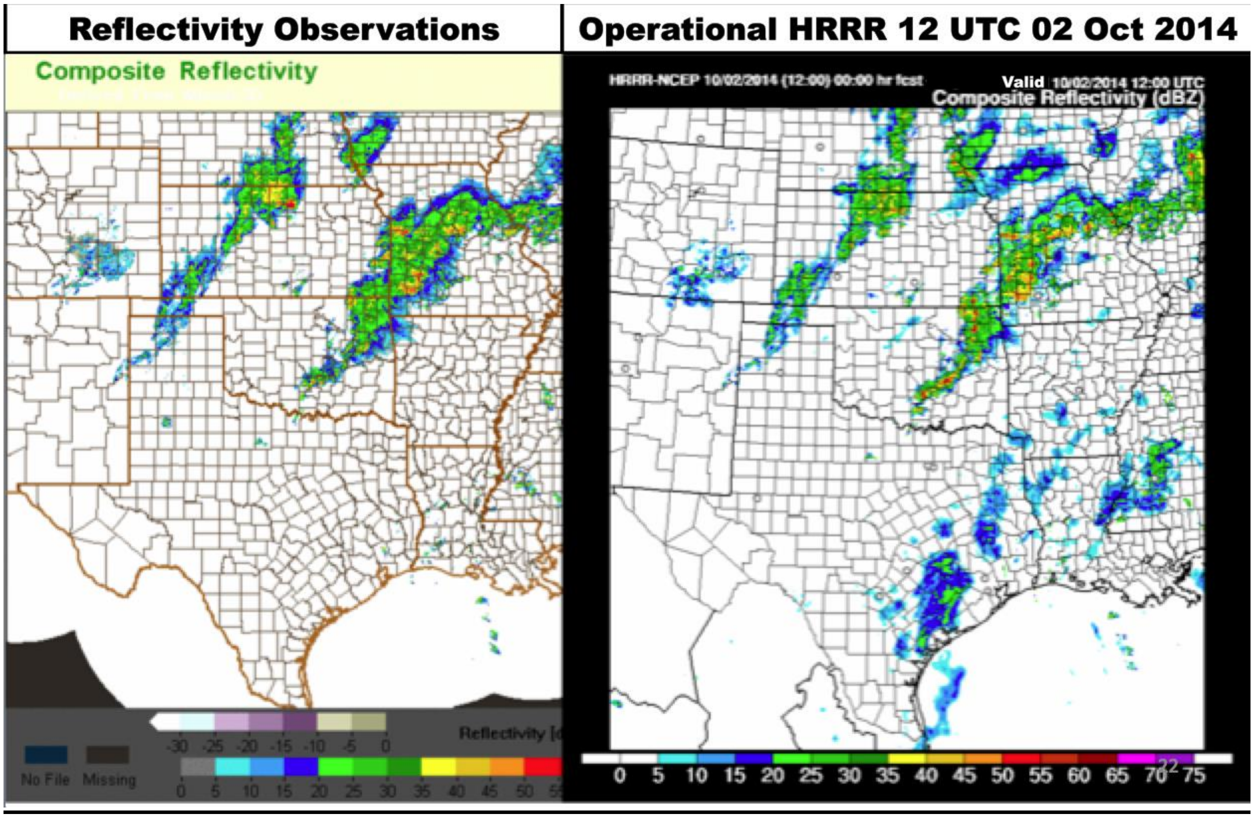


Figure 17.4. Comparison of reflectivity at 12UTC 2 Oct 2014 between observed (on left) and that diagnosed from the 0-h analyzed HRRR initial conditions of 3-d rain water, snow, and graupel mixing ratios.

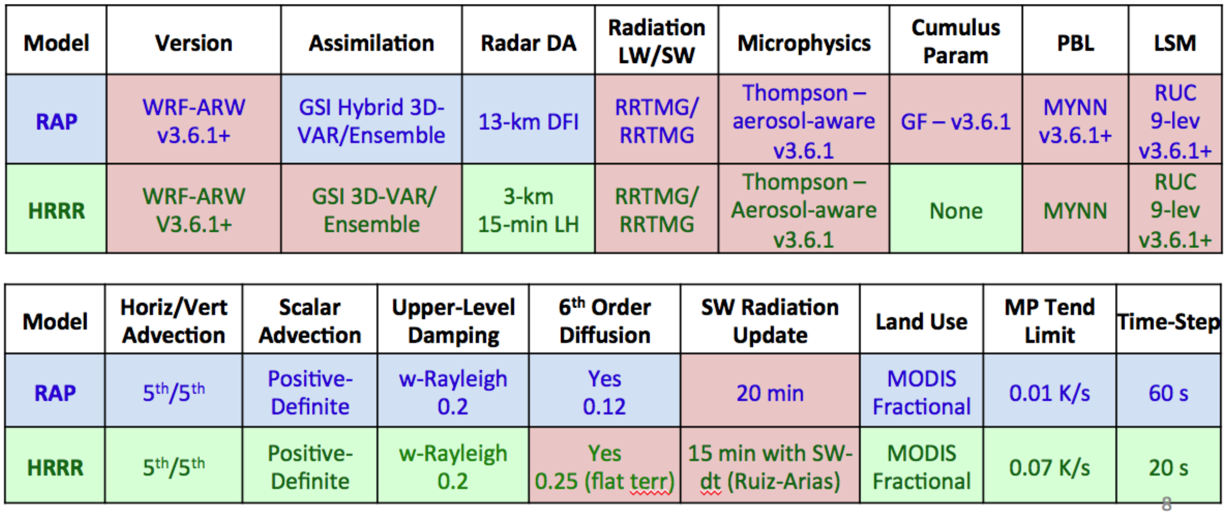
17.4 Future plans for RAP and HRRR

The next major HRRR/RAP upgrade at NCEP is tentatively planned for June 2015. Planned changes in this upgrade are summarized in Fig. 17.5 below with special changes shaded in red. This figure can be compared with the current RAP/HRRR characteristics back in Fig. 17.2. Physics changes are generally being applied to both the RAP-13km and HRRR-3km models. These changes are include

- Incorporation of physics improvements including use of aerosol-aware cloud microphysics and improved land-surface (RUC LSM), turbulent/PBL (MYNN), and radiation (RRTMG) processes, all within WRF-ARW version 3.6.1+.

- Assimilation will be added for lightning (proxy reflectivity), radial wind from NWS radars, and mesonet observations.

- Change in hybrid assimilation to more emphasis on ensemble-based background error covariance (up to a 0.75 weight).



Model	Version	Assimilation	Radar DA	Radiation LW/SW	Microphysics	Cumulus Param	PBL	LSM
RAP	WRF-ARW v3.6.1+	GSI Hybrid 3D-VAR/Ensemble	13-km DFI	RRTMG/ RRTMG	Thompson – aerosol-aware v3.6.1	GF – v3.6.1	MYNN v3.6.1+	RUC 9-lev v3.6.1+
HRRR	WRF-ARW V3.6.1+	GSI 3D-VAR/ Ensemble	3-km 15-min LH	RRTMG/ RRTMG	Thompson – Aerosol-aware v3.6.1	None	MYNN	RUC 9-lev v3.6.1+

Model	Horiz/Vert Advection	Scalar Advection	Upper-Level Damping	6th Order Diffusion	SW Radiation Update	Land Use	MP Tend Limit	Time-Step
RAP	5th/5th	Positive-Definite	w-Rayleigh 0.2	Yes 0.12	20 min	MODIS Fractional	0.01 K/s	60 s
HRRR	5th/5th	Positive-Definite	w-Rayleigh 0.2	Yes 0.25 (flat terr)	15 min with SW-dt (Ruiz-Arias)	MODIS Fractional	0.07 K/s	20 s