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In this final report we summarize the main upgrades implemented into the operational GFDL and GFDN models in the 2011 hurricane season. The forecast operations of both NOAA's National Hurricane Center and the Navy's Joint Typhoon Warning Center require more accurate HWRF and GFDL/GFDN models as integral parts of the multi-model ensemble forecast efforts. When the operational GFDL model was formally unfrozen by NCEP at the end of the 2010 hurricane season, it was an excellent opportunity to make major upgrades to the model, which had been frozen since 2006. Therefore, we made significant efforts during Year 2 of this project to accelerate the development, implementation, and testing of major upgrades to the GFDL/GFDN system for operational implementation in the 2011 hurricane season. Accordingly, our work plan for Year 2 was modified to achieve these goals.

As reported in our 2011 semi-annual report, we expanded the eastern Atlantic Ocean domain to eliminate an occasional loss of ocean coupling when a hurricane moves outside of the eastern domain during a forecast. Per request from EMC, we have now compared the impact of this domain expansion on the GFDL/POM and HWRF/POM coupled systems, and we offer new recommendations.

Here, we briefly summarize the main results.

a) Upgrades implemented into GFDN atmosphere and resulting performance

The primary upgrades implemented into the atmospheric component of GFDN in 2011 include the new GFS Simplified Arakawa-Shubert (SAS) deep convection scheme, modification of the surface exchange coefficient of momentum, and modified dissipative heating.

During the implementation of the upgrade, a major bug was discovered in June 2011 in the operational GFDN. This bug was caused by FNMOC personnel during a previous operational GFDN implementation when a line of computer code in the Optimum Interpolation routine was accidentally removed. It is likely that this bug caused a significant degradation of the GFDN forecast skill during the last two years. After the bug was fixed in the operational code on August 3, 2011, GFDN became a top preforming track model in the Atlantic basin, as illustrated in Table 1.

Table 1. Performance of the operational GFDN before and after fixing the bug (see the text for detail) in comparison to other operational models for the 2011 Atlantic Hurricane season through September 13th, 2011.

BEFORE BUG FIX (PRIOR TO AUGUST 3RD, 2011)
AVERAGE TRACK ERRORS (NM) FOR HOMOGENEOUS SAMPLE

	00	12	24	36	48	72	96	120
GFDL	13.7	29.3	44.3	57.5	73.2	109.1	221.5	
GFDN	12.0	35.9	51.9	74.5	124.4	318.5	601.6	
HWRF	8.3	24.9	31.0	45.6	70.7	105.1	113.7	
AVNO	11.9	23.9	29.4	44.0	71.6	165.9	289.7	
NGPS	24.8	35.0	51.0	70.1	90.5	118.2	70.7	
#CASES	40	28	24	20	14	5	1	0

AFTER BUG FIX (AUGUST 3RD THROUGH SEPTEMBER 13TH, 2011)
AVERAGE TRACK ERRORS (NM) FOR HOMOGENEOUS SAMPLE

	00	12	24	36	48	72	96	120
GFDL	9.4	31.5	42.6	55.7	70.9	116.3	170.8	245.1
GFD5	9.2	31.3	45.0	55.8	64.5	98.1	129.2	183.0
GFDN	8.0	33.2	51.3	64.9	75.5	100.4	119.1	166.1
HWRF	8.9	36.1	51.3	66.1	76.9	105.8	148.7	204.3
AVNO	8.3	28.0	40.3	56.3	65.8	94.0	126.2	194.6
NGPS	19.2	37.2	51.4	70.2	84.9	118.6	154.0	226.8
#CASES	128	120	109	96	85	66	54	45

FREQUENCY OF SUPERIOR PERFORMANCE (%)

	00	12	24	36	48	72	96	120
GFDL	20.4	9.2	17.9	24.7	17.4	11.9	9.3	13.3
GFD5	20.7	13.8	13.7	15.5	15.1	28.4	29.6	28.9
GFDN	23.3	16.2	17.1	17.5	16.3	22.4	27.8	35.6
HWRF	14.9	14.6	12.0	18.6	19.8	16.4	13.0	13.3
AVNO	17.5	30.8	23.9	13.4	23.3	14.9	14.8	4.4
NGPS	3.3	15.4	15.4	10.3	8.1	6.0	5.6	4.4
#CASES	128	120	109	96	85	66	54	45

The upgraded SAS deep convection scheme was transitioned into operations in GFDN in the western Pacific basin on August 15, 2011. Prior to the operational implementation, the upgraded GFDN was run for several of the 2011 storms, and the track predictions showed noticeable improvement, as illustrated in Figure 1. Here, the average track forecast error of the new GFDN (upgraded SAS and bug fix) is compared with the previous operational GFDN and NOGAPS.

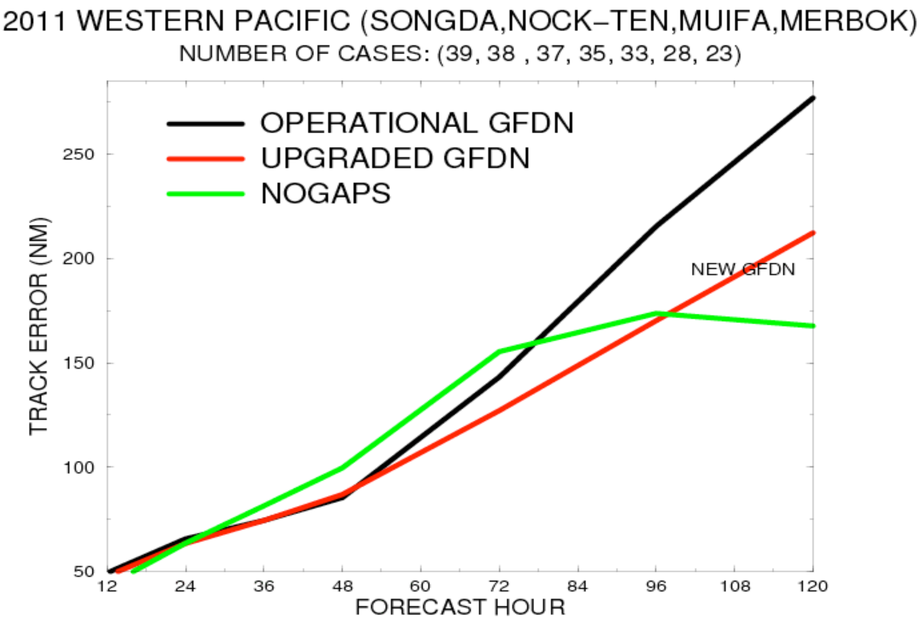


Figure 1. *Summary of the track forecast error in westpac with the new GFDN model (red) compared to the 2010 operational GFDN system (black) and NOGAPS (green).*

Figure 2 shows two examples of the improved track forecasts with the new GFDN system for Typhoon Muifa (2011) compared to the version of the GFDN operational at the time and NOGAPS.

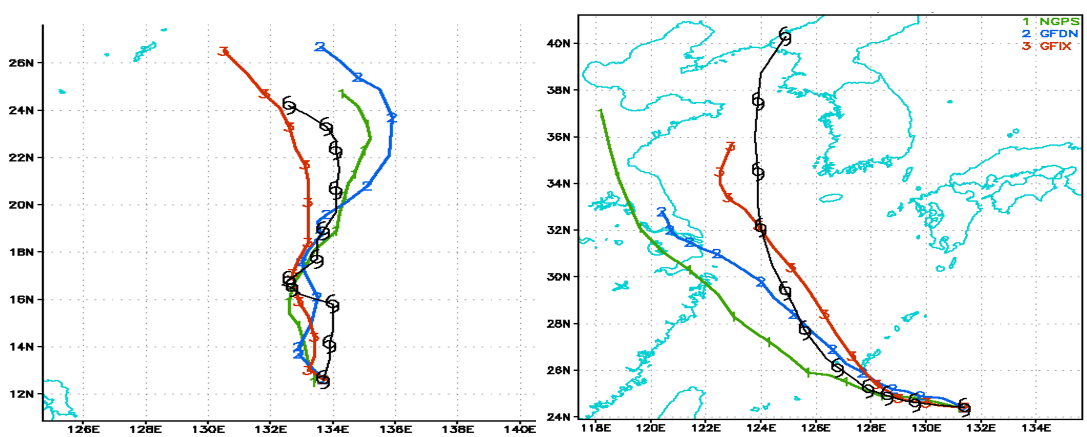


Figure 2. *Track forecasts for Typhoon Muifa July 29, 0Z (left) and August 3, 12Z (right) with the upgraded GFDN (red), previous operational GFDN (blue), and NOGAPS (green).*

Large improvement was also found in the intensity prediction in the Western Pacific at days 2, 4, and 5 (Fig. 3) with the upgraded GFDN model, particularly at days 4 and 5.

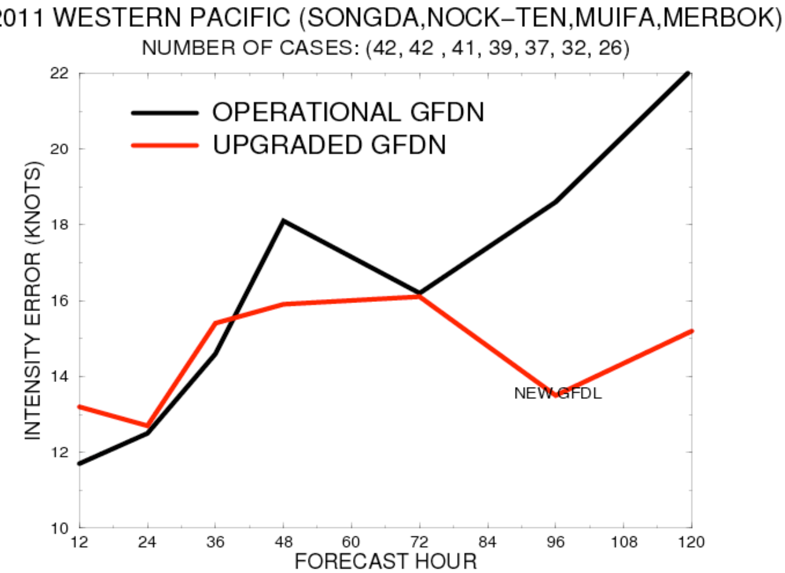
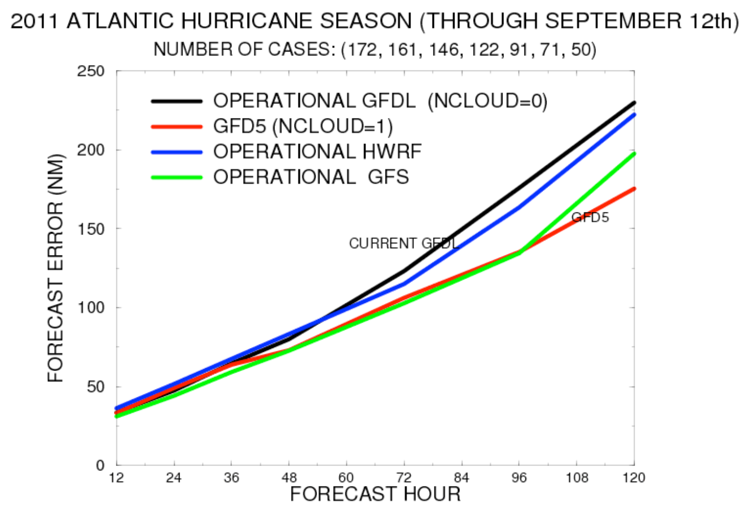


Figure 3. *Summary of the intensity forecast skill in westpac with the upgraded GFDN model (red) in comparison to the 2010 operational GFDN system (black).*

b) Upgrades implemented into GFDL atmosphere and subsequent performance

The main GFDL upgrades that were made operational in April 2011 are described in our 2011 semi-annual report. During the 2011 season, we continued to evaluate the upgrades and their performance. The forecasts of Hurricane Irene indicated significant westward biases in track prediction of the new GFDL system, especially compared to the HWRF and GFS forecasts. The primary difference between the SAS convective schemes implemented in the GFS/HWRF models and GFDL was in the treatment of the detrained condensates. 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 the 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 contributed to the large track degradation in Hurricane Irene. It also caused inaccurate northward-turning tracks in GFDL in the East Pacific. This behavior also occurred occasionally during the retroactive 2010 eastpac tests, but since the sample size was small and dominated by one hurricane (Hurricane Celia), it was believed to be anomalous. However, recent tests indicate that this severe northward bias is entirely removed when the detrainment of the microphysics species is included.

The fix to this convection/microphysics interaction problem involved a simple code change, and we have since rerun the 2010 cases in both 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.



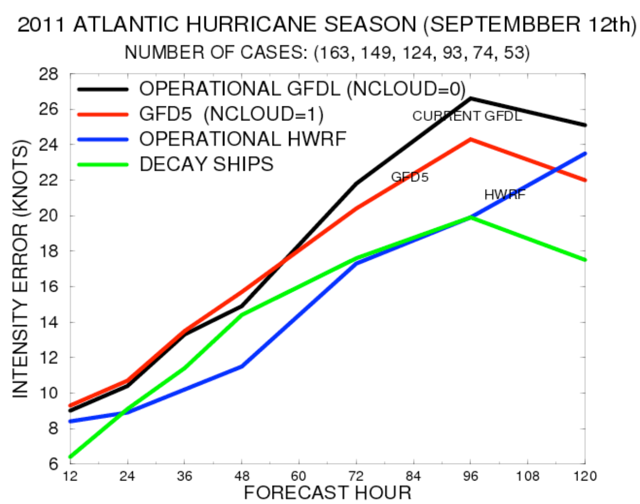


Figure 4. *Performance of the 2011 operational GFDL and upgraded GFD5 for track (top) and intensity (bottom), as of September 12th, 2011, compared to other operational guidance. See text for additional details.*

By the time of writing this report, GFD5 has shown 20% improvement in the 3-5 day range compared to the operational GFDL. It also appears to be showing superior skill to most of the other available guidance during the 3-5 day forecast period (see Fig. 4, top). This result strongly suggests that for future model improvements, we must not underestimate the critical importance of the convective/microphysics interactions as an important physical process that impacts the large-scale steering in a way that can have significant track implications, at least in the GFDL model. The improvement has not translated into intensity prediction improvements however (Fig. 4, bottom), the reason for which is not well understood and will require further investigation. We plan to conduct this investigation over the next few months in both HWRF and GFDL.

Other physics upgrades to be tested for possible operational implementation in 2012 include the addition of shallow convection and the advection of the individual microphysics species. In the current implementation of the Ferrier microphysics in both GFDL and HWRF, to reduce computational resources, the total condensate is treated as a single advected quantity rather than advecting the cloud water, rain water, and ice separately. Very preliminary tests indicated that further improvements in track and intensity might be possible by removing this simplification. However, careful evaluation of this change will be necessary before the change is recommended for operational implementation in either GFDL or HWRF in 2012.

c) Expanding the eastern Atlantic Ocean domain in GFDL/GFDN and HWRF

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. 5). 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 HWRF or GFDL model forecast. This POM domain expansion was implemented in the 2011 operational GFDL model, 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) forecasts of both track and intensity.

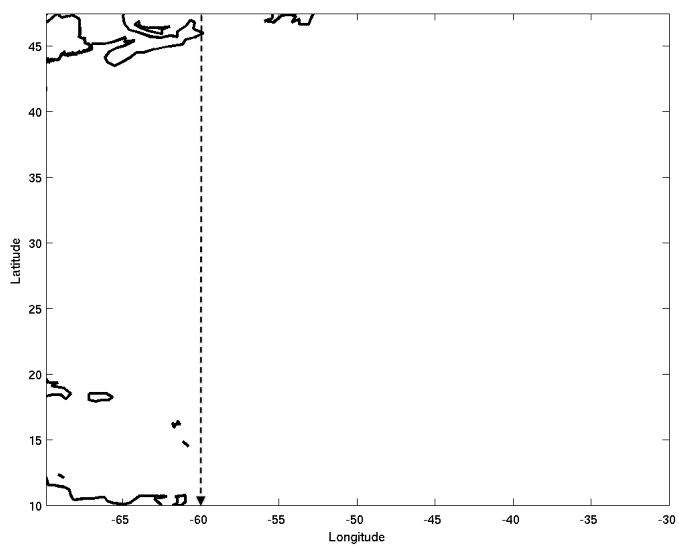


Figure 5. *Expanded East Atlantic POM domain in the 2011 operational GFDL model (and included as an option in the 2011 HWRF model). The original East Atlantic POM domain only extended westward to 60°W longitude, as indicated by the dashed arrow.*

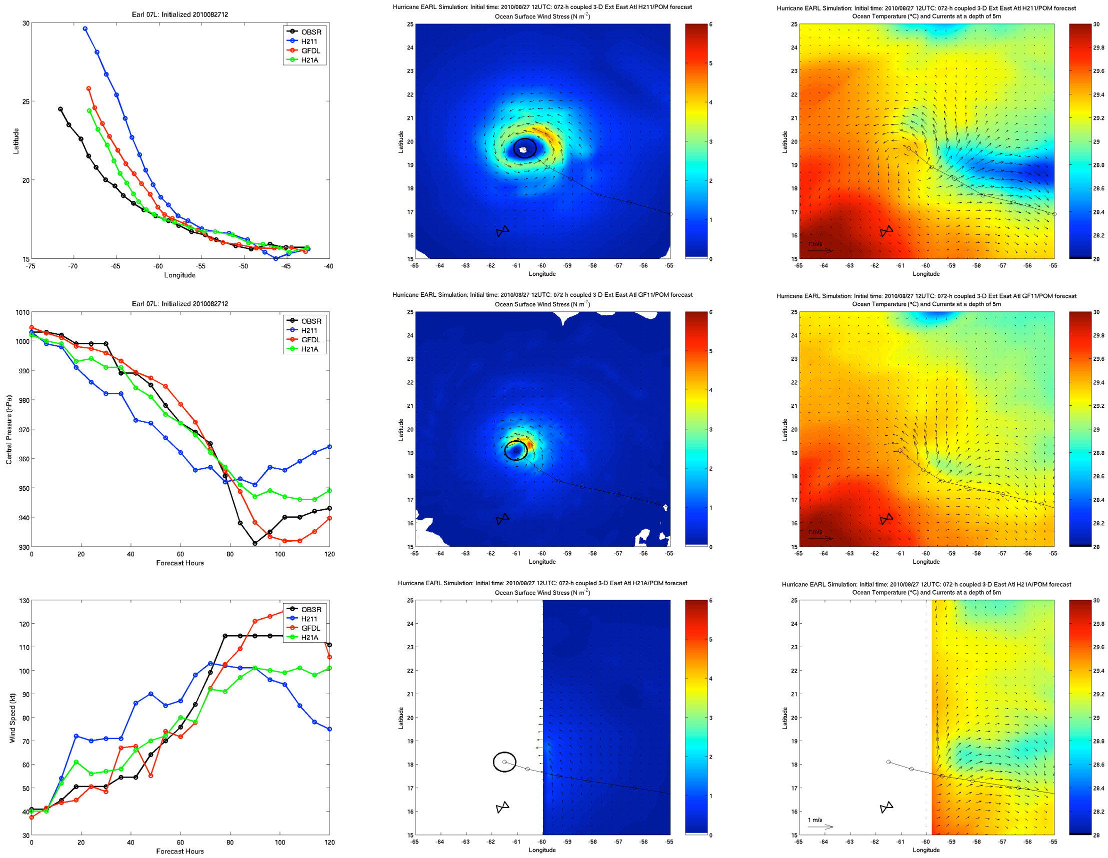


Figure 6. *Coupled HWRF/POM and GFDL/POM forecasts of Hurricane Earl, initialized at 12 UTC on 27 August 2010. In column 1, row 1 is track, row 2 is central pressure, and row 3 is maximum wind speed, where OBSR is observations, H211 is HWRF with expanded East Atlantic POM domain, GFDL has expanded East Atlantic POM domain, and H21A is HWRF with original East Atlantic POM domain. In columns 2 and 3, row 1 is H211, row 2 is GFDL, and row 3 is H21A. Column 2 shows the 72-h wind stress forecast, where the observed radius of maximum winds valid at the 72-h model forecast time is indicated by a black circle. Column 3 shows the 72-h SST forecast.*

To help determine the reason for this degradation, we in collaboration with EMC investigated the ocean response and subsequent intensity change for model forecasts of Hurricane Earl (2010) during a time when the forecasted storm track crossed 60°W longitude (Fig. 6). The key conclusion is that the HWRF-simulated radius of maximum winds (RMW) was approximately double the observed RMW, leading to overcooling of the SST over a wide area in the HWRF simulation with an expanded East Atlantic POM domain. This overcooling caused the HWRF storm to weaken erroneously and may have caused in a north bias by weakening of the subtropical ridge that was steering the storm west-northwest (Fig. 6). By contrast, the GFDL-simulated RMW was close to observed, so the SST cooling (with the same expanded East Atlantic POM domain) was more accurate (i.e. less extreme), preventing subsequent weakening and therefore creating a more accurate intensity forecast. Since the HWRF simulation with the original East Atlantic POM domain lost ocean coupling, the SST did not cool at all west of 60°W longitude, so subsequent weakening was prevented, thereby creating a more accurate intensity forecast (for the wrong reason) compared to the HWRF simulation with the expanded East Atlantic POM domain (even though the storm size was still anomalously large).

Our recommendation is to redo this analysis with the 27/9/3 km version of HWRF, which may produce a more accurate storm size, to determine if the SST cooling and subsequent intensity problems are rectified with the expanded East Atlantic POM domain. If so, then the logical assumption will be that the expanded East Atlantic POM domain will improve intensity forecasting in the HWRF like it does in the GFDL model. Also, it should be noted that the expanded East Atlantic POM domain is being improved further to rectify minor issues that have been found since the 2011 operational implementation in the GFDL model, so the plan will be to implement the improved version of this POM domain in both the GFDL/GFDN and HWRF and models for 2012.

d) Modification of the relocatable "global" one-dimensional ocean domain for GFDN

For the 2011 GFDN model, the relocatable "global" one-dimensional POM domain (hereafter global POM domain) was modified to allow it to cross the International Dateline, as needed. The global POM domain spans 50° in longitude and 50° in longitude. Previously, this domain was defined such that minimum possible longitude for the western edge of the domain was 180°W (i.e. -180) at the Dateline and the maximum possible longitude for the eastern edge of the domain was 180°E (i.e. +180) at the Dateline. This definition prevented the POM domain from crossing the dateline. By redefining the domain such that the minimum possible longitude for the western edge of the domain is 0° at the Prime Meridian and the maximum possible longitude for the eastern edge of the domain is 360° at the Prime Meridian, storms such as Cyclone Wilma (2011) in the South Pacific Ocean can now cross the Dateline in GFDN without losing ocean coupling.