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Project Title: Improving the Operational Tropical Cyclone Models at NOAA/NCEP and Navy/FNMOC
PIs/PDs: Isaac Ginis and Morris Bender
Report Type: Project Progress Report
Reporting Period: 08/01/2011 - 01/31/2012

Work Accomplishments:

1. Tasks scheduled for Year 1

a) Design and deliver a graphical software package to NHC for viewing the depth of the 26°C isotherm after the feature-based ocean model initialization procedure.
b) Upgrade the ocean model domain configuration in the eastern Atlantic.
c) Improve vertical representations of the Loop Current and warm/cold eddies during the feature-based ocean model initialization procedure.
d) Implement a unified GFDL/GFDN version control framework.
e) Upgrade the air-sea flux parameterization with full wind-wave-current interaction and sea-spray effects into the GFDL/GFDN models, evaluating its performance on an extensive set of real-world historical cases.
f) Implement the new GFS cumulus parameterization and shallow convection schemes and the improved GFS PBL scheme into GFDL/GFDN.

2. Tasks accomplished this period

Since the original writing of the Year 1 task list, certain tasks have been prioritized more than others, and new, related tasks have been developed to suit the most pressing needs of NOAA/NCEP and Navy/FNMOC. Below is a list of the tasks accomplished this period, based on the aforementioned task reprioritization.

a) Upgrade the ocean model domain configuration in the eastern Atlantic.

The eastern Atlantic ocean model domain in the GFDL and GFDN models has now been expanded westward. This task was included in our original JHT proposal, but accomplished prior to the official beginning of this project. A detailed description was included in the final report from the previous round of JHT funding. Here a short, updated description is included.

For the 2011 GFDL, GFDN, and HWRF models, the East Atlantic POM domain was expanded westward from 60°W longitude to ~70°W longitude (Fig. 1). This expansion prevents loss of ocean coupling when a storm originates east of 50°W longitude (the eastern boundary of the West Atlantic "United" POM domain) and propagates quickly westward during a 5-day GFDL, GFDN, or HWRF model forecast. This POM domain expansion was implemented in the 2011 operational GFDL and GFDN models, but the decision was made not to implement it operationally in the 2011 HWRF model because statistically, it degraded the retrospective HWRF (but not GFDL and GFDN) forecasts of both track and intensity. Please see the previous JHT final report for a description of the efforts undertaken to assess why the HWRF forecasts may have been degraded by the implementation of the expanded east Atlantic POM domain.

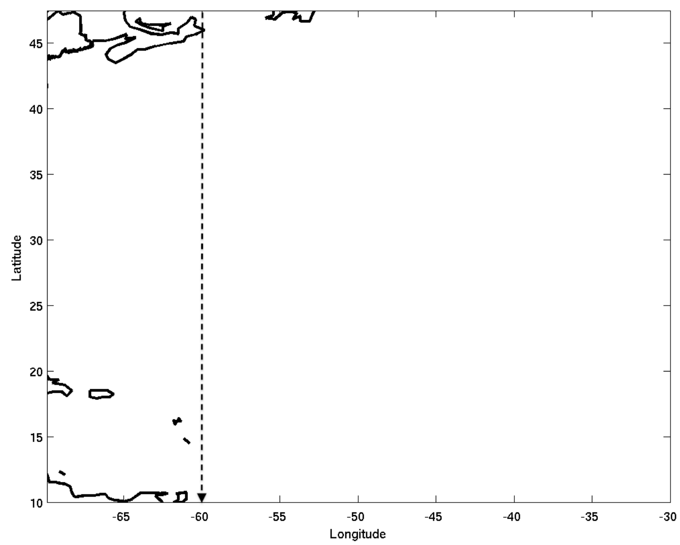


Figure 1. *Expanded East Atlantic POM domain in the 2011 operational GFDL model (and included as an option in the 2011 HWRF model). The original East Atlantic POM domain only extended westward to 60°W longitude, as indicated by the dashed arrow.*

b) Implement 3-D ocean coupling in the Indian Ocean and Southern Pacific Ocean.

This upgrade involved replacing 1-D ocean coupling with 3-D ocean coupling in the Indian Ocean and Southern Pacific Ocean in the GFDN model. The Princeton Ocean Model (POM) is used for 3-D ocean coupling. Three new ocean domains are set up with 1/6-degree horizontal grid spacing: North Indian, South Indian, and South Pacific. The new GFDN/POM domains are shown in Fig. 2. The bottom topography is constructed from the Navy's NCODA ocean depth coverage and interpolated into the model domains. A special horizontal smoothing is done in the areas with very steep topography and islands. The domains have closed land-water and open lateral boundaries where the domains are surrounded by the sea. At the ocean boundaries, transport and thermal conditions are specified according to the geostrophic assumptions.

The POM is initialized from the Navy's real-time NCODA analysis. The NCODA temperature and salinity 3-D fields are interpolated into the POM grid. After the interpolation, the model is integrated for a short period of time for spinning up the currents and for dynamical adjustment.

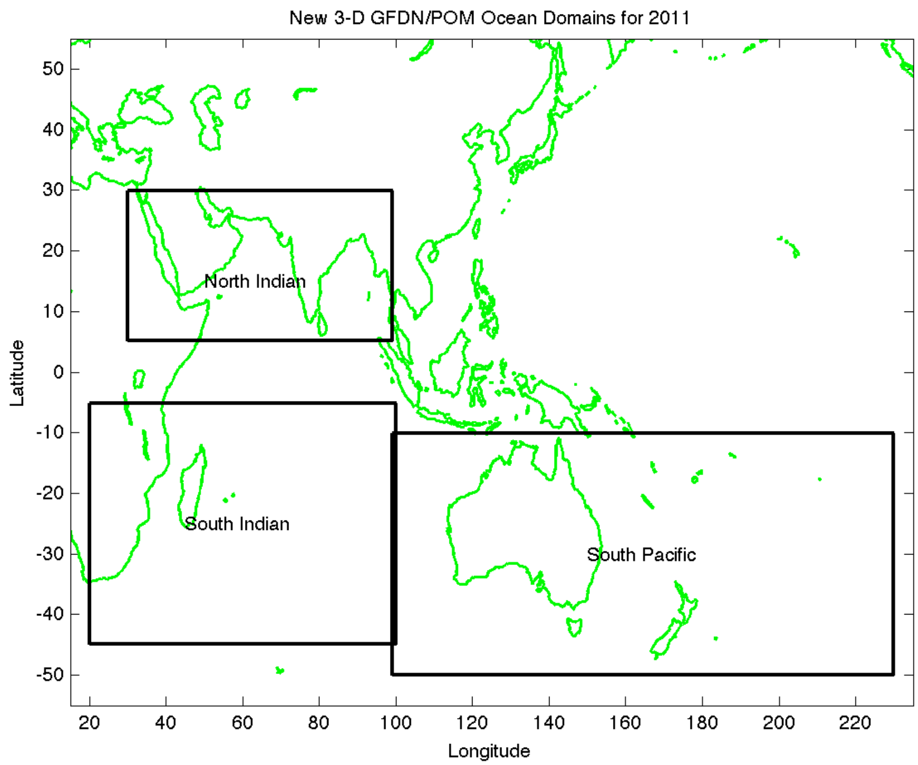


Figure 2. *New 3D GFDN/POM ocean domains in the Indian Ocean and South Pacific.*

The 3D ocean model was extensively tested in all the domains. Fig. 3 shows sea surface temperature and ocean current vectors during an extended GFDN/POM ocean initialization of Cyclone Wilma (2011), where the ocean is forced with the observed wind stress for 8 days (20110121/12UTC – 20110129/12UTC) to compare the ocean response between the 1D and 3D ocean simulations with the same wind stress.

The GFDN model coupler was modified to accommodate the new ocean domains and the upgraded GFDN/POM source code was ported to FNMOC for operational implementation.

c) Implement the new GFS deep cumulus parameterization and shallow convection schemes and the improved GFS PBL scheme into GFDL/GFDN.

This task was included in our original JHT proposal, but its execution was accelerated and the new deep cumulus parameterization was implemented operationally in NOAA's GFDL in 2011. We provided a detailed description of this upgrade in our final report from the previous round of JHT funding.

During this period of time we a) implemented the new GFS Simplified Arakawa-Shubert (SAS) deep convection scheme, b) made a modification of the surface exchange coefficient of momentum, and c) modified the dissipative heating in the GFDN model.

These are the same upgrades implemented into 2011 operational GFDL model. In the course of these upgrades, a major bug was discovered in the operational GFDN system. This bug was caused by FNMOC personnel during a previous operational GFDN implementation who accidently removed a line of computer code in one of the Optimum Interpolation routines. It is likely that this bug caused a significant degradation of the GFDN forecast skill during the last two years. The bug fix was implemented operationally by FNMOC shortly after the bug was discovered.

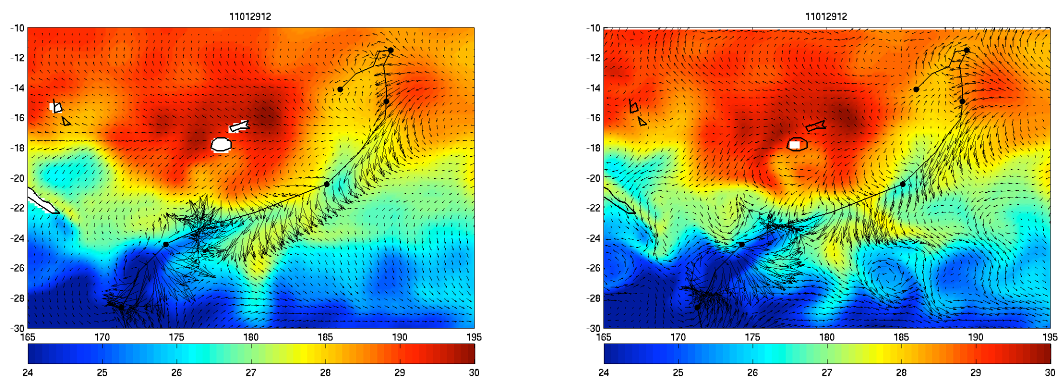


Figure 3. *Sea surface temperature (shaded in °C) and ocean current vectors during an extended GFDN/POM ocean initialization of Cyclone Wilma (2011), where the ocean is forced with the observed wind stress for 8 days (20110121/12UTC – 20110129/12UTC) to compare the ocean response between the 1D and 3D ocean simulations with the same wind stress. The left panel is updated 1D Global POM, and the right panel is the new 3D South Pacific POM.*

The SAS convective schemes implemented into the 2011 operational GFDL had a major difference compared to the one implemented in the GFS/HWRF models. GFDL did not allow the computation of cloud water and ice in the convective scheme and for the detrained species to get passed to the microphysics. However, the detrained condensates are correctly passed from one physics package to the other physics package in both HWRF and GFS. It appeared that the ice detrainment was having a significant impact on the large scale and lack of this effect in the GFDL model lead to significant track degradation in some cases. It also caused inaccurate northward-turning tracks in GFDL in the East Pacific. To fix this convection/microphysics interaction problem involved a modest code change, and we have since rerun the 2010 cases in Atlantic and East Pacific basins as well as most of the 2011 season by turning on the detrainment effect. The improvements were impressive, particularly for tracks. With strong support by NHC and EMC, the upgraded GFDL, called GFD5, began running in real-time, and the results have been provided to the NHC forecasters via the operational atcf decks. This upgrade is now implemented into GFDN in all ocean domains.

At the request of JTWC, the performance of the upgraded GFDN was evaluated based on a selected list of tropical cyclones, provided by JTWC. This list includes 51 cases from the following 2010 storms: 03W, 04W, 05W, 07W, 08W, 09W, 10W, 12W, 13W and 15W. Fig. 4 shows the average track forecast errors and the forecast skill relative to

CLIPER for the new GFDN compared with the 2010 operational GFDN and NOGAPS. The track forecast skill is evidently improved at all forecast lead times (Fig. 4). In regards to intensity, the results are somewhat mixed (Figs. 5 and 6). Despite a significant degradation at the 12-36h time periods the new GFDN model showed significantly improved skill in the 3-5 day range, beating the 10-member statistical ensemble (ST10) at day 5. Also, since the best intensity prediction model ST11 includes as input, the GFDN model forecast, it is likely a more reliable GFDN will translate into further improvements in the performance of ST11.

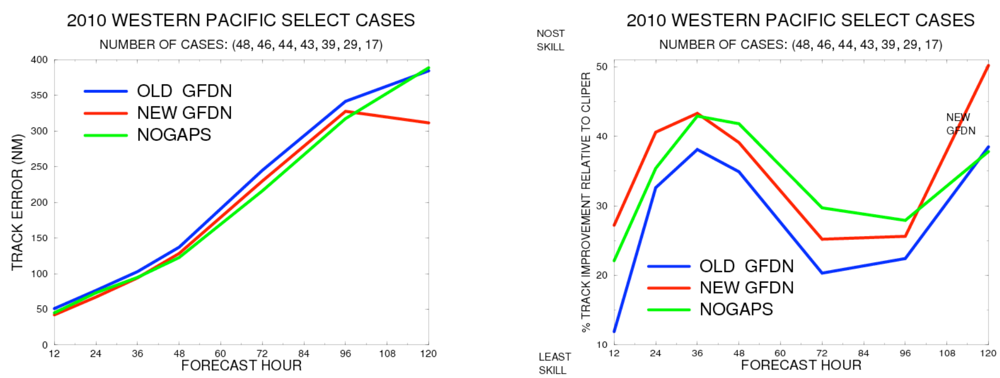


Figure 4. *Summary of the track forecast errors (left) and skill relative to CLIPER (right) with the new GFDN model (red) compared to the 2010 operational GFDN system (black) and NOGAPS (green) for the 2010 cases selected by JTWC (see text for details).*

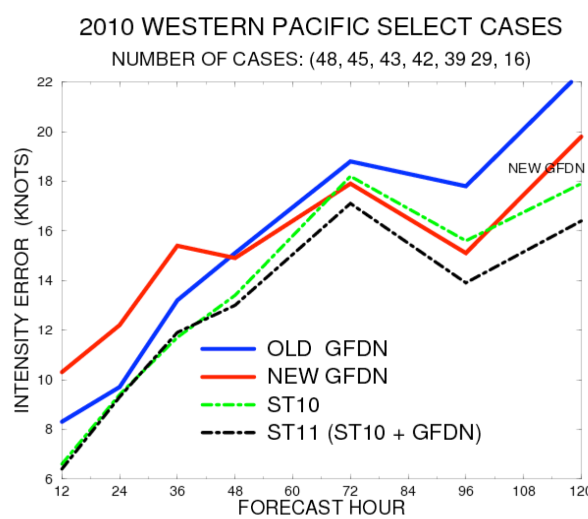


Figure 5. *Summary of the intensity forecast errors with the new GFDN model (red) compared to the 2010 operational GFDN system (blue) and the statistical-dynamical models ST10 (green) and ST11 (black), for the 2010 cases selected by JTWC (see text for details).*

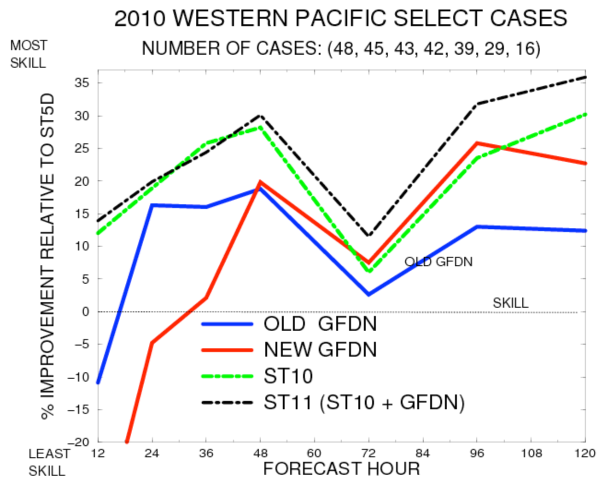


Figure 6. *Summary of the intensity forecast skill relative to ST5D with the new GFDN model (red) compared to the 2010 operational GFDN system (blue) and the statistical-dynamical models ST10 (green) and ST11 (black), for the 2010 cases selected by JTWC (see text for details).*

Prior to the operational implementation, the upgraded GFDN was run for several of the 2011 storms, and the track predictions showed noticeable improvement. A summary of the track forecasts errors based on 39 forecasts is shown in Fig. 7.

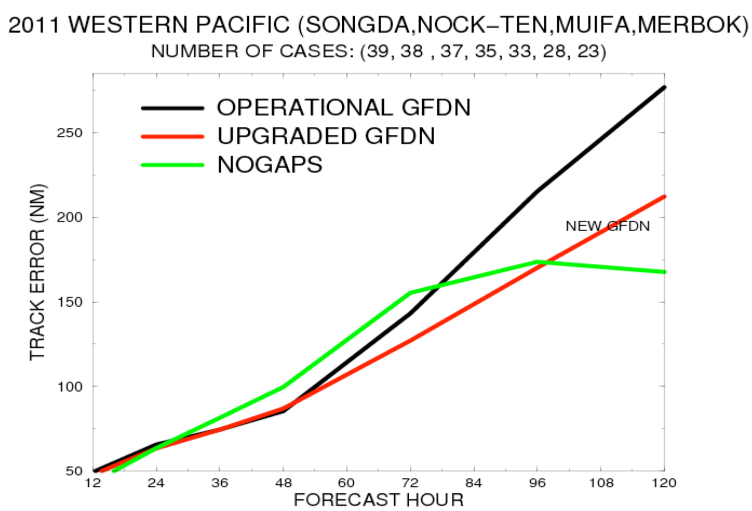


Figure 7. *Summary of the track forecast errors for selected tropical cyclones in 2011 with the new GFDN model (red) compared to the version of GFDN operational at that time (black) and NOGAPS (green).*

Large improvement was also found in the intensity prediction with the upgraded GFDN model, particularly at days 4 and 5 (Fig. 8).

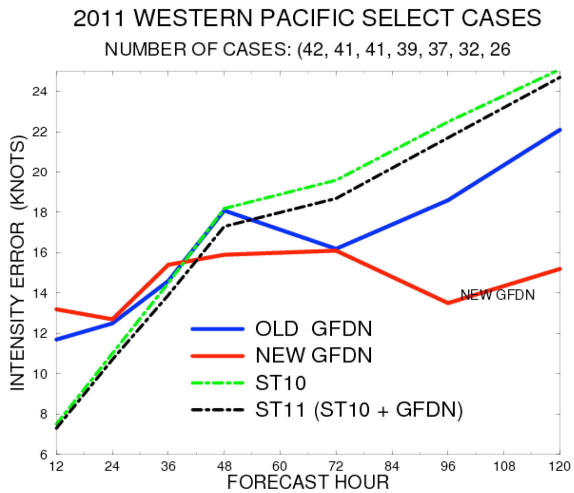


Figure 8. *Summary of the intensity forecast errors for selected tropical cyclones in 2011 with the new GFDN model (red) compared to the version of GFDN operational at that time (blue) and the statistical-dynamical models ST10 (green) and ST11 (black).*

During this time period other physics upgrades were tested for operational implementation in 2012. These upgrades include: detraining the microphysics generated in the SAS convective scheme into the micro-physics package (ncloud=1), fixing a bug in the current Planetary Boundary Layer (PBL) scheme (from 2003 implementation), fixing a bug in the current SAS convective scheme (from 2010 implementation), and retuning of momentum mixing. This model served as the benchmarked model against which further upgrades were tested over the past several months.

PBL FOR CURRENT GFDL MODEL **PBL FOR 2012 UPGRADED MODEL**

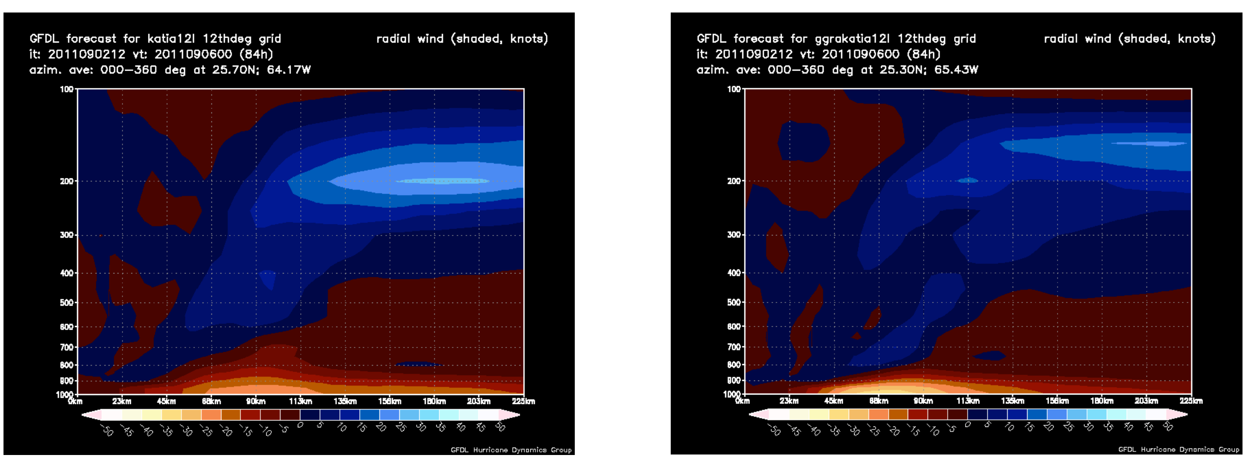


Figure 9. *Comparison of the azimuthally averaged radial wind at 60 hours, for the forecast of Hurricane Katia starting at 1200 UTC, 2nd September, 2011, for the operational GFDL model (left) and the 2012 upgraded model. The azimuthal average plotted is plotted from the storm center out to 225 km.*

The new physics upgrades which were evaluated in the benchmarked model lead to further improved model performance, particularly in the forecast of storm intensity. These upgrades included a) better formulation of the surface exchange coefficients (ch, cd), b) improved PBL structure, c) inclusion of the GFS shallow convection scheme and d) reduction in the storm size for larger storms.

Extensive tests were also made using the new GFS PBL scheme. Although the new scheme produced a much more realistic boundary layer structure compared to the current version, significant track degradation was noted in some storms in the GFDL model, with an introduction of a serious west bias. It is interesting that a similar tendency was found with the HWRF model causing this upgraded to be rejected for 2012. However, as shown in Fig. 9, the GFDL boundary layer structure was significantly improved by reduction of the Critical Richardson number from 0.5 to the value of 0.25 that is used operationally in the GFS, and reduction of the vertical mixing coefficient in the storm region. In the GFDL implementation, the vertical mixing coefficient is reduced 40% within the storm region (storm center to 3 degrees outward), then gradually increased in the 3 to 6 degree area and set to the current operational value beyond 6 degrees. This was done to eliminate a negative impact on storm track when the vertical mixing coefficient is reduced everywhere.

STORMS FROM 2010 ATLANTIC SEASON **STORMS FROM 2011 ATLANTIC SEASON**

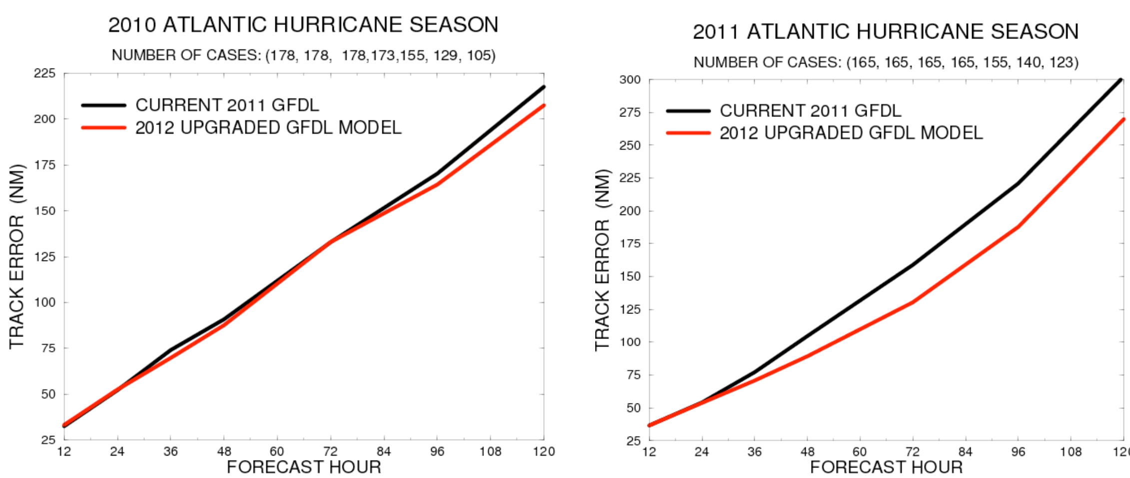
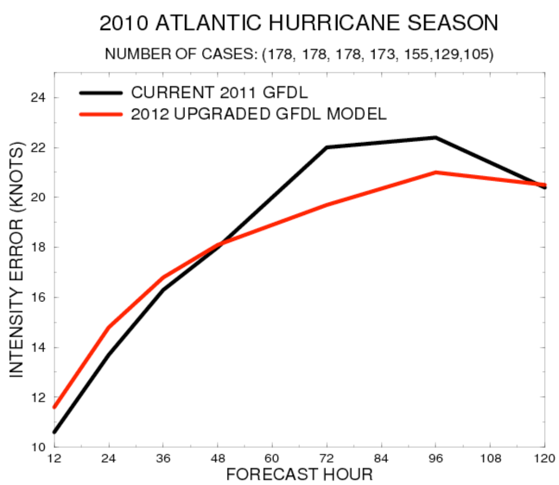


Figure 10. *Comparison of track error (nm) for selected storms from the 2010 (left) and 2011 (right) hurricane season. Comparison is made between the current operational GFDL model (black) and the upgraded version (red) to be made operational in 2012.*

Very promising intensity improvements were also found by the modification of the microphysics advection that includes advection of the individual microphysics species. In the current microphysics package operational in both GFDL and HWRF, only the combined cloud condensate is advected. However, this major change has not been thoroughly tested in time for the 2012 implementation, but will be run in parallel this summer for possible implementation in 2013. Finally, the asymmetries have been removed in the vortex initializations as tests have indicated that its impact on both track and intensity is now insignificant at all forecast time levels.

Improvements in the storm track (Fig. 10) and intensity (Fig. 11) forecasts for the upgraded model is shown, compared to the current operational model for selected storms during the past 2 seasons as well as the combined 2010 and 2011 seasons (Fig. 12). The 2010 Atlantic storms selected for these tests were Alex, Danielle, Earl, Igor, Julia, Lisa and Tomas. The 2011 Atlantic storms included Irene, Katia, Maria, Ophelia, and Philippe. It was assumed that these 12 storms selected from the two seasons gave a very representative sample of intense storms, which dominated 2010, and weak and sheared storms that dominated the 2011 season.

STORMS FROM 2010 ATLANTIC SEASON



STORMS FROM 2011 ATLANTIC SEASON

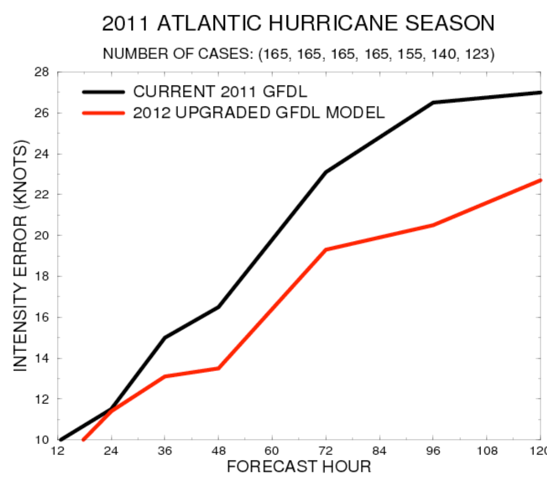


Figure 11. *Comparison of intensity error (knots) for selected storms from the 2010 (left) and 2011 (right) hurricane season. Comparison is made between the current operational GFDL model (black) and the upgraded version (red) to be made operational in 2012.*

The reduction in track error for the 2010 season (Fig. 10, left) was small (~4%) in the 2-5 day forecast periods, but averaged nearly 15% for the 2011 selected storms. For the 2011 season the frequency of superior performance in the 2-5 day forecast period averaged nearly 70% for the upgraded model, and was statistically significant at over the 95% confidence level. For the combined 2010 and 2011 seasons (Fig 12), with the very representative mixture of storm and weak storms, the track improvement was about 10% for the 2-5 day time period with frequency of superior performance of 60%.

The reduction in intensity error was particularly large for the 2011 season (Fig. 11, right), which was dominated by weak and sheared storm and averaged 18% for the 2-5 day forecast period. Also the excessive positive bias found in the operational GFDL model in 2011 which averaged nearly 15 knots in the 2-5 day period, was greatly reduced to only 3 knots. It is also encouraging that for the combined 2010 and 2011 seasons (Fig

12), the average intensity bias for the 2-5 day forecast period was only -1 knot, with average reduction in track error of about 12%.

COMBINED TRACK ERROR RESULTS **COMBINED INTENSITY ERROR RESULTS**

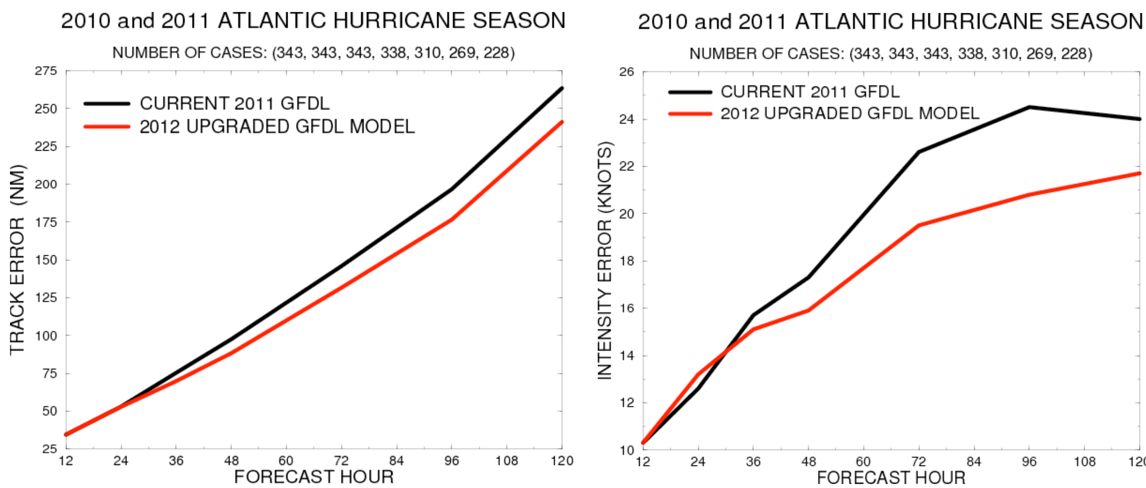
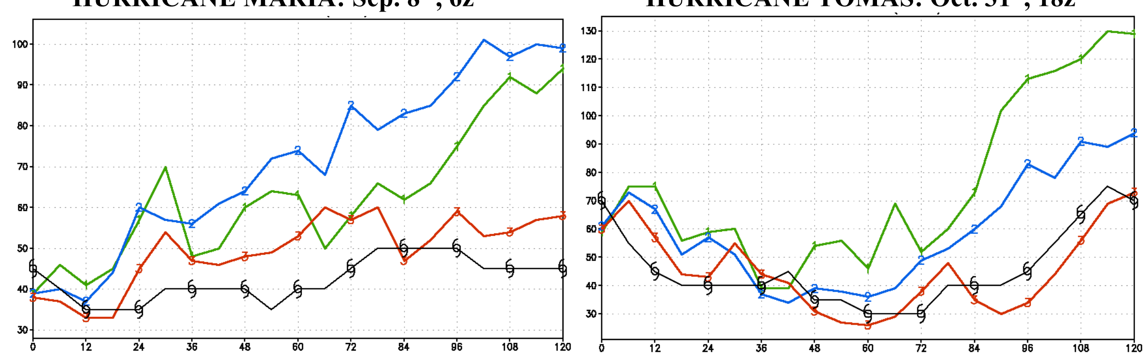


Figure 12. *Comparison of track (left) and intensity (right) error for selected storms from the combined 2010 and 2011 Atlantic hurricane seasons. Comparison is made between the current operational GFDL model (black) and the upgraded version (red) to be made operational in 2012.*

HURRICANE MARIA: Sep. 8th, 6z **HURRICANE TOMAS: Oct. 31st, 18z**



1 Current GFDL **2 Benchmarked GFDL** **3 2012 model**

Figure 13. *Time series of maximum surface winds for two forecasts of Hurricane Maria (left) and Hurricane Tomas for the operational GFDL (green), the upgraded model (red), and the intermediate benchmark model (blue), compared to the observed wind (black).*

Two examples of improved intensity prediction are shown in Fig. 13, with the new upgraded model (red) compared to the current operational version (green). Also plotted is the original benchmarked GFDL model (blue). Note in both examples, the dramatic reduction in the over intensification, with the combined bug fixes in the benchmarked version, and the improved physics (e.g., surface physics and PBL). These results suggest that the largest impact on improved intensity for these 2 storms likely came from the physics upgrades rather then the bug fixes. As already noted further improved intensity prediction for the weak and sheared storms (figure not shown) resulted when the advection of the individual cloud species was also included, rather then advecting the total cloud condensate, as is done currently in both the GFDL and HWRF operational models.