Princeton University

Carbon Mitigation Initiative

Sixth Year Report

February 2007

Capture

Storage

Science

Integration

PEI PRINCETON ENVIRONMENTAL INSTITUTE

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This report is dedicated to the memory of Douglas Jakobsen,
whose beautiful artwork helped define CMI and whose
dedication and good humor will be sorely missed.

May 2, 1965- August 18, 2006

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Overview

The Carbon Mitigation Initiative (CMI) at Princeton University is a university-industry partnership sponsored by BP and Ford Motor Company. The goal of the project is to find solutions to the carbon and climate problem that are safe, effective and affordable. Now entering our 7th year, our researchers are speeding progress in the areas of carbon science, carbon capture, carbon storage, and carbon policy.

The Capture Group assesses technologies for capturing CO_2 emissions from fossil fuels used in electricity, hydrogen, and synfuels production. Other research areas include studies of alternative fuel combustion and analysis of renewable energy.

The Storage Group studies potential risks of injecting CO_2 underground for permanent storage. Models of subsurface carbon dioxide behavior and laboratory studies of well cement degradation are helping the group evaluate that risk.

The Science Group collects data from the oceans, the atmosphere, ice cores, and the land biosphere to study how natural sources and sinks of carbon have varied in recent and ancient times, and how they will respond to future climatic change.

The Integration Group synthesizes research discoveries and explores the policy implications of carbon mitigation strategies. It also works to communicate issues of carbon and climate to industry, government, NGO's and the general public.

Led by CMI Co-Directors Stephen Pacala and Robert Socolow, the group has grown to include over 60 researchers. Together we are building a comprehensive view of the challenges of carbon mitigation - and how they can be overcome.

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Executive Summary

The Carbon Mitigation Initiative (CMI) at Princeton University has concluded its sixth year, which was marked by steady progress on our original goals plus some positive new developments.

Our co-sponsors, BP and Ford, provided welcome news after an extensive review of the Initiative's first 6 years of progress. The two companies renewed the CMI grant for 4 more years, and BP announced that it will also sponsor a "Vann Fellows" program, which will bring one senior executive to campus per year for five years.

More good news came as Co-Director Steve Pacala was appointed the Director of the Princeton Environmental Institute (PEI). Now head of CMI's umbrella institute, Pacala is working with the Woodrow Wilson School and the School of Engineering & Applied Sciences to establish several campus-wide programs ("Grand Challenges") that meld policy with science and technology. Co-Director Rob Socolow will head one of the first two of these programs, which will address energy, climate, and security. Both Co-Directors are also working with colleagues in Near Eastern Studies and Physics to build a new University-wide initiative on energy and the Middle East.

Having developed an arsenal of tools and identified promising pathways toward a low-carbon future, the research groups of CMI are at the forefront of their respective research communities and are interacting strongly with policymakers. The capture group has identified promising gasification energy options and is working to encourage early adoption of carbon capture and storage. The storage group has completed experimental work on brine-cement interaction that is now informing the group's modeling studies of the potential risks of carbon storage. The science group has made substantial progress in developing a Carbon Observing System and estimating carbon sources and sinks, while paleoclimate research shows an increasingly strong relationship between Southern Ocean conditions and glacial-interglacial changes. Finally, the integration group is reaching out to new groups in its outreach efforts while continuing to provide policy-relevant information on the detection of climate thresholds and links between air pollution and global warming.

The following pages document the major research results of the past year and near-term plans. For a comprehensive summary of the CMI program over the first 5 years and blueprint for the future, the 2006 annual report can be downloaded from our website:

http://www.princeton.edu/~cmi/summary/documents/annreport06.pdf

The Capture Group

The Capture group's research over the past year has focused on three primary areas:

(i) Analyses that would help catalyze widespread early action on CCS,

(ii) Development of an integrated approach to bioenergy (giving attention to storage of photosynthetic CO_2 and to high- vs low-intensity approaches to biomass production),

(iii) Understanding better the major competition to gasification energy with CCS in a climate constrained world.

Catalyzing widespread early action

During 2006 activities aimed at early CCS action included: (i) Bob Williams co-authoring a *Scientific American* article on the importance of early CCS action for coal power, (ii) activities by Williams and Eric Larson relating to production of synfuels in Montana with low GHG emissions, (iii) analysis by Williams on the opportunity for early CCS action in Texas using CO_2 from coal/petcoke power plants for enhanced oil recovery, and (iv) Tom Kreutz's participation in the technical experts group advising the FutureGen Industrial Alliance.

Coal Power in the Face of Climate-Change-Mitigation Constraints

For the September 2006 *Scientific American* special issue on Energy's Future Beyond Carbon, Williams co-authored with David Hawkins and Dan Lashof of NRDC the article "What to Do About Coal"—in which they: (i) argued the urgency of moving at the global level to CCS for coal plants, (ii) argued that the capture technology needed to do this is commercially ready and that enough is known about CO_2 storage to begin large-scale commercial CCS projects early in the next decade, (iii) showed that if the CCS infrastructure for coal power could be put into place worldwide by 2050 along with comparably aggressive measures in other sectors, the atmospheric CO_2 concentration could plausibly be stabilized at 450 ppmv, and (iv) argued for a U.S. climate change mitigation policy that complements carbon cap-and-trade with a coal power sectoral policy that would explicitly promote CCS for coal power.

Toward Early Action on Synfuels Production with low GHG emissions in Montana

The Governor of Montana is an advocate of making synfuels from coal using Montana's abundant low cost coal resources. In March 2006 the Governor and Williams were interviewed on *60 Minutes* about the Governor's vision, and in November Williams and Larson had an opportunity to meet with the Governor in the State's Capitol to discuss how this vision could be made climate friendly both by pursuing CCS and by coprocessing coal and biomass. In his presentation to the Governor, Williams pointed out that: (i) without CCS the GHG emission rate for synfuels would be ~ 80% more than for crude oil-derived fuels (see Figure 1); (ii) with CCS the emission rate could be reduced to about the level of crude oil-derived fuels (see Figure 1); (iii) CO_2 capture is cheap (in $/t CO2) for plants making synfuels (~ ½ and ~ ¼ of the capture cost for coal IGCC and coal steam-electric power plants, respectively), (iv) at current and prospective high oil prices it would often be cost-effective to use this low-cost CO_2 for enhanced oil recovery (EOR) even without a climate change mitigation policy in place, (v) the synfuel GHG emission rate with CCS could be further reduced significantly by gasifying with the coal modest amounts of biomass in the form of Montana's crop and forest industry residues, exploiting the negative GHG emissions potential of photosynthetic CO_2 storage, (vi) there is commercial experience with co-gasification of biomass with coal at modest biomass input levels, and (vii) coprocessing residues and coal with CO_2 capture and use for EOR is likely be able to provide synfuels at competitive prices while significantly adding to rural incomes in Montana. Before the November meeting the Governor he had already decided that he would insist on CCS for coal synfuels plants. Since the meeting he has focused attention on the coal/biomass co-processing idea in at least two major speeches.

Toward Early CCS Action for Coal Power in Texas

There are proposals to build many new power plants fueled with low-rank coals in Texas, including 9 GW_e that TXU wants to build before 2010—plans for which the Texas Governor is putting on a "Fast Track" for approval but which are encountering widespread opposition. Williams has carried out an analysis showing that the surge in demand for new coal power presents an opportunity for early CCS action by recovering CO_2 at new power plants for EOR in Texas, which accounts for about 35% of the ~ 50 billion barrel economic U.S. EOR expansion potential identified in studies for the US Department of Energy by Advanced Resources International—the exploitation of which, according to ARI, is constrained mainly by the availability of low cost CO_2. Williams' analysis shows that if new power plants were built to operate not on low-rank coal but on a blend of such coal and fuel-grade petcoke (which is abundantly available in Gulf Coast states) CO_2 capture at new power plants and use for EOR would probably be profitable to EOR producers while simultaneously reducing rates to electricity consumers, and that via this strategy the long-term decline in Texas oil production could be reversed for an extended period. But he identified major institutional obstacles to seizing this opportunity and proposed policies for overcoming these obstacles.

FutureGen "Surface" Technical Experts Group

Tom Kreutz participated as one of ten technical experts to advise the FutureGen Industrial Alliance in determining the final plant configuration of FutureGen, the U.S. government's $1 billion flagship demonstration project that will convert coal to hydrogen and electric power with CO_2 capture and storage in underground saline aquifers. The Technical Experts Group (TEG) met on three separate occasions in 2006 to discuss how many competing program goals might be best achieved using various combinations of cutting edge and commercially available technologies. The group heard presentations from technology vendors and debated the merits of numerous plant configurations. Ultimately, each group member provided quantitative assessments of 10 separate characteristics in each of 27 different plant configurations. This information was used by the Alliance in formulating the final design of FutureGen.

Integrated approach to bioenergy

Our bioenergy activities include: (i) completion of studies on production of fuels and electricity from switchgrass and from switchgrass + coal, (ii) launching an activity to explore system implications of using mixed prairie grasses instead of switchgrass in making energy with coal, and (iii) launching a new activity exploring prospects for co-processing with coal for energy crop residues and mixed prairie grasses on degraded grasslands in China.

Making Fuels and Electricity from Switchgrass and from Switchgrass + Coal

Major findings of studies modeling polygeneration systems based on switchgrass (led by Larson) and coal + biomass (led by Williams) are:

Systems using only switchgrass with either CO_2 vented or CCS would not be economically interesting if the value of GHG emissions were zero but would often be economically attractive if GHG emissions were valued at $100/t$C_{equiv}$. At $100/t$C_{equiv}$ the CCS options would often be more economically attractive than the systems that vent CO_2.

Systems with CCS using coal + modest amounts of switchgrass (separately gasified): (i) exploit simultaneously the low cost of coal, scale economies of coal conversion, and the negative emissions potential of photosynthetic CO_2 storage; (ii) could be characterized by GHG emission rates for synfuels that are significantly less than either for coal synfuels with CCS or hydrocarbon fuels derived from crude oil (see, for example, option 5 in Figure 1); (iii) would not be economically interesting if the value of GHG emissions were zero; (iv) would often be more economically attractive than coal-based synfuels with either CO_2 vented or CO_2 stored if GHG emissions were valued at $100/t$C_{equiv}$.

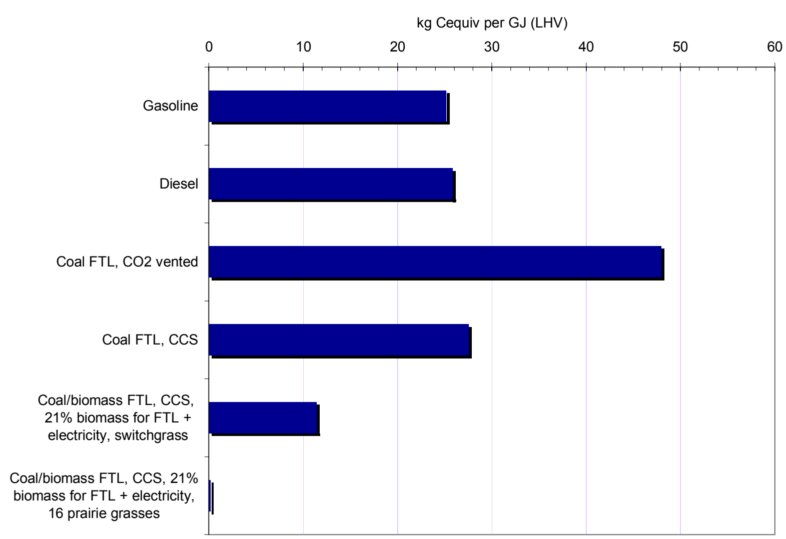

Figure 1. "Well to Wheels" GHG Emissions per GJ of Liquid Fuel for Alternative Options.
In comparing F-T liquids to crude oil-derived fuels (first two options), the third and fourth options use coal, with CO_2 vented and captured/stored, respectively. The sixth option adds enough biomass to realize net zero GHG-emissions (coal emissions are offset by negative CO_2 emissions both from underground storage of photosynthetic CO_2 and soil/root carbon buildup from planting mixed prairies grasses on carbon-depleted soils). The fifth option has the same biomass input fraction as the sixth but uses switchgrass (with no soil/root carbon buildup).

All technological elements for energy conversion are ready for deployment except the biomass gasifier—which could become commercial during 2010-2015. Early applications of these concepts are likely to be based on agriculture or forest industry residues and use of a single gasifier for coal plus a modest amount of biomass. There has already been considerable experience at one commercial facility co-gasifying biomass with coal.

Systems Implications of Using Coal/Mixed Prairie Grasses Rather Than Coal/Switchgrass

A new activity (led by Williams and Larson) has begun exploring the implications of producing synfuels + electricity from mixed prairie grasses grown via low-intensity techniques on carbon-depleted soils (as proposed in a 2006 *Science* article by David Tilman and collaborators) rather from a monoculture crop (e.g., switchgrass). The prairie grass strategy would help address biodiversity loss concerns while significantly increasing the negative emissions potential of biomass by complementing geological storage of photosynthetic CO_2 (described above) with root and soil carbon buildup during grass growing. Some preliminary findings (not yet published) are: (i) for a system fired with coal and mixed prairie grasses with the same biomass fraction of total fuel input and producing the same outputs as the switchgrass case discussed above, the net lifecycle GHG emission for F-T liquids would be reduced to zero (see Figure 1), (ii) the biomass required to produce a net zero GHG-emitting liquid fuel in this manner is ~ 1/3 of that required for making cellulosic ethanol (see Figure 2), and (iii) assuming a crude oil price of \$50 a barrel and a \$100/tC_{equiv} value of GHG emissions, it would be economically worthwhile for an Iowa corn grower to instead grow mixed prairie grasses for making F-T liquids in combination with coal.

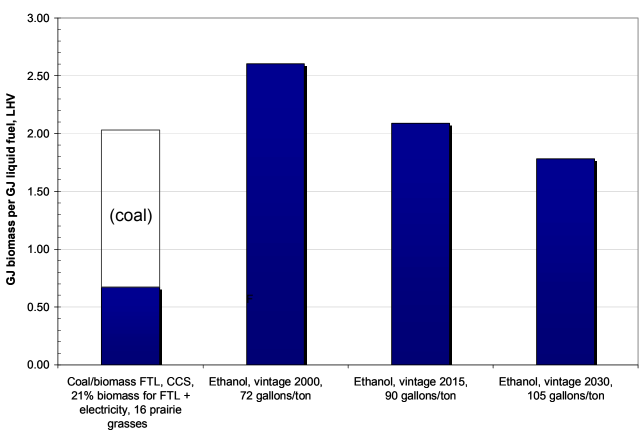

Figure 2. Biomass Required to Make 1 GJ of Liquid Fuel Using Alternative Technologies.
The bar on the left is for the zero net GHG emissions coal/biomass F-T liquids case described in the note to Figure 1. (The coal input is also indicated.) The other cases are estimates for cellulosic ethanol with three alternative vintages of the conversion technology.

Prospects for Co-processing Coal and Biomass for Energy in China

Plans have been announced for building many coal synfuels plants in China. Although it seems that there are no plans for including CCS at these plants, the capture group intends to explore CCS prospects at coal synfuels plants as well as at coal power plants in China over the remaining period of the CMI project. The group also intends to explore prospects for co-processing biomass with coal in making synfuels in China—considering as feedstocks both crop residues and mixed prairie grasses. Although China is generally not considered rich with biomass resources, the coal/biomass strategy (discussed above) enables biomass resources to be used far more effectively for low-carbon fuels production than with conventional biofuels strategies (see Figure 2). Articulating the overall strategy and policy issues related to its implementation will be the focus of the PhD thesis of Yuan Xu, a Woodrow Wilson School graduate student being co-supervised by Socolow and Williams.

Cathy Kunkel (a 2006 Princeton physics grad) is spending this academic year in Li Zheng's group at Tsinghua University (Beijing) doing exploratory work on the prospects for co-processing both crop residues (for all of China) and prairie grasses (in Inner Mongolia) with coal in the making of synfuels. What she has learned so far, considered in the context of the coal/biomass co-processing models the capture group has developed, indicates that neither of these options for China should be dismissed out-of-hand. China produces substantial amounts of crop residues (of which some 360 million tonnes per year seem to be available for energy). Moreover, grasslands account for about 40% of China's land area—much of which is heavily degraded and the restoration of which is a high political priority in China. Moreover, although yields on restored grasslands in Inner Mongolia (the focus of Kunkel's research) are low (~ 1.5 tonnes per hectare per year) our preliminary calculations suggest attractive economics for farmers growing grasses for energy relative to what they are doing with the land at present—if the oil price is ~ $50 a barrel and the value of GHG emissions is ~ $100/tC$_{equiv}$.

Understanding the Competition to Gasification Energy with CCS

During 2006 our research exploring the competition to gasification with CCS was focused on: (i) understanding the market competition between baseload wind power and baseload coal power, and (ii) getting a better understanding of compressed air energy storage.

Baseload Wind Power vs. Baseload Coal Power

During 2006 we focused our energy systems analysis for wind/compressed air energy storage (wind/CAES) systems on the competition in baseload power.markets between wind/CAES systems and coal power systems, considering for the latter both coal integrated gasifier combined cycle (IGCC) plants with CCS and coal IGCC plants with CO_2 vented. We found that the GHG emission rate of a baseload wind/CAES unit fired with natural gas would be ~ 1/10 of that for a coal IGCC with CO_2 vented or ~ ½ of that for a coal IGCC with CCS. We also found that although wind/CAES cannot come close to competing with today's new coal power plants in the absence of a climate change mitigation policy, its levelized generation cost (in $/MWh) would be very close to that for coal power in the presence of price on GHG emissions of about $100//tC$_{equiv}$—a benchmark emissions price that is about the minimum needed to induce a power generator by market forces to build a coal plant with CO_2 capture and storage instead of a plant with CO_2 vented (assuming that all power plants operate at the same "baseload" capacity factor of 85%).

In a real power market, capacity factors cannot be specified at a fixed value but rather are determined by market forces to reflect the relative dispatch costs (short-run marginal costs—i.e., fuel costs plus costs for GHG emissions plus variable operation and maintenance costs) of the competing options on the electric power grid. For a given set of power generating systems connected to the grid, the grid operator determines the capacity factors of these systems by calling first on the system with the least dispatch cost. Under this condition, deployment in sufficient quantity of the technology with the least dispatch cost can lead to a reduction of the capacity factors and thus an increase in the levelized generation cost of the competing options on the grid. Our research found that the wind/CAES option would have a lower dispatch cost than the coal options ~ 75% of the time and more than 90% of the time when the value of GHG emissions is $0/tC$_{equiv}$ and $100/tC$_{equiv}$, respectively. Thus adding more and more wind/CAES to the power grid would lead to lower and lower capacity factors for all the competing options—thus driving up the levelized generation costs for the coal power options.

Notably, the wind/CAES option enables both wind and natural gas to compete in baseload power markets in a climate change constrained world. The intermittency of wind makes it impossible for a "pure" wind system to provide baseload power. Moreover, high natural gas prices exclude natural gas combined cycle power technology from providing baseload power wherever there is a substantial amount of coal power on the grid. But coupling wind to CAES makes it possible for wind to deliver firm power. And the use of wind to provide compressor energy for CAES enables natural gas to be burned at low enough heat rates in CAES units to be competitive with coal in economic dispatch.

CAES Technology

The extent of the wind/CAES opportunity in mitigating climate change depends on the availability of suitable geologies for CAES. To better understand the issues involved, the group carried out an assessment of CAES technology for potential applications that include, but are not restricted to, wind/CAES. A draft final report on this assessment is nearing completion. The report discusses both the turbomachinery of CAES (essentially a gas turbine in which the compressor and expander functions are separated in time) and the geologies of underground air storage.

The major CAES storage options are mined hard rock (including abandoned existing mines), aquifers, and salt (salt domes or bedded salt). The only commercial plants have used salt domes but the world's first wind/CAES plant—plans for construction of which were announced in late 2006—will use aquifer storage. The CAES report gives focused attention to aquifer storage because it is the dominant geological storage option in most US regions where the good wind resources are located. Earlier assessments of CAES have suggested that aquifers are likely to be available in most wind-rich regions of the US. Moreover, although there is little experience with storing air in aquifers, there is extensive industrial experience with aquifer storage of natural gas.

However, our report points out that the true US CAES potential for aquifers cannot be determined without doing detailed studies of different aquifer types—giving focused attention to the implications of air storage. Most experience with natural gas storage relates to seasonal storage, whereas CAES coupled to wind would be characterized by charge/discharge cycles of the order of a day rather than a season. Moreover, air has physical and chemical properties that are different from natural gas (including the fact that storing air introduces oxygen underground that can lead to a wide range of chemical reactions and the introduction of aerobic bacteria) that imply rates of injection and recovery that are not only different from those for natural gas but also which can change over time as a result of chemical reactions and biological activity.

Publications

Azar, C., K.Lindgren, E.D. Larson, and K. Möllersten, 2006: Carbon capture and storage from fossil fuels and biomass – Costs and potential role in stabilizing the atmosphere, *Climatic Change*, **74**(1-3): 47-79, January.

Chiesa, Paolo, Thomas Kreutz, and Giovanni Lozza, CO_2 Sequestration from IGCC Power Plants by Means of Metallic Membranes, *Journal of Gas Turbines and Power*, **129:** 123-134 (2007).

Gale, J. (coordinating lead author) and J. Bradshaw, Z. Chen, A. Garg, D. Gomez, H.-H. Rogner, D. Simbeck, and R.H. Williams (lead authors), 2005: Sources of CO_2, Chapter 2 in *Carbon Dioxide Capture and Storage*, a Special Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 431 pages.

Greenblatt, J.B., S. Succar, D. Denkenberger, R. H. Williams, and R. H. Socolow, "Baseload wind energy: Modeling the competition between gas turbines and compressed air energy storage for supplemental generation," *Energy Policy*, **35**(3):1474-1492, March 2007.

Hawkins, D.G., D.A. Lashof, and R.H. Williams, "What to do about coal," *Scientific American*, **295** (3): 68-75, September 2006 (special issue: *Energy Future Beyond Carbon*).

Jin, H., E.D. Larson, and F.E. Celik, "Performance and Cost Analysis of Future, Commercially-Mature Gasification-Based Electric Power Generation from Switchgrass," *Biomass and Bioenergy*, forthcoming (submitted November 2006).

Kreutz, T.G., 2005: A Potential Role for "Slipstream" H_2 from Coal IGCC with CO_2 Capture and Storage in an Emerging H_2 Economy for Transportation, *Proceedings of Fourth Annual Conference on Carbon Sequestration*, Alexandria, VA, May 2-5.

Larson, E.D., 2006: A Review of LCA Studies on Liquid Biofuel Systems for the Transport Sector, *Energy for Sustainable Development*, **X**(2): 09-126 (based on background paper presented at the Workshop on Biofuels for the Transport Sector, organized by the Science & Technology Advisory Panel, Global Environmental Facility,New Delhi, India, Aug. 29-Sept 1, 2005).

Larson, E.D., R.H. Williams, and H. Jin, "Fuels and electricity from biomass with CO_2 capture and storage," *Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies*, Trondheim, Norway, 19-22 June 2006.

Larson, E.D., S. Consonni, R.E. Katofsky, K. Iisa, and W.J. Frederick, "A Cost-Benefit Assessment of Gasification-Based Biorefining in the Kraft Pulp and Paper Industry, Volume 1: Main Report," final report to US Department of Energy and American Forest and Paper Association under DOE contract DE-FC26-04NT42260, Princeton Environmental Institute, Princeton University, Princeton, NJ, 21 December 2006.

Larson, E.D., S. Consonni, S. Napoletano, R.E. Katofsky, K. Iisa, and W.J. Frederick, "A Cost-Benefit Assessment of Gasification-Based Biorefining in the Kraft Pulp and Paper Industry, Volume 2: Detailed Biorefinery Design and Performance Simulation," final report to US Department of Energy and American Forest and Paper Association under DOE contract DE-FC26-04NT42260, Princeton Environmental Institute, Princeton University, Princeton, NJ, 21 December 2006.

Larson, E.D., S. Consonni, R.E. Katofsky, M. Campbell, K. Iisa, and W.J. Frederick, "A Cost-Benefit Assessment of Gasification-Based Biorefining in the Kraft Pulp and Paper Industry, Volume 3: Fuel Chain and National Cost-Benefit Analysis," final report to US Department of Energy and American Forest and Paper Association under DOE contract DE-FC26-04NT42260, Princeton Environmental Institute, Princeton University, Princeton, NJ, 21 December 2006.

Larson, E.D., S. Consonni, R.E. Katofsky, K. Iisa, W.J. Frederick, C. Courchene, F. Anand, and M. Realff, "A Cost-Benefit Assessment of Gasification-Based Biorefining in the Kraft Pulp and Paper Industry, Volume 4: Preliminary Biorefinery Analysis with Low-Temperature Black Liquor Gasification," final report to US Department of Energy and American Forest and Paper Association under DOE contract DE-FC26-04NT42260, Princeton Environmental Institute, Princeton University, Princeton, NJ, 21 December 2006.

Larson, E.D., H. Jin, and F.E. Celik, "Large-Scale Gasification-Based Co-Production of Fuels and Electricity from Switchgrass," *Biomass and Bioenergy*, forthcoming (submitted July 2006).

Larson, E.D., H. Jin, and F.E. Celik, *Gasification-Based Fuels and Electricity Production from Biomass, without and with Carbon Capture and Storage*, Princeton Environmental Institute, Princeton University, Princeton, NJ, October 2005, 77 pages.

Larson, E.D., A. Shanker, and T.B. Johansson (guest co-editors), 2006, *Energy for Sustainable Development*, **X** (2), June (130 pages), special issue based on the Workshop on Biofuels for the Transport Sector in Developing Countries organized by the Science and Technology Advisory Panel of the Global Environment Facility, 29 August – 2 September, 2005, New Dehli, India.

Meng, K., R.H. Williams,and M.A. Celia, "Opportunities for low-cost CO_2 storage demonstration projects in China," *Energy Policy*, **35**: 2368-2378, 2007.

Succar, S., D. Denkenberger, J. B. Greenblatt, and R. H. Williams, "An Integrated Optimization Of Large-Scale Wind With Variable Rating Coupled To Compressed Air Energy Storage," *Proceedings of AWEA Windpower 2006*, Pittsburgh, PA, 2006.

Succar, S., J. B. Greenblatt, and R. H. Williams, "Comparing Coal IGCC with CCS and Wind-CAES Baseload Power Options in a Carbon-Constrained World," *Proceedings of Fifth Annual Conference On Carbon Capture And Sequestration - DOE/NETL*, Alexandria, Virginia, 8-11 May 2006.

Succar, S., J. B. Greenblatt, and R. H. Williams "Arguing the case for storage" *Windpower Monthly*, **22:** 4, pp. 8-10, April 2006.

Thambimuthu, K., M. Soltanieh, and J.C. Abanades (coordinating lead authors) and R. Allam, O. Boland, J. Davison, P. Feron, F. Goede, A. Herrera, M. Iijima, D. Jansen, I. Leites, P. Mathieu, E. Rubin, D. Simbeck, K. Warmuzinski, M. Wilkinson, and R. Williams, 2005: Capture of CO_2, Chapter 3 in *Carbon Dioxide Capture and Storage*, a Special Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 431 pages.

Wang, X., D.L. Mauzerall, Y. Hu, A.G. Russell, E.D. Larson, J-H. Woo, D.G. Streets, and A. Guenther, "A High-Resolution Emission Inventory for Eastern China in 2000 and Three Scenarios for 2020," *Atmospheric Environment*, **39** (32): 5917-5933, October 2005.

Williams, R.H., E.D. Larson, and H. Jin, "Comparing climate-change mitigating potentials of alternative synthetic liquid fuel technologies using biomass and coal, *Proceedings of the 5th Annual Conference on Carbon Capture and Sequestration-DOE/NETL*, Alexandria, Virginia, 8-11 May 2006.

Williams, R.H., E.D. Larson, and H. Jin, "Synthetic fuels in a world with high oil and carbon prices," *Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies*, Trondheim, Norway, June 19-22, 2006.

The Storage Group

The major goals of the Storage Group are:

(i) To incorporate experimental findings into Dynaflow simulations of brine-cement interactions and identify the important variables affecting CO_2 leakage rates

(ii) To use the well-scale information from geochemical modeling to complete a large-scale risk analysis of a representative North American oil field and develop rapid and robust tools for leakage risk assessment

The experimental work on lab cements is complete and geochemical modeling is beginning. Over the next two years of the grant, the researchers will incorporate the essential elements of geochemistry into the model that will allow simulation of carbonated brine flow through an annular gap and initial prediction of the resulting cement corrosion in an idealized well. This information will be used as input for large-scale simulations of CO_2 injection.

Experimental Work

Short-term effects of brine-cement interaction

Graduate student Andrew Duguid completed his study of the attack of cements by carbonated brines and defended his thesis in October, 2006. (He is now working for Schlumberger in Pittsburgh, PA.) His data on cement decomposition are being used by Prof. Jean Prévost and Dr. Bruno Huet to test the reactive transport module that they have implement in Dynaflow.

The team will assess the importance of pressure on the corrosion rate of cement as results from the high-pressure studies at NETL become available. The NETL results will be compared to predictions from the geochemical module of Dynaflow if necessary, improved pressure dependence will be introduced into the model.

Long-term effects of injection on cement properties

A new graduate student will also join the team in September, 2007, to study the transport and mechanical properties of cement subjected to attack by carbonated brine. Duguid's results indicate a catastrophic loss of integrity of the cements when the corrosion is well advanced. However, there may be a more subtle deterioration that occurs in limestone formations, where our short-term (i.e., 1-year) experiments indicate little or no attack, that might have significant impact on leakage over the course of a century. We will use NMR to measure diffusion coefficients and a variety of techniques to measure permeability changes during leaching. We will also study the change in strength and stiffness as corrosion proceeds. This information will be needed to refine the leakage model and expand our confidence regarding the risk of leakage over the long term. Andrew Duguid's experiments reveal that a layer of calcium carbonate precipitates in the reaction zone, resulting in a decrease in porosity and a temporary slowing of attack. It is possible that this precipitate would heal small cracks, while larger ones would be opened further. This possibility will be explored by forcing flow through cracks of controlled width to see whether there is a threshold size below which the flow is arrested.

Characterization of field samples

Following a visit to CMI by Tony Hayward, BP mobilized a team to acquaint us with BP's field experience regarding durability of cement exposed to carbon dioxide, and to obtain samples of cement from wells. Prof. Scherer has offered advice on the handling and analysis of those samples. If they are provided to Princeton, we will study their microstructure and composition, and subject them directly to corrosion testing to see how they compare to our home-made samples. This will provide the first systematic data regarding features of the structure and/or chemistry of samples subjected to long term aging at elevated temperature and pressure, and thereby enable us to refine our predictions of risk.

The direction of the experimental program beyond Year 7 will depend on availability of cement samples and field data for leakage rates from wells. Field samples, if available, will be used for direct tests of corrosion rate, as well as transport and mechanical properties. If we obtain field data regarding methane leakage rates, those results will be used to infer the size of annuli that are likely to be present in sealed wells and provide initial conditions for the simulations of corrosion of cement.

Geochemical modeling

Model development

Over the next two years, Jean Prevost and postdoctoral researcher Bruno Huet will complete the implementation of a geochemical module in Dynaflow that includes the constituents of cement. Dr. Huet has developed an extensive database of chemical properties (solubility and stability) of the constituents of cement. The geochemistry module has been developed and successfully tested in 2006. The effort now is focused on improving the kinetic aspects by coupling of a transport module with the geochemistry module. In 2006, the 1st version of the reactive transport module has allowed qualitative simulations of Andrew Duguid's experiments. The remaining challenges concerning the dynamic aspects are 1), the prediction of the change in diffusion rate as the porosity is changed by corrosion, and 2) the quantification of the advective flow driven by volume changes following chemical reactions.

The multiphase flash calculation will further be modified to allow for pressure and temperature changes as the plume rises toward the surface, including thermal effects. Dick Fuller, who was responsible for the development of this module, will be leaving the project by early February, 2007. We will hire a post-doctoral researcher to continue this aspect of the work.

The modular nature of the software is particular important. Dick Fuller has developed a module for non-reactive equilibration of the components (i.e., flash calculation) that includes all the CO_2 -rich phases, and is supported by a separate module that calculates all the thermodynamic properties of the system. Bruno Huet has assembled the most extensive database in existence for reactions involving components of phases in cement, and can calculate the composition of the solution in equilibrium with any assemblage of cement phases between 0 and 100˚C. All of these modules are currently integrated by Jean Prévost into Dynaflow, which has exceptional ability to couple geomechanics (including fracture) with geochemistry. However, all of these modules could be used with other systems, such as Eclipse.

Simulation of injection environments

Once the basic geochemistry is in place, Bruno Huet and Jean Prevost will simulate attack on cement by carbonated brine rising through an annular gap around the cement in a well. Multiple leakage scenarios will be examined, including the impacts of varying brine composition, initial gap width, and depth at which the leak originates. The simulations will also be extended to include corrosion of the steel casing in the well.

In summary, at the end of about 2 years from today, we will be able to put bounds on the risk of leakage under unfavorable conditions (brine in a sandstone formation encountering a pre-existing annular gap in typical cement). Should we discover that the brine is quickly neutralized as it flows through the gap, so that the leak is not significantly expanded over the course of a century, then the behavior of the wells under more benign conditions is academic. On the other hand, if our simulations indicate that leaks worsen at a significant rate in sandstone formations, then we will need to see whether there is any such risk under more favorable circumstances (such as limestone formations). That information will emerge from the thesis work to begin this fall; the results will start flowing in about two years, and final results will be available by year 4 or 5 (that is, by the end of the project).

The results from the combined experimental and geochemical modeling should predict the most important variables affecting leakage rates within a well. This information will be combined with statistical information about well properties to provide input for the semi-analytical and coarse resolution models developed by Mike Celia and colleagues for risk assessment (see below).

Large-scale Leakage Modeling

Semi-analytical models of single injection plumes

During the last year Michael Celia's group continued work on large-scale modeling of leakage along existing wells, and the large-scale leakage model they have developed is now being included in a comprehensive risk-assessment tool being developed by Los Alamos National Laboratory. In this general area, the researchers have continued to develop and test the semi-analytical solutions for CO_2 and brine migration, including leakage along wells. The current state of this model is that they now have put together almost all of the key components, including: the CO_2 plume model, the leakage model for multiple wells and multiple aquifers, and the local upconing model (which can have a strong impact on leakage behavior). The only major component missing from the model is a detailed phase-change package for rapid leaks along wells. Celia and colleagues are debating how much detail is needed, and have not yet reached a consensus on this issue.

The group is continuing to use the Alberta Basin as source for hypothetical test cases. The Wabamun Lake region, southwest of Edmonton, has an extensive data base put together by their continuing collaborator, Stefan Bachu, and his team in Edmonton. Those data are being used as a basis for simulations, with probability distributions for leakage being the main output. The team has also considered vertical distributions of wells, and is in the process of evaluating risk reduction as a function of depth of injection. They have also begun to examine injectivity as a function of depth, as part of the overall study of depth of injection.

Basin-scale injection model

In addition to these semi-analytical solutions, which have been applied at the scale of a single injection plume (of order 1,000 km^2), Celia's group has also put together a new modeling approach that they believe is appropriate for modeling at length scales much larger than a single plume. They do not have any publications on this yet, but the general idea is to relax some of the assumptions required for analytical or semi-analytical solutions, while maintaining sufficient simplicity to achieve reasonably efficient numerical solutions. The researchers plan to use this approach to model basin-wide systems, with a focus on overall CO_2 injection volumes and locations, and the associated migration of brine within and across formations. Such a basin-wide model would allow for direct interaction with models of surface facilities, can consider optimization for a range of objective functions, and can answer questions about short- and long-term migration of displaced brines.

Interactions with Field Experiments

In addition to interactions with CCP2-funded experiments, headed by Charles Christopher of BP, Celia's group has been considering how the most critical, and most uncertain, parameters associated with well leakage might be determined. For the well leakage models, by far the most important parameter is the effective permeability of the bulk materials that make up the well and its immediate surroundings. This includes the well cement, the casing, and any damage zone in the rock immediately surrounding the well. In the team's models, a value of (bulk) permeability is assigned to this collection of materials, with a different value assigned to each vertical segment of each well, as field experiments to determine these values do not yet exist.

Celia and colleagues have proposed one such test, and analyzed the ranges of sensitivity in regard to what values of well permeability can be identified from the experimental measurements. If the method proposed is found to be reasonable, it can form the basis of a targeted field measurement campaign whose result would be a great reduction in the uncertainty associated with the most critical parameter in all leakage models. Such a reduction of uncertainty could significantly enhance prediction reliability, and thereby contribute to timely development of a regulatory and permitting framework for CO_2 injection.

Related Activities

In addition to the work described above, Celia's group also published several papers related to CO_2 that were not directly funded by CMI, including the study by one of our undergraduate students, Kyle Meng, on early opportunities in China, analysis of geochemical reactions associated with CO_2 injection, and new streamline simulation methods for CO_2 modeling. The group has also been active in conference organization (Wellbore Integrity workshop at Princeton, Site Characterization Workshop at Lawrence Berkeley Laboratory) and on several oversight panels (Weyburn expert panel, In Salah Science Advisory Board, DOE panel for needs in the Basic Sciences). Through both research at Princeton and outreach activities, the storage group at Princeton has had a significant impact over the last year.

Publications

Bachu. S. and M.A. Celia, "Assessing the Potential for CO_2 Leakage, Particularly through Wells, from CO_2 Storage Sites", to appear, *The Science and Technology of Carbon Sequestration*, AGU Monograph, 2006.

Celia, M.A., S. Bachu, J.M. Nordbotten, D. Kavetski, and S. Gasda, "A Risk Assessment Modeling Tool to Quantify Leakage Potential through Wells in Mature Sedimentary Basins", *Proc. 8th Int. Conf. on Greenhouse Gas Control Technologies*, Trondheim, Norway, 2006.

Duguid, A., Radonjic, M., Scherer, G. W., "The effect of carbonated brine on the interface between well cement and geologic formations under diffusion-controlled conditions," 8th International Conference on Greenhouse Gas Control Technologies, June 19-22, 2006, Trondheim, Norway.

Duguid, A., Celia, M. A., "Geologic CO_2 sequestration in abandoned oil and gas fields and human health risk assessment," Proceedings of the 5th Annual Conference on Carbon Capture and Sequestration, May 8-11, 2006, Monitor and Exchange Publications and Forum, Washington, D.C.

Gasda, S.E., M.A. Celia, and J.M. Nordbotten, "Significance of Dipping Angle on CO_2 Plume Migration in Deep Saline Aquifers", in *Proceedings of the XVI International Conference on Computational Methods in Water Resources*, edited by Philip J. Binning Peter Engesgaard, Helge Dahle, George F. Pinder and William G. Gray. Copenhagen, Denmark, June, 2006 (http://proceedings.cmwr-xvi.org).

Haegland, H., H.K. Dahle, G.T. Eigestad, J.M. Nordbotten, M.A. Celia, and A. Assteerawatt, "Streamline Methods on Fault Adapted Grids for Risk Assessment of Storage of CO_2 in Geological Formations", in *Proceedings of the XVI International Conference on Computational Methods in Water Resources*, edited by Philip J. Binning Peter Engesgaard, Helge Dahle, George F. Pinder and William G. Gray. Copenhagen, Denmark, June, 2006 (http://proceedings.cmwr-xvi.org).

Huet, B., Fuller, R., Prevost, J. and G. Scherer, , "Development of a geochemical code to assess cement reactivity in CO_2/brine mixtures," Wellbore Integrity Workshop, Princeton University, New Jersey March 28, 2006.

Huet, B., Fuller, R., Prevost, J. and G. Scherer, "Development of a geochemical code to assess cement reactivity in CO_2/brine mixtures" CO2SC, International Symposium on Site Characterization for CO_2 Geological Storage, Berkeley, CA, March 20-22 2006.

Huet, B., Fuller, R., Prevost, J. and G. Scherer, "Numerical simulation of multiphase flow of CO_2 along low permeability path up the wells. Introduction of the interactions with cement," 5th CCS, Fifth Annual Conference on Carbon Capture & Sequestration, Alexandria, Virginia, May 8 - 11, 2006.

Huet, B., Fuller, R., and J. Prevost, "Development of a coupled geochemical transport code to simulate cement degradation in CO_2 saturated brine." GHGT8, 8th International Conference on Greenhouse Gas Control Technologies, Trondheim, Norway, June 19-22, 2006.

Huet, B., "Thermodynamics of cement degradation," Cementitious Materials for Waste Treatment, Disposal, Remediation and Decommissioning Workshop, SRNL, Aiken, SC, December 12-14, 2006.

Kavetski, D., J.M. Nordbotten, and M.A. Celia, "Analysis of Potential CO_2 Leakage through Abandoned Wells using a Semi-analytical Model", in *Proceedings of the XVI International Conference on Computational Methods in Water Resources*, edited by Philip J. Binning Peter Engesgaard, Helge Dahle, George F. Pinder and William G. Gray. Copenhagen, Denmark, June, 2006 (http://proceedings.cmwr-xvi.org).

Li, L., C.A. Peters, and M.A. Celia, "The Effects of Mineral Spatial Distribution on Reaction Rates in Porous Media", accepted for publication, *Water Resources Research*, 2006.

Li, L., C.A. Peters, and M.A. Celia, "Upscaling Geochemical Reaction Rates using Pore-scale Network Models", *Advances in Water Resources*, *29*(9), 1351-1370, 2006.

Meng, K., R. Williams, and M.A. Celia, "Opportunities for Low-cost CO_2 Demonstration Projects in China", *Energy Policy*, published online 27 October 2006.

Nordbotten, J.M. and M.A. Celia, "Analysis of Plume Extent using Analytical Solutions for CO_2 Storage", in *Proceedings of the XVI International Conference on Computational Methods in Water Resources*, edited by Philip J. Binning Peter Engesgaard, Helge Dahle, George F. Pinder and William G. Gray. Copenhagen, Denmark, June, 2006 (http://proceedings.cmwr-xvi.org).

Nordbotten, J.M. and M.A. Celia, "Interface Upconing around an Abandoned Well", *Water Resources Research*, *42*, (doi:10.1029/2005WR004738), 2006.

Nordbotten, J.M. and M.A. Celia, "Similarity Solutions for Fluid Injection into Confined Aquifers", *Journal of Fluid Mechanics*, *561*, 307-327, 2006.

Nordbotten, J.M., M.A. Celia, H.K. Dahle, and S.M. Hassanizadeh, "Interpretation of Pressure in Darcy's Law", revised version under review, *Water Resources Research*, 2006.

Nordbotten, J.M., M.A. Celia, H.K. Dahle, and S.M. Hassanizadeh, "On the Definition of Macroscale Pressure in Multi-phase Flow in Porous Media", in *Proceedings of the XVI International Conference on Computational Methods in Water Resources*, edited by Philip J. Binning Peter Engesgaard, Helge Dahle, George F. Pinder and William G. Gray. Copenhagen, Denmark, June, 2006 (http://proceedings.cmwr-xvi.org).

Peters, C.A., J.A. Lewandowski, M.L. Maier, M.A. Celia, and L. Li, "Mineral Grain Spatial Patterns and Reaction Rate Up-scaling", in *Proceedings of the XVI International Conference on Computational Methods in Water Resources*, edited by Philip J. Binning Peter Engesgaard, Helge Dahle, George F. Pinder and William G. Gray. Copenhagen, Denmark, June, 2006 (http://proceedings.cmwr-xvi.org).

The Science Group

The Science Group's research over the past year has focused on three basic themes:

(i) A carbon observing system to monitor the fate of anthropogenic carbon, the mechanisms that determine that fate, and the ongoing response of the natural carbon system to global warming.

(ii) Paleoclimate studies aimed at developing a deeper understanding of the earth system response to changes in biogeochemical and climate forcing.

(iii) A geoengineering "truth squad" that will investigate proposals for carbon and climate mitigation. Each of these is discussed in turn.

Carbon observing system

Over the past year, the Sarmiento, Pacala, and Bender groups have made substantial progress towards improving regional estimates of air-sea and air-land carbon fluxes using models and observations from multiple platforms, including aircraft observations, satellite retrievals, ship board measurements, and regular atmospheric observations at surface sites. In addition, these groups have conducted modeling and data analysis studies that have informed the measurement community about the optimal locations for new observations and the interpretation of data. Finally, further development and analysis of models has provided insight into the processes governing the carbon fluxes and how they are likely to respond under climate change.

Atmospheric inversions

Sarmiento's group has contributed to the development of the strategy for a high-density aircraft observation network over the United States. This network, comprising 20 stations, combines regional measurements of CO_2 and other trace gases. The first year of observations has recently become available, and these observations are being used to estimate carbon fluxes with the Direct Carbon Budgeting Approach (DCBA). Sarmiento's group used this approach to analyze the strengths and weaknesses of the network, leading to the implementation of a new station at Berms (Montana) to complement the network in a region that was poorly sampled by the existing network.

In parallel, Sarmiento's group has started to develop a multi-species approach to infer carbon surface fluxes through a combined atmospheric and oceanic inversion constrained by observations of multiple trace gases such as CO_2, CO, CH_4, O_3, and O_2. This approach takes advantage of the correlation existing between different species to add some constraint on the fluxes and the transport that affect trace gas distributions.

Exploiting aircraft measurements of SF_6 made around the globe, Manuel Gloor and colleagues have shown that state-of-the-art atmospheric transport models underestimate the ventilation of the boundary layer during winter over the continent, which could lead to substantial errors in the interpretation of atmospheric CO_2 data. To improve atmospheric model realism, Sarmiento's group is evaluating new parameterization of vertical transport using observations of CO_2 from space in collaboration with GFDL.

Air-sea fluxes/ Predicting carbon feedbacks in the ocean

Sarmiento's group has published a series of four papers in the past year that use ocean interior observations and Ocean General Circulation models to estimate regional air-sea fluxes. Using this technique, we have estimated the oceanic sink of anthropogenic carbon with a greater degree of certainty than any previous work, 2.2 ± 0.2 Pg C yr^{-1}.

Ocean modeling studies have also been employed to identify variability in natural air-sea CO_2 fluxes and the rate of uptake of anthropogenic CO_2. In particular, recent work has focused on the North Pacific Ocean, since the variability here has a significant impact on the carbon source and sink estimates in North America. Recent work with an ocean model has shown that interannual variability in uptake of anthropogenic CO_2 in this region consists primarily of modulations of the uptake maximum in winter, rather than a slowly evolving change in the mean. There is a substantial decadal trend towards increased winter uptake over time, primarily due to decadal changes in ocean circulation.

In addition, Sarmiento's group is engaged in modeling studies to aid in the interpretation of data from international repeat hydrography measurement campaigns that aim to sample selected transects once every ten years to detect changes in oceanic uptake of anthropogenic CO_2. Analysis of simulations from three models suggest that the amplitude of the natural variability of column inventories of dissolved inorganic carbon is of the same order of magnitude as the anthropogenic signal as it changes over a decade. The large magnitude of natural variability will complicate the interpretation of repeat hydrographic data because differences between past and present measurements may not be directly attributable to increasing anthropogenic carbon uptake by the oceans.

Air-land fluxes/ Predicting carbon feedbacks in the land biosphere

Changes in climate have the potential to affect the geographic distribution of ecosystems, and the mix of species that they contain. However, little is known about how these ecosystems might respond to climate change, or how these changes might feed back on climate. To improve our predictive skill, Pacala's group has continued to develop the Earth System Model. The team finished tuning the model, which is now the only model with a free running ocean and biosphere that produces a stable climate.

In addition, Sarmiento's and Pacala's group have started to develop a data assimilation scheme to constrain the new GFDL vegetation model LM3V in order to improve the estimation of carbon fluxes over North America. This effort, so far limited to the use of eddy flux tower and forest inventory data, is the first step towards the development of a full carbon observing system, which will use data on varied spatiotemporal scales (flux and tall towers, flask and aircraft atmospheric data, forest inventories, oceanic data), to better understand the key processes controlling carbon fluxes over the North American continent.

A particular focus concerns the modeling of carbon emissions by fires, because fire is responsible for most of the year-to-year variation in the growth rate of atmospheric CO_2. As part of this effort, a fire model, relying on *in-situ* and remote sensing observations, has been designed for boreal regions. Provided realistic climate predictors, the model successfully reproduces the spatio-temporal evolution of burned area in the boreal forest, including seasonality and interannual variability. The model is the first that predicts both the location and timing of forest fires, which makes it suitable to quantitatively study the evolution of fire with climate. The team is now turning to the more difficult problem of simulating tropical fires.

Pacala and colleagues also made considerable progress on a difficult technical problem. A modern and powerful method to estimate the parameters in models is called the Monte Carlo Markov Chain. It requires that one run the model many times while adjusting parameter values until the model has the best possible agreement with all available data. The researchers figured out how to run the model of the biosphere in the Earth System Model quickly enough so that this method can be used, and should have results using the new method next year.

Finally, Pacala's group cracked a problem that should lead to the next generation of biosphere models. Two years ago, they achieved a mathematical breakthrough with models of vegetation and can now analyze and understand them mathematically, whereas before they could only run them on a computer. The researchers have now exploited the mathematical breakthrough to develop a statistical method that estimates all the parameters in the biosphere model using the information in national forest inventories that have been established in many countries in response the Kyoto Accord. They can, for example, parameterize the model for every tree species in the US in every location. Because the inventories record how the biodiversity of forests change as forest age, the behaviors of the models can also be checked to make sure that their predictions are correct. This is the package that has always been missing in ecology: enough data to build quantitatively accurate models that can deal with realistic levels of biodiversity over large regions plus the capacity to analyze the models to extract general rules. The group has applied the new method to modeling forests of the northern Midwest, and can now predict which species occur where and how those forests will change through time. The researchers' next steps will be to apply their methods to mid-Atlantic, German, and Panamanian forests.

Inversion modeling and the CO_2 fertilization sink

One of the science group's major findings resulted from combining the inversion modeling team's large oceanic data set with atmospheric data in order to jointly estimate air-sea and air-land fluxes. The group's latest work has resulted in significant changes in the estimated terrestrial fluxes compared with previous analyses of atmospheric data, especially in tropical and southern hemisphere regions that are not well sampled by the atmospheric observations alone. The joint estimate finds that the tropical and southern land regions are a statistically significant source of carbon to the atmosphere, with a 77% chance that their total source exceeds 1 billion metric tons of carbon per year. This flux represents the sum of emissions due to tropical deforestation and a potential natural sink from plant fertilization via increasing atmospheric CO_2 levels. The net source estimated by the joint inversion is of about the same magnitude as independent estimates of the tropical carbon source due to deforestation and land use change alone. This suggests that CO_2 fertilization is less important a player in the tropics, and thus in the global carbon cycle, than previously thought.

Most of the current generation of climate models used to estimate the effects of climate change, including those being used for the International Panel on Climate Change (IPCC) Assessment Report 4, incorporate a substantial CO_2 fertilization sink. This sink reduces the amount of mitigation required to stabilize atmospheric CO_2 concentrations to about half what it would be without CO_2. The science group's studies challenge the existence of a substantial CO_2 fertilization sink.

Monitoring atmospheric oxygen

Bender's core CMI research has involved measurements of the atmospheric O_2/N_2 ratio. This ratio provides a primary constraint for partitioning the sequestration of fossil fuel CO_2 between ocean uptake and land biosphere uptake. The oceanic uptake of CO_2 has no effect on atmospheric O_2, while the land biosphere produces approximately one O_2 for every CO_2 it consumes. Therefore, measurements of the changing O_2/N_2 ratio of air allow us to determine the part of CO_2 sequestration due to the land biosphere, and the part due to the oceans.

This year, Bender's group has been using observations of Ar/N_2 ratios to interpret their O_2/N_2 observations. The quality of these data has improved markedly with the deployment of new sampling systems, and the Bender Group has produced new climatologies for the annual cycle of this gas at their 7 remote observing sites (Barrow, Sable Island, Samoa, Amsterdam, Cape Grim, Macquarie and Syowa). These values agree well with simulations, by Galen McKinley, of a model with active upper ocean gas exchange and atmospheric tracer transport.

Ocean model development

Sarmiento's group has been working to improve representations of two fundamental ocean processes in computer models – the return of deep ocean water to the ocean's surface and the release of nutrients from decaying marine organisms.

Understanding the processes that determine the return flow of deep water into the upper ocean is a central problem in oceanography. The potential of Helium-3 emanating from mid-ocean ridges as a tracer for the pathways of water mass conversion has led Sarmiento's group to initiate an investigation of the distribution of Helium-3 by a combination of model simulations and observations.

The available measurements of Helium-3 and Helium-4 from the WOCE program have been integrated to produce a three-dimensional gridded dataset, which provides an accurate estimate of the tracer inventories. Furthermore, Helium-3 has been implemented in a suite of simulations using GFDL models. The simulations from the suite of ocean models produced substantially different steady state distributions of the tracers. Comparisons between these model simulations and the new Helium-3 data set suggest that the currently accepted amount of Helium-3 injected into the interior of the ocean from mid-ocean ridges might be substantially overestimated. These Helium-3 injection estimates have been used widely in oceanography; therefore, this result has far-reaching implications for ocean circulation and the dynamics and geochemistry of Earth's mantle.

Remineralization ratios, e.g. the stoichiometric ratios associated with the remineralization of organic material into dissolved nutrients, are used to derive anthropogenic carbon storage in the ocean and are included in many models that are used to simulate ocean biogeochemistry. The Sarmiento group has developed a novel technique to compute remineralization ratios that does not rely on several of the assumptions that have been used in previous studies. Analysis of model simulations indicates that this method is more accurate than the alternative approaches. Preliminary results, suggest that the variability of remineralization ratios is small in the deep ocean, confirming previous results.

Paleoclimate

In order to improve our understanding of natural controls on atmospheric CO_2, we are investigating why atmospheric CO_2 varies with recent climate cycles, being lower during ice ages. Work conducted previously by CMI members and others suggests that the Southern Ocean, the continuous band of ocean surrounding the Antarctic continent, holds the answer.

Southern Ocean nutrients and glacial cycles

One hypothesis regarding glacial-interglacial cycles is that large scale iron fertilization by increased dust deposition stimulated biological productivity in the Southern Ocean, leading to increased oceanic uptake of atmospheric CO_2. Therefore, the interactions between iron and biological productivity in the Southern Ocean are closely linked to paleoclimate. Bender's group has synthesized a large dataset of net community production and gross primary production based on shipboard observations in the Southern Ocean and integrated the results with values of iron deposition rates simulated by S.-M. Fan at GFDL. This dataset is unique because it reflects production over the timescale of order one week, which is also the fundamental response time of oceanic plankton to environmental changes. Analysis of these data suggests a significant link between transient iron inputs and net community production, which supports the idea that addition of iron to these ecosystems stimulates a bloom.

Sarmiento's group is exploring how mechanisms of variability in ocean circulation impact the uptake of atmospheric CO_2 on centennial and millennial timescales, as reflected by marine sediment records. In order to apply the GFDL coupled ocean/ecosystem model to these long-timescale problems, a fast version of the model was developed during 2006. This model configuration requires only a fraction of the computational cost of the standard GFDL model, while still using the same biogeochemical model. Preliminary results show a previously unrecognized control on nutrient availability to the ocean surface of the southern hemisphere by the position of southern westerly winds, with important implications for CO_2. Sarmiento's group has also successfully carried out long-term iron fertilization experiments in order to test the hypothesis that higher glacial dust fluxes to the ocean caused greater CO_2 storage by increasing phytoplankton growth rates. This work builds upon previous CMI-funded work in Sigman's group, which indicated more complete consumption of nutrients in the Subantarctic Ocean during the last ice age.

Polar stratification during glacial periods

Daniel Sigman and his collaborators continue to pursue the evidence for reduced vertical exchange (i.e. "stratification") in the halocline-bearing polar ocean regions under colder climates of the past 3 million years. A major motivation for this focus is that the reconstructed polar ocean changes have the capacity to explain the low atmospheric concentration of CO_2 during ice ages, with polar stratification storing CO_2 in the abyssal ocean. Recent analysis of N isotopic data by Sigman's group indicates reduced nutrient supply to the Bering Sea surface from below during the last ice age, strengthening the case for a bipolar (Antarctic and North Pacific) increase in stratification during ice ages. This finding constrains the cause for polar ocean stratification upon cooling to a mechanism that applies to both of these regions.

Model simulations carried out by AOS postdoc Agatha de Boer showed that the reduced sensitivity of seawater density to temperature at low temperatures provides such a mechanism. In the case of a globally colder ocean, the drive toward Antarctic and North Pacific overturning due to temperature becomes weaker, allowing the net atmospheric deposition of fresh water on these polar ocean regions to stratify them. de Boer has demonstrated that the density/temperature effect described above fits into a common theoretical framework with the ocean's response to changes in southern hemisphere winds, thus relating to the ongoing work on wind/CO_2 connections mentioned above.

Impacts of recent climate variability on human societies

Daniel Sigman's long term collaboration with Gerald Haug of GFZ Potsdam has yielded a reconstruction of East Asian winter monsoon strength over the last 16 thousand years, based on sediment cores from Lake Huguang Maar in southeastern China. This study indicates a strong anti-correlation with the summer monsoon, and connections with our previous work in Cariaco Basin off Venezuela indicate Pan-Pacific shifts in tropical climate over the past 16 thousand years that may be explained by migration of the intertropical convergence zone. The coincident timings of multi-annual dry periods in both East Asia and Central America between AD 700 and 900 and their temporal correspondence with human societal events in both regions raise the possibility that Pacific-wide migrations in the tropical rain belt contributed to the coincident declines of both the Tang dynasty in China and the Classic Maya in Central America.

Impacts of geoengineering

The CICS Science group is working with GFDL through CICS to maintain a group of scientists able to analyze mitigation options as they arise. While iron fertilization and deep-sea injection do not appear to be gaining traction as viable options, there does continue to be strong interest in them, including amongst private commercial ventures. There are many unresolved questions that are of considerable interest scientifically, and the outcomes will have significant impact on our evaluations of the viability of these options.

Sarmiento's group has carried out a new set of iron fertilization simulations making use of the new generation of ecosystem and iron chemistry models that have been developed over the past decade at Princeton and GFDL. These new fertilization model results differ significantly from the major conclusions of our previous research by Gnanadesikan in showing much greater sequestration efficiency. The main reason for this is that the added iron is retained for a long period of time in the models and thus continues to draw carbon down each time it returns to the surface. In previous research, it had been assumed that the added iron would be scavenged very rapidly.

Two additional types of simulations have been performed. The first includes a simple global atmosphere for carbon. This reduces the efficiency of the carbon uptake by about 40% due to decreased uptake elsewhere in the ocean. The second simulation is designed to use the added iron only once before it is lost from the system. This simulation reduces the amount of carbon removed from the atmosphere by iron fertilization by up to a factor of 10 over the case where iron is allowed to be retained.

Publications

de Boer, A. M., D. M. Sigman, J. R. Toggweiler, and J. L. Russell, 2007. The effect of global ocean temperature change on deep ocean ventilation, *Paleoceanography*, in press.

Battle, M. S. E. Mikaloff Fletcher, M. L. Bender, R. F. Keeling, A. C. Manning, N. Gruber, P. P. Tans, M. B. Hendricks, D. T. Ho, C. Simonds, R. Mika, and B. Paplawsky, 2006. Atmospheric potential oxygen: New observations and their implications for some atmospheric and oceanic models, *Global Biogeochemical Cycles*, 20, doi: 10.1029/2005GB002534.

Behrenfeld , M. J., R. T. O'Malley , D. A. Siegel , C. R. McClain , J. L. Sarmiento , G. C. Feldman, A. J. Milligan , P. G. Falkowski , R. M. Letelier , E. S. Boss, 2006. Climate-driven trends in contemporary ocean productivity, *Nature*, 444: 752-755.

Brunelle, B. G., D. M. Sigman, M. S. Cook, L. D. Keigwin, G. H. Haug, B. Mingram, and G. Schettler, 2007. Evidence from diatom-bound nitrogen isotopes for Subarctic Pacific stratification during the last ice age and a link to North Pacific denitrification changes, *Paleoceanography*, in press.

Crevoisier, C., M. Gloor, E. Gloaguen, L. W. Horowitz, J. L. Sarmiento, C. Sweeney and P. P. Tans, 2006. A direct carbon budgeting approach to infer carbon sources and sinks. Design and synthetic application to complement the NACP observation network, *Tellus B* 58 (5), 366-375, doi: 10.1111/j.1600-0889.2006.00214.

Crevoisier C., Shevliakova E., Gloor M., Wirth C. and Pacala S., 2006. Climate and human drivers of fires in the boreal forests: data constrained design of a prognostic model for burned area, *Journal of Geophysical Research.* submitted.

Deutsch, C., J. L. Sarmiento, D. M. Sigman, N. Gruber, and J. P. Dunne, 2007. Spatial coupling of nitrogen inputs and losses in the ocean, *Nature*, 445: 163-167.

Gloor M., Dlugokensky E., Brenninkmeijer C., Horowitz L., Hurst D., Dutton G., Crevoisier C., Machida T. and Tans P., 2007a. 3D SF_6 data and tropospheric transport: 1. Signals, modeling accuracy and implications for inverse modeling, *Journal of Geophysical Research*, accepted.

Gloor M, Dlugokensky E., Brenninkmeijer C., Crevoisier C., Horowitz L.

and Tans P., 2007b. 3D SF_6 data and tropospheric transport: 2. Implications on transport, *Journal of Geophysical Research*, submitted.

Gorgues, T., C. Menkes, O. Aumont, K.B. Rodgers, G. Madec, and Y. Dandonneau. 2007. Indonesian Throughflow control of the eastern equatorial Pacific biogeochemistry, *Geophysical Research Letters*, in revisions.

Hurtt, G.C., S. Frolking, M.G. Fearon, B. Moore, E. Shevliakova, S. Malyshev, S.W. Pacala and R.A. Houghton. 2006. The underpinnings of land-use history: three centuries of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands. /Global Change Biology/ 12, 1208-1299.

Iudicone, D., K.B. Rodgers, R. Shopp, and G. Madec, 2007, An Exchange window for the injection of Antarctic Intermediate Water into the south Pacific, *Journal of Physical Oceanography*, in press.

Jacobson, A. R., S. E. Mikaloff Fletcher, N. Gruber, J. L. Sarmiento, M. Gloor, and TransCom Modelers, 2007. A joint atmosphere-ocean inversion for surface fluxes of carbon dioxide, I: Methods, *Global Biogeochemical Cycles*, in press.

Jacobson, A. R., S. E. Mikaloff Fletcher, N. Gruber, J. L. Sarmiento, M. Gloor, and TransCom Modelers, 2007. A joint atmosphere-ocean inversion for surface fluxes of carbon dioxide, II: Results, *Global Biogeochemical Cycles*, in press.

Jin, X., N. Gruber, J. P. Dunne, J. L. Sarmiento, and R. A. Armstrong, 2006. Diagnosing the contribution of phytoplankton functional groups to the production and export of particulate organic carbon, CaCO3, and opal from global nutrient and alkalinity distributions, *Global Biogeochemical Cycles*, 20, GB2015, doi10.1029/2005GB002532.

Laurian, A., A. Lazar, G. Reverdin, K.B. Rodgers, and P. Terray. 2006. Poleward propagation of spiciness anomalies in the North Atlantic Ocean, *Geophysical Research Letters*, 33, L13603, doi:10.1029/2006GL026155.

Lichstein, J.W., J. Dushoff, S.A. Levin, S.W. Pacala. 2007. Intraspecific variation and species coexistence. (Submitted to American Naturalist).

Marinov, I. A. Gnanadesikan, J. R. Toggweiler, and J. L. Sarmiento, 2006. The Southern Ocean biogeochemical divide, *Nature*, 441: 964-967.

Mignone, B. K., A. Gnanadesikan, J. L. Sarmiento, R. D. Slater, 2006. Central role of southern hemisphere winds and eddies in modulating the oceanic uptake of anthropogenic carbon, *Geophysical. Research Letters,* 33, L01604, doi:10.1029/2005GL024464.

Mikaloff Fletcher, S. E., N. Gruber, A. R. Jacobson, S. C. Doney, S. Dutkiewicz, M. Gerber, M. Gloor, M. Follows, F. Joos, K. Lindsay, D. Menemenlis, A. Mouchet, S. A. Müller, and J. L. Sarmiento, 2007. Inverse estimates of the oceanic sources and sinks of natural CO_2 and their implied oceanic transport, *Global Biogeochemical Cycles*, in press.

Mikaloff Fletcher, S. E., N. Gruber, A. R. Jacobson, S. C. Doney, S. Dutkiewicz, M. Gerber, M. Follows, F. Joos, K. Lindsay, D. Menemenlis, A. Mouchet, S. A. Müller, and J. L. Sarmiento, 2006. Inverse estimates of anthropogenic CO_2 uptake, transport, and storage by the ocean, *Global Biogeochemical Cycles*, **20**, doi: 10.1029/2005GB002530.

Moorcroft, P.R., S.W. Pacala, M.A. Lewis. 2006. Potential role of natural enemies during tree range expansions following climate change. /Journal of Theoretical Biology/ 241: 601-616.

Naegler, T., P. Ciais, K.B. Rodgers, and I. Levin, 2006. Excess radiocarbon constraints on air-sea gas exchanges and the uptake of CO_2 by the oceans, *Geophysical Research Letters*, 33, L11802, doi:1029/2005GL025408.

Ogle, K. and S.W. Pacala 2006. A modeling framework for inferring tree growth and allocation from physio-logical, starvation, and allometric traits. /Tree Physiology . /In Press.

Pacala, S.W., Coordinating Lead Author. And: R. Birdsey, S. Bridgham, J. Caspersen, R. Conant, K. Davis, B. Hales, R. Houghton, J. Jenkins, M. Johnson, G. Marland, K. Paustian, R. Socolow, R. Tol. and S. Wofsy. 2006. The North American Carbon Budget Past and Present.* In*: The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle. Departments of Energy and Commerce and NASA.

Patra, P. K., K. R. Gurney, D. A. S., S. Maksyutov, T. Nakazawa, D. Baker, P. Bousquet, L. Bruhwiler, C. Y.-H., P. Ciais, S.-M. Fan, I. Fung, M. Gloor, M. Heimann, K. Higuchi, J. J., R. M. Law, T. Maki, B. C. Pak, P. Peylin, M. Prather, P. J. Rayner, J. Sarmiento, S. Taguchi, T. Takahashi, and C.-W. Yuen, 2006. Sensitivity of inverse estimation of annual mean CO_2 sources and sinks to ocean-only sites versus all-sites observational networks, *Geophysical Research Letters*, 33, L05814, doi:05810.01029/02005GL025403.

Purves,D., J.W. Lichstein, S.W. Pacala. 2007. Crown shape and competition for canopy space: an individual-based model parameterised for 250 US tree species. DW. (in review).*

Raynaud, S., O. Aumont, K.B. Rodgers, P. Yiou, and J.C. Orr, 2006. Interannual-to-decadal variability of North Atlantic air-sea CO_2 fluxes, *Ocean Sciences Discussion*, 2, 437-472.

Reuer, Matthew K., Bruce A. Barnett, Michael L. Bender, Paul G. Falkowski, and Melissa B. Hendricks, 2007. New estimates of Southern Ocean biological production rates from O_2/Ar ratios and the triple isotope composition of O_2, *Deep Sea Research*, in press.

Rodgers, K.B., O. Aumont, C. Menkes, and T. Gorgues, 2007a. Decadal variations in equatorial Pacific ecosystems and ferrocline/pycnocline decoupling, *Global Biogeochemical Cycles*, submitted.

Rodgers, K.B., J.L. Sarmiento, O. Aumont, C. Crevoisier, C. de Boyer Monetgut, and N. Metzl, 2007b. A Wintertime uptake window for Anthropogenic CO_2 in the North Pacific, *Global Biogeochemical Cycles*, submitted.

Rodgers, K.B., J.L. Sarmiento, R.M. Key, O. Aumont, A. Gnanadesikan, N. Metzl, M. Ishii, L. Bopp, Y. Yamanaka, A. Ishida, E. Maier-Reimer, and P. Wetzel, 2007c. Detection of anthropogenic changes in column inventories of oceanic DIC, *Geophysical Research Letters*, submitted.

Shevliakova, S.W. Pacala, S. Malyshev, G.C. Hurtt, P.C.D. Milly, J.P. Caspersen, L. Thompson, C. Wirth and K.A. Dunne. 2006. The Land Carbon Cycle and Vegetation Dynamics in the Dynamic Global Land Model LM3V. /Global Change Biology/. In Press.

Socolow, R.H. and S.W. Pacala. 2006. A Plan to Keep Carbon in Check. / Scientific American/. Pgs 50-57.

Yancheva, G., N. R. Nowaczyk, J. Mingram, P. Dulski, G. Schettler, J. F. W. Negendank, J. Liu, D. M. Sigman, L. C. Peterson, and G. H. Haug, 2007. Influence of the Intertropical Convergence Zone on the East Asian Monsoon, *Nature*, 445, 74-77.

The Integration Group

The Integration Group has concentrated on three areas over the past year:

(i) Deepening the analysis of stabilization wedges and continuing outreach efforts to a variety of stakeholder groups

(ii) Assessing and improving the utility of climate observation systems

(iii) Predicting impacts and improving policy

Stabilization wedges

Wedges analysis

The stabilization wedges concept has been expanded and has reached new audiences through several articles published during the past year. For Scientific American, Co-Directors Rob Socolow and Steve Pacala wrote a new synthesis of the concepts that addressed division of responsibility between nominally industrialized and nominally newly industrializing countries. Socolow also collaborated with Jeff Greenblatt (now at Environmental Defense) and Keywan Riahi (IIASA) in a paper presented at the biannual Carbon Capture and Storage meeeting in Trondheim, Norway, in which they presented a simple mathematical method to display the "wedges" associated with any emissions trajectory and applied their method to show the strong "green" assumptions implicit in the IPCC "SRES" scenarios.

In another collaboration, Socolow and Harvey Lam of the Department of Mechanical and Aerospace Engineering co-authored "Good enough tools for global warming policy" for the Philosophical Transactions of the Royal Society A: Mathematical, Physical & Engineering Sciences. The paper allows the non-specialist to explore idealized emissions trajectories and to understand the magnitude of the stabilization assignment (depending on stabilization level) and how the time to get the job done depends on the maximum pace for disengagement from fossil fuels (a scarcely explored parameter). Finally, Socolow is also working with Bryan Mignone, a CMI alumnus at the Brookings Institution in Washington, D.C., to understand how assumptions about how the costs of mitigation options (non-carbon energy and CO_2 capture and storage among them) affect prescriptions for prospective CO_2 tax schedules. They hope to generate cross-talk between those, largely in the engineering community, who design energy conversion facilities and develop costs of low-carbon alternatives and those, largely economists, who insert costs into integrated assessment models.

Outreach

During the past year Co-Directors Pacala and Socolow continued efforts to inform a variety of stakeholders about the wedges concept and the need to start cutting emissions now. On the policy front, Pacala was invited to speak about available carbon-cutting strategies at a closed door roundtable discussion entitled "Exploring Greenhouse Gas Technologies" for the U.S. Senate Committee on Environment and Public Works. He also accepted an invitation to join the board of Environmental Defense. Professor Socolow is helping to identify “Grand Challenges for Engineering” for the National Academy of Engineering, participated in the World Economic Forum in Davos, served as principle consultant to the World Wildlife Fund’s Energy Task Force, and is a member of a small advisory group to former Vice President Al Gore.

In the realm of popular communication, both Socolow and Pacala provided technical guidance for Gore’s film “An Inconvenient Truth,” which shows a wedges diagram as part of a concluding argument that we already have the tools to get started on mitigation. Professor Pacala also contributed to two television shows about climate change – “Can We Save Planet Earth?” with David Attenborough for the BBC, and “Global Warming. What You Need to Know” with Tom Brokaw for the Discovery Channel.

The board game based on the stabilization wedges concept has continued to grow in popularity, and the group is now expanding outreach efforts to reach high-school teachers. In response to a request by advisory board member John Holdren (now President of the American Association for the Advancement of Science (AAAS)), Socolow and Roberta Hotinski (CMI’s former Information Officer) will be demonstrating the wedges game with electronic voting at the AAAS annual meeting for an audience of 500, roughly half of whom will be high school teachers. Hotinski, who is now serving as a consultant for CMI on outreach, developed a teachers’ guide to the Stabilization Wedges Game for this event that is now available on the CMI website. She is also providing guidance to teachers who use the board game in classroom settings and continues to present the wedges concept and facilitate wedge workshops for diverse groups around the country.

Assessing and improving the utility of climate observation system

Klaus Keller is analyzing two interrelated questions. First, how can we understand, detect, and predict potential anthropogenic threshold responses of the climate system? Second, how can we use this scientific information to design sound risk-management strategies? One potential climate threshold response involves an abrupt and/or persistent weakening of the North Atlantic meridional overturning circulation (MOC), an ocean circulation system that transports heat from low latitudes to the North Atlantic basin and the surrounding regions. The geologic record and model simulations suggest that the MOC may weaken or even collapse in response to climatic forcing. Such a threshold response could be associated with considerable ecological and economic impacts. The current predictions about the future fate of the MOC are, however, deeply uncertain. Reducing this uncertainty poses nontrivial scientific and operational challenges. Overcoming these challenges can provide potentially large economic value.

Keller *et al.* show that the currently implemented MOC observation system might well succeed in detecting anthropogenic MOC changes within a few decades. However, prediction of future threshold crossing – not just detection of past anthropogenic changes – is the relevant task for many decision-making frameworks. A confident prediction of a potential MOC threshold response requires, however, considerably longer observations or much higher signal-to-noise ratios than confident detection. This raises the distinct possibility that the current MOC observation system would provide a confident prediction of a MOC threshold response only after the forcing threshold has been crossed. Keller *et al.* also show how the MOC observation system might be considerably improved by optimizing the spatial design of the current observation system and by adding high-resolution oceanic oxygen observations.

Using impacts of climate change as guides for policy

Simon Donner continued his work linking greenhouse gas emissions to the viability of coral reefs. A key step forward was developing a method for double attribution of coral-reef bleaching; that is, isolating the GHG-induced component of coral bleaching. Developed in conjunction with Tom Knutson of GFDL, the approach, combining modeling and observations, was able to identify the likelihood of a human contribution to the 2005 Caribbean bleaching event, and project the probability of bleaching under various warming scenarios for this century.

The links between air pollution and global warming

Vaishali Naik and Michael Oppenheimer continued to investigate the linkages between air pollution and climate change. They examined the sensitivity of global radiative forcing to the geographical location of biomass-burning emissions, and are also laying the foundations for a study of the impacts of ethanol on air quality and climate.

Reducing biomass burning emissions has been estimated to cause a short-term warming (by reducing reflective aerosols), but a long-term cooling from reducing CO_2 (particularly by avoiding permanent deforestation) and other greenhouse gases. Reducing the 90% of global biomass-burning emissions attributed to human activities has thus been proposed as a control strategy for mitigating climate change.

Using global three-dimensional atmospheric chemistry and radiative transfer models, the researchers assessed the sensitivity of global radiative forcing to the location of biomass burning by considering the effects of a 10% reduction in ozone precursor and aerosol emissions from major biomass burning regions of the world. They concluded that global radiative forcing due to biomass burning is most sensitive to the amount of biomass burned in tropical regions, particularly the Indian subcontinent. Their analysis also showed that marginal reductions in both short-lived ozone precursors and aerosol species yield negative global radiative forcing, implying a cooling tendency (although the sign of radiative forcing due to biomass burning aerosols is highly uncertain).

Naik and Oppenheimer will further examine the long-range transport of ozone to and from the Indian subcontinent to provide a better understanding of the influence of ozone precursor emissions on surface air quality in neighboring countries. Such source-reception relationships can then potentially be used to design a regional regime to control air pollution in South Asia.

This year, Naik and Oppenheimer, in collaboration with GFDL scientists, will also perform research to advance our understanding of the present-day atmospheric budget of ethanol and its implications for global atmospheric chemistry. The atmospheric concentration of ethanol, an oxygenated volatile organic compound (OVOC), is expected to increase as use of ethanol as a fuel increases worldwide. In addition to the potentially adverse impacts on regional air quality, enhanced ethanol concentrations may also influence background tropospheric chemistry and climate.

There is currently a large discrepancy between the observed and simulated atmospheric ethanol concentrations over the U.S. To improve simulations, researchers will first assess the global atmospheric budget and distribution of ethanol, which will lay the groundwork for investigating the potential impacts of future increases in ethanol use on air quality and climate. This will provide us with a much needed understanding of the role of ethanol in atmospheric chemistry and is a critical first step to designing alternative domestic fuel strategies that do not compromise climate and air quality objectives.

Publications

Baehr, J., D. McInerney, K. Keller, and J. Marotzke: Global optimization of an observing system design for the North Atlantic meridional overturning circulation, *Journal of Atmospheric and Oceanic Technology*, in review (2007).

Baehr, J., K. Keller, and J. Marotzke: Detecting potential changes in the meridional overturning circulation at 26 °N in the Atlantic. *Climatic Change*, in the press (2007).

Brennan, K., R. Matear, K. Keller: Measuring oxygen concentrations improves the detection capabilities of an ocean circulation observation array, *Journal of Geophysical Research – Oceans*, in review (2007).

Budescu, D.V., R. Lempert, S. Broomell, and K. Keller: Aided and unaided decision making with imprecise probabilities, *Risk Analysis*, in review (2007).

Donner, S.D., T. R. Knutson, M. Oppenheimer, Model-based assessment of the role of human-induced climate change in the 2005 Caribbean coral bleaching event, submitted to Proc. Nat. Acad. Soc., 2006.

Greenblatt, J., Riahi, K. and Socolow, R.H., A Wedges Analysis of the IPCC SRES Scenarios, *Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies (GHGT-8)*, June 19-22, 2006, Trondheim, Norway.

Greenblatt, J.B., Succar, S., Denkenberger, D.C., Williams, R.H., and R.H. Socolow, Baseload Wind Energy: Modeling the Competition between Gas Turbines and Compressed Air Energy Storage for Supplemental Generation, *Energy Policy*. Vol. 35, Issue 3, Pages 1474-1492, March 2007.

De Lorenzo, L. and Socolow, R.H., Modeling Technology Choice under Alternative CO_2 Policies, *Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies (GHGT-8)*, June 19-22, 2006, Trondheim, Norway.

Keller, K. and D. McInerney, The dynamics of learning about a climate threshold. *Climate Dynamics*, in review (2007).

Keller, K., C. Deutsch, M. G. Hall and D. F. Bradford: Early detection of changes in the North Atlantic meridional overturning circulation: Implications for the design of ocean observation systems. *Journal of Climate*, 20, 145–157, (2007).

Keller, K., G. Yohe, and M. Schlesinger: Managing the Risks of Climate Thresholds: Uncertainties and Needed Information. *Climatic Change*, in the press (2007).

Keller, K., L. I. Miltich, A, Robinson, and R. S. J. Tol: How overconfident are current projections of carbon dioxide emissions? Energy Journal, in review (2007).

Keller, K., S.-R. Kim, J. Baehr, D. F. Bradford, and M. Oppenheimer: What is the economic value of information about climate thresholds? in:

"*Integrated Assessment of Human Induced Climate Change*", Chief Editor: Michael Schlesinger, in the press (2007).

Kunkel, C., Hallberg, R., and Oppenheimer, M., Coral Reefs Reduce Tsunami Impact in Model Simulations,Geophysical Research Letters , VOL. 33, L23612, doi:10.1029/2006GL027892, 2006

McInerney, D. and K. Keller: Economically optimal risk reduction strategies in the face of uncertain climate thresholds *Climatic Change*, in the press (2007).

Naevdal, E. and M. Oppenheimer, The Economics of the Thermohaline Circulation – A Problem with Multiple Thresholds of Unknown Locations (with E. Nævdal). *Resource and Energy Economics,* in press.

Naik, V., D. Mauzerall, L. Horowitz, M. D. Schwarzkopf, V. Ramaswamy, and M. Oppenheimer, On the sensitivity of radiative forcing from biomass burning aerosols and ozone to emission location, *accepted by Geophysical Research Letters,* December 2006.

O'Neill, B. C., P. Crutzen, A. Grübler, M. Ha Duong, K. Keller, C. Kolstad, J. Koomey, A. Lange, M. Obersteiner, M. Oppenheimer, W. Pepper, W. Sanderson, M. Schlesinger, N. Treich, A. Ulph, M. Webster, and C. Wilson, Learning and Climate Change, *Climate Policy*, in review (2007).

Oppenheimer, M., and A. Todorov. Global Warming: The Psychology of Long Term Risk, *Climatic Change*, **77**, 1–6, DOI: 10.1007/s10584-006-9086-6, 2006.

Oppenheimer, M., Science and Environmental Policy: The Role of Nongovernmental Organizations, *Social Research*, in press.

Patwardhan, A., S. Semenov, S. Schneider, I. Burton, C. Magadza, M. Oppenheimer, B. Pittock, A. Rahman, J. Smith, A. Suarez, F. Yamin, K. Keller, A Todorov, A. Finkel, D. MacMynowski, M. Mastrandrea, M. Fuessel, J. Corfee-Morlot, R. Sukumar, J.-P. van Ypersele, J. Zillman: Assessing Key Vulnerabilities and the Risk from Climate Change, *Chapter 19 in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, Working group II: Impacts, Adaptation and Vulnerability*, in review (2007).

Socolow, R.H. and S.-H. Lam, Good Enough Tools for Global Warming Policy Making, Accepted for publication in 2007 in Philosophical Transactions of the Royal Society.

Socolow, R.H. and S. Pacala. "A Plan to Keep Carbon in Check," *Scientific American*, Vol. 295, No. 3, pp. 50-57, September 2006.

Socolow, R. H., "Stabilization Wedges: An Elaboration of the Concept," in *Avoiding Dangerous Climate Change*, H. J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley, G. Yohe (eds), Cambridge University Press (Cambridge), pp. 347-354, 2006.

Socolow, R. H., Can We Bury Global Warming?, *Scientific American*, Vol. 293, No. 1, pp. 49-55, July 2005.

Yang, C.-J. and M. Oppenheimer, A "Manhattan Project" for Climate Change? *Climatic Change*, in press.