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Hurricane Model Development at GFDL: A Collaborative Success Story From a Historical Perspective

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HURRICANE MODEL DEVELOPMENT AT GFDL

A Collaborative Success Story from a Historical Perspective

Morris A. Bender, Timothy Marchok, Robert E. Tuleya,
Isaac Ginis, Vijay Tallapragada, and Stephen J. Lord

Successful collaborations played a pivotal role in transitioning the GFDL hurricane research model into a long-standing state-of-the-art operational system that provided critical guidance for over 20 years.

The Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model was retired from operations in the spring of 2017 by both the National Weather Service (NWS) and the U.S. Navy after providing operational guidance for hurricane prediction for over 20 years. A team of GFDL scientists supported and improved the model during its two decades of operational use by extensive collaborations with other scientists at GFDL, the National Centers for Environmental Prediction (NCEP) Environmental Modeling Center (EMC),[1] the National Hurricane Center (NHC), the Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC), as well as with scientists at the University of Rhode Island (URI), Old Dominion University (ODU), and the National Oceanic and Atmospheric Administration (NOAA) Hurricane Research Division (HRD). For example, the multiyear collaboration with URI resulted in development of the world's first fully coupled atmosphere–ocean hurricane model, which became operational by the NWS and the U.S. Navy in 2001 and 2006, respectively.

Today, increased collaboration is being recognized as an essential ingredient to further advance numerical weather prediction (NWP), from regional

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The abstract for this article can be found in this issue, following the table of contents.
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[1] In 1995, the National Meteorological Center (NMC) was renamed the National Centers for Environmental Prediction (NCEP) and its Development Division was renamed the Environmental Modeling Center (EMC).

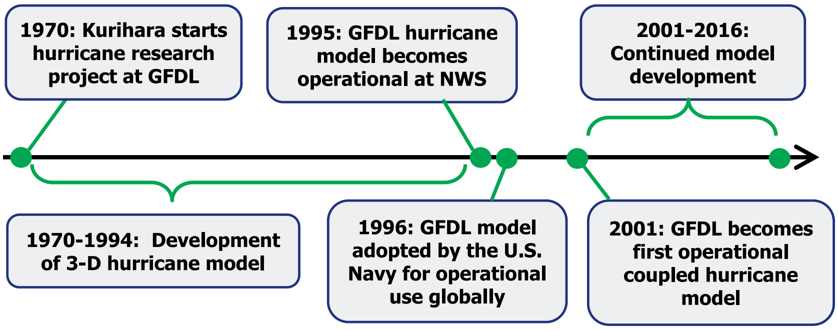


Fig. 1. Timeline detailing the historical overview of the GFDL hurricane model starting from its inception in 1970 as a research model, until its retirement in the spring of 2017 as an official operational hurricane system of the NWS and the U.S. Navy.

to global modeling. To make significant advancements in the operational forecasts, it is widely recognized that better collaboration will be required to draw from the expertise of academia as well as the expertise found in federal government agencies. Each of the authors of this paper played an important role in the development of the GFDL forecast system, in its unique transition from research into operations, and in the successful transition of key components of the GFDL hurricane model to the next-generation Hurricane Weather Research and Forecasting Model (HWRF) system. Thus, their historical perspective is a story that needs to be told.

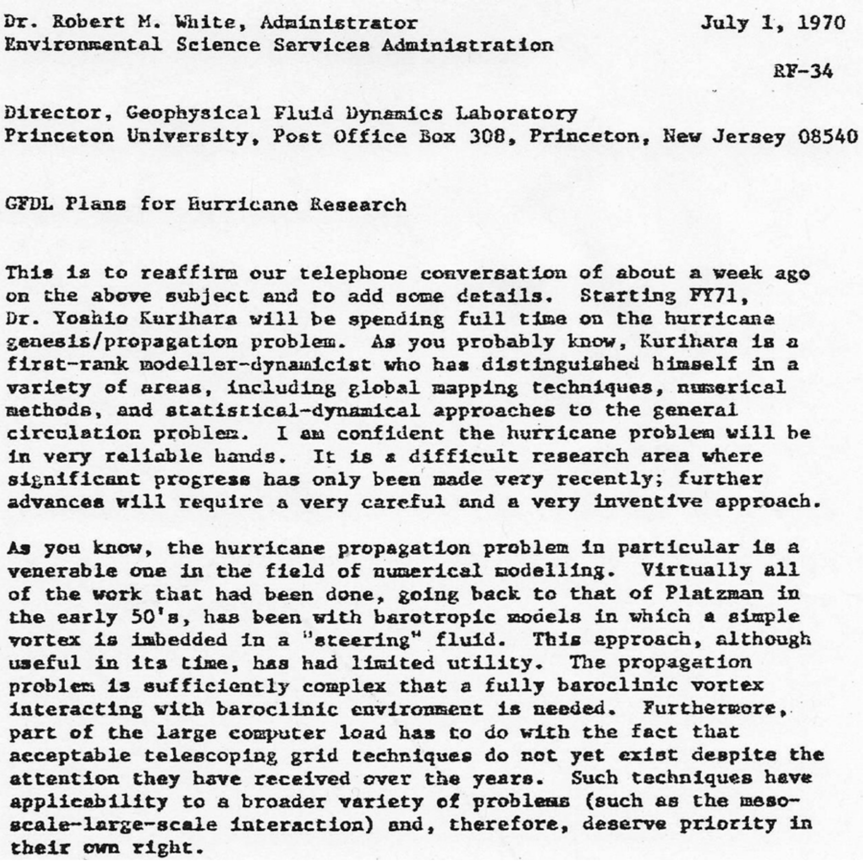
The purpose of the article is to recount how scientific collaboration between federal agencies and the academic community played a pivotal role in the transition of the GFDL hurricane model, initially developed for basic research, into a vital operational product and the later transition of this technology to the development and improvements of the operational HWRF. During the past decade, the synergistic efforts of these scientists aided in the advancement of both models, which led to significantly improved operational hurricane forecasts for the nation. It is hoped that the experiences of the authors will help foster future collaborations and serve as a framework for how focused collaboration can ultimately benefit the nation with better numerical weather prediction guidance.

DEVELOPMENT OF THE GFDL HURRICANE MODEL AND ITS PATHWAY TO OPERATIONS. The hurricane project at GFDL was established in 1970 by its director, Joseph Smagorinsky (Fig. 1). With the support of Robert White (Fig. 2), the administrator of the Environmental Science Services Administration (ESSA; the precursor of NOAA), Dr. Yoshio Kurihara was designated as the head of the new GFDL hurricane project. The purpose of the project was to perform basic hurricane research using numerical modeling. By 1973, the first experiments were made with a new three-dimensional hurricane model developed by the GFDL group (Kurihara and Tuleya 1974). A movable mesh framework was implemented by 1976 (Kurihara and Bender 1980), which enabled pioneering research to be conducted (Fig. 3) in such diverse topics as hurricane genesis (Tuleya and Kurihara 1981; Kurihara and Tuleya 1981), hurricane structure (Kurihara and Bender 1982), hurricane energetics (Bender and Kurihara 1983), mechanisms for hurricane decay over land (Tuleya and Kurihara 1978; Tuleya et al. 1984), impacts of topography (Bender et al. 1985, 1987), and impacts of hurricane–ocean interaction on hurricane intensity (Bender et al. 1993). Although these studies used an idealized numerical framework (e.g., hurricane embedded in a simple basic flow), they demonstrated the capability of the model to produce realistic hurricane structure and thus suggested the potential of improving hurricane prediction with a comprehensive three-dimensional model. The hurricane model that was made operational at the NWS in 1995 and at FNMOC in 1996 was an outgrowth of this research model.

As the reputation of the model was augmented via publication of research results in peer-reviewed literature and presentations at scientific conferences, Yoshio Kurihara was approached in 1985 by the NMC Director Bill Bonner about establishing a collaborative effort between GFDL and NMC to transition the hurricane model from a research tool developed within the research arm of NOAA into an operational modeling system for the NWS, to be used by agencies within the operational side of NOAA. As stated in the memo from GFDL Director Jerry Mahlman dated July 1986 (Fig. 4), it was recognized that a multiyear effort by GFDL scientists would be required to develop a robust system that could meet the rigorous requirements of NWS operations. However, this was a commitment that GFDL and its leadership accepted "with enthusiasm and resolve."

With the encouragement and support of the GFDL director, the hurricane group began to address a number of important improvements required to convert the research model into a real-time forecast system. This effort began in the late 1980s (Fig. 4) with development of a new lateral boundary condition specification method (Kurihara et al. 1989). A land surface temperature prediction scheme with a full radiation package was also introduced into the model (Tuleya 1994). Most importantly, a unique methodology was formulated in which the vortex was filtered from the global analysis and replaced with a vortex spun up from an axisymmetric version of the same hurricane prediction model (Kurihara et al. 1993, 1995).

The new GFDL hurricane prediction system was first successfully tested on a limited set of cases from the 1991 Atlantic hurricane season using initial conditions and forecast fields from the NWS Aviation (AVN) global model, which were provided by NMC personnel. Based on the promising performance from this limited set of cases compared to the operational guidance, the NMC Director Ron McPherson and the Director and Deputy Director Eugenia Kalnay and Stephen Lord of the NMC Development Division encouraged the GFDL group to evaluate their modeling system in near–real time for the 1992 Atlantic season, which was successful for a limited number of Atlantic storms (Fig. 4). With the assistance of NMC personnel, the initial conditions and forecast



Dr. Robert M. White, Administrator
Environmental Science Services Administration

July 1, 1970

RF-34

Director, Geophysical Fluid Dynamics Laboratory
Princeton University, Post Office Box 308, Princeton, New Jersey 08540

GFDL Plans for Hurricane Research

This is to reaffirm our telephone conversation of about a week ago on the above subject and to add some details. Starting FY71, Dr. Yoshio Kurihara will be spending full time on the hurricane genesis/propagation problem. As you probably know, Kurihara is a first-rank modeller-dynamicist who has distinguished himself in a variety of areas, including global mapping techniques, numerical methods, and statistical-dynamical approaches to the general circulation problem. I am confident the hurricane problem will be in very reliable hands. It is a difficult research area where significant progress has only been made very recently; further advances will require a very careful and a very inventive approach.

As you know, the hurricane propagation problem in particular is a venerable one in the field of numerical modelling. Virtually all of the work that had been done, going back to that of Platzman in the early 50's, has been with barotropic models in which a simple vortex is imbedded in a "steering" fluid. This approach, although useful in its time, has had limited utility. The propagation problem is sufficiently complex that a fully baroclinic vortex interacting with baroclinic environment is needed. Furthermore, part of the large computer load has to do with the fact that acceptable telescoping grid techniques do not yet exist despite the attention they have received over the years. Such techniques have applicability to a broader variety of problems (such as the meso-scale–large-scale interaction) and, therefore, deserve priority in their own right.

Fig. 2. Part of the 1970 memo from Dr. Joseph Smagorinsky, Director of GFDL, to ESSA (pre-NOAA) Administrator Dr. Robert White detailing plans to initiate a hurricane project at GFDL lead by Dr. Yoshio Kurihara.

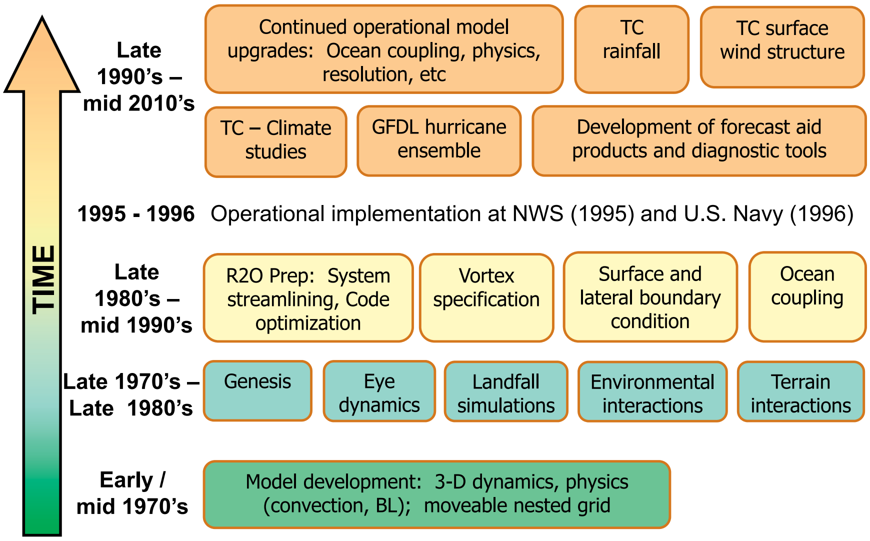


Fig. 3. Schematic detailing the history of the GFDL hurricane model, starting from some of the basic research topics that were studied by the GFDL hurricane modeling team at GFDL, the research-to-operations (R2O) period leading to operational implementation, and finally outlining an extensive period of operational model upgrades with continued research advancements.

fields from the AVN global model were sent electronically to GFDL. A 72-h forecast run on the GFDL Cray Y-MP8 supercomputer took approximately 6 h of wall clock time, using one CPU.

The first near-real-time forecast was the 0000 UTC 18 August 1992 cycle of Hurricane Andrew, which was a severe Cape Verde hurricane that made landfall six days later in south Florida as a category 5 hurricane. Of particular note, however, was the accurate prediction made of Andrew's second landfall on the central Louisiana coast late on the evening of 25 August. The GFDL model accurately predicted that the inner core of Andrew would pass well to the west of New Orleans (Fig. 5, left), although this guidance was not available to the NHC until 18 h after the initial synoptic time. Nevertheless, the forecast arrived in time to give NHC forecasters some confidence that New Orleans may be spared a direct hit from the hurricane based on the high respect they had for the GFDL model despite the very limited sample size of cases (R. Pasch 2019, personal communication). Another noteworthy forecast was the GFDL model's correct prediction of the recurvature of Hurricane Emily (1993) away from the U.S. East Coast (Fig. 5, right). In contrast, the operational guidance at the time [e.g., the AVN and the operational quasi-Lagrangian (QLM); Mathur 1991] forecasted a landfall in the Carolinas.

Based on these encouraging forecasts, the NWS agreed to run the GFDL prediction system in 1994 on their new Cray C90

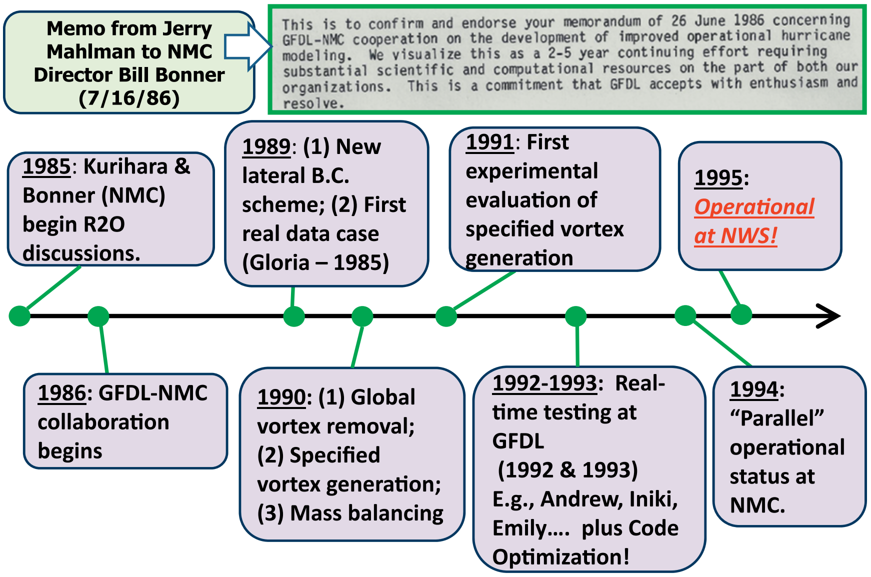

This is to confirm and endorse your memorandum of 26 June 1986 concerning GFDL-NMC cooperation on the development of improved operational hurricane modeling. We visualize this as a 2-5 year continuing effort requiring substantial scientific and computational resources on the part of both our organizations. This is a commitment that GFDL accepts with enthusiasm and resolve.

Fig. 4. Timeline detailing the model improvements undertaken at GFDL to transition the GFDL hurricane model from research to operations (R2O).

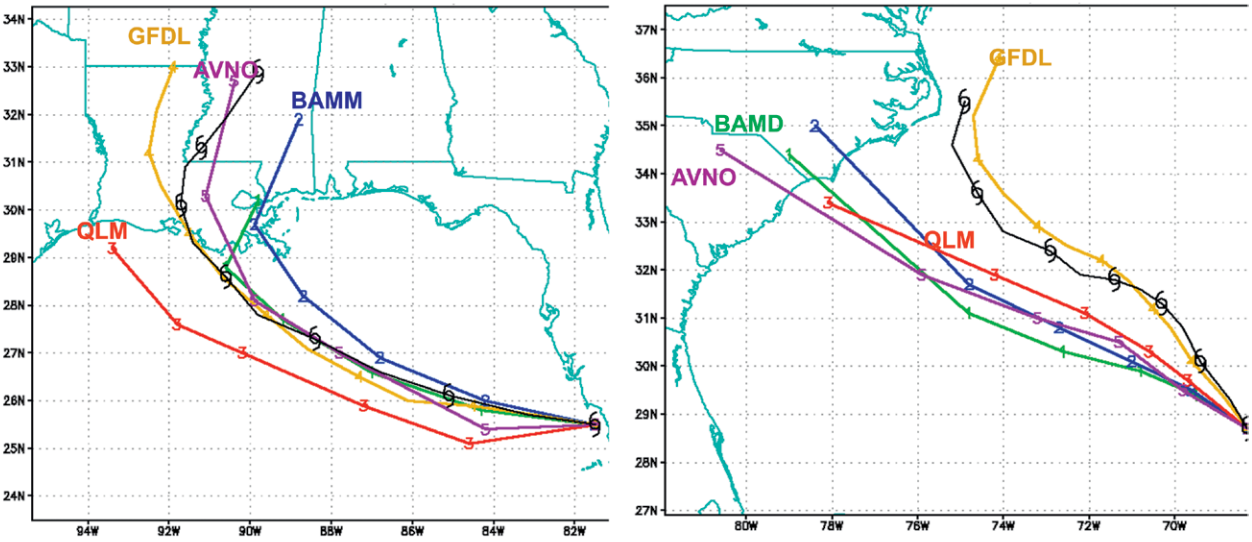


Fig. 5. The 72-h track predictions from the experimental GFDL hurricane model (yellow) compared to some of the available operational guidance including the QLM (red), the AVN (purple), and BAM (Beta-Advection Model) Medium (blue) for (left) Hurricane Andrew, initial time of 1200 UTC 24 Aug 1992, and (right) Hurricane Emily, initial time of 0000 UTC 29 Aug 1993.

supercomputer facility with the condition that the model had to be optimized to run on multiple processors and fit within the 20-min window allocated for the operational hurricane model (Kurihara et al. 1998). Optimization and parallelization of the model were achieved at GFDL within five months, which reduced the wall clock run time from 6 h to slightly less than 20 min using 14 CPUs on the NWS Cray C90. By spring of 1994 the entire GFDL forecast system was given to NMC's Automation Division. They worked closely with GFDL personnel to enable the new modeling system to run in parallel with the operational QLM hurricane model for the entire 1994 Atlantic and eastern North Pacific hurricane seasons (Fig. 6). The GFDL model performed very well in both basins, with average 72-h forecast errors of only 298 and 226 n mi (1 n mi = 1.852 km) for the Atlantic and eastern North Pacific, compared to 570 and 276 n mi for the QLM. Based on this excellent performance the GFDL hurricane forecast system was officially made operational in the spring of 1995, and replaced the QLM as the NWS primary operational hurricane forecast model.

Another collaboration was initiated in 1996 between GFDL and the U.S. Navy to port the GFDL operational forecast system to the FNMOC computer in order to provide operational guidance for the U.S. Navy and Air Force Joint Typhoon Warning Center (JTWC). The GFDL hurricane group worked extensively with Navy personnel to transition the identical hurricane model and initialization code to the FNMOC supercomputer. The model, designated GFDN, became an operational product of the U.S. Navy in 1996 for tropical cyclones in the western North Pacific. After very good performance of GFDN was demonstrated in the western North Pacific, extensive collaboration with GFDL scientists allowed the Navy to expand GFDN forecasts into all of the JTWC areas of responsibility (e.g., north Indian Ocean and the entire Southern Hemisphere) as well as the Atlantic and eastern North Pacific when computer resources were available. Throughout the next 20 years, personnel at GFDL as well as URI continued to collaborate with FNMOC personnel to provide support for GFDN. Funding provided by NOAA's Joint Hurricane Testbed (JHT; Rappaport et al. 2012) allowed periodic upgrades to the GFDL forecast system at the NWS to also be implemented in the GFDN in order to keep the two modeling systems as similar as possible.

Up to the time of initial implementation, the GFDL hurricane model was developed and maintained internally by GFDL scientists with advisory support by NCEP and FNMOC personnel. However, throughout the next two decades these collaborations with other federal government agencies, the U.S. military (i.e., the Navy), and academia increased (Fig. 7). For example, the GFDL hurricane group and NCEP worked together to test and transition the GFDL filtering technique as part of the vortex relocation system in the NWS Global Data Assimilation System (GDAS). This innovative approach was made opera-

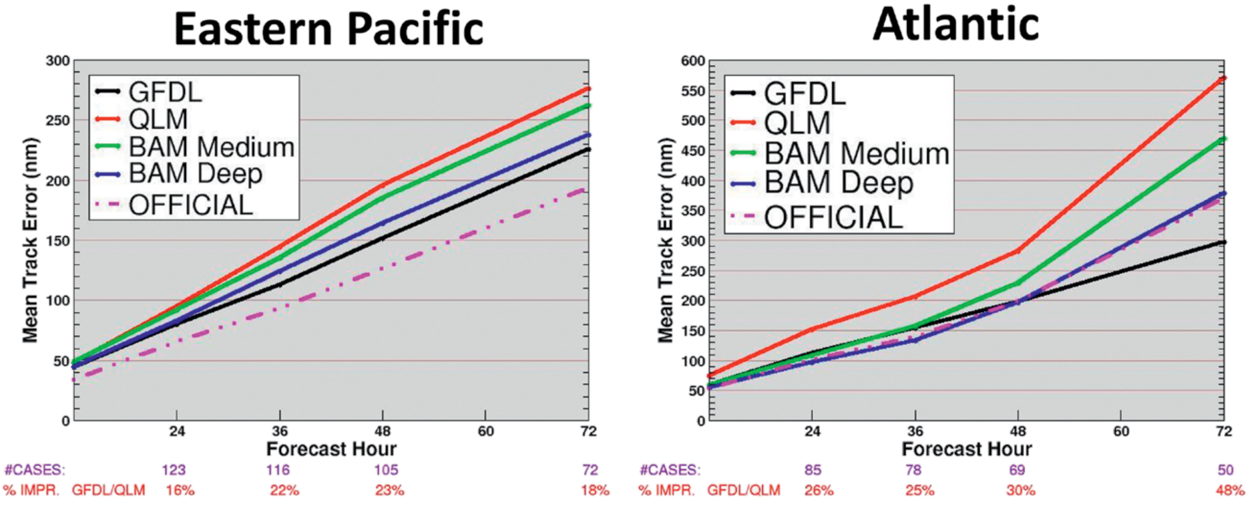


Fig. 6. Average track errors for the test version of the GFDL hurricane model (black) compared to the operational QLM (red), the BAM Medium (green), the BAM Deep (blue), and the NHC official forecast (magenta, dot–dashed) for the 1994 (left) eastern North Pacific and (right) Atlantic hurricane seasons. The version of the QLM and GFDL models plotted are time interpolated (early model guidance). The number of cases for each forecast lead time and the percent improvement of the GFDL model compared to the QLM are shown at the bottom.

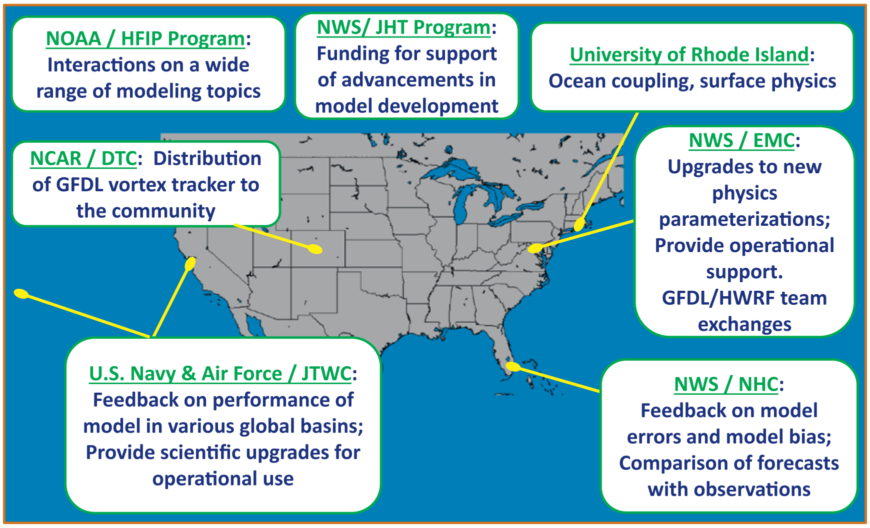


Fig. 7. Schematic detailing the collaborations that were established between the GFDL hurricane group and other agencies within the U.S. government and academia.

tional in the GDAS system beginning in 2000 (Liu et al. 2002) and remained in the operational Global Forecast System (GFS) until May, 2019. From the beginning, collaborative feedback from forecasters at the NHC and the JTWC aided the GFDL model developers in reducing biases in the model forecasts, which improved the model performance through subsequent upgrades. After the HWRF became operational in 2007, these types of exchanges continued with HWRF developers and played an important role in the improvements in the HWRF performance over the next decade.

Early collaboration between the GFDL hurricane group and URI Graduate School of Oceanography was an outgrowth of basic research at GFDL in the early 1990s. Dr. Isaac Ginis, while a visiting scientist at GFDL, led an effort to couple the GFDL movable nested hurricane model with a high-resolution (1/6°) multilevel primitive equation ocean model. As a result, Bender et al. (1993) demonstrated that sea surface cooling in response to tropical cyclone forcing can significantly impact storm intensity, particularly for slower-moving tropical cyclones. After moving to URI, Prof. Ginis and his research group continued to collaborate with GFDL, examined real-data cases from the 1995–98 seasons (Bender and Ginis 2000), and demonstrated that intensity predictions by the operational GFDL model could be significantly improved by including this tropical cyclone–ocean interaction in the operational model. Funding provided by JHT and the NWS's Collaborative Science, Technology, and Applied Research (CSTAR) program resulted in operational implementation in 2001 of the world's first fully coupled atmosphere–ocean hurricane model by the NWS. Through additional funding provided to URI by the National Science Foundation (NSF), Office of Naval Research (ONR), and NOAA, the atmosphere–ocean coupled system was continually improved in subsequent upgrades: for example, advancements in the ocean model initialization (Yablonsky and Ginis 2008), improved vertical mixing schemes, higher vertical and horizontal resolution, and implementation of the new Message Passing Interface Princeton Ocean Model (MPI-POM; Yablonsky et al. 2015). These advancements were ultimately transitioned to the HWRF when it became operational in 2007, as we discuss in the next section.

In an effort to make the GFDL hurricane model physics more compatible with the NCEP GFS, major upgrades to the GFDL hurricane model physics were made in 2003 and 2006 (Bender et al. 2007). Aided by scientists at EMC and with JHT funding, the Kurihara convective parameterization was replaced by the GFS simplified Arakawa–Schubert scheme (SAS), and its nonlocal boundary layer parameterization (Hong and Pan 1996). These upgrades contributed to significantly improved hurricane track performance in 2003 (Fig. 8), with about a 10% reduction in 48- and 72-h track errors compared to the NCEP global model. A second major upgrade to the GFDL model physics was made in 2006 with the replacement of the large-scale condensation package with the Ferrier (1994) microphysics scheme. Further refinements to the new microphysics package in the GFDL model were tested in collaboration with NWS scientists along with a new parameterization of the surface physics developed through the collaboration with URI (Moon et al. 2007; Bender et al. 2007). These two upgrades significantly contributed to the steady reduction in the intensity forecast errors in the GFDL hurricane model over the next 10 years (Fig. 8) and were also transitioned to the HWRF in 2007.

COLLABORATIONS BETWEEN GFDL AND HWRF DEVELOPERS. Formal planning for the development of HWRF as a nonhydrostatic,

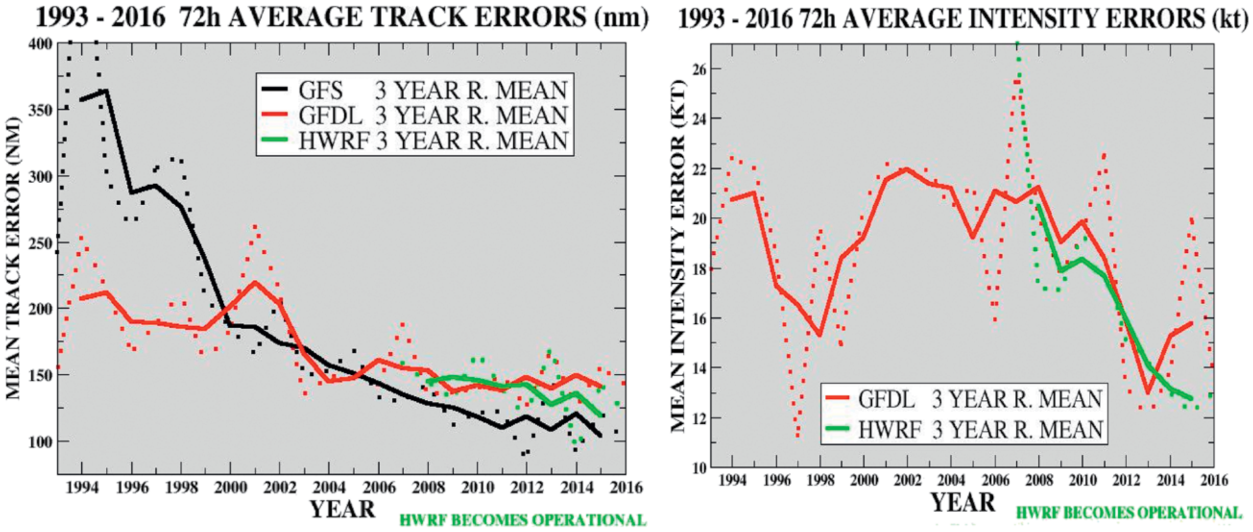


Fig. 8. The average 72-h (left) track and (right) intensity errors for the GFDL model (dotted red line) from 1993 until its retirement from the NWS after 2016, the HWRF (dotted green line) from its operational implementation in 2007 until 2016, and the GFS global model (dotted black line) from 1993 until 2016. A 3-yr running mean for each model is also shown with solid lines.

next-generation hurricane model began in 2002 with a joint NSF NOAA workshop. The impetus for starting development on a new hurricane model stemmed from the operational need for a high-resolution nonhydrostatic dynamical model with inner-core data assimilation and coupling to ocean and wave models, which would align the hurricane modeling infrastructure with other mesoscale models operational at NCEP. After considering other dynamic cores, the Weather Research and Forecasting (WRF) Nonhydrostatic Mesoscale Model (NMM; Janjić 2003) was selected since it was sufficiently mature and already in operational use at NCEP for the North American Mesoscale Forecast System. The HWRF development was accelerated through the hiring of new personnel at EMC including Robert Tuleya, a former GFDL hurricane model developer who now worked at EMC, and Sundararaman Gopalakrishnan, who led the effort to develop the HWRF movable nest.

Based on the success of the GFDL operational hurricane model as the NWS's primary operational hurricane prediction system, EMC developed a strategic plan for HWRF development that focused on transitioning most of the GFDL physics packages that were used in the operational GFDL hurricane model into HWRF for the initial implementation, to minimize the need for additional tuning. This plan was formulated by the HWRF team lead Naomi Surgi, and approved by Stephen Lord, the EMC Director. The HWRF development was greatly aided by JHT funding and was achieved through the efforts of the HWRF team and other EMC model physics developers.

In addition to transitioning physics packages to HWRF, GFDL also shared the GFDL vortex tracker system (Marchok 2002; T. P. Marchok 2019, unpublished manuscript) with HWRF developers. This tracker system analyzes postprocessed model data in order to quickly generate guidance for forecasters on model forecast track, intensity, and near-surface wind radii data. It has been a part of operations since the late 1990s at both NCEP and FNMOC for use with a variety of regional and global models. After integration into the HWRF forecast system, the GFDL tracker was adopted by the NOAA Hurricane Forecast Improvement Program (HFIP; Gall et al. 2013) as the standard vortex tracker to be used by the project for intercomparison among models and was subsequently released to the community at large via additional collaborations with the Developmental Testbed Center (DTC).

The development of the HWRF system continued throughout 2006, and an uncoupled version of the model was ready by the summer for preliminary testing. Although the original plan was to couple HWRF with the Hybrid Coordinate Ocean Model (HYCOM), the new coupled system was not ready for operational implementation in HWRF. The model developers at GFDL and URI were approached by EMC leadership about the possibility of transitioning the Princeton Ocean Model (operational in GFDL since 2001) to the HWRF. Leadership at GFDL readily agreed to allocate the necessary resources to make this transition possible. The GFDL hurricane group and URI scientists worked together and transitioned the GFDL coupled system into the HWRF coupler within a month, and the new coupled HWRF demonstrated improved intensity guidance compared to the uncoupled version.

Preimplementation testing during the spring of 2007 indicated that the track forecast performance of HWRF was very similar to that of the GFDL model, based on a 3-yr retrospective evaluation. In addition, the GFDL model track forecasts still provided added value to the model consensus that NHC used in their hurricane forecasts. Furthermore, the GFDL model intensity forecast skill was superior to that of HWRF. Based on additional input from the NHC, the decision was made to not retire the GFDL model after HWRF became operational in July 2007. Thus, the NWS supported both the HWRF and GFDL models as their official operational hurricane modeling systems. Over the next decade, improvements in the HWRF were made yearly, through a combination of modeling system upgrades and bug fixes that are typically found in any new model that has been transitioned into operations. Prior to each operational implementation of the new HWRF upgraded system, rigorous testing was required based on retrospective evaluation of the three previous hurricane seasons for both the Atlantic and eastern North Pacific. This requirement was made by the NHC and agreed to by the NWS leadership. Figure 9, which summarizes the results of each of the 3-yr retrospective set of forecasts, demonstrates the steady reductions in the HWRF track and intensity forecast errors achieved at most forecast lead times with each subsequent upgrade.

After the successful implementation of HWRF, the GFDL operational model became frozen in 2008, and no further model upgrades were made for the next three years. However, as the NHC forecasters continued to demonstrate that the GFDL model still added value to the model consensus, the NWS decided to allow the model to be upgraded again in 2011, and the GFDL hurricane model was officially unfrozen, with yearly upgrades continuing until it was finally retired from operations in the spring of 2017. A summary of GFDL model improvements through 2014 can be found in Tuleya et al. (2016).

While the HWRF was developed at NCEP as a highly advanced ocean–land–atmosphere forecasting system, it was not until 2012 that a series of fundamental improvements in the HWRF resolution and physics were incorporated into the operational system with significant funding and support from HFIP. An important upgrade to the HWRF system in 2012 was the addition of a third nest with a cloud-resolving innermost grid operating at 3-km horizontal resolution, which enabled the HWRF to resolve the inner-core hurricane structure much more accurately and significantly improved the model's pressure/wind relationship. Apart from obtaining significant improvements in the track forecast skill compared to previous versions, the 2012 version of the operational HWRF conclusively demonstrated the positive impact of resolution on storm size and structure forecasts (Tallapragada et al. 2014). These upgrades were achieved through extensive collaborations among scientists at EMC, GFDL, URI, and a newly established modeling group at NOAA's HRD.

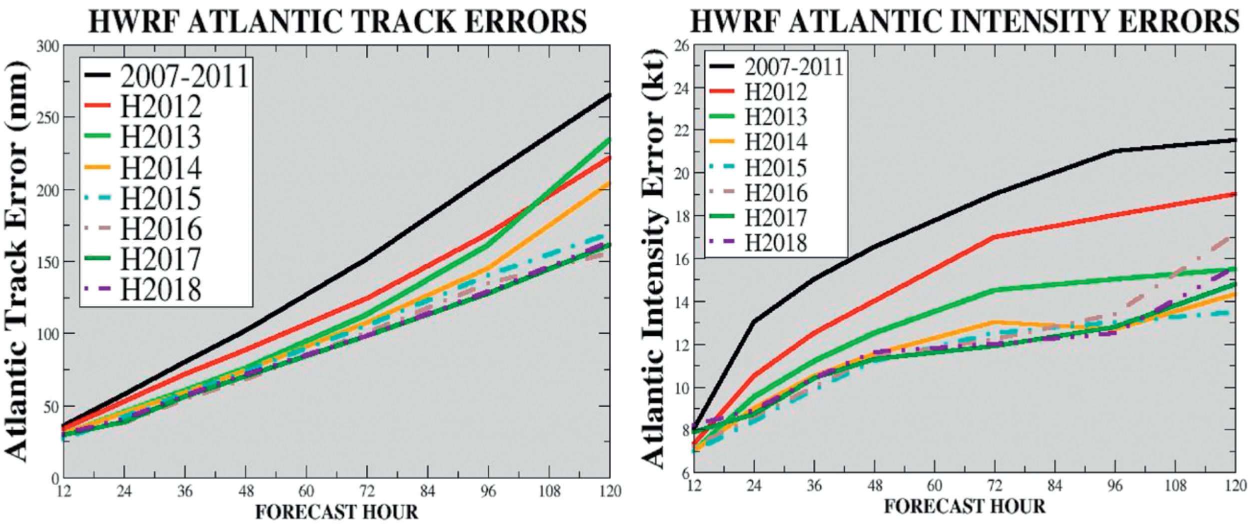


Fig. 9. HWRF improvements in Atlantic forecast (left) track and (right) intensity errors for the required 3-yr retrospective testing done prior to each yearly HWRF upgrade both for the 2007–11 combined seasons (black line) and for each year (colored lines) from 2012 through 2018 (Gopalakrishnan et al. 2018).

After 2012 the HWRF track and intensity forecasts (Fig. 8) became more accurate than those of the GFDL hurricane model.

Since the Navy's version of the GFDL forecast system (GFDN) had provided useful hurricane guidance to the JTWC since 1996 in the western North Pacific, through discussions with the JTWC, the HWRF group at EMC was encouraged in 2011 to evaluate HWRF performance in that basin. This initial testing was made possible through computing resources at the NOAA's Jet/Boulder supercomputer facility made available through HFIP. After demonstrating the value of these western North Pacific forecasts, the testing of the HWRF was expanded to cover all ocean basins in 2014. In 2015, this global version of HWRF became part of the official NWS suite and began to run operationally on the NWS Weather and Climate Operational Supercomputer System (WCOSS) as an official operational product. Indeed, HWRF has become one of the leading hurricane prediction models in the world and is now providing high-resolution forecast guidance for all global tropical cyclones (Tallapragada 2016).

The close collaborations established between EMC, GFDL, URI, HRD, and Old Dominion University continued to play a vital role in each yearly modeling system upgrade, with valuable feedback provided by forecasters at NHC and JTWC. Through funding from HFIP and the DTC Visiting Scientist Program, many other organizations have also contributed substantially to HWRF development and improvements. These include but are not limited to contributions from University of California, Los Angeles, and University at Albany, State University of New York (HWRF PBL scheme improvements), Atmospheric and Environmental Research [Rapid Radiative Transfer Model for GCMs (RRTMG) radiation scheme improvements], and the University of Oklahoma (data assimilation system improvements). In addition, HWRF uses software developed at the National Center for Atmospheric Research (NCAR; e.g., WRF Preprocessing System) and physics and data assimilation packages that have been improved by many developers [e.g., the NOAA/NCEP–Oregon State University–Air Force Research Laboratory–NOAA/Office of Hydrology land surface model (Noah)]. DTC is a distributed organization across NOAA's Earth System Research Laboratory and NCAR and has hosted the community-based model development activities through effective code management and user/developer support that led to significant improvements transitioning to the operational HWRF system over the years (Bernardet et al. 2015). Through these ongoing collaborative efforts, the HWRF has emerged as a true community-based hurricane model for research and operations, and many countries across the world have benefited from the tutorials and training workshops conducted by EMC and DTC in building the next-generation scientific expertise in tropical cyclone research and operations.

A unique aspect of the upgrades made to the NOAA operational hurricane modeling systems was that most were simultaneously transitioned to both the HWRF and GFDL operational models at the same time, which demonstrates the effectiveness of the ongoing collaborations and the leveraging of scientific innovations that have been funded in part by JHT and HFIP. Among the most significant improvements in the numerical guidance (Fig. 8) is that between 2011 and 2016 the 3-day intensity forecast errors for the Atlantic were reduced nearly 30% in both the HWRF and GFDL models. With the strong support at all levels of NOAA leadership, these collaborations continued through the time when the GFDL model was officially retired from operations.

CONCLUDING THOUGHTS AND LESSONS LEARNED. In this article the authors have provided a historical perspective on the key role that collaborations have played in the unique transition of the GFDL hurricane research model into a robust operational forecast system that provided valuable operational hurricane prediction guidance for over two decades. Indeed, the GFDL operational hurricane model's longevity and success would not have been achieved without the extensive and ongoing collaborations between research and operations. These successful collaborations continued as the next-generation HWRF system was initially developed, via a transfer of components of the GFDL forecast system to the new HWRF. As annual upgrades to both models were tested and implemented, these collaborative efforts, particularly among GFDL, URI, Old Dominion University, NCEP's Environmental Modeling Center (EMC), and also NOAA's HRD played a key role in the steady improvement of HWRF performance until HWRF became one of the top performers for providing hurricane guidance to the operational forecast centers, both at NHC and later at JTWC.

Based on their own personal experiences, the six authors of this article have provided their perspectives on how future collaborations can be successfully fostered within NOAA, other government agencies, and academia to improve the nation's NWP capabilities. Once the GFDL hurricane model became operational for the NWS, the GFDL hurricane group recognized the importance of sharing resources between basic research and specialized collaborative efforts to facilitate further improvements to the NWS hurricane modeling efforts. Leadership at both GFDL and the NWS strongly encouraged the collaborative environment that made the GFDL hurricane model transition to operations possible, and ultimately led to it remaining a premier hurricane prediction system for many years.

A number of these collaborations spanned nearly two decades. It is widely recognized within NOAA that better collaborations are needed to help our nation advance NWP, which has huge economic implications as well as the potential for the savings of lives and property. NOAA leadership recognizes the critical need to draw upon the expertise within the nation's academic community and in federal agencies through programs such as JHT and HFIP, but challenges remain. The authors believe it would be helpful to consider some of the experiences described in this article particularly while developing the NOAA next-generation Unified Forecast System (UFS) as a community-based model for research and operations. There is a critical need for leadership to continue to foster a collaborative environment that will encourage and enable agencies and people to work together for the success of a common goal. The success of the operational implementation of the GFDL model in 1995, as well as the development, timely transition, and successful implementation of the HWRF in 2007 and its subsequent annual upgrades would not have been possible without this commitment.

One example that demonstrates this, and that stands out to the authors, involved the willingness of GFDL model developers to transition the GFDL/Princeton Ocean Model coupled system to the HWRF after it was realized that the alternative solution for ocean coupling being developed for HWRF was not ready for operations. The dedication of the GFDL and URI teams to immediately commit to successfully transition the operational GFDL coupled system to HWRF in one month is an example of the potential benefit of collaboration by personnel that had years of experience working closely together and were willing to make a formidable task happen because of past successful collaboration and the resulting years of mutual trust. This also would not have been possible without the commitment of NOAA leadership particularly at GFDL and the NWS to allocate necessary resources when this need arose even without any additional funding.

The human element is extremely important in successful collaborations but is often overlooked. Collaborations are, by definition, people working together for a common cause. A key element that makes collaborations successful is having individuals who enjoy working together and are able to do so. This human element was key to making the GFDL prediction system a top hurricane modeling system that was transitioned so successfully to HWRF. It also remained an essential ingredient in so many of the successful annual upgrades to both models that required a team effort between the GFDL and HWRF hurricane groups. As we have discussed in this article, these improvements were usually applied to both models during the same implementation cycle, until the GFDL model was finally retired from operations in the spring of 2017.

Finally, we note that some of the support and model improvements were done without special funding, because of the commitment of the personnel involved who recognized the critical importance of providing operational centers with the best hurricane numerical guidance products. The ability of these teams to successfully work together for a common goal, and in a collaborative environment, was fostered from the top down within the agencies involved.

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