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Introduction

The Cooperative Institute for Climate Science (CICS) was founded in 2003 to foster research collaboration between Princeton University and the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanographic and Atmospheric Administration (NOAA). Its vision is to

*be a world leader in understanding and predicting climate and the co-evolution of society and the environment – integrating physical, chemical, biological, technological, economical, social, and ethical dimensions, and in educating the next generations to deal with the increasing complexity of these issues.*

CICS is built upon the strengths of Princeton University in biogeochemistry, physical oceanography, paleoclimate, hydrology, ecosystem ecology, climate change mitigation technology, economics, and policy; and GFDL in modeling the atmosphere, oceans, weather and climate. CICS is an outgrowth of a highly successful forty-year collaboration between Princeton University scientists and GFDL under Princeton University’s Atmospheric and Oceanic Sciences (AOS) Program that contributed to the development of oceanic and atmospheric models, performed research on climate and biogeochemical cycling, and educated several generations of graduate students. CICS was founded by expanding the existing AOS cooperative agreement into a Joint Institute.
Research Themes Overview

CICS has four research themes all focused around the development and application of earth system models for understanding and predicting climate.

(1) Earth System Studies/Climate Research. Earth System modeling at GFDL and in CICS has emerged from an intense period of model development during which we have produced fundamentally new atmospheric, oceanic and land models, coupled models, chemistry-radiative forcing models, cloud resolving models with new microphysics, and a non-hydrostatic limited area model. These models are already producing useful products, but new and more sophisticated tools will continually be required for increasingly realistic representation of the processes and interactions in the Earth's climate system.

In addition to its model-development activities, CICS is also pursuing a number of topics in climate dynamics that will lead to both improved understanding of the climate system itself, and to improved models in the future. These topics include the parameterization of cloud-radiation-convection interactions and land-surface heterogeneity; investigations of regional climate changes to natural and anthropogenic forcings; hydrologic cycle-climate feedbacks; anthropogenic influence on modes of climate variability including, for example, the dynamics of the North Atlantic Oscillation; and various fundamental issues in the dynamics of the ocean and atmosphere. Included in this last category are investigations of the general circulations of the atmosphere and ocean themselves, and the investigation of the dynamical processes that give rise to climate variability on interannual to multi-decadal timescales and that might lead to potentially catastrophic abrupt climate change in the future.

Investigators at CICS and GDFL are also pursuing holistic investigations of the climate system, to try to understand how the climate system operates as a whole. Such investigations are crucial if we are to properly simulate complex phenomena that defy simple explanations and that are not properly simulated with current models (such as the Intertropical Convergence Zone).

CICS is also continuing to pursue approaches to confronting models with observations in order to diagnose problems and judge reliability. The ability to simulate the observed climate, and its variability, with reasonable accuracy is a sine qua non of a sound climate modeling system. That variability arises from and is moderated by a host of factors, including ENSO, volcanic eruptions, the reddening by the ocean of weather variability in the atmosphere, the changes in the radiatively-active short-lived species and their climate forcing, clouds and the hydrologic cycle, soil moisture, interdecadal oceanic variability, and the glacial-interglacial cycles of the Pleistocene. These all represent distinct challenges that must ultimately be addressed simultaneously by a successful Earth System model, and the research presented below describes some of the efforts along these lines.

Research in Earth System Studies/Climate Research within CICS generally takes place at two levels. At the individual or small-group level, scientists, sometimes with postdocs and graduate students, may investigate processes and dynamics and write research papers accordingly, and this activity is represented by the individual reports below. At the second level, these activities come together synergistically in model development activities in which larger groups and teams work together, bringing their various expertise together. It is more difficult to describe and categorize this activity, but it is an essential aspect of the CICS endeavor.

Finally, CICS also sponsors a limited number of symposia and workshops that explore the relationship among natural science, social science, economics and policy options for dealing with climate change.
(2) **Biogeochemistry.** CICS is contributing to the development of the land and ocean biogeochemistry components of the Earth System model. The new model components are being used to study the causes and variability of land and oceanic carbon sinks and to develop a data analysis system for carbon that will provide improved estimates of the spatial distribution of carbon fluxes.

The new dynamic land model that has been developed simulates carbon, but still lacks nitrogen or phosphorus dynamics that are likely to limit the growth of the land carbon sink caused by CO₂ fertilization. CICS is developing a global model for nitrogen and phosphorus in natural and agricultural ecosystems. In addition to improving predictions of the future land sink, this model will predict nutrient inputs into coastal waters. CICS is also performing a series of modeling experiments to investigate the causes of the current terrestrial sink (e.g., CO₂ fertilization vs. land use) and the large interannual variability in its size.

The development of a new fully predictive ocean biogeochemistry model of carbon, nitrogen and phosphorus, is nearing completion in a close collaboration between CICS and GFDL. The model includes critical processes such as iron limitation and the formation of organic matter in the surface of the ocean and its export to the abyss. CICS is performing a series of modeling experiments to examine variability of air-sea CO₂ fluxes on seasonal, interannual, and decadal time scales and its response to global warming, and study the impact of global warming on marine biology.

CICS is also building a data inversion capability for our models of the carbon cycle that integrates data from flask stations, tall towers, eddy correlation towers, shipboard ocean transects, and forest inventories, in order to provide ongoing estimates of the air-sea and land-atmosphere CO₂ fluxes particularly over North America.

(3) **Coastal Processes.** The coastal oceans are being severely impacted by human activities and climate change, and these impacts will grow with time. Traditionally, the main models used for climate prediction at GFDL have not included processes like tides and bottom boundary layers that play a dominant role in the dynamics of the coastal zone, nor have they had the lateral resolution to fully represent physical, geochemical and biological processes on the narrow continental shelves. CICS has recently initiated a collaborative project with Rutgers University that will enable the development of tools that link coastal models to global climate models. These linked models will be used to provide the best scientific information possible to decision makers, resource managers, and other users of climate information. To address the specific research questions, the project will use a multi-disciplinary approach including analyses of in situ and remotely obtained data sets, circulation modeling, biogeochemical models with explicit carbon chemistry, and data assimilation techniques using dynamical and/or biological models.

(4) **Paleoclimate.** The most valuable observational constraints that we have to test our understanding of the response of the Earth System to changes come from the geological and ice core record. GFDL has a long history of important contributions to our understanding of climate change through the application of climate models. In recent years, Princeton University has attracted several new faculty with active research programs in the empirical and theoretical analyses of paleoclimate. CICS is supporting research on critical issues that Princeton has particular expertise in that are likely to be of importance in determining future climate response. These include the changing response of the climate to solar insolation forcing, the influence of tropical ocean-atmosphere states on climate, and the influence of freshwater fluxes and temperature changes on ocean circulation.
CICS research is closely aligned with the U.S. Climate Change Science Plan (US-CCSP) that was issued in July 2003 and with NOAA’s Strategic Plan for FY 2003-2008. The US-CCSP identified five goals: (1) to increase understanding of the past and present climate, including variability and change, (2) to improve the quantification of the forces causing climate change and related changes, (3) to reduce uncertainty in predictions about future climate and related changes, (4) to understand ecosystem responses to climate change, and (5) to develop resources to support policies, planning and adaptive management (decision support). The research that is being carried out under CICS is obviously central to the first, second, and third of these goals. In addition, our research on improved estimation of carbon source and sinks is directly called for in the US-CCSP document under goal 2. The coastal work and the global ecosystem modeling required in the biogeochemistry section contribute to goal 4, and all of the modeling work supplies tools that aid in decision support (goal 5).

NOAA’s Strategic Plan identified four mission goals: (1) protect, restore and manage the use of coastal and ocean resources through ecosystem-based management, (2) understand climate variability and change to enhance society’s ability to plan and respond, (3) serve society’s needs for weather and water information, and (4) support the nation’s commerce with information for safe, efficient and environmentally sound transportation. The research being carried out by CICS is highly relevant to the first three of these goals, particularly the second one. The Research Reports provided list which of the mission goals is addressed by each research project.

A key aspect of all four themes of CICS is the synergistic effect of each on the others. This leveraging effect across components enhances the prospect that this research will prove of critical importance to the community of scientists and decisions makers concerned with impacts between Earth systems and human systems.

**Education/Outreach**

This year, CICS continued its collaboration with a Princeton University professional development institute for New Jersey teachers. This well-established summer program, QUEST, is led by Princeton University’s Teacher Preparation Program. A one-week Weather and Climate unit for teachers in fourth through twelfth grades, held this summer, offered a wide range of inquiry-based experiences through which the teachers could develop an understanding of atmospheric processes. In addition to exploring the greenhouse effect and human impacts on climate and global warming, participating teachers evaluated technological solutions including solar energy conversion, fuel cells, and wind energy. They learned new methods to teach about weather and climate change, with an emphasis on earth system modeling and analysis. The unit was developed and taught by Dr. Steven Carson, formerly a scientist and Outreach Coordinator at GFDL, and currently a middle school science teacher in Princeton. Fourteen teachers participated in the Weather and Climate unit, including two former Teacher Preparation Program graduates, one of whom is currently teaching high school physics and one who is now student teaching. Five of the teachers are from either urban or urban rim school districts thus increasing the participation of underrepresented groups in science education.
Structure of the Joint Institute

Princeton University and NOAA’s Geophysical Fluid Dynamics Laboratory have a successful 40-year history of collaboration that has been carried out within the context of the Atmospheric and Oceanic Sciences Program (AOS). The Cooperative Institute for Climate Science (CICS) builds and expands on this existing structure. The CICS research and education activities are organized around the four themes discussed previously in the Research Themes Overview. The following tasks and organizational structure have been established to achieve the objectives:

I. **Administrative Activities** including outreach efforts are carried out jointly by the AOS Program and Princeton Environmental Institute (PEI).

II. **Cooperative Research Projects and Education** are carried out jointly between Princeton University and GFDL. These will continue to be accomplished through the AOS Program of Princeton University. They include a post-doctoral and visiting scientist program and related activities supporting external staff working at GFDL and graduate students working with GFDL staff. Selections of post doctoral scientists, visiting scholars, and graduate students are made by the AOS Program, within which many of the senior scientists at GFDL hold Princeton University faculty appointments. The AOS Program is an autonomous academic program within the Geosciences Department, with a Director appointed by the Dean of Faculty. Other graduate students supported under Principal Investigator led research projects are housed in various departments within Princeton University and the institutions with which we have subcontracts.

III. **Principal Investigator led research projects** supported by grants from NOAA that comply with the themes of CICS. These all occur within the newly formed Princeton Climate Center (PCC) of the Princeton Environmental Institute (PEI) and may also include subcontracts to research groups at other institutions on an as needed basis.

The CICS Director, currently Jorge Sarmiento, is recognized by the Provost as the lead for the interactions between NOAA and GFDL. The Director is the principal investigator for the CICS proposal. The Director is advised by an Executive Committee consisting of the Directors of the AOS Program and PCC, and three faculty members each from the AOS Program and the PCC. The Director is also advised by an External Advisory Board consisting of representatives from NOAA and three senior scientists independent of NOAA and Princeton University.
Princeton Environmental Institute Structure

Princeton Environmental Institute (PEI)
Director, Stephen W. Pacala

- Carbon Mitigation Initiative (CMI)
- Center for Biocomplexity (CBC)
- Energy Group
- Center for Environmental BioInorganic Chemistry (CEBIC)

Princeton Climate Center (PCC)
Jorge L. Sarmiento, Director
Research Portion of CICS to be managed within PCC
Task III

Cooperative Institute for Climate Science Structure

Cooperative Institute for Climate Science (CICS)
Jorge L. Sarmiento, Director
Geoffrey K. Vallis, Assoc. Director

- CICS Executive Committee
- CICS External Advisory Board

Task II: Cooperative Research Projects and Education
managed by AOS Director
Jorge L. Sarmiento

Task III: Individual Research Projects
managed by CICS Director
Jorge L. Sarmiento

Task I: Administrative Activities
managed by Jorge L. Sarmiento
CICS Committees and Members

**PEI’s Princeton Climate Center (PCC) Advisory Committee**
Jorge L. Sarmiento – Director of CICS and Professor of Geosciences
Stephen W. Pacala – Director of PEI, Professor of Ecology and Evolutionary Biology
Michael Oppenheimer – Professor Geosciences and Public and International Affairs, WWS
Denise Mauzerall – Associate Professor of Public and International Affairs, WWS

**Executive Committee**
Anand Gnanadesikan – Oceanographer
Isaac Held – GFDL Senior Research Scientist
V. Ramaswamy – Acting Director of GFDL, GFDL Senior Research Scientist
Geoffrey K. Vallis – Associate Director of CICS and Senior Research Oceanographer

**Plus PCC Advisory Committee**
Jorge L. Sarmiento – Director of CICS and Professor of Geosciences
Stephen W. Pacala – Director of PEI, Professor of Ecology and Evolutionary Biology
Michael Oppenheimer – Professor Geosciences and Public and International Affairs, WWS
Denise Mauzerall – Associate Professor of Public and International Affairs, WWS

**Administrative Committee**
S. George H. Philander – Professor of Geosciences
Francois Morel – Professor of Geosciences
Bess Ward – Chair and Professor of Geosciences
Stephen W. Pacala – Director of PEI, Professor of Ecology and Evolutionary Biology
V. Ramaswamy – Acting Director of GFDL, GFDL Senior Research Scientist

**External Advisory Council**
Jeffrey T. Kiehl – Director of NCAR’s Climate Modeling Section
A.R. Ravishankara – Director of NOAA’s ESRL Chemical Sciences Division
Dave Schimel – Senior Scientist at NCAR’s Terrestrial Sciences Division
Peter Schlosser – Professor at Columbia University’s Earth and Environmental Science Dept.
Chet Koblinsky – Director of NOAA’s Climate Program Office
Research Highlights

The following highlights ongoing research in the major research and education themes we identified in the Research Themes Overview.

Earth System Studies/Climate Research

Research in Earth System Studies/Climate Research may be divided into Ocean Dynamics and Modeling, Large-Scale Atmospheric Dynamics, Chemistry, Aerosols and Radiative Forcing, Climate Variability and Coupled Atmosphere-Ocean Modeling, and Clouds, Moist Convection and Hurricanes. Research in all areas involves cooperative activities between the University and GFDL, in particular post-doctoral fellows and research students working with GFDL staff, as well as University researchers and faculty whose activities are funded through CICS. In the paragraphs below we summarize and highlight some of the activities going on in these areas. There is an entire spectrum of fascinating and important activities, from fundamental to quite applied; the Earth System, as complex as it is, demands such a wide range of activities. However, these activities also provide the essential building blocks for understanding the system and come together in a coherent mosaic, so enabling us to build better models of the system and, ultimately, to better predict it.

Ocean Dynamics and Modeling

The ocean plays an important role in the climate variability on timescales from interannual to millennial. The global thermohaline circulation plays an important role in transporting heat, and the sequestration of both heat and carbon by the ocean modify the adjustment of the climate to increased levels of atmospheric carbon dioxide. Accurate, credible predictions of climate variability and projections of climate change require sophisticated ocean models. CICS supports several students, postdocs and research scientists engaged in studies of the ocean circulation, and development of improved ocean models for the GFDL coupled climate modeling system.

Recent model development activities have focused on delivery of the CM2G, the first viable isopycnal coupled model, which will be used in future IPCC simulations. In parallel, algorithmic developments necessary for a hybrid coordinate ocean model have been completed, and a hybrid coupled model is a near-term goal. Much recent model development work has focused on the parameterization of small-scale processes, including dense overflows and eddy-mixed layer interactions, both of which were the focus of NOAA and NSF-funded Climate Process Teams. CICS participants in the overflow CPT have developed a new parameterization of the shear-driven mixing in overflows, which is now implemented in CM2G, while the eddy-mixed layer CPT has led to the development of a new parameterization of the effects of submesoscale eddies in the mixed layer. Other parameterizations implemented in the CM2G model with the participation of CICS researchers include the mixing effected by tides over ocean ridges and seamounts, and a new model of the transport of calving land-ice by icebergs.

Other ocean modeling activities carried out by CICS researchers include the development of data assimilation techniques for regional ocean models focused on the Denmark Straits and the Arctic. In addition, several researchers are actively using the GFDL models to understand
aspects of the ocean circulation. Examples include studies of the large-scale meridional overturning circulation and its dependence on surface forcing and parameterizations of subgrid-scale processes, and investigations of the flow under ice-shelves.

These studies are all described in more detail in the individual reports.

**Large-Scale Atmospheric Dynamics**

Atmospheric dynamics remains at the core of the large-scale circulation of the atmosphere, and so is and will remain an essential activity within climate dynamics. Work in this area within CICS proceeds both through the support of graduate students and postdocs working with GFDL scientists, and by the work of University research scientists located at GFDL. The work in this area varies between fundamental aspects of the large-scale circulation and more applied work in model development and parameterization. This year we highlight one aspect of fundamental research that tries to understand one of the most fundamental aspects of the atmosphere, namely the mechanisms that determine the scale and intensity of mid-latitude weather systems.

To this end, CICS researchers explored the behavior of a simplified, Boussinesq, atmospheric model in an idealized, channel domain. It is found that, perhaps surprisingly, quasi-geostrophic theory works quite well in circumstances, provided the stratification is given. The model does not exhibit baroclinic-adjustment-like, and the criticality changes with the external parameters. However, at the same time it is quite difficult to make the model highly supercritical, because of the rapid changes of both vertical and horizontal heat fluxes as the mean baroclinicity increases. Consistent with all this, the model appears to produce inverse cascades under some parameter regimes. These results are important because they have implications for how the meridional temperature gradient of the Earth’s atmosphere might vary in a warmer world, or might have varied in the past in different paleoclimate regimes.

**Chemistry, Aerosols and Radiative Forcing**

Natural and anthropogenic chemical tracers and aerosols are an important element of climate studies both for the direct impact such tracers can have on the climate, for example by modifying the radiative forcing, and also through their direct impacts on air quality. CICS supports several students and postdocs working with GFDL scientists to understand these problems. Of particular importance to GFDL’s climate modeling efforts are studies designed to improve the model predictions of aerosol properties by comparison with datasets from South Asia and southern Africa, where seasonal biomass burning is the primary source of aerosols. Other studies focus on the role of the atmospheric circulation in exporting aerosols, in the Ganges valley and from South America to Antarctica. An overall evaluation of the model’s capability in simulating the outgoing longwave spectrum, by comparison with satellite observations, reveals that cloud induced radiative responses are underestimated, due to biases in the model mean state.

Chemical tracers important for air quality are examined using the MOZART chemical transport model. One such study shows that total pollutant export from the United States is not dominated by episodic events, and most export occurs under non-episodic conditions. Another study aims to understand the source of atmospheric ethanol in remote environments. Further details of these studies are given in the individual reports.
Climate Variability and Coupled Atmosphere-Ocean Modeling

Climate varies on timescales from the inter-annual to the millennial and beyond, and this variability typically involves interactions between the atmosphere and the ocean; both systems are important. Studies within CICS have occurred both via researchers employed by CICS and via postdocs and students working with Princeton University and GFDL scientists. The dynamics of the coupled climate system are enormously complex, and understanding these dynamics – one of NOAA’s main goals – necessitates, among other things, the construction and use of simpler models that can make a connection to fundamental theoretical ideas. To that end, an idealized coupled ocean-atmosphere-land-ice model has been developed to study climate variability at interannual to interdecadal and longer time scales and to identify mechanisms of ocean-atmosphere. The model has now been incorporated into the GFDL ‘Flexible Modeling Structure’ framework, and is available for all investigators to use. The model uses the three-dimensional primitive equations for both ocean and atmosphere, but is simplified from a ‘state of the art’ model in two respects: the model uses simplified physics and parameterization schemes, especially in the atmosphere, and the geometry and geography are much simplified. These simplifications provide considerable savings in computational expense and, perhaps more importantly, allow mechanisms to be investigated more cleanly and thoroughly than with a more elaborate model. For example, the model allows integrations of several millennia as well as broad parameter studies. A complementary coarse resolution model in a realistic domain has also been constructed. This is more computationally demanding, but at the same time provides a closer link to the full Earth System Model that is undergoing development. This model also allows biogeochemical interactions to be more closely studied. Taken together, and in conjunction with the full ESM being developed and still simpler models being explored at CICS, a very useful hierarchy of models is being developed that spans a range of complexity from extremely complex and quasi-realistic to much simpler models that allow theoretical ideas to be tested.

Clouds, Moist Convection and Hurricanes

Moisture produces clouds. Clouds affect the radiation budget, and they also transport heat and (to a lesser extent) momentum vertically, in convection. The uncertainty involved in predicting clouds and their associated effects is the single greatest cause of uncertainty in our global warming projections. We have a number of postdocs and students working in related areas, generally with members of the GFDL scientific staff.

A technical but extremely important aspect of this research is to develop and utilize improved cloud microphysical schemes. For example, the roles of physical mechanisms for nucleation of cloud-droplets and crystals is a continuing area of study, and CICS researchers are also implementing a new, two moment bulk microphysics scheme. The particular focus here is in evaluating and improving the simulation of ice in the upper troposphere. Unlike in the bulk scheme (which has traditionally being used in the GFDL model) the sedimentation velocity of ice crystals in a new parameterization depends on the size distribution. Due to the high sensitivity of the outgoing longwave radiation (OLR) and poor quantification, this has been a main tuning parameter in recent simulations. Preliminary tests have indicated that topical upwelling is strongly influenced by the version of the deep convection parameterization used in simulations.
All of this work is, in itself, quite technical and not conducive to easy summary, yet it is vital to the ongoing efforts to improve the models that GFDL develops for climate simulation and prediction.

Convection is of course intimately related to hurricanes, and another activity in CICS is to try to better understand the theoretical and practical limits to hurricane intensity. Interestingly, it seems that such theories can be most easily tested in the context of a dry model, indeed a dry, axisymmetric model turns out to be a very useful idealization of a hurricane. Scaling arguments have been developed that relate the thermodynamic intensity to the turbulent diffusivity within the planetary boundary layer, and this scaling is found to be consistent with the results from numerical simulations. Such theoretical developments are a key component in understanding the possible future behavior of hurricanes in a warmer world.

**Biogeochemistry**

CICS research in “Biogeochemistry” identifies, explores, and quantifies the links between anthropogenic changes in the physical climate, human alterations of elemental cycles, and the impact of humans on the land surface through management and agriculture. In addition, the research seeks to quantify feedbacks among the main components of the earth system. Biogeochemistry research in CICS follows two complementary paths: (1) characterizing the global cycling of carbon and other elements in terrestrial and oceanic systems through data compilation and synthesis techniques, and (2) developing and evaluating models to identify and understand underlying processes that lead to observed exchanges of carbon, nitrogen and other elements within and among ocean, atmosphere and land, but also allow for comprehensive predictions of past and future changes in the earth system.

**Characterization and Modeling of Global Land Biogeochemistry including Anthropogenic Activity**

The various groups contributing to the land model development (Pacala/Hedin groups in Princeton, Vörösmarty/Hurtt groups at the University of New Hampshire) have made great progress in advancing the characterization and understanding of land biogeochemical cycling that includes natural processes but also the disruption of the terrestrial element cycle and the land surface due to anthropogenic activities. In addition, they have worked to develop and improve models of terrestrial biogeochemical cycling.

A great success is the new development of the next generation land model by Malyshev, Shevliakova and Milly that links the advanced hydrology model LM2 and the dynamic vegetation model LM3V into LM3. The product is a synthesis that allows for a more realistic hydrologic representation of snow and soil water, but also explicitly links plant carbon assimilation and transpiration through leaf-level processes. The model has a comprehensive representation of canopy air physics and thus resolves exchanges of water and energy between land surface and the atmosphere. This makes LM3 a valuable tool for GFDL’s atmospheric circulation models and LM3 is now the standard land component of the next-generation atmospheric model AM3.

Further model development has focused on the inclusion of a prognostic nitrogen cycle. Nitrogen is an essential nutrient that limits forest growth and agricultural productivity.
Human inputs of nitrogen in terrestrial systems through fossil fuel combustion, application of fertilizer and through cultivation of nitrogen fixing crops have caused leaching of nitrogen into freshwater and coastal systems and caused eutrophication and harmful algal blooms. At the same time the rate of anthropogenic carbon assimilation is thought to be controlled by available nitrogen. Gerber, within the Hedin group, has developed and coded a prognostic nitrogen cycle in the land model LM3V. Simulations with the new model explore the degree to which anthropogenic carbon sequestration is limited by the availability of fixed nitrogen, but also investigate the capacity of terrestrial systems to convert N₂ from the atmosphere into plant available N. This capacity is found to be much stronger in tropical systems.

Under the lead of Vörösmarty of the University of New Hampshire, research has been conducted on how nitrogen and other nutrients are transferred to and removed from freshwater systems. The team explored how temporal changes in flow alter nutrient cycling in rivers and removal of nitrogen and thereby control the delivery of nitrogen to coastal systems. Model development efforts have been directed towards routing of different constituents, i.e. carbon, different forms of nitrogen and phosphorus. This exciting new development will be implemented into the GFDL’s land model code once it matures.

Of particular interest is the way in which past and current land-use affect land surface and biogeochemical cycling. The groups of Pacala at Princeton and Hurtt at the University of New Hampshire have worked together to improve reconstruction of past land-use and investigate the implication of land-use transitions on global carbon cycling. Hurtt and his group have reached out to other researchers to foster a product that brings together data on historical cultivation and wood harvest practices with projections of future land-use. While this is an ongoing project, the first results have already been made publicly available. This work also is great value to earth system models, including that of GFDL, in allowing quantification of the effect land-use changes have on elemental cycling and, ultimately, climate, through feedbacks between the physical climate system and biogeochemistry.

**Ocean Biogeochemistry: Making Better Use of Observations**

Oceanographers have collected a vast array of measurements over recent decades, much of which has gone under-utilized due to lack of public access and incomplete analysis. CICS researchers have been adding value to this pool of existing measurements by developing new data compilations, and by using numerical ocean models to better interpret the data.

Years of exploratory work and relationship-building between US, Japanese and European scientists contributed to Key’s recent success in obtaining a huge volume of data from ocean basins that had previously been underrepresented in global data products. Hundreds of thousands of measurements from the Arctic and its marginal seas, the Atlantic, and the Southern Ocean were compiled and submitted to quality checking procedures over the past year. This new database, which spans decades of observations, will build on Key’s previous work with GLODAP to provide an invaluable resource for model validation and process studies.

New work by Rodgers, published in two papers this year, highlights the great value that model analysis can provide in improving the interpretation of ocean biogeochemical observations. Rodgers showed that ocean models predict a substantial degree of interannual variability in the distribution of dissolved inorganic carbon (DIC), due to natural fluctuations in ocean circulation. This variability is of similar order to decadal changes in anthropogenic
DIC inventories, which presents a challenge to efforts such as the CLIVAR CO\textsubscript{2} repeat hydrography program, which seeks to measure changes in the anthropogenic inventory directly. However, Rodgers also showed that changes in sea surface height, a readily available satellite observational product, can be used as an index to correct for natural variability in the DIC distribution. In related work, Rodgers showed that the uptake of anthropogenic CO\textsubscript{2} in the North Pacific occurs within two geographical windows, both of which ‘open’ during the boreal winter. In short, Rodgers’ insight shows that the variability of DIC inventories is largely related to internal ocean variability (dominated by Rossby waves), while variability in the air-sea flux of CO\textsubscript{2} is dominated by the seasonal cycle and interannual variability.

Historical simulations with the ORCA2-PISCES model were used by Rodgers to investigate the oft-discussed ‘regime shift’ of 1976/77 in the equatorial Pacific. Rodgers concluded that the changes in the equatorial Pacific ecosystem could be understood as a compound response to the decoupled pathways of nitrate and iron supply to a reduction in wind-driven upwelling. Because iron is supplied steadily from the seafloor sediment at fixed depths, its supply pathway is decoupled from that of macronutrients like nitrate that are entirely recycled within the water column and therefore are more likely to follow isopycnal surfaces.

**Ocean Biogeochemistry: Developing New Models**

The development of new models for studying ocean biogeochemistry, over the past year, included efforts to design new biogeochemical and ecosystem models, as well as to provide a new global computational framework suitable for long integrations with a coupled ocean-atmosphere system.

Galbraith developed a new, conceptually-simple and computationally-efficient biogeochemistry module for use within the GFDL ocean model. The module treats all ecosystem processes implicitly, calculating the uptake and remineralization of nutrients, and the cycling of dissolved gases, through simple relationships with the available solar radiation and water temperature. The new module can be used as a low-cost alternative to the more complex TOPAZ biogeochemistry module, and promises to be particularly useful for computationally-intensive, high-resolution runs.

At the other end of the biogeochemical modeling spectrum, Kearney and Stock succeeded in developing functional models of higher trophic levels. Kearney undertook a complete overhaul of the widely-used Ecopath with Ecosim fisheries model, recasting the underlying assumptions to allow coupling to a physically-resolved biogeochemical model. Initial work with the model has focused on a modification of the PICES Ecosim model of the eastern subarctic Pacific, where Kearney has already achieved a dramatic reduction in the necessary complexity of the food web, by removing functionally redundant groups. The modified PICES model is now being coupled to a 1-dimensional physical-biogeochemical model.

Meanwhile, Stock has made fundamental advances in the effort to include realistic mesozooplankton in the global GFDL model. By constructing a simple ecosystem model with multiple plankton and zooplankton types, Stock was able to undertake a global analysis of observed ecosystem characteristics to show fundamental patterns underlying the fraction of total algal growth that ends up supplying mesozooplankton production. The dynamics revealed by the simple model are now being adapted for use in the three-dimensional
prognostic GFDL global model. Ultimately, this will be coupled with the work of Kearney to produce a predictive bio-physical model with explicit fisheries dynamics.

Galbraith succeeded in developing a usable, low-resolution version of the GFDL global coupled climate model. The model has a stable and reasonably accurate climate simulation, without flux adjustments, and with robust interannual variability. The computational cost is roughly one tenth that of the high-resolution GFDL equivalent, paving the way for exploring long-timescale ocean biogeochemical processes in a coupled earth system framework.
Task I-Administration covers the administrative activities of the Cooperative Institute and support of outreach activities. Funding during the past year included minimal support of the CICS Director and full support for the part-time administrative assistant. Funding was also provided for QUEST, a well-established summer program for elementary teachers in New Jersey.
Progress Reports:

Earth System Studies/Climate Research
**Progress Report:** Hybrid Ocean Model Development

**Principal Investigator:** Alistair Adcroft (Princeton Research Oceanographer)

**Other Participating Researchers:** Laurent White (Princeton Univ.), Torge Martin (Princeton Univ.), David Marshall (Oxford, UK), Robert Hallberg (GFDL), Stephen Griffies (GFDL)

**Theme #1:** Earth System Studies/Climate Research

**NOAA’s Goal #1:** Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (20%)

**NOAA’s Goal #2:** Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (75%)

**NOAA’s Goal #3:** Serve Society’s Needs for Weather and Water Information (5%)

**Objectives:** Develop CM2G for IPCC; develop iceberg model for coupled models; develop hybrid coordinate capabilities in GOLD

**Methods and Results/Accomplishments:**

**CM2G:** Development of GOLD has peaked this last year with the delivery of CM2G, the first really viable isopycnal coupled model. Most of this last year has been spent developing and analyzing this model which includes all the algorithmic developments conducted over the last four years.

**Hybrid GOLD:** Hybrid coordinate work has progressed significantly, in parallel to CM2G development; we may be able to unveil a hybrid coupled model by the end of the year. Progress towards this goal include the publication of a new, very accurate, reconstruction method, we call PQM [White and Adcroft, 2008] and a recent demonstration of adiabatic dynamics in GOLD using \( z^* \)-coordinates.

**Icebergs:** Analysis of CM2.1 by Eric Galbraith revealed systematic biases due to the treatment of calving in the coupled model. Working with Torge Martin, I have built a Lagrangian iceberg model that properly redistributes the frozen water (calving) in time and space. The impact of icebergs is dramatic, more so than anticipated. These results are being written up Martin and Adcroft, 2008; see Figs. 1 and 2 on next page.

**References:**
- CICS Annual Report 2007

**Publications:**
Figure 1: Change in SST after 100 year due to inclusion of icebergs (5 year average).

Figure 2: Change in CFC column inventory due to inclusion of icebergs, average of years 1995-2000. The increase in inventory in the Southern Ocean is due to an increase in ventilation around Antarctica.
**Progress Report:** Flexible Modeling System (FMS)

**Principal Investigator:** V. Balaji, (Princeton Senior Technical Staff)

**Other Participating Researchers:** Alistair Adcroft (Princeton), Isaac Held (GFDL), Keith Dixon (GFDL), Karl Taylor (DoE/PCMDI), Max Suarez (NASA/GMAO), Steve Hankin (NOAA/PMEL), George Philander (Princeton), Tony Rosati (GFDL), S-J Lin (GFDL), Steve Pacala (Princeton), Jorge Sarmiento (Princeton)

**Theme #1:** Earth System Studies/Climate Research

**NOAA’s Goal #2:** Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (50%)

**NOAA’s Goal #3:** Serve Society’s Needs for Weather and Water Information (50%)

**Objectives:** Building model components and data standards consistent with the common model infrastructure FMS in support of PU/GFDL modeling activities.

**Methods and Results/Accomplishments:**
- Development of Flexible Modeling System (FMS) and FMS Runtime Environment (FRE) in support of Earth system modeling activities at PU/GFDL.
- Extension of FMS and FRE to support Mosaics and the cubed-sphere grid.
- Design and development of high-resolution climate models (ChiMES Project: [http://www.gfdl.noaa.gov/~vb/chimes](http://www.gfdl.noaa.gov/~vb/chimes)).
- Formulation of a draft community-wide standard specification of model grids ([http://www.gfdl.noaa.gov/~vb/gridstd/gridstd.html](http://www.gfdl.noaa.gov/~vb/gridstd/gridstd.html)) which is under consideration for adoption within the Climate and Forecasting conventions.
- Development of FMS infrastructure and modeling components for next generation physical climate model CM3 and Earth system model ESM3.
- Provided design oversight for Sergey Nikonov (CICS) in design and implementation of the GFDL Curator, which maintains a database of model results delivered to the public from PU/GFDL models for IPCC AR4 and other projects.
- Provided oversight to Yana Malysheva (HPTi) in design of web services for display of model output.
- Joined architecture and design committees of NOAA’s National Environmental Modeling System (NEMS) and National Unified Operational Prediction Capability (NUOPC)
- Design of next-generation model and data frameworks (Earth System Curator project) in collaboration with the Earth System Modeling Framework (ESMF), Program for Integrated Earth System Modeling (PRISM), Global Organization of Earth System Science Portals (GO-ESSP) and CF Conventions groups, whose steering committees I serve on.
- METAFOR Project gets EU-FP7 award for building a common information model for climate models following on Curator work.
- Organized workshops for GO-ESSP (June 2007, Paris); Earth System Curator (October 2007, Princeton NJ); ACCESS (March 2008, University of Cape Town) GFD-Dennou (Kobe University, Japan).
References:
   FMS homepage: http://www.gfdl.noaa.gov/fms
   Balaji homepage: http://www.gfdl.noaa.gov/~vb

Publications:
   Rocky Dunlap, Spencer Rugaber, Leo Mark, V. Balaji, Cecelia DeLuca, 2008: Earth System Curator: Metadata Infrastructure for Climate Modeling. Accepted for publication in Earth Science Informatics.
Progress Report: Cooperative Institute for Climate Science Professional Development Summer Institute in Weather and Climate July 14-18, 2008

Principal Investigator: Steve Carson (Princeton Regional Middle School Chemistry Teacher)

Other Participating Researchers: Andrew Bocarsly, Chemistry, Princeton University, Dr. Steven Carson, formerly for the Geophysical Fluid Dynamics Laboratory and currently a middle school teacher in Princeton Township, NJ with the assistance of Anne Catena, Program in Teacher Preparation, Princeton University

Theme #1: Earth System Studies/Climate Research

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: In support of the Cooperative Institute for Climate Science’s (CICS) intent to educate society about the increasing complexity of understanding and predicting climate and environmental consequences, we designed and delivered professional development for teachers in New Jersey to improve their students’ understanding of earth system modeling. This work is a collaboration of Professor Andrew Bocarsly, Chemistry, Princeton University, with Dr. Steven Carson, formerly of the Geophysical Fluids Dynamics Laboratory and currently a middle school science teacher in Princeton Township, New Jersey and Anne Catena, Program in Teacher Preparation at Princeton University.

Methods and Results/Accomplishments:
The July 14-18, 2008 program, offered inquiry-based experiences through which the grade 4-12 teachers developed an understanding of atmospheric physics and chemistry. They explored fundamental content regarding the Earth’s climate including the greenhouse effect, human impacts on climate and global warming, as well as consequences of climate change. The teachers evaluated technological and social solutions that allow control over man’s impact on climate, including solar energy conversion, fuel cells and wind energy. They learned new methods to teach about weather and climate change to promote an understanding of Earth system modeling and analysis.

Fourteen teachers participated in the professional development, including one former Teacher Preparation Program graduate who is now teaching high school physics and one Teacher Preparation Program student who will be student teaching in the fall of 2008. Five of the teachers are from either urban or urban rim school districts. This outreach effort increases educators’ and students’ understanding of data, information and research programs resulting in more informed decisions, and increases the participation of underrepresented groups in science education.
Feedback from teachers:

“I feel like I changed my understanding of not just the subject matter, but of myself, my teaching and my understanding of learning.”

“I think the content knowledge that can be gained is far superior to other professional development offered to elementary school teachers.”

“The climate change class clarified many misconceptions and gave a good foundation for understanding all sorts of energy sources.”
“I was able to strengthen knowledge I already had, introduce new information and raise questions for further exploration of concepts. I drew from philosophies, experiences and knowledge from all the people involved.”

“I feel more informed about global warming and how I can make a difference.”

“QUEST is a unique opportunity to work with professionals in the science field.”

“I have gained a better understanding of the science behind climate change and now I feel prepared to educate my students on the topic. The chemistry activities will be utilized in other areas as well.”
**Progress Report:** Estimating the Episodic Contribution to Total Pollutant Export From the United States in Summer

**Principal Investigator:** Yuanyuan Fang (Princeton graduate student)

**Other Participating Researchers:** Hiram Levy - advisor (GFDL/Princeton), Arlene Fiore and Larry Horowitz (GFDL)

**Theme #1:** Earth System Studies/Climate Research

**NOAA’s Goal #2:** Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

**Objectives:** Estimate the episodic contribution to pollutant export from the United States during summer

**Methods and Results/Accomplishments:**

Emissions from the United States can affect air quality over downwind regions through strong episodic outflow under favorable conditions or by increasing the background hemispheric burden [i.e., Auvray and Bey, 2005; Guerova et al., 2006].

We use the MOZART chemical transport model [Horowitz et al., 2007] to provide a first estimate of the overall contribution of episodic export to the total burden during summers. Focusing on the major export pathway from the United States, namely eastward export to the North Atlantic, we develop a criterion to identify episodic export events using daily CO export fluxes from a 15-year simulation. Our diagnosed episodic export fluxes are confirmed by strong outflow plumes sampled on subsequent days during the 2004 INTEX-NA field campaign [Singh et al., 2006]. Both model results and aircraft observations indicate that strong outflow of anthropogenic pollution occur in the boundary layer as well as in the upper troposphere during these episodic export events. Enhanced surface export is associated with the approach and passage of cyclones which swept previously accumulated surface pollutants eastward. Upper tropospheric export is driven by lifting of surface pollutants by Warm Conveyor Belts associated with cyclones. Generally, simulated pollutant concentrations in anthropogenic plumes agree with observed concentrations to within 30% for CO and O3, while in some places surface PAN is overestimated by a factor of 2. The concentrations of CO in plumes originating from Alaskan Fires and O3 in stratospherically-influenced air are underestimated by the model.

Comparing episodic and total export during 15 summers, we find that episodic export accounts for 15% to 35% of total export each summer, and episodic export is poorly correlated with total export. In summer 2004, due to a weak Bermuda High, episodic export of CO contributes over 30% to the total export, ranking the second among the 15 summers considered, while the total export is relatively low. Episodic contribution of NOy and O3 during this time period is similar to that of CO which implies that export of all species is largely driven by meteorology.

We conclude that focusing only on episodic export neglects a majority of the total export since most export (65%-85%) occurs under non-episodic conditions.

**References:**


Publications:
Y Fang, A M Fiore, L Horowitz, et al., Estimating the episodic contribution to total pollutant export from the United States in summer, to be submitted to Journal of Geophysical Research
Progress Report: Idealized Studies of the Ocean-Atmosphere Coupled System

Principal Investigator: Riccardo Farneti (Research Associate)

Other Participating Researchers: Geoffrey K. Vallis (AOS, Princeton)

Theme #1: Earth System Studies/Climate Research

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives:
To understand the natural decadal-to-centennial climate variability, low frequency air-sea interactions and meridional energy transports with the help of an idealized coupled ocean-atmosphere model.

Methods and Results/Accomplishments:
An idealized coupled ocean-atmosphere-land-ice model has been developed to study climate variability at interannual to interdecadal and longer time scales and to identify mechanisms of ocean-atmosphere interactions (Farneti and Vallis, 2008a).

The model uses the three-dimensional primitive equations for both ocean and atmosphere, but is simplified from a ‘state of the art’ model in two respects: the model uses simplified physics and parameterization schemes, especially in the atmosphere, and the geometry and geography are much simplified. These simplifications provide considerable savings in computational expense and, perhaps more importantly, allow mechanisms to be investigated more cleanly and thoroughly than with a more elaborate model. For example, the model allows integrations of several millennia as well as broad parameter studies.

In a control integration an interdecadal oscillation of a period of around 20 years is found involving the oceanic meridional overturning circulation and propagating surface buoyancy anomalies. The oceanic variability is found to imprint itself on the atmosphere, which covaries affecting an atmospheric state similar to the North Atlantic Oscillation at the preferred period while the atmospheric coupling seems necessary to catalyze the oscillation (Farneti and Vallis, 2008b). In fact, ocean-only integrations can produce decadal scale variability, as in the coupled integrations, although the presence of an interacting, dynamical atmosphere broadens the parameter regime over which such variability occurs (Farneti and Vallis, 2008c). The presence of an atmosphere amplifies the oscillations because an interactive atmosphere effectively reduces the damping felt by the ocean. Comparisons with the natural variability of the GFDL CM2.1 model shows encouraging similarities.

Within the same idealized framework, we later turned our attention to the mean state and variability of the oceanic and atmospheric meridional heat fluxes. Fundamental studies on scaling laws, dependence on oceanic and atmospheric parameters as well as compensation mechanisms at decadal and longer time scales have been carried out with several experiments and settings thanks to the speed and flexibility of our coupled model (Vallis and Farneti, 2008d; Vallis and Farneti, 2008e).

We are presently integrating a ‘full-Earth’ solution, where a spherical atmosphere is exchanging freshwater, heat and momentum fluxes with an Earth that is totally covered by water with the only exception of two polar caps and, in a particular experiment, a few meridional ridges that constraint the flow. The coupled model now resembles the Aquaplanet configurations of Smith et al. (2006) and Marshall et al. (2007), the only modelling initiatives where a dynamical atmosphere is coupled to a dynamic ocean with no continents.
Finally, an upgraded version of the model will be used within a hierarchy of coupled models available at GFDL in order to study the mechanisms that lead to decadal and longer variability of the Atlantic meridional overturning circulation.

**References:**


**Publications:**

Vallis, G. K. and R. Farneti (2008e), Theory and modelling of the meridional energy transport in the atmosphere-ocean system. Part II: Scalings and parameters dependence. in preparation for QJRMS.


**Progress Report:** Aspects of the MOC-ACC Dynamics and Their Interaction With the Ocean Stratification in a Hierarchy of Models

**Principal Investigator:** Neven-Stjepan Fuckar (Princeton Graduate Student)

**Other Participating Researchers:** Geoffrey K. Vallis - advisor (Princeton/GFDL), S. George H. Philander (Princeton), Anand Gnanadesikan (GFDL) and Isaac Held (GFDL)

**Theme #1:** Earth System Studies/Climate Research

**NOAA’s Goal #2:** Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

**Objectives:** To advance understanding of the connections between global pycnocline structure, the Meridional Overturning Circulation (MOC) and the Antarctic Circumpolar Current (ACC), and their relevance in climate dynamics.

**Methods and Results/Accomplishments:**

The crucial role of the ocean in climate dynamics stems from its enormous capacity to absorb heat, freshwater and chemical substances (i.e., tracers) and the redistribution of these tracers on time scales from decades to centuries or millennia. The MOC, which exerts critical influence on remapping of the ocean surface buoyancy conditions onto the vertical density profile, has an important role in the transport of tracers (primarily in the north-south direction). However, a truly global character of the oceans’ tracer transport is enabled by the zonally unconstrained flow around the Antarctica with the significant climatic relevance due to the interbasin exchange and ventilation of the deep and abyssal waters in the Southern Ocean. For example, an MOC-induced change in depth and/or thickness of the pycnocline in the tropical and subtropical ocean(s) can significantly alter ocean heat content and baroclinic (thermal wind) component of the ACC (due to the change in stratification at its northern edge).

This study explores dependence of aspects of the ocean stratification and the MOC-ACC dynamics on the surface forcing fields and representation of internal mechanisms. Specifically, we investigate interhemispheric and interbasin elements of ocean structure and dynamics in a hierarchy of idealized Ocean General Circulation Models (OGCM). We conducted a set of sensitivity experiments with Modular Ocean Model 4 (MOM4) in simplified single-basin and two-basin configurations. Some striking results from the single-basin experiments, such as strong dependence of the southern hemisphere circumpolar current on the northern hemisphere surface buoyancy conditions (while keeping the southern hemisphere surface conditions constant), are already published in Geophysical Research Letters. A robustness of this finding was confirmed in the two-basin configuration under a number of different surface forcing (restoring) conditions and with different parameterizations of subgrid-scale processes.

A paper that establishes nexus between OGCM results and scaling theory for the processes that govern conversion of water between different density classes is in preparation. Also, an ocean-ice MOM4 configuration is being prepared for a set of experiments with realistic bottom topography in order to confirm key findings on interhemispheric and interbasin oceanic interaction from models with idealized bathymetry. These experiments with “real world” configuration should be completed in two or three months and they should provide a base for another paper on aspects of oceanic tunnel by the end of the year.
References:


Publications:
Progress Report: Investigating the Effect of Aerosols on the Climate Over South-Asia Using the GFDL General Circulation Model

Principal Investigator: Dilip Ganguly (Postdoctoral Research Associate, AOS Program, Princeton University)

Other Participating Researchers: V. Ramaswamy (GFDL), Paul Ginoux (GFDL)

Theme: Earth System Studies/Climate Research

Objectives: Inferring the composition and concentration of aerosols by combining AERONET and MPLNET data: comparison with measurements and GCM output

Methods and Results/Accomplishments:

Comparisons of aerosol optical depth (AOD) simulated by the GFDL Atmospheric General Circulation model AM2 with the observations available from India [Ganguly et al., 2006a; 2006b] reveal that AM2 is either overestimating or underestimating the observations over this region depending on the location and season. Therefore, it is important to understand which aerosol component is causing the problem in AM2. It is not sufficient to compare AOD from model and observations because AOD is not generally the prognostic variable in global aerosol models, which actually predicts quantities like aerosol mass and number concentration. Unfortunately, measurements of aerosol mass concentration are not available from worldwide locations for comparisons with model output.

In order to overcome this problem, Ganguly et al., [2008] developed a new method to derive the concentration of aerosol components from the spectral measurements of AOD and single scattering albedo along with their size distribution and extinction profile available from Aerosol Robotic Network (AERONET) and Micro-pulse Lidar Network (MPLNET) stations. The technique involves finding the best combination of aerosol concentration by minimizing differences between measured and calculated values of aerosol parameters such as AOD, single scattering albedo and size distribution. We applied this technique over selected sites in three different regions of the United States (West coast, Great Plains, and North-East). In general, the concentrations retrieved by our technique compare well with the ground-based measurements available from this region. Over continental North America, the GFDL model AM2 appears to overestimate sulfate approximately by a factor of two and underestimate organic carbon by nearly the same amount. We find that the knowledge on the vertical distribution of aerosols is crucial for an accurate retrieval of aerosol concentration using our method. We also determine the composition and concentration of elevated aerosol layers using this technique.

Our next objective is to apply this technique over South Asia where measurements of aerosol composition are scarce. Since there are not may MPLNET stations available over this region, we are trying to improve our minimization technique by including the CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) data along with AERONET observations over Asia. Once this is done, we plan to adjust appropriate parameters or emission inventories used by AM2 such that the model results compare well with the observations and then proceed towards quantifying the impact of aerosols on the climate over South Asia.

References:


Presentations given:

Constraining the composition and concentration of aerosols in GFDL AM2 model: Method description, validation over US and plans for Indian region, Lunch time seminar at Geophysical Fluid Dynamics Laboratory, February 2008.
**Progress Report:** Irminger Sea/Denmark Strait Regional Ocean Circulation Model and Data Assimilation System

**Principal Investigator:** Thomas Haine (Johns Hopkins University Professor)

**Other Participating Researchers:** Alistair Adcroft (Princeton), Bob Hallberg (GFDL), Sonya Legg (Princeton)

**Theme #1:** Earth System Studies/Climate Research

**NOAA’s Goal #2:** Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

**Objectives:** Simulation and Assimilation of Irminger Sea and Denmark Strait Ocean Circulation

**Methods and Results/Accomplishments:**

- **Code Development:** The forward code has only been modified slightly and is now being used in production mode. The 4DVAR data assimilation code (including the adjoint model) has been extensively developed in the last year. The improvements include an updated adjoint model, an improved optimization algorithm, and code to provide experimental posterior covariance information.

- **New Runs:** Six new experiments have been performed on the GFDL HPCS. One set of experiments explores the impact of the KPP mixing parametrization on entrainment into the Denmark Strait overflow plume using a passive tracer. The other set uses atmospheric forcing from the GFDEx aircraft experiment over Denmark Strait in February and March 2007 (GFDEx is the Greenland Flow Distortion Experiment; Renfrew et al., 2008). A 12-km, hourly atmospheric reanalysis based on the GFDEx data is used to force the ocean circulation model and results are compared to experiments using NCEP forcing and Blended SeaWinds scatterometric windspeed data. An article on these experiments is in preparation.

- **Denmark Strait Overflow Volume Transport Results:** We have determined that the excellent correlation between Denmark Strait overflow volume flux and sea level anomalies seen in our models can be reconstructed using the real TOPEX/Poseidon, Jason, Envisat, ERS, and GFO orbits. This is good news because it raises the possibility that the altimeter records might be used to reconstruct the real overflow flux history during the satellite altimeter era. Instrumental noise (at the level of 1-2cm) is a serious obstacle to direct reconstruction using correlations, however. Our earlier data assimilation experiments are more encouraging and suggest that the altimetric record could be reanalysed using assimilation (Lea et al., 2006). Moreover, the model results strongly suggest that bottom pressure recorders could be used as a cheap, convenient method to monitor the overflow plume in the future. We are also exploring the prospects for next-generation wide-swath altimeters to monitor the overflow. An article on this topic is in preparation.

**Dissemination:** During the past year these results have been presented at invited seminars and conference papers to:
- Atmospheric, Oceanic, & Planetary Physics, University of Oxford, UK,
- Civil Engineering, Johns Hopkins University,
- Earth, Atmospheric, & Plantary Sciences, MIT,
- Department of Meteoratology, University of Maryland,
- Woods Hole Oceanographic Institution,
- AGU Ocean Sciences Meeting [Haine, 2008],
- Royal Meteorological Society Conference [Renfrew et al., 2007].
References:


Publications:

No publications directly related to this collaboration have yet appeared, although two are in preparation.

Publications indirectly related to this collaboration include:


Progress Report: What should a subgridscale parameterization look like?

Principal Investigator: Arno Hammann (Princeton graduate student)

Other Participating Researchers: Anand Gnanadesikan (GFDL)

Theme #1: Earth System Studies/Climate Research

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: To improve subgridscale parameterizations in the meso- and sub-mesoscale of ocean dynamics.

Methods and Results/Accomplishments:

We approach the problem of finding a subgridscale closure scheme by (1) defining the parameterizable terms in the context of a two-resolution model setup. The fields from an eddy-resolving version of our adiabatic two-layer channel model (cf. Hallberg and Gnanadesikan, 2001) are averaged onto a coarse grid, from which a low-resolution version steps them forward one timestep at a time. Subgridscale forcings are computed as the differences between the fine and coarse fields at every timestep. The method is somewhat similar to that used by Berloff (2005) (2) The step-by-step differences between the two models (the subgridscale) are then related to the mean fields by linear regression. The regression uses information from all available model variables in a certain area surrounding each point to be predicted. The method has the advantage of (1) not making any a priori assumptions on the functional form of subgridscale terms (e.g. diffusion), and (2) using the correct type of average to define subgridscale terms (as opposed to, for example, zonal or temporal averages).

The results are very encouraging. The mean spatial patterns of the subgridscale terms computed from the dual-model setup can be predicted with high accuracy from the mean fields; the temporal variability is also captured, albeit to a lesser degree. Moreover, the spatial patterns of regression coefficients can be interpreted in terms of discrete differential operators, which allows the derivation of functional forms for the subgridscale terms. These forms include, besides a dominant term which reminds of the bolus velocity formulation implicit in the Gent-McWilliams parameterization (Gent and McWilliams, 1990), negative diffusion-like terms that are the source of instabilities in a naïve use of the regression as a parameterization in forward integrations.

References:


Publications:

In preparation

Principal Investigator: Yi Huang (AOS Program, Princeton University)

Other Participating Researchers: V. Ramaswamy (advisor, GFDL)

Theme #1: Earth System Studies/Climate Research

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: 1. To conduct a comparison between GCM simulation and satellite observation to assess the model’s capability in simulating the outgoing longwave spectrum; 2. To detect signature of climate forcing and associated feedbacks in the infrared spectrum.

Methods and Results/Accomplishments:
Using the established method of synthesizing OLR spectrum from GCM simulation and processing the satellite observation [see Huang et al., 2007 and last year's report], we analyze the seasonal variations of Outgoing Longwave Radiation (OLR) accompanying the variations in sea surface temperatures (SST) from satellite observations and model simulations, focusing on the tropical oceans where the two quantities are strikingly anti-correlated. A spectral perspective of this “super-greenhouse effect” is provided, which demonstrates the role of water vapor line and continuum absorptions at different altitudes and the influences due to clouds. A model-satellite comparison indicates that the GFDL General Circulation Model can fairly well represent the total-sky radiative response to SST in the water vapor infrared absorption band despite the significant bias in the mean state, but this comprises compensating water vapor- and cloud-related errors. The analysis reveals that the GCM significantly underestimates the cloud induced radiative responses in the window region which is related to the bias in the mean state. Thus, spectral decomposition proves essential to understand and assess the OLR-SST relationship and the impacts of water vapor and cloud upon this linkage.

We also investigate the variability and change of OLR spectrum by combining the simulation and observation. First, the natural variability in unforced climate is simulated. Then, the change of OLR spectrum in forced changing climate is analyzed both for a continuous 25-year time series and for the difference between two periods 140-year apart. Spectrally resolved radiances have more pronounced and complex changes than broadband fluxes. In some spectral regions, the radiance change is dominated by one controlling factor (e.g. the window region and CO2 band center radiances are controlled by surface and stratospheric temperatures, respectively) and well exceeds the natural variability under climate change. In some other spectral bands, the radiance change is influenced by multiple and often competing factors (e.g. the water vapor band radiance is influenced by both water vapor concentration and temperature) and, although still detectable against natural variability at certain frequencies, puts stringent requirements (spectral resolution no less than 1 cm⁻¹; drift less than 0.1 K / decade) for observational instruments. The difference between clear-sky and all-sky radiances measures the cloud radiative effect, but is subject to temperature lapse rate change (non-cloud radiative effect). These results demonstrate that accurate continuous observation of OLR spectrum can provide an advantageous means for monitoring the climate system and for validating climate models.
Publications:


Progress Report: Gravity Current Entrainment Climate Process Team

Principal Investigator: Laura Jackson (Princeton Associate Research Scholar)

Other Participating Researchers: Robert Hallberg (GFDL), Sonya Legg (Princeton)

Theme #1: Earth System Studies/Climate Research

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: To work with the GCE Climate Process Team in developing parameterizations of gravity current entrainment and in testing these in regional and global climate models

Methods and Results/Accomplishments:
I have developed a shear-driven diapycnal mixing parameterization for use in ocean climate models. This new parameterization describes vertically non-local quasi-equilibrium shear-driven mixing which we believe will capture shear-driven mixing in both gravity currents and the Equatorial Undercurrent. We have published a paper describing this new theory and comparing it to high resolution numerical simulations of shear-driven stratified turbulence. Our parameterization captures the mixing well and is simpler (and more appropriate for climate studies) than two equation models such as k-epsilon and Mellor-Yamada.

Our parameterization has been implemented in the GFDL isopycnal coordinate ocean model GOLD where it has proved to be robust and efficient and follow up work describing our parameterization's performance in a global climate model is in progress. Additionally I have been examining the mixing in a regional model of the Mediterranean overflow, both with and without barotropic tides. With the tides there is more mixing over the sill, creating a less dense plume which then mixes less downstream. Although the mixing is partially compensated for, the entrained water originates from different depths, changing the temperature and salinity characteristics of the plume. We also examine the two mixing parameterisation for mixing at the top and bottom of the plume separately.

Publications:
Progress Report: The Response of the ITCZ to the Extratropical Thermal Forcing

Principal Investigator: Sarah M. Kang (Princeton Graduate Student)

Other Participating Researchers: Isaac Held -advisor (GFDL/Princeton), Dargan Frierson (University of Washington)

Theme #1: Earth System Studies/Climate Research

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: To understand the mechanism by which ITCZ displacements can be forced from the extratropics

Methods and Results/Accomplishments:
In the past year, Kang has published a paper (Kang et al., 2008) discussing the mechanism by which the position of the ITCZ in the tropics responds to extratropical thermal forcing, using a comprehensive model, GFDL AM2. This problem is of relevance to the tropical rainfall response to extratropical aerosol forcing, to cooling of the Northern Hemisphere in glacial periods, and to perturbations in the strength of the Atlantic meridional overturning circulation. A simple approach towards understanding this tropical response is described, from the perspective of the compensation between atmospheric and oceanic meridional heat transports. In AM2, clouds feedbacks are found to amplify the displacement of the ITCZ, as shown by carrying out simulations with prescribed clouds and by altering parameters in the convection scheme.

The identical set of experiments have been also carried out with the idealized moist GCM of Frierson et al. (2006), which has no water vapor or cloud feedbacks, simplifying the analysis. A research article on this topic is now in preparation. As in earlier studies, in response to high latitude forcing, tropical precipitation is skewed towards the warmed hemisphere. Comparisons with AM2 reveal that the tropical responses are much larger in the comprehensive GCM, consistent with positive cloud and water vapor feedbacks amplifying the response in AM2. The magnitude of the tropical precipitation response is sensitive to convection scheme parameters. Included in the manuscript is a simple theory that predicts this sensitivity to the convection scheme with two ingredients: first, the changes in poleward energy fluxes are predicted using a one-dimensional energy balance model; second, a measure of the total gross moist stability of the model tropics converts the energy flux change into a mass flux and a moisture flux change. It can be understood from this theory that the sensitivity of the tropical response to the convection scheme in the idealized model results from different values of the gross moist stability.

References:

Publications:

**Progress Report:** Ocean Tidal Mixing

**Principal Investigator:** Sonya Legg (Research Oceanographer)

**Other Participating Researchers:** Jody Klymak (Univ of Victoria), Rob Pinkel (SIO) and other members of Hawaiian Ocean Mixing Experiment, GFDL researchers.

**Theme #1:** Earth System Studies/Climate Research

**NOAA’s Goal #2:** Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

**Objectives:**
To understand and quantify the conversion of tidal energy into internal waves and mixing over topography and incorporate this understanding into mixing parameterizations in GFDL climate models.

**Methods and Results/Accomplishments:**
In the past year a manuscript (Legg and Klymak, 2008) describing numerical simulations of tidal mixing occurring near the top of the flanks of tall topography such as the Hawaiian Ridge has been accepted for publication by JPO. Included in this manuscript is a theoretical analysis of the regimes in which mixing by internal hydraulic jumps can occur, and an examination of global data to identify other topographic features where such mixing is likely. An interesting feature of these simulations is a region of enhanced overturning and dissipation near the top of the slope. Sensitivity studies carried out with an idealized version of the ridge topography and stratification show that the overturning is associated with an internal hydraulic jump generated during maximum ebb tide, which subsequent to relaxation of the flow propagates toward the slope and breaks at a region of near critical slope. This mixing is highly sensitive to details of the slope, but should be generic to any steeply sloping tall topography topped by a finite region of critical slope.

Another related manuscript published during the past year is Green et al, 2008, describing 2D simulations of internal tide generation on the Celtic Sea shelf, carried out with the nonhydrostatic MITgcm model.

In the past year Legg has been engaged in ongoing discussions with other members of GFDL’s ocean model development team, regarding the implementation of existing parameterizations of tidal mixing in both MOM and GOLD, and we are exploring ways in which to improve these parameterizations, incorporating results from the above studies.

**Publications:**

Progress Report: Dense Overflows

Principal Investigator: Sonya Legg (Research Oceanographer)

Other Participating Researchers: Robert Hallberg, Laura Jackson, Ulrike Riemenschneider (WHOI postdoc), Steve Griffies, Jim Price (WHOI), other members of the NSF/NOAA funded Gravity Current Entrainment Climate Process Team.

Theme #1: Earth System Studies/Climate Research

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives:
To develop improved parameterizations for dense overflows in ocean climate models

Methods and Results/Accomplishments:
This effort to improve parameterizations of overflows in climate models has been carried out as part of the NSF/NOAA funded USCLIVAR Climate Process Team on Gravity Current Entrainment. As the coordinating PI, Legg has been responsible for organizing workshops, the most recent being held in Miami in November 2007. A significant effort over the past year, for which Legg has had principal responsibility, has been the preparation of a synthesis manuscript, recently accepted for publication in the Bulletin of the American Meteorological Society (Legg et al, 2008a). Other overflow-related articles published or in press during the past year include Legg et al, 2008b and Jackson et al, 2008.

Legg supervised the work of postdoctoral researcher Ulrike Riemenschneider at Woods Hole for the three years ending July 2007. As a follow-on to their numerical study of the Faroe Bank Channel overflow published in Ocean Modeling (Riemenschneider and Legg, 2007), Legg has been working with Riemenschneider (now based in Ireland) and Jim Price at WHOI to evaluate and improve the Marginal Sea Boundary Condition for the Faroe Bank Channel. The MSBC is a parameterization of overflows suitable for large scale models which is now implemented in the CCSM ocean model. A significant result of this effort is a new description of the widening of the overflow plume, which in the FBC region takes the form of a transverse hydraulic jump. This work was presented by Price at the Ocean Sciences 2008 meeting in Orlando (Legg co-author) and is currently being prepared for submission to Ocean Modeling (Riemenschneider et al, 2008).

A new effort which Legg has begun in the past few months is an examination of the influence of the new overflow parameterizations implemented in GOLD on the large-scale overturning circulation. This study is being carried out with idealized simulations of the thermohaline circulation, to examine how changing the entrainment rate impacts the overturning.

Publications:


**Progress Report:** Transport of South American Dust to East Antarctica

**Principal Investigator:** Fuyu Li (Princeton Graduate student)

**Other Participating Researchers:** V. Ramaswamy (GFDL), Paul Ginoux (GFDL)

**Theme #1:** Earth System Studies/Climate Research

**NOAA's Goal #2:** Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

**Objectives:** To understand the mechanisms of dust transport to Antarctica from South America and other sources.

**Methods and Results/Accomplishments:**

In the past year, I have been working with V. Ramaswamy and Paul Ginoux to study the transport of South American dust to east Antarctica, using the GFDL state-of-the-art Atmospheric Model. The detailed mechanisms of the dust transport from major sources are one of the issues missing in our previous work [Li et al., 2008], which focused on more general characteristics of dust in high latitude Southern Hemisphere. This study serves as a continuation of Li et al. [2008] and helps to better understand the variability of dust records in Antarctica ice cores.

Patagonia is indicated by the model as the predominant dust source in South America, with the two hot spots centered at ~ (44° S, 67° W) and ~ (49° S, 69° W). The air masses from these two sources tend to fall within two corridors, southeast corridor and south corridor, to get to Antarctica by forward trajectory analysis using HYSPLIT model. The satellite observed arc pattern of a South American dust plume [Gasso and Stein, 2007] falls into the southeast corridor, while this study shows another corridor going directly southward. The simulated transport of South American dust seems to be associated with the high pressure systems normally located over Saint Helena Island and low pressure systems within the Subpolar Low-pressure Zone (SPLPZ). The high centers move towards into SPLPZ, but at different parts of South Atlantic Ocean (SA) for the two corridors. High dust optical depth (DOD) in the southeast corridor is seen correlated with the negative sea level anomaly in west SA and positive anomaly in the east. The variation of DODs in the south corridor has high correlation with positive anomaly in west SA.

The southeast-corridor transport of South American dust dominates the dust reaching Antarctica. The journey of dust transport through this corridor, from its source in Patagonia to east Antarctica, was analyzed in daily basis by following a typical dust plume. Our simulation shows that it usually takes 2-3 days for Patagonian dust to reach high-latitude SA after its emission, and ~ 6 days for the dust to get into Antarctica. This timing is in agreement with the forward trajectory simulations. The dust plume moves to east Antarctica along with the movement of the surface pressure systems over SA and the associated changes of near surface winds. We also found that big east to west zonal gradient of SLP over SA is a prerequisite for the dust transport to Antarctica. It produces strong south-eastward winds over SA, which permits the long-distance south-eastward transport into high latitude SA and Antarctica.

This study shows that satellite products could be useful for the model validation, but their role is largely limited in this region, due to (1) the low dust concentration, (2) the mixture of dust with other aerosols, and (3) existence of clouds. Model is an essential tool in studying the dust transport in high-latitude SH.

**References:**


Publications:
Li, F., P. Ginoux, and V. Ramaswamy, Transport Of South American Dust To East Antarctica, in preparation.
**Progress Report:** Interactions Between Atmospheric Variability Over the Pacific and North Atlantic Basin - Role of Transient Eddies

**Principal Investigator:** Ying Li (Princeton Research Associate)

**Other Participating Researchers:** Gabriel Lau (GFDL/Princeton)

**Theme** #1: Earth System Studies/Climate Research

**NOAA’s Goal** #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

**Objectives:** To understand which dynamical processes are responsible for the atmospheric-ocean variability over the tropical Pacific, North Pacific and North Atlantic in late winter

**Methods and Results/Accomplishments:**

By applying state-of-the-art analysis tools on a 2000-year integration of a coupled atmosphere-ocean model at GFDL, Ying has demonstrated the important role of synoptic-scale weather disturbances in linking the slowly varying circulation patterns over the North Pacific with those over the North Atlantic.

First, stationary wave propagation does not seem to explain ENSO influences on atmospheric variability over the North Atlantic since the ENSO-related stationary wave train is characterized by equatorward propagation over the North Atlantic.

Second, the barotropic component of the transient eddies may play an important role in linking ENSO to North Atlantic variability. Specifically, in the El Nino case, the SST forcing over the central and eastern Pacific induces the anomalous low over the North Pacific, followed by the equatorward shift of both the jet stream and storm track. Furthermore, the El Nino-induced transient eddy forcing measured by the barotropic component of the geopotential height tendency at 250-hPa resembles the NAO(-) pattern, especially over the western North Atlantic. The reinforcement of the NAO(-)-like pattern by El Nino-related transient eddy forcing over the North Atlantic leads to patterns with high degree of zonal symmetry. This process may contribute to the formation of hemispheric-scale annual modes.

Further work will focus on the Aleutian Low (AL) and Icelandic low (IL) seesaw, which is another possible mechanism. Honda et. al (2001) found that the influence of the North Pacific anomalies could generate the circulation anomalies in the Euro-Atlantic sector a month later through the AL/IL seesaw.

**References:**

**Progress Report:** Constraining Ocean Circulation And Basal Melting Under Ice Shelves

**Principal Investigator:** Christopher Little (Princeton Ph.D. Student)

**Other Participating Researchers:** Anand Gnandesikan and Robert Hallberg (GFDL), Michael Oppenheimer (Princeton)

**Theme #1:** Earth System Studies/Climate Research

**NOAA’s Goal #2:** Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

**Objectives:** The melting of ice shelves from beneath constitutes a loss of ice from the cryosphere and a source of freshwater to the ocean; it also influences ice sheet dynamics. My overarching goals are to understand the key dynamic controls on the location and rate of basal melting, as well as its sensitivity to changed oceanic conditions, and its influence on ice shelf-sheet stability, oceanic freshwater balance, and global climate.

**Methods and Results/Accomplishments:**

I use a NOAA GFDL numerical ocean model (the Hallberg Isopycnal Model), modified to represent the unique conditions under ice shelves (notably, a solid surface boundary and a thermodynamically active ice interface). To date, I have employed idealized configurations to illuminate the mechanisms by which cavity shape influences heat transport within these regimes. These idealized simulations are also used to examine sensitivity to changes in model formulation and parameterizations, improving our confidence as we look towards realistic, coupled studies of ocean-ice shelf interaction (Little et al. 2007).

In 2007, I submitted a paper describing oceanographic constraints on circulation and melting patterns under larger ice shelves (Little et al., in press). In simulations of idealized “cold” shelves, asymmetry in melting is driven by deep coupling of flow and melting. Bathymetry’s influence on melting is weak.

This fall, I am presenting results from a series of simulations focusing on smaller, warmer ice shelves, with particular emphasis on the role of ice shelf cavity geometry and scale. In contrast to Little et al. (in press), ongoing simulations indicate that the dynamics of the ice-ocean boundary layer -- and its model representation -- are critical in “warm” regimes. In these smaller cavities, ice shelf shape strongly influences velocity and temperature profiles, and thus the distribution of melting. Mixed layer dynamics also control the area-integrated efficiency of heat use.

**Publications:**


Progress Report: Submonthly Indian Ocean Cooling Events and their Relation to Large-scale Conditions

Principal Investigator: Ian Lloyd (Princeton Graduate Student)

Other Participating Researchers: Gabriel Vecchi (GFDL), Gabriel Lau -advisor (Princeton)

Theme #1: Earth System Studies/Climate Research

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: To analyse submonthly Indian Ocean cooling events, and to relate cooling events to large-scale conditions in the Indo-Pacific region.

Methods and Results/Accomplishments:
Submonthly cooling events in the southern tropical Indian Ocean, first recognised by Harrison and Vecchi (2001), involve SST changes of several degrees or more over timescales of a few weeks or less. To diagnose cooling events, a composite approach was used for both observations and models.

SST observations from the Tropical Rainfall Measuring Mission (TRMM) Tropical Microwave Imager (TMI) indicate that, for a composite of 16 cooling events in the period 1998-2007, cooling events can only be partially explained by air-sea fluxes (from NCEP Reanalysis-2 data). A simple two layer approximation suggests the importance of Ekman upwelling, which is reinforced by chlorophyll SeaWIF data, though improved observations of daily, three-dimensional ocean data are still needed.

Cooling events were reproduced in three models: A 1-dimensional mixed layer ocean model, a version of GFDL MOM2 for the Indian Ocean, and a 50 year control run of the GFDL coupled model CM2.1, with 1990 levels. Cooling events in the 1-dimensional mixed layer ocean model and in the MOM2 model were both too weak, and driven by air-sea fluxes. However, cooling events in CM2.1 could not be fully explained by air-sea fluxes, with Ekman upwelling playing an important role.

In addition, observations and CM2.1 indicate that cooling events are associated with a strong Madden-Julian Oscillation (MJO) signal, and that cooling events are favored under La Nina conditions with increased Walker circulation. Future work will involve clarifying the role of intraseasonal SST variability in modulating the MJO, and whether the representation of the MJO could be improved in coupled models if SST variability in the Indian Ocean were to be stronger.

References:
Progress Report: Evaluating Current and Historic Biomass Burning in Africa

Principal Investigator: Brian I. Magi (Princeton Postdoctoral Research Associate)

Other Participating Researchers: P. Ginoux (GFDL), V. Ramaswamy (GFDL), Y. Ming (GFDL)

Theme #1: Earth System Studies/Climate Research

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: To better understand the simulation of biomass burning in the GFDL GCM

Methods and Results/Accomplishments:
Through statistical comparisons in Magi et al. (2008b), we were able to show that the simulation of southern African aerosol properties by the NOAA GFDL general circulation model (GCM) are not consistent with available datasets from aircraft, NASA AERONET ground-based sites, and the NASA MODIS satellite. In Fig. 1, we show the discrepancy between regionally-averaged aerosol optical depth (AOD) output from the GFDL GCM (blue) and from MODIS (black). The root-mean-squared (rms) discrepancy does not improve for the different temporal averaging. By exploring mechanisms that control the aerosol properties in that region, we determined that the cause for the discrepancy is most likely due to underestimates in the aerosol mass input into the GFDL GCM, with an emphasis on underestimates in carbonaceous mass. The aerosol in southern Africa is strongly affected by seasonal biomass burning, so another conclusion we reached was that even with updated biomass burning emissions inventories, the GFDL GCM does not accurately simulate a biomass burning aerosol. We will apply results by Magi et al. (2008a) to learn what the discrepancies imply about radiative forcing.

To address the discrepancies, I have been exploring interdisciplinary collaborations with scientists in the paleoclimate community as well as with scientists in Africa to learn more about data availability related to biomass burning. I was accepted as a part of a competitive application process for the DISCCRS (DISsertation initiative for the advancement of Climate Change ReSearch) Symposium (September 2007) to foster discussions of potential research paths for better understanding and synthesizing global fires.

Finally, I have participated as a member of the science community as a peer-reviewer for multiple journals. I was awarded "Best Reviewer for Lower Atmosphere and Climate" by the editors of the European Geophysical Union journal called "Annales Geophysicae".

Publications:

Refereed Publications
Non-refereed publications


Magi, B.I., Evaluation of the GFDL GCM simulation of southern hemisphere African aerosol (which is dominated by biomass burning emissions), Informal seminar presentation, NOAA Geophysical Fluid Dynamics Laboratory, February 2008.


Figure 1. Comparison of (a) daily averaged, (b) monthly averaged, and (c) seasonally averaged aerosol optical depth (AOD) at a wavelength of 550 nm retrieved from MODIS satellite measurements (black) and derived from GFDL GCM (Atmospheric Model, Version 2) output (blue) for available data between January 2000 and December 2006. The AOD is averaged over land surfaces in Southern Hemisphere tropical Africa. We discuss the details of the figure in Magi et al. (2008b).
**Progress Report:**  Coupling of a Dynamic-thermodynamic Iceberg Model

**Principal Investigator:** Torge Martin (Princeton Postdoctoral Research Associate)

**Other Participating Researchers:** Alistair Adcroft (Princeton)

**Theme #1:** Earth System Studies/Climate Research

**NOAA’s Goal** #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

**Objectives:** Implementing icebergs as a climate system component in a coupled climate model in order to improve the distribution of freshwater fluxes from ice sheets in the ocean

**Methods and Results/Accomplishments:**

Present coupled climate models lack the ability of simulating any ice sheet processes. The resulting difficulties in conserving mass and energy are treated in different ways. GFDL’s global climate models CM2x accumulate frozen precipitation (snow) on ice sheets and glaciers in a buffer layer of 1 m thickness. The overflow of this buffer is called calving and enters the ocean directly at the coast as frozen precipitation. This resulted in unrealistic sea-ice growth and salt extraction particularly around Antarctica, because calving turns immediately into frazil ice as the ocean is at freezing temperature. However, sea ice is saline in contrast to the fresh calving and thus salt is extracted from the ocean to maintain the constant sea-ice salinity.

Icebergs are the missing link in the water cycle of the model. In order to treat calving correctly and to achieve a better, realistic distribution of the related freshwater flux a dynamic-thermodynamic iceberg model has been implemented to CM2x. Based on the work of Bigg et al. (1997) and Gladstone et al. (2001) icebergs are treated as Langrangian objects, their drift is forced by wind, sea-ice drift and ocean currents and melting is mainly caused by wave erosion and turbulent heat exchange. We updated the Bigg and Gladstone model in some details and extended it by forcing the release of icebergs with the calving rate generated by the climate model. Now, calving accumulates at the land-sea boundary in 10 different iceberg size categories representing bergs of $\sim 10^8$ to $10^{12}$ kg and berg releases, i.e. calving events, are derived dynamically by the model depending on the amount of frozen runoff in each coastal grid cell.

The introduction of icebergs resulted in a much more realistic distribution of the freshwater input from the ice sheets of Antarctica and Greenland (Figure 1). This improved distribution has for instance an important, positive effect on the ventilation of the Southern Ocean and in the Greenland Sea in the coupled model (here CM2G). Figure 2 shows the water age along an Atlantic cross section in simulations without and with icebergs. The water age in the deep Southern Ocean is reduced by up to 20 years compared to previous runs. Here, icebergs transport the calving fresh water much farther north importantly changing the input locations.

**References:**


**Publications:**

Figure 1: Freshwater flux to the ocean from iceberg melt. An average of years 80-99 is shown.

Figure 2: Water age without (upper panel) and with icebergs (lower panel). An average between 60°W-0° and of years 80-99 is shown.
Progress Report: Observational Constraints on the Tropospheric Ethanol Budget: Implications for U.S. Air Quality, Global Chemistry and Climate

Principal Investigator: Vaishali Naik (Princeton Associate Research Scholar)

Other Participating Researchers: Arlene Fiore (GFDL), Larry Horowitz (GFDL), Michael Oppenheimer (Princeton), Hiram Levy (GFDL), J. de Gouw (NOAA), D. Millet (Harvard University), Hanwant B. Singh (NASA), C. Wiedinmyer (NCAR), Alex Guenther (NCAR), Paul D. Goldan (NOAA), William C. Kuster (NOAA), and Allen Goldstein (University of California at Berkeley)

Theme #1: Earth System Studies/Climate Research

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: To use atmospheric observations of ethanol together with the MOZART-4, three-dimensional global model of tropospheric chemistry, to advance our understanding of the present-day ethanol budget and its implications for atmospheric chemistry.

Methods and Results/Accomplishments:
We continued to enhance our analysis of the atmospheric budget of ethanol using the global three-dimensional chemical transport model, MOZART-4, and atmospheric observations from large-scale aircraft campaigns and field experiments conducted over the last decade. Our preliminary analysis suggested that an in-situ atmospheric source of ethanol was needed to explain the observed concentrations in remote regions (for example, abundances observed over the pristine Southern Pacific Ocean by Singh et al., 2001). On further investigation, we have found that secondary atmospheric production of ethanol from measured precursor hydrocarbons, such as propanal, is unlikely to explain the ethanol concentrations measured in remote environments. Further research is therefore needed to fully explore the sources of atmospheric ethanol including probable sources from aqueous-phase chemistry and marine biosphere. A research paper presenting our analysis of the atmospheric budget of ethanol is being communicated to the Atmospheric Chemistry and Physics journal (Naik et al., to be submitted to Atmospheric Chemistry and Physics, 2008).

References:

Publications:
Progress Report: Modeling Sea Ice-Ocean-Ecosystem Responses to Climate Changes in the Bering-Chukchi-Beaufort Seas with Data Assimilation of RUSALCA Measurements

Principal Investigator: L. Oey (Princeton Research Scholar)

Theme #1: Earth System Studies/Climate Research

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: To understand the role of the Arctic Ocean to climate

Methods and Results/Accomplishments:

We have completed developing a data assimilation module in support of the project. The module was tested on a model of the Bering Sea based on the Princeton Ocean Model at a resolution of about 5km and with 50 vertical levels. The results were presented at the Pacific Arctic (Country) Group (PAG) Model-Data Fusion Workshop, Feb.18-20/2008, held in Sanya, Hainan, China. The title the talk is “An Optimal Interpolation Data Assimilation Analysis of the Bering Sea” and a brief abstract is:

A data assimilation analysis using optimal interpolation method is conducted to study the circulation and water-mass pathways of the Bering Sea. This is a first step towards a more complete description of the regional circulation in a dynamically consistent manner using the high-resolution (4-km) Coupled Ice-Ocean Model (CIOM; Fig.1; Wang et al. 2002, 2005) and observations; the work will in the future also include the Chukchi and Beaufort Seas. The power-point of the talk was also submitted to the Workshop Committee.

Year 2 and future plans – the following problems will be investigated:

1. Forcing to Bering Sea – Bering Strait:
   (A). The role of Alaskan stream - are eddies important to fluxes, what about the Stream’s transport strengths? How are these related to the stream’s separation? What are the effects of tides and wind-waves? How may the fluxes be connected with subtropical/tropical variability – atmos. (wind) forcing? Have models been used to address and separate these processes and effects of these forcing?
   (B). North of Aleutian islands, the importance of the slope current – again, fluxes? How are they related to processes south of the islands? Which is dominant, shelf or slope? How is shelf driven (apart from by wind and rivers etc)? Is there an asymmetry between western and eastern (Bering Sea) currents, and why? And also their contribution to the Bering Strait outflow?

2. North of Bering Strait:
   Pickard’s observations presented during the PAG show a branching processes. What are the roles of eddies, atmospheric forcing, and topography? And why?
Progress Report: Sea-ice and the Quasi-stationary Circulation

Principal Investigator: Dr. Isidoro Orlanski, Princeton Senior Researcher

Other Participating Researchers: Dr. Silvina Solman (CIMA, Argentina).

Theme #1: Earth System Studies/Climate Research

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Methods and Results/Accomplishments:
The Role of the Mesoscale Atmospheric Phenomena on Climate Simulations.

A review of the importance of the cyclone-frontal scale system in climate variability and the ability of present climate models to simulate them has been presented (Orlanski 2007). The analysis of three different Climate models, GISS, the NCAR community climate model CCM3 and the GFDL Finite volume AM2 (M90) have been discussed. The intention here was not to determine which one is better but rather to indicate what deficiency may be common to all of them. Evidence shows that the three models tend to be deficient in the generation of cyclone wave activity with the consequences that heat, momentum and moisture may be deficient in the extra-tropical and sub-polar regions. This will affect cloudiness, wind stress and precipitation. It was concluded, that the deficiency of moisture and cloudiness over the sub-polar regions was due to the lack of cyclone waves to transport moisture and clouds to these regions. Consistent with the present analysis, this study also showed that differences in trajectories between reanalysis and model simulation for extra tropical cyclones was interpreted to be related to the lack of intense high frequency eddies of the GCM.

It is clear that to adequately resolve the mesoscale, it is necessary to not only improve the resolution but also to improve the physic parameterizations used in these models. For the present low resolution climate models, this improvement is probably unattainable. However, since cloudiness and sea ice over the sub-polar regions are important to the overall climate, this should be an attainable goal because no sophistication in the moist convection or sea-ice model could correct those deficiencies due to the unresolved dynamics.

The Mutual Interaction of Sea-ice and the Quasi-stationary Atmospheric Circulation.

It is well know that the atmospheric circulation could affect the sea-ice distribution in sub-polar regions. In Antarctica, the katabatic winds blowing from the continent extend the sea-ice boundary well into the southern oceans. On the other hand, warmer air blowing on the western side of high pressure systems produced a significant decrease of the sea ice. It has been established that in the warmer phase of ENSO, a train of Rossby waves sets as a response to the equatorial warming. As a consequence, a high pressure system locates over the eastern South Pacific Ocean. It is speculated that the high pressure pattern maybe responsible of the low sea ice concentration that it is observed on the warmer phase of ENSO, over the sub-polar regions of western Antarctica.

A clear relation of low sea-ice and the high pressure pattern (500HPa) is shown in Fig 1a. In the figure the composite for the height field over the 50 years (1950-2000) of Sept-Nov (when climatologically the sea-ice cover is at maximum) is shown. In order to detect the sensitivity of the pressure and sea-ice, an index was constructed. A Ross sea index was defined by taking the averaged surface temperature over the Ross sea basin for the entire fifty years period, the
anomalous temperature divided by its standard deviation. The composite heights where done for
values of the Ross sea index above 1. The fact is that whether ENSO or any other interannual
variability produce a reduction of sea ice over the sub polar region, a high pressure system is also
observed in the neighborhood of it.

Our assumption is that there must be a mutual interaction between the reduction of sea ice and
the maintenance of the high pressure system. To prove this hypothesis, we have run a strip down
global atmospheric model, with the idealized climatology of Held and Suarez (1994). The model
was forced with a local forcing due to diabatic heating, for instance like produced by convection.
The location of the forcing was around the sup-polar regions of the South Hemisphere. It is found
(Fig 1b) that the atmospheric response is a high pressure consistent with the observed patterns.
Moreover, this circulation could reduce the sea ice, as well as produce areas of very active
convection, the source of the assumed diabatic heating.

In a complementary study with Dr. Silvina Solman (CIMA, Argentina) it was found that the
periods of intense precipitation over the center of South America correlates very well with a
Rossby wave pattern that originates in the sub-polar regions of the eastern Pacific Ocean, very
similar to the observed train of waves emanating from the high pressure system shown in Fig 1b.
These results suggest that the interaction of the quasi-stationary circulation and sea-ice could
have great climatic implications even as far as the subtropical regions of the globe.

References:

Orlanski, Isidoro, The rationale on why Climate Models should adequately resolve the
Mesoscale; Chapter 2 of the Book, High Resolution Numerical Modeling of the Atmosphere and

I.M. Held and M.J. Suarez, (1994), "A proposal for the intercomparison of the dynamical
Fig 1: Heights anomalies at 500HPa for a) composite of NCEP/NCAR reanalysis data for the ROSS sea index is above one (anomalous high temperatures over the Ross sea (SON). b) Idealize simulation with a spectral global model due to a localized diabatic heating in the neighborhood of the Ross sea. The contours are every 8m and the color shade every 4 m from -40m to 40m. The X marks the center of the localized heating.
Progress Report: Topographic Venting Of Ganges Valley Pollutants

Principal Investigator: Arnico K. Panday (Princeton Postdoctoral Research Associate)

Other Participating Researchers: Larry Horowitz (GFDL), Hiram Levy (GFDL)

Theme #1: Earth System Studies/Climate Research

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (80%)
NOAA's Goal #3: Serve Society’s Needs for Weather and Water Information (20%)

Objectives: To quantify the export of pollutants from the Ganges Valley via topographic venting in Himalaya, especially of the "brown cloud" aerosol haze that commonly forms in the dry season, as well as to study the effects of this on downwind atmospheric chemistry, meteorology, hydrology, and climate.

Methods and Results/Accomplishments:

I am pursuing this research topic with a two-pronged approach. I am using high resolution numerical modeling, combined with satellite observations, to explore transport pathways, to make a first attempt at quantifying the export fluxes, and to make a first assessment of the effects. At the same time, given the scarcity of surface observations in the region, I am preparing plans for future observation stations and intensive field campaigns in the region.

For the modeling work, I have successfully set up, compiled, and started running the NCAR Weather Research and Forecast (WRF) model on the GFDL computer system, running it at resolutions as fine as 1 km, over complex terrain in the Himalaya. I am in the process of testing it against meteorology field data I collected in Nepal 2004-2005, field data collected at high-mountain observatories at the base of Mount Everest, and earlier model runs I had done using the MM5 model. I am also in the process of learning to retrieve and use satellite data available from MODIS and CALYPSO, as well as setting up the chemistry-transport model WRF-Chem. The work is now at a stage whereby it should start producing results some time in the Fall of 2008.

With few exceptions, the existing atmospheric data from the Himalaya region is sparse enough that modeling alone would at best produce hypotheses. Testing the hypotheses and improving understanding of the changes taking place in the region requires new field data. It needs both long term monitoring at multiple sites, as well as intensive field campaigns aimed at collecting datasets to test and validate models. I have spent part of my time preparing proposals for future field research in the Himalaya, meeting with and talking to fellow researchers who would be interested in joining both long term monitoring and field campaigns. During summer 2008 I spent almost two months as a Visiting Scientist at headquarters of ICIMOD (International Center for Integrated Mountain Development). ICIMOD carries out some measurements in the Himalaya on behalf of the UNEP - Atmospheric Brown Clouds project, and will be hosting the ABC Science Team meeting in December 2008. Through a series of meetings with scientists at ICIMOD, at UNEP's regional office in Bangkok, and at local universities, as well as through site visits, I have been working on proposals for a new atmospheric observatory in the Himalayan foothills that would host instruments from diverse research groups. WRF model runs at GFDL will be used to assess each site's exposure to air masses of different origin. The proposals will be presented to the ABC Science Team in December 2008.

Publications:
* Works in progress*
Progress Report: Cloud Microphysics and Feedbacks in the GFDL General Circulation Model

Principal Investigator: Marc Salzmann (Princeton Postdoctoral Research Associate)

Other Participating Researchers: Leo Donner (GFDL)

Theme #1: Earth System Studies/Climate Research

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: Reduce uncertainties related to the cloud microphysics parametrization in the GFDL general circulation model and study cloud-climate feedbacks.

Methods and Results/Accomplishments:
Since the beginning of the project in March 2008, a two moment bulk microphysics scheme (Morrison and Gettelman, 2008) has been implemented into the GFDL general circulation model and coupled to two different stratiform cloud cover parameterizations. Currently, the focus of this study is on evaluating and improving the simulation of ice in the upper troposphere. Unlike in the bulk scheme which is traditionally being used in the GFDL model, the sedimentation velocity of ice crystals in the two moment bulk parameterization depends on the size distribution. Due to the high sensitivity of the outgoing longwave radiation (OLR) and poor quantification, this has been a main tuning parameter in recent simulations. Fairly pronounced tropical upwelling in the current model setup and rather efficient ice nucleation in the upper troposphere (calculated using the fairly simplistic temperature dependent approach currently implemented in the two moment scheme) result in too widespread areas of low OLR. In order to radiatively balance the model around the observed OLR, it is necessary to artificially enhance the sedimentation velocity by an unrealistically high factor. Preliminary tests have indicated that the upwelling is strongly influenced by the version of the deep convection parametrization used in these simulations, which is still subject to revisions. There is, however, also a strong need for improving the representation of ice phase processes, in particular nucleation rates, and to account for the high supersaturations over ice frequently observed in the upper troposphere prior to drawing any final conclusions. Eventually, after evaluation based on newly available observations, it will most likely be possible to significantly limit the possibilities of using the ice sedimentation velocity as a tuning parameter.

References:
Progress Report: Dynamics And Thermodynamics Of Hurricane Boundary Layer

Principal Investigator: Agnieszka Smith-Mrowiec (Princeton University)

Other Participating Researchers: Stephen Garner (GFDL), Olivier Pauluis (NYU)

Theme #1: Earth System Studies/Climate Research

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: To understand hurricane intensity and connection to boundary layer dynamics.

Methods and Results/Accomplishments:

In this study, we show that mixing within the boundary layer can lead to an intensification of the hurricane winds. The Maximum Potential Intensity theory (MPI) of Emanuel (1986) determine the intensity of a steady hurricane forced by surface energy flux. The MPI theory is based on three assumptions. First, due to slantwise convection, both the entropy and angular momentum are constant along the streamlines within the free troposphere. Second, it is assumed that the azimuthal wind is in gradient wind balance. These two first assumption make it possible to derive the entire wind field from the distribution of entropy and angular momentum at the top of the boundary layer. The third assumption is that the entropy and angular momentum distributions can be determined directly from a simple closure on the surface fluxes of entropy and momentum. By combining these three assumptions, Emanuel (1986) can predict the maximum theoretical intensity of a hurricane. Recent studies based on both observations and numerical modeling have shown that the hurricane wind speed can actually exceed this theoretical prediction. We show how such super-intensity obtained in our numerical model can be attributed in part to dynamical effects associated with the over-shoot of the hurricane inflow and in part to thermodynamics effects. The present work discusses these thermodynamic effects in greater detail and shows that mixing within the boundary layer can lead to more intense hurricane.

Within the boundary layer, entropy and angular momentum surfaces are often strongly tilted. This implies that due to the intense turbulence, both entropy and momentum should be mixed across angular and entropy surfaces. When the effects of mixing are included in the closure for the boundary layer entropy and momentum, these results in stronger entropy gradient near the radius of maximum wind, and, as a result of the gradient wind balance, to stronger wind speed. It should be stressed here that mixing does reduce the entropy gradient in the inner part of the eye and eye-wall, but enhances near the radius of maximum wind, which in the MPI theory is located at the outer end of the eye-wall.

In numerical simulations, we evaluate that mixing enhances the entropy gradient at the radius of maximum wind by 10 to 20%, which translates in an increase of 5 to 10% in the maximum wind speed. We also propose scaling arguments that relate this thermodynamic super-intensity to the turbulent diffusivity within the planetary boundary layer. This scaling is consistent with the results from numerical simulations. This theoretical framework indicate that the MPI theory do indeed provide a solid framework to analyze the hurricane intensity, but its prediction should not be construed as a strict upper bound on hurricane intensity. These results also point out that the maximum wind speed in a hurricane can depends on the turbulence within the eyewall.

References:

Progress Report: Dynamics Of The Atmosphere And Ocean

Principal Investigator: Geoffrey K. Vallis (Princeton faculty)

Other Participating Researchers: P. Zurita-Gotor (Madrid), R. Farneti (AOS), R. Zhang (GFDL), S. Garner (GFDL), I. Held (GFDL), E. Gerber (Columbia University)

Theme #1: Earth System Studies/Climate Research

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: To understand the dynamics of and the interactions between the atmosphere and ocean, and in particular to understand the mechanisms giving rise to natural climate variability, the meridional transport of energy in the ocean-atmosphere system, the stratification of the atmosphere, and the effects of mesoscale eddies on the ocean circulation.

Methods and Results/Accomplishments:
In one study with R. Farneti, we constructed an idealized coupled climate model and used it to study the decadal variability of the ocean-atmosphere system, as well as fundamental aspects of the meridional energy transport in the combined system. We showed that the atmosphere will tend to compensate for decadal changes in the ocean circulation, but that the total meridional transport of the system is not constrained to be constant, as sometimes thought. This work is described in more detail in Farneti's report.

In work with P. Zurita-Gotor, we explored the mechanisms maintaining the stratification of the atmosphere, and the role of baroclinic turbulence. We showed that quasi-geostrophic theory is relevant to the equilibration, and that for a range of parameters supercritical flow can be maintained. We are now examining the mechanisms that determine the height of the tropopause.

We have explored the mechanisms of the North Atlantic Oscillation, which is the single most important source of climate variability in the extra-tropics. We showed that the NAO is intimately linked to the storm tracks and the baroclinic activity. The zonal nature of the EOFs of the related so-called Southern Annular Mode are largely an artifact of the zonality of the statistics of the storm tracks, and do not represent the a zonally symmetric dynamics.

Finally, we explored a novel way of incorporating the effects of baroclinic eddies into non-eddy resolving ocean models, using the so-called transformed Eulerian Mean method whereby the parameterization appears in the momentum equation. Comparisons with a primitive equation model that resolves eddies were performed, and the scheme was shown to perform quite well.

Publications:


Vallis, G. K. and R. Farneti (2008e), Theory and modelling of the meridional energy transport in the atmosphere-ocean system. Part II: Scalings and parameters dependence. in preparation for QJRMS.


**Progress Report:** The Influence Of Land Surface State Initialization On Seasonal Forecasts Skill In The Ncep Noah-Lsm Climate Forecast System (Cfs-Noah)

**Principal Investigator:** Eric F. Wood (Princeton Professor) and Lifeng Luo (Princeton Research Associate)

**Other Participating Researchers:** N/A

**Theme #1:** Earth System Studies/Climate Research

**NOAA’s Goal #2:** Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (70%)

**NOAA’s Goal #3:** Serve Society’s Needs for Weather and Water Information (30%)

**Objectives:** To study the seasonal predictability of the NCEP Climate Forecast System (CFS) when the land surface component of CFS is upgraded from the current OSU model to the more advanced Noah model

**Methods and Results/Accomplishments:**

The project officially began in the late 2006 when access to two supercomputers, haze at NCEP and orangena at Princeton University were granted. Orangena is a single rack IBM Blue Gene/L system that is a highly specialized proprietary architecture specifically designed for codes to scale out to many processors. The GFS code and its associated software libraries were obtained from NCEP and were compiled on orangena. Although both haze and orangena are built by IBM and both have the IBM Fortran and C++ compiler, their architectures are very different. With help from many people, we successfully compiled GFS on orangena and were able to make runs we needed by the end of the first year.

The major tasks for the second year were the following:

1) **PORTING GFS TO A LINUX CLUSTER**

   This is a continuing effort from the first year. Dr. Jeffery Whitaker at NOAA/CDC has been collaborating with us on this part. His Linux version of GFS has included changes we contributed to help porting GFS to Linux. Jeff has already successfully run GFS on their 64-bit Linux cluster, but the same version crashes on our and 64-bit clusters (della). We were able to identify where exactly the problem, but could not understand why it crashed, and the solution for fixing the problem is beyond the scope of the project. As this task does not have the highest priority, we were not dedicated to pursue further in this direction.

2) **EXPERIMENTS ON Orangena**

   Before carrying out the series of experiments designed in the project on Orangena, we need to test the model performance on this machine. An important issue arose when we compared the model output from Orangena with the output from NCEP haze. Jeff has already successfully run GFS on their 64-bit Linux cluster, but the same version crashes on our and 64-bit clusters (della). We were able to identify where exactly the problem, but could not understand why it crashed, and the solution for fixing the problem is beyond the scope of the project. As this task does not have the highest priority, we were not dedicated to pursue further in this direction.

3) **GLACE2 EXPERIMENTS WITH GFS/NOAH**
As part of the project, we are also involved in the GLACE 2 experiment organized by Dr. Randal Koster at NASA/GSFC. We are the official participant using GFS/NOAH for NCEP. Experiments required for the GLACE2 experiments are:

a) Background Offline run with Princeton Forcing or GSWP2 forcing
b) AMIP run with the current operational GFS
c) Forecast experiments

To run the background offline run with the Princeton forcing (Sheffield 2006), we need to run it under Land Information System (LIS)(Kumar et al. 2006). This involves customizing the code to properly processing the 50 year ½ degree global forcing (Sheffield 2006) and interpolated to the right T126 grid. This run is essential to the project as it can provide “accurate” land surface initial conditions for weather and seasonal forecast. Jesse Meng of Ken Mitchell’s group had LIS installed on haze, and our tasks were to customize LIS to use the Princeton global forcing dataset (Sheffield et al., 2006). The 50 year run with a 40 year spin-up was finished in February 2008.

References:


**Progress Report:** Implement, Develop And Evaluate Moist Physics Parameterizations For A Hierarchy Of Gfdl Atmospheric Models

**Principal Investigator:** Ming Zhao (Princeton Associate Research Scholar)

**Other Participating Researchers:** Isaac Held and Leo Donner (GFDL/Princeton), S-J Lin (GFDL), Geoffrey Vallis (Princeton)

**Theme #1:** Earth System Studies/Climate Research

**NOAA’s Goal #2:** Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

**Objectives:** To incorporate, develop and evaluate moist physics parameterization schemes for use in a hierarchy of GFDL atmospheric models ranging from highly idealized to comprehensive GCM at different horizontal and vertical resolutions. To support these models being used by the GFDL community for investigating climate variability, climate prediction, climate sensitivity, and atmospheric circulation.

**Methods and Results/Accomplishments:**

In the past year, Zhao continued to work with Isaac Held on the understanding of GFDL column physics and their interactions in a simplified dynamical framework (Held et al. 2007, Held and Zhao 2008). We have examined rotating radiative-convective equilibria simulated using the GFDL AM2 physics at a range of resolutions in a very large domain with fixed SST and uniform Coriolis parameter. The large domain allows a number of tropical storms to exist simultaneously. The number of storms decreases as SST increase, while the average intensity increases. As the background rotation is decreased, the number of storms also decreases. At these resolutions and with this parameterization of convection, a dense collection of tropical storms is always the end-state of moist convection in the cases examined. We propose these horizontally homogeneous rotating radiative-convective equilibria at GCM resolutions as a useful framework for studying the tropical storm-like vortices produced by global models.

In the past year, Zhao has been working with Isaac Held, S-J Lin and others in the development of GFDL new high resolution atmospheric model with special emphasis on applications on hurricane and climate research. The new model incorporates the University of Washington shallow cumulus scheme (Bretherton et al. 2004), a simple PDF stratiform cloud scheme and GFDL newly developed cubed-sphere dynamic core. This configuration targets on simplifications of moist processes as model resolution increases. We have pursued a series of AMIP simulations with observed SSTs at resolutions of 50-100 km. The model is able to reproduce reasonably well the inter-annual variability and recent decadal upward trend of Atlantic hurricanes as well as the global time-mean climatology. The figure below shows the simulated Atlantic hurricane numbers (with time-mean subtracted and normalized by variance) for the past 25 year from a 4-member ensemble integrations of 50 km resolution model. The ensemble mean (blue) captures well the interannual variation of Atlantic hurricane with correlation coefficient ~0.8 although the simulated upward trend is weaker than the observations. We are currently carrying out further analysis to better understand these simulation results with an ultimate goal to improve our capability in simulating and predicting hurricane statistics from seasonal to interannual and decadal time-scales.
References:

Publications:
Progress Report: Equilibration Of Baroclinic Turbulence In Primitive-Equation Models

Principal Investigator: Pablo Zurita-Gotor (Visiting associate research scholar)

Other Participating Researchers: Geoff Vallis (Princeton)

Theme #1: Earth System Studies/Climate Research

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: To assess the relevance of quasi-geostrophic turbulence theories in a primitive-equation model that determines its own stratification, and to develop a theory for the stratification in that model.

Methods and Results/Accomplishments:
We have constructed a primitive-equation, hydrostatic, Boussinesq two-level model on the beta plane, using a dynamical core based on the MIT GCM. The model was forced with Newtonian cooling and was also damped by Rayleigh friction in the lowest level. The setup was chosen to be as similar as possible to the canonical quasi-geostrophic two-layer model on which the turbulence theories are based, except for the internal determination of the stratification in this model.

We have shown that QG theory works well when the stratification is known, by comparing the model's results to those from a similar QG model taking the diagnosed stratification from the primitive-equation model. We also performed an exhaustive analysis of the sensitivity of the mean state and eddy fluxes in our model on the external parameters. The key result is that this model does not exhibit baroclinic-adjustment-like behavior (i.e., robust isentropic slope), and the criticality changes with the external parameters. Consistent with this, the model appears to produce inverse cascades under some parameter regimes. The sensitivity of the eddy fluxes on the criticality is reasonably well captured by the quasi-geostrophic turbulence theory of Held and Larichev. We have also extended the quasi-geostrophic theory to derive a prediction for the eddy vertical heat flux, assuming that the eddy mixing slope agrees with the isentropic slope.

Publications:
Progress Reports:

Biogeochemistry
Progress Report: Latitudinal Gradients Of Atmospheric Δ14c: A New Window Onto Dynamical Controls Of The Southern Ocean

Principal Investigator: Sara Mikaloff Fletcher, Princeton Research Scholar

Other Participating Researchers: Keith Rodgers (Princeton), Eric Galbraith (Princeton), Annand Gnanadesikan (Princeton), Richard Slater (Princeton)

Theme #2: Biogeochemistry

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives:

Measurements of radiocarbon in tree rings over the last 1000 years indicate that there was a pre-industrial latitudinal gradient of atmospheric radiocarbon of 3.9- 4.5‰ and that this gradient has temporal variability on the order of 6‰ [Figure 1]. Previous efforts to explain the variability in the latitudinal gradient have suggested that it is caused by changes in the frequency of ENSO in the tropics [Turney et al., 2002]. We test the alternative hypothesis that the natural latitudinal gradient of radiocarbon is primarily controlled by ventilation of the Southern Ocean through a suite of model simulations, and demonstrate that this tracer may be a useful proxy for understanding dynamical controls of Southern Ocean ventilation over the last 1,000 years as well as detecting contemporary and future changes in the Southern Ocean carbon sink induced by climate change.

Methods and Results/Accomplishments:

We used fluxes from a suite of model simulations from the Modular Ocean Model version 3 coupled to the OCMIP-2 biogeochemical model as boundary conditions for the Tracer Model version 3 atmospheric transport model in order to determine the sensitivity of atmospheric radiocarbon to changes in wind stress and wind speed over the Southern Ocean. The results from this suite of simulations indicate that winds over the Southern Ocean play a first order role in the natural, preindustrial latitudinal gradient of atmospheric radiocarbon.

Increased wind stress in this region leads to greater upwelling of strongly radiocarbon depleted Circumpolar Deep Waters to the surface, leading to a strong decoupling of the air-sea fluxes of 12CO2 and 14CO2 in this region. This results in the ocean having a pronounced net uptake of 14CO2 relative to 12CO2 in the Southern Ocean. Increased wind speed has an even more pronounced effect on the gradient through its role in determining gas exchange rates. These dynamical perturbations to the Southern Ocean are much more efficient that dynamical perturbations in the tropics or the North Atlantic in changing in atmospheric radiocarbon signal. Perturbations of amplitudes similar to those of observed decadal trends in Southern Ocean winds for the NCEP reanalysis (~25%) are sufficient to account for changes in the latitudinal gradients in atmospheric radiocarbon from the tree-ring proxy records over the last 1000 years.
Figure 3. The latitudinal gradient of atmospheric $\Delta^{14}C$ (northern hemisphere minus southern hemisphere) over the last 1000 years based on tree ring data from the INTCAL04 [Reimer et al., 2004] and SHCal04 [McCormac et al., 2004] data sets.

References:


Publications:

**Progress Report:** Coarse Resolution Coupled Model Development

**Principal Investigator:** Eric Galbraith (Princeton Research Associate)

**Other Participating Researchers:** Jorge Sarmiento (Princeton), Stephen Griffies (GFDL), Anand Gnanadesikan (GFDL), Isaac Held (GFDL), Jennifer Simeon (Princeton)

**Theme #2:** Biogeochemistry

**NOAA’s Goal #2:** Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

**Objectives:** To develop and optimize a version of the GFDL Coupled Model at relatively low (3-degree) resolution for making long integrations and exploring parameter space.

**Methods and Results/Accomplishments:**

During the past year, the coarse resolution model was configured with a new ocean grid and the computational performance was optimized. This provided the desired reduction in computational cost of roughly one order of magnitude compared to the GFDL ESM2.1 model. Small adjustments were made to the atmospheric parameters in order to balance the global energy budget. The bathymetry of the ocean grid was thoroughly evaluated and adjusted to ensure that key channels and bottom features are reasonably represented. The model is run with no flux corrections. In terms of the climate simulation, the coarse model generally displays the same biases as the higher-resolution progenitor to the current model, CM2.1 (Delworth et al., 2006), but with slightly greater errors.

Additional model development focused on improving the ocean circulation. Code changes have been made that allow for improved ocean mixing parameterizations, including schemes for tidal mixing over rough topography and downslope mixing, as well as geothermal heating at the ocean bottom. The Antarctic glacial discharge was modified to capture the effect of freshwater transport by large drifting iceberg, the absence of which had introduced a coastal freshwater bias that prevented Antarctic Bottom Water formation.

In addition, a new ocean biogeochemical model was created by Galbraith as a low-complexity complement to the GFDL TOPAZ module. The simple model (iBGC) handles all ecosystem processes implicitly, with nutrient uptake and remineralization being predicted by simple relationships with the available solar radiation and water temperature. The iBGC model is intended as a low-cost alternative to TOPAZ (requiring only a few prognostic tracers), as well as a diagnostic tool to aid interpretation of TOPAZ behavior.

The model has been integrated for up to 800 years and displays a stable, robust North Atlantic meridional overturning cell (~20 Sv), a strong Antarctic Circumpolar Current (~160 Sv), robust ENSO variability (see Figure) and an RMS SST error of less than 2°C.

**References:**


**Publications:**

Galbraith, Eric et al., Radiocarbon variability and ENSO in a coarse-resolution global coupled model, in preparation.
NINO3.4 SST from an 800 year run

(a) Timeseries (monthly, annual, decadal): $s=1\text{degC}$

(b) Spectral density ($s^2\text{ octave}^{-1}$)

(c) Mean spectra, first/last/min/all epochs

(d) Integrated variance: short $< 1.4\text{yr} <$ long

Overview:
- Mean:
  - Monthly: 25.5
  - Annual: 25.5
  - Decadal: 25.5
- SD:
  - Monthly: 0.14
  - Annual: 0.34
  - Decadal: 0.34
- Skew:
  - Monthly: -0.038
  - Annual: 0.333
  - Decadal: -0.64
- Max:
  - Monthly: 28.9
  - Annual: 28.2
  - Decadal: 28.2
- Min:
  - Monthly: 21.9
  - Annual: 21.1
  - Decadal: 21.1

Contour: $0.4$

Integrated variance:
- Short: $< 1.4\text{yr}$
- Long: $> 1.4\text{yr}$

Wavelet df: $1.17$ (90.4%)
**Progress Report:** Modeling Nutrient Controls in the Terrestrial Biosphere

**Principal Investigator:** Prof. Lars O. Hedin, Prof. Michael Oppenheimer (Princeton)
Other Participating Researchers: Stefan Gerber (Princeton) Prof. Stephen W. Pacala (Princeton)

**Theme #2:** Biogeochemistry

**NOAA’s Goal** #1: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (10%)
**NOAA’s Goal** #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (80%)
**NOAA’s Goal** #3: Serve Society’s Needs for Weather and Water Information (10%)

**Objectives:** Investigate Nitrogen Dynamics and Feedbacks in the Terrestrial Biosphere

**Methods and Results/Accomplishments:**
We have completed the Princeton-GFDL LM3V land model with dynamics for nitrogen (N) that include essential carbon(C)-N interactions aboveground and belowground. The model first allows for C-N feedbacks aboveground in plants and belowground during decomposition, in order to balance C-N stoichiometry of the vegetation and in the soil-microbial complex. These feedbacks are critical for resolving how N limitation influences C dynamics, including the down-regulation of photosynthesis in plants, the increase of litter decomposition in N rich soils, and the stabilization of C by reactions of available N with lignins and polyphenols in recalcitrant soil organic matter. Second, the model resolves dynamically important vectors of N input and losses that are a function of the vegetation-soil dynamics itself: namely biological N fixation (BNF) and losses of dissolved inorganic N (DIN) and dissolved organic N (DON). These fluxes are essential as they affect N budgets and C-N feedbacks over time. Our resolution represents a substantial improvement over all previous and existing dynamic global vegetation models. For example, the dynamics of biological N fixation is based on very recent observations in tropics that N fixers, while often present in canopies, are able to adjust rates of BNF according to N demands. In contrast N fixing trees in temperate and boreal forests lack such a capability, and are often present in early succession but displaced later by non-fixers. We combined these findings with energetic constraints (light) and economic considerations (N fixation is expensive) to formulate BNF dynamics that allows for quick adjustments when N demand is high in tropical forests, while the response of N fixers to increased N demand in other biomes depends on light availability.

Our model is capable to reproduce the dynamic features following a disturbance, namely a spike of N losses immediately after the disturbance, a temporarily increased BNF, followed by a prolonged period N limitation. However, at steady state C-N interactions have little influence on land C fluxes (e.g. primary productivity) and inventories (e.g. biomass). The property of the model showing strong C-N feedback during transient reorganization but little influence of N on C dynamics at steady state agrees with the notion of high N retention capabilities of terrestrial systems; but it contrasts existing models, where the inclusion of N dynamics has greatly altered the model's equilibrium geographical distribution of land surface characteristics [see e.g. Thornton et al., 2007]. Our basic model and its implications for understanding terrestrial C-N interactions are summarized in a manuscript that we currently are in the process of submitting to Global Biogeochemical Cycles (Gerber et al. in. prep.).

One of the urgent questions relating to global change is whether terrestrial systems can sequester anthropogenic carbon via CO2 fertilization mechanism, thereby reducing radiative forcing and mitigating climate change. N-limitation could potentially restrict the biosphere to act as a substantial carbon sink. Indeed, allowing for C-N feedbacks when subjecting the model to projected CO2 rise, reduces the overall storage of terrestrial carbon up to year 2100, compared to
a simulation where C-N feedbacks are neglected (Figure). Moreover we show that a great portion of carbon sequestration can only occur via adjustments in BNF which occurs mainly in tropical systems. Holding BNF constant at low levels (as many models do) reduces the capacity of the terrestrial biosphere to act as a carbon sink even further. This fundamental result illustrates the importance of N dynamics in the larger Earth System, and nutrient feedbacks remain a urgent concern for projecting global change.

References:

Figure: Modeled change in terrestrial carbon storage due to the CO2 fertilization effect for projected CO2 increase according to scenario IS92a. The simulation show how nitrogen acts to limit terrestrial uptake (dashed vs. solid line). The effective sink strength depends on the ability of the terrestrial system to respond with biological nitrogen fixation (solid vs. dashed-dotted lines).
Progress Report: Modeling Land-Use Dynamics In The Earth System

Principal Investigator: George Hurtt, UNH Associate Professor

Other Participating Researchers: Steve Frolking (UNH), Louise Parsons Chini (UNH), Berrien Moore (UNH), Elena Shevliakova (Princeton), Sergey Malyshev (Princeton), Steve Pacala (Princeton)

Theme # 2: Biogeochemistry

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: To understand the influence of land-use activities on Earth System dynamics

Methods and Results/Accomplishments:

For 2007-2008 we proposed to continue our current global land-use modeling efforts, revise our existing products, and concentrate on the development of projections of future land-use activities. Over the past year, we have made substantial progress on each of these proposed activities.

1) In 2007-2008 we continued our efforts to study the effects of historical land-use on the carbon/climate system. Our research directly contributed to two key publications: Shevliakova et al. 2008 (in review) showed their use of our data in the land sub-model of the Princeton GFDL model and Ito et al. 2008 used our data in a comparison study of several different models.

2) In 2007-2008 we made the following key upgrades to our historical Global Landuse Model (GLM): enabled simulations at half-degree fractional spatial resolution; enabled GLM to track urban land-use and transitions in and out of urban land; incorporated new historical crop, pasture, and urban input data from HYDE 3.0 (Klein Goldewijk et al. 2008); extended the timeframe for our historical simulations to 1500-2000; reconstructed our wood harvest input data (by country) based on new population data from HYDE 3.0 as well as FAO data and data for the USA (Houghton & Hackler 2000) and China (Houghton & Hackler 2003); added a new map defining areas where shifting cultivation occurs, based on the map from Butler 1980. The data produced from this improved historical GLM is being used by several Integrated Assessment Models (IAMs) to provide a base for their gridded future projections, and it is also being used by Earth System Models (ESMs) to simulate the land component of their global climate models.

3) In 2007-2008 we initiated an international collaboration with several Earth System Modeling teams (including the Princeton GFDL Team) along with several Integrated Assessment Modeling teams to develop a plan for “harmonizing” landuse data based on the IPCC Representative Concentration Pathways (RCPs) for the next IPCC Assessment. Together with our collaborators, we developed a proposal to the EMF/IAM Working Group (Hurtt et al. 2008 b) that outlines our plan to incorporate IAM future projection data for landuse and wood harvest into our Global Landuse Model, and to use this data to generate a set of gridded landuse and landuse transition products suitable for input into ESMs. This proposal has been well received by the community and we have already begun the process of developing connections with the IMAGE IAM team in the Netherlands as well as IAM and ESM teams here in the USA. As part of this effort, several key presentations were made: Hurtt et al. 2008 a, c, & d and Frolking 2008
4) In 2007-2008 we developed the capability for future projections using our Global Landuse Model that are consistent with our historical reconstructions as well as IAM future estimates and that are in the format required by ESMs. Although initially our projections were computed at 1 degree spatial resolution and based upon regional IPCC SRES data, we are now using half degree gridded data from IAM implementations of the new RCPs (particularly that from the IMAGE team). Using future gridded crop and pasture data resulted in significant challenges to ensure that there are no discontinuities in landuse or landuse transitions in the year 2000. However, our resulting simulations from 1500-2100 transition smoothly in the year 2000 and provide our first spatial estimates of future landuse activities (see Figure 1). This is an ongoing effort that is being coordinated with IAMs from around the world. Our data is available to the community via our FTP site and we have already received much positive feedback.

5) In 2007-2008 we initiated a new effort to reduce uncertainties resulting from our shifting cultivation sub-model. Shifting cultivation (the practice of clearing land, farming it for a short period until it becomes infertile, and then burning/clearing new land) is responsible for large amounts of secondary forest, yet there is much uncertainty in estimates of these areas. Our new sub-model replaces a fixed map of shifting cultivation locations and a constant rate of abandonment with a new dynamic, spatio-temporally varying model that will enable predictions of shifting cultivation impacts into the future.

Figure 1: (a) Time series showing global crop, pasture, primary land, and secondary land area 1500-2100 from GLM along with IMAGE crop and pasture area. Although the IMAGE data is an input to GLM, the differences between GLM and IMAGE crop and pasture data are due to the “harmonization” required to ensure the data is continuous at the year 2000 in each gridcell. (b) Root-Mean-Square of the differences between IMAGE crop and pasture grids and the GLM “Harmonized” Grids showing that there are significant changes needed to match the historical and future crop and pasture grids.

References:
Klein Goldewijk et al. (2008) - In preparation. See the HYDE database: http://www.mnp.nl/hyde

Publications:
Shevliakova et al. 2008 - In review. Carbon Cycling under 300 years of Land-use Changes in the Dynamic Land Model LM3V.

Presentations:
S. Frolking, G. Hurtt (2008) "Global Landuse Data" Presentation at Global landuse Data Workshop, Vienna, Austria
Progress Report: Developing a Upper Trophic Level Model with Climate Forcing

Principal Investigator: Kelly Kearney (graduate student)

Other Participating Researchers: Jorge Sarmiento - advisor (Princeton), Charles Stock (Princeton/GFDL)

Theme #2: Biogeochemistry

NOAA’s Goal #1: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (40%)

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (60%)

Objectives: To extend current biogeochemical models to include upper trophic level functional groups and top-down forcing.

Methods and Results/Accomplishments:

Over the past year, I have been working to develop a prototype of an end-to-end food web model, encompassing both bottom-up climate forcing and top-down predatory forcing (both natural and anthropogenic). In order to do this, I have been adapting the algorithms that underlie the Ecopath with Ecosim fisheries model so that they can be introduced to a climate model framework.

The Ecopath algorithm was originally developed to estimate the standing stock and production budget of a coral reef ecosystem (Polovina, 1984). Since then, it has been developed into a full software package to investigate trophic mass balance in general (Christensen & Walters, 2004). The Ecopath model uses path analysis statistics to calculate an internally consistent snapshot of all the flows of biomass throughout a system, based on certain field-measured parameters. The strength of this model is in analyzing fluxes associated with upper trophic level predator-prey interactions, and in incorporating losses due to fishing activities.

However, the primary production included in the original Ecopath with Ecosim is very basic, and does not include any environmental dependency, such as light, temperature, or nutrient-based limitation. Therefore, I have rewritten the underlying algorithms of the Ecosim model, reproducing the predator-prey fluxes and losses due to disease and old age, but replacing the primary production with a more traditional biogeochemical model.

As a test region, I have chosen to focus on the Gulf of Alaska ecosystem. The northern Pacific ecosystem provides an ideal environment to develop a model of interacting physical and ecological parameters due to the well-documented decadal variability of both physical and ecological variables in this region (Mantua et al., 1997; Francis et al., 1998). To set up the initial food web for the model, I began with the Ecopath with Ecosim model of the Eastern Subarctic Pacific, constructed as part of the PICES Basin Scale Studies (BASS). The original model consisted of 48 functional groups, including phytoplankton, zooplankton, fish, birds, and whales (Figure 1), and had been fully parameterized using a synthesis of data during various PICES workshops (Aydin 2003). For this project, I reduced the number of functional groups to 17 by combining groups with similar diets and predators (Figure 2).

I am currently working to integrate the food web model described above into a one-dimensional water column model. This model, originally written by Charlie Stock, uses observed solar radiation and wind speeds as forcing, and provides a simple test environment to analyze my ability to integrate upper trophic level functional groups into a physical ocean model. Currently I have tested the model with a nutrient-phytoplankton model that uses the same primary production
scheme that I will be using in my modified form of the Ecosim model (Figure 3). As this work continues, I will be adding the modified Ecosim model with the PICES-derived food web described above into this physical model.

References:


Figure 1. Food web for original PICES/BASS model. The axis on the left represents trophic level as defined by Ecosim. The shading of boxes and lines indicates the total biomass and flux between groups, respectively, with darker shades being higher.
Figure 2. Generalized food web for Gulf of Alaska test ecosystem.

Figure 3. Seasonal cycle of phytoplankton simulated using the one-dimensional water column model for the Gulf of Alaska region with 2005 wind and radiation forcing. This biology in this simulation included only phytoplankton, using a constant rate of loss.
Progress Report: Global Carbon Data Management and Synthesis Project

Principal Investigator: Robert M. Key, (Princeton Research Oceanographer)

Other Participating Researchers: Chris Sabine and Richard Feely (NOAA-PMEL), Rik Wanninkhof and T.-H. Peng (NOAA AOML); Frank Millero (Miami), Andrew Dickson (UCLA)

Theme #2: Biogeochemistry

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: Monitor the oceanic inventory of anthropogenic carbon dioxide

Methods and Results/Accomplishments:

Over the duration of this project and its predecessors, the work carried out at Princeton has evolved. A very brief history is given here and work for the past year is described in more detail than usual.

During the WOCE/JGOFS/OACES survey era, Princeton actively participated in cruise work including measurement of various carbon parameters (alkalinity, total inorganic carbon, underway pCO$_2$, $^{14}$C, $^{13}$C). Ocean research interests at Princeton have always been global rather than basin specific largely due to the fact that data-based and modeling interests interact continually. These interests, combined with the fact that we had been heavily involved in earlier large-scale measurement programs (TTONAS, TTOTAS, SAVE), required development of an oceanographic database focused on chemical tracers and the ability (software, etc.) to efficiently process large quantities of discrete data. When the global survey ended in 1998, Princeton probably had the most complete version of the one-time survey bottle data because we had repeatedly requested proprietary and updated data sets from the individual PIs rather than waiting for release/posting of the data at the WOCE office (now CCHDO) and because we had PI status on most of the cruises. During this time Princeton also became the primary center for initial quality control (assignment of data flags) of all carbon data generated during the survey. The software and expertise for primary QC were transferred to CDIAC (A. Koczyr) who now shares primary carbon QC duties for CLIVAR carbon data.

Once the WOCE fieldwork was completed, the Ocean Carbon Science Team (the group funded by this grant) began analysis and synthesis. This work was supported by NOAA and NSF (under JGOFS and WOCE) and resulted in a series of papers by team members in which we described the global distribution and inventory of anthropogenic carbon, described the global carbonate chemistry including anthropogenic changes in saturation depths, described the global distribution of chlorofluorocarbons and described the global distribution and inventory of both bomb-produced and natural $^{14}$C. The carbon and isotope data together were used to estimate a new value for the global air-sea gas exchange rate. Princeton was very actively involved in each of these research activities and took the lead for many tasks that required significant manipulation of the large database. These papers and the GLODAP data product continue to be very heavily referenced and used by the community, including modelers. A subsequent calculation with the GLODAP data led to the current “ocean acidification” research/publications by our group and other independent researchers (only very minor Princeton involvement).

The Science Team remained together during the WOCE to CLIVAR transition, however there were significant changes. Several of the WOCE analytical labs were closed (including Princeton, though we did retain responsibility for NSF funded $^{14}$C work). The scientific research focus shifted from distribution and inventory to decadal (and shorter) change. CDIAC became fully functional and CCHDO assumed full responsibility for virtually all U.S. hydrographic work in
addition to public offering of modern cruise based data (CTD and bottle). CDIAC assumed responsibility for hosting the GLODAP discrete and gridded data products in addition to individual cruise data sets that included carbon measurements. CDIAC and CCHDO are mentioned here because of the close working relationship that has developed over the years between these two organizations and Princeton. Princeton acts as a data source to CCHDO providing data sets that would otherwise be unobtainable. All parameters in all data sets provided to CCHDO are quality checked (flags assigned) at Princeton and accompanied by whatever metadata has been collected. The data are provided to CCHDO in a format that needs little or no additional work prior to being made public through their web site. With respect to CDIAC, Princeton provides data and scientific expertise. Key has served on a previous CDIAC review panel to CDIAC and is currently chair of the external advisor board for CDIAC.

When the NOAA funding mechanism for the science team changed, Princeton’s responsibilities included: helping to gather original CLIVAR data from PIs involved in the repeat hydrography measurement program, independent primary quality control of all carbon data (alkalinity, total carbon dioxide, and pH along with A. Kozyr); secondary quality control of CLIVAR data (direct comparison of new data against existing data to check for any non-random measurement bias); direct comparison of new data against old to quantify temporal property change in the thermocline (invasion of anthropogenic carbon dioxide, decadal oxygen change, etc.); providing graphics and summary statistics (results from multiple linear calculations, etc.) to other team members and the general community (including modelers); providing whatever specialized data products were needed to the science team and community and working with the science team to try to improve calculation methods used to estimate anthropogenic carbon dioxide accumulation and to document and understand the decadal changes found in the various CLIVAR parameters. The “data service” to the science team decreased with time as other team members developed the required tools, however, similar service to the general community and to modelers in particular increased. These outside activities were directly responsible for the alternative GLODAP based estimate of anthropogenic carbon dioxide using the transit-time method (with D. Waugh), for the estimate of the global air-sea gas exchange rate based primarily on the GLODAP radiocarbon data (with C. Sweeney) and for recent biogeochemical nutrient budget calculations (with J. Sarmiento).

All of the listed activities continue at Princeton except for seeking CLIVAR data from PIs which is now done by CCHDO and CDIAC. Keeping up with the CLIVAR data base activities required by the NOAA science team is now much easier than during WOCE, however, it is not as quick as originally envisioned. The extra time required derives primarily from the fact that preliminary data are initially posted on-line, then each PI updates the preliminary values with final values as the data workup is completed. Obviously, anyone working with the CLIVAR data wants the “best available” version, consequently each cruise must be processed multiple times. This isn’t particular difficult, however it has caused “record log chaos” for CDIAC, CCDHO and Princeton and one particularly egregious case of preliminary data being widely distributed as “final” (by another agency). A small workshop was convened between CCHDO personnel, Kozyr (CDIAC), NODC representatives and Key to develop procedures that would prevent future occurrences of similar problems and to ease communication amongst the groups.

After preparing all of the GLODAP maps, I was aware of the deficiencies of those data products and of the need to improving the situation for the stated NOAA science team research goals. The various shortcomings were further demonstrated by the research projects mentioned above, especially the air-sea gas exchange calculations. The problems were all due to data sparseness, or in some areas a complete lack of data. GLODAP has no modern data, for example, in the Greenland-Norwegian Seas, the Mediterranean Sea, the entire Arctic Ocean, the Gulf of Mexico and only a very few casts in the Caribbean. Additionally, there are large data “holes” in the southwestern Pacific and southwestern Indian Oceans. The entire Southern Ocean, the
Atlantic north of 40N, the extreme northwest Pacific and the Indonesian throughflow region are extremely data sparse relative to the importance of the regions, gradients, etc.

Approximately 5 years ago I learned of a European effort called CARINA (CARbon in the North Atlantic), which had similar research goals to the original GLODAP science team effort, but restricted to the North Atlantic. Shortly afterward, CARINA disbanded with the only tangible result being the accumulation of ~30 older cruise data sets that had subsurface carbon values. I asked A. Kozyr to obtain a copy of the CARINA data files to prevent loss in case of a computer failure (which occurred a few months later). Kozyr obtained the files and forwarded a copy to Princeton to see if any of the data were worth a salvage effort. Initial investigation of these data were done with the backing of the NOAA science team (this grant) and demonstrated three things: (1) the carbon data were of reasonable quality for the time of the measurements, (2) ancillary data in the files was incomplete and basically a total mess and (3) most importantly the data were from regions where the GLODAP data was sparse or absent. Equally important was the fact that the carbon scientists who had made the measurements were some of the best in Europe and were still doing research. Workup of these first 30 cruises was supported with NOAA science team monies as an “added project”, but was little discussed because the potential for total failure was rather large. Relative to a WOCE or CLIVAR cruise, the amount of work required per cruise was disproportionately large for the potential scientific gain. This level of effort was needed largely because close communication between European and U.S. ocean carbon scientists was very limited and the concept of “public” data sets was totally novel to the Europeans (very few had participated in WOCE). By the time these initial few cruises had been processed it was apparent that the data did have significant value and equally important the beginning of a “collaborative agreement” had developed between Princeton and Europe.

Approximately 3.5 years ago the European Union sponsored a large research contract called CARBOOCEAN. The goals of this work are very similar to those of WOCE and CLIVAR and CARBOOCEAN sought and obtained varying degrees of participation and “membership” by U.S. scientists. One requirement of the contract was that funded scientists make all of their historical (older than 2 years) public. Because of the relationships developed while working up the original 30 CARINA cruises and experience gained from GLODAP, I was asked to serve as the gathering and processing center for all these data. CDIAC was asked to be the primary data distribution center and the CARBOOCEAN internet data portal would “echo” the CDIAC archive with “CARINA” used as the banner name. At the time the estimate was that 60 cruises (30 new) could be accumulated, quality controlled, released and merged into a data product similar to GLODAP. Not surprisingly, the EU contract could not support a U.S. scientist other than paying travel expenses for the annual meetings. Regardless, I agreed for four primary reasons: (1) the EU data would be sufficient to solve the GLODAP data problem in the North Atlantic and Greenland-Norwegian Seas areas, (2) it was a mechanism by which the NOAA science team could acquire early research rights to a significant body of new data, (3) it seemed that the required work would be manageable and (4) it was an ideal way to build ties between the EU and US ocean carbon communities. By this time it was obvious that the US alone could not afford to generate the volume of data required to answer the scientific questions asked by CLIVAR and NOAA research goals, so the fourth reason above was critical.

Progress with the CARINA collection was steady until the group met in Iceland in July 2006. The primary reason for this workshop was to transfer GLODAP experience on secondary QC to the EU scientists. By this time the CARINA cruise list had grown to 89. This was the first CARINA meeting attended by other NOAA science team members (Sabine, Feely, Wanninkhof & Kozyr). Also attending were prominent Japanese ocean carbon scientists. By the end of the meeting the scope of CARINA had grown significantly. Rather than being a pure EU data set focused on the northern North Atlantic, CARINA would be 3 collections: the Arctic and its marginal seas, the Atlantic, and the entire Southern Ocean. Additionally, the collection would include all US and Japanese data in these 3 regions that had been generated since WOCE. Over
the next six months the inflow of new cruise data exploded. The increase was partly due to the expanded scope, but mostly due to the fact that CARBOOCEAN is a contract rather than a grant and has deadlines that are strictly enforced. Including the US data wasn’t a problem because these cruises had already been added to the Princeton holdings as part of the funded NOAA science team work. Also, adding the Japanese data was relatively easy because the number of cruises they had in the Southern Ocean was small and the data files were in excellent condition, only needing reformat and primary QC in most cases. One year later when the CARINA group met the cruise total was up to 160+ and this number does not include the US cruises. The final number will be about 175 cruises none of which were in GLODAP and very few of which had previously been available to the scientific community.

Accumulating high quality data from 175 cruises which had previously been available only to the original PIs is clear indication that this effort has been successful beyond any expectation. The inflow of about 100 partial data sets in less than a year also meant that the workload required to complete the accumulation, do QC, etc. was no longer manageable – in fact it wasn’t possible given the CARBOOCEAN deadlines. This became obvious shortly after the Iceland meeting and additional NOAA funding was requested via a new proposal. This proposal was ranked highly and was funded in full. Xiaohua Lin was immediately hired to help with the data processing.

As of now all of the EU and Japanese cruises that will be included in CARINA have been processed, critical missing parameters accumulated and merged, primary QC completed, metadata acquired and summarized, and the individual data sets distributed to the CARINA working groups. All US CLIVAR cruise data is again being updated (earlier versions already distributed). Over the next year the CARINA data work will be completed. In June the working groups will meet in Paris to finalize the secondary data quality decisions.

Publications:

Talks: Many more given by other PIs are not listed


Rodgers, K. A. Gnanadesikan, R. Key and J.L. Sarmiento, Altimetry helps to explain patchy changes in Repeat Hydrography carbon measurements, Gijon, Spain, June, 2008.
Key, R.M. and A. Kozyr, Ocean carbon dioxide: Observations, data management and data synthesis projects, SCAR/IASC Polar Research - Arctic and Antarctic Perspectives in the International Polar Year, St. Petersburg, Russia, 7/8-11/08.


Key, R.M., 20 years after WOCE: What we’ve learned from radiocarbon, Plenary talk, AMS-11, Rome, Italy, 2008.
**Progress Report:** Development Of Lm3 Land Model

**Principal Investigator:** Sergey Malyshev, Elena Shevliakova, P. C. D. Milly

**Other Participating Researchers:** Krista A. Dunne, Kirsten Findell

**Theme #2:** Biogeochemistry and also contributes to:

**Theme #1:** Earth System Studies/Climate Research

**NOAA’s Goal #2:** Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

**Objectives:** To design and implement an advanced land surface and dynamic vegetation model to enhance the ability to simulate Earth climate system, including biological and carbon cycle.

**Methods and Results/Accomplishments:**

Sergey Malyshev, in collaboration with Chris Milly, Elena Shevliakova, Krista Dunne and Kirsten Findell has implemented a subsequent release of the next version of the land model LM3. The model is a descendent of the two models extensively used in previous research at GFDL, LM2 (Milly and Shmakin, 2002, Delworth et al., 2006) and LM3V (Shevliakova et al., 2007, Malyshev et al., 2008), and combines major features of both, but also adds features that aren’t present in either of the ancestors.

Compared to LM2, one of the characteristic features of LM3 is a mechanistic model of stomatal conductance and photosynthesis that introduces realistic stomatal control on transpiration and carbon uptake by the vegetation, similar to LM3V. The model includes comprehensive representation of vegetation and canopy air physics, including exchanges of water and energy between ground surface, canopy, canopy air, and atmosphere.

An important feature of LM3 that distinguishes it from its ancestors LM2 and LM3V is the capability to represent vertically-resolved hydrological processes within soil and snow pack, including the vertical transport of liquid water and phase changes.

LM3 includes representation of surface heterogeneity that goes beyond the capabilities of the previous models. While it uses traditional tile-based approach to the sub-grid-cell variability of surface properties, the number of tiles per grid cell is not limited by model design, nor severe model performance considerations. Moreover, it is possible for different kinds of tiles to have totally different surface parameterizations and sub-models associated with them, opening a possibility to implement comprehensive representation of special kinds of surfaces, such as, for example, lakes. LM3 includes new comprehensive high-resolution model of river transport of water, heat, and other substances.

LM3 is currently used as the standard land component of the next-generation GFDL’s atmospheric model, AM3. It has been extensively exercised in the course of AM3 development and the results were examined from various points of view. These results are generally consistent with those obtained with traditional LM2; however, there are some improvements, in particular in the tropical precipitation, probably associated with more detailed representation of canopy processes.

Over the course of the year, the vegetation dynamics has been implemented in the LM3 framework. It is currently undergoing testing and tuning under the leadership of Elena Shevliakova and Sergey Malyshev.

A capability to run LM3 surface physics and dynamic vegetation on irregular grids has been recently implemented. This feature is important for applications where the atmosphere uses so-called “cubic sphere” mosaic grid: while the GFDL’s Flexible Modeling System (FMS) allows to mix-and-match different grids on the atmospheric and the surface side, for the sake of numerical
efficiency and consistency the land model should be able to run on the same grid. With the “cubic sphere” atmospheric dynamical core gradually becoming the standard in the GFDL’s models, this capability is indeed necessary. A number of simulation has been performed to examine the influence of the land model grid on the simulated climate with the same atmosphere, with both AM2p14 (Anderson et al., 2004, Delworth et al., 2006) and AM3 configuration. The results indicate that the difference between atmospheric and land grids doesn’t have overwhelming effect; however there are places where the grid inconsistency leads to perceptible changes in near-surface climate, in particular in winter time in high latitudes of Eurasia and North America.

Land Model Development Team in general, and Sergey Malyshev in particular, continue to collaborate closely and actively with GFDL’s Atmospheric Model Development Team to address the issues that become apparent in the results of the AM3 simulations.

References:


**Progress Report:** Altimetry Helps To Explain Patchy Changes In Hydrographic Carbon Measurements

**Principal Investigator:** Keith B. Rodgers

**Other Participating Researchers:** Jorge Sarmiento (AOS), Robert Key (AOS), Anand Gnanadesikan (GFDL)

**Theme #2:** Biogeochemistry

**NOAA’s Goal #2:** Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

**Objectives:** An important objective of carbon cycle research is to identify the rate at which anthropogenic carbon is absorbed by the ocean. To this end, the CLIVAR CO2 Repeat Hydrography Program is designed to build on the success developed through the WOCE program for quantifying ocean carbon uptake. However, interpreting measurements collected through the CLIVAR sampling has proven to be difficult, as anthropogenic changes are in many regions smaller than the natural background variability of carbon. The main goal of this work is to use models to improve the empirical detection methods that are used to interpret repeat carbon measurements.

**Methods and Results/Accomplishments:**

Observations and five models have been used to evaluate the relative amplitudes of natural variability and the anthropogenic perturbation in dissolved inorganic carbon (DIC) over the upper ocean. There are three main results to the research conducted thus far. First, the amplitude of the natural variability of column inventories of DIC on seasonal to interannual timescales is of the same order of magnitude as the anthropogenic transient as it changes over a decade. Second, the latitude/longitude pattern of natural variability is distinct from what is found for the decadal changes in anthropogenic DIC inventories. Third, that dynamically-driven variability constitutes at least a first-order component of the total background variability for DIC inventories. In particular, we wish to emphasize that convergence and divergence (column stretching) through the action of Rossby waves can redistribute DIC horizontally in a coherent and persistent way.

Importantly, observations and models indicate that for many regions of the ocean DIC inventory variations on seasonal to interannual timescales are closely related to variability in sea surface height (SSH), which itself reflects variations in the column inventory of density. A notable exception is the well-ventilated North Atlantic, where dynamical variations are not reflected in DIC inventory variations. The implications for the detection of anthropogenic DIC using Repeat Hydrography measurements are currently being investigated.

**Publications:**

Progress Report: A Wintertime Uptake Window for Anthropogenic Co2 in the North Pacific

Principal Investigator: Keith Rodgers (Princeton Research Staff)

Other Participating Researchers: Jorge Sarmiento (Princeton), Olivier Aumont (IRD, France), Cyril Crevoisier (Princeton), Clement de Boyer Montegut (FRCGC, Japan), and Nicolas Metzl (LOCEAN, France)

Theme #2: Biogeochemistry

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: The goal of this modeling study is to identify the pathways and timescales relevant to the uptake of anthropogenic CO2 over the North Pacific.

Methods and Results/Accomplishments:

An ocean model was forced with NCEP reanalysis fluxes over 1948-2003 to evaluate the pathways and timescales associated with the uptake of anthropogenic CO2 over the North Pacific. The model revealed that there are two principal regions of uptake, the first in the region bounded by 35-45°N and 140-180°E, and the second along a band between 10-20°N and between 120°W and 180°E. For both of these regions, the dominant timescale of variability in uptake is seasonal, with maximum uptake occurring during winter and uptake being close to zero or slightly negative during summer when integrated over the basin. A decadal trend toward increased uptake of anthropogenic CO2 consists largely of modulations of the uptake maximum in winter. For detection of anthropogenic changes, this implies that in situ measurements will need to resolve the seasonal cycle in order to capture decadal trends in pCO2. As uptake of anthropogenic CO2 occurs preferentially during winter, observationally based estimates which do not resolve the full seasonal cycle may result in underestimates of the rate of uptake of anthropogenic CO2. There is also a sizable circulation-driven decadal trend in the seasonal cycle of sea surface delta-pCO2 for the North Pacific, with maximum changes found near the boundary separating the subtropical and subpolar gyres in western and central regions of the basin. These changes are due to a trend in the large-scale circulation of the gyres, which itself is driven by a trend in the wind stress over the basin scale. This trend in the three-dimensional circulation is more important than the local trend in mixed layer depth (MLD) in contributing to the decadal trend in delta-pCO2.

Publications:

Progress Report: Decadal Variations in Equatorial Pacific Ecosystems and Ferrocline/Pycnocline Decoupling

Principal Investigator: Keith Rodgers (Princeton Research Staff)

Other Participating Researchers: Olivier Aumont (IRD, France), Christophe Menkes (IRD, France), Thomas Gorgues (U. Washington)

Theme #2: Biogeochemistry

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond

Objectives: An ocean model has been used to investigate the dynamical mechanisms which may underly decadal variability in ecosystems for the Equatorial Pacific.

Methods and Results/Accomplishments:

The equatorial Pacific Ocean is known for its large interannual to decadal variability in circulation. In particular, the changes that occurred in 1976/77 have received considerable attention in the climate dynamics literature, and recently there has been much attention focused on changes that may have occurred there in 1997/1998. Unfortunately, because of data sparsity, the impact of these changes or shifts on ocean biogeochemistry and ecosystems remains largely unknown. A three-dimensional ocean circulation model (the ORCA2 configuration of OPA) which has a food web/biogeochemistry model (PISCES) imbedded in it, and which has been forced with both NCEP-1 and ERA-40 reanalysis fluxes over multiple decades, has been used as a tool to investigate decadal changes and their associated mechanisms. Our main finding with the model was that a decrease in the amplitude of the surface zonal wind stress in the tropical Pacific in the mid-to-late-1970s leads to a decrease in Fe and Chl concentrations in the upwelling regions of the eastern equatorial Pacific after 1976/77. These changes find expression predominantly during the upwelling season (the seasonal maximum for Fe and Chl concentrations), when surface Fe and Chl concentrations tend to be significantly higher pre-1976/1977 than post-1976/1977. The changes in Chl concentrations need to be understood as modulations of the amplitude of the seasonal cycle, rather than as a “biological regime shift” (an abrupt transition from one mean state to another). In contrast to what is found for Fe and Chl, for NO3 the decadal changes in surface concentrations in the upwelling region about 1976/1977 can be described as a shift in the mean state. It was shown that the response in surface Fe and Chl in the upwelling region about 1976/1977 is proportionally larger than the decadal changes in surface wind stress forcing, and it is also larger than the previously reported change in the strength of the meridional overturning strength of the subtropical cells (STCs). Importantly, this amplified response reflects a decoupling of the ferrocline and pycnocline within the equatorial Pacific. In this way, the presence of a time-invariant sediment source for Fe can substantially amplify the ecosystem response to decadal variability in ocean circulation.

Publications:
Progress Report: Global Patterns in Mesozooplankton Production

Principal Investigator: Charles Stock (Associate Research Scholar, Princeton University)

Other Participating Researchers: John Dunne (GFDL), Kelly Kearney (Princeton)

Theme #2: Biogeochemistry

NOAA’s Goal #1: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (50%)

NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (50%)

Objectives: 1. Develop a biogeochemical model that includes explicit zooplankton dynamics and bacterial dynamics, 2. Use this model and observations to understand global patterns in the flow of primary production to higher trophic levels (e.g., fisheries) 3. Implement zooplankton dynamics into the GFDL's biogeochemical model TOPAZ to study the impact of global warming on the energy flow to higher trophic levels.

Methods and Results/Accomplishments:

A simple ecosystem model was developed as a first step toward explicitly linking ocean biogeochemistry and fisheries (Fig. 1). The nutrient, phytoplankton and detritus dynamics in this model are simplified versions of the dynamics used in TOPAZ, which is the GFDL's full biogeochemical model. Explicit bacterial and zooplankton have been added to provide a more fully resolved picture of the energy flow through the ecosystem - particularly between primary producers and fish. Fish enter the present model as a simple loss term, but we have been working closely with CICs researchers Kelly Kearney and Jorge Sarmiento to link this model to an explicit model of fisheries dynamics (see the Kearney's progress report "Developing an upper trophic level model with climate forcing").

The simple model in Figure 1 has been used to explore global patterns in the ratio of mesozooplankton production to primary production as a step toward understanding the ratio of fisheries production to primary production. To validate the model, we have used a global compilation of ecosystem observations constructed previously by CICS researchers (Dunne et al., 2005), as well as the National Marine Fisheries Service's Global Copepod Database (O'Brien, 2005) This work is presently described in a detailed manuscript that has been submitted for peer review. Results suggest that the ratio of mesozooplankton production to primary production varies from ~1-3% in oligotrophic, unproductive regions, to ~10% in highly productive regions (Fig. 2). The mechanisms that underlie these patterns are related to shift toward primary production by larger phytoplankton in more productive systems accompanied by zooplankton consumption rates that are much greater than basal metabolic costs.

We are presently beginning the process of implementing the zooplankton dynamics in Fig. 1 into the GFDL's biogeochemical model, TOPAZ. This work is still in its early stages, but once it is completed it will allow us to assess how the flow of primary production through mesozooplankton to fish will be influenced by global warming, which is a key uncertainty for understanding the impact of climate change on fish production (Brander, 2007).

References:


Publications:
Stock, CA, Dunne, JP. Controls of the ratio of mesozooplankton production to primary production in marine ecosystems. To be submitted to Progress in Oceanography, 50 pages.

Figure 1: A simple ecosystem model developed to link primary production to fish. N = nutrients, SP and LP = small and large phytoplankton, SZ and LZ = small and large zooplankton, B = bacteria, LD = large detritus, SD-S and SD-L = semi-labile and labile small detritus. Fish enter as a loss term on LZ. Explicit models for fisheries are being developed (see Kearney progress report).

Fig. 2: The modeled ratio of mesozooplankton (LZ) production to primary production as a function of primary production (abscissa) and temperature (ordinate). This “z-ratio” is a measure of the efficiency with which primary production is passed up the food chain where it is available to fish. Note that there is a systematic increase in efficiency as primary production increases.
Progress Report: Continued Development of a Freshwater Biogeochemical Model for the Princeton/GFDL Earth System Model

Principal Investigator: Charles Vörösmarty (Research Professor, University of New Hampshire)

Other Participating Researchers: Wilfred Wollheim (UNH), Balazs Fekete (UNH)

Theme #2: Biogeochemistry

NOAA’s Goal #1: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (40%)
NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (40%)
NOAA’s Goal #3: Serve Society’s Needs for Weather and Water Information (20%)

Objectives: To continue development and refinement of a process-based freshwater carbon and biogeochemical model for the GFDL Earth System Model that incorporates the role of inland aquatic ecosystems in regulating material fluxes.

Methods and Results/Accomplishments:

During the past year we developed several capabilities for modeling freshwater aquatic processes at global scales, and worked closely with Chris Milly to implement certain components into the GFDL Earth System Model. We:

1) Published two papers that describe the role of aquatic systems in controlling nitrogen fluxes a) globally at mean annual time scales (Wollheim et al. 2008b), and b) at watershed scales when accounting for temporal variability in flow and processing rates (Wollheim et al. 2008a). The global analysis quantified the relative contribution of small rivers, large rivers, lakes and reservoirs in the global N cycle under mean annual conditions and will help to inform/prioritize future aquatic biogeochemical modeling in the GFDL ESM. The watershed scale work (Wollheim et al. 2008a) identified the constraints of aquatic control of N fluxes imposed by hydrologic variability. This latter analysis was the basis of a model experiment implemented within the GFDL model in coordination with Chris Milly (see below).

2) We implemented a nutrient removal algorithm to explore how hydrologic variability at global scales influences nutrient fluxes and aquatic processing. This work resulted in a poster presented at AGU in December 2007 (Wollheim et al. 2007). The analysis accounted for a) point and non-point source inputs to aquatic systems in contemporary and pre-industrial settings (based on Green et al. 2004), b) two scenarios of aquatic N removal kinetics, including one with the assumption linear denitrification rates as a function of nitrate concentration and one with the non-linear rates recently reported by Mulholland et al. (2008). Data sets and algorithms were provided by UNH, and the removal function was coded into the LM2 by Chris Milly. Milly executed the model using the GFDL AM2/LM2 16 yr run (1980-1996). Results were analyzed and summarized by UNH. Predicted concentrations roughly matched those observed for the linear model, but the non-linear model showed much greater seasonal swings than observed (Figure 1). Further analysis suggested that model predicted discharge is too low during summers, which leads to extreme response of nitrate concentration. Although unrealistic in the current climate regime, it suggests possible responses under future climate change with increasing droughts. This dynamic is currently being further investigated in more detail by UNH. Results indicate global N removal efficiency has declined by 50% between pre-industrial and contemporary time frames.
Figure 1. Monthly DIN concentration at the mouth of the Mississippi assuming conservative mixing (cD), process saturation (D), and 1st order kinetics (1D), with observed values.

3) UNH has begun to develop algorithms in its modeling environment (FrAMES, Wollheim et al. 2008b) to route multiple constituents simultaneously, allowing linkages across biogeochemical cycles (C,N,P) and among multiple N forms (NH4, NO3, DON). The implementation of the carbon model is being conducted in this environment, and as it matures will be transferred to the GFDL code. The carbon model under development accounts for particulate and dissolved organic carbon inputs from land, and their fate in the fluvial network. Particulate inputs will be a function of leaf litter inputs and phenology, while DOC will be a function of wetland distribution, land use, and runoff characteristics. Removal processes will be a function of temperature and hydraulic conditions within the river network. A water temperature routing module was recently developed in FrAMES to allow testing of temperature related respiration functions.

4) GWSP/GRAND. Working within the context of the Global Water System Project, the CICS research team facilitated a multi-investigator activity to produce a state-of-the-art Global Reservoirs And Dams (GRAND) data base, with several thousand individual geo-referenced entries. Work continued this year on the GRAND impoundment data set, in conjunction with McGill U. (B. Lehner). The first version Global Reservoir and Dam (GRanD) Database was completed in June consolidating several previously developed data sets in a unified database. GRanD is linked to HydroSHEDS high resolution gridded network and Shuttle Water Body Database. This is probably world's largest single data compendium on impoundments and is currently being used in the GWSP State of the Global Water System prototype study. This first version of GRanD was aimed to catalog reservoirs exceeding 0.1 km$^3$ capacity, but numerous smaller reservoirs between 0.01 - 0.1 km$^3$ capacity were also included. The database consist of 7000 reservoir entries with 5500 km$^3$ cumulative capacity, which is less than previous estimates of the reservoirs in the same size range due to the removal of duplicate entries. Currently, members of the international data development team (including UNH) are testing GRanD, which will be publicly available by the end of 2008.

5) River Network and channel hydraulics. The long awaited HydroSHEDS high resolution gridded network is nearing completion. Africa, Asia, Australia and South America are complete. Europe and North America are almost finished and test versions of these continents were made available to the UNH team by the developers at McGill University. The data set is available in 15 and 30 arc second spatial resolution (approx. 500 m and 1 km). The 15" resolution turned out to
be too big for our hydrology oriented GIS software RiverGIS (part of the Global Hydrological Archive and Analysis System developed at UNH). But the coarser resolution version at 30" is still manageable continent by continents allowing us to upscale HydroSHEDS to coarser resolutions more suitable to continental or global scale applications. We already used HydroSHEDS to rescale Australia and merge the regridded HydroSHEDS with our experimental 6-minute network which was derived from HYDRO1k at a time when Australia was not completed. According to our first tests HydroSHEDS is indeed have a very high quality and will provide excellent basis for derivation of river networks at coarser resolutions. We tested the impacts of network resolution on flow routing by applying Muskingum type routing on 3, 15, 30 minute and 1 degree resolutions and found that the flow routing depends on network resolutions but capturing the spatial variation of the runoff generation at the same resolution is not necessary. In other words, operating land surface models at coarse (30 minute to 1 degree) in conjunction with high resolution routing (3-6 minute) is adequate for large basins for daily discharge simulations.

We continued our work on parameterizing flow routing based on river channel considerations. We followed Dingman (2007) by approximating cross-section geometry with power function which is consistent with empirical “at-a-site” relationships. We implemented a Muskingum type routing in our water balance/transport modeling environment, and applied to several watersheds in New England, calibrating the Muskingum coefficients using observed hydrographs. We are using the calibrated coefficients to inverse calculate the river channel parameters (exponent and coefficient of the approximating power function).

References:


Progress Reports:

Coastal Processes
Progress Report: Ecological Forecasting in the Coastal Zone: Transitioning of the Regional Ocean Modeling System to the National Ocean Service

Principal Investigator: Dale B. Haidvogel (Professor, IMCS, Rutgers University)

Other Participating Researchers: Enrique Curchitser (Rutgers), Emmanuel Di Lorenzo (Georgia Tech), Kate Hedstrom (ARSC)

Theme #3: Coastal Processes

NOAA’s Goal #3: Serve Society’s Needs for Weather and Water Information (50%)

NOAA’s Goal #4: Support the Nation’s Commerce with Information for Safe, Efficient, and Environmentally Sound Transportation (50%)

Objectives: The long-term objectives of this activity are: LT1) to develop, to evaluate, and to apply physical and ecological forecasting systems for the coastal ocean suitable for both short-term and longer-term (e.g., climate-scale) applications; and LT2) to transition these capabilities to operational use at the NOAA National Ocean Service.

Methods and Results/Accomplishments:

Activities in AY2007/2008 focused on objective LT2, the transitioning of the ROMS system to NOAA NOS for operational applications to coastal ocean forecasting. The initial target has been an operational forecast system for synoptic time scale forecasts of water levels and currents in U.S. estuaries. Four prediction systems based upon ROMS are now in pre-operational status, undergoing refinement and evaluation. These systems cover: 1) the Chesapeake Bay, 2) The Delaware River and Bay, 3) Tampa Bay, and 4) the South Florida Shelf.

Our partnership with NOAA NOS encompasses several activities: the readying of ROMS for routine operational applications, the training of NOAA personnel on advanced features of the ROMS system, and consultation on the evaluation and improvement of the proto-type regional forecasting systems. A 3-day training workshop was held in May 2008 at NOAA NOS in Silver Spring MD. The lead Workshop personnel this year included Drs. Haidvogel, Curchitser, Di Lorenzo and Hedstrom. The Workshop agenda included a comprehensive review of the status of the four regional coastal forecast systems, training on the ROMS Numerical Toolbox (RNT), and presentations on several advanced ROMS features (e.g., wetting/drying, data assimilation, etc.).

Publications:

2007-2008 CICS Publications

Peer Reviewed:


Chapters in Books:


Non-Peer Reviewed:


Key, R.M. and A. Kozyr, Ocean carbon dioxide: Observations, data management and data synthesis projects, SCAR/IASC Polar Research - Arctic and Antarctic Perspectives in the International Polar Year, St. Petersburg, Russia, 7/8-11/08.

Key, R.M., 20 years after WOCE: What we’ve learned from radiocarbon, Plenary talk, AMS-11, Rome, Italy, 2008.

Magi, B.I., Evaluation of the GFDL GCM simulation of southern hemisphere African aerosol (which is dominated by biomass burning emissions), Informal seminar presentation, NOAA Geophysical Fluid Dynamics Laboratory, February 2008.


Plagge, C., L. P. Chini, S. Frolking, **G. Hurtt** (2008) “Slash and Burn Agriculture: Incorporating Shifting Cultivation into a Global Land Use Model for Earth System Model Applications”, presentation at University of New Hampshire

Plagge, C., L. P. Chini, S. Frolking, **G. Hurtt** (2008) “Slash and Burn Agriculture: Incorporating Shifting Cultivation into a Global Land Use Model for Earth System Model Applications”, presentation at NASA Goddard Spaceflight Center


**Rodgers, K.** A. Gnanadesikan, **R. Key and J.L. Sarmiento**, Altimetry helps to explain patchy changes in Repeat Hydrography carbon measurements, Gijon, Spain, June, 2008.


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<tr>
<th>JI Lead Author</th>
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99
CICS Fellows - Princeton University

The CICS Fellows will be principally responsible for carrying out the research proposed under this project. Fellows will be selected by the Executive Committee of the CICS. The CICS Fellows include senior research staff at GFDL and the following faculty members at Princeton University:

Lars O. Hedin, Professor of Ecology and Evolutionary Biology and Princeton Environmental Institute, a biogeochemist who does research on the terrestrial nitrogen cycle.

Sonya A. Legg, Lecturer of Geosciences and Research Oceanographer in the Program of Atmospheric and Oceanic Science, who does research on turbulent mixing in the ocean, with primary tools being numerical simulation and theory.

Michael Oppenheimer, Albert G. Milbank Professor in Geosciences and International Affairs, Woodrow Wilson School, an atmospheric chemist who does research on the impacts of climate change and also the nitrogen cycle.

Stephen W. Pacala, Frederick D. Petrie Professor in Ecology and Evolutionary Biology, Acting Director of Princeton Environmental Institute, a biogeochemist who does research on the terrestrial carbon cycle and is co-Director of the Carbon Mitigation Initiative of Princeton University.

S. George H. Philander, Knox Taylor Professor in Geosciences, Director of the Program in Atmospheric and Oceanic Sciences, who does research on ocean dynamics and paleoclimate.

Ignacio Rodriguez-Iturbe, Theodora Shelton Pitney Professor in Environmental Sciences, Professor of Civil and Environmental Engineering, who does research on hydrology.

Jorge L. Sarmiento, Professor of Geosciences, Director of CICS, a biogeochemist who does research on the ocean carbon cycle and biological response to climate change.

Daniel M. Sigman, Professor of Geosciences, Dusenbury University Preceptor of Geological and Geophysical Sciences, a biogeochemist who does research on paleoceanography.

Eric F. Wood, Professor of Civil and Environmental Engineering, who does research on hydrology.
ADMINISTRATIVE STAFF

**CICS Director**
Jorge L. Sarmiento  
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Princeton University  
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**CICS Associate Director**
Geoffrey K. Vallis  
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Lecturer with the rank of Professor in Geosciences and Atmospheric and Oceanic Sciences  
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**CICS Administrative and Financial Contact**
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**CICS Administrative Assistant**
Joanne Curcio  
Administrative Assistant, CICS  
Phone: 609-258-6047  
Fax: 609-258-2850  
jcurcio@princeton.edu
Task I: Administrative Activities and Outreach Supported Personnel

<table>
<thead>
<tr>
<th>Name</th>
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<th>Advisor</th>
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<tr>
<td>Curcio, Joanne</td>
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<td>Jackson, Al</td>
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<td>Sarmiento, Jorge L.</td>
<td>CICS Director</td>
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<tr>
<td>Wachtin, Heidi</td>
<td>QUEST Lead Teacher</td>
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Departures - Task II and Task III:

Research Associates/Research Staff
Laura Jackson - 3/21/08 Hadley Centre, MET Office, United Kingdom
Qian (Scott) Song - 9/7/07 Deutsch Bank, New York, NY
Ming Zhao - 11/16/07 University Corporation for Atmospheric Research (UCAR), Boulder, CO

Ph.D. Defenses
Student: Gang Chen  Advisor: Isaac Held - August 1, 2007
Dissertation: Mechanisms that Control the Latitude of Jet Streams Surface Westerlies
Massachusetts Institute of Technology - Postdoctoral Associate

Student: Cynthia Randles  Advisor: V. Ramamswamy - September 7, 2007
Dissertation: Impacts of Carbonaceous Aerosols on Climate: Examination of the Sensitivity of Simulated Regional Climates to Absorbing and Scattering Aerosols
NASA Goddard - Research Scientist
## Task II: Cooperative Research Projects and Education Supported Personnel

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<thead>
<tr>
<th>Name</th>
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<td>Anderson, Whit</td>
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### Task III: Individual Projects Supported Personnel

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Ph.D. Defense – Task II: August 1, 2007  
*Student:* Gang Chen  
*Advisor:* Isaac Held  
*Dissertation:* Mechanisms that Control the Latitude of Jet Streams Surface Westerlies  

*Student:* Cynthia Randles  
*Advisor:* V. Ramaswamy  
*Dissertation:* Impacts of Carbonaceous Aerosols on Climate: Examination of the Sensitivity of Simulated Regional Climates to Absorbing and Scattering Aerosols
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<td>Ocean and Atmospheric Inverse Modeling for Global Carbon Flux Determinations (CPO-Task III)</td>
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<td>$ 184,614</td>
<td>Stephen W. Pacala</td>
<td>Development of Carbon Sink Models (Task III)</td>
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<td>$ 159,575</td>
<td>Robert M. Key</td>
<td>Global Carbon Data Management and Synthesis Project (CPO-Task III)</td>
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<td>George Hurtt (New Hampshire)</td>
<td>Modeling Land Use Changes in the Earth Systems (Task III)</td>
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<td>Charles Vörösmarty (New Hampshire)</td>
<td>Global Methods of Constituent Flux in Continental Aquatic Systems (Task III)</td>
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<td>Kelly Kearney</td>
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<td>Adding nitrogen cycling to the NOAA/GFDL LM3V model (Task III)</td>
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<td>Coarse model development for paleoclimate and biogeochemical Simulations (Task III)</td>
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<td>Keith Rodgers</td>
<td>Characterizing anthropogenic change and natural variability in oceanic DIC and marine ecosystems (Task III)</td>
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<td>Modeling sea-ice-ocean-ecosystem responses to climate changes in the Bering-Chukchi-Beaufort Seas with data assimilation of RUSALCA measurements (CPO-Task III)</td>
</tr>
<tr>
<td>$2,064,462</td>
<td>Jorge L. Sarmiento</td>
<td>Cooperative Research Projects and Education (Task II)</td>
</tr>
</tbody>
</table>

*note: some FY’08 projects were funded with unspent prior year project balances.*