An Introduction to GFDL (Updated for the 2014 GFDL Review)

The history of the Geophysical Fluid Dynamics Laboratory (GFDL) is closely intertwined with the history of the computer, numerical weather prediction, and climate modeling. Shortly after computers first became available for scientific research in the early 1950's, it was realized that weather prediction would be a natural application. The first signs of the feasibility of numerical weather prediction began accumulating in the 1950's, in large part as the result of work conducted by a group organized by John von Neumann at the Institute for Advanced Study in Princeton, of which Joseph Smagorinsky was a young member. It quickly became apparent that one could use the same technique to study what von Neumann referred to as the "infinite forecast", that is the climate, or "general circulation", of the atmosphere. The Geophysical Fluid Dynamics Laboratory was created in 1955 with this goal in mind, initially as part of the U. S. Weather Bureau in Washington D.C., and with Joe Smagorinsky as the founding Director. GFDL moved to a new building on Princeton's Forrestal Campus in 1967, a building that it continues to occupy. It was first part of the Environmental Science Services Administration (ESSA), and then the National Oceanic and Atmospheric Administration (NOAA) when NOAA was formed in 1970. It is currently one of NOAA's Research Laboratories within the Office of Ocean and Atmospheric Research. Joe Smagorinsky was the Director until 1983, followed by Jerry Mahlman (1984-2000), Ants Leetmaa (2001-2007), and the current director V. "Ram" Ramaswamy, appointed in 2008.

GFDL scientists in the 1960's and early 70's built some of the first numerical models of the global atmosphere. The success of these models led to a series of breakthroughs in our understanding of the climate system and in the predictability of weather. In this period, studies at GFDL of the radiative transfer and other physics components led to simplified models of the vertical structure of the atmosphere. These resulted in the first modern estimates of the sensitivity of the temperature of the Earth to increasing levels of atmospheric carbon dioxide.

Central to Smagorinsky's initial vision for GFDL was the broader goal of simulating the climate of the Earth, including especially the oceanic circulation and the interactions between ocean and atmosphere that are integral to the maintenance of climate. The first numerical ocean models were developed at GFDL in the 1960's, leading to the pioneering efforts in constructing the first coupled atmosphere-ocean-land-sea ice models (named by *Nature* magazine in 2003 as one of history's

'Milestones in Computing'), the first examples of what are referred to today as simulations of the Earth's physical climate system. While considered by many at the time to be premature, a number of the insights from the initial simulations have stood the test of time, ranging from estimates of the strength of water vapor feedback, the importance of polar amplification of the surface temperature response to increasing greenhouse gases, and key differences between transient (less than a century) and longer term climate responses to anthropogenic forcings.

GFDL efforts related to ocean modeling resulted in the first community ocean climate model in 1984, with many hundreds if not thousands of scientists making use of the original and subsequent versions of the GFDL Modular Ocean Model (MOM). Besides its use in coupled atmosphere-ocean modeling at GFDL, MOM has been part of NOAA/NCEP's global prediction systems since the 1990s, and it is used by numerous other research and operational centers worldwide.

Also as part of Smagorinsky's initial vision, the laboratory's efforts expanded into studies of the limits to deterministic weather forecasting, modeling of the stratosphere, hurricane dynamics, clouds and circulation, mesoscale circulations such as fronts, observational studies of the general circulation of the atmosphere and climate diagnostics, coupled atmosphere-ocean models of El-Niño, and the modeling of atmospheres of other planets. Especially noteworthy was the evolution of the first three-dimensional simulations of hurricanes at GFDL into a key operational model that has been in continuous use for predicting hurricane tracks by the Weather Service and the Navy over roughly the past 20 years.

The first report of the Intergovernmental Panel on Climate Change (IPCC) in 1990 contained several findings based directly on results from the GFDL climate models. Throughout the 1990s, the growing awareness of the climatic importance of non-CO2 trace gases and short-lived species such as ozone and aerosols, expanded the scope of GFDL's modeling, research and applications.

By the third IPCC assessment in 2001, the world's climate modeling enterprise had begun to grow dramatically, with important new institutions in the U. S. and around the world devoted to climate modeling, in some cases with larger computational resources and scientific staffs. It had become clear that, to be competitive, GFDL needed to evolve from several relatively distinct "unicellular" groups, each organized around one of the first generation of key scientific leaders, to a larger "multicellular" level of organization, which worked more coherently to generate laboratory-wide modeling platforms for research and assessment activities. The new paradigm that evolved, beginning in the mid-1990s, centered on the development of a software framework, the Flexible Modeling System (FMS), on which all of the models at GFDL are now built. This software system provides both an infrastructure that facilitates the utilization of scalable computer architectures and insulates the scientific staff from the layers of programming needed to adapt to new platforms, and a superstructure that allows climate models to be easily configured from atmosphere, ocean, land, and ice components developed independently from the coupled system. Models began to be developed by laboratory-wide teams that cut across the scientific group structure. The CM2 class of models utilized in the 4th IPCC assessment (2007) and generally recognized as among the best of the world's climate models were the first major accomplishment of this fundamental reorganization and a clear sign of a successful transition to this higher level of organization demanded by the scale of the climate modeling enterprise. The evolution in the organization has been accompanied by GFDL's sharper focus of research on climate change, given the central importance of this issue to NOAA's mission and to the nation. This transition has also enabled GFDL to play leading roles in other major assessments such as the World Meteorological Organization's Stratospheric Ozone Assessment and the US Climate Change Science Program (now the Global Change Research Program).

For the 5th Coupled Model Intercomparison Project (CMIP5), GFDL and its partners (including UCAR and the Cooperative Institute for Climate Science at Princeton University) pursued four distinct but related "streams" of model development. One stream emphasized higher spatial resolution of global atmospheric models (scales as fine as 12.5 km) to afford insights into regional climate. Another stream used GFDL's CMIP3/IPCC AR4 model, CM2.1, to investigate the viability of decadal predictability and to make experimental decadal predictions starting from observationally based analyses of the ocean state. A new coupled atmosphere-ocean data assimilation system was developed for this purpose.

Two other streams focused on complexity, with the goal of increasing the realism of models. With increasing knowledge of the importance of ozone and aerosols in climate gleaned from basic theory and observations, the CM3 model, a successor to CM2.1, was developed. This model is a fully-coupled global climate model with complex stratospheric and tropospheric gas-phase chemistry and aerosol microphysics including aerosol-cloud interactions. This took into consideration the chemistry associated with ozone, and natural and anthropogenic aerosols. Similarly, with the increase in the understanding of climate-relevant terrestrial and marine biogeochemical processes, and the need to include a realistic treatment of the ocean and land carbon cycle, coupled carbon-climate Earth System Models (ESM series) were developed keying off the physical climate model, CM2.1. Two different ocean configurations (traditional Z-coordinate vs. isopycnal-coordinate) have provided unique insights into the impact of oceanic processes and model formulations on climate change and marine ecosystems.

NOAA's new R&D high-performance computers funded by the 2008 American Reinvestment and Recovery Act (ARRA) have made possible a substantial increase in model resolution and complexity. GFDL has refined the resolution of the atmosphere and ocean in its world-class CM2 family of climate models to produce a series of high-resolution coupled climate models, including CM2.4, CM2.5 and CM2.6, and a newer model, CM2.1_FLOR (Forecast-oriented Low Ocean Resolution). Improved access to High Performance Computing resources has enabled the development of experimental prediction systems through optimal data assimilation approaches. These modeling and assimilation systems have been used to assess observing systems and to perform experimental seasonal climate predictions which are submitted to the North American Multi-Model Ensemble (NMME), an experimental multi-model seasonal forecasting system consisting of coupled model results from several US modeling centers and Canada.

GFDL has remained deeply engaged in the understanding and prediction of tropical storms and hurricanes. GFDL's 1-5 day operational hurricane forecasting model continues to evolve with significant improvements in intensity prediction. Extensive research into the century-scale response of hurricanes to climate change has yielded new insights into hurricane genesis that are harnessed to improve seasonal predictions of Atlantic hurricane activity. These predictions are provided to the NWS to contribute to NOAA's seasonal hurricane outlooks.

GFDL's 2009 review was followed up by the development of a strategic plan, a Lab-wide effort completed in 2011. The Laboratory's scientific group structure was reorganized to address the next series of science challenges with an appropriately calibrated research portfolio, broaden representation by more junior and early career scientists, and increase diversity in the Laboratory's day-to-day scientific functionality and governance. Simultaneously, a senior-level peer leadership group, GFDL's Science Board, was instituted to provide long-term vision and guidance for the Laboratory's scientific horizons. A new Lab-wide model development effort at GFDL has been launched, led by the Model Development Team (MDT) with participation from groups throughout the Laboratory on various components of the climate system. Working in the 2013-2016 time frame, the MDT is steering the advancement of GFDL's next-generation atmosphere and ocean models, with the goal of developing the next-generation climate and Earth System models for: projection of climate change up to several hundred years into the future; attribution of climate change over the past century; prediction on seasonal to decadal time scales; and quantifying climate interactions with atmospheric chemistry and biogeochemistry. Following GFDL's team approach to model development over the past 15 years, the MDT has conceptualized a "trunk" model, with the design of capabilities that allow for flexibility in terms of resolution and/or comprehensiveness, consistent with the available computing resources. The atmospheric modeling is aided by a newly constituted long-term Clouds-Climate Initiative to meet the formidable challenge of modeling the role of clouds in climate, while the Model Evaluation and Diagnostics team aids in the test of the model's climate metrics against observations.

As always, the scientific choices in model development are bounded by computational constraints. Model choices of resolution, complexity and ensemble size for understanding and quantification of uncertainty are always targeted to the available machine capabilities and capacity. GFDL has a strong history since the days of von Neumann and Smagorinsky of building models pushing the very limits of computational capability, and of delivering novel scientific results for each new generation of computational technology.

To fulfill GFDL's mission "To advance scientific understanding of climate and its natural and anthropogenic variations and impacts, and improve NOAA's predictive capabilities, through the development and use of world-leading computer models of the Earth System," the Laboratory maintains synergistic partnerships with academic partners, other NOAA institutions and other Federal agencies in a wide range of areas involving modeling, model-observation comparisons and analyses of model simulations. Research within GFDL and with its collaborators continues to adhere to the long-standing GFDL commitment to developing state-of-the-art models based on fundamental knowledge, using them to provide timely and reliable assessments on climate change consistent with NOAA's strategic goals, developing tools of potential operational significance for NOAA, and making both data and models available in the public domain after scientific vetting. GFDL has made available nearly 190 terabytes of simulation data in the recent round of the CMIP exercises (CMIP5) which coincided with the IPCC AR5 culminating in 2013.

GFDL's connection with Princeton University since 1967 has proven to be fruitful and mutually beneficial. Since its inception, laboratory scientists have contributed time to graduate education. As a result, many national and international leaders in climate research and operations were trained by GFDL mentors working within Princeton's Atmospheric and Oceanic Sciences (AOS) Program, a part of the Princeton University Geosciences Department. The AOS Program has also facilitated a substantial postdoctoral visitors program that is essential to the laboratory's vitality and recruitment of young scientists. This Princeton-GFDL relationship was solidified in 2003 with the formation of the Cooperative Institute for Climate Science (CICS). The recent evolution of GFDL towards Earth System Modeling has emphasized the importance of these connections with Princeton University even more forcefully, as the University's world-class expertise on the global carbon and nitrogen cycles and land vegetation modeling have played essential roles in GFDL's model development. Other interactions with Princeton University scientists, within the Engineering, Computer Science, Chemistry and Applied Mathematics Departments, and the Woodrow Wilson School for International Affairs, have augmented the laboratory's research in the past and hold promise for increased interactions in the future.

In the 21st century, there are newer classes of challenges consisting of problems straddling traditional boundaries and involving increased levels of complexity. Society and policy makers need information that require as rapid advances as possible in our understanding on many topics, including the fate of anthropogenic carbon, regional climate change, decadal-scale predictability, the interactions between air quality and climate involving short-lived gases and aerosols, changes in climate extremes, polar regions and oceans, and climate impacts on ecosystems. With the goal of remaining at the pinnacle of climate science, and with the planning in place for sustained advances in research, GFDL is well-positioned to address NOAA's key issues in climate change and deliver improved models, information, and products to the Nation.