The GFDL 5-10 Year Strategic Science Plan

09/26/19

Executive Summary

This Plan outlines GFDL's research strategies and priorities in the next 5-10 years, with the goal of supporting NOAA's mission by advancing scientific understanding and the prediction capability of the Earth System. The complex nature of weather and climate phenomena and downstream impacts calls for sustained development and application of state-of-the-art Earth System Models (ESM) across a wide range of temporal (hours to centuries) and spatial (regional to global) scales. This in conjunction with observations and theories, will yield products, information, and services critical for decision- and policy-making.

The current-generation GFDL models, namely CM4 (physical climate), ESM4 (Earth System), SHiELD (weather forecasting and sub-seasonal to seasonal predictions) and SPEAR (seasonal to multidecadal predictions and projections), use common components includingthe atmospheric dynamical core FV3, the Modular Ocean Model MOM6, the LM4 land model and the SIS2 sea-ice model, the whole being built upon the Flexible Modeling System common infrastructure. They constitute major contributions to community-wide weather and climate modeling, and facilitate the sharing of many key components (atmosphere, ocean, sea ice and land). The unified modeling system concept provides the basis for understanding earth system phenomena, processes, variations, and change, and for developing a seamless prediction capability across timescales. Future developments will focus on increasing model horizontal and vertical resolutions, improving the representations of unresolved processes, and exploring new data assimilation techniques.

GFDL's efforts to understand the Earth System, enabled by models and observations, can be broadly organized into four areas: atmospheric, oceanic, biospheric and cryospheric processes; biogeochemical processes; weather and climate extremes; and climate variability and change. The resulting peer-reviewed accomplishments contain fundamental insights into many of the leading questions in the field. GFDL will continue to pursue cutting-edge research in mission-critical areas, such as aerosol-cloud-convection-radiation-circulation-climate connections, ocean dynamics and subgrid-scale parameterizations, interactions within and between Earth System components, internal climate variability and climate responses to external forcings, and predictions and projections covering a range of space and time scales.

By enhancing both the realism and comprehensiveness of its prediction tools, GFDL has gained experience in using them to provide skillful, real-time predictions of weather and climate to external partners and inform their forecasts and seasonal outlooks. GFDL will continue to develop and build collaborations across NOAA, and with the academic, private, and other sectors to address the crucial needs. GFDL will continue to perform advanced research towards the goal of seamless predictions and projections by developing new Earth System modeling capabilities, improving predictions of high-impact events, and narrowing the gap between the potential predictability and realized skill.

The underpinning of GFDL's scientific endeavors is a computational and software infrastructure built upon the unified modeling concept which contributes to the NOAA endeavors in understanding and prediction of the Earth System. GFDL will continue to explore innovative ways to support community model development, harness the power of Machine Learning, and adapt to the rapid evolution of high-performance supercomputing.

Chapter 1: Introduction

GFDL's mission is to be a world leader in the development of comprehensive, integrated and unified models of the Earth System comprising the atmosphere, oceans, cryosphere, land, biosphere and ecosystems; and the application of these models for the seamless understanding, predictions and projections of the Earth System, from hours to centuries and from global-to-regional spatial scales, accounting for natural variations and forced changes. The focus is on the long lead-time research on weather and climate that is fundamental to advancing scientific understanding of the dynamical, physical, biogeochemical and ecological processes governing the behavior of the atmosphere, oceans, ice, and land components and their interactions. The development and application of state-of-the-art coupled Earth System Models provide a suite of societally-relevant information and decision-supporting products.

GFDL directly supports NOAA's priorities in "reducing the impact of extreme weather and water events" and "increasing the sustainable economic contributions of our fishery and ocean resources." By advancing the understanding, predictions and projections of the Earth System critical for informed decision-making, GFDL strives to fulfill OAR's vision of "delivering NOAA's future" and mission of "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." GFDL research on weather/climate prediction and extremes is central to the goal of "making forecasts better." GFDL research on ocean, coast and ecosystem processes, predictability and predictions supports the goal of "exploring the marine environment." GFDL research on detection/attribution of observed weather/climate phenomena contributes to the goal of "detecting changes in the ocean & atmosphere." By collaborating with partners both within NOAA and the community at large, GFDL is actively engaged in the goal of "driving innovative science."

GFDL researchers seek to answer a wide range of application-inspired basic scientific questions central to fulfilling its mission. Some prominent examples are as follows:

- How can one improve the model simulation of, and predictive skill for, important weather and climate phenomena by deploying the most advanced technologies?
- What are the roles of aerosols, clouds, microphysics, convection, boundary layer and radiation in modulating weather and climate?
- How can one simulate the interactions between the cryosphere and oceans to produce more confident projections of future sea level rise?
- How do terrestrial and ocean biogeochemical cycles influence the atmospheric abundances of greenhouse gases, aerosols and other climate forcing agents?
- How can one best use observations from diverse platforms to evaluate Earth System models, initialize predictions and reduce the uncertainty range of future projections?

The development of this Plan has been a GFDL-wide activity guided by the management and facilitated by the writing team. The Research Council conceived the basic structure of the Plan. The writing team produced the first draft, based on extensive consultation with the GFDL personnel. This draft was then reviewed by the Science Board, Research Council, Divisions and Cooperative Institute. The writing team carefully addressed the review comments and revised the draft. The final version of the Plan was formally adopted at an All-Hands meeting in late August 2019.

As scientific research is opportunistic and rarely follows a prescribed course of action, we intend that this plan will likewise be aspirational in spirit. By articulating our strategy to identify and meet future research and development needs, we make the case that GFDL, guided by the broad set of priorities outlined in this Plan, is well-positioned to exploit unforeseen opportunities as they arise over the next five to ten years. In light of the rapidly shifting landscape of weather and climate modeling, we stand ready to make timely adjustments and take calculated risks.

As detailed in Chapter 2, GFDL's model suite has been consolidated under the last Strategic Science Plan into four major configurations, namely physical climate modeling (CM4), Earth System modeling (ESM4), weather forecasting and sub-seasonal to seasonal predictions (SHiELD), and seasonal to multidecadal predictions and projections (SPEAR). These models share many key components developed at GFDL such as the atmosphere (AM4), ocean (OM4), sea ice (SIS2) and land (LM4), and are branched off from the atmospheric dynamical core FV3 and the Modular Ocean Model MOM6, which have been adopted by other institutions as well. Plans for further model development are also described in this chapter.

The aforementioned model suite is utilized to study key atmospheric, oceanic, cryospheric and biogeochemical components of the climate system with the goal of improving the fundamental understanding of weather and climate phenomena and impacts. The resulting process-level understanding is also critical for model development. Chapter 3 describes the plans to better elucidate the processes and emergent behaviors of the Earth System.

Models and prediction systems developed at GFDL are used to seamlessly predict and project the Earth System from weather to climate scales, with emphasis on assessing predictive skill, exploring venues to realize potential predictability, predicting high impact events and expanding societally-relevant predicted quantities. Assessments of climate predictions and projections identify sources of uncertainties and seek out observational constraints to reduce them. Chapter 4 outlines the plans for future development and use of GFDL prediction systems to meet societal challenges.

GFDL's scientific endeavors are supported by a computational and software infrastructure built upon the concept of **unified modeling**. The infrastructure embodies not only the software aspects of performing computation on advanced parallel architectures, but also the scientific, computational and technical challenges of coupling between Earth System components. Plans to support community model development and adapt to the rapid evolution of supercomputing are given in Chapter 5. Chapter 6 summarizes GFDL's organization, partnerships and collaborations.

Chapter 2: Modeling of the Earth System

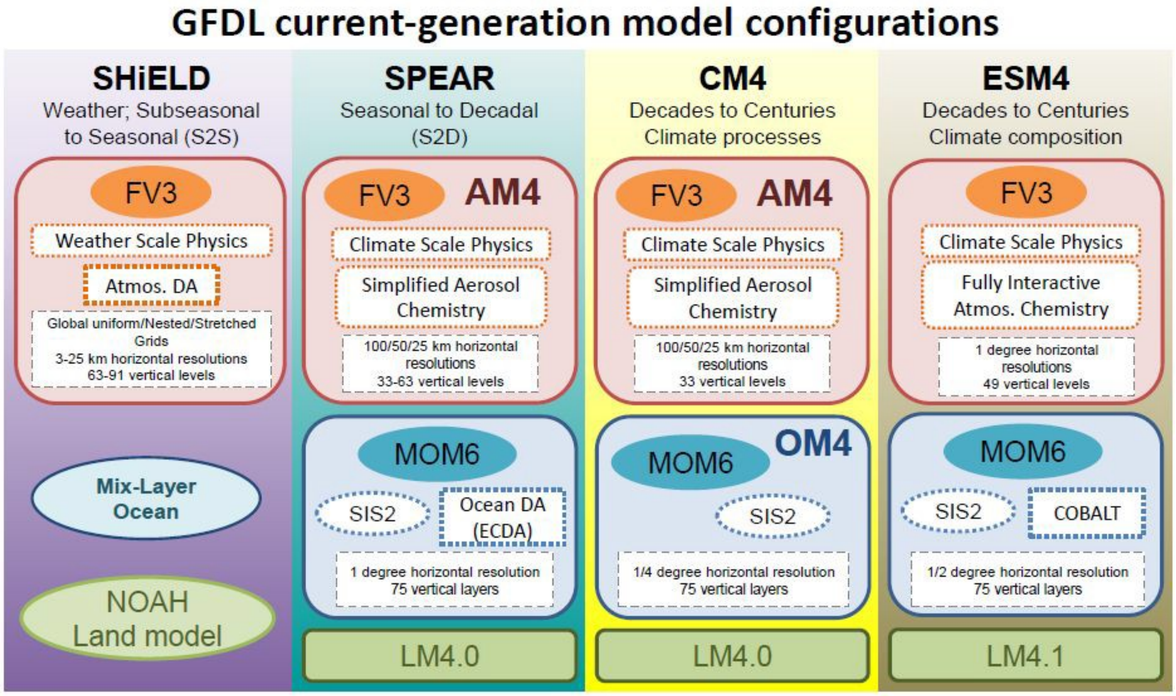

Figure 1: A schematic of GFDL model components and configurations.

To support NOAA's mission and goals by continuously enhancing modeling and prediction capabilities, GFDL has been developing numerical tools for weather, climate and ecosystem research since its founding in 1955. As called for in the last Strategic Science Plan, earlier-generation GFDL models have been unified into a suite of four major configurations:

1. Physical Climate Models for climate research applications
2. Earth System Models for ecosystem and biogeochemical cycle research applications
3. Regional to global models for weather time scales and for sub-seasonal to seasonal (S2S) predictions
4. Regional to global models for seasonal to multidecadal (S2D) predictions and projections.

All these model configurations share a set of in-house developed components. Two of them, the atmospheric dynamical core FV3 and the Modular Ocean Model MOM6, have been adopted widely by many other institutions and constitute GFDL's major contributions to the community-wide weather and climate modeling.

The current-generation workhorse model configurations are CM4 (physical Climate Model), ESM4 (Earth System Model), SHiELD (System for High-resolution prediction on Earth-to-Local Domains) and SPEAR (Seamless system for Prediction and EArth system Research). Over the next 5-10 years they will form the basis for further model development and configurations designed for specific prediction/projection activities.

It is worth emphasizing that model development and application are intricately tied to fundamental understanding of the underlying physical and chemical processes, and emergent phenomena. On the one hand, model simulation, along with observation and theory, is a powerful research tool for understanding the Earth System, which is turbulent and multi-scale in nature. On the other hand, model development ought to be guided by process-level understanding of key Earth System phenomena based on theoretical and observational developments. The efforts to understand and parameterize the processes that cannot be resolved explicitly by models are discussed in Chapter 3.

2.1 Key contributions to community-wide weather and climate modeling

2.1.1 Finite Volume Cubed-sphere Dynamical Core (FV3)

FV3 is a scalable and flexible dynamical core capable of both hydrostatic and non-hydrostatic atmospheric simulations (Lin 2004; Putman and Lin 2007; Lin et al. 2017). All recently-developed GFDL models use FV3 within the atmosphere components. Besides the option of nearly-uniform global resolution, FV3 provides capabilities for global variable-resolution and regional modeling which open new frontiers for GFDL models (Harris and Lin 2013; Harris et al. 2016; Zhou et al. 2019). FV3 has been chosen as the dynamical core for the Next Generation Global Prediction System project (NGGPS), which is an upgrade to the operational Global Forecast System (GFS) and to be run as a unified, fully-coupled system in NOAA's Environmental Modeling System infrastructure. The FV3-based GFS has been fully operational for global forecasts since June 2019 at the National Centers for Environmental Prediction (NCEP).

Further development of FV3 will focus on three main areas. A major thrust will be continued tightening of the physics-dynamics coupling between FV3 and GFDL weather and climate physics suites, and improved treatment of moist and diabatic thermodynamics within dynamics. The energetically-consistent integration of the GFDL microphysics within FV3 is an early success of this effort. GFDL is also working with several external partners to refactor critical parts of the code for non-traditional computing architectures, particularly multicore systems such as Graphics Processing Units (GPU). A longer-lead time goal is to advance the numerics in FV3 by exploring new solution techniques such as simplified Riemann solvers and to improve the accuracy and shape-preservation abilities of the advection schemes, nonhydrostatic solver, and vertical remapping. Further development will also entail improved ingestion of external analyses, initial conditions, and nudging data; refinement of the variable-resolution capabilities; collaboration with other laboratories on variable-composition and deep atmosphere dynamics; and development of regional modeling capabilities.

2.1.2 Modular Ocean Model (MOM6)

MOM6 differs from its predecessors in the use of a new algorithm, the Arbitrary Lagrangian-Eulerian method (ALE), to permit arbitrary general vertical coordinates. MOM6 is being adopted by national centers and universities, in addition to GFDL and Princeton, including the NOAA Environmental Modeling Center (EMC) and the National Center for Atmospheric Research (NCAR). The U.S. Navy is also evaluating a pathway to merge MOM6 into its modeling systems. This rapid adoption of MOM6 is enabled by the numerical integrity of the model, GFDL's commitment to the model, and an "open development" paradigm for code management and collaboration.

Future plans for ocean model algorithm development include the development of new hybrid coordinates optimized locally to follow neutral directions; creation of a hierarchy of fine-resolution global configurations; development of scale-aware parameterizations of mesoscale and sub-mesoscale processes; inclusion of non-hydrostatic effects through algorithmic development with the ALE method; and regional modelling capabilities in collaboration with Rutgers University. To accurately represent ocean-ice-sheet interactions, GFDL will continue to develop MOM6 capabilities (including vertical representations) and configurations that resolve ice-shelf cavities and account for thermodynamic interactions between ice shelves and sub-ice-shelf cavity circulations.

2.2 Model configurations

2.2.1 CM4 - Physical Climate Model

CM4, the current-generation trunk Physical Climate Model, consists of the atmosphere (AM4), ocean (OM4), sea ice (SIS2) and land (LM4) components.

AM4 uses the hydrostatic version of FV3, with 100-km horizontal resolution and 33 vertical levels. The University of Washington shallow convection scheme is augmented with a second plume to simultaneously represent shallow and deep convection; the resulting double-plume convection scheme improves the simulation of not only the climatological distribution of precipitation, clouds, top-of-the-atmosphere (TOA) radiative fluxes but also the tropical transient activities such as tropical cyclones and the Madden-Julian Oscillation (MJO). A simplified aerosol chemistry scheme is used to efficiently incorporate aerosol-cloud-radiation effects into the model. Other improvements include a new topographic drag scheme to represent the effect of subgrid orography, upgrades to the absorption bands, and a new representation of the water vapor continuum in the GFDL radiation scheme. Other details of AM4 can be found in Zhao et al. (2018a, b). Future advances in AM4 will involve increased resolution (horizontal and vertical), with a target of 0.125°; revised aerosol/cloud microphysics (especially aerosol-ice cloud interactions), convection, boundary layer and radiation parameterizations; and advanced nonhydrostatic dynamics and moist thermodynamics.

OM4 is built on MOM6, with 0.25° horizontal resolution and 75 vertical layers and employs a hybrid, pressure/isopycnal, vertical coordinate. Over the next 5-10 years, using experience in the development of high resolution climate models, GFDL will create a suite of climate model configurations with a hierarchy of OM4 horizontal resolutions that progressively increase from global 0.25°, 0.125° and 0.083° to 1 km at high latitudes. This suite will be a powerful tool for addressing science questions regarding the ocean's role in climate, including transient eddies, boundary currents, coastal/shelf processes, and ice-sheet and ice-shelf/ocean interactions.

The GFDL's dynamical/thermodynamical sea ice model SIS has been upgraded to **SIS2** by recasting the dynamics on a C-grid for compatibility with MOM6 and by incorporating the layer structure and radiative transfer treatment used by the Community Ice CodE (CICE) sea ice model. Future development of SIS2's column physics will make use of the Icepack (CICE column physics) code.

LM4 is the latest in a series of land numerical codes for simulating the land hydrological, physical, ecological and biogeochemical processes as well as land interactions with the atmosphere and oceans. A version with simplified vegetation dynamics and soil biogeochemistry (LM4.0) is used in CM4.

2.2.2 ESM4 - Earth System Model

ESM4 focuses on the comprehensiveness of Earth System interactions and combines both the interactive carbon and chemistry of earlier-generation models. The land component LM4.1 (a version of LM4) includes a new vegetation dynamics model with explicit treatment of plant age and height structure as well as interactions with soil microbes. The ocean biogeochemical component COBALT (Carbon Ocean Biogeochemistry And Lower Trophics) represents ocean ecological and biogeochemical interactions. Key features of ESM4 include: revised parameterizations relative to GFDL's previous generation ESM2 series models; doubled horizontal resolution of the atmosphere (2° to 1°) and ocean (1° to 0.5°); fully interactive atmospheric chemistry built on GFDL's previous generation CM3; improved representation of aerosols and their natural precursor emissions; representation of key land ecosystem features, such as vegetation and canopy competition with the perfect plasticity approximation, daily fire, and nitrogen cycling; fully interactive land-atmosphere-ocean system cycling of not only CO_2 but also dust and iron; and fully interactive ocean-atmosphere cycling of both oxidized and reduced nitrogen species.

2.2.3 SHiELD - Model for Weather and Sub-seasonal to Seasonal (S2S) Predictions

The System for High-resolution prediction on Earth-to-Local Domains (SHiELD) model originates from the GFDL fvGFS model which was built during the NGGPS Phase II. The original version of fvGFS used the FV3 dynamical core coupled to the physics package from NCEP's GFS (Zhou et al. 2019). The 2018 updated fvGFS has demonstrated its superior skill on 10-day synoptic scale forecasts and hurricane predictions (Chen et al. 2019a,b). The model was renamed to SHiELD in early 2019. In contrast to CM4, SHiELD uses the Noah land model and physics suites for weather time scales. Comparing to the NCEP GFSv15 which just launched on June 12, 2019, SHiELD includes some advanced features, e.g. positive definite advection scheme and inline cloud microphysics scheme. Moreover, SHiELD provides the option to use Yonsei University (YSU) planetary boundary layer (PBL) scheme and a mixed-layer ocean model. Five sub-configurations have been built for SHiELD to accommodate global and synoptic circulations, hurricanes, severe weather events, S2S predictions, and global cloud resolving research. Each of the individual SHiELD configurations receives regular updates every one to two years to incorporate new science developments and to address new GFDL scientific goals. SHiELD can rapidly take advantage of new FV3 and physics developments from both the GFDL team and the external community as well as new updates in FMS to permit coupling between weather-scale physics and other core components such as LM4 and MOM6.

The globally-uniform medium-range model will refine both horizontal and vertical resolution, with a goal in the next few years to reach 6.5-km resolution with 127 levels. A data assimilation system is also being built to take advantage of developments in the GFDL microphysics and land surface model. The global- and nested-grid cloud-resolving simulations will continue to push to higher resolutions as resources permit; the nests will be useful as specialized tools to focus in on specific extreme events such as hurricanes, severe weather, or winter storms. S2S prediction using SHiELD will focus on improving predictions of both intraseasonal oscillations (including MJO), and hydroclimate (especially floods and droughts). A longer-term research goal is to apply SHiELD as a high-resolution climate model capable of convection-permitting simulation (globally or regionally) to study the effects of external forcings and internal variability on extreme weather and climate events. Regular, significant increases in GFDL computing resources are necessary for enabling SHiELD to address these societal needs and tackle new scientific questions.

2.2.4 SPEAR - Model for Seasonal to MultiDecadal (S2D) Predictions and Projections

The Seamless System for Prediction and EArth System Research (SPEAR) is designed as a seamless climate prediction and projection system for time scales from one season to multiple decades. SPEAR can run as a prediction model starting from observed conditions, and also responds to changing radiative forcings. SPEAR is composed of the same building blocks as CM4, but configured at resolutions optimized for seasonal to multidecadal predictions and projections, given computational constraints. The data assimilation and predictions require large ensembles; this computational burden is offset by using 1° ocean and sea ice models in SPEAR (versus 0.25° in CM4). There are multiple versions of SPEAR using different atmospheric resolutions (100 km, 50 km, 25 km); the finer atmospheric resolutions enhance predictions of regional climate and extremes, including heat waves and hurricanes. SPEAR is initialized using the GFDL Ensemble Coupled Data Assimilation (ECDA) system, described in Sec. 4.1.2.

Efforts are underway to develop a version of SPEAR with a better resolved stratosphere to capture troposphere-stratosphere interactions and their influence on seasonal to decadal predictions and teleconnections. A version of SPEAR is being planned that will incorporate ongoing developments in LM4, including an improved representation of dust and its impacts on phenomena such as drought. A version of SPEAR is being developed with a 25 km atmospheric resolution in order to improve the simulation and prediction of regional climate and extremes, especially the seasonal risks of intense hurricanes. To facilitate prediction of regional climate and extremes over North America, a version of SPEAR is planned that incorporates a refined 10 km atmosphere and land grid over North America using the capabilities of SHiELD. As computing resources permit, the ocean horizontal resolution of SPEAR will be enhanced from 100 km towards 25 km or even finer, to better simulate oceanic eddies and the ocean circulation and variability near coastal zones, straits, and islands. Earth system components from ESM4 — including atmospheric chemistry and ocean biogeochemistry — will gradually be integrated into the assimilation and prediction systems to support reanalyses, predictions, and projections relevant to air quality, marine and land ecosystems, fisheries, forestry, and agriculture.

Chapter 3: Understanding of the Earth System

GFDL is well-positioned to use numerical modeling, in conjunction with available observations, to advance the fundamental understanding of major Earth System phenomena and their underlying mechanisms. The resulting knowledge base proves crucial for **informing model development**, and provides **scientific foundations for Earth System predictions and projections**, both of which are central to fulfilling NOAA’s mission and goals. The efforts can be broadly organized into four research areas: (1) atmospheric, oceanic and cryospheric processes, (2) biogeochemical processes, (3) weather and climate extremes, and (4) climate variability and change.

A cross-cutting theme of GFDL research is identifying and understanding the causes of biases in models and predictions, and understanding the inter-model diversity of behaviors. We do this by confronting the models and predictions with a diverse and rapidly-growing wealth of observations. This comparison identifies and addresses gaps in current understanding, and often leads to **discoveries of new processes, phenomena, and sources of predictability**. Model studies help guide future observing strategies, by targeting measurements of poorly understood phenomena, sources of error in predictions, and sources of uncertainty in climate projections.

3.1 Past Accomplishments

3.1.1 Atmospheric, Oceanic and Cryospheric Processes

We seek to elucidate the dynamical and physical mechanisms through which the atmospheric, oceanic and cryospheric processes affect the weather and circulation patterns, climate variability and long-term changes in sea ice and sea level, with special emphasis on those that are an impediment to seamless modeling and predictions. Recent accomplishments include:

- Improved simulation and understanding of **aerosols, clouds, microphysics, boundary layer and radiation**, which give rise to large model biases and uncertainties. Jones et al. (2017) attributed some of the uncertainty in aerosol direct forcing to the radiative transfer parameterizations used in climate models. The biases in cloud-related metrics such as the TOA shortwave and longwave radiative fluxes in AM4 were reduced substantially (almost by half in many cases) when compared to previous generations of GFDL models (Zhao et al, 2018a and 2018b). Applying a developmental version of AM4, Zhao et al. (2016) demonstrated that cloud feedbacks and climate sensitivity were affected strongly by the different treatments of turbulent mixing and cloud microphysics in convection parameterizations. Guo et al. (2014) implemented a unified turbulence and cloud scheme based on multi-variate probability density functions in the GFDL AM3 model. Shin et al. (2018) evaluated the performance of different boundary layer schemes in simulating the diurnal cycle.

- Development of efficient, physically-based parameterizations to represent **small- and meso-scale oceanic processes** in ocean climate models with resolutions not fine enough to resolve them realistically. These processes help maintain climate by mixing and transporting heat, salt and carbon around the ocean, influencing large-scale circulation and climate. For example, parameterizations have allowed accounting for meso-scale baroclinic eddies (e.g., Hallberg 2013; Griffies et al., 2015), local breaking of internal tides (Melet el al, 2013), topographic lee-waves (Melet et al, 2014), the inverse cascade of mesoscale eddy energy (Jansen et al, 2015a,b), the transport constraints of unresolved topography (Adcroft, 2013), the surface mixed layer (Reichl and Hallberg, 2018) and Langmuir turbulence (Reichl et al, 2018).

- Better understanding of the **interactions between the oceans and ice-shelves, icebergs and sea ice** and their representation in GFDL models for skillful predictions of sea level rise and changes in the rate of ice melt and large-scale ocean currents in response to changing climate. For example, to improve understanding of dynamics of ice streams that account for about 90% of ice discharge from ice-sheets into surrounding oceans, Sergienko and Hindmarsh (2013) used inverse techniques to constrain subglacial processes underneath them. Stern et al. (2017) developed an improved approach to represent icebergs in GFDL ocean models and shed light on the consequences of large-scale calving events for the Earth System.

3.1.2 Biogeochemical Processes

Human activities are transforming local, regional and global biogeochemical cycles in fundamental ways, both directly (for example through pollution or land modification) and indirectly (through modification of Earth's climate). We seek to advance comprehensive understanding of the biogeochemical processes that influence the atmosphere, land, and ocean components of the Earth System, and the sensitivity of those processes to climate and human activities and associated feedbacks and impacts. Recent accomplishments include:

- Better understanding of long-term variations in and processes that influence **atmospheric chemical composition** (greenhouse gases and aerosols), which affect climate, weather and air quality, using GFDL models that resolve atmospheric chemistry and aerosol processes over the full atmospheric domain. For example, Lin et al. (2015) identified a mechanistic link between strong La Nina winters and transport of stratospheric ozone into the troposphere leading to high surface ozone concentrations at high-elevation western U.S. regions during spring. Paulot et al., (2016; 2018) demonstrated the important role of ammonia emissions in influencing the production of inorganic aerosols with implications for future air quality and climate.

- Improved understanding of **land-climate interactions** and feedbacks via mechanistic treatment of ecological, biogeochemical and hydrological processes and heterogeneity in the GFDL land model, with implications for atmospheric rivers, and coastal environments. For example, implementation of dust emissions into the LM4 has greatly improved the simulation of dust interannual variability (Evans et al. 2016). Representation of the fully coupled plant-mycorrhizal-soil interactions in LM4 helped demonstrate that ecosystems can adapt to plant-microbe symbioses sustaining future carbon sink (Sulman et al., 2019) contrary to the prevailing view that future plant growth and carbon storage will be limited by the availability of soil nutrients, such as nitrogen.

- Improved understanding of the role of **ocean biogeochemistry** in the carbon and nutrient cycles, and the marine resources upon which society relies using the COBALT ocean biogeochemical model that resolves plankton food web processes. COBALT has been applied to understand the amplification of climate-driven ecosystem shifts in ocean food webs (Stock et al., 2014), global relationships between ocean productivity and fisheries (Stock et al., 2017), and the predictability of biogeochemical signals on seasonal to multi-annual time-scales (Park et al., 2019).

3.1.3 Weather and Climate Extremes

Skillful forecasts and improved knowledge of the linkages between weather and climate are crucial for NOAA's objective of reducing loss of life, destruction of property, and disruption from high-impact events. Research at GFDL focuses on elucidating the drivers and impacts of climate and weather extremes, such as tropical cyclones, hurricanes, droughts and flooding, wildfires, monsoon depressions, the El Niño/Southern Oscillation (ENSO), and heat waves. Recent accomplishments include:

- Increasingly realistic global and regional modeling of **tropical cyclones and hurricanes** (Hazelton et al. 2018, Chen et al., 2019a,b), supporting skillful forecasts of sub-seasonal to seasonal timescales (Gao et al. 2017). GFDL global and regional models have been used to explore changes in tropical cyclone risks in a changing climate (Knutson et al. 2013; 2015; Murakami et al. 2017; Bhatia et al. 2018; 2019). Idealized models developed at GFDL have probed fundamental questions about tropical cyclones and their climatology (e.g., Merlis et al. 2016).
- A theory of the dynamics of **South Asian monsoon depressions**, synoptic-scale disturbances that originate over the Bay of Bengal and propagate westward over the Indian subcontinent. GFDL's analyses of the dry static energy and moisture budgets of these depressions simulated in AM4 led to development of a linear theory combining quasi-geostrophic dynamics with convection (Adames and Ming, 2018a, 2018b).
- Better understanding of the influence of land surface processes in modulating **regional climate extremes**. For example, Findell et al (2017) used the GFDL ESM to show that conversion of forests to cropland contributed to more frequent extreme hot and dry summers over much of the upper central U.S. and central Europe.

3.1.4 Climate Variability and Change

Deep understanding of the causes and effects of climate variability and change is needed to support development of policy options to **mitigate** the human causes of climate change and **adapt** to climate impacts. We conduct research on natural and anthropogenic radiative forcings, climate sensitivity, regional circulation and hydrological changes, and detection/attribution of observed climate variations and change. Recent accomplishments include:

- Improved understanding of **regional hurricane variability and change**. GFDL's seasonal prediction system was used to identify the dominant role of tropical Atlantic sea surface temperature (SST) in producing enhanced major hurricane activity in the Atlantic basin in 2017 (Murakami et al., 2018), and to diagnose the causes of unusually strong Pacific hurricane activity including the roles of anthropogenic forcing and internal variability (Murakami et al., 2017b, 2018). The system was further used to identify emerging threats of increased severe cyclonic storms in the Arabian Sea due to anthropogenic forcing (Murakami et al., 2017a).
- Better understanding of **hydroclimate variability, predictability, and extremes**. GFDL researchers assessed the seasonal predictability of precipitation and storminess over North America (Yang et al., 2015, 2018) and the Intra-Americas Seas (Krishnamurthy et al., 2019). Additional studies explored the dependence of rainfall extremes on model resolution, and probed future changes in hydroclimate extremes – including Mississippi flooding and extreme rainfall (Van der Wiel et al., 2016, 2017, 2018), the North American monsoon (Pascale et al., 2017, 2018), decadal hydroclimate extremes over North America (Zhang and

Delworth, 2017, 2018), and tropical rainfall sensitivity to local variations in SST (He et al., 2018).

- Better understanding of **ENSO dynamics and seasonal-to-interannual predictability**. Recent GFDL studies illuminated the processes responsible for the diverse and changing characteristics of ENSO in coupled global climate models (GCM) (Atwood et al. 2017; Chen et al. 2017; Graham et al. 2017; Wittenberg et al, 2018; Ray et al, 2018a,b). Further studies highlighted the key role of atmospheric initialization in predicting the impacts of the 2015/2016 El Niño (Yang et al., 2018), and the role that the stratosphere plays in seasonal predictions (Jia et al., 2017). GFDL research and models also advanced understanding of the impacts of explosive volcanic eruptions on ENSO (Predybaylo et al., 2017), and the effects of ENSO and North Atlantic SST variability on tornado outbreaks over the U.S. (Lee et al. 2016).

- Improved understanding of the sources of **decadal variability and predictability**. Delworth et al (2016, 2017) showed an important role for oceanic heat transport variations in driving Atlantic Multidecadal Variability and its climatic impacts, including Arctic sea ice change, North American heat waves (Ruprich-Robert et al, 2018), and monsoonal precipitation. Further work has shown the presence of highly predictable multidecadal variability that may have played a role in recent observed changes in Southern Ocean sea ice and temperature (Zhang et al., 2017, 2019). Research on the Pacific Decadal Oscillation (PDO) has assessed both its mechanisms (Zhang and Delworth, 2015) and its sensitivities to anthropogenic radiative forcings (Zhang and Delworth, 2016).

- Improved understanding of **direct and indirect aerosol forcings**, a major source of uncertainties in climate projections. Enhanced representation of inorganic aerosols and processes in AM3 helped constrain the sensitivity of future climate projections to aerosol emissions (Paulot et al., 2018). Xin and Ming (2019) demonstrated that aerosols, by increasing cloud droplet numbers, induce stronger convective updrafts, via mechanisms independent of cloud ice microphysics. A series of GFDL model simulations forced with observed SST and different forcing combinations were used to constrain historical aerosol forcing and climate sensitivity (Shen et al., 2019).

- Improved understanding of three key **climate sensitivity** metrics that contribute to uncertainties in climate projections: the transient climate response (TCR; Winton et al., 2019), the transient climate response to cumulative carbon emissions (TCRE; Frölicher et al., 2014; Krasting et al., 2014), and the equilibrium climate sensitivity (ECS; Krasting et al., 2018; Paynter et al., 2018). In particular, TCRE is used to quantify the emission limits implied by specified warming limits. Recent GFDL research has explored the linkages among these sensitivities, cumulative carbon emissions, and climate change.

- Better understanding of **past climate** variations and changes, and assessing projections of **future climate** change. Knutson and Zeng (2018) identified an anthropogenic influence on observed regional precipitation trends over the northern U.S. and other extratropical regions; CMIP5 (the fifth phase of the Coupled Model Intercomparison Project) simulations underestimate these trends, raising questions about the reliability of the CMIP5 models for projections of future hydroclimate in those regions. Numerous GFDL studies have also examined internal (unforced) climate variability, which is a key contributor to observed climate variations. They include mechanisms of Atlantic Multidecadal Variability (AMV)

(Zhang et al. 2016, 2019; Zhang, 2017; Yan et al. 2019), low frequency variability of Arctic sea ice extent (Zhang, 2015; Li et al. 2017, 2018), interactions between the North Atlantic Oscillation (NAO), Atlantic variability, and Arctic sea ice (Delworth and Zeng, 2016; Delworth et al, 2016; Delworth et al, 2017), and multidecadal variability of Atlantic hurricane frequency (Yan et al. 2017).

- Development and application of "perfect-model" and sensitivity study experimental designs (Dixon et al., 2016; Lanzante et al., 2017) to evaluate the performance of **statistical downscaling** methods that aim to address shortcomings in large-scale dynamical climate models on time scales of weeks to multiple decades. In addition to quantifying downscaling effects on climate forecasts and projections, these studies highlight strengths and weaknesses of the statistical methods and dynamical models, which informs future development efforts.

3.2 Future Plans

Over the next 5-10 years, GFDL will continue to conduct cutting-edge research in mission-critical areas. As a federally funded research institution, GFDL is well suited for long lead-time work with the potential for significant scientific breakthroughs. Yet, it remains important to carefully balance competing needs (risk vs. return, process-level understanding vs. simulation of emergent phenomena, simplicity vs. comprehensiveness, etc.). The planned activities detailed below reflect our latest thinking on these fronts.

The suite of GFDL models (AM4, CM4, SHiELD, and SPEAR, as well as FV3-based global cloud system resolving models) presents an opportunity to tackle some long-standing issues related to **aerosol-cloud-convection-radiation-circulation-climate connections**, including: 1) improved representation of fundamental processes such as aerosol/cloud microphysics, aerosol-ice cloud interactions, boundary layer process and radiative transfer; 2) inter-model diversity in climate sensitivities (TCR/ECS), cloud feedbacks, and aerosol-cloud interactions (aerosol indirect effects), via sensitivity experiments; 3) creative use of observations together with multi-model outputs to derive emergent constraints on the role of clouds in climate sensitivity; and 4) effects of convection and clouds in model simulations and predictions of weather and climate extremes, including tropical and winter storms, floods, and droughts. We will employ a hierarchy of models from complex to highly idealized (including process-level models such as global line-by-line radiative transfer models, cloud parcel models, limited-domain large-eddy simulation and cloud resolving models), to explore, understand and quantify mechanisms underlying aerosol-cloud-radiation-weather-climate interactions, collaborating with outside communities, for example via the Climate Forcing Model Intercomparison Project (CFMIP).

Improvements to **ocean subgrid parameterizations** will be explored to enhance understanding of the role of the oceans in the climate system. The porous barrier representation of topography (Adcroft, 2013) will be applied in three-dimensional circulation models, to better represent topographically-controlled exchange processes. The energetically-constrained tidal mixing parameterization (Melet et al, 2013; Melet et al, 2016) will be extended to include variations in the fraction of internal tide energy dissipated locally (Nikurashin and Legg, 2011; Yi, Legg and Nazarian, 2017), subgrid-scale topography (Melet et al, 2013b; Lefauve et al, 2015), trapped breaking waves in high latitude regions, and far-field dissipation of propagating internal tides.

The lee-wave driven mixing scheme will incorporate critical layer wave-breaking. Parameterizations of mesoscale eddies will be increasingly resolution-aware (Hallberg, 2013), and account for vertical structure and standing eddy fluxes. We will evaluate alternative eddy parameterization approaches in eddy-permitting models (e.g. Bachman et al, 2017). The inverse cascade of mesoscale eddy energy (Jansen et al, 2015a,b), the surface mixed layer (Reichl and Hallberg, 2018) and Langmuir turbulence (Reichl et al, 2018) will be extensively studied. The mixed layer eddy parameterization will be improved to account for heterogeneity of vertical convection (Ilicak et al, 2014). We will explore parameterization of submesoscale instabilities in the bottom boundary layer adjacent to topography (Yankovsky and Legg, 2018). Parameterizations of the surface mixed layer and fluxes across the air-sea interface will incorporate wave effects, through the WAVEWATCHIII model coupled to the ePBL vertical mixing framework, and wave-based parameterizations for gas transfer and sea spray will be developed. The capability in Stern et al. (2017) will be used extensively to simulate the subsequent evolution of large-scale calving events to better understand their consequences for the Earth System.

GFDL will continue to deepen understanding of **interactions within and between Earth System components**. With the development of ESM4 now complete, we envision continued innovative applications of this model to advance understanding of atmospheric, terrestrial and oceanic biogeochemical cycles (e.g., carbon, nitrogen, dust and iron). Model development efforts will be directed towards improved representation of processes within individual Earth System components, and biogeochemical interactions between them to enable novel investigations of natural and human influences on the biosphere and climate. More realistic representation of atmospheric composition and chemistry, including long-range transport of air pollutants, secondary organic aerosols from anthropogenic and biogenic precursors, stratospheric aerosols in both background and volcanic conditions, and enhancements in chemical mechanisms (e.g., tropospheric halogen chemistry) will advance understanding of changing atmospheric composition and its influence on climate and air quality. Improved coupling of atmospheric chemistry with land and ocean components, involving representation of trace gas and aerosol emissions (e.g., biogenic volatile organic compounds, marine aerosols, dust, nitrogen and sulfur gases) and deposition will enhance understanding of interactions and feedbacks between climate and the biosphere. Enhancements in the representation of hydrological (e.g., irrigation and reservoirs, lakes and rivers) and urban processes in LM4.1 will provide further means to assess the contribution of anthropogenic activities to composition and climate changes. Integration of ocean biogeochemistry with terrestrial (e.g., nutrient loading from rivers, Lee et al., 2019) and atmospheric dynamics (e.g., dust and nutrient deposition/exchange, Evans et al., 2016; Paulot et al., 2015) will elucidate the oceanic imprint of carbon and nutrient flows across Earth System components. Assimilation of satellite and biogeochemical-ARGO observations will advance seasonal to decadal ocean ecosystem predictions. Research advances will continue to be integrated to improve biogeochemical model robustness, prioritizing coastal and sedimentary processes in light of the burgeoning capacity to resolve shelf ecosystems and the land-sea margin.

Model simulations will be used to help **interpret observations** of physical processes and of past weather and climate variations, to advance scientific understanding of the drivers of variability and predictability. GFDL will continue to improve the understanding of low-frequency Atlantic Meridional Overturning Circulation (AMOC) variability, AMV, and impacts on various climate phenomena and ecosystem system. We will investigate how long-standing model biases affect low-frequency AMOC variability and associated climate impacts for future improvements. These studies are important for understanding and attributing observed historical changes in terms of externally forced response and internal variability, and the projections of future changes in regional- and hemispheric-scale climate phenomena.

Model development and application efforts will push towards **increasing resolution**, to address societally-important scientific questions at regional and local scales. To understand the role of ocean weather in the Earth System, high-resolution ocean modeling with biogeochemistry will build upon CM2.6/ESM2.6 to provide a more advanced ESM4 framework. The coupled interactions between ocean and ice sheet/ice shelf/icebergs will be integrated into the ESM framework to understand their impacts on the Earth System. To further advance GFDL's seamless weather-climate research, we seek to incorporate comprehensive atmospheric chemistry and land-atmosphere interactions into high-resolution atmospheric models and prediction systems. Simulations with high-resolution ESMs will clarify connections among atmospheric composition, regional and global climate, and implications for air quality and human health.

CM4 and ESM4 will produce simulations of **internal climate variability** and **climate responses to external forcings**. The new SHiELD, SPEAR models, and FV3-based global cloud system resolving models will offer platforms for continued exploration of weather and climate extremes and their responses to changing climate. Careful analysis, detection/attribution, and consistency studies will identify emerging signals and threats from anthropogenic climate change. GFDL's ESMs will be used to evaluate transient climate responses, understand terrestrial and oceanic carbon sinks, and explore links between climate-carbon cycle feedbacks and climate sensitivity. There will be a continued focus on characterizing the response of global temperatures to increasing greenhouse gas concentrations, and on identifying anthropogenic climate signals at the regional scale, particularly for challenging but societally-relevant weather and climate phenomena such as tropical cyclones, droughts, floods, ENSO, atmospheric or ocean circulation changes, regional sea level rise, and statistics of extreme events.

Confronting models with **observations** will remain a crucial activity. A wide range of observations (ground and satellite remote sensing, field campaigns involving aircrafts and ships, long-term surface temperature and radiative flux records, etc.) will continue to be used for model evaluation and development. In cases where inconsistencies between observations and simulations are found, these imply possible problems with model representation of key processes, model-simulated responses to forcings, model-simulated internal variability, climate forcing estimates, or even observational issues. Such identified inconsistencies can eventually lead to improved predictive understanding and improved models, forcings, and observing strategies.

Chapter 4: Predictions and Projections of the Earth System

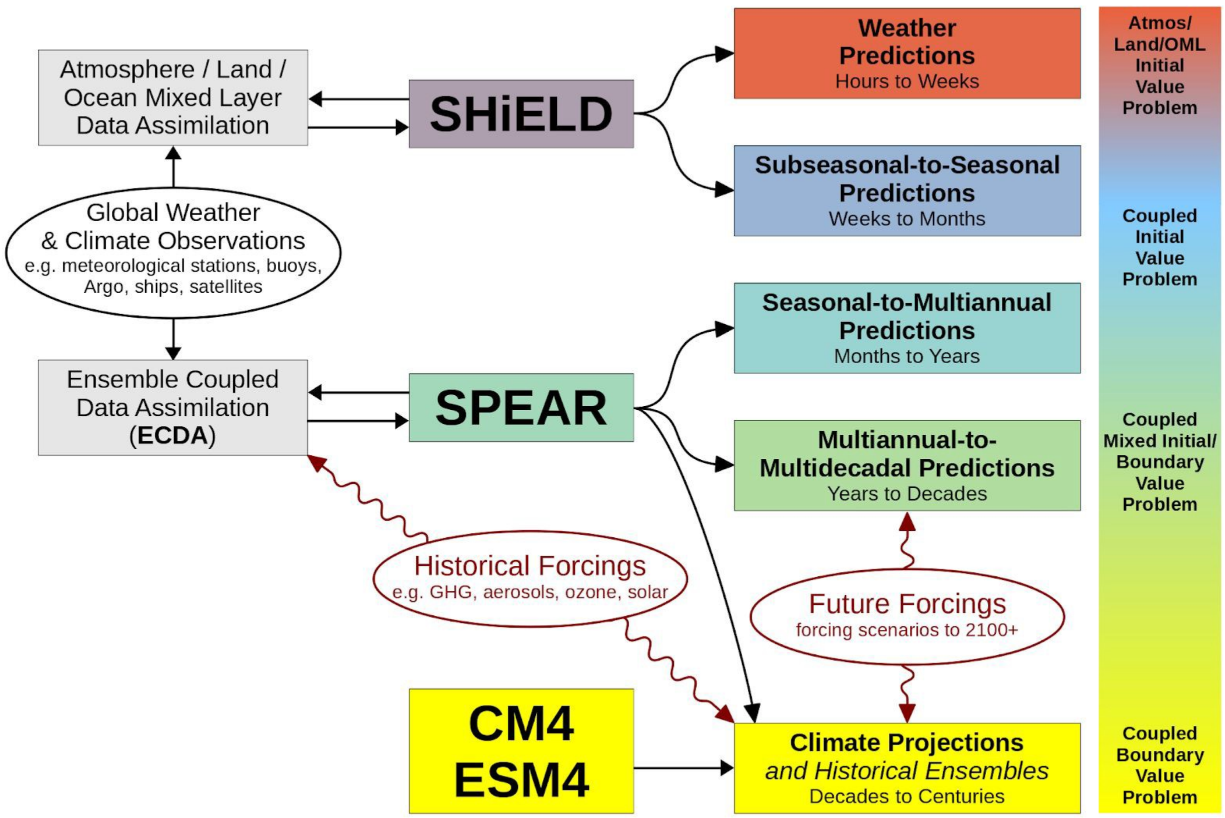

Figure 2. GFDL's 5-10 year strategy for seamless global predictions and projections of weather and climate. Figure adapted from Tommasi et al. (2017).

Weather and climate predictions and projections provide information for the Nation's businesses, communities, and people's daily lives, and are a key part of NOAA's mission and the Weather Research and Forecasting Innovation Act of 2017. To support these goals, GFDL seeks to **improve predictions and projections of future weather and climate, using approaches that are seamless across temporal and spatial scales**. GFDL will build upon a strong scientific foundation and history of engagement with interagency and academic partners, to develop next-generation prediction and projection systems that serve its stakeholders and build weather and climate resiliency. These systems will be used to quantify existing and potential predictive skill; identify the sources of predictability and skill; and develop more skillful and useful predictions on timescales of hours to decades. They will also generate historical reanalyses and future projections to inform national and international assessments of climate variations and change, societal impacts and vulnerability, and mitigation and adaptation strategies [e.g. National Climate Assessments (NCA), IPCC, CMIP].

Hurricane predictions and projections offer a clear example of the value of using a seamless multiscale approach. Hurricane genesis and track depend on ocean temperatures and weather systems occurring at synoptic-to-global scales, and are influenced by MJO, seasonal cycle, ENSO, decadal climate modes, and by climatic responses to radiative forcings. Hurricane intensity depends acutely on mesoscale-to-microscale air-sea interactions, convective feedbacks, and turbulence. Hurricanes also feed back onto climate at larger scales — by enhancing the upper-ocean mixing that mediates decadal-scale ocean heat uptake and sea level rise, and by generating equatorial Pacific wind bursts that can trigger an El Niño event with global impacts.

Complex multiscale interactions are also characteristic of many other phenomena and their impacts, including ENSO, monsoons, droughts and floods, heat waves, severe storms, wildfires, air quality, crop freeze events, Arctic sea ice variability, and the impacts of climate on ecosystems, fisheries, food security, and water supply. Capturing these interactions and impacts therefore requires a seamless multiscale framework for modeling, data assimilation, predictions, and projections. Seamless predictions also illuminate predictability and variability across timescales, and drive further technological development — honing the robustness, reliability, efficiency, and utility of the models and prediction systems.

4.1 Past Accomplishments

4.1.1 Track Record

Since 1955, GFDL has pioneered weather and climate modeling, predictions, and projections with increasing realism across a wide range of spatial and temporal scales. Some recent highlights include:

- Development of HiRAM, an atmospheric GCM that produced skillful retrospective subseasonal-to-seasonal simulations and predictions of hurricane activity in the North Atlantic, Gulf of Mexico, and Caribbean Sea (Chen and Lin 2011, 2013; Gao et al. 2017).
- Development of FLOR, a coupled GCM that produced the first skillful global seasonal forecasts of regional hurricane activity (Vecchi et al. 2014), and greatly improved global seasonal forecasts of temperature and rainfall over land (Jia et al. 2015).
- Since 2015, delivery of real-time global seasonal predictions to the North American Multi-Model Ensemble (NMME), Climate Prediction Center (CPC), National Hurricane Center (NHC), and Sea Ice Prediction Network (SIPN).
- GFDL's seasonal prediction system has been shown to predict previously elusive phenomena, including: predicting seasonal hurricane activity by location, successfully predicting the enhanced major hurricane activity in the Atlantic basin in 2017 (Murakami et al., 2018), and skillfully predicting western US snowpack nine months in advance (Kapnick et al., 2018).
- The first global coupled GCM to simulate category-5 hurricanes (Murakami et al. 2015).
- Substantiation of the importance of aerosol direct and indirect effects for future climate projection (Levy et al., 2013).
- Delivery of experimental convective-scale short-range forecasts to NOAA's Hazardous Weather Testbed and Hydrometeorology Testbed, and participation in key extreme weather prediction experiments (Spring Forecasting Experiment, Flash Flood and Intense Rainfall Experiment).

- The FV3 atmospheric dynamical core, selected for operations as the Next-Generation Global Prediction System (NGGPS, Zhou et al. 2019, Chen et al. 2019a,b).
- Since 2017, participation of a nested version of SHiELD in the annual Spring Forecasting Experiment of the Hazardous Weather Testbed, which evaluates the utility of convective-scale prediction models and ensemble systems for real-time severe storm and tornado forecasts (Harris et al. 2019).
- Participation as a Contributing Center in the WMO Annual-to-Decadal Climate Prediction (ADCP) Project coordinated by the U.K. Met Office (UKMO).
- Participation in CMIP6 and its endorsed MIPs to support IPCC and NCA, including model intercomparisons directed at understanding historical changes and future projections.
- Extensive use of high resolution and comprehensive GFDL model results by Fisheries and Ocean Service partners, to translate Earth System variability into vulnerability and impact assessments.

Within NOAA, GFDL's role is to focus on **application-inspired basic research**. In particular, GFDL's real-time forecasts are proving grounds for next-generation technologies and methods. Once a new system demonstrates clear improvements, GFDL works with partners across NOAA to adapt it for operations.

4.1.2 Readiness

GFDL is well-positioned to advance seamless predictions and projections. Over the past decade, GFDL has steadily improved both the realism and comprehensiveness of its prediction tools, and has gained experience in using them to provide skillful, real-time predictions of weather and climate to external partners (including the NMME, NCEP/NHC, NCEP/CPC, SIPN, and IRI), to inform their forecasts and seasonal outlooks.

The new System for High-resolution modeling of Earth-to-Local Domains (**SHiELD**) — comprising the nonhydrostatic FV3 atmospheric dynamical core, GFDL microphysics, and other weather-scale physical parameterizations — is already enabling seamless experimental **weather and subseasonal to seasonal (S2S)** predictions. Since 2016, this system has provided real-time global 13-km resolution 10-day forecasts initialized every 6 hours. The stretched and nested grid capabilities of FV3 enable resolution refinement where it is needed, to capture severe weather events and regional climate variations. The 3-km nested hurricane grid version of SHiELD is run every 6 hours during the north Atlantic hurricane season. The 3-km nested continental U.S. configuration is run every 24 hours, focusing on the prediction of severe weather events in the warm season and on heavy snow and ice events in the cold. The real-time forecasts are provided via the GFDL data portal. A 25-km configuration of SHiELD is now being tested for S2S forecasts, with preliminary simulations showing a realistic climatology. All-sky radiance assimilation has recently been developed for multiple hydrometeors within the GFDL microphysics scheme, and is expected to improve S2S forecast skill.

A new Seamless system for Prediction and Earth System Research (**SPEAR**) has also been developed for **seasonal-to-multidecadal** predictions and projections. SPEAR and CM4 use the same underlying component models (AM4, LM4, MOM6, and SIS2), but the components in SPEAR are specifically configured to support seasonal to decadal prediction efforts, given limitations on available computational resources. Multi-century simulations of SPEAR — using

100, 50, and 25 km global grid meshes for the atmosphere and land components, coupled to 1° ocean and sea ice components — have already demonstrated good physical realism and computational performance. The 100 km and 50 km versions are now being tested in prediction mode using retrospective seasonal-to-decadal ensemble forecasts.

GFDL's seasonal predictions are initialized using GFDL's **Ensemble Coupled Data Assimilation (ECDA)** system, which uses multiple concurrent coupled simulations to represent the evolving state of the coupled climate system and quantify its uncertainties. The ECDA solutions are constrained by global observations of SST, subsurface temperature and salinity, and atmospheric temperature and winds, by updating the local analysis based on the prior distribution of the ensemble for each variable and observational location. Each observation also influences a spatiotemporal neighborhood of gridpoints and other variables, according to statistical relationships diagnosed from intra-ensemble covariances that evolve in both space and time according to the model dynamics. The ECDA has proved to be a powerful and adaptable framework for data assimilation, enabling new models and observational data types to be readily incorporated and adapted for predictions. GFDL's existing ECDA, based on CM2.1, has been used to initialize seasonal forecasts from CM2.1, FLOR, and hiFLOR, and has provided global coupled reanalyses of the climate system to the community for over a decade. Preliminary integration of aspects of ocean biogeochemistry with an earlier version ECDA has shown exciting potential for global ocean-ecosystem prediction. A more complete integration of ocean biogeochemistry with ECDA would further build connections between SPEAR and ESM4-related development, leading to more robust capabilities for global ocean-ecosystem prediction.

For **decadal-to-centennial** projections, GFDL has pursued targeted research projects and contributed to international efforts through participation in CMIP6. These efforts and contributions highlight areas needed for model improvement, and research projects required to push innovation and scientific knowledge. **CM4**, **ESM4** and **SPEAR** are enabling more comprehensive decadal-to-centennial projections of global climate, ecosystems, air pollution, and the carbon cycle under various forcing scenarios. Model data will be provided to the public via GFDL's Data Portal, and used in assessments of climate change and its impacts. These models produce excellent simulations of historical climate and variability, with greatly reduced biases relative to previous GFDL models. In addition to enhanced simulation quality and spatial detail, CM4 and ESM4 also provide new capabilities for simulating atmospheric chemistry, ocean biogeochemistry, and ecosystems. In combination with GFDL's growing scientific expertise and collaborations with Princeton University and the broader scientific community, these new capabilities will support future advances in predictions and projections to serve NOAA's Climate, Weather and Water, and Ecosystems goals.

4.2 Future Plans

4.2.1 Overview

Over the next 5-10 years, GFDL will continue leveraging its recent advances in understanding and modeling to enable seamless hourly to multidecadal predictions and projections of weather and climate variability and change. Key research foci will be:

- Improving predictions of high-impact events (such as hurricanes, floods, severe storms, and droughts) at lead times of hours to years.
- Narrowing the gap between the potential predictability and realized prediction skill of various climate phenomena.
- Expanding the range of Earth System metrics of societal interest or actionable value to stakeholders that can be skillfully predicted.
- Predicting and projecting how the climate system, particularly with regard to extremes, will evolve over the next several decades on global and regional scales.
- Anticipating how the climate system (e.g., temperature, precipitation, sea level, sea ice, drought, circulation, extremes, interannual variability, etc.) will evolve over the coming century and longer time scales, in response to future emission scenarios and other human activities.
- Developing Earth System modeling capabilities to predict the climate, weather, and ecosystem impacts of abrupt global-scale forcing events (such as volcanic eruptions, major industrial accidents, large fires, war, or bolide impacts).
- Understanding the sources of variability and predictability in living marine resources, and what tipping points may exist.

4.2.2 Weather and Subseasonal-to-Seasonal Predictions

At timescales of hours to months, high-impact weather and climate events include thunderstorms, winter storms, hurricanes, floods, drought, and heat waves. Predicting these events requires accurate simulation and initialization of the atmosphere, land, and the surface layer of the ocean. By leveraging the variable-resolution capabilities of FV3, SHiELD will enable improved forecasts of extreme events at regional scales, and will capture interactions between large and small scales. GFDL plans to further develop SHiELD by:

- Improving the numerical algorithms and model resolution (vertical and horizontal) in the FV3 dynamical core.
- Better representing the atmospheric boundary layer and stratosphere.
- Improving the assimilation of atmospheric, land, and ocean data.

Forecast biases will be studied in order to understand their sources and impacts, and to guide further improvements in model physics. Key research foci will be:

- Improving forecasts of hurricane track and intensity.
- Improving hour-to-day forecasts for severe weather events, including severe thunderstorms and tornadoes
- Extending weather forecasts through 2 weeks.
- Extending extreme-event forecasts through S2S time scales.

4.2.3 Seasonal-to-Interannual Predictions

At time scales of seasons to years, climate anomalies are driven mainly by large-scale coupled interactions between the atmosphere and upper ocean, particularly in the tropics. These interactions give rise to the monsoon variations, ENSO, tropical Atlantic variability (TAV), tropical meridional modes, and the Indian Ocean Dipole (IOD), which alter the atmospheric and oceanic circulation and affect weather patterns, ecosystems, fisheries, and economies worldwide. In addition, seasonal-to-interannual variations in Arctic sea ice, alpine snowpack, regional soil moisture, and drought have major impacts on shipping, agriculture, water resources, forest management, and wildfire risk.

To predict these events and impacts, GFDL will leverage its global coupled prediction system based on the SPEAR model and ECDA initialization system. Key research foci will be:

- Improving understanding of the sources and limits of predictive skill on seasonal to multi-annual time scales, including phenomena such as ENSO, interactions between the stratosphere and troposphere, and modes of tropical and extratropical variability.
- Advancing initialization systems for predictions, by:
  - Improving the ECDA system.
  - Incorporating sea ice data assimilation and strategic improvements to sea ice model physics.
- Translating improved understanding into improved prediction skill, for phenomena such as ENSO, tropical storms, North American hydroclimate, Arctic sea ice, winter storminess, and others.
- Determining what additional observations are needed to improve predictions.

SPEAR's global atmospheric and land grids will be refined to 50 km and eventually 25 km, to better represent impacts of climate modes on continental temperatures, hydroclimate, and extremes. GFDL will also experiment with embedding into SPEAR a regional 10 km SHiELD atmospheric and land mesh, to support improved representation of regional climate and extremes over North America. Further work will aim to improve SPEAR's representation of stratosphere/troposphere interactions and their impacts on predictability. If computing resources permit, the ocean grid will be refined to 25 km to better represent oceanic eddies, islands, and passages and improve predictions for coastal zones; and biogeochemical capabilities from ESM4 will be added to the ocean, land, and atmosphere components of the prediction system to enhance forecast utility for ecosystems, fisheries, forests, and air quality.

Prediction accuracy critically depends on the initialization system. The ECDA system will be adapted to support assimilation in SPEAR and enable direct initialization of both seasonal-to-interannual forecasts and decadal predictions. The analysis system will also be enhanced to incorporate more diverse observations, including sea level and atmospheric surface pressure. The ECDA will produce global coupled analyses of the instrumental era to serve as targets for model development, and to initialize retrospective forecasts that will be used to assess forecast skill.

GFDL will continue to serve its multi-seasonal predictions to the NMME and NCEP. Forecast drifts will be studied in order to understand their sources and impacts, and to guide further improvements in SPEAR and the ECDA. Extensive exploratory simulations, assimilations, and forecasts will be conducted to correct model biases, illuminate sources of predictability, and support improved predictions.

4.2.4 Initialized Decadal-to-Multidecadal Predictions and Projections

At time scales of years to decades, climate predictions depend not only on the initial state of the Earth System but also on radiative forcings from natural and anthropogenic sources. Decadal and multidecadal climate signals can arise from many sources. There are sources intrinsic to the climate system, such as the AMV, AMOC, Interdecadal Pacific Oscillation (IPO), PDO, North Pacific Oscillation (NPO), North Pacific Gyre Oscillation (NPGO), and ocean/ice/atmosphere interactions in the Arctic and in the Southern Ocean. ENSO's behavior also varies from decade to decade, and this modulation can induce decadal-scale climate changes. Natural decadal forcings from volcanoes and atmospheric dust, and anthropogenic forcings from sulfate aerosols, greenhouse gases, and changes in land use, can also induce climate variations at decadal scales. These decadal signals impact water resources by affecting drought and alpine snow cover, and also have major implications for sea ice extent, ecosystems, fisheries, and agriculture. Decadal climate shifts can further induce changes in the patterns, behavior, and impacts of shorter-timescale variability such as ENSO, hurricanes, and extreme weather.

To understand and predict these decadal variations and impacts, GFDL plans to utilize the SPEAR/ECDA system, with atmosphere/land grid meshes of 100 km and eventually 50 km. Key research foci will be:

- Predicting and projecting multi-annual to multidecadal changes in climate and climate extremes, including:
    - surface temperature, hydroclimate and storms
    - the cryosphere, including snowpack
    - ocean circulation, especially in the North Atlantic and Southern Ocean
    - internal variability, such as ENSO or NAO
- Determining the fundamental sources and limits of decadal predictability in the climate system.
- Determining what additional observations are needed to improve predictions.

SPEAR's predictions, in combination with statistical and dynamical downscaling, will be used to predict changes in extreme weather and regional climates with an emphasis on North America. To assess decadal predictability and forecast skill, a novel ECDA system using only SST and surface pressure observations will be leveraged to extend the set of initial conditions as far back as possible into the instrumental era, to provide a broader set of initial conditions with which to evaluate the retrospective decadal predictions. GFDL will also continue to generate real-time decadal predictions and provide them to the UKMO-coordinated WMO ADCP Project.

The ultimate goal is to combine these advances into a unified initialization system for seamless seasonal to decadal predictions. Improving the data assimilation may require improved ocean/atmosphere resolution, as well as increased ensemble sizes and more diverse observational input data streams. Thus, a critical limiting factor for these developments will be the availability of High-Performance Computing (HPC).

4.2.5 Multidecadal-to-Centennial Projections

For more than 30 years GFDL has developed models to contribute projections to the multi-model ensembles used by the climate science and policy communities [e.g. IPCC, World Climate Research Program (WCRP) and NCA]. While this is partly done as a service based on credible science, it also provides valuable points of comparison, particularly for the historical simulations that precede projections. GFDL climate change research, for the most part, is focused on the model characteristics that influence projections, particularly radiative forcing and sensitivity (see Section 3), and on high-resolution variants of the CMIP-contributed model that are used for projecting regional changes and extreme events. GFDL climate models are first vetted by assessing the quality of historical climate simulations against those of other CMIP models. This approach allows the model to be developed at lower resolution in climate mode prior to combination with a data assimilation system and subsequent evaluation of hindcasts. At the time of this writing a new generation of GFDL CMIP models has been completed which will lead into the future development of prediction systems and a new generation of high-resolution climate models.

Chapter 5: Unified Modeling and Infrastructure

Since the early 2000's, GFDL has relied upon unified modeling to support seamless understanding and prediction of the Earth System. GFDL's Flexible Modeling System (FMS) provides a framework for constructing model hierarchies, including stand-alone atmosphere (AM4), ocean (OM4) or land (LM4) models, as well as the coupled CM4, ESM4, SHiELD and SPEAR models — all of which are configurations of FMS. An end-to-end workflow system, the FMS Runtime Environment (FRE), helps automate the process to manage multiple experiments and efficiently utilize computing resources. FRE aids model development, exploratory science, and production workloads, by managing all aspects of an experiment — from provisioning the model and shepherding it through multiple executions, to diagnosing and storing the intricate detail needed for quality control and publication of data and scientific results. The unified modeling framework and workflow embodied by FMS and FRE provide a uniform platform that supports scientific research and products, including CMIP6 and the NMME.

5.1 Past Accomplishments

For nearly two decades, the flexibility of FMS has allowed GFDL scientists to build models of varying complexity. The features of FMS include a flux-conserving coupler, a message-passing library interface (MPP), automated regression testing, and Input/Output and diagnostics managers. FMS has been continually updated with new capabilities for simplified aquaplanet models, nesting of high-resolution regions within a global model, and limited-area models with doubly-periodic lateral boundary conditions. Other features include regional and grid-coarsened diagnostics to reduce data volume, limited mixed precision, multiple nested regions within a domain, and telescoping refinement within nests and limited-area models. FMS-enabled recent accomplishments include:

- Timely implementation of the GFS physics suite into GFDL's modeling system and its coupling to the FV3 dynamical core during the NGGPS Phase II. The template-based approach of the FMS framework made it possible to complete the coupling of the FV3 dynamical core to the GFS physics suite in less than two months.
- A highly-efficient, lightweight interface between the physics and dynamics, called the Interoperable Physics Driver, was built by GFDL for the follow-up model transfer in the NGGPS Phase III. The interface has become a standard; it has been adopted by the U.S. Navy, and NCAR is using it as the basis for the Common Community Physics Package.
- Making more efficient use of computing resources through empty grid masking (assigning compute resources only in areas where the land or ocean exist), unstructured

data representations in the land model for improved load balance, and concurrent execution of different physics parameterizations (Balaji et al.,2016).

- Harnessing the computing power of Graphical Processing Units (GPUs). GRT-code, a line-by-line radiation code developed at GFDL, can be run on both CPU and GPU architectures, with superior computational performance in a multicore environment.

5.2 Future Plans

GFDL will build upon the success of the **open development** precedent set with creation of the MOM6 project. The land development team sees the same opportunity to work with the external science community and will be transitioning to open development. Further, the incorporation of FV3 into the NGGPS/UFS framework has necessitated transitioning its code base into a community development framework. These changes have driven the need to support community collaboration while continuing to meet the lab's internal development goals. This requires continuous maintenance of the various model configurations, and unit testing of the FMS infrastructure, which will be achieved by enhancing and extending the automated testing framework. GFDL will also create a cloud computing environment that meets government security standards, as a way to augment available resources and deliver compatible environments for code testing and development. Using cloud resources for automated testing will further protect government assets during testing of community contributions. FRE will similarly transition to open development, and exist in the DOC's NOAA-GFDL GitHub to serve outside parties.

The FRE workflow was originally designed primarily to support long-running climate studies, which output data aligned with model year boundaries. With an increasing GFDL focus towards seamless understanding and prediction, the FRE workflow infrastructure must evolve to better support **sub-annual analysis**, for seasonal to decadal variability and predictability studies as well as model development. This capability will be especially important for developing ultra-high resolution models, including a global cloud resolving model, which will generally consist of short runs of hours to months.

GFDL's predictions, projections, data assimilation, and detection/attribution studies all require infrastructure support for **ensembles** of parallel model runs. The current support for ensembles is limited and ad-hoc. Requirements gathering and prototyping have begun in order to support ensembles for model configurations and data assimilation within FMS and the automated workflow. Efforts will also be made to understand how to use ensemble statistics and other analyses to evaluate climate reproducibility across model and compiler changes, in the event that future computing environments no longer guarantee exact numerical reproducibility.

GFDL collaborates on the development and adoption of numerous **diagnostics** efforts in the modeling and research community. Most active are the collaborations with the PCMDI Metrics Package (PMP), NCAR's Climate Variability and Diagnostics Package, the Earth System Model Evaluation Tool (ESMValTool), the International Land Model Benchmarking Project (ILAMB), and efforts within international CLIVAR to develop community tools to evaluate and intercompare climate simulations. GFDL also collaborates with the NOAA Pacific Marine Environmental Laboratory (PMEL) to develop the PyFerret package for climate analysis and visualization, and the Live Access Server (LAS) for data distribution. In addition to these community packages, GFDL plays a central role in the development of NOAA's Model

Development Task Force (MDTF) Diagnostics Package. The MDTF Diagnostics Package facilitates the development of new process-based diagnostics to help understand and improve the representation of key processes in models. Further plans are to foster these collaborations with our external partners, and sustain/grow efforts to further integrate these packages into GFDL's modeling and research workflows.

GFDL provides **external data access** to many of its datasets through the GFDL Data Portal, and through the Earth System Grid Federation (ESGF) to help publications to meet data and code availability requirements of publishers. GFDL is also standardizing its definitions, processes, procedures and infrastructure to support these provisions. GFDL maintains a cache of observational and modeling data from sources outside the lab, and work is ongoing to replace the current manual processes with an automated data request fulfillment system.

Machine Learning (ML) and **deep learning** in particular, are increasingly driving the computing industry, which in turn presents new opportunities. Current work at GFDL includes the ability to augment model output with fine-scale detail via ML-based downscaling: Chaney et al (2018), Muhling et al (2017, 2018), Ross and Stock (2019). We expect future applications of ML that will augment models themselves, rather than refine their output, a literature that is beginning to emerge across the field — see Brenowitz and Bretherton (2018) for an atmospheric example; Bolton and Zanna (2019) for one in the ocean. An ongoing activity along this line is to apply ML to FV3-based global cloud system resolving simulations to develop convection parameterizations. The same methodology can be adopted for other fundamental processes such as boundary layer and radiative transfer. As another way to take advantage of our unified modeling framework, one can embed inline learning agents which can directly sample the state of a running model.

GFDL is actively preparing for **exascale computing**, via a foundational rewrite of the FMS core infrastructure. The MPP layer supporting interprocess communication and parallel I/O will be the first component deployed, followed by diagnostic output, interpolation algorithms, tracer management, and full support for mixed-precision. Exploring **heterogeneous computing** (e.g. GPUs and many-core processors) is on-going, and collaborations with external organizations to support specific architectures are underway (e.g. a collaboration with the Swiss Supercomputing Center on implementing FV3 within the GridTools framework). Scientists and computational specialists at GFDL will continue developing new algorithms and methods for the next generation of models. Modeling Systems is also examining new hardware technologies, and the role that large pools of shared, solid state disk and non-volatile memory may play in post-processing and analysis workflows.

Chapter 6: Organization, Partnerships, and Collaborations

Accomplishing GFDL's mission embodied by the scientific objectives described above requires individuals with diverse expertise. **GFDL researchers** are organized into six Divisions covering major components of Earth System science: Atmospheric Physics; Biogeochemistry, Atmospheric Chemistry and Ecosystems; Seasonal to Decadal Variability and Predictability; Oceans and Cryosphere; Weather and Climate Dynamics; and Modeling Systems. Mission goals are further enabled by robust administrative, facilities and information technology support.

More detailed descriptions of each division's research foci and GFDL's overall organization can be found here.

While divisions are organized around themes, division members work collaboratively to produce comprehensive climate and Earth System models and meet GFDL's science objectives. This is done periodically through the establishment of **cross-disciplinary** model development teams or internal lab initiatives, but also arises organically through cross-division partnerships to address problems of common interest.

To achieve its mission, GFDL must continue advancing NOAA science for applications and operations (consistent with mission goals) and be a sustained authoritative source of knowledge and guidance for NOAA and the global community in world-leading modeling of the Earth System. While the expertise of GFDL researchers is broad, the scope of GFDL's mission and scientific objectives exceeds the capacity of any single laboratory. GFDL thus leverages diverse **partnerships** to address gaps in expertise and capacity for model development and applications (e.g., climate impacts across diverse sectors). Natural partnerships across NOAA's Office of Oceanic and Atmospheric Research (OAR) (such as ESRL/PSD, GSD, GMD and CSD, and PMEL) and other NOAA line offices — the National Weather Service, National Marine Fisheries Service, National Ocean Service, and National Environmental Satellite, Data and Information Service — emerge through the roles that GFDL model development and science play in achieving NOAA's broad mission goals. Where mission goals benefit, these collaborations extend across government agencies (including NASA, U.S. Navy, DOE, USGS) and to industry partners (including Exxon, British Petroleum). Active participation in national and international research programs and assessments [e.g. the U.S. Global Climate Change Program (GCRP), National Research Council (NRC), WCRP and IPCC] ensures GFDL's long-standing leadership role in the community.

Princeton University and GFDL have a long-running partnership which dates back to the creation of Princeton's Atmospheric and Oceanic Sciences (**AOS**) program in 1967, and the subsequent move of GFDL to Princeton. NOAA's Cooperative Institute for Modeling the Earth System (**CIMES**), the latest manifestation of this partnership, supports extensive research collaborations with academic colleagues across Earth System fields in several Princeton University Departments, including Geosciences, Ecology and Evolutionary Biology, the Woodrow Wilson School of Public and International Affairs, Civil and Environmental Engineering, and the Princeton Environmental Institute. This partnership allows GFDL science to benefit from the diverse scientific expertise of **Princeton faculty**, and has led to numerous past innovations in GFDL science. Simultaneously, the academic partnership with Princeton allows for the training of **graduate students** in GFDL- and NOAA-relevant science, often advised by GFDL scientists appointed to the AOS program faculty. CIMES is also the primary route for early career **postdoctoral scientists** to work at GFDL, under the mentorship of GFDL scientists. Some of these postdoctoral scientists may then be recruited for longer-term appointments at GFDL, either as federal employees or through CIMES or UCAR. Alumni of both the graduate and postdoctoral programs who go on to work in academic or government research help to create and strengthen links between GFDL and numerous other academic and government institutions. CIMES is also an important route for **diversifying the workforce** involved in GFDL science. An internship program now in its 4th year brings undergraduate and masters students from diverse backgrounds to conduct research for the summer, under the mentorship of GFDL scientists. This internship program is complemented by a Visiting Faculty

Exchange program, which creates ties between GFDL/AOS and faculty at academic institutions serving diverse student populations. This core academic partnership with Princeton is augmented by a variety of diverse collaborations with national and international partners. A complete list of collaborations can be found in the appendix.

Recruiting, retaining, developing, and advancing exceptional scientists, administrators and technical/computational experts are all critical for GFDL to achieve the scientific objectives laid out in this document. GFDL's seeks to meet this challenge by striving for excellence in four main areas:

- Maintaining scientific resources (human and computational) to provide the tools needed for world-class climate and Earth System research, modeling, predictions, and projections.
- Fostering an environment conducive to the collaborative, integrated efforts essential for climate and Earth System research.
- Fostering an environment that maintains high standards of excellence, while enabling a sustainable work-life balance.
- Creating opportunities for all employees to develop new skills and grow into leadership roles.

Excellence in these areas is pursued by:

- Maintaining and expanding HPC
- Clear policies of Fair Use and co-authorship
- Awards and recognition (including the Amy Langenhorst "Unsung Hero" Award)
- Mentoring
- EEO Curriculum
- Transparency and Advancement
- Affinity and career stage Early Career/EEO committees
- Ombuds
- Adapting approach to the challenges of an integrated workforce (federal, contractor and academic).
- An active GFDL Employees Association, which organizes frequent lab-wide social events

In accordance with NOAA's 2018 Diversity and Inclusion and EEO Policies, GFDL is committed to working towards solutions that benefit all members of the community, and will continue to develop a workplace and workplace culture that is safe and welcoming to all. GFDL seeks to promote diversity, equity, inclusion, and belonging in all aspects of the workplace and will continue to develop transparency and accountability in its practices and procedures, especially in the areas of recruitment, retention, and advancement. Diversity and inclusion seminars or workshops can serve to build awareness to help address eliminating unconscious biases. Community and group discussions on work-life challenges can serve to share experiences, provide advice, and develop a support system for members of the GFDL community.

Appendix

Collaboration with other national and international research groups, both inside and outside of NOAA including Cooperative Institutes and universities.

U.S. Federal and Federal-Sponsored

1. DOD/Navy/ONR/Naval Research Laboratory/Marine Meteorology Division, Monterey, CA
2. DOE/ Lawrence Berkeley Laboratory, Berkeley, Richland, WA
3. DOE/ Pacific Northwest National Laboratory, Richland, WA
4. DOE/Lawrence Livermore National Laboratory, Livermore, CA
5. DOE/Los Alamos National Laboratory/Fluid Dynamics and Solid Mechanics, Los Alamos, NM
6. DOE/Oak Ridge National Laboratory/Computing and Computational Sciences Directorate, Oak Ridge, TN
7. NASA Ames Research Center, Moffett Field, CA
8. NASA Goddard Space Flight Center, Greenbelt, MD
9. NASA Langley Research Center, Hampton, VA
10. NOAA/ National Severe Storms Laboratory, Norman, OK
11. NOAA/ Pacific Marine Environmental Laboratory, Seattle, WA
12. NOAA/NESDIS/Office of Satellite Technology and Research/Advanced Satellite Products Branch, Madison, WI
13. NOAA/NMFS/Northeast Fisheries Science Center, Woods Hole, MA
14. NOAA/NMFS/Southwest Fisheries Science Center, Monterey, CA
15. NOAA/NOS/National Centers for Coastal Ocean Science, Silver Spring, MD
16. NOAA/NWS/NCEP/Climate Prediction Center, College Park, MD
17. NOAA/NWS/NCEP/Climate Prediction Center, Silver Spring, MD
18. NOAA/NWS/NCEP/Environmental Modeling Center, College Park, MD
19. NOAA/NWS/NCEP/National Hurricane Center, Miami, FL
20. NOAA/OAR Office of Weather and Air Quality (OWAQ), Silver Spring, MD
21. NOAA/OAR/Atlantic Oceanographic and Meteorological Laboratory, Miami, FL
22. NOAA/OAR/Earth System Research Laboratory/Physical Sciences Division, Boulder, CO
23. NOAA/OAR/Pacific Marine Environmental Laboratory, Seattle, WA
24. US Environmental Protection Agency, Washington DC
25. US Environmental Protection Agency/National Exposure Research Laboratory/Computational Exposure Division, Research Triangle Park, NC
26. US Environmental Protection Agency/Region VIII, Denver, CO
27. US Geological Survey, Reston, VA
28. US Naval Research Laboratory, Washington DC.

U.S. Non-Federal

1. Atmospheric and Environmental Research, Inc., Lexington, MA
2. Atmospheric and Oceanic Sciences Department, University of Wisconsin-Madison, Madison, WI
3. Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
4. Atmospheric Sciences Program, Department of Geography, The Ohio State University, Columbus, OH

5. Atmospheric Sciences Research Center, University at Albany, State University of New York, Albany, NY
6. Bren School of Environmental Science & Management, University of California at Santa Barbara, Santa Barbara, CA
7. Byrd Polar and Climate Research Center, The Ohio State University, Columbus, OH
8. Center for Analysis and Prediction of Storms, University of Oklahoma, Norman, Oklahoma
9. Center for Earth and Environmental Science, University at Plattsburgh, State University of New York, Plattsburgh, NY
10. Center for Environmental Medicine, Asthma, and Lung Biology, University of North Carolina, Chapel Hill, NC
11. Center for Global and Regional Environmental Research & Department of Chemical and Biochemical Engineering & Interdisciplinary Graduate Program in GeoInformatics, University of Iowa, Iowa City, IA
12. Center for Ocean–Land–Atmosphere Studies, George Mason University, Fairfax, VA
13. College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, OR
14. Cooperative Institute for Climate Science, Princeton University, Princeton, NJ
15. Cooperative Institute for Mesoscale Meteorological Studies, and School of Meteorology, University of Oklahoma, Norman, OK
16. Courant Center for Atmosphere Ocean Science, New York University, New York
17. Davidson Laboratory, Stevens Institute of Technology, Hoboken, NJ
18. Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY
19. Department of Atmospheric and Oceanic Science, University of Colorado Boulder, Boulder, CO
20. Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA
21. Department of Atmospheric Science, and School of Environmental Sustainability, Colorado State University, Fort Collins, Colorado
22. Department of Atmospheric Sciences, University of Hawaii at Mānoa, Honolulu, HI
23. Department of Atmospheric Sciences, University of Miami
24. Department of Atmospheric Sciences, University of Washington, Seattle, WA
25. Department of Atmospheric, Oceanic, and Earth Sciences and Center for Ocean-Land-Atmosphere Studies, George Mason University, Fairfax, Virginia
26. Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY
27. Department of Biological Sciences, Center for Ecosystem Science and Society (ECOSS), Northern Arizona University, Flagstaff, AZ
28. Department of Biological Sciences, Purdue University, West Lafayette, IL
29. Department of Chemistry and Biochemistry, University of Maryland, College Park, MD
30. Department of Chemistry, University of California, Irvine, CA
31. Department of Civil & Environmental Engineering, University of Washington, Seattle, WA
32. Department of Civil & Environmental Engineering, University of California Los Angeles, Los Angeles, CA
33. Department of Civil and Environmental Engineering, Duke University, Durham, North Carolina
34. Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ
35. Department of Civil, Construction, and Environmental Engineering, University of Alabama, Tuscaloosa, AL
36. Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY

37. Department of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA
38. Department of Earth and Atmospheric Sciences, University of Houston, Houston, TX
39. Department of Earth and Environment, Boston University, Boston, Massachusetts
40. Department of Earth and Environmental Engineering, Columbia University, New York, NY
41. Department of Earth and Environmental Science, University of California, Berkeley, CA
42. Department of Earth and Environmental Sciences, and Department of Applied Physics and Applied Mathematics, Columbia University, New York, New York
43. Department of Earth and Planetary Sciences, Northwestern University, Evanston, IL
44. Department of Earth System Science, Stanford University, Stanford, California
45. Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA
46. Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafeyette, IN
47. Department of Earth, Environmental, and Planetary Sciences, Brown University, Providence, RI
48. Department of Earth, Ocean, and Atmospheric Science, Florida State University, Tallahassee, FL
49. Department of Ecology and Evolutionary Biology, University of Tennessee, Knoxville, TN
50. Department of Environmental Sciences, Environmental & Natural Resource Sciences Building, Rutgers University, New Brunswick, NJ
51. Department of Environmental Toxicology, University of California, Davis, CA
52. Department of Geography, University of California, Santa Barbara, CA
53. Department of Geological Sciences, University of North Carolina Chapel Hill, Chapel Hill, NC
54. Department of Geology & Geophysics, Yale University, New Haven, CT
55. Department of Geosciences, University of Arizona, Tucson, AZ
56. Department of Global Ecology, Carnegie Institution for Science, Stanford, CA
57. Department of Marine Sciences, University of North Carolina at Chapel Hill, Chapel Hill, NC
58. Department of Marine, Earth, and Atmospheric Science, North Carolina State University, Asheville, NC
59. Department of Mathematical Sciences, Worcester Polytechnic Institute, Worcester, MA
60. Department of Meteorology, Pennsylvania State University, University Park, PA
61. Department of Natural Resources and the Environment, University of New Hampshire, Durham, NH
62. Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA
63. Earth and Environmental Sciences, University of Michigan, Ann Arbor, MI
64. Earth and Ocean Sciences, Nicholas School of the Environment, Duke University, Durham, NC
65. Environmental Defense Fund, Washington DC
66. Geography Department, University of California, Berkeley, CA
67. Geophysical Institute and Department of Chemistry, University of Alaska Fairbanks, Fairbanks, AK
68. Graduate School of Oceanography, University of Rhode Island, Narragansett, RI
69. Institute for Geophysics, University of Texas at Austin, Austin, TX
70. International Research Institute for Climate and Society (IRI), Earth Institute, Columbia University, Palisades, New York

71. Iowa Institute of Hydraulic Research (IIHR)-Hydroscience & Engineering, University of Iowa, Iowa City, IA
72. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
73. John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA
74. Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY
75. Marine Fisheries Division, Connecticut Department of Energy and Environmental Protection, Old Lyme, CT
76. National Center for Atmospheric Research (NCAR), Boulder, CO
77. Princeton Environmental Institute, Princeton University, Princeton, NJ
78. School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA
79. School of Forestry & Environmental Studies, Yale University, New Haven, CT
80. School of Global Environmental Sustainability, Colorado State University, Fort Collins, Colorado
81. School of Marine and Atmospheric Sciences, Stony Brook University, State University of New York, Stony Brook, NY
82. Scripps Institution of Oceanography, University of California at San Diego, La Jolla, CA
83. Sierra Nevada Research Institute, University of California, Mercede, CA
84. University of Illinois at Urbana-Champaign, Urbana, IL
85. Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ
86. Woods Hole Oceanographic Institution, Massachusetts Institute of Technology, Woods Hole, MA

International – Government, National, and International

1. Agenzia Nazionale per le Nuove Tecnologie, l'energia e lo Sviluppo Economica Sostenible (ENEA), Bologna, Italy
2. Barcelona Supercomputing Center, Barcelona, Spain
3. Center for Climate Physics, Institute for Basic Science (IBS), Busan, South Korea
4. Central Weather Bureau, Taipei, Taiwan
5. Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune, India
6. CNRM, Centre National de Recherches Météorologiques, Toulouse, France
7. Commonwealth Scientific Industrial Research Organization, Oceans and Atmospheres, Hobart, Australia
8. Council of Agricultural Research and Economics (CREA), Research Centre for Forestry and Wood, Arezzo, Italy
9. Estellus, and Laboratoire de l'Etude du Rayonnement et de la Mati ere en Astrophysique, CNRS, Observatoire de Paris, Paris, France
10. Federal Environment Agency (UBA), Oberried, Germany
11. Hong Kong Observatory, Kowloon, Hong Kong
12. India Meteorological Department, New Delhi, India
13. Indian Institute of Tropical Meteorology, Pune, India
14. Instituto Nacional de Pesquisas Espaciais (INPE), Sao Paulo, Brazil
15. Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan
16. Laboratoire de Meterologie Dynamique (LMD/IPSL), Paris, France
17. Laboratoire de Sciences de Climat et Environnement (LSCE), Saclay, Paris, France
18. Max-Planck Institut fur Meteorologie, Hamburg Germany

19. Meteorological Research Institute, Tsukuba, Japan
20. UK Meteorological Office – Hadley Centre, Exeter, UK
21. National Typhoon Center, KMA, Jeju, Republic of Korea
22. Research Center for Environmental Changes, Academia Sinica, Taipei, Taiwan
23. Royal Netherlands Meteorological Institute, De Bilt, Netherlands
24. Shanghai Typhoon Institute, China Meteorological Administration, Shanghai, China
25. State Key Laboratory of Numerical Modelling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute for Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

International - Non-Government

1. Center for Earth System Science, Tsinghua University, Beijing, China
2. Center for International Climate and Environmental Research (CICERO), Oslo, Norway
3. Center für Erdsystemforschung und Nachhaltigkeit, Universität Hamburg, Hamburg, Germany
4. Center of Excellence for Climate Change Research, Department of Meteorology, King Abdulaziz University, Jeddah, Saudi Arabia
5. Centre for Marine Socioecology, University of Tasmania, Hobart, Australia
6. Centre for Ocean Life, Technical University of Denmark (DTU-Aqua), Denmark
7. Centre for Research in Earth and Space Science, York University, Toronto, Canada
8. Christian-Albrechts University of Kiel, Kiel, Germany
9. Climate and Environmental Physics, Physics Institute, University of Bern, Bern, Switzerland
10. Climate Change Research Centre, University of New South Wales, Sydney, Australia
11. Department of Chemistry, University of Cambridge, Lensfield Road, Cambridge, UK
12. Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong
13. Department of Earth and Environmental Sciences, Chonbuk National University, South Korea
14. Department of Earth and Planetary Sciences, McGill University, Montreal, Canada
15. Department of Earth Sciences, University of Oxford, Oxford, United Kingdom
16. Department of Earth System Sciences, Tsinghua University, Beijing, China
17. Department of Environmental Science and Engineering, Fudan University, Shanghai, China
18. Department of Environmental Systems Science, Institute for Environmental Decisions, and Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland
19. Department of Meteorology, NCAS/University of Reading, Reading, UK
20. Department of Oceanography, Dalhousie University, Halifax, Canada
21. Department of Physical Geography, Faculty of Geosciences, Utrecht University, Utrecht, Netherlands
22. Department of Statistics, University of Bologna, Bologna, Italy
23. Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands
24. Department of Earth, Ocean and Ecological Sciences, University of Liverpool, Liverpool, UK

25. Dirección de Meteorología e Hidrología, Asunción, and Facultad Politécnica, Universidad Nacional de Asunción, San Lorenzo, Paraguay
26. Divecha Centre for Climate Change, Indian Institute of Science, Bangalore, India
27. Division of Earth and Planetary Sciences, Faculty of Science, Hokkaido University, Sapporo, Japan
28. Division of Physical Sciences and Engineering, King Abdullah University of Science and Technology, Saudi Arabia
29. Earth Sciences, Department Barcelona Supercomputing Center (BSC-CNS), Barcelona, Spain
30. Earth System Physics Section, International Centre for Theoretical Physics, Trieste, Italy
31. ECMWF (European Centre for Medium Range Forecast), Reading, United Kingdom
32. Eurasia Institute of Earth Sciences, Istanbul Technical University, Istanbul, Turkey
33. Finnish Meteorological Institute, Helsinki, Finland
34. First Institute of Oceanography, State Oceanic Administration, Qingdao, China
35. Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici, Bologna, Italy
36. GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
37. Geophysical Institute, University of Bergen, Bergen, Norway
38. Grantham Institute & Department of Physics, Imperial College London, UK
39. Institute for Atmospheric and Climate Science, ETH Zürich, Switzerland
40. Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia
41. Institute for the Oceans and Fisheries, The University of British Columbia, Vancouver, CA
42. Institute of Physics and Meteorology, University of Hohenheim, Stuttgart, Germany
43. International Council for the Exploration of the Sea, København V, Denmark
44. Lancaster Environment Centre, Lancaster University, Lancaster, United Kingdom
45. LOCEAN/IPSLSorbonne Universités (UPMC)-CNRS-IRD-MNHN, Paris, France
46. Mathematics and Physical Sciences, University of Exeter, Exeter, UK
47. Max Planck Institute for Biogeochemistry, Jena, Germany
48. Max Planck Institute for Meteorology Hamburg, Germany
49. McGill University, Montreal, Canada
50. Meteorology and Air Quality Group, Wageningen University, Wageningen, Netherlands
51. Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science, and Joint Center for Global Change Studies (JCGCS), Tsinghua University, Beijing, China
52. Nagoya University, Furocho, Chigusa-ku, Nagoya, Japan
53. National Institute for Environmental Studies (NIES), Tsukuba, Japan
54. National Oceanography Centre, University of Southampton, Southampton, UK
55. NERC (Natural Environment Research Council) Centre for Ecology and Hydrology, Environment Centre Wales, Bangor, United Kingdom
56. Research Center for Advanced Science and Technology, University of Tokyo, Tokyo, Japan
57. Research School of Earth Sciences and ARC Centre of Excellence for Climate System Science, Australian National University, Canberra, Australia
58. Royal Netherlands Meteorological Institute, De Bilt, Netherlands
59. School of Earth & Environmental Sciences, University of Wollongong, New South Wales, Australia
60. School of Earth and Environment, University of Leeds, Leeds, United Kingdom
61. School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea

62. School of Energy and Environment, City University of Hong Kong, Hong Kong, China
63. School of Earth Sciences, University of Melbourne, Victoria, Australia
64. School of Environmental Science, University of East Anglia, Norfolk, United Kingdom
65. School of Geographical Sciences, University of Bristol, Bristol, United Kingdom
66. School of GeoSciences, The University of Edinburgh, Edinburgh, United Kingdom
67. Scottish Association for Marine Science, Oban, United Kingdom
68. Uni Research Climate, Bjerknes Centre for Climate Research, Bergen, Norway
69. United Nations Environment Programme World Conservation Monitoring Centre, Cambridge, United Kingdom
70. Universidad Complutense de Madrid, and Instituto de Geociencia, Centro Mixto del Consejo Superior de Investigaciones Científicas, Madrid, Spain
71. University of New South Wales, Australia.
72. University of Oslo, Oslo, Norway
73. Wegener Center for Climate and Global Change and Institute for Geophysics, Astrophysics, and Meteorology (IGAM)/Institute of Physics, University of Graz, Austria