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Project Title: Improving the GFDL/GFDN Operational Tropical Cyclone Models at NOAA/NCEP and Navy/FNMOC
Recipient Name: University of Rhode Island
PIs/PDs: Isaac Ginis and Morris Bender
Report Type: Project Progress Report
Reporting Period: 09/01/2014 - 02/28/2015
Final Report: No
Report Due Date: 03/30/2015

Work Accomplishments:

1. Tasks scheduled for Year 2

The primary upgrades to the atmospheric model:
a) Increasing the number of vertical levels, particularly in the PBL and lower/middle troposphere
b) Upgrading the microphysics, radiation, and PBL schemes to account for the increased vertical resolution
c) Including spinup of the microphysics during the initialization of the atmospheric model.

The primary upgrades to the ocean model:
a) Implementing alternative ocean analyses for the initialization
b) Three-way atmosphere-wave-ocean coupling with advanced physics of the air-sea interface

2. Tasks accomplished this period, adjusted based on evolving priorities and results

2.1. Atmospheric model upgrades

Through JHT funding, the number of vertical levels in the GFDL hurricane model were increased from 42 to 60 vertical sigma levels. The configuration selected was nearly identical to the HWRF vertical configuration with two differences (lowest model level of the current operational GFDL model was retained and an additional vertical level was added to the upper troposphere). The radiation code in the current operational model was modified and fully generalized to run from any specified vertical sigma level distribution.

During the past year it was discovered that the coding to include ocean surface currents in the computation of the surface fluxes, was not correctly implemented in 2014. In addition, a bug was found in the GFDL coupler. The impact of these coding errors was carefully evaluated and found to be mostly neutral, and will be fixed in the 2015 upgraded model.

In the present GFDL hurricane forecast system, the resolved vortex in the initial global analysis is removed and replaced with a model consistent vortex that is spun up during a 60 hour integration of an axisymetric version of the 3d hurricane model. The tangential component of the wind is gradually forced toward a profile obtained from the operational tcvitals file, while the remaining prognostic variables evolve in a model consistent way. Additional analysis made during the past year indicated that the initial vortex often had too low humidity for weak storms. The reason was the methodology of spinning up the initial moisture field (r) from an environmental value determined beyond the filter domain of the global vortex (Equation 1), which was dryer than in the storm region. A better strategy that was considered and tested was to replace the environmental moisture with the value from the global analysis, and add in the moisture deviation computed relative to this value (Equation 2) instead of the previous environmental moisture field. This resulted in a much more reasonable initial moisture field, as shown in Fig. 1 for one case of Hurricane Earl. Even by forecast hour 42 (Fig. 1, bottom left), the moisture in the middle troposphere was still anomalously dry compared to the revised moisture initialization method (bottom right), which resulted in underprediction of storm intensity (blue line, Fig. 2). Since this problem was worse for weak storms in the current operational system, the vortex initialization was not run in 2014 for storms of 40 knots or less, to enable better intensification for rapid developing cases (red line, Fig. 2). However with the improved moisture initialization, the intensity is much better forecasted (green line, Fig. 2) and the vortex initialization will be introduced again in 2015 for all systems regardless of intensity.

$$(U, V, T, r, p^*) = (U, V, T, r, p^*)_{\mathrm{Envr}} + (U, V, T, r, p^*)_{\text{axi-sym vortex}} \qquad (1)$$

$$(U, V, T, p^*) = (U, V, T, p^*)_{\mathrm{Envr}} + (U, V, T, p^*)_{\text{axi-sym vortex}} \qquad (2)$$

$$r = r_{\mathrm{gfs}} + r_{\mathrm{vortex}}$$

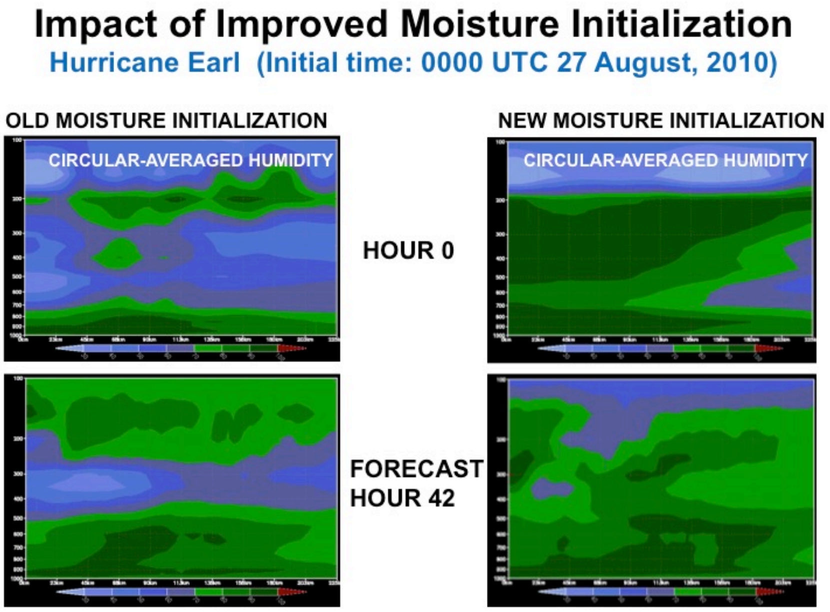


Figure 1. *Circular-averaged cross-sections of relative humidity at hour 0 (top) and forecast hour 42 (bottom), for one case of Hurricane Earl (2010) using the moisture initialization procedure (left) used in the current operational GFDL forecast system, and the proposed improvement (right).*

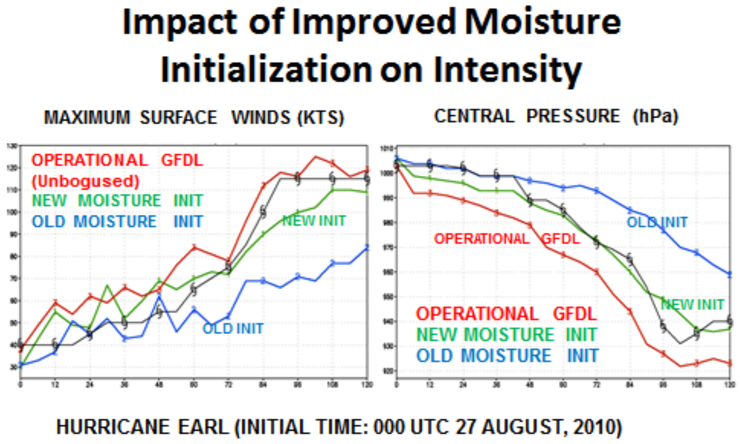


***Figure 2**. Time series of central pressure (left) and maximum surface wind (right) for the case of Hurricane Earl predicted in the current operational GFDL model (red, which is run without bogusing), compared to the forecast using the old bogusing initialization procedure (blue) and the improved moisture initialization procedure (green) being tested for implementation in 2015.*

In the operational GFDL initialization, an important parameter used in the axisymmetric vortex spinup, is the radial extent of the storm (Rb) defined as the radius where the positive tangential winds go to zero. During the spinup, the tangential wind is targeted toward a storm profile determined by the reported wind radii from the operational tcvitals file. In the current system, Rb is assumed to be a function of the reported radius of the last closed isobar RCLI (e.g., Rb = 1.5 *RCLI). Examining the performance of the Navy's operational version of the GFDL model (GFDN) for the 2013 Western Pacific season, it was found that the track and intensity was significantly degraded in some of the forecasts, due to too small reported RCLI compared to the observed satellite estimates (e.g., Knaff, personal communication). A new formulation independent of RCLI was developed. It is based on the assumption that absolute angular momentum M(r) is roughly conserved for a parcel moving inwardly toward the storm center from R_b. Following the methodology outlined in Carr and Elsberry (1997), the following formula was derived for R_b, and tested throughout most of the 2014 Western Pacific system in near real time, in a parallel version of the GFDL model run on the JET supercomputer facility using the NCEP (National Centers for Environmental Prediction) GFS (Global Forecast System) analysis:

$$(R_b) = e^{(MLG/(1 + x))}$$

where

$$MLG = log(2(M(r))_{gale} / f r_{gale}^{(1-x)}$$

The expression $M(r)_{gale}$. Absolute angular momentum of the storm at the radius of the gale force winds is defined as:

$$M(r)_{gale} = r_{gale} v_{gale} + \frac{1}{2} f r_{gale}^{2}$$

where r_{gale} is computed as the average of the 4 gale force wind radii reported from the tcvitals file and x is a scaling factor set to .4, as suggested by Carr and Elsberry (1997). This formulation has also been recently tested for the 2014 Atlantic season in both the 42 and 60 level versions of the GFDL model and found to produce very encouraging results, and was added to the list of possible upgrades for operational implementation in 2015.

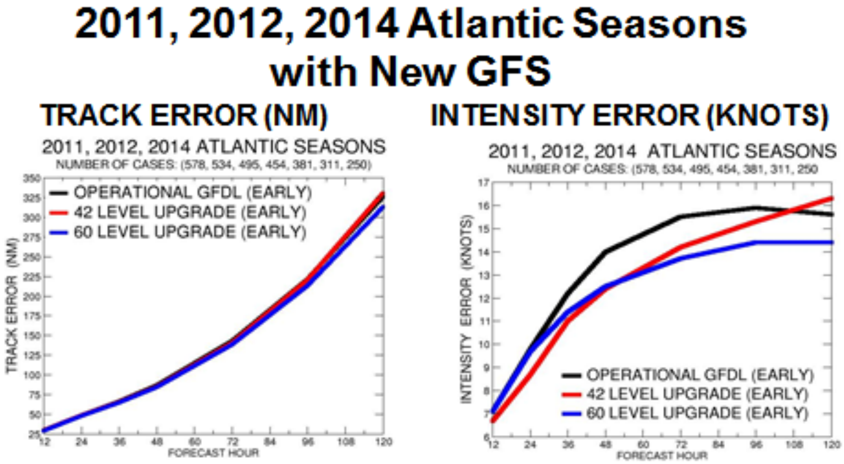


***Figure 3**. Average track error (left) and intensity error (right) for storms from the 2011, 2012, and 2014 Atlantic hurricane season, comparing the current operational GFDL model (black), with the 42 level (red) and 60 level (blue) upgraded GFDL. All of the results shown are for the early model interpolated guidance and all forecasts are run off of the new GFS.*

The operational GFDL model was tested for tropical cyclones during the 2011, 2012 and 2014 Atlantic Seasons. with the above mentioned changes using the new version of the GFS made operational at NCEP in 2014, Due to the limitations in disc storage needed to run these tests using the new high resolution GFS, it became impractical to run every storm for this multi-year sample. Nevertheless, a sample size of 638 cases (which contained all of the significant tropical systems during that period) was considered sufficient to evaluate the performance for both the 60 level and 42 level versions of the upgraded GFDL system. Results are shown in Figure 3 for the interpolated forecasts (early guidance), to exactly represent the version that is available to the operational hurricane forecasters in real time.

Impact on track was mostly neutral for this multi-year sample size, although both versions of the model had about 3% reduced error in the critical 2-3 day forecast lead times, with a reduced error of about 5% at days 4-5 with the 60 level model. These improvements were statistically significant at over the 96% for all forecast lead times for the 60 level model except forecast hour 36h. For the late model guidance (not shown) statistical significance was also obtained for the 42 level model through forecast hour 72. For intensity, the improvement was much more significant, with reduced intensity errors averaging about 11% for the 42 level model for days 1-3 and about 10% for the 60 level model at days 2 through 5.

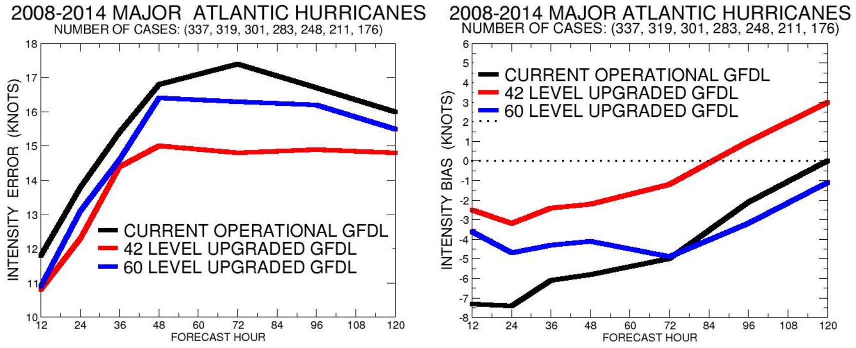


Figure 4. *Average intensity error (left) and intensity bias (right) for major hurricanes during the 2008-2014 Atlantic Hurricane seasons, comparing the current operational GFDL model (black) and the 42 level and 60 level upgraded GFDL model (blue and red lines). The storms during the 2008 and 2010 seasons (Ike, Danielle, Earl, Igor and Julia) were run using the old GFS background fields, while the storms run during the 2011-2014 seasons (Irene, Katia, Edouard and Gonzola) were run using the new GFS fields.*

Although the results outlined above for the 60 level upgraded version of the GFDL hurricane model were promising, closer evaluation raised several concerns about upgrading the model vertical resolution in 2015, as originally planned. The multi-year sample upon which these tests were performed had only a few major hurricanes and only one category 4 hurricane (Gonzolo, 2014). The intensity of Gonzolo was very poorly predicted with the 60 level model, with an average error of 23 and 18 knots at 48 and 72 hours, compared to 20 and 14 knots for the current operational model, and 15 and 11 knots for the 42 level upgraded model. This was due to an average negative intensity bias of over -20 knots in the 60 level model during the 1-3 day forecast time period, compared to -17 and -14 knots for the operational and 42 level upgraded models, respectively.

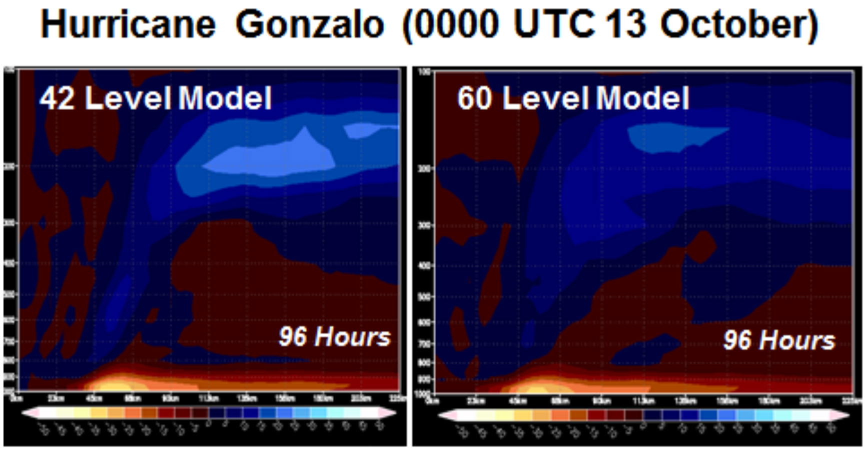


Figure 5. *Circular-averaged cross-section of radial component of the wind for the upgraded 42 level (left) and 60 level (right) GFDL hurricane model, at forecast hour 96 for Hurricane Gonzalo initialized at 0000 UTC 13th October, 2014. Forecasts were run using the new GFS fields.*

For Edouard, an excessive negative bias was also noted compared to the 42 level model. When additional tests were made on major hurricanes during the 2008-2014 seasons (Fig. 4) using both the new and old GFS, it was found that the intensity prediction (left) and bias (right) using the 60 level upgraded model (blue) was unacceptably degraded compared to the 42 level model (red) which had much reduced negative bias and improved intensity prediction compared to both the current operational model (black) and the 60 level version.

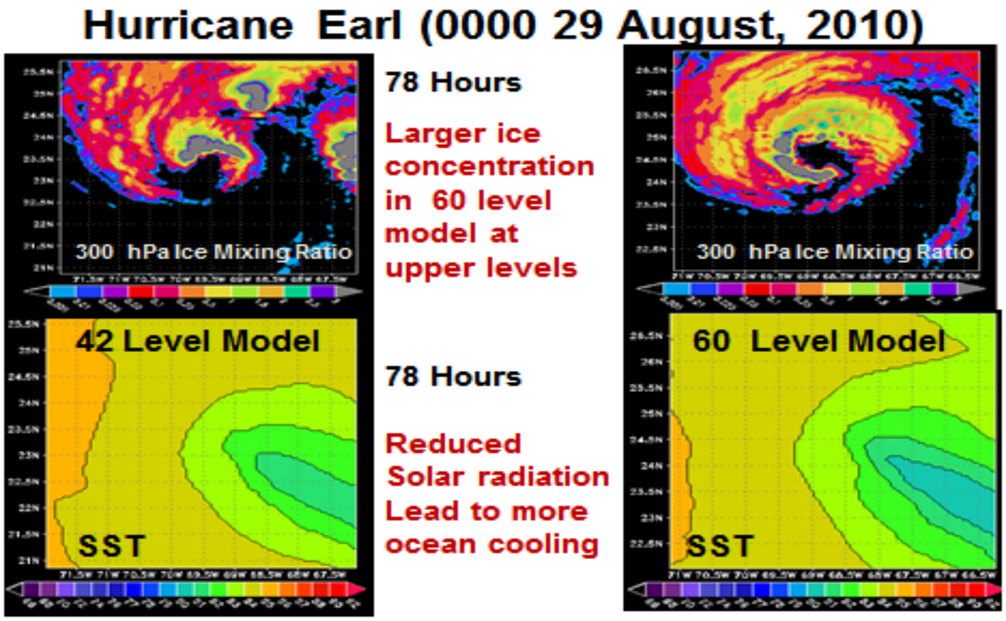


Figure 6. *Horizontal distribution in the innermost nest for the 300 hPa ice mixing ratio (top) and SSTs (bottom) comparing the 42 level model (left) and 60 level model (right) at forecast hour 78 for Hurricane Earl initialization at 0000 29 August, 2010. Both forecasts are run using the new GFS fields.*

A number of likely reasons were found for this excessive negative bias. Analysis indicated that even for storms of comparable intensity, the secondary circulation and upper level outflow was typically weaker with the 60 level model with increased vertical resolution (Fig. 5). This result was consistent with Zhang et.al (2015), who found a weaker secondary circulation and reduced outflow with increased vertical resolution in the hurricane outflow region, for idealized simulations using Hurricane WRF (HWRF). This also negatively impacted the intensification in their simulations. We are planning to evaluate different distributions of vertical sigma levels this summer, to try to reduce this tendency, particularly reducing the number of levels in the outflow region, as suggested by Zhang et al. (2015) and adding more vertical levels in the middle troposphere, where the impact on the storm steering is greatest.

Another source of the increase negative bias in the 60 level model is reduced sea surface temperatures (SST) in the 60 level version of the upgraded model compared to the 42 level model (Fig. 6, bottom). The primary source of this is likely due to decreased amounts of solar radiation reaching the ocean surface possibly related to increased amounts of ice in the upper troposphere (Fig. 6, top) as well as increased humidity and cloudiness in the upper boundary layer (not shown) at around 800 hPa, with the 60 level model. To help remedy this problem, we are planning to evaluate in the 60 level GFDL model, the improved vertical diffusion scheme with enhanced turbulence diffusion in stratocumulus regions that was introduced in 2010 in the GFS, to help to reduce a similar tendency for excessive ocean stratocumulus in the GFS model (Han and Pan, 2011).

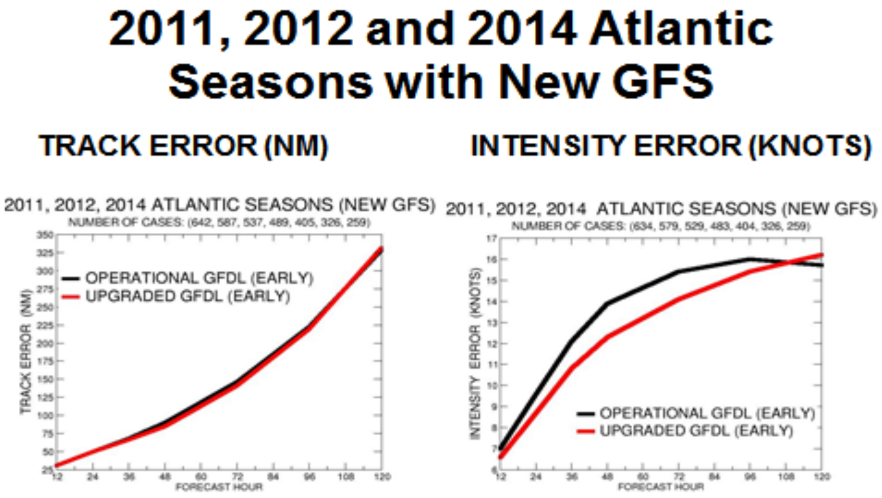


Figure 7. *Average track error (left) and intensity error (right) for storms in the 2011, 2012, and 2014 Atlantic hurricane season, comparing the current operational GFDL model (black) and the 42 level upgraded GFDL model (red). All of the results shown are for the early model interpolated guidance and all forecasts are run off of the new GFS fields.*

Based on these concerns, the decision was made not to upgrade the vertical resolution of the GFDL model into operations in 2015, but to first reduce the negative bias through the strategy outlined above and hopefully implement an improved version of the GFDL model in 2016 with increased vertical resolution. For 2015, a more conservative approach is to upgrade the 42 level model with the other changes proposed that have positively impacted the performance of both versions of the model. Evaluation of the impact of these proposed changes in the 42 level model was made for a slightly more extensive sample size (697 forecasts) for the 2011, 2012 and 2014 Atlantic hurricane seasons as well as 587 cases in the Eastern Pacific. For this larger sample, the impact on track was still mostly neutral in the Atlantic, except at forecast hours 48 and 72, where the reduction in track error was nearly 5% (Fig. 7, left). The impact on intensity was again much more significant (Fig. 7, right), averaging about 10-11% at 1-4 days forecasted lead times.

Evaluation of the upgraded 42 model in the Eastern Pacific showed a mostly neutral impact of track for days 1-3 (Fig. 8, left) but a 10% reduction in track error in the 4-5 day forecast lead time. For intensity, similar to the Atlantic, the intensity error was reduced about 10% for days 1-4 with small positive impact at day 5.

Finally, an additional positive impact of the upgraded model was, a significantly reduced negative intensity bias in both the Atlantic and Eastern Pacific (Fig. 9). This improvement was particularly encouraging in the Eastern Pacific, which had a very large number of intense hurricanes compared to the Atlantic and an excessive negative bias in the currently operational model.

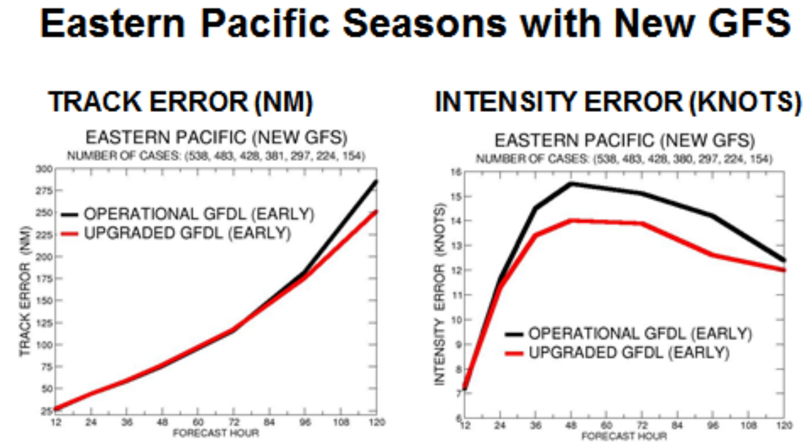


***Figure 8**. Average track error (left) and intensity error (right) for all of the storms in 2014 and select storms from the 2011 and 2012 Eastern Pacific hurricane season, comparing the current operational GFDL model (black) and the 42 level upgraded GFDL model (red). All of the results shown are for the early model interpolated guidance and all forecasts are run off of the new GFS.*

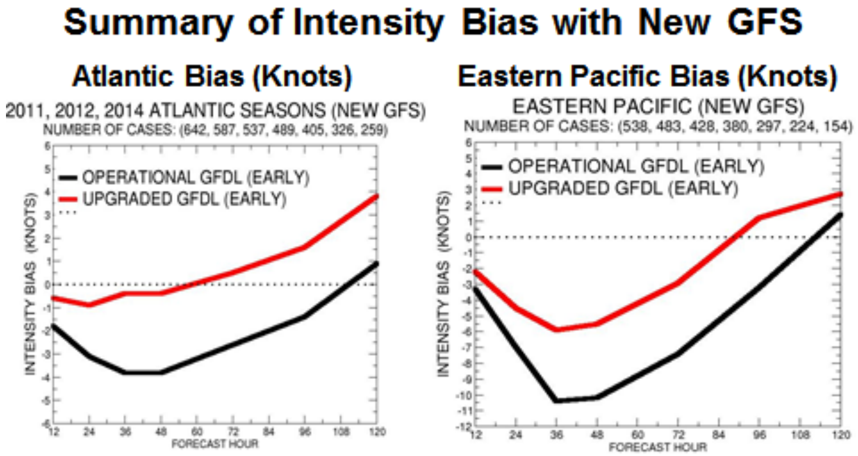


***Figure 9.** Summary of the Early Model Intensity Bias for forecasts made from the current operational GFDL model (black) and the 42 level upgraded GFDL model (red) for forecasts for both the Atlantic (left) and Eastern Pacific (right) basins. All of the results shown are for the early model interpolated guidance and all forecasts are run off of the new GFS.*

2.2 Ocean model upgrades

a) MPIPOM-TC upgrades

The ocean component of GFDL/GFDN system is the MPIPOM-TC model implemented operationally at NCEP in 2014 in the Atlantic basin. In the upgraded operational GFDL/GFDN version MPIPOM-TC replaces the old ocean model, POM, in all ocean basins. In order extend MPIPOM-TC capabilities worldwide, the computational domains have been designed to be relocatable to regions around the world. These regions include the Transatlantic, East Pacific, West Pacific, North Indian, South Indian, Southwest Pacific, Southeast Pacific, and South Atlantic domains (Fig. 10). Domain overlap helps to prevent loss of ocean coupling. To avoid domain-specific code, all worldwide domains are set to the same size: 869 (449) longitudinal (latitudinal) grid points, covering 83.2° (37.5°) of longitude (latitude) and yielding a horizontal grid spacing of ~9 km.

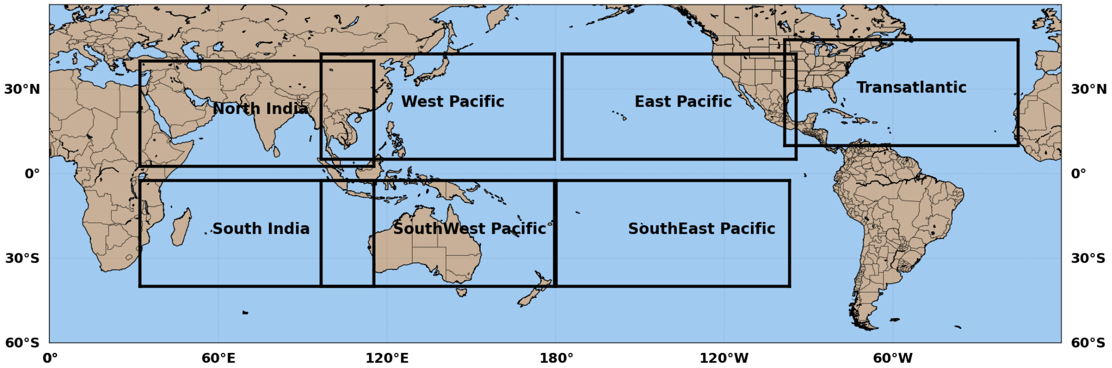


Figure 10. *MPIPOM-TC worldwide ocean domains.*

In the 2014 GFDL model, the initial condition module in the Atlantic Ocean involves feature-based modifications to the U.S. Navy's Generalized Digital Environmental Model (GDEM) monthly temperature (*T*) and salinity (*S*) climatology (Falkovich et al. 2005; Yablonsky and Ginis 2008; Teague et al. 1990), followed by assimilation of a daily GFS SST product. The initial condition module in the eastern North Pacific Ocean uses GDEMv3 (Carnes 2009), assimilated with daily GFS SST. For the upgraded global GFDL/GFDN system the initial condition modules for MPIPOM-TC have been developed using the stand-alone Navy Ocean Data Assimilation (NCODA) daily *T* and *S* fields (Cummings 2005) and versions of the HYbrid Coordinate Ocean Model (HYCOM) that use NCODA (Chassignet et al. 2009).

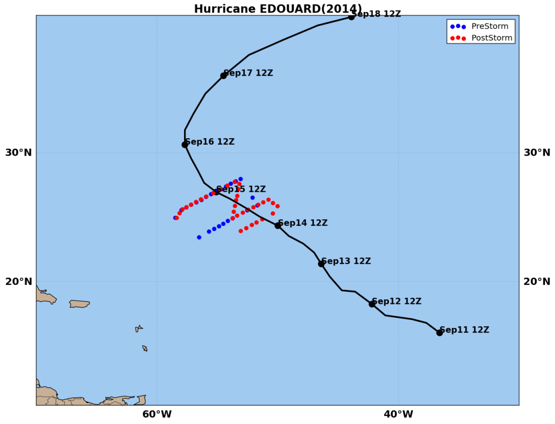


Figure 11. *The Hurricane Edouard track and locations of the AXBTs (blue - September 12; red – September 17, 2014).*

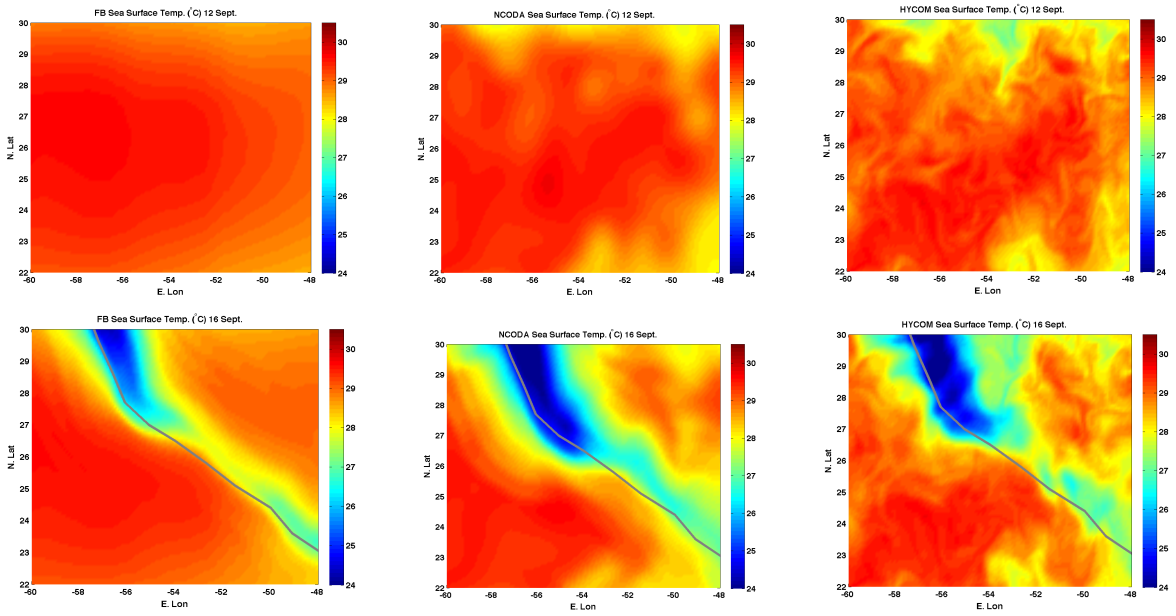


Figure 12. *Top: SST in MPIPOM-TC initialized with feature-based (left), NCODA (middle), HYCOM (right) products on September 12, 2014. Bottom: SST simulated with observed winds based on the NHC tcvitals on September 16, 2014.*

During this reporting period, the flexible MPIPOM ocean initialization options have been tested in the Atlantic and East Pacific domains. In the Atlantic basin, the ocean initial conditions were evaluated for Hurricane Edouard (2014). During the NOAA HRD field program on September 12-17, *in situ* observations were made before, during and after the storm and included temperature profiles from expendable probes (AXBT/AXCTD/AXCP). Fig. 11 shows the track of Edouard and the locations of the *in situ* observations. The pre-storm SSTs on September 12 initialized from the different ocean products indicate surface warm water between 28.5 and 30^{o}C (Fig. 12, top), consistent with satellite-measured SST data (not shown). The feature-based (FB) initialization that uses GFS SST has the mostly uniform temperature distribution in this area, while the HYCOM-based initialization has the largest spatial variability. The simulated SST changes on September 16 indicate notable differences: the FB initialization causes a smaller SST cooling and a narrower cold wake. One of the main reasons for such differences is due to the different representations of the pre-storm upper ocean temperature profiles. Comparison with pre-storm AXBT temperature profiles (Figure 13) indicates quite substantial differences in the SSTs and the mixed layer depths in the different ocean products. Strong SST cooling and deepening of the mixed layer in the wake are seen in both the model and AXBT post-storm temperature profiles (Figure 14). The simulated temperature profiles using different ocean initial conditions lead to significant differences in the ocean response at some locations. This will be the subject of future analysis that will be conducted in collaboration with HRD scientists.

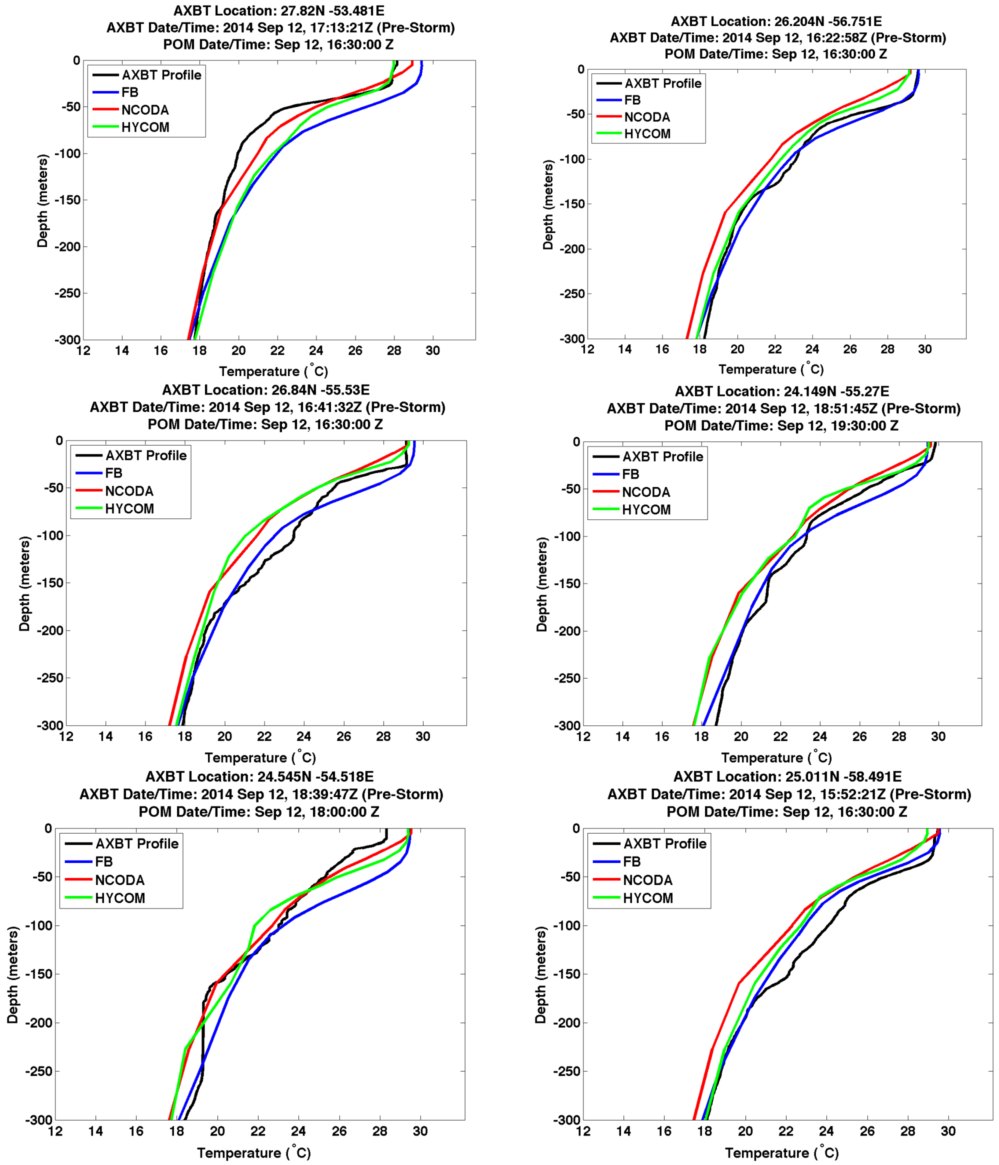
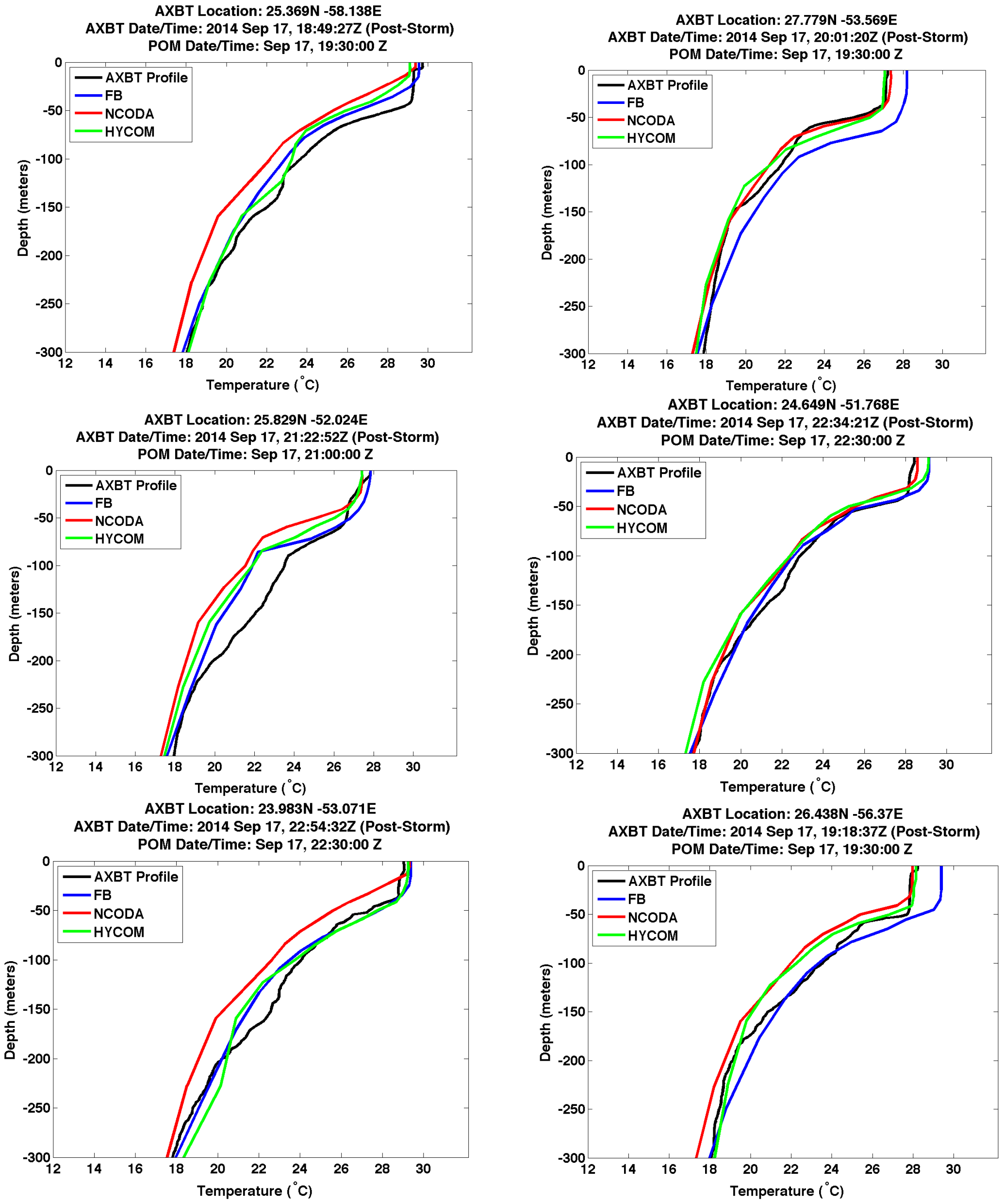


Figure 13. *Comparison of the AXBT and the model temperature profiles on September 12, 2014 at selected locations (black – AXBT, blue – feature-based initialization, red – NCODA initialization, green – HYCOM initialization).*



AXBT Location: 25.369N -58.138E
AXBT Date/Time: 2014 Sep 17, 18:49:27Z (Post-Storm)
POM Date/Time: Sep 17, 19:30:00 Z

AXBT Location: 27.779N -53.569E
AXBT Date/Time: 2014 Sep 17, 20:01:20Z (Post-Storm)
POM Date/Time: Sep 17, 19:30:00 Z

AXBT Location: 25.829N -52.024E
AXBT Date/Time: 2014 Sep 17, 21:22:52Z (Post-Storm)
POM Date/Time: Sep 17, 21:00:00 Z

AXBT Location: 24.649N -51.768E
AXBT Date/Time: 2014 Sep 17, 22:34:21Z (Post-Storm)
POM Date/Time: Sep 17, 22:30:00 Z

AXBT Location: 23.983N -53.071E
AXBT Date/Time: 2014 Sep 17, 22:54:32Z (Post-Storm)
POM Date/Time: Sep 17, 22:30:00 Z

AXBT Location: 26.438N -56.37E
AXBT Date/Time: 2014 Sep 17, 19:18:37Z (Post-Storm)
POM Date/Time: Sep 17, 19:30:00 Z

Figure 14. *The same as Fig. 13, but on September 17, 2014.*

Fig. 15 shows the track and intensity forecasts for Hurricane Edouard initialized on September 12, 00Z using the three different ocean products. It is interesting to note that the track forecast is most accurate with the NCODA ocean initialization, while the intensity prediction is most accurate using the feature-based initialization. We are planning to investigate the impact of different ocean initial conditions on the hurricane forecast skill further on a larger sample size.

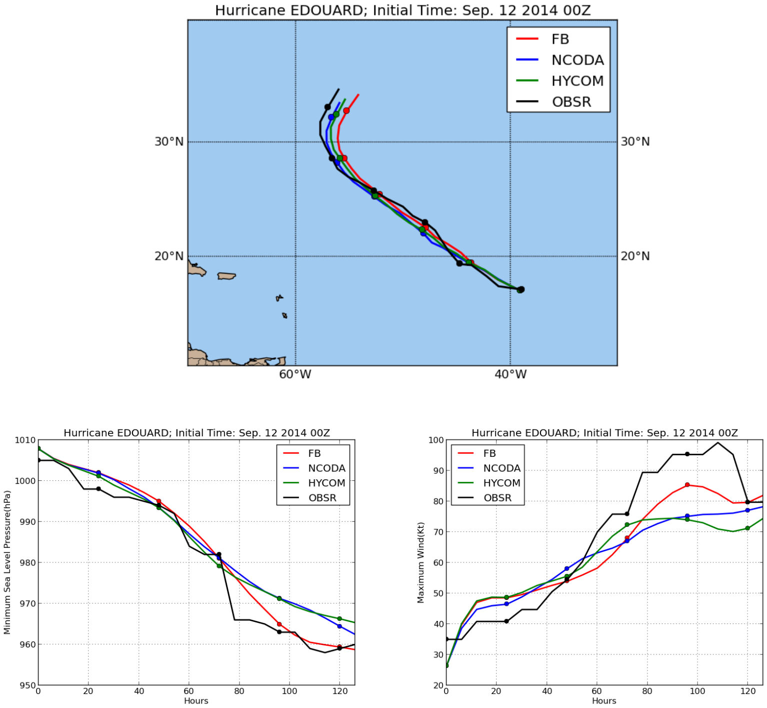


Figure 15. *The GFDL track and intensity forecasts for Hurricane Edouard (Initial time: September 12, 00Z) in which the ocean model is initialized from different ocean products (red – feature-based, blue – NCODA, green – HYCOM).*

b) <u>Implementing the new global MPIPOM-TC in the GFDL ensemble system</u>

The new global MPIPOM-TC ocean scripts have been successfully implemented into the GFDL real-time ensemble forecast system and now world-wide forecasts are available to the JTWC forecasters. An example of real-time forecast for Topical Cyclone Ola in the Southwest Pacific is shown in Fig. 16.

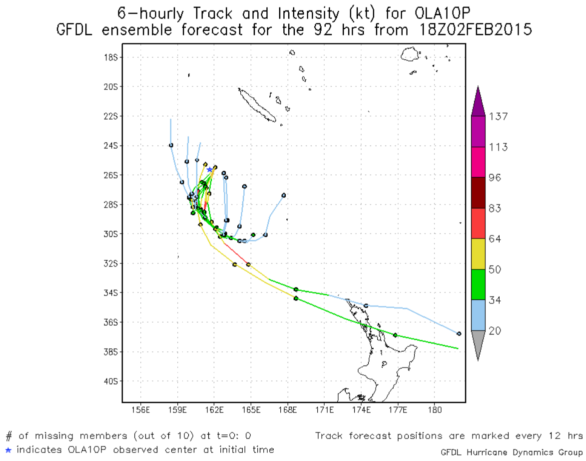


***Figure 16**. GFDL ensemble system real-time forecast of Tropical Cyclone Ola on February 2, 2015.*

c) Improving and evaluating the wave coupling in the GFDL model

We continued improving and evaluating the experimental GFDL/WAVEWATCH III/MPIPOM-TC system. In the three-way air-wave-sea coupled framework, 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). The wave coupling, implemented into the 2014 GFDL version, was tested on a set of selected storms in the Atlantic without the effect of sea spray. The overall impact on the track and intensity is neural for these storms (Fig. 17). Since these tests we done with old version of GFDL, we are in the process of upgrading the atmospheric component with the changes described in section 2.1. We are also making additional changes to the wave-coupling framework. The upgraded system will evaluated and possibly run in near real-time during the 2015 hurricane season.

***Figure 17**. Average track and intensity forecast errors for selected storms during the 2010-2012.Atlantic Hurricane Seasons comparing the 2014 operational GFDL model (black) with the experimental GFDL/WW3/MPIPOM coupled system (red).*

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