# Descriptions of GFDL Research Themes

### *1. Modeling the Earth System*

By enabling new science and applications, model development serves as the cornerstone of GFDL's research mission. This theme will cover recent progress in enhancing model resolution and representation of key climate processes, which can be organized broadly into three sections: 1) atmospheric physics, 2) atmospheric dynamics, and 3) ocean/ice sheet modeling. We will show that the new modeling capabilities greatly facilitate the research into some fundamental science questions, such as the radiative effects of short-lived climate forcers, the dynamics of tropical storms and waves, and the parameterization of ocean mesoscale eddies at different resolutions. The resulting understanding, in return, proves to be essential for guiding model development. The healthy interplay between model development and basic research is borne out in the activities highlighted in each section, namely 1) the development of a high-resolution trunk model with advanced aerosol/cloud physics, 2) the formulation of two-way nesting and stretched grid dynamical cores, and 3) the incorporation of ice sheet dynamics into fully coupled models.

### *2. Climate Variability and Change: Understanding and Prediction*

This review theme focuses on GFDL activities that have addressed the NOAA mission goal to understand and predict climate variability and change. In this section we provide results from research projects that seek to use both observational analyses and model experimentation to increase our understanding of key climate processes and phenomena including investigations into factors affecting climate change. Topics covered include trends in surface and atmospheric temperatures, large-scale tropical climate change, ENSO, hurricane activity, drought, ocean circulation, snow cover and sea ice changes. The increased understanding of these processes and phenomena is then used as a foundation to develop a "predictive understanding" of the global climate system. This understanding combined with a coupled data assimilation system and enhanced dynamical and statistical downscaling techniques, is leading to robust science-based evaluations of the predictive capability of the climate system on time scales from seasonal to centennial.

### *3. Chemistry, Carbon, Ecosystems, and Climate*

This theme focuses on research to understand the diversity of chemical and ecological processes that influence, or are influenced by, climate. For example, carbon uptake by the land and ocean slows atmospheric accumulation of CO2, ameliorating the warming effect of fossil fuel emissions. Natural and anthropogenic aerosols alter the earth's radiation balance by scattering and absorbing sunlight, while climate-sensitive patterns of aerosol production, transport and removal profoundly impact regional air quality. Changes in air temperature, precipitation and atmospheric CO2 can shift boundaries between deserts, grasslands and forests and alter agricultural outputs. Likewise, projected changes in ocean temperature, stratification, and acidity will impact ocean ecosystems and the valuable marine resources they support. This session will highlight studies that harness advances in earth system modeling and climate understanding to gain new insights into these and other societally important interactions between climate and chemical/ecological systems.

# Theme 1. Modeling the Earth System

Since 2009 and the previous Review, GFDL has developed a variety of climate models and model components motivated by NOAA's strategic goals and objectives, especially the objective of "improved scientific understanding of the climate system and its impacts". Our model suite allows us to optimize our computational resource toward answering the broad range of questions that fall under this objective. Four GFDL modeling streams contributed to the CMIP5 archive for use in the AR5 assessment: one stream (CM3) focusing on aerosols/atmospheric chemistry and stratospheric simulation; an earth system modeling stream with ocean/atmosphere/land carbon cycles producing two models (ESM2M and ESM2G) differing in their ocean components; a high horizontal resolution stream (HiRAM) providing simulations of extremes and regional detail given ocean/ice boundary conditions; and a decadal predictions stream based on our AR4 model (CM2.1) initialized with a new coupled atmosphere-ocean data assimilation system.

In addition, the CM2.1 coupled climate model has evolved into higher resolution coupled versions: CM2.5, and CM2.6, as well as FLOR, the basis of our new experimental forecast model. The high resolution atmosphere, HiRAM, has been extended into a global non-hydrostatic model with the option of variable resolution meshes focusing on regions of special interest. The capabilities of our two ocean models, utilized in ESM2M and ESM2G, are being merged into a new ocean model, MOM6. There is continuing progress on scale-aware oceanic eddy parameterizations and ocean mixing parameterizations to be incorporated in this model. A new sea ice model is also being developed for coupling to MOM6. Work has started on an ice sheet model with a focus on ice/ocean interaction and grounding line movement. Our land model, LM3, incorporated in all current models, simulates impact-relevant quantities such as lake levels, stream flows and groundwater, and continues to evolve in both its hydrology and ecology/carbon cycling. A suite of oceanic biogeochemistry models of varying comprehensiveness has been employed in coupled model simulations.

CM3's physics and chemistry enhancements have allowed exploration of variability in the distribution of stratospheric and tropospheric ozone as well as the role of the different natural and anthropogenic aerosols in past and future temperature and precipitation changes. Pushing the models to high resolution has produced: remarkably realistic simulations of the climatology, interannual variability, and recent trends in hurricane genesis; a simulation of tornadogenesis in the atmospheric model as a demonstration of the power of the non-hydrostatic variable mesh technology; and a high quality ocean temperature simulation with an eddy-resolving-ocean climate model.

We have also gained a much-improved understanding of the factors that control the responses of our climate models when perturbed with anthropogenic emissions. In particular, the aerosol indirect effect has been found to be sensitive to the parameterization of rain formation; cloud feedback, the primary uncertainty in equilibrium sensitivity, is influenced by the treatment of detrainment in the convective parameterization; and the ratio of the transient and equilibrium climate sensitivities, incorporating the role of the ocean, is significantly influenced by the magnitude of the control climate's Atlantic overturning in our model suite.

Consistent with GFDL's Strategic Science Plan, development of a new trunk model, CM4/ESM4, is underway as a lab-wide project to consolidate advances from all existing modeling streams. The initial target resolution is 50km in the atmosphere and 1/4 degree in the ocean. Lower resolution versions will be developed in tandem. This project is in the second year of a four-year plan. Atmospheric development has focused on convection parameterization and microphysics. Ocean development has focused on configuring the new MOM6 model. The first coupled simulations with MOM6 are underway, and the remainder of this year will be devoted to development of the physical model in coupled mode. Earth system model development will take place within this new framework in the final two years of this project. This trunk model will provide a new center from which diversification is expected to occur to pursue the varied science objectives consistent with NOAA's mission.

Outstanding issues include balancing the need for a variety of models of different comprehensiveness and resolution with the difficulty of optimizing a coupled climate model; merging process-level and more holistic constraints on climate sensitivity, aerosol indirect effects, and carbon exchanges into the model development; improving the scalability of the model by increasing the levels of concurrency; and improving collaboration with university groups and other modeling centers to enable expansion of efforts into areas with subcritical in-house expertise.

# Theme 2. Climate Variability and Change: Understanding and Prediction

Climate variations arise from internal modes of climate variability and radiatively forced changes. GFDL has sought to build predictive understanding of climate and its impacts, including extremes, and understanding of the causes of past changes. This work has progressed through a focus on: understanding the mechanisms behind, and impacts of, climate variations; establishing and refining data assimilation methodologies; improving the fidelity of models; creating novel prediction methodologies; and generating and applying methods to assess model quality, forecast skill, and causes of past climate changes.

Efforts at prediction, attribution, and understanding have progressed by unifying across timescales and phenomena (one example being the tropical cyclone/climate problem). Particular focus has been placed on high-resolution models, as they offer the potential for improved representation, attribution, prediction and projection of regional-scale variations, including precipitation (e.g., Australian drought; global snowpack response to greenhouse forcing; predictable precipitation patterns over land), the El Niño-Southern Oscillation (ENSO), and tropical and extratropical cyclones. Other GFDL attribution studies have focused on regional surface temperatures and Arctic sea ice, including extremes, and on aerosol influences on the South Asian monsoon. GFDL has contributed to the understanding of Atlantic Meridional Overturning Circulation (AMOC) variability and change, including the role of AMOC in Atlantic Multidecadal Variability (AMV) and decadal predictability. GFDL researchers have explored multi-year initialized predictability and predictions, focusing on both large-scale climate (such as AMOC and ENSO), as well as regional impacts and extremes – made possible by high-resolution coupled seasonal-to-decadal prediction systems.

Hierarchies of models, including high-resolution models, statistical models, and multi-model analyses, enable estimates of future changes in regional climate and extremes, as well as understanding of the causes of past changes. Empirical statistical downscaling techniques are being systematically tested using a perfect-model approach.

GFDL predictions are contributing to NOAA and the world, for example through the North American Multi-Model Ensemble. GFDL's hurricane model is used operationally by the National Weather Service (NWS) and other agencies. GFDL has been contributing results of experimental real-time predictions of tropical cyclone activity to the NWS in support of NOAA's Seasonal Hurricane Outlook. Experimental Arctic sea ice seasonal predictions have been contributed through the SEARCH sea ice outlook program. Experimental initialized decadal predictions were made available through the CMIP5 experiment. GFDL has contributed to IPCC, WMO and other assessments of climate variability and change, and to a *Bulletin of the American Meteorological Society* series examining causes of recent extreme events from a climate perspective.

Going forward, GFDL will continue efforts to understand and predict the Earth system, with a focus on unified approaches that span timescales and phenomena. Yet tools, including models and analysis methods, will be targeted to research objectives, with clearly defined goals. Targeted attribution and prediction studies will continue and expand into new areas (e.g., ecosystems, extremes, regional precipitation) leveraging off of local and collaborative expertise. We will incorporate new models (CM4) into prediction efforts as resources permit and work towards high-resolution coupled data assimilation. Large-ensembles will be used to better understand the nexus of natural variability and radiative forcing. We will continue exploring high-resolution models to understand, attribute, and predict regional-scale climate. Upgraded state-of-the-art computing resources will be crucial to the success of these activities. Even with such upgrades, resource constraints will require judicious and balanced use of complexity, high resolution, and large ensembles.

# Theme 3. Chemistry, Carbon, Ecosystems, and Climate

The Earth's climate is strongly influenced by greenhouse gases and aerosols and these, in turn, are affected by chemical reactions in the atmosphere and interactions with ecosystems. Meeting NOAA's mission to understand and predict changes in climate and to conserve and manage coastal and marine ecosystems and resources requires an understanding of the complex interactions of the full Earth system. Theme 3 describes GFDL's effort to build on its long history of global physical climate modeling to holistically understand the intricacies of the Earth system and its interdependencies with human health and prosperity, based on an enhanced scientific understanding of the changing climate system and impacts. To meet the challenge of improving understanding of the integrated Earth System, GFDL is developing self-consistent representations of chemistry, ecosystems, and the associated climate feedbacks for incorporation into physical component models (atmosphere, land, sea-ice, ocean) that will be coupled into Earth System Models (ESMs). This highly interdisciplinary effort extends well beyond GFDL's traditional core competencies in physical climate and weather and necessitates strong leveraging of expertise at Princeton University, in particular, and across NOAA and the scientific community at large.

GFDL demonstrated its continuing leadership in atmospheric chemistry-climate interactions through participation in the Atmospheric Chemistry-Climate Model Inter-comparison project (ACCMIP) and CMIP5 with its CM3 coupled model. CM3's applicability to both climate and air pollution advances understanding in both the consequences of short-lived pollutant emissions to climate variability and change, and well as many of the meteorological mechanisms that control the atmospheric abundance of gas-phase and particulate air pollutants. GFDL has also made great strides in representing land-atmosphere interactions by linking the sources and sinks of dust and other aerosols to land processes.

Efforts to close the carbon cycle have focused on developing state-of-the-art representations of terrestrial and marine ecosystems and biogeochemistry and their interactions with climate. GFDL has investigated structural model uncertainty in historical and projected ocean carbon and heat uptake through developing ESMs based on two different ocean component models. Furthermore, the Princeton/GFDL efforts have focused on the combined effects of climate and land -use and -cover change on land carbon sources and sinks. GFDL's research with new ESMs contributed to increasing understanding of coupled carbon-climate feedbacks. In addition, by contributing output from the ESMs to CMIP5, GFDL has provided a critically important community service for the carbon cycling, climate change and impacts communities.

With this initial set of Earth System Models successfully now in place, GFDL plans to address current research gaps on four fronts:

1. Applying current models to observational comparison efforts (e.g. SENEX, PPAR5, MAREMIP, etc.), multi-member ensembles for detection and attribution of climate change, impacts assessments, and idealized sensitivity simulations
2. Advancing model realism, beyond closing the $CO_2$ cycle, by including fully comprehensive and self-consistent representation of biogeochemical cycles of dust/Fe, $CH_4$, nitrogen, phosphorus, and

biogenic aerosols throughout the components of the Earth system, and improving current representation of chemistry and ecosystems

3. Prototyping models with ultra-high resolution for improved regional atmosphere-land interactions and the ocean mesoscale for improved base state and change, to address important climate, air quality, and marine resource applications, and
4. Earth system prediction of chemical and ecological processes and phenomena through improved integration with GFDL's seasonal-decadal climate prediction effort.

Through these efforts, GFDL will continue to push the envelope in both comprehensiveness and resolution, as permitted through optimal use of available computational resources, to execute on NOAA's strategic plan, playing a critical integrative and collaborative role in pushing the frontier of Earth System Modeling.