The GFDL 5-10 Year Strategic Science Plan

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I. Introduction

GFDL seeks to understand, through comprehensive numerical modeling, the processes, interactions and mechanisms governing the climate system, and to estimate climate forcings, sensitivities and variability toward the goal of making accurate predictions and reliable projections of climate change. Specifically, we address our planned activities toward the following science questions:

1. *Basic climate processes and their representations in models*. How can representations of the basic processes constituting the Earth's climate system be improved and made more realistic based on advances in the physical, dynamical, chemical, mathematical and biogeochemical sciences (involving theory, observations, numerical techniques), leading to qualitatively and quantitatively better simulations of climate and climate change? In particular, as important processes (including atmospheric convection, tracer transport, and mesoscale ocean eddies) become more fully resolved, how will our understanding of the climate system change?

2. *Comprehensive modeling of climate system variability and change*. What are the spatial and temporal distributions of the atmospheric composition, climate forcings and responses arising due to natural (Sun, volcanoes) and human activities (greenhouse gases; aerosols; land-use)? How does this contrast with the behavior of the unforced system? How do the forcings and feedbacks (water vapor, clouds, land surface, sea ice, carbon and other biogeochemistry) influence the Earth's transient and quasi-equilibrium climate sensitivity from the global to regional scales? What are the impacts on the radiation budget and hydrological cycle?

3. *Understanding, detection and attribution, and prediction of extreme events*. What are the characteristics and how do the frequency and amplitude of climate extremes such as droughts, floods, and frequency and intensity of severe weather such as tropical storms, respond to a changing climate? Can this response be detected in the observational record, and can it be attributed to specific natural and anthropogenic forcings? Can this understanding be translated into an ability to predict the future evolution of regional and local climates, including the risks of extreme events?

4. *Understanding, detection and attribution, and predictability of modes of climate variability*. How do different modes of internal variability (e.g., MJO, ENSO, QBO, NAO, PDO, teleconnection patterns, … spanning synoptic, intraseasonal, interannual, interdecadal time scales) interact with each other, and how do they respond to a changing climate? Can this response be detected in the observational record, and can it be attributed to specific

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natural and anthropogenic forcings? Which modes of variability carry predictability and what are the prospects for long-range (decadal and beyond) climate prediction?

5. *Cryospheric amplification of climate change and sea-level rise*. What are the stability characteristics of the climate considered as a nonlinear system? In particular, can cryospheric amplification of warming lead to the possibility of abrupt climate change (e.g., rapid Arctic warming) and other possible "climate surprises" (e.g accelerated sea level rise)? How do we understand and improve the representation of the relevant processes (e.g ice sheets) in climate models?

6. *Understanding the Earth system including biosphere and human activities*. What are the roles of terrestrial and marine ecosystems in past and future climates and in climate change? What are the interactions (e.g. land use, emissions, fire, species migration, ocean acidification) between human activities, ecosystems and climate? What gaps remain in our ability to understand and model the very long-range (e.g., millennial) drivers of Earth system response, such as carbon and other biogeochemical cycles?

7. *Ocean processes in climate*. What are the roles of mesoscale eddies and of 3-dimensional oceanic mixing and stirring processes in regulating the mean-state and response to forcings of the physical and biogeochemical ocean climate system? How can this process-level understanding be represented in Earth system models (explicitly resolved or parameterized), and how do these models refine our understanding of climate and climate change?

8. *Climate science, impacts and services*. How can we use models, theory, and observations to improve the scientific understanding of major cross-disciplinary linkages to climate that are of societal relevance and constitute key science inputs for adaptation and mitigation decisions (e.g air quality; climate change impacts on fisheries, agriculture, and human health)? Can we extract policy-relevant information from comprehensive global models through various techniques: e.g. dynamical or statistical downscaling? How scientifically robust are these methods?

The breadth and interconnectivity of these questions require GFDL to make long-range plans for its research. GFDL's strategic plan over the next 5-10 years is based upon these framing questions. They will be addressed by building, running and analyzing comprehensive and computationally challenging models. Observations play a key role: the models are built upon empirically constrained process representations, and global observations are used for verification as well as to understand overall model biases to build and sustain model credibility.

The pursuit of our goals will be built around a commitment to providing products and services of utility to the scientific community, and policy- and decision-makers downstream. These products and services include the highest quality science in the peer-reviewed literature, with the models, model output data, and the resulting analyses and information made freely available to users. Strategic collaborations on the key scientific challenges with partners within NOAA, and with other appropriate Federal agencies, academia and related sectors, will be important and targeted, including downstream sectors such as fisheries. Addressing the above science objectives will also enable GFDL to participate in globally coordinated scientific studies such as CMIP5, and to contribute to the US National and international assessments such as the IPCC, the WMO expert teams and the Quadrennial Ozone Assessment.

An important activity towards addressing these scientific questions at GFDL is the development and use of mathematical models and computer simulations of the atmosphere, oceans, and climate system. The current climate models are fully coupled earth system models incorporating land and ocean carbon cycles into the major physical components important for the transient response to anthropogenic forcing: atmosphere, land, ocean and sea ice. The next five to ten years of climate science and model development at GFDL will see important enhancements in resolution and comprehensiveness -- two major directions of climate model development that will likely lead to more realistic climate simulations. The availability of new computing resources will enable our models to enter the resolution threshold where ocean eddies, boundary currents and coastal features are resolved. This, along with significant refinement of the atmospheric model resolution, will enhance the fidelity of simulated regional details as well as the overall magnitude of change. Meanwhile, the push toward cloud resolving scales will continue within atmosphere-only models. The effort to increase the comprehensiveness of the earth system simulation will build from GFDL's current ESMs toward additional coupling of the atmosphere and surface models - the impact of fire on the atmosphere and aerosols on the biosphere and other surface characteristics, for example, and including ice-sheets as a new component of the physical climate system. An important aspect of our planning is the assessment of the relative need for comprehensiveness and resolution in addressing different scientific problems.

The development of this plan was a lab-wide activity facilitated by the writing team. The effort was launched with an all-hands meeting in September 2010 to elicit the views of GFDL staff on the 5-10 year science goals and pathways to achieve them. Subsequently, the writing team organized a meeting with experts and several smaller meetings on particular topics. The team also met with academic collaborators to plan joint efforts. Through these meetings the key science questions listed above were defined and the needed tools identified. The following sections address the plans and interim goals required to address these questions, as well as their modeling requirements. These plans are organized by research area, in sections II through V. Section VI outlines the pathways required to develop the largest models in terms of development team structure and management. A plan for external collaborations is presented in section VII.

GFDL Model Glossary

IPCC AR4 – Intergovernmental Panel on Climate Change Fourth Assessment

IPCC AR5 – Intergovernmental Panel on Climate Change Fifth Assessment

CM2.1 – IPCC 4th assessment model containing a 2° resolution atmosphere and a 1° resolution ocean.

ESM2M – IPCC 5th assessment earth system model based on CM2.1 but containing dynamic vegetation and new biogeochemical components in the ocean and land models.

ESM2G – Twin to ESM2M but with a GOLD-based ocean model replacing the MOM-based ocean in ESM2M. GOLD is an ocean code that uses an isopycnal vertical coordinate.

CM2.5 – High resolution climate model loosely based on CM2.1 with 0.5° atmosphere and 0.25° or finer ocean.

HIRAM – High resolution (0.5° or finer) atmosphere model primarily used for studying storms.

CM3 – IPCC 5th assessment model containing the AM3 atmospheric component and a land formulation with dynamic vegetation. The ocean and sea ice components are the same as CM2.1. The AM3 atmosphere contains comprehensive atmospheric chemistry, the aerosol indirect effect, and extra resolution in the stratosphere.

CM4 – IPCC 6th assessment model planned in section VI of this document. The resolution is expected to be about 0.5° in the atmosphere and 0.25° or finer in the ocean. The atmospheric component of CM4 is referred to as AM4.

II. Atmospheric dynamics, chemistry and physical processes

II.1. Motivation and goals

Research in this area is addressed primarily towards scientific question 1 *Basic climate processes and their representations in models*, and scientific question 2 *Comprehensive modeling of climate system variability and change*. Our goal is an atmospheric modeling system that represents our best current understanding of physical, chemical and dynamical atmospheric processes, that can simulate important atmospheric phenomena on frequencies ranging from hours to years, and that can be coupled successfully to land, ocean, and ice models to simulate climate variations and change on longer time scales. Improved models are needed to simulate clouds and tropical convection, modes of tropical variability, tropical storms, cloud feedbacks, aerosol forcing including indirect effects, troposphere-stratosphere interactions, and the nexus of air quality-atmospheric chemistry-climate connections.

Scientific question 3, *Understanding, detection and attribution, and prediction of extreme events,* is an additional motivator, particularly as it pertains to tropical cyclones. Research in land-atmosphere interactions is motivated by question 6 *Understanding the Earth system including biosphere and human activities*, while air-quality studies form a component of efforts toward question 8 *Climate science, impacts and services.*

Clouds are a vitally important climate-system feedback, accounting for the biggest part of the uncertainty concerning future climate. The degree to which the planet warms as a result of anthropogenic changes is determined by changes in radiative forcing and climate sensitivity. Clouds play key roles in both processes. The interaction between clouds and aerosols affects the magnitude of the indirect effect (e.g. Golaz et al., 2011). The evolution of the cloud distribution as the planet warms is key to understanding climate sensitivity. Improvements in basic cloud simulation will require fundamental advances in cloud parameterization.

The simulation of tropical convection remains a challenge for our atmospheric models, being responsible for some of the most significant model biases. It plays a central role in climate variability on time scales from tropical storms to ENSO and helps control regional climate responses, not only in the tropics but also outside of the tropics through teleconnections.

The composition of the atmosphere (gases and aerosols) plays a critical role in connecting human activities with global and regional climate. Model simulations of past and future climates reveal the crucial role of stratospheric ozone in driving southern-hemisphere circulation change (Son et al., 2010). Also critical are the climatological and, especially, hydrological responses to aerosol forcings (Ming and Ramaswamy, 2009). Recent modeling has alerted us to global and regional climate sensitivity to both direct (Levy et al., 2008) and indirect (Ming et al., 2007) aerosol effects. Short-lived aerosols have highly inhomogeneous distributions and can interact through complex chemical processes. This makes it difficult to ascertain the effects of gases and aerosols on climate from observations, requiring models to advance our understanding.

One of the pressing challenges in climate change assessment and prediction is to quantify the interactions and feedbacks among the atmosphere, land, and ocean. For example, changes in land cover due to changes in climate and land use will alter patterns of land emission and deposition of both gases and aerosols, with implications for climate, air quality, and nutrient cycling. Aerosol interactions with radiation and clouds, which alter vegetation growth, constitute a potentially significant feedback. The coupling of ocean biogeochemistry to the flux of atmospheric species at the ocean surface may affect climate, water quality and nutrient cycling. Assessing the sensitivity of climate to black carbon deposition on snow requires coupling the atmosphere with the cryosphere.

Improvements in stratospheric simulations will require more physically-based treatments of sub-grid scale gravity waves, both orographic and non-orographic. The modeling of stratospheric water, a radiative forcing agent as well as a player in stratospheric chemistry, must be improved by focusing specifically on the mechanisms by which water moves from the troposphere to the stratosphere.

Tropical cyclones may be the most intensely observed features of the atmosphere. Their representation in climate models is conspicuous, and a bellwether of success in physical parameterization (air-sea fluxes, microphysics, aerosol effects) and resolution changes in both the horizontal and vertical. Successful simulation and prediction of these systems will remain a high priority.

II.2. Past accomplishments

Atmospheric models at GFDL have evolved towards both greater comprehensiveness and finer horizontal resolution. Over the past few years, a major revision of GFDL atmospheric model has been accomplished, leading to the development of AM3 (Donner et al., 2011). This model contains new capabilities to quantify the aerosol direct and indirect effects and to evaluate feedbacks between atmospheric chemistry and climate, achieved by coupling chemical schemes for the troposphere (Horowitz et al., 2003) and stratosphere (Austin and Wilson, 2006), as well as for aerosol distributions interacting with cloud microphysics (Ming et al., 2007). These algorithms have been developed and tested in collaboration with other laboratories (NCAR, NASA, MPI-Hamburg), and by participating in model intercomparison projects (e.g. Quaas et al., 2009, Son et al., 2010).

The AM3 model has been coupled with the other GFDL components (land, ocean and sea-ice models) to produce CM3, which has been used to simulate climate change for the IPCC Fifth Assessment Report (AR5). Preliminary evaluation indicates that global-mean aerosol optical depths, scattering properties, and surface clear-sky downward shortwave radiation are more realistic than in previous versions (Donner et al., 2011). The model's climate sensitivity and the spatial structure of projected warming and hydrological changes differ significantly from previous CM2 simulations.

Because of this additional complexity, AM3 has been developed at the same horizontal resolution as AM2, while another branch of model development has explored the value of finer horizontal resolutions, with more modest changes to the AM2 physics, resulting in the HIRAM model (Zhao et al., 2009). Extensive ensemble integrations at seasonal and annual time-scales conducted at higher resolutions (C180 and C360, roughly 50 and 25km respectively) have yielded information about the sensitivity of tropical cyclones to natural and anthropogenic forced variability in the sea-surface temperatures. The models are being used to generate "timeslice" simulations of climate change at these high resolutions, using boundary conditions from a variety of coupled model simulations. Regional models run at even higher resolution have been used to explore the behavior of intense hurricanes under climate change (e.g., Bender et al. 2010).

Many of these recent modeling efforts, but especially the high resolution global models, have benefited from the successful development of the "cubed-sphere finite volume" dynamical core (Putman and Lin 2007), aimed at providing a suitable balance between accuracy and efficiency in the fluid dynamical framework underlying all of our global atmospheric models.

II.3. Implementation and model development

Achieving the goals in section II.I will require improvements on both the comprehensiveness branch of model development (exemplified by AM3) and the resolution branch (exemplified by HIRAM). In addition, for the variety of multi-century coupled simulations that address GFDL's core goal of climate projection, we will periodically need to combine the benefits of both branches in a merged trunk model. But, the push for merger must allow the exploration of comprehensiveness and resolution independently of design requirements of the trunk.

For the next few years, AM3 simulations for the IPCC AR5 will be analyzed in the context of detection and attribution of climate change, with a focus on the relative role of anthropogenic gases and aerosols. Participation in model intercomparison projects, such as AeroCom for aerosol modeling, will be particularly helpful for identifying the need for future aerosol-related modeling initiatives. Improvement in the representation of fundamental aerosol-related physical processes such as emission, chemical transformation and removal need to continue to be a main objective. It is important to advance the aerosol and cloud microphysics by adding prognostic size distributions and transformations by nucleation and coagulation. The treatment of surface sources needs to be improved and generalized to allow important interactions with land, ocean, and ice, such as iron deposition in oceans and black carbon effects on ice.

Improvements in the representation of clouds are key to better quantify uncertainties in aerosol indirect effects, cloud feedbacks on climate change, and regional aspects of hydrological and extreme event changes, especially in the tropics. GFDL's work within a Climate Process Team to develop a sub-grid cloud and turbulence parameterization for shallow clouds is a promising new development. This will use a multivariate probability density function to represent the sub-grid variability in vertical velocity, temperature and moisture (e.g. Larson et al. 2002; Golaz et al. 2002). The inclusion of joint variations in vertical velocity, linking cloud thermodynamics and dynamics, is novel. It moves us towards a consistent framework for representing clouds and their associated turbulence transport.

Possible important developments in radiative transfer include further improvements in continuum absorption, improved consistency between radiative flux and photolysis schemes, the incorporation of simulators allowing better comparisons with satellite data (e.g., spectral measurements), and, possibly, non plane-parallel capability for high resolution simulations.

The high-resolution atmospheric modeling effort will continue to focus on tropical cyclones in a changing climate, as well as other regional aspects of climate change, especially in the continental U.S. Increased resolution in the atmospheric model is needed to properly simulate extreme events and mesoscale phenomena that may impact atmospheric composition, for example, localized dust sources. Phenomena such as intrusions of stratospheric air via tropopause folding, aerosol enhancement by passing fronts, coastal jets, orographic drag, and katabatic flows gradually emerge by direct simulation, and GFDL must track all of these as we evaluate the benefits of higher resolution in climate projections.

Model diagnostics and climate change detection/attribution studies will take advantage of the newly comprehensive and high resolution models, as well as multi-model archives, in studies of modes of variability, stratosphere-troposphere interaction, the effects of climate change on air quality, the simulation of regional extremes, and the sources and cycling of methane, nitrogen, combustion products and dust.

Two directions on the higher resolution pathway that need to be explored aggressively are 1) the cloud-resolving, non-hydrostatic limit, invaluable for exploring cloud feedbacks as well as problems such as hurricane intensity in a warmer world; and 2) a nested-mesh or variable resolution model that facilitates the study of regional climate and, for example, the effects of climate change on severe weather in the central US. Existing stand-alone regional models are important for the continuation of existing projects, but will likely be replaced by this more integrated regional modeling facility. Collaborations with other government agencies will be vitally important for the non-hydrostatic initiative.

The development of a ``trunk'' model (see section VI) designed for future decadal-centennial projections will require decisions and tradeoffs regarding stratospheric vertical resolution, near-surface vertical resolution needed to improve low cloud simulations, horizontal resolution, and the comprehensiveness of the chemistry/aerosol suite of tracers.

It is desirable to have several goals for atmospheric model development efforts in addition to the trunk model for decadal-centennial projections, if these efforts are to be optimally useful to the laboratory. While this trunk model would need to be able to simulate about 5 years per day, there are applications throughout the lab that would benefit from models with efficiencies of approximately 1yr/day and 100yr/day. The former model would be useful for atmospheric-only simulations relevant for climate change and simulation of extreme phenomena, while the latter would be invaluable for earth system simulations as well as paleo-climotological studies that help us to understand and constrain climate sensitivity.

The complexity of the atmospheric code poses special challenges to software design and to maintaining flexibility within a unified code structure. This enhances the need for detailed documentation. Re-examination and substantial recoding of the atmospheric component within GFDL's Flexible Modeling System (FMS) would be very desirable in the near future to support these varied future developments.

III. Ocean and sea level

III.1. Motivation and goals

Ocean modeling efforts at GFDL focus in particular on understanding the role of the ocean in climate. This contributes to addressing scientific question 1: *Basic climate processes and their representations in models*. The representation of ocean processes and the influence of these processes on the large-scale circulation and climate (scientific question 7), along with the role of the ocean in climate impacts such as ecosystems (scientific question 6) and sea-level rise (scientific question 5), are important overall motivations.

Goal i: Sea-level rise

The prediction or projection of sea-level rise in response to anthropogenic forcing is a major goal of societal importance. The problem involves both the water mass budget, in particular the changes in water storage in ice-sheets, and the steric contribution due to the warming of the ocean, including the pattern of change induced by ocean dynamics. A full prediction of the spatial distribution of sea-level rise on the small scales relevant to society would further require high resolution at the coastal scale, as well as predictions of the geological component of geodesic changes, both of which are beyond the scope of GFDL efforts. Instead we will focus on basin-scale changes, and incorporate those aspects of geodesic changes that are well understood (e.g. gravitational effects).

Goal ii: Role of ocean processes, including mesoscale eddies and mixing, in climate

Eddy-resolving simulations will allow effects of mesoscale eddies to be explicitly captured, as well as providing better resolution of boundary currents. The resulting modeled ocean circulation will be more energetic, more variable and contain sharper gradients. Lateral fluxes by resolved eddies will dominate over parameterized fluxes; these fluxes will not necessarily be down-gradient.

Eddies and narrow boundary currents are important in numerous ocean and climate problems. Examples include the restratification of convection regions such as the Labrador Sea, the ocean uptake of heat in regions such as the Western Boundary currents and Southern Ocean, biological processes sensitive to gradients of tracer quantities, and the response of the Southern Ocean to changes in winds.

Even for high-resolution ocean models, there will be many processes that still cannot be resolved, and for which sub-grid-scale parameterizations will be necessary. Perhaps most important among these is diapycnal mixing, which is a consequence of many different ocean processes. The magnitude and distribution of diapycnal mixing is likely to influence oceanic heat and CO_2 uptake and penetration, ocean meridional circulation, and regional variations in climate and distributions of both dynamical and physically passive (but biologically important) tracers. Until recently, model diapycnal mixing parameterizations did not attempt to account for the physical processes responsible for mixing, but rather imposed a horizontally and temporally invariant diffusivity profile. Such a formulation for diapycnal diffusion is not consistent with conservation of energy, and does not allow for mixing rates to evolve as the circulation changes. Recently, advances have been made in representing the mixing by tides and due to resolved shear but these are still incomplete. An ongoing goal is therefore to develop physically based parameterizations of sub-grid-scale mixing processes, and examine the sensitivity of the climate system to these processes.

III.2. Past Accomplishments

GFDL has a long history as an innovator in ocean model development, beginning with the Cox-Bryan model and leading to its descendent, the MOM model. This geopotential coordinate model forms a component of GFDL coupled models (e.g. CM2.1 and ESM2M), but is also the most widely-used large-scale ocean model in the world, and benefits greatly from the input of the ocean modeling community outside of GFDL. Maintaining GFDL's position at the vanguard of ocean model innovation has led to the recent exploration of isopycnal coordinates, in the context of the Generalized Ocean Layer Dynamics model (GOLD), which now also forms part of the GFDL coupled model suite (e.g. ESM2G). Isopycnal coordinates have distinct advantages over geopotential coordinates for some problems (e.g. ocean overflows, ice-shelf cavities, adiabatic interior circulation), yet have difficulties in other areas (e.g. the mixed layer). We therefore have at our disposal one of the most well-used, thoroughly tested ocean models (MOM) as well as the more experimental GOLD assisting us in our evaluation of the robustness of ocean climate signals.

III.3. Implementation and model development

i. Sea-level rise
In order to account for the contribution of ice-sheets to sea level rise, a dynamic-thermomechanical ice sheet model will need to be coupled with the GFDL climate system model. It is anticipated that a two-way coupled, fully interactive ice-sheet model will be available in a 10 year time line. Such a model will advance our qualitative understanding of the

ice-sheet contribution to SLR. However, quantitative projections will lack error and uncertainty estimates for several reasons, including the poorly known present state of the ice sheets ('known unknowns') and gaps in understanding ongoing rapid changes ('unknown unknowns'). A first step toward developing a dynamical ice-sheet model as a component of the coupled model is to port an existing ice-sheet model (developed by D. Pollard at Pennsylvania State University) to FMS . The Pollard model has been tested and validated against existing geological records and is capable of producing the present-day configuration of the Antarctic Ice Sheet after several glacial-interglacial cycles (Pollard and DeConto 2009). Since the coupling of a model component with dynamical boundaries (both ice-sheet/shelf surface and their extent vary with time) is new science territory, we cannot foresee all the issues which may arise, but we anticipate that the presence of the ice-sheet component in the ESM will have implications for atmospheric and ocean components, e.g., the ability to handle the moving ice-surface for the former, and wetting and drying for the latter.

On a centennial time scale the major physical process is the interaction of the marine terminated parts of ice sheets (ice shelves and outlet glaciers) with the ocean. The ice-shelf/ocean interaction strongly affects both components through heat and mass exchange, leading to changes in geometrical configuration and thermal state of the ice sheet, and modification of the water masses affecting large scale ocean circulation. Therefore, the ice-shelf/ocean interaction requires both detailed physical representation and high resolution in two-way interactively coupled models. A proof of concept is close to completion in an idealized model. Based on these developments, we estimate that regional simulations of coupled ice-sheet/ice-shelf/ocean interactions will be possible in the next few years. If the effect of ice-shelf cavity flow on large-scale circulation is to be represented in climate simulations, 2-way nested high-resolution modeling will be needed in the vicinity of the ice-shelves. While some ice-shelf cavities may be resolved at 1/4 degree, 1/8-1/16 degree resolution will be needed for the smaller ice-shelves.

The ice-sheets are of course not the only contributor to changes in water mass storage, and improvements in hydrology models and the representation of the atmospheric hydrological cycle will also impact the prediction of sea-level rise. Mountain glaciers are also an important component of the land hydrological cycle for which nested land-surface model components would be required.

In order to address the steric contribution to sea-level rise, which may be more important on shorter timescales, we will need to simulate the oceanic heat uptake, including the penetration of that heat, and the water-mass changes induced. Oceanic eddies and diapycnal mixing processes (see below) may have an impact on this aspect of the problem. It is simpler and more accurate (since more direct) to calculate the steric effect in a non-Boussinesq formulation (Gregory et al, 2001). This formulation has already been implemented in both MOM and GOLD and we expect the non-Boussinesq formulation to replace the Boussinesq formulation for the next CMIP round (potentially, CMIP6). With the non-Boussinesq model we can tackle experiments such as the oceanic response to specified meltwater fluxes (i.e. decoupled from the ice-sheet).

We anticipate that our basin-scale results for sea-level rise could then be used in conjunction with wave and tide models to downscale to the coastal scales of interest to end users. We do not anticipate running the wave and tide models here, but rather such downscaling might be done through a climate service. Our emphasis at GFDL would be on ocean models of sufficient resolution (e.g. 1/4 degree) to provide meaningful boundary conditions for 1-way nesting of higher resolution coastal model run elsewhere for regional prediction.

ii. Ocean processes in climate
While the principal requirement for an understanding and quantification of the role of eddies in climate is increased horizontal resolution--about 1/8 degree for resolution of the baroclinic eddies important for exchange of properties between the surface and interior--attention must also be given to (a) the role of smaller scale processes in dissipating eddy energy; (b) minimizing numerical diffusion which may otherwise increase as resolution is increased, due to increased variance on smaller scales.

In recent years the GFDL ocean mixing focus has been on processes driven by tides and gravity currents. We expect to develop more sophisticated, physically based parameterizations of the tidally-generated mixing, and include mixing due to internal waves generated by other sources (winds, mean flows, mesoscale eddies) through the recently begun Internal Wave-Driven Mixing Climate Process Team (involving GFDL, NCAR and several academic partners, and with a substantial observational component). Other mixing processes (e.g. estuarine mixing, salt fingering, Langmuir circulations) will be incorporated as advances become available in the academic community. There may well be ocean processes we have not yet considered which future observations indicate to be important (tides were thought to be unimportant for the open ocean as recently as 15 years ago), and we will maintain the flexibility to pursue parameterizations of new processes, as motivated by observations and theoretical basis.

As resolution increases, the resolved motion will include more scales of motion, and parameterizations of the mixing driven by these different resolved motions (for example, eddies over small-scale topography) must then be included.

A persistent barrier to understanding the role of mixing processes on the ocean and climate has been the dominance of uncontrolled numerical mixing in earlier ocean models. The sensitivity to explicitly parameterized mixing can only be examined if this is not swamped by numerical mixing. This has been one motivation for our effort over the past few years to develop ocean models with less numerical mixing, through the use of isopycnal coordinates and/or higher order advection schemes. This effort needs to be continued as resolution is increased, otherwise the net effect of increased variance on smaller scales could be an increase in numerical mixing.

A significant effort must be made, as we move to better representations of physical processes, to understand the impact of these processes on the ocean circulation and variability, and the new feedbacks that may be introduced (for example changing sea-level may change the distribution of tidal energy dissipation, which may in turn impact the ocean circulation).

Since particular research applications favor different model formulations (e.g. an isopycnal coordinate model being more suitable for studies of flow under ice-sheets), both isopycnal and geopotential formulations will therefore continue to be pursued for research purposes within GFDL. However a decision must be made as to the ocean code to be contributed to the lab-wide high-resolution coupled modeling effort (see section VI). This decision will be based on the ongoing analysis of AR5 simulations and ocean-only high-resolution simulations.

IV. Earth System

IV.1. Motivation and goals

Earth system modeling activities at GFDL are focused on expanding beyond the physical climate to represent the marine and terrestrial biosphere and atmospheric chemistry. This research has two foci: the impact of ecosystems and human activities on climate change (science question 6 *Understanding the Earth system including biosphere and human activities*), and the impact of climate change on ecosystems and human activities (science question 8 *Climate science, impacts and services*). An overarching influence of the biosphere on climate is that land and ocean geochemical and ecological dynamics impact the concentration of CO2 in the atmosphere. Current estimates suggest that the earth's biosphere exerts a strong damping effect on human-induced global warming by taking up about 50% of the human emissions of CO_2 (Sabine et al 2004). One of the primary Earth System Modeling efforts is thus to understand the dynamics controlling CO2 uptake by the biosphere and better constrain how it will change in the future. In many cases, certainty is confounded by fundamental conceptual alternatives for model construction with only limited observations of key variables needed to evaluate model performance and to improve the models. This uncertainty motivates a strong, cross-disciplinary need to combine modeling, theory and observations to make progress, and requires scientists at GFDL to reach out to experts in many areas.

IV.2. Past accomplishments

Over the last decade, a prototype earth system model of coupled carbon/climate (ESM2.1) and two descendant models (ESM2M and ESM2G) have been built at GFDL with the critical involvement of Princeton collaborators. ESM2M and ESM2G simulations will be a significant part of GFDL's contribution to AR5 and will have diverse utilities to study past, present and future climate and biosphere dynamics. Uncertainties in oceanic heat and carbon uptake dynamics play key roles in generating differences among models for future projections of climate changes. Fundamental differences in ocean model formulations between ESM2M (e.g. z-level vertical coordinate) and ESM2G (e.g. isopycnal coordinates) provide a unique opportunity to investigate the role of the ocean in both carbon and heat uptake under transient climate change. Detailed diagnosis of the impact of different ocean model formulations will elucidate the underlying causes and consequences of inter-model differences and thus reduce uncertainty in future projections of climate change.

Now that the primary development phase of our initial ESMs is complete, we are moving focus from development onto assessment of the utility of the various ESMs to improve understanding of climate impacts on ecosystems and human activities. These activities have been augmented by a suite of novel collaborations with postdocs at GFDL, partners in NOAA, within academia, and elsewhere. Some of the novel initial analyses have been on terrestrial climate change and CO2 fertilization impacts. Progress has also been made in assessing the impact of climate change and variability on a variety of living marine resources using our new ESMs. The limitations of the existing models for impacts studies identified in this research are being used to inform future model development.

IV.3. Implementation and model development

Over the next decade, we envision continued innovative applications and model improvements in GFDL Earth System Modeling, including: migration to the next generation physical climate model, refinement of components, incorporation of additional biogeochemical cycles, exploration of higher resolution, exploration of the initialization problem for seasonal-to-decadal scale ecological forecasts, and exploration of longer time scale climate variability and change including past climates. As ESM development necessarily follows physical climate model development, migration of ESM components into next generation physics and dynamics (e.g. cubed sphere) is expected to be ongoing as these components evolve. The representation of the ocean ecology will be expanded beyond its current biogeochemical emphasis to provide a more complete and mechanistic representation of ecological dynamics across trophic levels. This will improve the resolution of biogeochemical dynamics and increase the utility of simulations for assessing climate change impacts on marine resources. Additional nutrient cycles will be added to the land ecology model to resolve the impact of nutrient-limitation on land carbon dynamics. A model for terrestrial nitrogen, for example, has been developed for incorporation into GFDL's next generation ESMs. Enhancing the ecosystem and biogeochemical dynamics within the ESMs will also allow novel investigation of human impacts on both the biosphere and on climate (e.g., ocean acidification, coastal eutrophication, hypoxia and anoxia, air pollution, biodiversity loss).

Many strong interactions between climate, ecosystems and human activities occur at the margins between the land and ocean (rivers, wetlands, estuaries, near-shore and continental shelves). These margins are not well resolved in the present generation of ESMs restricted to ~1 degree resolution. This will be addressed in the next 5-10 years by adopting enhanced resolution ocean, atmosphere, and land models presently under development for earth system model applications. These fine-resolution (¼ degree and better) ESMs will be used to further elucidate connections between global and continental/ocean-basin scale dynamics and regional climate impacts, quantify the role of continental shelves on global-scale biogeochemical cycles, and resolve the role of estuaries and wetlands in controlling the flow of carbon and nutrients between land and shelf and ocean waters. These efforts will be enhanced by the development of robust approaches for nesting with existing regional estuarine, ocean and climate models to resolve critical impacts and biogeochemical fluxes. Additional dynamics, sediment, ecology, and biogeochemistry modules will be developed to capture the dynamical exchanges between the benthos and water column in shallow-water ecosystems.

In addition, we will also seek to understand past observed climate and carbon changes, including studies of the distant past climates such as the Last Glacial Maximum (LGM – about 21,000 years ago). For example, drawing on the experience of the LGM study with CM2.1, we will use ESM2.1 to explore biosphere-climate interactions and their implications for both physical climate and the carbon cycle at that period. It is likely that these studies will expose aspects of our models that need to be improved. These activities are essential steps in building confidence in our model projections of future climate changes and they highlight various model strengths as well as model weaknesses that need to be addressed.

We see a number of logistical challenges within our Earth System Modeling effort as we move forward, including questions of configuration, initialization, and computational efficiency. By its design, the Earth System Model is comprehensive and critically depends on all upstream component development as it is built upon the successful representation of myriad climate processes and components developed across GFDL, many of which were constructed to answer specific scientific questions outside of biospheric impacts and feedbacks. As a result the ESM will not necessarily be efficiently constructed for any particular scientific question, and is singularly challenged, with the tension between the need for parsimony and the desire for comprehensiveness. Initialization is one of the greatest challenges for ESMs, as the coupled nature of the climate and biosphere implies variability of a multitude of tracers on a continuum of time scales, and biases in the model may develop over centuries to millennia of integration. This challenge is particularly acute for application to initial value problems such as ecological forecasting. Finally, the issue of computational efficiency confounds each of the above as it limits our ability to gather foresight and intuition as to how the model will eventually behave. This is anticipated to become an even greater challenge in the current environment of multi-core parallel processing, and motivates serious investigation into both statistical inverse methods towards sophisticated initialization as well as computational methods for enhanced parallelization of the GFDL codes to conform to this new computational paradigm.

We also see a set of strategic challenges to Earth System Modeling, which we anticipate to become increasingly problematic over the coming years. This includes the difficulty in choosing the most appropriate set of research objectives to take advantage of the unique strengths at GFDL, in the face of myriad potential earth system foci and the external requests and demands placed on GFDL by the myriad impacts communities that have an interest in having us help them analyze and interpret the output of our models for their particular application. We see a valuable role for GFDL personnel to serve as advisors to guide the proper use of coupled models within the impacts community. While we feel that having any single 'impacts' group at GFDL is not viable, everyone in the earth system modeling effort at GFDL should have some involvement in impacts. We also consider that Princeton University may be able to play an invaluable scientific leadership role on the implementation of impacts science in the coming years should their own plans come to fruition.

V. Prediction and attribution

V.1. Motivation and goals

The central goal of climate prediction and attribution research activities at GFDL is to improve our ability to predict and project climate variability and change for the 21st century, with a vision of providing societally relevant information and understanding to policymakers and other stakeholders. These activities address the science questions 2, *Comprehensive modeling of climate system variability and change,* 3, *Understanding, detection and attribution, and prediction of extreme events,* 4, *Understanding, detection and attribution, and predictability of modes of climate variability,* and 5, *Cryospheric amplification of climate change and sea-level rise* and contribute to efforts to address question 8, *Climate science, impacts and services.*

We have a number of important goals moving forward, including:

• Explore the predictability of the climate system on seasonal to decadal time scales, leading to experimental decadal climate predictions (questions 2, and 4).
• Improve our understanding of how extremes in the climate system (hurricanes, droughts, floods) may change in the future in response to radiative forcing changes and natural variability (question 3).
• Better quantify the relative roles of radiative forcing changes and natural variability in observed climate change (questions 2 and 4).
• Better characterize and understand the dynamics of climate variability and change, including interactions across time scales and the potential for abrupt change (questions 4 and 5).
• Use observations to improve climate models (and use models to improve observational systems) in order to enhance our ability to predict climate variability and change (questions 2,3,4).

V.2. Past accomplishments

One of the hallmarks of GFDL's CM2.1 climate model activity was the development of a single model capable of being used for both experimental seasonal predictions and centennial scale climate change projections. Since the development of CM2.1, there have been extensive further development efforts along several lines, including models with higher spatial resolution, new physical and numerical formulations, and the inclusion of physical processes not previously considered. There has also been substantial progress in developing a new coupled data assimilation system that is the cornerstone of experimental climate prediction efforts. Future development efforts will leverage the knowledge gained through these explorations in the design and construction of next generation models. A selection of other recent accomplishments is highlighted in the following section on implementation and model development.

V.3. Implementation and model development

Model development and research activity over the next decade will likely lead us along the following paths:

(i). Develop and use models of higher spatial resolution to better represent important small-scale processes, and to better simulate regional climate and climate extremes: Preliminary efforts with a new coupled climate model (GFDL CM2.5) with a 50 km atmospheric grid and an ocean grid of 10-27 km have been very encouraging. The simulation of many regional scale climatic features has improved substantially, including very significant improvements in the Tropics. For example, the error associated with a double ITCZ in the eastern Pacific has been cut in half; the simulation of rainfall over the Amazon and Indian monsoonal regions has improved significantly. We speculate that part of this overall improvement comes from improved representation of small-scale processes, such as the interaction of oceanic coastal upwelling zones with the steep topography and associated winds along the west coast of South America. These small-scale changes can lead to improvements in simulating large-scale climate processes.

The simulated response of the climate system to perturbations can also change significantly at higher resolution. For example, Hallberg and Gnanadesikan (2006) and Farneti et al (2010) show that the response of the Southern Ocean to changing wind stress is significantly different at high resolution due to the impact of oceanic mesoscale eddies. This has important implications for oceanic uptake of heat and carbon in the Southern Ocean.

Ongoing work aims to explicitly simulate the response of tropical storms to natural climate variability and changing anthropogenic forcings (e.g., greenhouse gases) in a high-resolution global coupled ocean-atmosphere model, thereby allowing a more complete suite of ocean-atmosphere interactions at a relatively fine scale. Even higher resolution downscaling simulations (e.g., Bender et al. 2010) will continue to be used to explore the behavior of intense hurricanes under climate change. An additional focus with such high-resolution models will be studies of North American drought; these models can provide a much more realistic representation of North American rainfall, especially for the western US where topographic effects are important. This has important implications for an assessment of future water resources in the western United States.

Future model development and climate research efforts will benefit from the knowledge and insights gained from this effort. A goal on the 5 to 10 year time scale is to move to a model with resolution of several km in the ocean and 25 km in the atmosphere, thereby vastly improving the representation of small-scale processes in the climate system. It is hoped that higher resolution models will permit a more realistic simulation and projection of crucial features such as sea surface temperature patterns that are vital for projecting changes in climate extremes e.g., , hurricanes (Knutson et al. 2008; Zhao et al. 2009; Vecchi et al. 2011) and drought (Findell and Delworth 2010). This will enhance our confidence in projected changes in high-impact regional weather and climate phenomena, and thus will be extremely valuable for climate change assessments.

(ii). Develop climate predictions initialized from the observed state of the climate system: These climate predictions attempt to predict not only the response of the climate to changing radiative forcing, but the evolution of natural variability over the next decade, such as the state of Atlantic and Pacific ocean temperatures and their implications for weather and climate extremes.

This effort is at a very early stage, but substantial progress has been made to date. A pioneering coupled data assimilation system has been developed at GFDL. This system combines oceanic and atmospheric observations, together with the CM2.1 coupled model, to provide optimized initial conditions for seasonal to decadal climate predictions. The system has already yielded substantially improved seasonal predictions (S. Zhang et al. 2007). A prototype decadal prediction system has now been developed, and in the near-term the skill of this system will be evaluated through the detailed analysis of suites of decadal-scale hindcast and prediction experiments, in concert with IPCC AR5/CMIP5.

Future efforts will seek to improve the coupled data assimilation and prediction system. In addition, we will also move to the use of higher resolution models for predictions and coupled data assimilation. Over the next 1-3 years, experimental predictions will be performed with a higher resolution model (CM2.5) with initial conditions from the reanalysis using CM2.1. In the longer term, a new reanalysis system will be developed based on the CM2.5 high-resolution model. This will be extremely demanding computationally, as the coupled assimilation system requires large ensembles of simulations to be run. It is hoped that using higher resolution systems for decadal predictions will better represent important small-scale processes in the climate system, leading to skillful decadal predictions of changes in regional climate and climate extremes, such as tropical storm activity (Vecchi et al. 2011) and droughts (Findell and Delworth 2010).

(iii). Enhance model development with statistical parameter estimation: One pathway toward development of models with improved physics is through the development of improved parameterizations of physical and biophysical processes, such as clouds and their radiative feedbacks, for inclusion in climate models. With such parameterizations, there are always sets of adjustable parameters that have typically been tuned in a somewhat ad-hoc fashion to produce a simulated climate that is more realistic according to a given set of metrics. A potential new pathway is the use of advanced statistical techniques that optimize the choices of parameters in various parameterizations in such a way as to produce more realistic models for a set of climate metrics. This methodology, which exploits the ensemble Kalman filter at the heart of the coupled assimilation system, is in its infancy, but shows substantial promise in tests with idealized models. Although this technique offers the promise of a more systematic pathway toward quantified model improvement, much research is needed to better establish this technique and evaluate its utility.

(iv). Improve understanding of natural variability of the climate system on time scales of seasons to decades, along with the potential for abrupt climate change: On smaller spatial scales and shorter time scales, the relative importance of natural variability of the climate system increases compared to radiatively forced changes. For example, regional temperature variability on subcontinental spatial scales and time scales of a decade or two can be dominated by natural variability, with the radiatively forced component becoming dominant on longer time scales. These smaller time and space scales are societally important for many planning horizons, such as water resources, and it is thus crucial to better understand the dynamics of decadal variability. In addition, the processes involved in decadal variability can be an important part of any potentially abrupt changes in the climate system, such as rapid changes to more arid climates, or sudden changes in Arctic sea ice and climate.

Extensive research is underway to better understand the mechanisms controlling the decadal variability of the Atlantic Meridional Overturning Circulation (AMOC), and its impact on Atlantic temperature and large-scale climate. Ongoing work has demonstrated that AMOC fluctuations can influence monsoonal rainfall from India to Africa and North America, and can influence tropical climate conditions important for tropical storm formation (Zhang and Delworth,2005;

Zhang et al, 2008; Zhang and Delworth, 2009). These efforts have provided part of the motivation to aggressively move to models of higher spatial resolution, in order to better resolve smaller-scale processes. This will continue to be a focus, especially in conjunction with the decadal prediction and attribution activities described above. Significant work is underway, and will continue on the processes controlling decadal changes in tropical storm activity, and their relationship to large-scale climate variations and change (Vecchi and Soden, 2007; Vecchi et al., 2008; Vecchi and Knutson, 2008; Vecchi et al., 2010). In addition, a planned new focus is on the processes influencing North American drought on decadal time scales. Again, the development and use of higher resolution models should be extremely useful for this problem.

(v). Elucidate the relative roles of radiative forcing changes and natural variability in explaining observed changes: For example, we need to better understand what fraction of the observed increase in hurricane activity from the 1970s to the last decade was due to changing radiative forcing (including contributions of specific forcings), and what fraction was a manifestation of internal variability of the climate system. A related question would be what processes (internal variability or radiative forcings) governed the observed multidecadal changes in Atlantic SST? Another example is the relative role of radiative forcing changes and natural variability in western U.S. drought. Such research is currently being conducted at GFDL, and will be refined and expanded over the next decade (some related work includes Zhang and Delworth, 2009; Zhao et al, 2009; Zhang et al, 2009; Zhang, 2008; Vecchi and Knutson, 2008). In addition to the above topics, we will attempt to assess the roles of natural variability and human activities in the changing Arctic climate. The pursuit of these topics will be aided by the decadal prediction effort, since that activity attempts to explicitly predict both natural variability and forced climate change. Pursuing these topics requires large ensembles of experiments using various subsets of radiative forcing changes. Because tradeoffs will always be necessary between using more comprehensive models at higher resolution versus less complex, lower resolution models that are much faster computationally, a hierarchy of models with varying complexity and associated computational costs will be required.

Projections, Predictions, and Attribution: An example for Arctic sea ice

As Arctic sea ice has declined sharply in recent decades, there has been increasing interest both in making future predictions of Arctic sea ice and in understanding whether the recent decreases result primarily from greenhouse warming, or whether natural variability or other anthropogenic forcings such as soot may have played significant roles. These questions and issues illustrate the distinction between climate projections, predictions, and attribution in the context of Arctic sea ice changes.

* Climate projections are decadal to centennial-scale scenarios that are based on plausible, but uncertain, emissions scenarios. In this case, predictability comes from the dominant role of radiative forcing compared to natural variability on longer time scales. Only the forced component of change is predicted, and climate sensitivity is a key uncertainty (Winton 2011).

* Decadal climate predictions seek to obtain predictability from both radiative forcing and initialization of the ocean (in particular, initialization of the natural variability modes as expressed in the ocean state). Both forced and natural variability components of change are predicted. Ongoing coupled data assimilation efforts are crucial to this activity.

* Attribution studies seek to quantify the influence of natural variability and various forcings on past changes. If the forcings can be estimated and the natural variability component quantified, the sensitivity to forcings can be constrained from observations (estimate forcings and residual forced response). Mahajan et al (2011) show the connection of sea ice cover to the Atlantic meridional overturning circulation (AMOC). If we can diagnose the AMOC state (Zhang 2008) we may be able attribute some sea ice change to natural variability and narrow our observational sensitivity estimate.

VI. Model Development and Infrastructure

VI.1. Motivation and goals

Many of the science questions described above can only be achieved with a high-resolution comprehensive coupled climate model. For example, the impact of ocean processes on climate, particularly mesoscale eddies, is best studied with a coupled model that explicitly resolves the eddy-scale. An examination of ice-ocean coupling requires sufficient resolution to capture under ice-shelf cavities. Many questions regarding impacts and extremes can only be addressed with sufficiently high resolution. A comprehensive model will include many of the important physical, chemical and biological processes being examined in pursuit of individual research questions. Hence, the development of a comprehensive high-resolution model requires coordination between different research areas to pull together the expertise in each area into a single model. Our goal is therefore to develop a single ``trunk'' high-resolution model that is capable of addressing a large number (but not all) of the science questions. In addition to being a tool to be used to address the principal science questions, we anticipate that such a model would be suitable for the next climate model assessment (a potential CMIP6).

VI.2. Past accomplishments

GFDL's climate models trace their roots back to the early 1960's when a radiative transfer model of the earth's greenhouse effect was incorporated into a three-dimensional atmospheric model (Manabe and Moller, 1961). Fifty years of development has brought these precursors to their present state -- fully coupled earth system models incorporating land and ocean carbon cycles into the major physical components important for the transient response to anthropogenic forcing: atmosphere, land, ocean and sea ice. GFDL has participated in Climate Model Intercomparison Projects (CMIP), a set of coordinated experiments designed to help define the distribution of possible responses to increases in CO_2. The CMIP model results are distributed for analysis periodically for the IPCC assessments, about every 6 years. GFDL participated in the first three IPCC assessments using climate models developed by a single science group -- the Climate Dynamics group. Other GFDL global models developed prior to 2000 e.g., developed by the Middle Atmosphere Group were employed in the WMO Ozone Assessments, while the model developed by the Numerical Weather Prediction group found usage in experimental seasonal predictions. In the 2000's, the push toward sophistication and comprehensiveness motivated a move to lab-wide development of models coordinated by development teams with leadership and membership cutting across the six science groups. This change occurred as the computer platforms were shifting to massively parallel architectures. The Flexible Modeling System (FMS) was developed to make the transition to new architectures easier, to share utility codes among components and to allow for interchangeability of model components. The development teams and the FMS coding framework are both important for the lab-wide organization of modeling efforts at GFDL.

In the 2000's an increasing number of development teams have participated in producing GFDL's IPCC model suite. The current model development teams (MDTs) are: GAMDT (global atmosphere), OMDT (ocean) CMDT (coupled model), ESMDT (earth system), LMDT (land model), MI (model infrastructure), and DPDT (data portal). The IPCC AR5 generation of GFDL models includes CM2.1, CM3, ESM2M, ESM2G, CM2.5 and HIRAM. All except the last two, which were science group-based efforts, were developed by collaborations of development teams. The exploration of parameterizations and formulations in the low-resolution models (CM2.1, CM3, ESM2M, and ESM2G) has been well served by the team structure.

VI.3. Implementation

Over the next five years GFDL plans to develop a high-resolution climate model for resolving climate impacts and improving the fidelity of important climate change processes with an emphasis on resolving small ocean scales. This model will be named CM4 and its atmospheric component will be AM4. The tentative resolution for AM4 is 1/2 degree and the ocean component of CM4 will have resolution of 1/4 degree or higher. CM4 will be useful for making predictions and projections from seasonal to century timescales. This places both real time performance and total cost requirements on the model. In past IPCC cycles, GFDL has used the following rough specification to size its high-cost climate model: The model must run about 5 year per day using no more than 1/8 of GFDL's main computer resource. These specifications allow the development of the requisite models, and the preindustrial ("1860") spin-up, historical runs and projections to be produced in a timely fashion while allowing approximately 1/2 of the computer resource for other projects. Decadal predictions are expected to have a similar expense. Although the runs are shorter owing to the use of initialization, the data assimilation that produces the initialization involves running an ensemble. Therefore, the additional cost of making decadal forecasts may tighten the cost requirements on CM4.

The computational resource we expect to have available for development and production runs of CM4 over the next few years is only marginally adequate to achieve this goal. Given the size of the resource, the computational requirement is open-ended because important ocean eddy and boundary current effects are known to occur at scales that we will not likely be able to afford. Aerosol chemistry sufficient to do the aerosol-cloud interactions and ocean biogeochemistry sufficient to do ocean carbon uptake are high priorities for inclusion in the model. Together they are expected to increase the cost about 50% above that of the core physical model. The nature of this requirement calls for careful management of the cost of the model, a focus on optimization, and model development experiments that maximize progress. Additionally, the current suite of climate models contains differing formulations and parameterizations. Choices or mergers will be necessary to construct a single high-resolution model from their parts.

To address these challenges, it is suggested that GFDL unify the management of the AM4/CM4 development under two teams: an AM4DT that develops the atmospheric component using fixed SST atmosphere experiments for evaluation and a CM4DT that develops the coupled climate model, CM4, using AM4 as the atmospheric component. Each team will be led by three team leaders, who will rotate as the focus of the team evolves, and to share the burden. The team leaders have responsibility for achieving the scientific goals of the project. It is expected that team leadership will be drawn from multiple science groups. Team decisions are made after consultation with the team and represent, if possible, a consensus of experts. Some decisions may be contentious, and no consensus may be possible, in which case team decisions will be made by a majority vote between the three team leaders. The GFDL Director and research council will review all non-unanimous team leader decisions and give the final approval.

The AM4DT should commence in 2011 toward improving the modularity of the atmospheric code to make a broad-based model development possible. The CM4DT should commence in 2012 when the first AM4 is ready for coupled experimentation. By 2012 a choice will have been made as to the initial ocean code for CM4, based upon ongoing analysis of AR5 simulations and high-resolution ocean-only simulations. The AM4DT and CM4DT should coordinate closely to refine and test the atmospheric model.

While the intent of this plan is to "prune" the model branches that have grown over the last decade, it is recognized that model innovation is also important for scientific progress. Cost issues, in particular, may make AM4 and CM4 unsuitable for certain applications where the models are either too costly or have sacrificed processes to achieve their performance specifications. The AM4DT and CM4DT are charged with identifying and developing major branches of the models to satisfy groups of scientists who focus on addressing particular but nevertheless urgent science problems. Examples might include lower resolution-reduced cost versions, a comprehensive chemistry atmosphere, or higher vertical resolution atmosphere for stratosphere or boundary layer studies.

The modeling plans presented here will benefit greatly from software enhancements for performance and data management. We will be stressing the limits of our computing and archive in three ways:

- Complexity (as measured by number of tracers, for example),
- Resolution, and
- Capacity (ensembles of runs for uncertainty quantification).

Although increasing processor numbers allow higher resolution, clock rates are not increasing, making real-time performance challenging. While all climate modeling benefits from real-time performance, this is especially important for the long runs needed to study past climates or assess simulated natural variability. Additionally, earth system modeling introduces long oceanic biogeochemical timescales, and so has a larger simulation-years-per-day requirement. Enhancing the parallelization of codes is one way to maintain real-time performance as grids are refined. We plan to explore concurrent execution of the atmospheric radiation physics and other components as a way to apply more processors to the atmosphere model in a scalable fashion. Floating point precision reduction for some calculations and algorithmic optimizations to improve code speed will also be investigated. Another pathway to better real-time performance is through emerging computer architectures that make use of arrays of GPUs (Graphics Processing Units) to enhance the throughput of individual processing elements. The potential to use these architectures for GFDL climate modeling will be monitored in coming years as the programming model matures.

As the comprehensiveness and resolution of climate models increase, the data volumes produced become increasingly more difficult to manage. Strategies involving improved through-flow to reduce intermediate space, diagnostic coarsening, and output regeneration will be explored to control data volumes.

VII. Collaborations

As a federal research laboratory, GFDL's central mandate is to accomplish the kind of deeply cooperative, interdisciplinary, long lead-time, and computationally demanding research that would be impossible to accomplish through independent and isolated academic research. However, since the early days, Joseph Smagorinsky recognized the critical importance of collaborations to successfully meet the challenges of numerical modeling of climate and weather phenomena. This commitment is highlighted in the creation of Princeton's AOS program in 1967 and the subsequent move of GFDL from Washington DC to Princeton in order to advance this frontier science through collaboration with some of the greatest minds in the field. Since those early days, the scope of GFDL's collaborations with the academic community has continued to grow, and now encompasses long standing collaborations with various Princeton Departments including Geosciences, Ecology and Evolutionary Biology, Woodrow Wilson School of Public and International Affairs, Civil and Environmental Engineering, Physics, as well as collaborations with climatologists and oceanographers at Rutgers University. In general, collaborations allow GFDL to explore frontiers of science beyond its central mandate, so that the mandate can be fulfilled in a more comprehensive, creative and robust way. One of the central benefits of these collaborations is that they tend to synergize research perspectives between collaborative tool building and the need to push the envelope of novel scientific frontiers. Thus, the collaborations can serve to continually reinvigorate the creative process of model building as well as allow the frontiers of modeling inform the scientific enterprise. Specifically, these collaborations have proven most successful through the collaborative exploration of novel approaches in five main areas: 1) process-level model development in interdisciplinary areas beyond the classical physical climate arena for representation of critical interactions such as terrestrial ecosystems (e.g. Pacala); 2) broadened configuration and application of models to include additional tracers to inform model construction and fidelity such as in the case of ocean biogeochemistry (e.g. Sarmiento); 3) implementation of novel configurations to test paleoclimate, geoengineering and other hypothetical scenarios of societal relevance (e.g. Philander); 4) targeted analysis of model simulations for interpretation to particular impacts communities (e.g. Oppenheimer, Smith); and more recently, 5) the creation of climate process teams for the targeted improvement of model processes through the collaboration of observationalists, theoreticians and modelers.

Moving forward, we see the role of collaborations continuing much as at present and perhaps even expanding into new domains as science advances. We envision GFDL scientists to continue taking the lead in the core development, implementation of state of the art models for climate and earth system science, and Princeton and other collaborators contributing to and complementing the exploration of novel long lead time representational approaches and applications, and continued GFDL participation in multi-investigator climate process teams. Two areas where we see the potential to grow collaborations led by the academic side in the near future are paleoclimate and climate change impacts. In the area of paleoclimate, formal GFDL collaborations include the ongoing Cooperative Institute for Climate Application and Research with Lamont Doherty Earth Observatory which has a millennial scale focus, but also include many peer-to-peer collaborations on a variety of topics from glacial-interglacial interactions to the paleocene-eocene thermal maximum. These paleoclimate studies serve as an independent means of verifying the models' ability to represent different climate scenarios, thereby improving the credibility of future climate projections. In the area of climate change impacts, collaborations have been largely limited, targeted studies of individual topics. While the central focus of GFDL is on representation of climate itself in a general scope rather than on any individual impact communities, we also recognize the importance of impacts as an important rationale and justification for the climate modeling enterprise. With that in mind, rather than seeking to develop a single, impacts-dominated group internally, GFDL plans to continue having many scientists allocate a minor part of their efforts in impacts, and work with academic collaborators to address impacts goals, while maintaining primary focus on representation of climate. A stronger collaborative effort on impacts may depend on future faculty hires at Princeton, particularly in impacts areas involving social sciences (e.g. agricultural impacts). Given the interests and expertise of current faculty, we see the potential for expanding collaborations on hydrological impacts, which would tie in well with the water resources theme of a climate service.

In addition to research collaborations, GFDL has a long history of educational collaboration with Princeton University through the graduate student degree-granting Atmospheric and Oceanic Sciences Program. With the ongoing expansion of the earth system science enterprise beyond the classical climate science to ecosystems, chemistry and related fields, and the ever increasing interest in climate and earth system impacts from interdisciplinary fields such as policy, hydrology, biology, geology and others (particularly as evidenced by the interest in a climate service), we recognize that the need for training in such fields is evolving and that GFDL's education-related collaborations with Princeton and general outreach efforts will need to evolve in kind.

References

Austin, J., and R. J. Wilson, (2006): Ensemble simulations of the decline and recovery of stratospheric ozone, J. Geophys. Res., 111, D16314, doi:10.1029/2005JD006907.

Bender, M. A., T. R. Knutson, R. E. Tuleya, J. J. Sirutis, G. A. Vecchi, S. T. Garner, and I. Held, (2010): Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. Science, 327(5964), doi:10.1126/science.1180568.

Donner, L. J., et al. (2011): The Dynamical Core, Physical Parameterizations, and Basic Simulation Characteristics of the Atmospheric Component of the GFDL Global Coupled Model CM3. J. Climate, in press.

Farneti, R., T. L. Delworth, A. Rosati, S. Griffies, and F. Zeng, 2010: The role of mesoscale eddies in the rectification of the Southern Ocean response to climate change. Journal of Physical Oceanography, 40(7), doi:10.1175/2010JPO4353.1.

Findell, K. L., and T. L. Delworth, 2010: Impact of common sea surface temperature anomalies on global drought and pluvial frequency. Journal of Climate, 23(3), 485-503.

Golaz, J.-C., V. E. Larson and W. R. Cotton (2002): A PDF-based model for boundary layer clouds. Part I: Method and model description. J. Atmos Sci., 59(24), 3540-3551, doi:10.1175/1520-0469(2002)059<3540:APBMFB>2.0.CO;2

Golaz, J.-C., M. Salzmann, L. J. Donner, L. W. Horowitz, Y. Ming and M. Zhao, (2011): Sensitivity of the aerosol indirect effect to subgrid variability in the cloud parameterization of the GFDL Atmosphere General Circulation Model AM3. J. Climate, doi:10.1175/2010JCLI3945.1, in press.

Gregory, J. M., J. A. Church, G. J. Boer, K. W. Dixon, G. M. Flato, D. R. Jackett, J. A. Lowe, S. P. O'Farrell, M. M. Rienecker, G. Russell, R. J. Stouffer, and M. Winton, 2001: Comparison of results from several AOGCMs for global and regional sea-level change 1900-2100. Climate Dynamics, 18(3/4), 225-240.

Hallberg, R., and A. Gnanadesikan, 2006: The role of eddies in determining the structure and response of the wind-driven Southern Hemisphere overturning: Results from the Modeling Eddies in the Southern Ocean (MESO) project. Journal of Physical Oceanography, 36(12), 2232-2252.

Horowitz, Larry, S. Walters, D. L. Mauzerall, L. K. Emmons, P. J. Rasch, C. Granier, X. Tie, J. F. Lamarque, M. Schulz, G. S. Tyndall, Isidoro Orlanski, and G. P. Brasseur, (2003): A global simulation of tropospheric ozone and related tracers: description and evaluation of MOZART, version 2, J. Geophys. Res., 108(D24), 4784, doi:10.1029/2002JD002853.

Knutson, T. R., J. J. Sirutis, S. T. Garner, G. A. Vecchi, and I. Held, 2008: Simulated reduction in Atlantic hurricane frequency under twenty-first-century warming conditions. Nature Geoscience, 1(6), 359-364.

Larson, V. E., J.-C. Golaz and W. R. Cotton, (2002): Small-scale and mesoscale variability in cloudy boundary layers: Joint probability density functions. J. Atmos. Sci., 59(24), 3519-3539, doi:10.1175/1520-0469(2002)059<3519:SSAMVI>2.0.CO;2

Levy II, H., M. D. Schwarzkopf, L. Horowitz, V. Ramaswamy, and K. L. Findell, (2008): Strong sensitivity of late 21st Century climate to projected changes in short-lived air pollutants. J. Geophys. Res., 113, D06102, doi:10.1029/2007JD009176.

Liu, J., S. Fan, L. W. Horowitz, and H. Levy II (2011): Evaluation of Factors Controlling Long-Range Transport of Black Carbon to the Arctic, J. Geophys. Res., doi:10.1029/2010JD015145, in press.

Manabe, Syukuro, and F Möller, 1961: On the radiative equilibrium and heat balance of the atmosphere. Monthly Weather Review, 89(12), 503-532.

Ming, Y., V Ramaswamy, L. J. Donner, V. T. J. Phillips, S. A. Klein, P. Ginoux, and L. Horowitz, (2007): Modeling the interactions between aerosols and liquid water clouds with a self-consistent cloud scheme in a general circulation model, J. Atmos. Sciences, 64(4), doi:10.1175/JAS3874.1.

Ming, Y., V. Ramaswamy (2009): Nonlinear climate and hydrological responses to aerosol effects, J. Climate, 22, 1329-1339.

Pollard, D. and R.M. DeConto. 2009. Modelling West Antarctic ice sheet growth and collapse through the past five million years. Nature, 458, 329-332.

Putman, W M., and S.-J. Lin (2007): Finite-volume transport on various cubed-sphere grids**.** *Journal* of Computational Physics, 227(1), 55-78.

Quaas, J, Y. Ming, L. J. Donner, and P. Ginoux, et al., (2009): Aerosol indirect effects - general circulation model intercomparison and evaluation with satellite data. Atmospheric Chemistry and Physics, 9(22), 8697-8717.

Sabine, C. L., Richard A. Feely, N. Gruber, R. M. Key, K. Lee, J. L. Bullister, R. Wanninkhof, C. S. Wong, D. W. R. Wallace, B. Tilbrook, F. J. Millero, T.-H. Peng, A. Kozyr, T. Ono, A. F. Rios (2004): The Oceanic Sink for Anthropogenic CO2. Science, 305, 367–371.

Son, S.-W., et al. (2010): Impact of stratospheric ozone on Southern Hemisphere circulation change: A multimodel assessment, J. Geophys. Res., 115,D00M07, doi:10.1029/2010JD014271.

Vecchi, G. A., M. Zhao, H. Wang, G. Villarini, A. Rosati, A. Kumar, I. Held, and R. Gudgel, 2011: Statistical-dynamical predictions of seasonal North Atlantic hurricane activity. Monthly Weather Review (in press). doi:10.1175/2010MWR3499.1.

Vecchi, G. A., and T. R. Knutson, 2008: On estimates of historical North Atlantic tropical cyclone activity. Journal of Climate, 21(14), 3580-3600.

Vecchi, G. A., K. L. Swanson, and B. J. Soden, 2008: Whither hurricane activity. Science, 322(5902), doi:10.1126/science.1164396.

Vecchi, G. A., and B. J. Soden, 2007: Increased tropical Atlantic wind shear in model projections of global warming. Geophysical Research Letters, 34, L08702, doi:10.1029/2006GL028905.

Winton, M., 2011: Do climate models underestimate the sensitivity of Northern Hemisphere sea ice cover? Journal of Climate, in press.

Zhang, R., and T. L. Delworth, 2009: A new method for attributing climate variations over the Atlantic Hurricane Basin's main development region. Geophysical Research Letters, 36, L06701, doi:10.1029/2009GL037260.

Zhang, R., 2008: Coherent surface-subsurface fingerprint of the Atlantic meridional overturning circulation. Geophysical Research Letters, 35, L20705, doi:10.1029/2008GL035463.

Zhang, R., T. L. Delworth, and I. M. Held, 2007: Can the Atlantic Ocean drive the observed multidecadal variability in Northern Hemisphere mean temperature? Geophysical Research Letters, 34, L02709, doi:10.1029/2006GL028683.

Zhang, R., and T. L. Delworth, 2005: Simulated tropical response to a substantial weakening of the Atlantic thermohaline circulation. Journal of Climate, 18(12), doi:10.1175/JCLI3460.1.

Zhang, S., M. J. Harrison, A. Rosati, and A. T. Wittenberg, 2007: System Design and Evaluation of Coupled Ensemble Data Assimilation for Global Oceanic Climate Studies. Monthly Weather Review, 135(10), doi:10.1175/MWR3466.1.

Zhao, M., I. M. Held, S.-J. Lin and G. A. Vecchi, (2009): Simulations of Global Hurricane Climatology, Interannual Variability, and Response to Global Warming Using a 50-km Resolution GCM. J. Climate, 22, 6653-6678, doi:10.1175/2009JCLI3049.1.