Theme 1. Modeling the Earth System

Over 2013-2019, GFDL's existing models were further developed and consolidated under the 2011 strategic science plan into a unified modeling suite of four major configurations for weather and subseasonal-to-seasonal forecasting (SHiELD), seasonal-to-multidecadal forecasting (SPEAR), high-resolution-ocean-based climate modeling (CM4), and earth system modeling (ESM4). These models share many major components: the atmospheric models use the FV3 dynamical core; and SPEAR, CM4 and ESM4 use the OM4 ocean with the MOM6 dynamical core and physics, SIS2 for sea ice, and LM4 for land. Both FV3 and MOM6 are being widely adopted by national centers and universities. Over the next 5-10 years, these configurations will form the basis for further model development and specialized configurations for a diverse range of understanding and prediction objectives. SPEAR will be discussed in more detail in the Theme on Projections and Predictions.

The FV3 is widely used, notably as the dynamical core for NOAA's Next-Generation Global Prediction System, and now forms the 'engine' for the National Weather Service operational weather forecasts. With the development goals of physical consistency and realism, fully finite-volume numerics, adaptability to other model components, and computational efficiency, FV3 has evolved from an accurate and efficient transport module for atmospheric chemistry modeling into flexible plug-compatible usage for a wide array of research, prediction, and projection applications. FV3-based models are used at spatial and temporal scales ranging from centennial- and millennial-scale climate simulation to storm-scale short-range predictions, and to study the effects of resolved convection on larger scales. New capabilities are being built into the core, including rigorous moist thermodynamics, new grid domains (including variable-resolution and regional domains), variable-composition and deep-atmosphere dynamics, improved interfaces for data assimilation and nudging, and new numerical schemes. FV3 will advance the integration of physical parameterizations within the dynamics, leading efforts towards unified and global cloud-resolving modeling.

Compared to the earlier GFDL atmospheric models (i.e., AM2 and AM3), AM4 has increased horizontal resolution, an improved radiative transfer scheme, new convection and mountain drag parameterizations, and significantly updated aerosol-cloud interactions. AM4 predicts aerosols from emissions with two complexity options for atmospheric chemistry. The fast chemistry version (AM4.0) allows AM4 be used at high spatial resolution (e.g., 50km and 25km) or be coupled with high resolution ocean model. AM4 forced by the observed SSTs produces superior quality results compared to most CMIP5 models in simulations of top-of-the-atmosphere radiative fluxes, clouds, and precipitation. It also improves simulations of aerosol spatial distributions, Madden-Julian Oscillation, and tropical cyclone statistics, as well as the response to El Nino-Southern Oscillation (ENSO) SST anomalies compared to earlier GFDL models.

MOM6's hybrid vertical coordinate and open source development framework combines the strengths of the previous generation codes of MOM5, Generalized Ocean Layer Dynamics, and the MIT model. These advances have stimulated adoption by NCEP, NCAR and other institutions. The OM4 eddy-permitting configuration of MOM6 used in CM4.0 has reduced spurious heat uptake largely due to improvement in the treatment of the vertical coordinate. Separation of dynamics, tracers and coupling time steps provides a low-cost solution to the addition of tracers. SIS2 uses the same C-grid stencil as MOM6. It has thermodynamics and radiative transfer from CICE version 4. SIS2 is being upgraded to CICE version 5-level capabilities making use of CICE's Icepack physics package.

GFDL's CM4 and ESM4 coupled models build directly on the component model developments described above. CM4.0 emphasizes ocean horizontal resolution while ESM4 emphasizes Earth system comprehensiveness with coupled carbon, chemistry, and climate. In CM4, CM3's capability to simulate aerosol composition and distribution driven by emissions was retained, but with prescribed oxidants ("fast chemistry") reducing the number of tracers, chemical interactions, and the overall cost. In ESM4, interactive chemistry was improved by adding explicit interactions and exchanges with land and ocean. Notable achievements in CM4 include the relatively small biases in seasonal spatial patterns of top-of atmosphere fluxes, surface temperature, and precipitation; reduced double Intertropical Convergence Zone bias; dramatically improved representation of ocean boundary currents; a high quality simulation of climatological Arctic sea ice extent and its recent decline; and excellent simulation of the ENSO spectrum and structure. ESM4 captures much of the baseline simulations characteristics of CM4 with improvements in Southern Ocean mode and intermediate water ventilation, aerosols over the Southern Ocean, and a reduction in ocean heat uptake. ESM4 has an improved representation of historical climate warming and reduced climate sensitivities relative to CM3 and CM4. Significant improvements such as better treatment of nitrate aerosols, online biogenic secondary organic aerosol source from online biogenic emissions, and interactive dust emissions allow ESM4 to capture trends and variability in tropospheric ozone and surface air quality. In spite of some fidelity concerns regarding SST biases, aerosol representation in some regions and strong centennial scale climate modulation by Southern Ocean convection, ESM4 represents an important advance in coupled carbon-chemistry-climate modeling and should prove applicable to a broad range of studies in both physical climate variability and forced response, as well as impact studies across climate, land and ocean ecosystems, and air quality and carbon feedback applications.

Theme 2. Advancing the Understanding of the Earth System: Phenomena, Processes, Variability and Change

Using Earth System Models in conjunction with available observations, GFDL scientists have conducted cutting-edge research to advance the fundamental understanding of major Earth System phenomena, and their underlying mechanisms, relevant for NOAA priorities. The resulting knowledge base is crucial for informing model development and provides scientific foundation for Earth System predictions and projections, both of which are central to fulfilling OAR vision, mission and goals.

GFDL scientists have strengthened the understanding of atmospheric and oceanic processes that are critical for large-scale circulations and climate, and advanced the understanding of the unresolved sub-grid scale processes in Earth System Models. GFDL has improved the shortwave and longwave radiative transfer, and the accuracy of global aerosol radiative transfer calculations, using novel line-by-line benchmarking. The treatment of cloud microphysics used in convection parameterizations has been shown to exert strong control over climate sensitivity. The temperature-dependence of natural aerosol emissions in ESM4 has led to a strong negative climate feedback and contributes to a much lower climate sensitivity than in CM4. GFDL has participated in the NSF/NOAA funded Climate Process Team (CPT) effort to parameterize internal-wave driven ocean mixing, which is crucial for oceanic heat and carbon uptake and the meridional overturning circulation. A new energetic Planetary Boundary Layer (ePBL) parameterization has been developed for surface boundary layer mixing, in combination with the effects of surface Langmuir turbulence on mixing. Collaboration with NCEP/EMC has explored the impacts of surface oceanic waves on weather and climate using the WAVEWATCH III model.

The process-level understanding has led to improved simulation and understanding of aerosols, clouds, microphysics, boundary layer and radiation, and of land-climate interactions and feedbacks, via mechanistic treatment of physical, ecological, biogeochemical and hydrological processes and their heterogeneity. GFDL has advanced the understanding of the: biogeochemical processes that influence the atmosphere, land, and ocean components of the Earth System; the sensitivity of those processes to human activities; and the associated feedbacks. Research has elucidated the drivers and impacts of climate and weather extremes, such as tropical cyclones, hurricanes, droughts, flooding, wildfires, monsoon depressions, and heat waves.

GFDL has conducted extensive research on the fundamental aspects of: large scale climate variability across different timescales; regional hydroclimate; and the associated important interactions between climate and ecosystems. These include studies on the: dynamics of South

Asian monsoon low pressure systems; response of the Inter-Tropical Convergence Zone (ITCZ) location to top-of-the-atmosphere radiative imbalance; role of stratospheric processes in modulating the response to ozone depletion; land-climate interactions and implications for air quality and the global nitrogen cycle; interannual ENSO variability that is important for the seasonal predictability of tropical climate and biogeochemical signals; and interannual SST variability which forms a key source of seasonal prediction skills for winter sea ice extent in the Barents Sea. Research has led to understanding the mechanisms of Atlantic Multidecadal Variability (AMV) and its linkage to multidecadal Atlantic Meridional Overturning Circulation (AMOC) variability, which is crucial for the decadal predictability of regional and hemispheric-scale phenomena e.g., frequency of major Atlantic hurricanes and Arctic sea ice extent.

GFDL research has focused on attributing observed historical changes of climate parameters in terms of externally forced response and internal variability. Scientists at GFDL have also sought to improve the physical understanding of model-projected centennial-scale changes, such as the decrease of the Sahelian rainfall in response to oceanic warming, and the projected enhanced Atlantic sea level rise and warming along the U.S. East Coast induced by the modeled AMOC weakening in response to future greenhouse gas emissions. Advances have been made in quantifying uncertainties in radiative forcings and climate sensitivity associated with centennial-scale Earth system model projections. Interactions in the Earth System have been investigated including: between the atmosphere and land; between the ocean and ice-shelves, icebergs and sea ice; and between the physical processes and biogeochemical cycle and ecosystems.

Over the next 5-10 years, GFDL will continue to make use of its suite of modeling tools and combine these with observations to improve the: process-level understanding of atmospheric and oceanic subgrid-scale parameterizations; understanding of the role of atmosphere, land, ocean, and cryosphere in weather, climate, sea level, and ecosystems; understanding of internal climate variability and climate responses to external forcings; and quantification of the drivers of future predictions and projections across timescales. GFDL will deepen the understanding of the interactions between Earth System components, e.g., the coupled interactions between ocean and ice sheet/ice shelf, for skillful predictions of future sea level rise in response to changing climate. GFDL will investigate the causes of long-standing model biases in key Earth System forcings, and develop innovative ways to bridge the gap between model simulations and fundamental understanding such as emergent constraints and model hierarchies.

Theme 3. Earth System Predictions and Projections

GFDL has focused on developing and using new modeling systems that are capable of making seamless predictions and projections across a range of space and time scales. These modeling systems are both an embodiment of our scientific understanding as well as leading edge tools that advance our understanding and predictive capabilities. This activity supports the OAR mission “Research, Develop, Transition. Conduct research to understand and predict the Earth system; develop technology to improve NOAA science, service, and stewardship; and transition the results so they are useful to society”. The products of these advancing capabilities inform stakeholders, policymakers, and the general public as to weather and climate impacts and hazards, and work towards a weather-ready and climate-resilient nation.

GFDL has made significant progress towards a seamless, unified modeling suite built around shared components, including FV3, MOM6, and FMS. This allows GFDL scientists to address critical problems of predictability and interactions across time- and space-scales, including weather to subseasonal, subseasonal to seasonal (S2S), seasonal to decadal (S2D), as well as multidecadal and beyond. Improved understanding and skill on shorter timescales can inform and build credibility for longer-scale interannual-to-decadal predictions and centennial-scale climate projections. Most notably, our seamless system permits improved understanding and simulation of extreme Earth System events on all temporal scales and how they are affected by more-predictable larger-scale circulation features, radiative forcings, and internal climate variability, with substantial societal benefit. GFDL in particular has made great advances in the prediction and understanding of tropical cyclones, hydrological extremes, and the impact of ocean conditions on marine ecosystems, and has done significant work in projecting how they are affected by climate variability and change.

Recent work has shown how seamless prediction and projection systems can advance our understanding through a unified approach across time scales. For example, recent studies have used seasonal hurricane predictions combined with multidecadal projections to identify and quantify the causal factors behind unusual seasonal hurricane activity in both the Atlantic and Pacific, showing the power of a system able to perform both seasonal and shorter-range predictions and to incorporate radiative forcing changes on both decadal and shorter timescales. Other recent studies have shown prediction skill for dust, as well as marine ecosystems, demonstrating the growing breadth and future potential of these seamless prediction activities.

Model initialization is critical for improved predictions. In particular, as evidence mounts that skillful prediction is possible at annual, interannual, and decadal scales, initialization of the entire ocean as well as of the cryosphere is of critical importance. For initialization of our next generation prediction systems, GFDL has streamlined and optimized a comprehensive and efficient new ensemble coupled data assimilation (ECDA) system built using MOM6 and SPEAR. Active work is under way to advance our atmosphere, land, and sea ice assimilation systems as well.

Many of the advances in prediction and projection model development rely heavily on new capabilities within the unified modeling system, as well as a better understanding and continual improvement and optimization of how the modeled Earth System works as a holistic system rather than as discrete components. Significant advances in the numerical algorithms in FV3 and MOM6 have enabled improved simulations of the mean climate and of extreme events, reductions in model biases, and better conservation properties.

All prediction and projection models at GFDL are well-positioned to take advantage of new capabilities in both FV3 and MOM6 to extend into new regimes, including variable-resolution and regional domains, nonhydrostatic scales for atmospheric convection, and improved compatibility with unresolved subgrid processes. Further model advances are enabling representation of other earth system features beyond physical atmosphere and ocean conditions, such as sea ice, sea level rise, air and water quality, and ecosystem prediction.

GFDL has historically made significant efforts to transition the lab's innovations so they can be of use to society. Prominent examples include MOM6 and the NGGPS effort with FV3, as well as GFDL participation in the North American Multimodel Ensemble (NMME), in seasonal hurricane predictions with the National Hurricane Center, and in the Hazardous Weather Testbed (HWT) and Hydrometeorological Testbed (HMT). GFDL will continue to develop leading edge model components and use them to advance our unified and seamless prediction and projection systems as part of the OAR mission. An important future direction will be the growing incorporation of earth system components as integral pieces of these unified and seamless prediction and projection systems.