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In this final report, we summarize the main results accomplished during this two-year project and the upgrades implemented into the operational GFDL and GFDN models for the 2012 and 2013 seasons. We also describe the upgrades prepared for the operational implementations at NCEP and FNMOC for the upcoming 2014 hurricane/typhoon/tropical cyclone seasons.

a) Implemented a unified GFDL/GFDN version control framework.

It has been recognized that a unified GFDL/GFDN code system with version control will result in a more efficient transition to operations when improvements are made to one of the versions of the model. To accomplish this unification, we have incorporated the Subversion (svn) software system into GFDL/GFDN on the URI computing cluster, and we are helping to setup the GFDL and GFDN systems under Subversion control at NCEP and FNMOC to track future changes to all of the various components of the forecast systems. It is anticipated that this work will reduce the possibility of coding errors introduced during future implementations.

b) Absolved the need for NHC's active participation in the ocean model initialization.

During the 2012 Atlantic hurricane season, it became clear that NHC did not always have the time or resources to regularly update the Loop Current and Loop Current eddy files associated with the feature-based ocean model initialization procedure, especially during potentially high-impact events when up-to-date versions of these files are most needed. Since the feature-based ocean model initialization procedure continued to be used in the operational GFDL and HWRF coupled models in 2013 and will most likely continue to be used in 2014, URI and GFDL have been actively collaborating (and will continue to actively collaborate) with EMC and NHC during hurricane season to update these files whenever necessary with minimal participation by NHC. Hence, there is no longer a need for a graphical software package at NHC for viewing the depth of the 26°C isotherm after the feature-based ocean model initialization procedure.

c) Implemented upgrades into the operational GFDL and GFDN models in 2012.

The following is a list of the physics upgrades implemented into the operational GFDL model in 2012:

a) Implemented the GFS shallow convection scheme.
b) Improved the current PBL scheme.
c) Incorporated communication of detrained microphysics from the SAS convective scheme into the Ferrier microphysics package.
d) Fixed a bug in the PBL scheme from the 2003 implementation.
e) Fixed a bug in the SAS convective scheme from the 2011 implementation.
f) Retuned the momentum mixing.
g) Improved the formulation of the surface exchange coefficients (Ch, Cd).
h) Evaluated the new GFS PBL scheme but rejected it for implementation due to degraded track performance.
i) Reduced the storm size and removed asymmetries in the vortex initialization.

d) Implemented additional upgrades into the operational GFDN model in 2012.

One of the major upgrades transitioned to the operational GFDN model included the replacement of 1-D ocean coupling with 3-D ocean coupling in the North and South Indian Ocean and Southern Pacific Ocean. Similar to the Atlantic, Eastern Pacific, and Western Pacific, the Princeton Ocean Model for Tropical Cyclones (POMTC) with 1/6 degree horizontal grid spacing is used for the 3-D ocean coupling in these other basins. During testing associated with the GFDN upgrade implementation, it was noticed that the GFDN tracks were occasionally displaying erroneous motion, prompting the URI and GFDL scientists to carefully evaluate all of the source code. This evaluation resulted in finding a major bug in the operational GFDN system, which had seriously degraded the track performance. This bug was caused when FNMOC accidentally removed a critical line of computer code in one of the Optimum Interpolation routines during the transition of the model to a new computer system. The bug fix was implemented operationally prior to the beginning of the 2012 hurricane season.

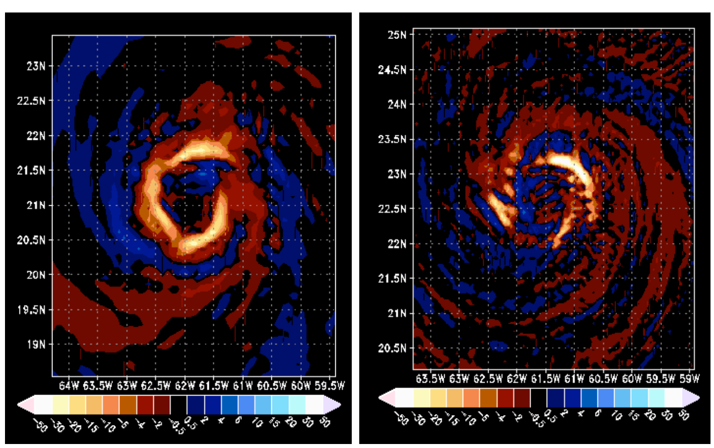


Figure 1. *An example of improved storm structure (500 hPa omega) comparing the current operational GFDL model simulation (left) and the high-resolution GFDL model simulation (right) at forecast hour 96 for Hurricane Katia (initialized 00 UTC 01 Sept. 2011).*

e) Worked toward 2014 implementation of increased GFDL/GFDN horizontal resolution and improved physics and initialization.

GFDL and URI have developed a high-resolution version of the GFDL and GFDN models with improved physics. The new modeling system has been recently coupled to a new version of the Princeton Ocean Model (MPIPOMTC), which is described below, in the Atlantic basin. Pending final test results, it may be possible to implement this high-resolution version of the models into operations in 2014 In the new model configuration, the area of the innermost nest with highest resolution remains the same as the present version, but with an increased horizontal resolution from 1/12° to 1/18° grid spacing. This 1/18° grid spacing is the highest resolution physically justified for the GFDL model because of its hydrostatic dynamics. Several modifications to the model physics and initialization have been made to maximize the benefit of the increased resolution. These modifications include the reduction of the gravity wave damping term in the time differencing scheme (Kurihara et al. 1980), initiation of large-scale condensation at 100% humidity for inner nests, improved specification of the maximum wind in the vortex initialization (which significantly reduces the initial negative wind bias), and improvements in the PBL scheme and Ferrier microphysics package. Results indicate a significantly improved storm structure for most storms (Fig. 1), with a reduction in the negative intensity bias in stronger storms (Fig. 2 top) and overall reduced track error, particularly in days 3-5 (e.g., 5-10%). In storms with significant SST cooling, such as Hurricanes Katia (Fig. 2 bottom, Fig. 3) and Hurricane Leslie, reduced over-intensification is being seen with the new model system, compared to the current model. Part of the reason for the improvement is the more accurate ocean response to the hurricane winds using MPIPOMTC relative to the currently operational POMTC.

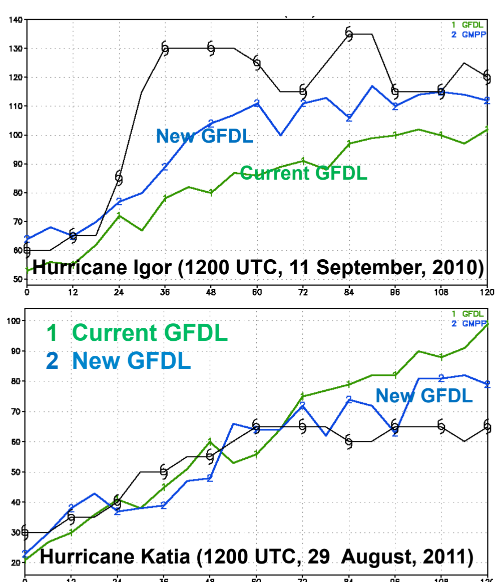


Figure 2. *Forecasted maximum surface winds for two forecasts of Hurricanes Igor (top) and Katia (bottom) using the current operational GFDL model (green) compared to the new high-resolution model (blue) with MPIPOMTC ocean coupling.*

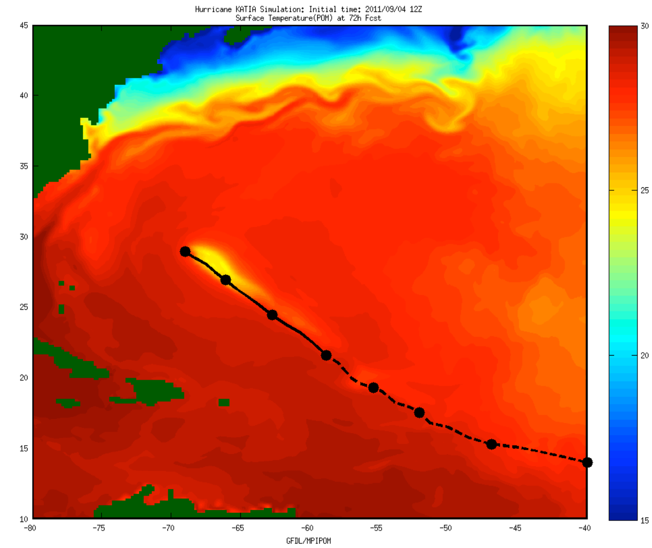


Figure 3. *Sea surface temperature in the high-resolution GFDL/MPIPOMTC for Hurricane Katia (12 UTC, 29 Aug, 2011) at forecast hour 72.*

f) Implemented wave coupling into GFDL/GFDN for future operations.

The new GFDL-WAVEWATCHIII-MPIPOMTC system has now been developed and prepared for real-time testing and evaluation. In the three-way coupled framework (Fig. 4), which is based on a comprehensive, physics-based treatment of the wind-wave-current interaction, the bottom boundary condition of the atmospheric model incorporates sea-state dependent air-sea fluxes of momentum, heat, and humidity, and it includes the effect of sea-spray. The wave model is forced by the sea-state dependent wind stress and includes the ocean surface current effect. The ocean model is forced by the sea-state dependent wind stress and includes the ocean surface wave effects (i.e. Coriolis-Stokes effect, wave growth/decay effect, and Langmuir turbulence).

At the heart of the coupled framework is a computationally efficient, unified Air-Sea Interface Module (ASIM) that establishes a physically based representation of the air-sea interface. Two wind stress parameterizations are implemented into the ASIM, which include: (1) an updated URI wind stress calculation with a new tail parameterization (Reichl et al. 2013) and (2) the new University of Miami (UM) wind stress calculation (Donelan et al. 2012). These two methods differ in the following two ways: (1) the growth rate is parameterized based on the wind *stress* in the URI approach but based on the wind *speed* in the UM approach; (2) inside the wave boundary layer, the mean wind profile *is not* logarithmic and *does* rotate in the URI approach but *is* logarithmic and *does not* rotate in the UM approach. Both approaches have been carefully evaluated using identical surface wave spectra and wind speed conditions under uniform wind forcing (fetch dependent seas) and under tropical cyclone conditions (Reichl et al. 2013).

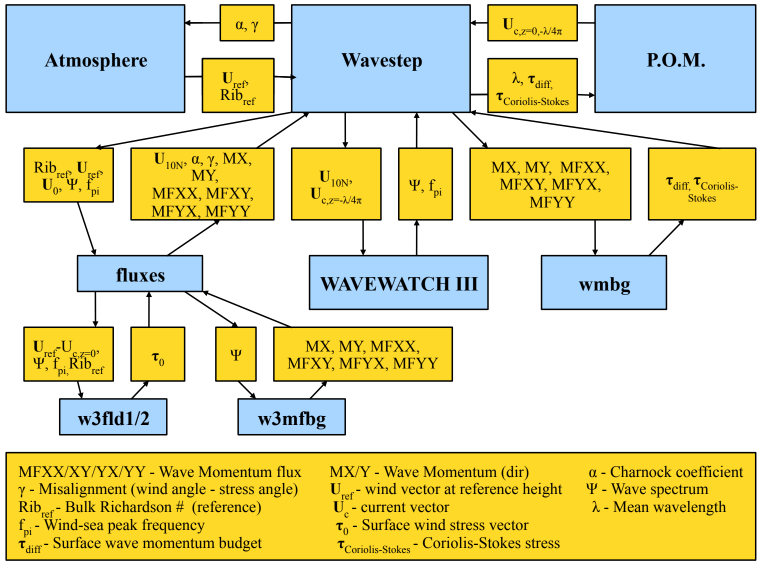
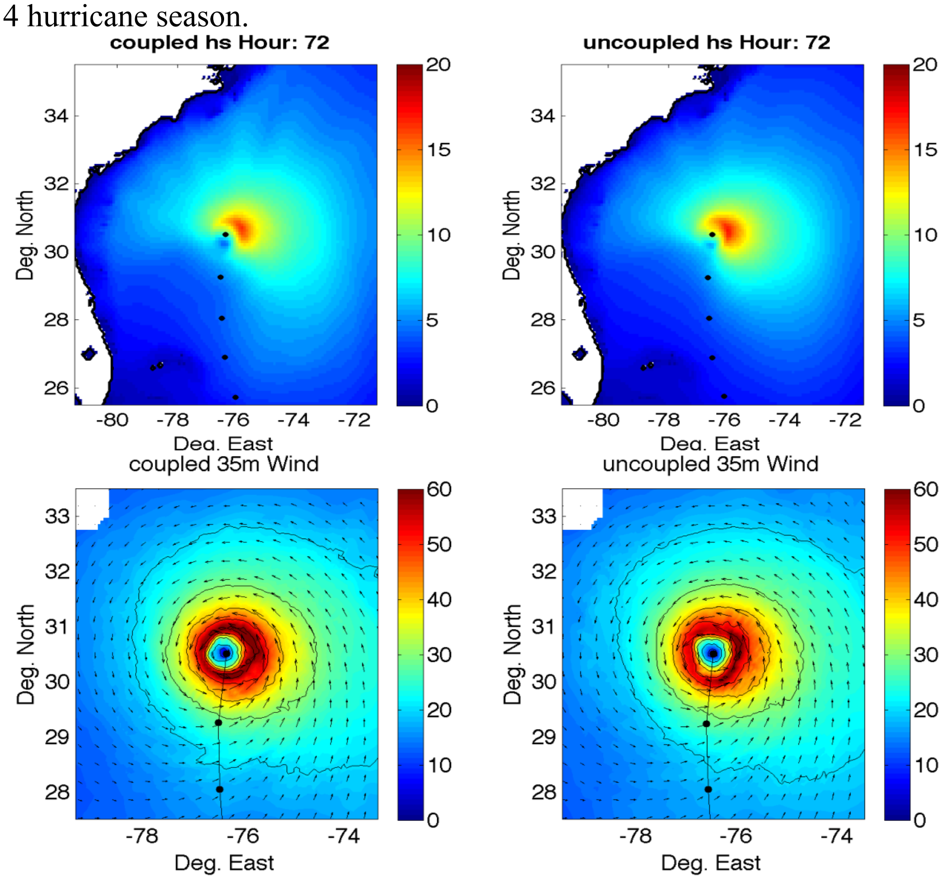


Figure 4. *Coupled GFDL-WAVEWATCHIII-MPIPOMTC framework.*

Figures 5 and 6 show the results of a test simulation of the GFDL/WAVEWATCHIII/MPIPOMTC system for Hurricane Irene (2011). After extensive testing on retrospective storms, this system will be run in near real-time during the 2014 hurricane season.



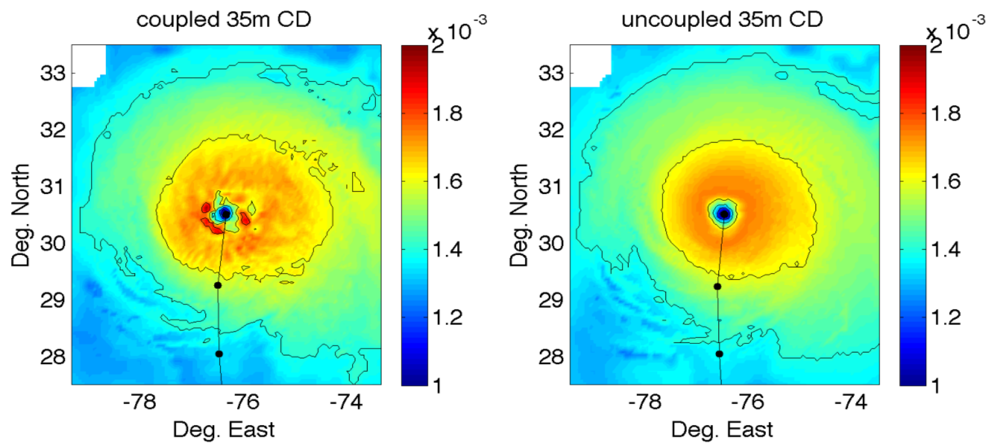


Figure 5*. Results from the GFDL-WAVEWATCHIII-MPIPOMTC simulation of Hurricane Irene (Initial time 12 UTC 26 Aug 2011) at forecast hour 72 (left panels). For comparison, results without wave coupling are shown as well (right panels). Top - significant wave height, middle – 35 m wind speed, bottom – 35 m drag coefficient (Cd).*

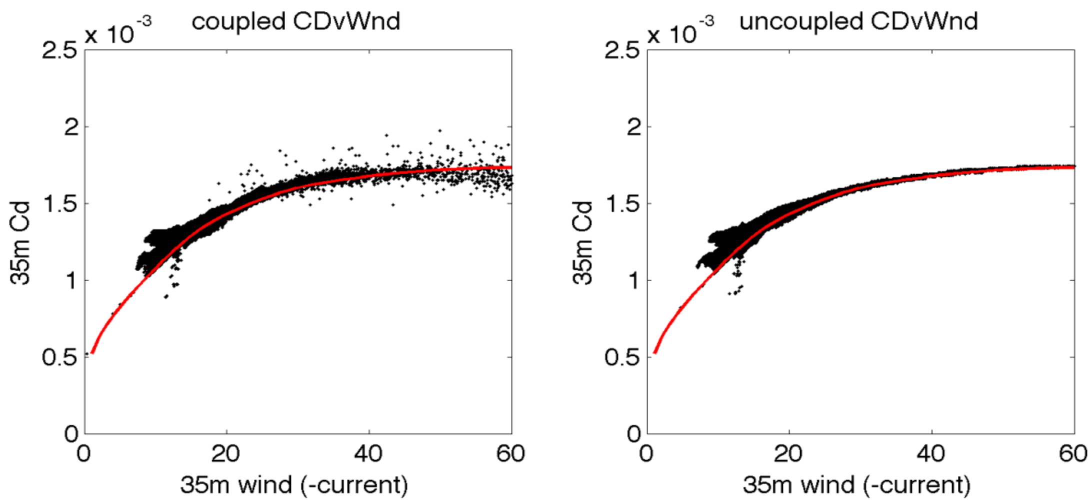


Figure 6. *Drag coefficient vs. wind speed-current at 35 m in the GFDL model with (left) and without (right) wave coupling for Hurricane Irene (Initial time 12 UTC, 26 Aug 2011) at forecast hour 72.*

g) Implemented improved surface physics parameterization over land in GFDL and GFDN for possible operations in 2014.

The current operational GFDL and GFDN hurricane models specify the land surface roughness (Z_o) and the land surface evaporation efficiency (i.e. wetness, W) based on the static global vegetation and land use databases (Matthews 1983), which have a 1° spatial resolution (Bender et al. 1993, Appendix A). Since both Z_o and W are used to calculate Land Surface Temperature (LST), close analysis indicated that the static Z_o and W values (left panels of Figs. 7 and 8, respectively) were contributing to large errors in the LST, particularly during the daytime when a significant negative bias was apparent in the southwestern U.S. Tests suggested that the erroneous LST values contributed to a severe north bias in some GFDL model forecasts in the East Pacific, for storms close to the Mexican coast, such as Hurricane Dalila (2013).

To upgrade the specification of the land surface roughness and the land surface evaporation efficiency in the GFDL/N model, the currently operational values of Z_o and W were replaced with Z_o and W values derived from NCEP's Global Forecast System (GFS) model (right panels of Figs. 7 and 8, respectively). Note that the GFS-derived W values shown here are based on the current GFS soil moisture, but additional modifications are not made (at least yet) based on the GFS vegetation/land use information. Using the improved surface specification, there was some reduction of the negative LST bias over the deserts of the southwestern U.S., and the LST was significantly improved over the Midwestern U.S. compared to the verifying analysis. The improved LST resulted in reduction of the north bias for many of the forecasts of Hurricane Dalila. Further tests with this improved land surface formulation indicated a positive impact on GFDL track forecasts for storms near land, particularly in the Gulf of Mexico and Western Caribbean. For Hurricanes Isaac and Ernesto (2012), the track error at days 4 and 5 was reduced ~7% with the improved surface physics parameterization. The improved surface physics parameterization over land has now been incorporated into the new high resolution GFDL model, which has an increased inner nest resolution from 1/12° to 1/18° grid spacing and is currently being rigorously tested for 2014 implementation in GFDL and GFDN.

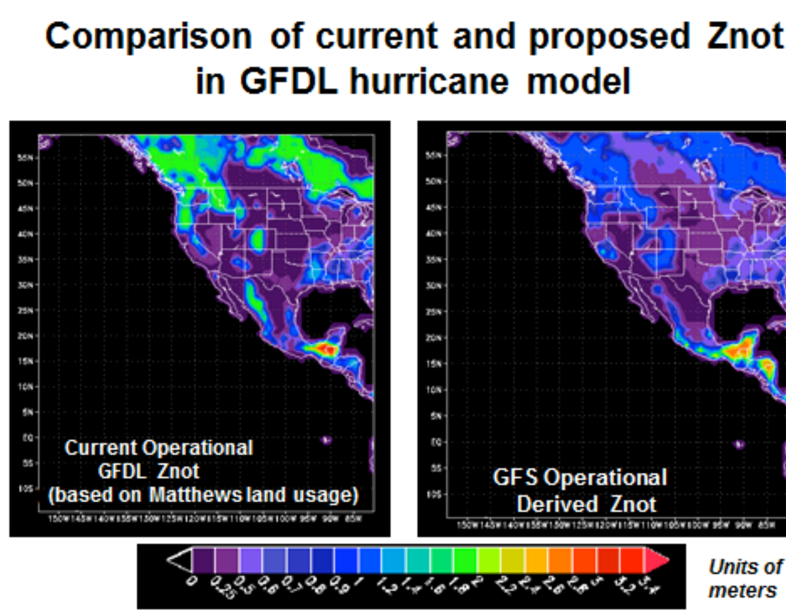


Figure 7. *Comparison of the current Z_o used in the operational GFDL model (left) and the new Z_o based on the current GFS model (right).*

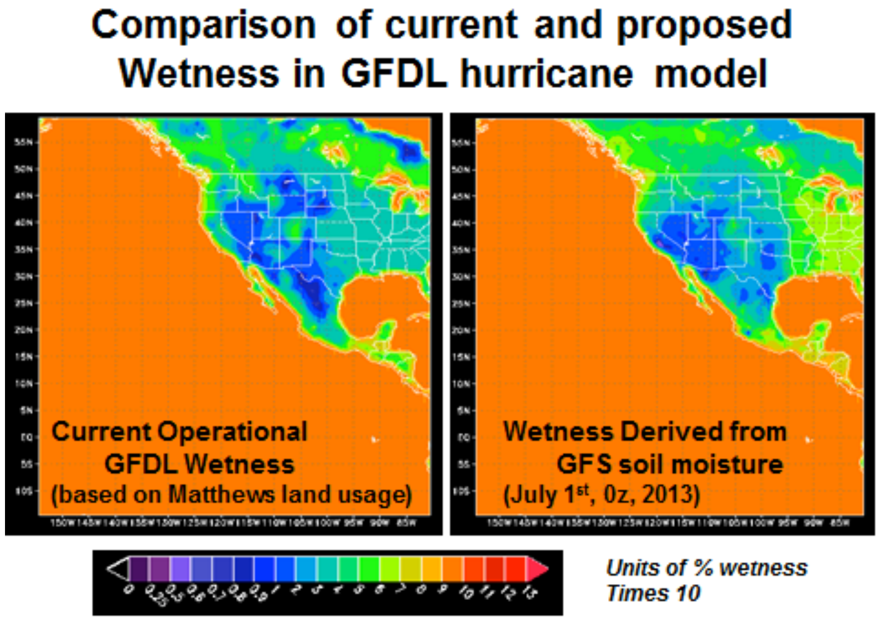


Figure 8. *Comparison of the current wetness (W) used in the operational GFDL model (left) and the new wetness (W) derived from the GFS soil moisture specification (right).*

h) Developed a new MPI version of POMTC (MPIPOMTC) for GFDL and GFDN.

URI's version of the Princeton Ocean Model for Tropical Cyclones (POMTC) has been the ocean component of the operational GFDL coupled model since 2001. Some significant improvements to POMTC have been made since then, including implementation of a feature-based ocean initialization for ocean coupling in the western Atlantic in both GFDL and GFDN (Falkovich et al. 2005; Yablonsky and Ginis 2008) and an NCODA-based initialization worldwide outside of the Atlantic in GFDN. However, no upgrades have been made to the ocean model resolution, and none of the community-based upgrades to POM have been incorporated into POMTC since 1994. Indeed, since POMTC runs on only one processor, future upgrades to the ocean model resolution are not computationally feasible. Hence, URI has now completed a major new effort to develop a new version of POMTC (primarily under HFIP funding to improve HWRF, but with direct application to GFDL and GFDN); this version shall hereafter be known as MPIPOMTC.

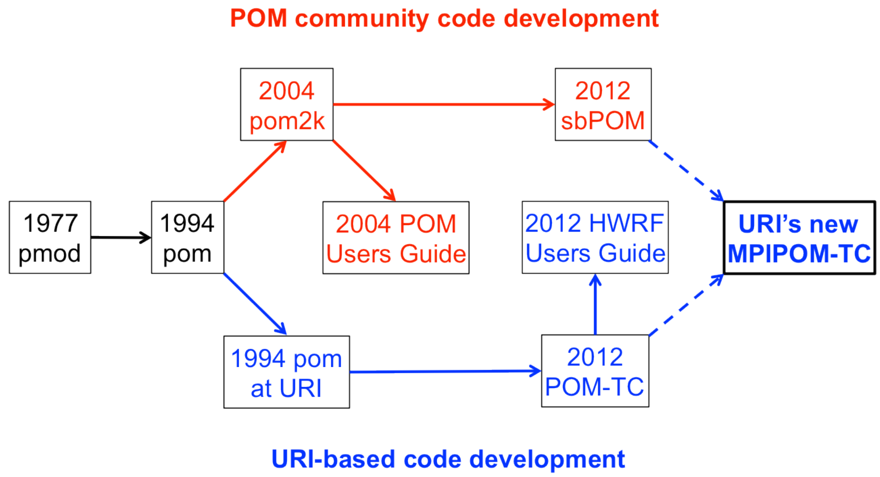


Figure 9. *Schematic detailing the history of POM from its initial development at Princeton in 1977 to the version transferred to URI in 1994, which ultimately led to the 2012 version of POMTC in GFDL, GFDN, and HWRF, and the subsequent merging of the 2012 POMTC with the community-based 2012 sbPOM to form URI's MPIPOM-TC.*

MPIPOMTC incorporates many of the community-based upgrades to POM that have occurred between 1994 and 2012 by blending the community-based sbPOM (Jordi and Wang 2012) with the existing version of POMTC (Yablonsky and Ginis 2008) (Fig. 9). Since it has MPI capabilities, MPIPOMTC allows for higher spatial resolution and a larger domain size than POMTC. In fact, one of the key improvements now included is the replacement of the two overlapping POMTC domains in the Atlantic Ocean, each of which have ~1/6° horizontal grid spacing, with a single, new, transatlantic domain, which has ~1/12° horizontal grid spacing (Fig. 10). MPIPOMTC is also very computationally efficient and scalable, and it has netCDF I/O.

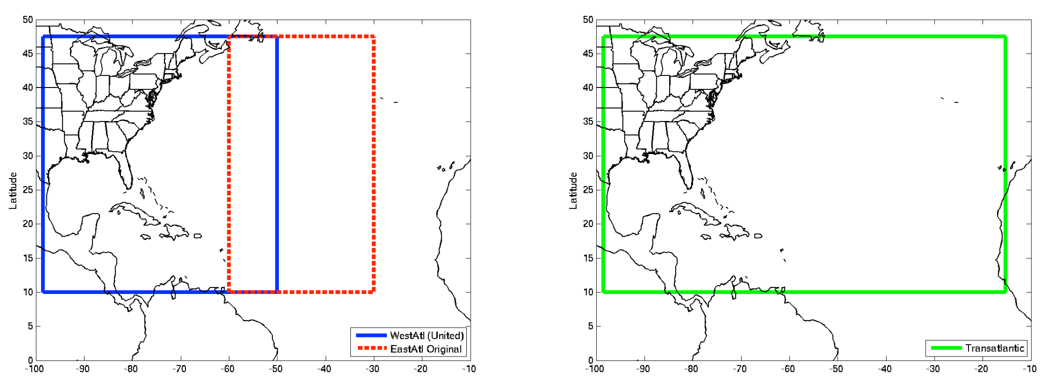


Figure 10. *Overlapping United and East Atlantic POMTC ocean domains (in the current operational GFDL and GFDN), each of which have ~1/6° horizontal grid spacing (left panel), and the new transatlantic MPIPOMTC ocean domain, which has ~1/12° horizontal grid spacing (right panel).*

Proposed domain configurations for the GFDN model in all ocean basins are shown in Fig. 11.

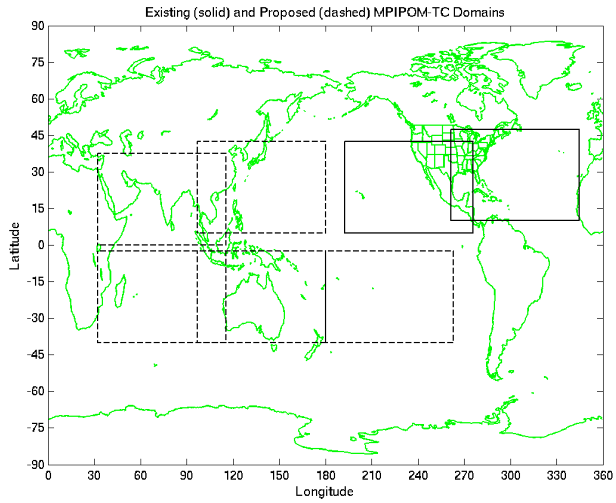


***Figure 11**. Proposed new ocean domains for the GFDN coupled with MPIPOMTC in all ocean basins.*

i) Developed a new ocean initialization methodology.

Currently, POMTC utilizes different initialization procedures in different ocean basins in the GFDL and GFDN coupled systems, and the architecture of the POMTC code varies from basin to basin to accommodate the various initialization procedures and grid specifications. URI has developed a new methodology to initialize a unified, basin-independent MPIPOMTC code from different global real-time ocean products available at NOAA and the Navy. As an alternative to the feature-based initialization in the Atlantic and the NCODA elsewhere, NCEP's Global HYCOM RTOFS and the Navy's Global HYCOM are being tested as ocean initial conditions in the GFDL-MPIPOMTC (Fig. 12). By continuing to perform careful evaluation of various ocean initialization products in all ocean basins, it will be possible to ensure that MPIPOMTC is initialized with the best product available for subsequent GFDL and GFDN operational implementations. In parallel, however, the feature-based ocean initialization procedure will continue to be improved in the Atlantic basin until an alternative initialization product is proven to have sufficient accuracy to render the feature-based initialization obsolete.

By separating the ocean initialization and grid specification module from the core MPIPOMTC code, the initializations and grid specifications become a plug-and-play feature that facilitates simplified testing, evaluation, and operational implementation. The implementation of the MPIPOMTC in the operational GFDL and GFDN is a major proposed task in our JHT proposal for 2014 pending positive test results.

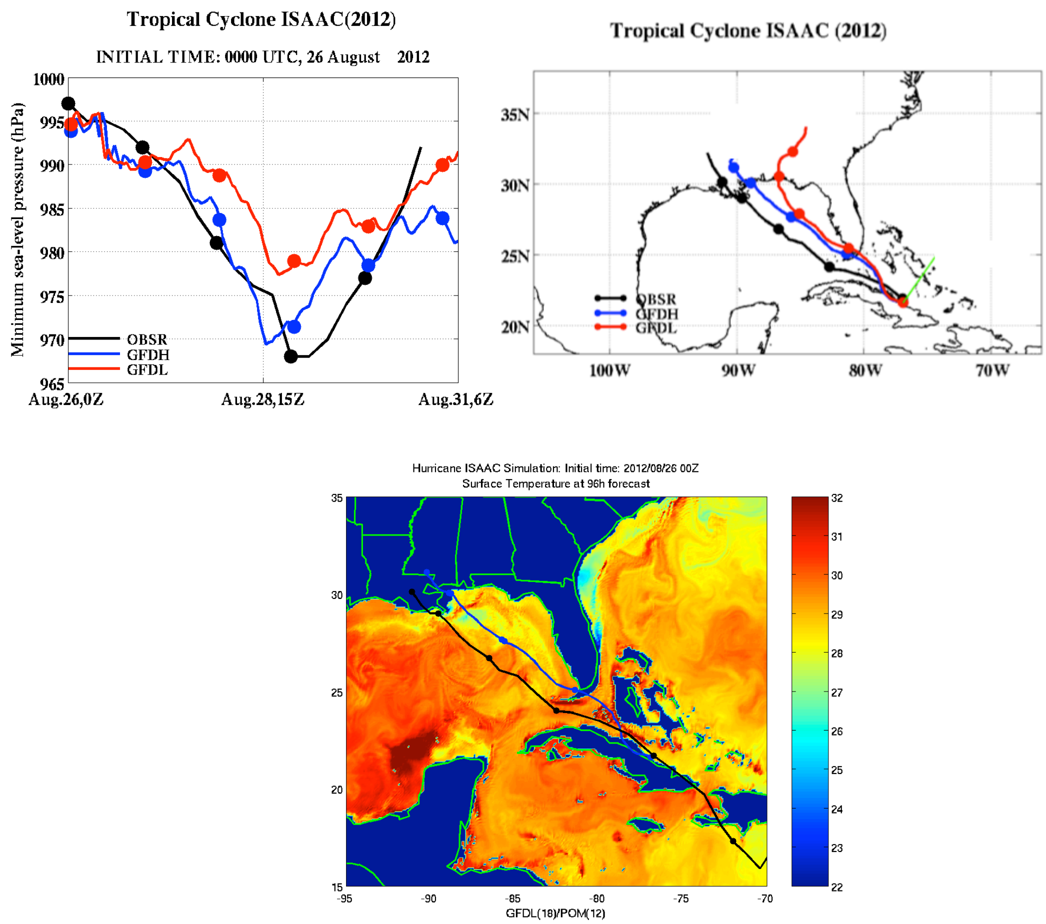


Figure 12. *GFDL intensity (upper left) and track (upper right) forecasts of Hurricane Isaac (2012), initialized at 00 UTC on August 26, 2012, using either the operational GFDL-POMTC system (GFDL, red) or the new high-res GFDL-MPIPOMTC with Global HYCOM RTOFS ocean initialization (GFDH, blue), as compared to the observed intensity and track (OBSR, black). Sea surface temperature after 96-h of the GFDH simulation is shown in the lower panel.*

j) Implemented improved vortex initialization operationally in GFDN on Oct. 24, 2013.

The GFDL/GFDN vortex initialization includes a 2-D spinup with an axisymmetric version of the 3-D model. During the vortex spinup, a Newtonian damping term in the tendency equation is introduced for the tangential wind (maximum forcing at 850 hPa) that gradually adjusts the winds toward the estimated observed wind profile. The 2-D spinup lasts 60 hours. However, due to uncertainty in the observed storm component of the tangential wind in the free atmosphere, several assumptions are made. First, we estimate the 850 hPa winds and decrease the magnitude of the winds with height that the tangential winds are forced toward. No forcing is done below 850 hPa, but the winds in the boundary layer are allowed to freely evolve, similar to the mass and moisture fields. However, observed values of the wind in the free atmosphere are typically not available in real time and are therefore estimated in our approach from the observed surface winds provided from the operationally available storm structure (tcvitals file). Second, we assume the radial wind component is very small (which is usually a very good approximation at 850 hPa). Third, since we target the vortex winds (not the total winds), we have to subtract off the environmental winds at that storm radius. Finally, if the pressure (plus an epsilon which is a function of observed intensity) reaches the observed pressure before the spinup of the vortex completes, we terminate the integration before hour 60, with the assumption that the central pressure is a more accurate value than the estimated winds. All of these assumptions can cause the initial winds to vary from the observed winds provided from the tcvitals file. In the modification implemented in GFDN on October 24, 2013, we use a better estimate of the environmental winds that are subtracted from the maximum winds at the four storm quadrants. Also, the pressure "epsilon" has been relaxed to values used several years ago, and the factor used to estimate the 850 hPa tangential winds from the observed maximum surface winds has been modified based on more recent values estimated from the literature.

Improvement in the GFDN model performance using the improved initialization is demonstrated in Fig. 13 for four recent typhoons in the Western Pacific. Improved track and intensity prediction are noted in each case. It is anticipated that the new high resolution GFDL/GFDN with improved physics that is currently being developed will result in further reduced negative bias for intense typhoons, such as Typhoon Wipha.

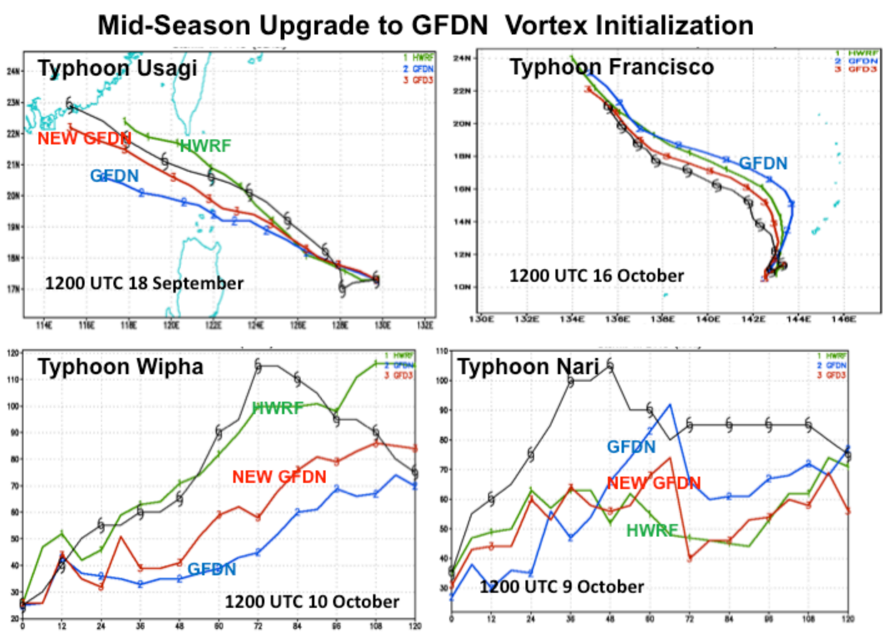


Figure 13. *Examples of forecasted storm track (top) for Typhoons Usagi (left) and Francisco (right) using the current operational GFDN (blue), the GFDN with improved vortex initialization (red), and the HWRF model (green). Examples of forecasted surface winds are also shown (bottom) for Typhoons Wipha (left) and Nari (right) using the same three modeling systems.*

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