Improving the GFDL/URI Coupled Hurricane-Ocean Model for Transition to Operations

Annual Progress Report

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Executive Summary

This is the first annual report for this program. During this time period, significant progress has been made toward our overall project objectives, which are to:

- To improve the ocean component of the GFDL/URI coupled model in the Atlantic basin and implement the ocean coupling into the GFDL model used for operational forecasting in the East Pacific
- To evaluate and transition to operations a new high resolution version of the GFDL/URI coupled model
- To test and implement operationally new air-sea flux parameterizations in the coupled model

The major accomplishment during the first year of this project is the operational implementation the new coupled GFDL ocean model in the Eastern Pacific at NCEP. The model was approved for operations on April 30, 2004 and became operational on May 11, 2004.

The new high-resolution version of the GFDL hurricane has been implemented at NCEP computers and tested for Hurricane Isabel (2003). The high resolution model shows significant improvements in the intensity prediction in this case. Some improvements are also found in the track prediction. The high-resolution system is presently being prepared for near real-time testing during the 2004 hurricane season. If it continues to demonstrate the superior skill it will most likely be implemented to operations in 2005.

A new ocean initialization procedure has been developed for initialization of the Loop Current. It will be tested during the second year of this project and planned for operational implementation in 2005.

We have conducted sensitivity studies to evaluate the sensitivity of the GFDL model hurricane predictions to various surface flux parameterizations. We concluded that the maximum wind speed predictions can be substantially improved if a new wave-wind coupled model recently developed by our group at URI is implemented into the GFDL model. This will be one of the major tasks during the second year of this project.

1 Personnel, Logistics and Facilities

There are three scientists committed to this project: Drs. Isaac Ginis and Biju Thomas at URI and Dr. Alexandr Falkovich at NCEP. In addition, Dr. Il Ju Moon at URI helped with the evaluation of the momentum fluxes in the GFDL hurricane model. Our group works in close collaboration with Morris Bender and Tim Marchok at GFDL and NCEP scientists. The majority of the model development is done on the URI Silicon Graphics (SGI) ORIGIN 2000, 10-processor computer. The more computer-intensive numerical simulations and testing of the operational version of the GFDL/URI coupled model are performed on the GFDL and NCEP supercomputers.

2 Tasks Completed and Work in Progress

a. Operational implementation of ocean coupling in the East Pacific

The GFDL hurricane model has been coupled with a 1-D ocean model in the East Pacific. The 1-D model is derived from the 3-D Princeton Ocean Model used in the GFDL/URI coupled model in the Atlantic. For the East Pacific, the ocean model is configured on a 40 x 40 degree relocatable grid with a horizontal resolution of 1/6 degree and 16 levels in vertical. The center of the grid coincides with the center of the GFDL hurricane model's outer mesh which is determined at the beginning of each forecast. The monthly Levitus climatology is used to specify initial temperature and salinity fields. An illustration of this system for Hurricane Elida (2003) is shown in Fig. 1. Because of the shallow mixed layer in some regions of the Eastern Pacific significant cooling of the ocean surface can be generated by a hurricane (Fig. 1, left). As a result, the hurricane intensity can be affected by the ocean coupling (Fig. 2, right).

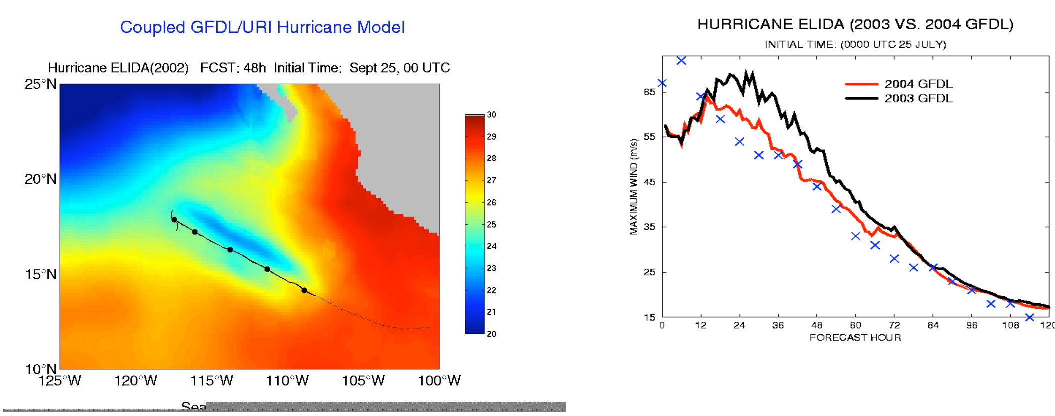

Fig. 1 Sea surface temperature after Hurricane Elida passage (left) and the intensity forecasts made by the 2003 GFDL operational (uncoupled) model and the 2004 GFDL coupled model (Initial time 00 Z July 25, 2003).

The final testing of the 2004 version of the GFDL forecast system for the East Pacific was made in April. 60 cases from the 2002 and 2003 East Pacific season were selected after consultation with Dr. Richard Pasch, the TPC contact person for this JHT project. The improvement in both the track and intensity prediction was significant. The average track error at 3, 4 and 5 days was reduced by about 10%. The average decrease in the intensity error was about 17%. The model shows skillful forecasts relative to SHIFOR at all time levels beyond 12h (Fig. 2). We hope the new operational GFDL coupled model will provide useful intensity guidance for forecasters at TPC in the upcoming hurricane season in the East Pacific.

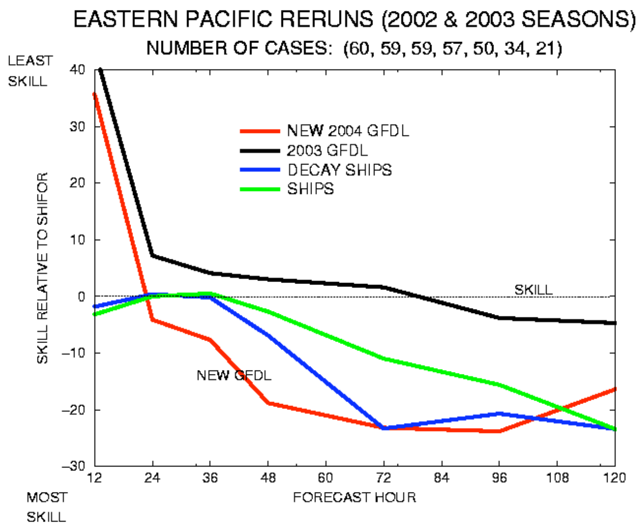

Fig. 2 Summary of the new coupled GFDL model in the East Pacific based on 60 cases in 2002 and 2003 hurricane seasons.

b. Development of the high resolution GFDL hurricane model

One of the limitations of the present GFDL hurricane model has been its relatively coarse horizontal resolution in the hurricane core region most likely contributing to the model's limited hurricane intensity forecast skill. During the fist year of the project we developed a new fully coupled, three-nest high resolution version of the GFDL/URI model. In the new model, the highest resolution in the movable innermost mesh is 1/12 degree. Although forecast using this high-resolution model are now only feasible in research mode, they could be operationally feasible in 2005 with the planned computer upgrade at NCEP in the fall of 2004.

The operational GFDL model domain consists of doubly nested meshes. The coarse outer mesh of 1/2 degree resolution remains stationary during model integration while inner mesh of resolution 1/6 degree follows the forecast storm center. Even though a coarse resolution is fairly enough to capture the outer region of the storm and its environment, a very fine resolution is required to simulate inner core region of the hurricane. The ~18km resolution of the inner mesh of operational GFDL model is certainly not enough to resolve the sub-mesoscale motion in hurricane core region. To better resolve the fine eye-wall structure of hurricane we additionally introduced a finer third mesh inside the second mesh of GFDL operational model (Fig. 3). This third mesh has resolution of 1/12 degree (~9 km). In this high resolution model (GFD3), the second and third meshes are movable and follow the center of the storm. GFD3 has 42 vertical levels and uses same physical parameterization as in GFDL operational model. This includes simplified Arakawa-Schubert (SAS) cumulus parameterization and non-local boundary layer scheme. The ocean component of GFD3 is a high-resolution version of Princeton Ocean Model.

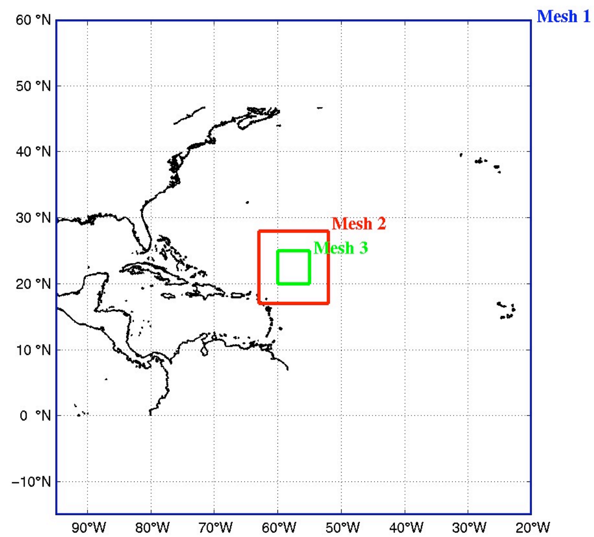

Fig. 3 The configuration of the triply nested mesh structure in the high resolution GFDL model. The outer most coarse mesh, Mesh 1 (blue box), has resolution of _ degree. The medium mesh, Mesh 2 (red box), has 1/6 degree resolution. The resolution of inner fine mesh, Mesh 3 (green box), is 1/12 degree.

We conducted twenty four 78 hour forecasts with GFD3 that covered the whole life cycle of Hurricane Isabel (2003). Several sets of 126 hour forecasts were also made for Isabel. Hurricane Isabel was an intense storm that reached category 5 in the central Atlantic, well before it made landfall in North Carolina on 18 September 2003 during the heart of the Atlantic hurricane season. This made Isabel an interesting case for testing high resolution intensity prediction with this version of the GFDL model.

Some results of Isabel simulations are illustrated in Fig. 4. The high resolution GFDL model shows significant improvements in the intensity prediction in this case. This is primarily due to improved simulation of the storm core region during the time when Isabel was a major hurricane (Fig. 5). Some improvements are also found in the track prediction.

We plan to continue testing the high resolution GFDL model for more cases in the 2003 and 2002 hurricane seasons. We are also going to run the model in near-time during the 2004 hurricane season and compare the results with the present operation GFDL model.

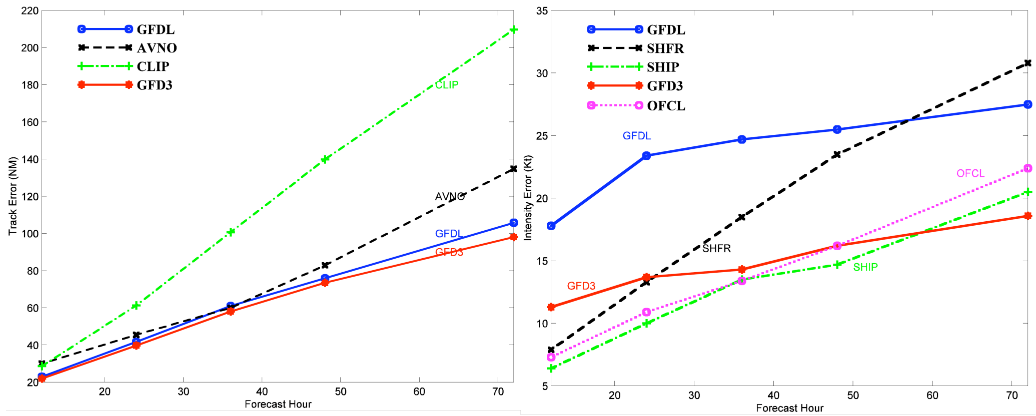

Fig. 4 Summary of average track (left) and intensity errors (right) for 24 cases of Hurricane Isabel for the operational GFDL model, GFS model, CLIPER, SHIP, official forecasts and the high resolution GFDL model.

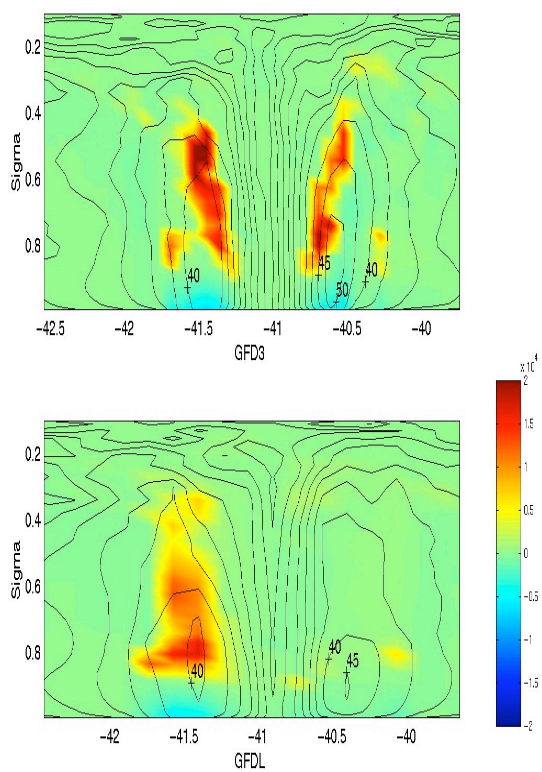

Fig. 5 (Upper) longitude sigma cross section of wind speed (contours) and total heating (shading) for GFDL high resolution model for Isabel forecast at t=36 hours beginning at the 0000 UTC 07 Sept. (Lower) Same as upper but for GFDL operational model.

c. Improving the ocean initialization in the GFDL hurricane model

We have developed a new data ocean assimilation and initialization procedure to improve simulation of the Loop Current (LC) in the GFDL/URI operational coupled hurricane prediction system. This procedure is based on feature modeling and involves cross-frontal "sharpening" of the background temperature and salinity fields according to data obtained in specialized field experiments in the GS. An example of this procedure is presented in the semi-annual report.

The new initialization procedure has been implemented into the GFDL coupled system is presently being tested for past hurricanes in the Atlantic basin. Also, we are going to test it during the 2004 hurricane season. It is planned for operational implementation in 2005.

d. Investigation of the momentum flux under hurricane conditions

As we have illustrated in our semi-annual report, the GFDL model shows important sensitivity to the parameterization of the momentum fluxes at high wind speeds. Therefore, we hope that the GFDL model intensity predictions can be significantly affected by improved air-sea flux parameterizations. In strong winds, typical under hurricane conditions, momentum exchange at the sea surface should be described by a sea-state-dependent drag coefficient. However, presently the GFDL hurricane model, as most atmospheric models do, utilizes the bulk parameterization, i.e., the boundary layer parameterization based on the Monin-Obukhov similarity theory with the behavior of the drag coefficient ($C_d = u_*^2/U_{10}^2$) based on extrapolations from field measurements in much weaker winds. These extrapolations describe an increase in C_d with wind speed. Recent theoretical, laboratory and observational studies suggest that the C_d levels off or even decrease as the wind speed increases above hurricane force.

Using a new coupled Wave-Wind (CWW) model developed by our group recently (Moon et al. 2004a) we investigated the behavior of the momentum fluxes under hurricane wind fields. The CWW model was applied for idealized hurricanes with various forward speeds: stationary, slow-moving (2.5 m/s), typical-speed (5.0 m/s), fast-moving (10 m/s) hurricanes (Moon et al., 2004b). In these experiments, waves to the right and front of the hurricane track become trapped as the hurricane translation speed becomes faster and waves are exposed to prolonged forcing from the wind. As a result, higher, longer and more developed waves (i.e., higher wave ages) are formed to the right and front of the track and yield higher drag coefficients, while lower, shorter and younger waves (i.e., lower wave ages) to the rear and left yield lower drag coefficients (see Fig 6.).

Fig. 6. Wave fields (left panel) simulated by the WW3 for a northward fast-moving hurricane. The arrow direction indicates the direction of dominant waves and the arrow length is proportional to the mean wavelength. Contours are drawn for the significant wave height. Wave age, c_{pi}/u_* (central panel) is determined from the peak input frequency f_{pi}, which is defined as the peak frequency of the wind sea part of the spectrum. The Charnock coefficient z_{ch} (right penal) is calculated using the CWW model. Dashed lines are radii of the maximum wind speeds.

Finally, the CWW model has been applied to 10 hurricanes in the Atlantic basin during 1998-2003. Fig. 5 shows the tracks, maximum wind speed, and translation speeds of the storms used for these simulations. The upper and lower bounds of C_d (Fig. 8), which are estimated from the C_d scatterplot for these hurricanes as a function of wind speed, show leveling-off and even decrease of C_d at high winds being consistent with the recent observations of Powell et al. (2003). These results thus clearly show that the dependence of the C_d (and z_{ch}) on wave age at high wind speeds is completely different from that at weak wind speeds and that the C_d varies significantly depending on the relative position from the storm center.

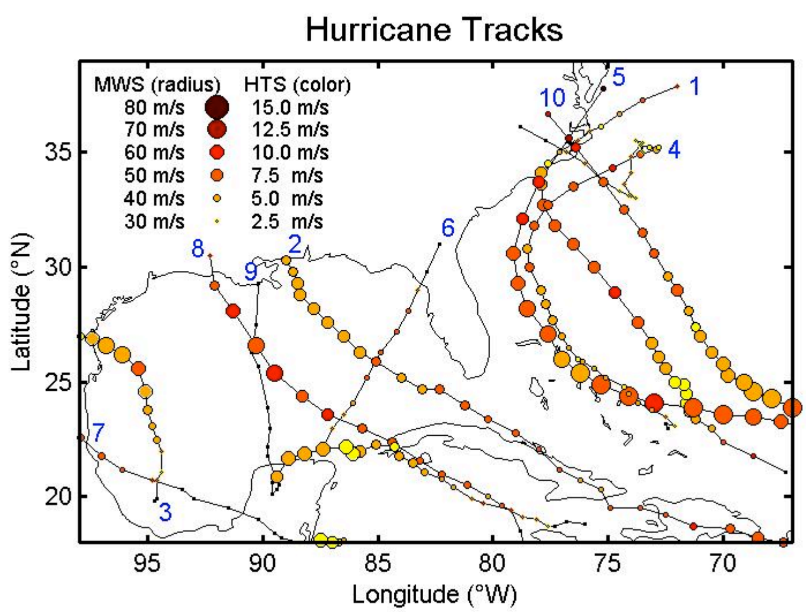

Fig. 7 The hurricanes used in our simulations with the coupled wave-wind model.

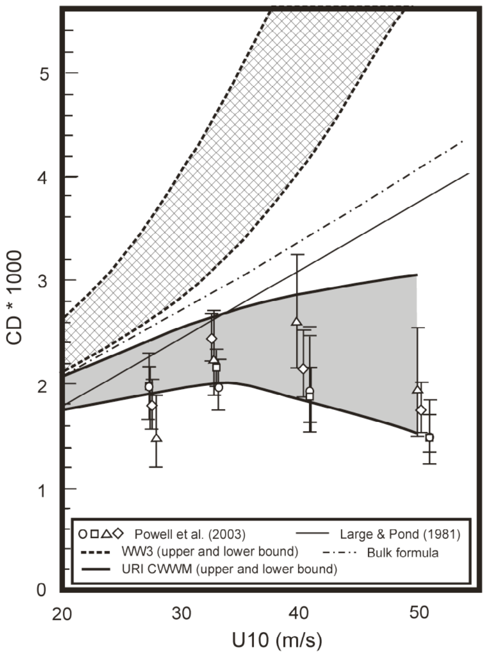

Figure 8. Comparison of drag coefficient (C_d) between various observation-based values, formulas, and model outputs as a function of U_{10}. Symbols represent observations from GPS sonde wind profiles (Powell et al. 2003) above hurricane forces. Vertical bars represent 95% confidence limits. Solid line is an extrapolation of the Large and Pond (1981) formula. Dash-dot line is the Bulk formula used in GFDL model. Shaded and hatched areas represent ranges between upper and lower bound of C_d obtained by the coupled wave-wind model and internal estimation of NCEP WAVEWATCH model for hurricane Bonnie in 1988, respectively. Both observations and ourI model results show leveling–off of the drag coefficient as the wind speed increases.

3 Future Plans

During the second year of this project we plan to continue the development and testing of the high resolution GFDL model coupled with the improved ocean model. The coupled model will be run in near real-time mode for most of the storms in the Atlantic and Eastern Pacific basins during the 2004 hurricane season. If the tests are successful the new model can be implemented to operations at NCEP in 2005.

Another major task will be the implementation of the new URI wave-wind coupled model into the GFDL hurricane model and the investigation of its effect on hurricane track and intensity forecasting for both idealized and real cases.

References

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