Carbon Mitigation Initiative

Annual Report 2011

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CMI Overview

The Carbon Mitigation Initiative (CMI) at Princeton University is a university-industry partnership sponsored by BP. The goal of the project is to find solutions to the carbon and climate problem that are safe, effective and affordable. Now entering our 12th year, our researchers are speeding progress in the areas of low-carbon energy, carbon storage, carbon science, and carbon policy.

The Low-Carbon Energy Group studies the production of power and fuels from fossil fuels with CO_2 capture, biomass as an energy source on its own and combined with fossil fuels, wind power, and batteries for power and storage.

The Storage Group studies potential risks of injecting CO_2 underground for permanent storage. Models of subsurface CO_2 behavior coupled with laboratory studies and field tests 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 Policy & 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 70 researchers. Together we are building a comprehensive view of the challenges of carbon mitigation - and how they can be overcome.

For more information, visit us at CMI's website - http://cmi.princeton.edu - or email us at cmi@princeton.edu.

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Summary

2011 was a year of growth for CMI. Long-term members continued to refine and apply tools developed in our first decade to better understand CO_2 capture and storage, natural carbon sinks, and carbon policy, while also striking out in new directions. At the same time, new faculty members have joined the CMI community with projects that complement and extend existing research.

The **Low-Carbon Energy Group** (formerly the Capture Group) has continued developing innovative strategies to advance a low-carbon energy economy, including motivating CO_2 capture and storage in the near-term (even in the absence of carbon mitigation policy) and improving energy storage for renewable power. Researchers continued work on novel fossil-fuel/biomass systems with carbon capture and storage that produce fuels and electricity, showing that using the captured CO_2 for enhanced oil recovery can make these facilities profitable even at low CO_2 prices, while also substantially decreasing fuel-related carbon emissions. They also found that achieving this vision will require incentives for commercializing co-production facilities and a substantially expanded infrastructure for transporting CO_2 over long distances. In energy storage research, new models have substantially improved prediction of the amount of energy stored in batteries with variations in charging power, laying the groundwork for better design of battery storage systems for wind and solar power.

The **Carbon Storage Group** has been investigating challenges in CO_2 storage from the field scale down to the molecular level. In field-based studies, researchers have collaborated with BP and Schlumberger to measure effective permeabilities of existing wells and have completed an analysis of the overlap of shale gas formations and potential CO_2 storage aquifers. The modeling teams continue to refine basin- and injection-scale models and use them to study potential storage sites, while bench-scale experiments are providing new insights into controls on CO_2 transport and dissolution. The group's molecular-scale modeling effort has been expanded through collaboration with new CMI members Athanassios Panagiotopoulos and Jeroen Tromp.

Carbon Science Group researchers have continued to monitor the marine and terrestrial carbon sinks and to develop new tools to improve both carbon cycle observations and the simulation of natural processes in Princeton's Earth System Model. Satellite observations show increased evidence for a recent abrupt increase in carbon uptake on land and new models are shedding light on the future of the CO_2 fertilization sink. A project with new CMI members Lars Hedin and David Medvigy on the future of the Amazon rainforest is augmenting existing terrestrial carbon cycle studies, and work on the impacts of climate change and ocean acidification on marine ecosystems has also been expanded. Finally, studies of the causes of long-term climate variability have been boosted by the discovery of Antarctic ice over 1 million years old that might enable extension of the atmospheric CO_2 record back 500,000 years or more, and by new modeling of the decadal-scale impacts of volcanism on carbon cycling.

The **Carbon Policy & Integration Group** has continued to develop and improve tools to enhance understanding of the challenges of carbon mitigation and the impacts of climate change, particularly sea-level rise. New work focuses on the communication of uncertainty about future "high-consequence" outcomes of climate change. The team has also added a focus addressing the practical challenges of scaling up low-carbon energy solutions, including a project by new CMI member Alexander Glaser to assess the promise of small modular nuclear reactors.

For the first time in 11 years, this report also pays homage to CMI's role in educating and mentoring graduate students. "CMI Student Update" features eight Ph.D. students, four past and four present, who are breaking new ground in scientific research and policy and whose varied career paths show the imprint of CMI support.

Finally, CMI's efforts are being enhanced by other energy-related initiatives on campus now more than ever. The Siebel Energy Challenge, directed by Robert Socolow, has awarded several new grants this year to strengthen undergraduate education in energy and the environment. Another complementary effort, Princeton's new Andlinger Center for Energy & the Environment, is a focal point for research on renewable energy and energy efficiency on campus in which several CMI members are involved. Ground has now been broken on the Andlinger Laboratory, an ambitious complex of three interconnected buildings that is intended to meet LEED silver standards and will provide more than 125,000 square feet of laboratory, cleanroom, classroom and lecture hall, and faculty and student space. We expect these complementary campus initiatives to offer continuing opportunities for research collaboration and cooperative educational efforts.

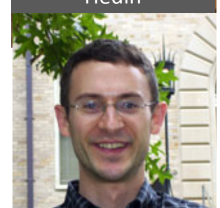
Now entering its second decade, the well-established CMI program is continuing to sprout in new directions. This report outlines progress in 2011 – for previous reports, including a comprehensive overview of our first decade, see http://cmi.princeton.edu/annual_reports.

News from the CMI community


Glaser


Ramana


Hedin


Medvigy


Panagiotopoulos


Tromp


Debenedetti

New CMI Investigators

In 2011, CMI competitively awarded three projects that have brought new faces to the program. The projects involve faculty from the School of Engineering and Applied Science, the Woodrow Wilson School of Public and International Affairs, and the Departments of Geosciences and Ecology & Evolutionary Biology.

Re-engineering the nuclear future

Alexander Glaser, an assistant professor of mechanical and aerospace engineering and international affairs, and M.V. Ramana, an associate research scholar at the Woodrow Wilson School, will focus on emerging nuclear technologies that emphasize small-scale solutions. They will examine how nuclear power potentially fits into a modern low-carbon energy system – one that may be more decentralized than today's system. The research project will draw expertise from the fields of computing, engineering, and policy to evaluate a range of possible alternative energy futures.

Investigations of the Amazon as a carbon sink

David Medvigy, assistant professor of geosciences, and Lars Hedin, professor of ecology and evolutionary biology, will coordinate field- and model-based assessments of the response and resilience of tropical ecosystems to global environmental change. Their study will seek to understand how nutrient feedbacks can affect the strength of the tropical forest carbon sink in the future, to better resolve the processes responsible for the conversion of soil carbon to atmospheric carbon dioxide (CO_2), and to investigate how plant diversity impacts the response of tropical forests to climate change.

Molecular modeling of CO_2 capture and storage (CCS)

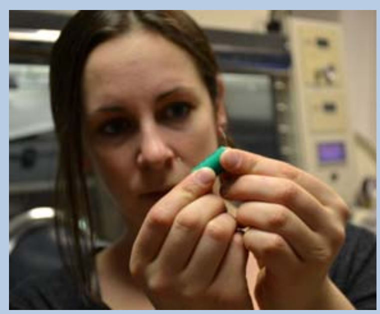
Athanassios Panagiotopoulos, professor of chemical and biological engineering, and Jeroen Tromp, professor of geosciences and director of the Princeton Institute for Computational Science and Engineering, will join the Storage Group's Pablo Debenedetti in developing molecular-based computational tools for predicting the physical and chemical behavior of systems relevant to CCS. In particular, the group will study CO_2/water/salt phase and interfacial behavior, examine systems for the separation of CO_2 from flue gases using novel solid adsorbents, and improve on the accuracy of seismic monitoring of CO_2 sequestration projects.

CMI Student Update

CMI has funded over 50 graduate students and over 60 postdoctoral fellows and research staff members since 2000, providing support for interdisciplinary research and an environment that encourages examination of issues from science, technology, and policy perspectives. Here are a few examples of impacts the CMI program has had on its graduate students' research and careers:

Samir Succar is a Staff Scientist at the Natural Resources Defense Council (NRDC) in Washington, D.C. His current work addresses key barriers to continued growth in renewable energy related to the development of electrical grid infrastructure for accessing and integrating variable energy resources. These include multi-region planning activities in the electric power sector as well as federal and regional transmission policy to facilitate large-scale renewable energy deployment.

This work has allowed him to expand on the research he undertook at CMI with Robert Williams from 2003-2008 on compressed air energy storage systems coupled to large-scale wind farms. His work in the Capture (now Low-Carbon Energy) Group focused on the technical and economic aspects of providing baseload power from hybrid wind/storage systems over long distance, high voltage direct current transmission lines. At NRDC, Samir interacts with federal and regional policy makers on matters of market design and regulatory policy for planning transmission and integrating renewables with variable output. His Princeton research and the interactions with CMI collaborators fostered a broad understanding of power system technologies, fuels, and carbon abatement pathways, which provides the foundation for all the work he does today at NRDC. Samir has also been able to continue to build on collaborations with Williams and others at Princeton to further the work on wind/storage systems, including several recent and forthcoming publications.



Elena Krieger is a fifth year doctoral student in Craig Arnold's Energy Storage Group. Her research includes modeling the fundamental rate limitations of battery charging, characterizing the frequency response of energy storage systems, and exploring how stochastic charging affects the poor practical lifespan of batteries in stand-alone wind and solar systems. This work can be translated into optimized design and control of energy storage systems in variable charge applications, leading to improvements in battery lifespan and total system efficiency.

Elena's broader interests are in the area of energy and international development. She has previously worked on clean energy technology in Brazil, Guatemala and Eritrea, and continues to stay engaged in development projects. Her involvement in CMI has allowed her to contextualize her work within the international energy field and better understand the challenges of simultaneously increasing access to energy while reducing reliance on carbon-emitting fuel sources. She hopes that her future work will have the same interdisciplinary nature as CMI, allowing her to integrate science, technology and policy while working on efficient clean energy systems in the developing world.

Sarah Gasda's affiliation with CMI started in the fall of 2001, when she began as a master's student in the Storage Group with Michael Celia. The focus of her master's thesis was the Alberta Basin, Canada, where she examined CO_2 capacity estimates and the age and spatial distribution of existing oil and gas wells in the Viking formation.

Sarah continued as a doctoral student in the Celia Group, developing new modeling tools for simulating CO_2 migration in saline aquifers and potential leakage through abandoned wells, particularly vertically integrated models that simplified the physics of large-scale CO_2 migration coupled with small-scale wellbore leakage more efficiently than a full-physics simulator. During her time at Princeton, Sarah also collaborated with BP Alternative Energy to quantify in-situ wellbore integrity using a downhole pressure test that she and Celia designed. To date, several wellbores have been field-tested using this technique, which provides valuable data concerning the leakage potential of abandoned wells (see page 28).

After receiving her Ph.D., Sarah took a postdoctoral position at the University of North Carolina, where she continued to study CO_2 simulation techniques while also publishing research on more efficient modeling of general problems of flow in porous media and groundwater remediation technologies. In 2011, she was appointed to a senior researcher position at the Center for Integrated Petroleum Research (Uni CIPR), a Norwegian Centre of Excellence at the University of Bergen, Norway. Having benefited greatly from her decade-long involvement with CMI, particularly her interactions with the CMI research network and industrial partners, she plans to continue work on problems of geological CO_2 storage. Her long-term goals are to further develop modeling tools that can be used for risk assessment of industrial-scale CCS projects.

Benjamin Court's doctoral work (2006-2011) focused on two critical aspects of CO_2 sequestration: CO_2 sequestration safety and the newly identified issue of water management coupled to CO_2 capture and sequestration operations. He was advised by Michael Celia of the Storage Group and also benefited from insights and advice from Robert Williams and other members of the community.

CMI support allowed Ben to study not only the technical aspects of CCS, but also its legal and policy implications. His coursework spanned engineering and natural sciences, and included courses taught by BP-Vann Visiting Fellows. Working with Michael Oppenheimer, and the Science, Technology and Environmental Policy (STEP) program, Ben's research was further informed by eye-opening courses at the Woodrow Wilson School and NYU Law School. CMI's continued commitment also provided Ben the freedom to work with a team from the Environmental Defense Fund at the Copenhagen climate conference and collaborate with Schlumberger on water and software projects.

The experiences and insights Ben gained from Princeton and CMI are now serving him well at Boston Consulting Group. He recently joined the Paris office as a Senior Associate contributing to the BCG Sustainability, Energy, and Public Sector practices.

Bryan Mignone pursued doctoral work with Jorge Sarmiento in the Science Group on questions related to the ocean carbon cycle. He focused on mechanisms by which the ocean takes up and sequesters anthropogenic carbon dioxide, one aspect of the larger set of processes that shape the evolution of global climate. He also worked with other members of the CMI community, including Robert Socolow and Michael Oppenheimer, on policy research questions related to carbon management.

Upon graduating from Princeton in 2006, Bryan moved to Washington, D.C. to focus full-time on climate change and energy policy issues. Over the last six years, he has served as a fellow and research director at the Brookings Institution, as a professional staff member on the Senate Energy and Natural Resources Committee, and as a senior advisor at the Department of Energy (DOE).

In his current role at DOE, Bryan coordinates domestic climate change activities within the Office of Policy and International Affairs, oversees a broad research portfolio spanning climate change impacts, adaptation and mitigation, and advises DOE leadership on a variety of related policy matters. He has been involved in several specific activities, initiatives and reports, including the U.S. Government's first social cost of carbon estimates, the President's clean energy standard proposal, and DOE's report on electric system resource adequacy implications of forthcoming EPA air quality regulations, among others. Bryan's approach to research and policy problems continues to be heavily influenced by his experiences at Princeton across the Department of Geosciences, the Woodrow Wilson School, and CMI. In particular, his interdisciplinary and inclusive approach to problems was developed and facilitated by a collaborative CMI research environment that brought together natural scientists, engineers, and economists in pursuit of a common objective.

Joseph Majkut currently works with Jorge Sarmiento in the Science Group, using modeling tools, observations and statistical methods to understand the processes that govern the ocean circulation, the distribution of chemical tracers within the ocean, and the carbon cycle. Using ocean simulations and a newly released database of surface ocean carbon content, Joe has developed a novel estimate of the historical air-sea carbon flux that reveals where in the ocean the flux was changing significantly over the last half century. The results show significant multi-decadal trends in the flux rate that he is currently working to attribute to various phenomena related to the upwelling of deep water, biological export and mesoscale temperature variability. He has also started using output from coupled atmosphere-ocean simulations and ocean models forced with averaged surface conditions to consider longer timescales.

Joe's work is one example of the many new tools developed as part of the Carbon Observing System supported by CMI to characterize natural sinks of carbon and better understand the carbon cycle. As an example of the kind of opportunity CMI support provides, Joe attended a summer school in Corsica hosted by SOLAS, the international Surface Ocean and Lower Atmosphere Science organization in 2011, spending two weeks interacting with students and young researchers from around the world and learning about the latest groundbreaking work in carbon cycle studies.

Luca de Lorenzo was part of the Capture (now Low-Carbon Energy) and Policy & Integration Groups from 2003 to 2006, working primarily on understanding the interaction between climate change policies and the energy sector, with a particular focus on power. His research with Tom Kreutz and Robert Williams tried to shed light on the best configurations for coal power plants with carbon capture and storage and explored the possibilities of co-producing electricity and hydrogen via syngas generation. Luca also worked with Robert Socolow and Tom Kreutz to understand to what degree such plants would be able to penetrate the power market.

In 2006, Luca joined BP Alternative Energy in London in a Group looking to develop/acquire novel carbon capture technologies. His career eventually led him to join BP Upstream and move to the Sahara desert at In Amenas (sister plant of In Salah gas, although with no CO_2 re-injection). There he experienced hands on what producing high amounts of CO_2 and possibly re-injecting them in the ground would "really" entail, beyond simple models. It was an eye opening experience.

In the last year Luca has joined the Energy Practice of the Boston Consulting Group and is continuing to apply the fundamental lessons he learned in CMI's university-industry partnership. He now works on several energy-related projects, ranging from Oil & Gas country entry strategies to advising big European utilities on how to deal with policy changes (e.g. nuclear acceptance or the ETS market).

Nicolas Lefèvre is a fifth year Ph.D. candidate working with Robert Socolow in the Policy & Integration Group. His research focuses on China's growing wind power industry, and aims to assess the mechanisms which have allowed Chinese wind turbine manufacturers to close the gap in terms of technological capabilities with western companies at the technological frontier. In particular, Nicolas is interested in the role of China's system of technological change, including interactions among firms, government institutions, and the research community that catalyze progress.

CMI supported Nicolas on two trips to China in 2011. During these trips Nicolas was hosted by long time CMI collaborators Professor Li Zheng, Director of the Tsinghua-BP Clean Energy Research and Education Center, and Professor Ni Weidou, who founded the center.

With the help of Professor Li and Professor Ni, Nicolas conducted interviews throughout the country with technology managers at several of China's largest wind power manufacturers, policy makers from various government bodies working on the wind power sector, officials with the main wind power industry associations, and professors and other researchers working on wind power technology at some of the country's leading research institutions. These meetings and interviews were the source of a wealth of quantitative and qualitative data that Nicolas is integrating into his dissertation.

Low-Carbon Energy

The goal of the Low-Carbon Energy Group is to develop cost-effective strategies to advance a low-carbon energy economy.

Recent work of Robert Williams and colleagues Tom Kreutz and Eric Larson explores novel ways of combining fossil fuels with biomass and CO_2 capture and storage (CCS) to produce low-carbon synfuels and electricity. Work on energy storage technologies has been initiated by Craig Arnold and colleagues to promote integration of renewable energy into the energy system.

Highlights

Combining Carbon Capture & Storage with Enhanced Oil Recovery

- The low cost of capturing CO_2 at coproduction facilities that make synfuels or synfuels plus electricity presents a strategic opportunity to get started with CO_2 capture and storage via enhanced oil recovery (EOR) even in the absence of a carbon mitigation policy, while simultaneously reducing oil imports.

- Coproduction systems fueled with coal or natural gas and a modest amount of biomass would enable a reduction in greenhouse gas emissions of 50% or more for the synfuels and electricity provided, but elevating such CO_2 EOR opportunities to more than a niche status will require an expanded CO_2 pipeline infrastructure.

- Before the CO_2 EOR strategy can become a commercial reality, first-of-a-kind commercial-scale coproduction projects are needed to demonstrate that these technologies can offer low-cost CO_2.

New Pathways to Synthetic Fuels

- Low-carbon synthetic gasoline made from methanol at a facility via separate gasification of coal and biomass with CCS, followed by methanol synthesis, has economics comparable to production of low-carbon Fischer-Tropsch transportation fuels in plants also using separate gasifiers for coal and biomass.

- New analysis of synthetic low-carbon gasoline production from coal and biomass via co-gasification in an entrained flow coal gasifier shows economics that are surprisingly competitive with economics of plant designs using separate coal and biomass gasifiers. The feasibility of co-gasification improves the prospects for near-term implementation of commercial coal/biomass to synfuels projects.

International Collaborations

- Collaborations with Chinese colleagues are growing and are being carried out in the context of strong Chinese interest in polygeneration technologies in the Chinese chemical process industry.

- Collaboration with the Energy Conversion Systems Group at Politecnico di Milano is leading to deepened insights relating to the thermodynamic performances of systems coproducing liquid fuels and electricity. The collaboration with Dr. Andrea Lanzini at the Politecnico di Torino is bringing forward new research opportunities relating to solid oxide fuel cells.

Energy Storage

- New simulations of battery storage efficiency have substantially improved prediction of the amount of energy stored in batteries for variations in charging power, laying the groundwork for better design of energy storage systems for wind and solar power.

Combining Carbon Capture & Storage with Enhanced Oil Recovery

During 2011, the Williams Group investigated CO_2 enhanced oil recovery (EOR) as a CCS market launch opportunity for coal and natural gas energy conversion systems without and with biomass coprocessing, low-carbon synthetic gasoline production from coal and coal + biomass, and the co-gasification approach to coproduction. During this period, collaborations with Chinese and Italian colleagues intensified.

CO_2 enhanced oil recovery: a CCS market launch opportunity

Since early 2011, Robert Williams and colleagues have been exploring the potential for launching CO_2 capture technologies in the market by selling captured CO_2 into EOR markets. In CO_2 EOR, a commercially established technology, CO_2 is injected into suitable mature oil fields to enable more oil production (typically CO_2 dissolves in the oil, reducing its viscosity and enabling more oil to flow to the well bore for recovery).

The Williams Group is carrying out analyses on the oil import reduction/carbon mitigation nexus for CO_2 EOR, the prospective economics of EOR, and public policy issues relating to EOR. These issues are discussed below in relation to five systems with CO_2 capture listed in Table 1, which are compared to an old "written-off" pulverized coal plant (WO PC-V) that vents CO_2 to the atmosphere. (Acronyms used to distinguish these plants are given at the bottom of Table 1.)

The first system is a widely discussed approach to CCS for coal power: the retrofit of a "CO_2 scrubber" to capture dilute CO_2 from the flue gases of a pulverized coal plant (PC-CCS retrofit). An attraction of this option is that it requires a relatively low capital investment. The scrubber uses a strong solvent to absorb CO_2 from the plant's flue gases. Then the CO_2 is recovered from the solvent via an energy intensive process, pressurized, and transported via pipeline to an EOR site.

The other four systems are plants that use coal or natural gas to make electricity plus Fischer-Tropsch liquid (FTL) synthetic diesel and gasoline with CO_2 capture, providing CO_2 for EOR. For these systems, the energy and cost penalties for CO_2 capture are much less than for the PC-CCS retrofit—both because the CO_2 is captured from pressurized synthesis gas streams at high concentrations, and because some CO_2 has to be removed from synthesis gas as an inherent part of making synthetic fuels.

Two of the four coproduction plants are coal-based "repowering" options, in which existing written-off pulverized coal plants are scrapped and replaced with new plants: one is a coal only plant (CTLE-CCS); the other coprocesses 9.2% switchgrass with coal (CBTLE-CCS-9.2%). The remaining two coproduction plants are natural-gas based systems located at the natural gas wellhead (GTLE-CCS and GBTLE-CCS-4.8%, with 4.8% switchgrass).

Table 1. Alternative Power and FTL Coproduction Options

Technology options[a]	10^3 (t/y biomass)	Output capacities FTL barrels/day (% of energy)	Electricity, (MW_e)	% of feedstock C captured	CO_2 stored, (10^6 t/y)	Total plant cost ($$10^6$)
WO PC-V	0	0	543	0	0	0
PC-CCS retrofit	0	0	398	90	3.47	426
Repowering options for the same coal plant site						
CTLE-CCS	0	7,619 (68)	226	52	2.06	1280
CBTLE-CCS-9.2%	246	8,366 (67)	257	52	2.27	1364
Options considered for deployment at the natural gas wellhead						
NGCC-V	0	0	560	0	0	321
GTLE-CCS	0	4,896 (57)	235	45	0.73	672
GBTLE-CCS-4.8%	83	5,236 (59)	237	52	0.81	727

[a] All coal options have the same coal input rate as the written-off pulverized coal plant being displaced (1613 MW). All natural gas options have the same gas input rate of 1102 MW. Acronyms: PC = pulverized coal power plant; WO = written off (a very old plant); V = CO_2 is vented; CCS = CO_2 is captured and stored; NGCC = natural gas combined cycle power plant; XTLE = plant that makes from X synthetic FTL fuels + electricity as a major coproduct, where X = G (natural gas), X = C (coal), X = GB (natural gas + biomass), CB (coal + biomass), TLE = "to liquids and electricity," FTL = Fischer-Tropsch liquid fuels (diesel + gasoline). Percentages appended to options coprocessing biomass are the percent of biomass in energy input.

The oil import reduction and carbon mitigation nexus for CO_2 EOR

There are currently 114 U.S. CO_2 EOR projects producing 272,000 barrels/day of crude oil (6% of U.S. production), using 50 million tonnes/year of CO_2 delivered from CO_2 sources to oil fields via 5800 km of CO_2 pipelines. Most projects use naturally occurring geologic CO_2, the supply of which is limited. However, EOR could be greatly expanded by using CO_2 captured from energy conversion facilities. A recent DOE report estimates that by 2030 some 3.4 million barrels per day of additional crude oil could potentially be produced from such anthropogenic sources (equivalent to 62% of U.S. crude oil production in 2010).

If all CO_2 captured at a PC-CCS retrofit plant like that described in Table 1 were used for EOR, incremental crude oil production would be 37,000 barrels/day. For the coproduction options in the table, each barrel of synfuel produced using captured CO_2 leads to ~ 1.5 incremental barrels of crude oil in the natural gas cases and ~ 2.7 incremental barrels in the coal cases.

The oil provided via CO_2 EOR makes it possible to displace oil that would otherwise be imported, while enabling carbon mitigation at the plants providing CO_2. Assuming that the CO_2 sold for EOR stays underground after oil recovery operations are concluded, the emission rate (kg CO_{2eq} per MWh) for the PC-CCS retrofit would be ~ 20% of that for the original coal power plant. The situation is more complicated for coproduction plants. Suppose that the greenhouse gas (GHG) emission rate assigned to electricity generation is that for a new natural gas combined cycle power plant venting CO_2 (NGCC-V plant), in anticipation of a plausible near-term regulation specifying that new power plants must have GHG emission rates no greater than that. Under this condition, the Williams Group has estimated (Figure 1) that the GHG emission rate for the F-T liquid fuels produced (red bar) is remarkably low: 50%, 35%, and 50% of the rate for the crude oil products displaced (brown bar) in the GTLE-CCS, GBTLE-CCS-4.8%, and CBTLE-CCS-9.2% cases, respectively.

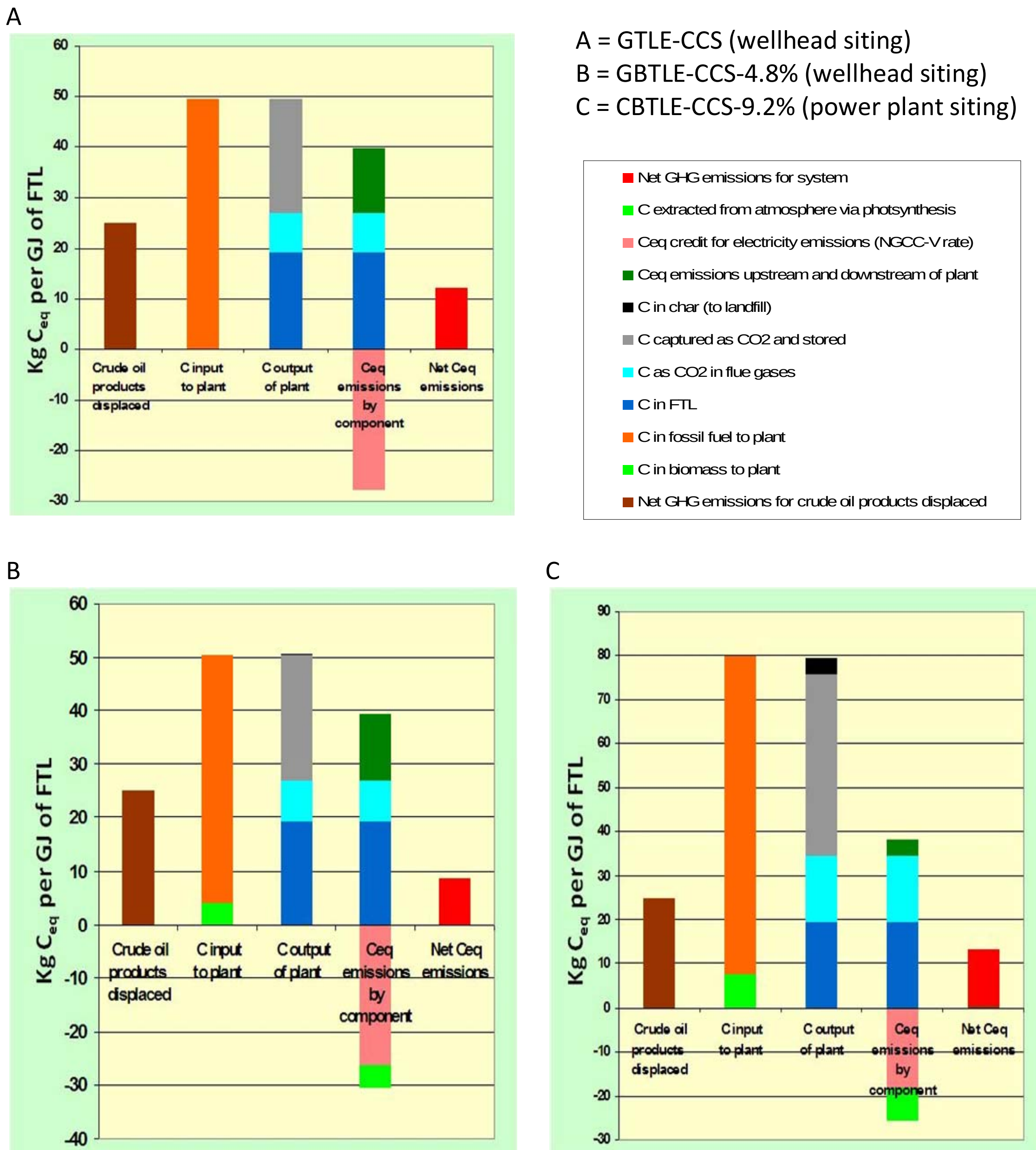


Figure 1. Carbon and GHG balances for three alternative coproduction options using natural gas, coal, and biomass to produce liquid fuels and electricity listed in Table 1. A) GTLE-CCS, B) GBTLE-CCS-4.8%, and C) CBTLE-CCS-9.2%. 1st Bar shows fuel-cycle-wide GHG emission rate for crude oil products displaced by FTL; 2nd and 3rd bars show plant's C balance (C output = C input); 4th bar shows fuel-cycle-wide GHG emissions by component (positive and negative elements); 5th bar shows net fuel-cycle-wide GHG emissions for FTL.

The economics of energy conversion coupled to CO_2 EOR

The Williams Group has carried out an internal rate of return on equity analysis for the energy conversion systems listed in Table 1 to illuminate the economics of CO_2 EOR in the absence of a carbon mitigation policy. Figure 2 shows that the most attractive option at high CO_2 prices is the PC-CCS retrofit, but at low CO_2 prices coproduction options are more profitable.

Most CO_2 EOR opportunities are in Texas and near the Gulf of Mexico. There are some old coal plants near such sites, the retrofit of which with CO_2 scrubbers would be very profitable, because the current price paid for CO_2 at the EOR site is $25 to $40 a tonne. But if an adequate CO_2 pipeline infrastructure were in place, then coproduction plants located up to a couple of thousand km from EOR sites would be able to compete in EOR markets because these plants would be profitable even at plant gate selling prices of $0/t (Figure 2), while the cost of long-distance transport via trunk pipelines is likely to be in the range $20 to $30 a tonne. This finding implies that with this infrastructure, captured CO_2 from as far away as wellhead-sited gas-based coproduction plants in Pennsylvania and New York using Marcellus and Utica shale gas and coal-based repowering coproduction plants in West Virginia could plausibly be competitive in CO_2 EOR markets in both the Gulf region and in Texas.

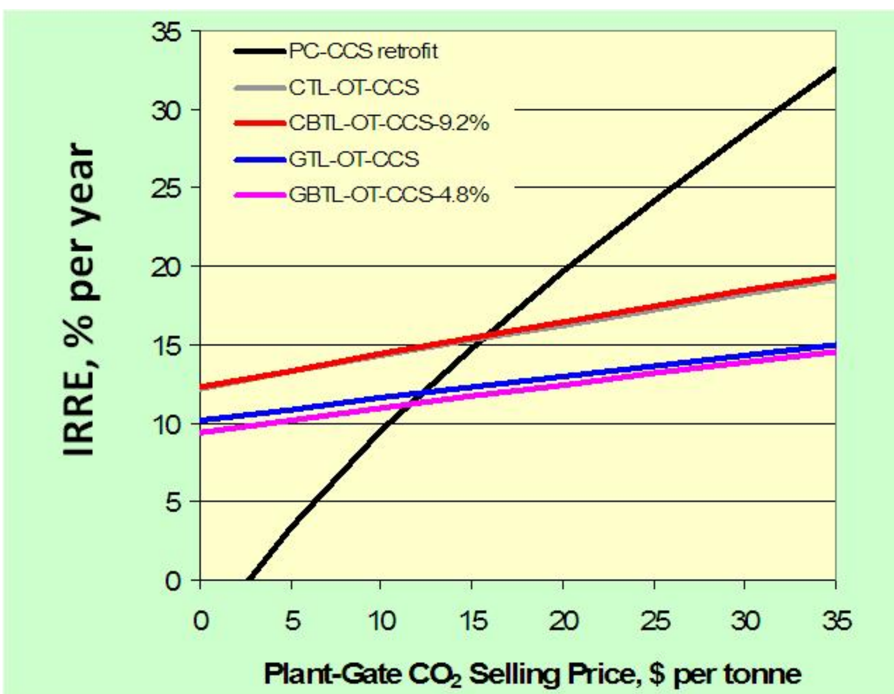


Figure 2. Internal rate of return on equity (IRRE) for the alternatives to a written-off coal plant (WO PC-V - Table 1), as a function of the plant-gate CO_2 selling price for EOR markets. Assumed prices: $2.0, $4.5, and $5.0 per GJ for coal, natural gas, and biomass, and $90/barrel for crude oil.

Policy analysis relating to CO_2 EOR and early action on CCS

The above analyses show that CO_2 EOR offers the opportunity to launch CCS technologies in the market — even in the absence of a carbon mitigation policy, while generating significant reductions in GHG emissions for both power generation and liquid fuels production, using technologies that could be brought into the market now. Technologies making synthetic fuels and synfuels + electricity are key to making CO_2 EOR a major CCS activity, because such systems would be able to compete even in distant EOR markets if an adequate CO_2 pipeline infrastructure were in place.

But most energy investors and policymakers are unaware of the technologies offering these strategic opportunities, and this situation is likely to persist until one or more of these technologies coupled to CO_2 EOR is demonstrated at commercial scale—an undertaking that is likely to require some kind of public sector support. Williams is investigating alternative public policy options by which some support might be provided, giving particular attention to opportunities that don't require federal government expenditures, in light of fiscal constraints facing the federal government.

One of Williams' 2011 activities was his participation in the Department of Energy's Quadrennial Technology Review, the goal of which was to find ways to make the Department more effective in establishing the technologies it is trying to advance in the market. Williams discussed in both QTR meetings and in written submissions to the QTR the strategic importance of CO_2 EOR and of tying synfuels and synfuels + electricity projects to CO_2 EOR applications. The QTR report released in September 2011, though, made no mention of CO_2 EOR.

In October 2011, Energy Secretary Chu asked the National Coal Council to prepare reports on CCS, CO_2 EOR, and synfuels. Subsequently the NCC invited Williams to participate in this study. Williams has accepted and intends to bring to that study the perspective discussed here.

New Pathways to Synthetic Fuels

Low-carbon synthetic gasoline production

Building on its earlier analyses of coproduction of F-T fuels and electricity from coal and biomass with CCS, the Williams Group investigated another commercially-demonstrated route for converting solids into a "drop-in" replacement fuel for transportation: synthetic gasoline synthesized from syngas-derived methanol. Methanol-to-gasoline (MTG) processes produce primarily a finished-grade gasoline, with a co-product of propane and butane.

Haldor Topsoe and Exxon Mobil offer commercial processes for syngas conversion to gasoline. The Exxon Mobil MTG process operated commercially in New Zealand for a decade, before the facility was converted to methanol production in the mid-1990's when methanol became more profitable. Recent oil prices are driving renewed interested in MTG plants. Commercial coal-to-MTG projects are under construction in China and have been proposed for the U.S.

The Williams Group developed detailed process simulations for a number of different coal- or coal/biomass-to-MTG plant designs, along with fuel-cycle-wide GHG emission balances and prospective capital and operating costs. Systems with substantial co-production of electric power were of particular interest, considering the favorable economics demonstrated for such designs in the group's earlier work on production of Fischer-Tropsch fuels. Comparisons of MTG results with prior FTL results have been facilitated by the group's use of a common analytical framework that includes Aspen process simulations and an in-house cost database and system evaluation software tool.

A key finding is that coal/biomass-to-MTG process designs and coal/biomass-to-FTL designs with similar features (separate coal and biomass gasifiers, similar biomass:coal input ratio, same biomass input rate, similar electricity:fuel output ratio – two left-most columns in Table 2) offer comparable economics (Figure 3). A detailed paper reporting on the MTG analysis is in preparation for publication.

Table 2. Comparison of Alternative Coproduction Options

	FTL via separate gasifiers (GE, coal; GTI, bio)	MTG via separate gasifiers (GE, coal; GTI, bio)	MTG via co-gasification (Shell) + biomass torrefaction
Biomass Fraction, %	39.5	28.6	28.2
Electricity Fraction, %	33.6	28.2	28.4
Greenhouse gas emissions index	0.11	0.09	0.12
<u>Feedstocks in</u>			
Biomass, MW (HHV)	661	661	587
Coal, MW (HHV)	1,011	1,651	1,492
<u>Products out</u>			
Gasoline, bpd	8,036	11,582	9,937
Gasoline, MW (LHV)	508	675	579
LPG, MW (LHV)	0	68	59
Electricity, MW	257	292	253
Efficiency, % (HHV)	48.9	47.6	45.9

MW = megawatt, bpd = barrels per day, HHV = higher heating value, LHV = lower heating value

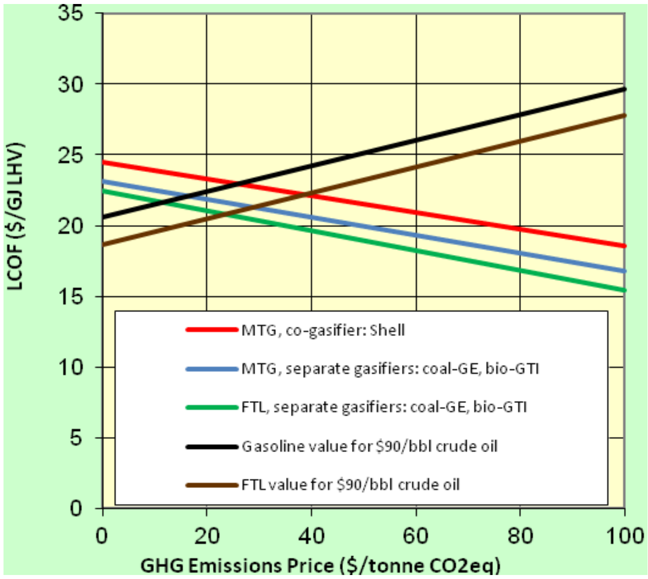


Figure 3. Levelized cost of transportation fuel (LCOF) from coal and biomass in systems with CCS that co-produce electricity. See Table 2 for system characteristics.

Co-gasification approach to coproduction

Co-supported by a grant from the National Energy Technology Laboratory, the Williams Group has been investigating a variety of process designs for coproducing electricity and synthetic gasoline or electricity and chemicals (olefins, ammonia, or hydrogen) from a mixture of coal and biomass with CCS. The work has focused on co-gasification of the feedstocks in commercially established entrained-flow coal gasifier designs, unlike earlier work (see above) that examined systems with separate coal and biomass gasifiers.

Co-gasification is technically feasible, but pretreatment of the biomass is important to facilitate feeding. Torrefaction, a slow cooking process that destroys the fibrous nature of biomass (making it easier to feed the biomass into the gasifier along with coal), was investigated as a promising pretreatment strategy. Surprisingly, for a system using dry-feed gasification (Shell) of coal and torrefied biomass and achieving ~90% reduction in GHG emissions (Table 2, right column), the economics are only slightly worse than for a system using separate coal and biomass gasifiers to achieve a similar GHG reduction (Figure 3). This result is surprising, because the co-gasification system utilizes a more costly gasifier (Shell instead of GE) and a more costly pretreatment process (torrefaction), and a less energy-efficient approach to biomass gasification. But shifting from two gasifiers to one leads to scale economy benefits that go a long way in offsetting the cost penalties.

Another notable finding in Figure 3 is that the GHG emission price for breaking even with petroleum-derived gasoline (16 to 26 \$/t CO_{2eq}) is far lower than the GHG emission price needed to induce decarbonization of stand-alone coal-fired power plants, which suggests that coproduction systems such as those modeled here offer an attractive way to decarbonize electric power generation as well as providing low-carbon fuels. The work described here will be submitted for publication in the coming year.

International Collaborations

Chinese collaborations

The Williams Group continues to maintain strong collaborations with Chinese colleagues. Three activities in 2011 are notable:

- Larson and Tsinghua University colleague Zheng Li collaborated as Co-Convening Lead Authors, and Williams as a Lead Author, of the Fossil Energy Systems chapter of the Global Energy Assessment (GEA), an IPCC-style study involving several hundred authors and reviewers globally. The GEA describes sustainable technologies and strategies for addressing major societal challenges connected to energy. It will be published in book form by Cambridge University Press in 2012 and is anticipated to be "essential reading" for public and private sector decision-makers worldwide.

- Collaboration continued with former post-doctoral fellow, Guangjian Liu, who returned to China in late 2010 to take a faculty position at North China Electric Power University (NCEPU). During 2011, Liu collaborated on the MTG analyses described in earlier paragraphs. Liu was the lead author of a paper that won the CMI's award for best paper published in 2011 by a CMI post-doctoral fellow.

- Larson, together with Guangjian Liu, and former visiting fellow, Dr. Xiangbo Guo (visiting from SINOPEC during 2010), presented a coordinated set of three papers at the Sixth Sino-U.S. Joint Chemical Engineering Conference held in Beijing in November 2011. The conference, with a theme of clean energy, was well attended by high-level decision makers and national academy members from both sides of the ocean. These papers, dealing with various aspects of coal/biomass conversion to liquid fuels and electricity, were well received.

- Williams and Larson initiated their participation in a 5-year Coal Conversion and Utilization Research and Education Program led by colleagues at NCEPU in Beijing. The program is a collaboration of investigators from NCEPU and U.S., Australian, Swedish, and British universities. The program was established in 2011 when a prestigious "111 Program" grant was awarded by the Chinese Ministry of Education to NCEPU. The Ministry created the 111 Program to support collaboration between scholars from the world's top 100 universities and colleagues at China's top 100 universities.

These Chinese collaborations are especially important in light of the high level of interest in China in coproduction technologies where they are labeled "polygeneration" technologies. The coal chemical process industry in China has extensive experience with modern coal gasification technologies (more than all the rest of the world combined), and there is much interest in extending this industrial experience from niche chemicals markets to the much larger fuels and electricity markets that require very similar energy conversion technologies.

Italian collaborations

In 2011, the Williams Group continued its longstanding collaboration with the Energy Conversion Systems Group at Politecnico di Milano. The research used the novel bottoming cycle optimization methodology of Professor Emanuele Martelli (former visiting researcher with the group) to re-analyze and understand more deeply the efficiencies of energy conversion facilities that produce electricity and liquid fuels. By generating both theoretically optimal and more realistic (i.e. economically viable) plant configurations for waste heat recovery, Martelli's software provides important context for the Williams Group's previous work, highlighting both opportunities for optimizing designs and the need to make practical concessions for improved system operability and economics. This work resulted in a peer-reviewed paper (Martelli et al., 2012).

The Williams Group also continues to collaborate with Dr. Andrea Lanzini at the Politecnico di Torino, who was a visitor with the group as a Fulbright scholar in 2010. The collaboration in 2011 focused on solid oxide fuel cells (SOFCs) and fuel cell/gas turbine (FCGT) hybrids. Lanzini applied the Capture Group's systems analysis methodology to advanced power plants, coupling coal gasification and an FCGT hybrid, with an emphasis on strategies for "methanating" synthesis gas upstream of the SOFC in order to significantly improve overall conversion efficiency. Lanzini presented these findings at the 11th European Fuel Cell Conference and as a result was invited to submit a paper on the findings to a peer-viewed journal. Also, a second paper by Lanzini, Kreutz and Martelli was accepted for presentation at the ASME Turbo Expo 2012 and publication in an ASME journal (Lanzini et al., 2012).

In December 2011, Kreutz gave the keynote presentation at the kickoff meeting of "SOFC CCHP with poly-fuel: operation and maintenance" (SOFCOM), a 3-year EU research project that explores - both experimentally and analytically - combined heat and power production in SOFC systems. SOFC systems analyses will be carried out with both Lanzini (lead researcher) and Ilkka Hannula of the Finnish Technical Research Center, who was a visiting researcher with the Capture Group in 2011.

Optimizing Energy Storage for Renewable Energy Systems

Craig Arnold and colleagues study energy storage systems, particularly for use with renewable energy. This past year the researchers have been studying the amount of energy stored in commercially available batteries in response to variable rates of charge and discharge. Energy harvesting systems like wind and solar generators or regenerative braking in cars deliver power in a very non-constant manner. Therefore, when one tries to store this energy, one has to consider the effects of variable rates on the efficiency of charge storage in batteries. Traditional measures of battery efficiency are based on constant charge and constant discharge, but to truly meet the demands of alternative energy and electric vehicles, the effects of variations in charging and discharging must be understood.

Battery *discharge* efficiency is known to decrease with increasing power, i.e., the faster one tries to pull energy out of a battery, the less energy the system can provide. This relation is known as the Ragone relation between power and energy density. The Arnold Group has modeled a similar but critically important trade-off - between charging power and battery *storage* efficiency. The team found good agreement with experimental measurements in lithium-ion batteries in their simulations, in contrast to traditional resistance-only models that fail to reproduce the dramatic fall-off in storage efficiency at high powers (Figure 4).

Efficiency loss at large charging rates is found to result from internal losses as well as premature arrival at voltage limits which are a practical safety feature in all battery systems. The latter effect was found to have a greater impact on battery charging as compared to discharge, which is a significant interpretation of how the way a battery is used affects its storage capacity. These results represent a first step toward determining the projected efficiency of a complete storage system operating over a wide range of charging powers and will help improve the design of such systems.

The group has further initiated a set of experiments to determine the effect of variable wind turbine input on the lifespan of four different battery chemistries. The results of this aging experiment will allow for improved design of battery storage systems for small-scale wind energy storage and offer insight into the effects of variability on battery degradation.

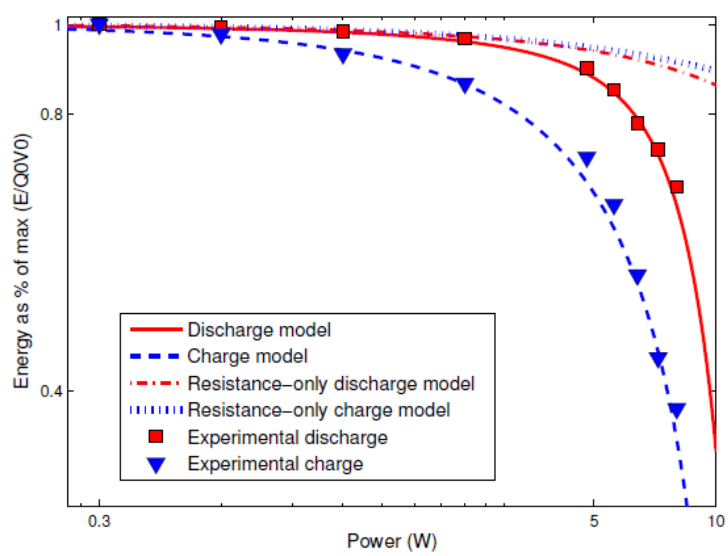


Figure 4. Battery storage efficiencies calculated from simulations and experiments. Battery storage efficiency is lower when charging versus discharging (blue versus red shapes). Simulations using traditional techniques (labeled "resistance only models") do not accurately represent the amount of energy stored in the batteries, but the Arnold Group's simulations match the measured data well.

Low-Carbon Energy Publications

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Peabody, C. and C.B. Arnold. "The role of mechanically induced separator creep in Lithium ion battery capacity fade" *J. Power Sources*, 196, 8147-8153, 2011.

Skone, T.J. (Project Lead), D.T. Allen, C.Allport, K. Atkins, D. Baniszewski, D.G. Choi, J.S. Cooper, A. Curtright, R.M. Dilmore, R.S. Eckard, A. Elgowiny, W. Gillette, W.M. Griffin, W.E. Harrison III, J.I. Hileman, S. Kennedy, E. Larson, A. Levy, K. Lewis, J. Marriott, D.J. Morgan, C.F. Murphy, M.A. Nippert, M. Pearlson, G. Rhoads, G. Schivley, R.W. Stratton, T.Tarka, P.H. Taylor, V.M. Thomas, M.Q. Wang, and H. Willis. "Life Cycle Greenhouse Gas Analysis of Advanced Jet Propulsion Fuels: Fischer-Tropsch Based SPK-1 Case Study." AFRL-RZ-WP-TR-2011-2138, Air Force Research Lab, Propulsion Directorate, Wright-Patterson Air Force Base, Ohio, September 2011.

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Williams, R.H., G. Liu, T.G. Kreutz, and E.D. Larson. "Biomass and coal to fuels and power." *Annual Review of Chemical and Biomolecular Engineering*, 2, 529-553, 2011.

Williams, R.H., G. Liu, E.D. Larson, and T.G. Kreutz. "Low-C power from fossil fuel and biomass with synthetic fuels coproduction." Paper prepared for ACS Fuel Division Symposium on Fuels, Chemicals, Materials, and Energy from Biomass, Coal, and Natural Resources, Anaheim California, 27-31, March 2011.

Carbon Storage

The Storage Group works to evaluate the effectiveness and safety of geological CO_2 sequestration. The group's large-scale modeling investigations of the challenges of CO_2 sequestration in saline aquifers are complemented by field-based analyses, bench-scale laboratory experiments of flow in porous media, pore-scale network modeling, and molecular-scale modeling of processes relevant to carbon storage.

The PI's of the Storage Group are Michael Celia, Pablo Debenedetti, Athanassios Panagiotopoulos, Jean-Hervé Prévost, Howard Stone, and Jeroen Tromp.

Highlights

Field-Based Analyses

- Comparison of areas suitable for shale and tight gas production and those suitable for CO_2 storage show significant overlap, indicating potential conflict in subsurface usage and reduction of CO_2 storage capacity due to fracturing of possible caprock formations.

- In situ determination of effective wellbore permeability shows a range from about 1 milliDarcy to about 50 Darcy, values much larger than one would expect from intact cement and in the range of reservoir permeabilities.

Large-Scale Modeling

- Efficient multi-scale models are simulating a wide range of practical, large-scale problems and show good agreement with full-physics simulators.

- Simulations suggest that successful implementation of full-scale CO_2 injection operations will likely require active reservoir management through brine production, along with innovative strategies for resource utilization.

- Detailed analyses have been performed using our in-house simulator *dynaflow* to investigate the effects of thermal stresses on wellbore and cap-rock integrity.

Small-Scale Processes

- Pore-scale network models can provide insights and quantitative information about hysteresis and phase trapping in two-phase displacements, and about impacts of geochemical reactions on changes in porosity and permeability.

- Using bench-scale experiments and theory, a new hydrodynamic instability has been identified with relevance for flow in porous media.

- Modeling and experimental studies indicate self-similar behaviors for gravity current propagation in and leakage from porous media in some specific cases.

Molecular-Scale Simulations

- State of the art molecular simulation techniques have been successfully applied to the calculation of the phase behavior of carbon dioxide-brine mixtures under conditions relevant to carbon capture and storage.

- New simulations of methane hydrate formation are the first to show nucleation in the absence of an interface.

- Simulations confirm that inclusion of poroelastic behavior is important for description of physical properties of reservoirs.

Field-Based Analyses

In situ measurement of effective wellbore permeability

There are millions of old oil and gas wells in North America. Because these wells represent potential leakage pathways for injected CO_2 as well as displaced brines, it is important to characterize the properties of these wells. Both BP (through collaboration with Walter Crow) and Schlumberger (through collaboration with Princeton alumnus Andrew Duguid) have used a technique called a Vertical Interference Test (VIT) to determine, in situ, the effective permeability of materials (mostly cements) outside of well casings. These tests provide permeability estimates over distances of a few meters along the well. Michael Celia and colleagues have analyzed these test results to infer the effective permeability of the materials outside of casing.

These tests are not easy to perform, and to date nine tests have been performed in six different wells. The Celia Group has analyzed each of these data sets, and from this analysis approximated the well permeability. Of the permeability values from tests that yielded usable numbers (6 of the 9 tests), 3 have been approved for publication (Table 3). They range from about 1 milliDarcy (mD) to about 50 Darcy (D). To put this into perspective, permeability of a good reservoir rock is typically about 100 mD; the Utsira formation, which is the injection formation for the Sleipner operation, has permeability of about 1 D, while the In Salah reservoir has permeability of about 10 mD. Cement cured at room conditions usually has a permeability of about 0.01 microDarcy. These initial numbers indicate that effective permeabilities outside of casing, over distances of a few meters along the well, are higher than expected and are roughly in the range of reservoir permeabilities. These numbers can form the basis of more realistic simulations to estimate leakage along old wells.

Table 3. Estimated permeability of materials outside well casings

Well	No. VIT	Estimated Permeability	Notes
CCP1	1	1.15 mD	Analysis published in collaboration with BP (Crow et al., *IJGGC*, 2010)
DOE1	1	45 D	Will be published in collaboration with Schlumberger
DOE2	1	5.9 mD	Will be published in collaboration with Schlumberger

Shale gas interference with CCS

Geological sequestration requires a deep permeable geological formation into which captured CO_2 can be injected, and an overlying impermeable formation, called a caprock, that keeps the buoyant CO_2 within the injection formation. Shale formations typically have very low permeability and are considered to be good caprock formations. Production of natural gas from shale and other tight formations involves fracturing the shale with the explicit objective of greatly increasing the permeability of the shale. As such, shale gas production is in direct conflict with the use of shale formations as a caprock barrier to CO_2 migration.

The Celia Group has examined the locations in the United States where deep saline aquifers, suitable for CO_2 sequestration exist, as well as the locations of gas production from shale and other tight formations (Figure 5). While estimated sequestration capacity for CO_2 sequestration in deep saline aquifers is large, up to 80% of that capacity could be adversely affected by shale and tight gas production. Analysis of stationary sources of CO_2 shows a similar effect: about two-thirds of the emissions from these sources are within 20 miles of a deep saline aquifer, but shale and tight gas production could affect up to 85% of these sources. These analyses indicate that co-location of deep saline aquifers with shale and tight gas production could significantly affect the sequestration capacity for CCS operations. This suggests that a more comprehensive management strategy for subsurface resource utilization should be developed.

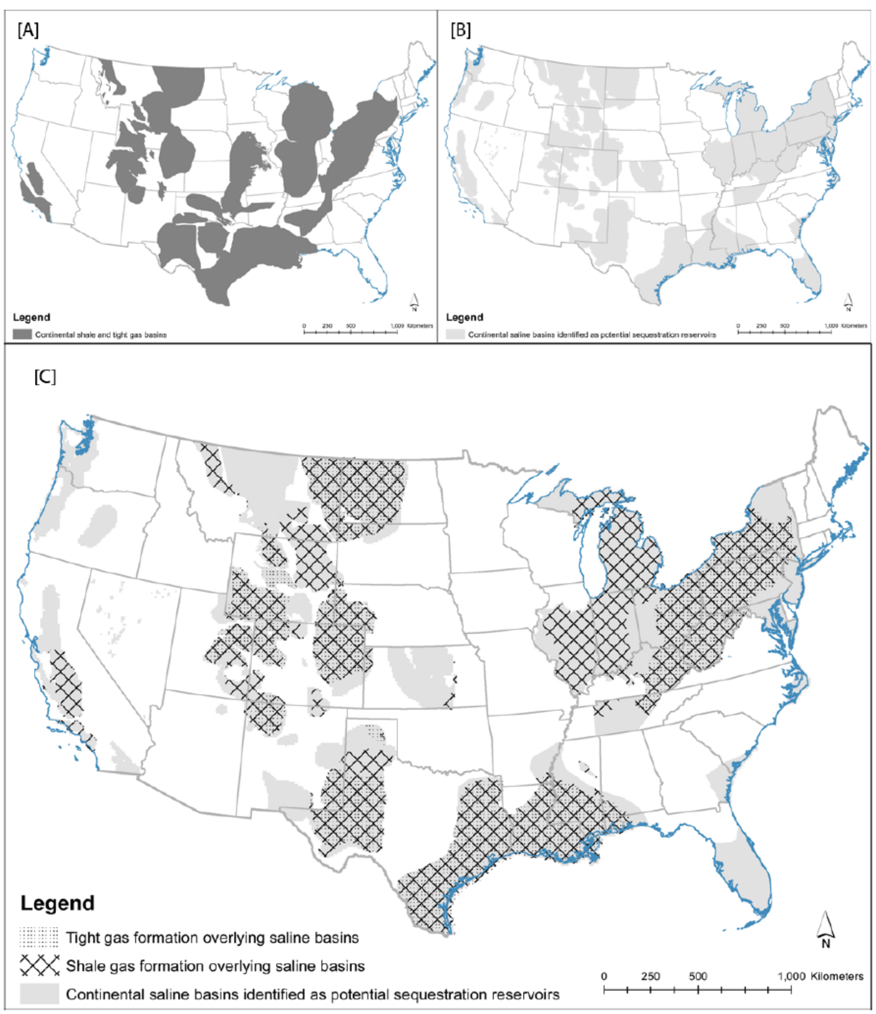

Figure 5. A) EIA identified tight and shale gas basins, which could be use for unconventional gas production; B) saline basins identified by NATCARB as ideal storage formations; and C) overlap of (A) and (B). The gas basins overlap over 60% of the targeted saline formations within the contiguous continental United States.

Basin-Scale Modeling

Large-scale models for CO_2 injection, migration, and leakage

The Celia Group continues to develop a suite of models to simulate CO_2 injection, migration, and potential leakage, with applications to a number of potential injection sites. These models predict pressure buildup in the formation, movement of both CO_2 and brine within the injection formation and across confining units into other formations, capillary trapping of CO_2, and dissolution of CO_2 into the brine phase (that is, solubility trapping). The models are developed in a multi-scale framework so that scaling issues in both space and time are addressed explicitly and large-scale simulations can be performed easily.

To show how these models behave, the researchers have systematically compared the models, which are based on the assumption of vertical equilibrium, with full three-dimensional simulations using the industry standard Eclipse. For most formations suitable for CO_2 injection there are excellent matches in results (Figure 6).

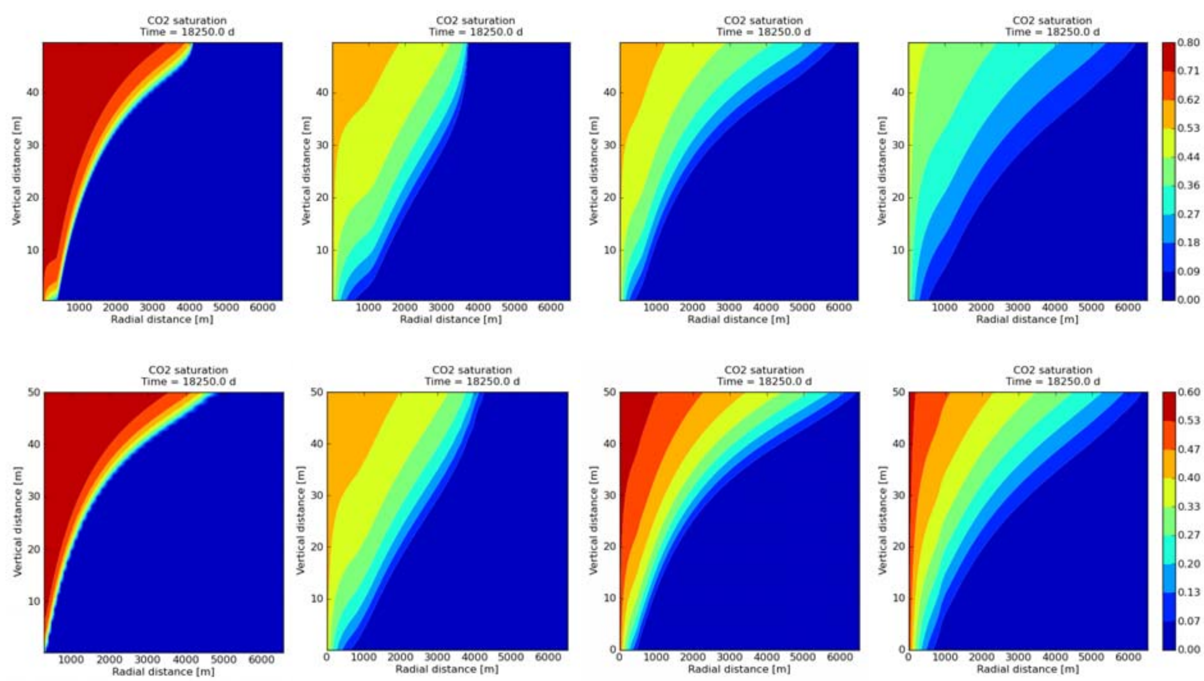

Figure 6. Comparison of radial saturation profiles from Eclipse (top row) and vertically integrated simulations (bottom row) using different combinations of saturation-relative permeability and saturation-capillary pressure relationships. The first column use values from a study by Ebigbo et al. (2007), the second one is from Pruess et al. (2002), the third and fourth are from Zhou et al. (2008, 2010) . Figure from Court et al. (2012a).

Another recent study shows how local capillary pressure effects, which lead to a capillary transition zone in the vertical saturation profile, can impact the development and migration of a CO_2 plume. An application to the Johannson formation, under the North Sea, shows the relative importance of the capillary transition zone, convective mixing associated with large-scale dissolution, and buoyant migration. Finally, a recent study focused on leakage along old wells shows how the estimated leakage rates for a field in the Alberta Basin can be related to the statistical properties used to define the permeability of the wells in the field. Such a relationship allows both operators and regulators to determine the range of statistical properties required in order to reach a specified target threshold for leakage.

Basin-scale modeling including active reservoir management

Celia and colleagues have applied their modeling tools to several sedimentary basins that have practical importance, including the Illinois Basin, the Michigan Basin, and the Alberta Basin. In the Illinois Basin, they have focused on injection into the Mount Simon formation, considering scenarios in which most of the emissions from power plants and ethanol plants within the basin are captured and injected. This leads to injection of about 140 Mt CO_2/yr.

Simulation results show that such a large-scale injection strategy is feasible. Without any spatial optimization of the injection operations, the CO_2 plumes all remain relatively small while the pressure pulse expands across most of the basin (see Figure 7, left and middle panels). None of the injection well pressures exceeds estimated fracture pressures, but the spatial extent of pressures that exceed the threshold pressure defining the Area of Review is large. Both the large spatial extent of the pressure footprint and the overlapping footprints among neighboring injection operations motivates an expanded strategy to control the spatial extent of the pressure field.

The researchers have also examined the impacts of brine production for the Illinois Basin, as shown in the right panel of below (Figure 7). Note that extraction of brine volumes similar to the volume of injected CO_2 isolates individual injection operations and greatly reduces the overall areas of review. The challenge now is to find beneficial uses for the extracted fluid, which leads to broad considerations of geothermal energy, water management and overall resource management and utilization. Studies similar to those being pursued for the Illinois Basin are ongoing for the Michigan and Alberta Basins.

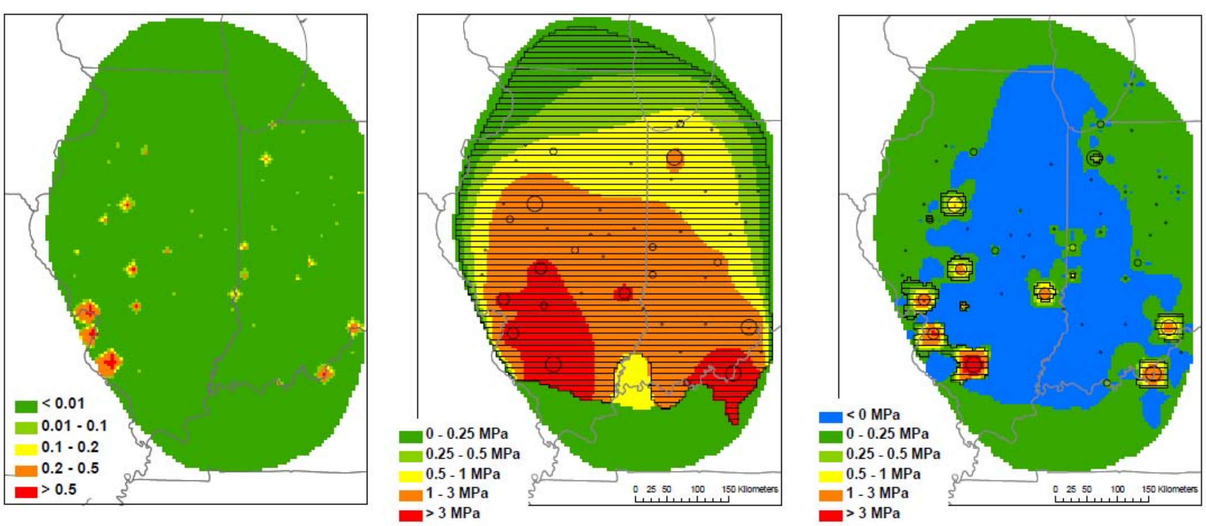

Figure 7. Results from full-scale Illinois Basin simulations. Left image shows CO_2 plumes, middle image is pressure increase with no active management, right image is pressure increase with active management of pressure.

Injection-Scale Modeling

Simulation of CO_2 injection with *dynaflow*

Several numerical tools aimed at improving simulation of geological storage of CO_2 have been developed and incorporated into the Prévost Group's finite element software *dynaflow,* which offers a modular, hierarchical approach for multiphase and multiphysics simulations. These tools allow capturing of the effects of coupling between fluid flow and thermal and geomechanical effects.

In their previous simulation of the In Salah (Algeria) injection operation, Prévost and colleagues detected the potential for thermal fracturing in the cap-rock as a result of cold CO_2 injected in a reservoir at higher temperature. In 2011, the group used *dynaflow* to further investigate the effects of thermal stresses on wellbore and cap-rock integrity. The researchers have performed detailed analyses and parametric studies that include the effects of injection temperatures, in-situ initial stresses (in particular for a strike-slip stress regime), rock fracture toughness, friction angle and cohesion. They are in the process of assessing the risks for thermal and hydraulic fracture and shear failure.

Further work will be done to improve the compositional aspects of *dynaflow*, in particular in modeling boiling of CO_2 as it moves from the storage formation to the surface in a leakage scenario.

Small-Scale Processes

Pore-scale network models

The Celia Group also has funding from the National Science Foundation to support mathematical developments related to CO_2 modeling on very small scales. One aspect they are studying is hysteresis and phase trapping, with a focus on trapping models for nonwetting phases, including CO_2. To understand how trapped nonwetting fluids evolve as a function of phase saturation, they are using pore-scale network models to simulate two-phase displacement and extracting a wide range of information about trapped nonwetting fluids. This information is being used to compare and test existing theories as well as new theories that include explicit representation of trapped phases.

In a project funded by the Department of Energy, with Catherine Peters as the lead PI, Celia and colleagues are using pore-scale network models to simulate reactive transport including dissolution and precipitation associated with carbonated brines injected into carbonate formations (Figure 8). These models provide insights into conditions under which dissolution, precipitation, or a complex combination of the two will occur, with associated calculations of changes in porosity and permeability. Like the two-phase hysteretic relationships, the response of porosity and permeability to geochemical reactions shows non-uniqueness, implying a complex relationship that depends on additional subscale factors.

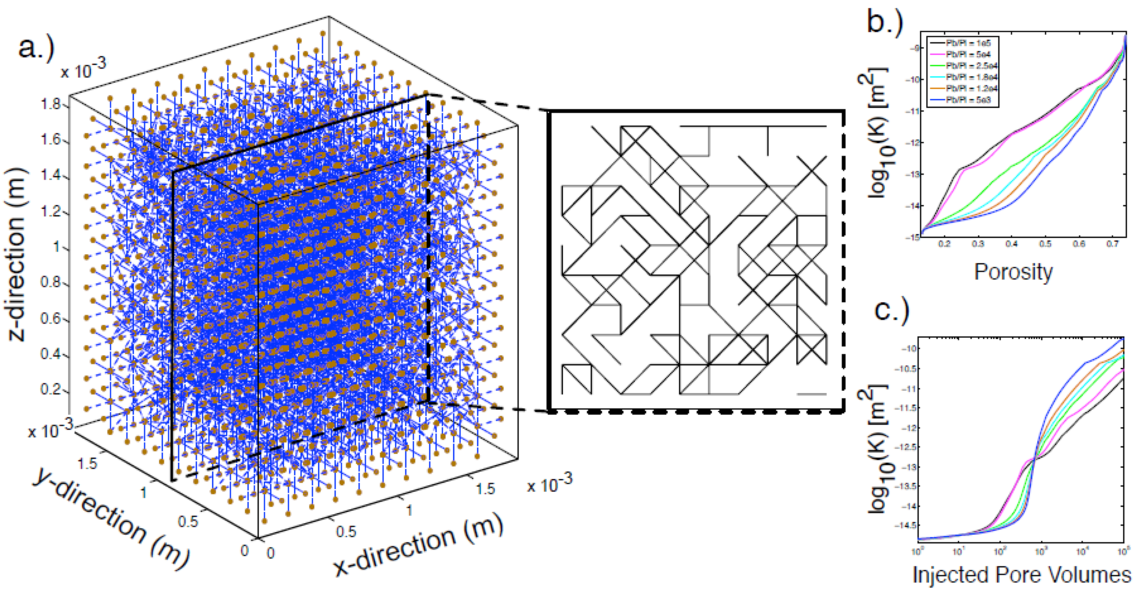

Figure 8. Results from single-phase reactive pore-scale network models showing (a) pore network, (b) evolution of permeability and porosity for different invasion conditions, and (c) evolution of permeability as a function of injected pore volumes. Figure from Nogues et al. (2012).

Bench-scale investigations of multiphase flow

Carbon sequestration raises new questions regarding multiphase flows in porous media, which the Stone Group is investigating with a combination of bench-scale laboratory experiments and theory. The group is investigating four distinct scenarios: (i) two-phase injection flows with permeability gradients in the flow direction, (ii) two-phase invasion flows in a parameter space expected for CO_2 injection, including the influence of vertical gradients of permeability, (iii) leakage from a porous medium, and (iv) buoyancy-driven flows driven by dissolution of one phase in a second phase, with the parameter space comparable to that expected for carbon sequestration. The group's work on micron-scale processes is providing new insight into the controls on CO_2 transport and dissolution, which can be used to inform large-scale models for predicting the fate of CO_2 in injection reservoirs.

Impacts of permeability gradients on flow stability

In heterogeneous media, it is well known that when a fluid of high viscosity displaces a less viscous fluid, the interface can still be unstable and exhibit finger-like patterns due to capillary fingering. For two-phase injection flows with permeability gradients in the flow direction, the Stone Group has shown that surface tension triggers a new type of hydrodynamic instability (analogous to the traditional form of "viscous fingering") relevant to flows in model porous materials. Using a Hele-Shaw configuration of two parallel plates, the researchers showed that, for given parameters, there is a critical speed (or capillary number) for which the flow is either stable or unstable. The researchers found that a dimensionless parameter, Ca (the ratio of the permeability gradient to a traditional capillary number) determines the stability of the interface (Figure 9).

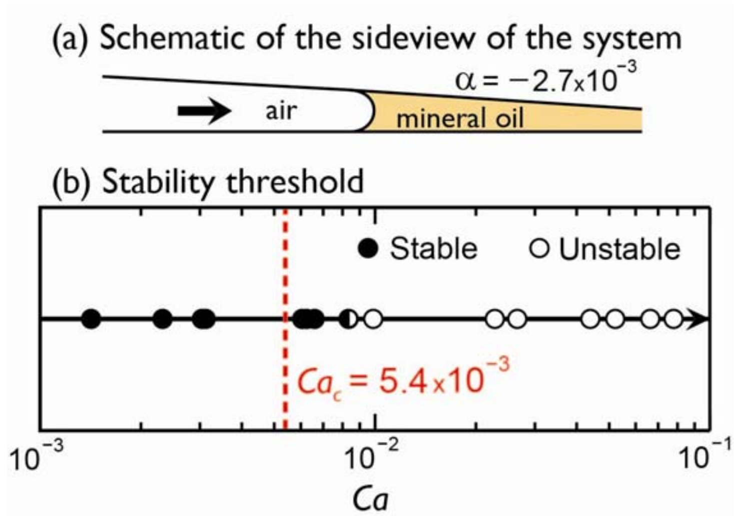

Figure 9. a) Schematic of the Hele-Shaw experimental apparatus and b) the results from the two-phase injection experiment with a permeability gradient in the flow direction (Ca_c from theory is shown). Height of apparatus is 1.4 cm at right, length is approximately 40 cm, and width (not shown) is 5.1 cm.

Propagation of gravity currents in porous media with vertical permeability gradients

In related work on invasion flows, the Stone Group has shown that the influence of a permeability gradient produces qualitative differences in the solution, and that the rate of spreading is influenced by transverse gradients of permeability. Zhong Zheng, co-advised by Stone and Robert Socolow, simulated the influence of a vertical permeability gradient on the horizontal propagation of gravity currents in porous media. A self-similar solution was found for the flow, which indicated a power-law behavior for the front propagation (Figure 10). To verify the modeling work, he designed fluid displacement experiments in Hele-Shaw cells using liquids that are expected to have similar dynamical responses as the case for CO_2 injection, and measured the profile shape and the front propagation dynamics. Experimental results fit well with model predictions.

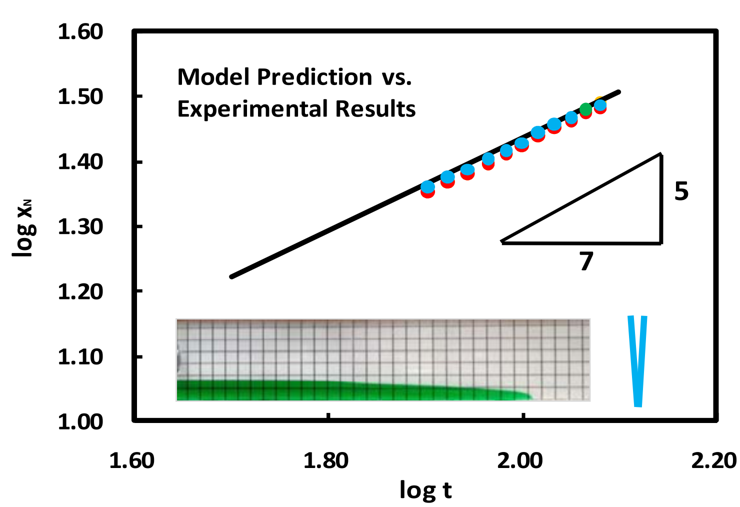

Figure 10. X_n, the position of the leading edge of the current, versus time (t). Blue "V" shape at lower right shows cross-sectional shape.

Dissolution-driven flows

For flows driven by dissolution, as expected for brine solutions, the influence of inclination of the bounding walls has been explored with systematic experiments (Figure 11). Stone and colleagues found that the tilting angle of the inclined boundary profoundly affects the dynamics of the density-driven plumes, and that the permeability of the porous medium strongly changes the convective rate. These findings have key implications for geological CO_2 storage in a saline aquifer when the dissolved CO_2 into brine produces a heavier mixture with an enhancement of the mass transfer by convection. In such a scenario, inclined boundaries tend to increase the influence of convection in bounded systems, which should increase the dissolution rate of CO_2.

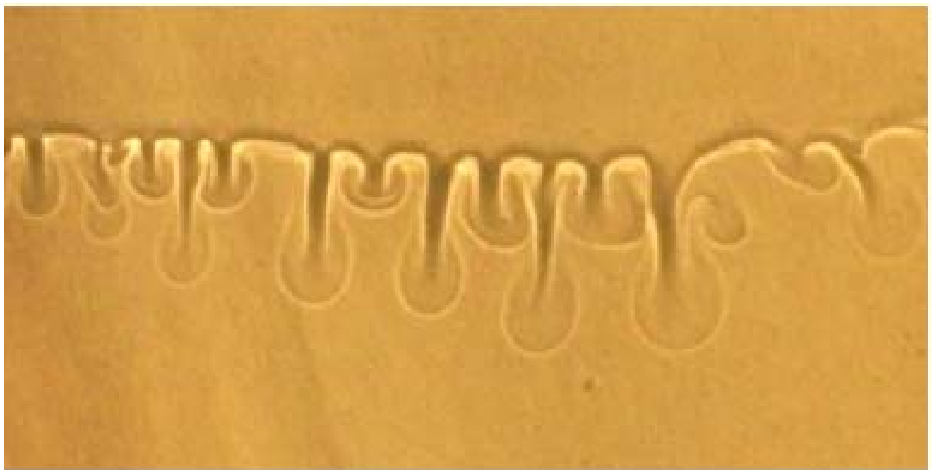

Figure 11. Density-driven plumes in a Hele-Shaw cell inclined 10^{o} to the horizontal.

Future directions by the Stone Group will include experiments with model porous materials in the form of packed beds of particles, with particular focus on gradients in the permeability. Where possible, analytical solutions are being developed to give quantitative descriptions to the experimental results.

Molecular-Scale Modeling

To assess the long-term behavior of the carbon dioxide disposal and geological storage, it is important to understand the phase behavior of CO_2-H_2O mixtures over a broad range of thermodynamic conditions, as well as in confined geometries. CMI researchers Pablo Debenedetti, Athanassios Panagiotopoulos, and Jeroen Tromp are using a variety of molecular modeling tools to study CO_2 hydrate phase behavior, the kinetics of hydrate formation and dissociation, and phase behavior of CO_2/water and CO_2/brine mixtures. These studies will provide insights important to geological storage of carbon dioxide as well as for the rational design of hydrate-based CO_2 storage systems over broad ranges of temperature and pressure.

Monte Carlo simulations of CO_2+H_2O+NaCl mixtures in geological environments

During the past year, Pablo Debenedetti and colleagues investigated the phase behavior of CO_2+H_2O+NaCl mixtures, a system that is commonly seen in geological environments relevant to CO_2 capture and storage. The solubility of CO_2 in brine was calculated via Gibbs Ensemble Monte Carlo simulations over the broad temperature and pressure ranges of 50 to 250°C and 0 to 600 bar, and the NaCl molality range of 0 to 6 mol/kg. The SPC, EPM2 and SD models were used to represent water, carbon dioxide and sodium chloride, respectively.

The computed CO_2 solubility was found to possess the qualitatively correct monotonic dependence on pressure. Reasonable agreement between experimental data and simulation results is achieved at 150°C and at 200°C. At temperatures below 150°C or above 200°C, the simulations underpredict the solubility of CO_2 by 10 to 50% percent, depending on the temperature, pressure and NaCl molality. The solubility of CO_2 was found to decrease as the NaCl concentration increased in the liquid phase, indicating a strong salting-out effect.

The next step in this project will be to perform an extensive investigation of various intermolecular potentials for water, carbon dioxide and sodium chloride in order to assess their ability to reproduce the experimental phase behavior over even broader temperature and pressure ranges. The ultimate goal of this study is to understand and quantify the influence of NaCl on the phase behavior of CO_2+H_2O mixtures over a broad range of temperatures and pressures relevant to carbon capture and storage, as well as to CO_2-assisted geothermal energy production.

Molecular simulation of hydrate melting and formation

Engineering any technology to sequester CO_2 in the solid form as a hydrate, or as pool of liquid CO_2 below a cap of its hydrate, requires an understanding of both the thermodynamics and kinetics of CO_2 hydrate formation. Having completed a computational study of CO_2 hydrate dissociation, attention during the past year focused on the kinetics of hydrate formation. The methane-water system was chosen as a starting point, as the corresponding hydrate forms under milder conditions than for CO_2. Several 1-microsecond-long molecular dynamics simulations of supersaturated methane-water solutions at 240 K and 200 bar were performed. A hydrate phase was nucleated in every simulation under these conditions.

This study represents the first example of hydrate nucleation in the absence of an interface. The final structures formed in the course of the simulations comprised elements of sI hydrate structure (i.e., 5^{12} (twelve pentagons) and $5^{12}6^{2}$ cages (twelve pentagons and two hexagons) – see Figure 12), but lacked long-range order. This is consistent with previous studies of hydrate nucleation and indicates that the formation of a crystalline hydrate phase may involve two steps: formation of a hydrate-like cluster and growth of the crystalline hydrate phase from the cluster. In addition to the cages found in the sI hydrate structure, a few $5^{12}6^{3}$ and $5^{12}6^{4}$ cages were also present. In all simulations, the 5^{12} cages appeared first, followed by $5^{12}6^{2}$ cages. Further analysis of the simulations to understand the mechanisms of hydrate nucleation is currently in progress.

Although this study provides important insights into hydrate nucleation, this approach does not yield the statistics needed to compute the rate of hydrate nucleation accurately. To this end, the

Debenedetti Group is currently investigating the use of path-sampling techniques such as forward-flux sampling. This should eventually allow the accurate estimation of hydrate nucleation rates under conditions relevant to carbon capture.

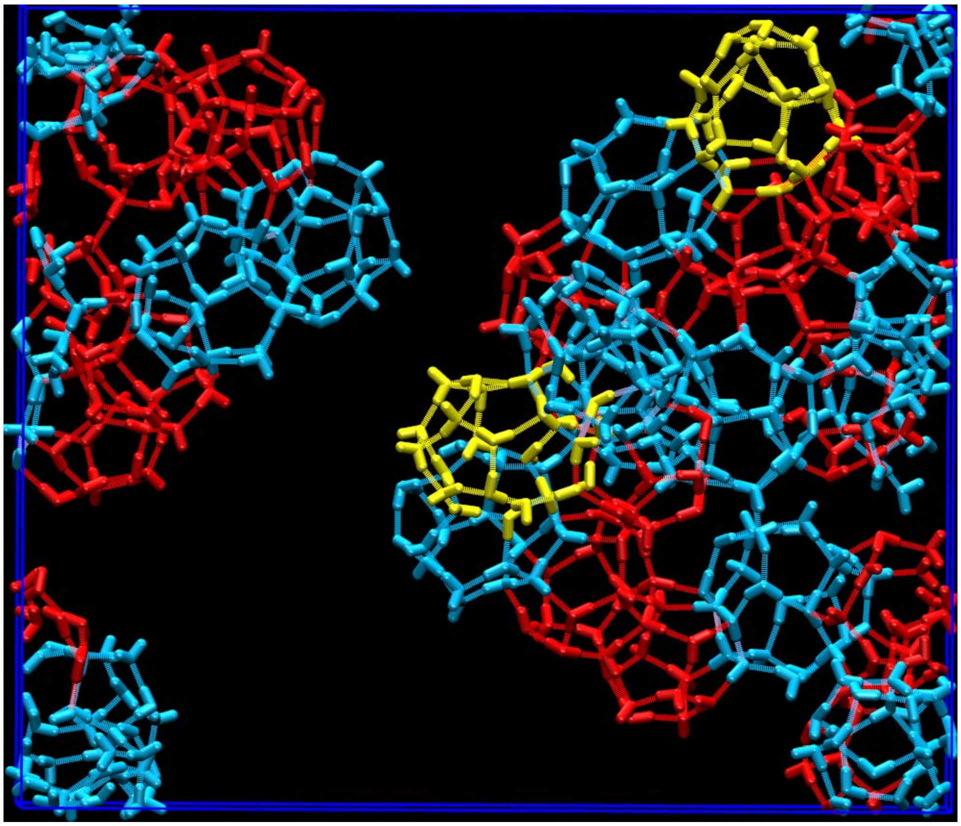

Figure 12. Snapshot of a configuration obtained after 1 μs-long molecular dynamics simulation of the methane-water system at 240 K and 200 bar. The different water cages formed are shown (cyan: 5^{12}, red: $5^{12}6^{2}$; yellow: $5^{12}6^{3}$). For clarity, only the water molecules forming cages are shown.

Molecular modeling of CO_2 capture and storage

A recently started (Oct. 2011) project, led by Pablo Debenedetti and new CMI researchers Athanassios Panagiotopoulos and Jeroen Tromp, aims to develop molecular-based computational tools for predicting the physical and chemical behavior of systems relevant to CCS.

In the first three months of the project, Debenedetti and Panagiotopoulos have recruited Arun Prabhu, one of the top first-year graduate students in Chemical and Biological Engineering, to work on the CMI project. Arun will be completing his required core courses in the Spring of 2012 and will start simulations related to phase behavior and transport properties of CO_2-brine mixtures in the early summer. In order to rapidly optimize parameters for describing the phase behavior, a molecular-based equation-of-state description (based on the Statistical Associating

Fluid Theory, or SAFT, approach) will be developed by Dr. Thomas Lafitte, a postdoctoral associate in the Panagiotopoulos Group who has significant experience with SAFT modeling.

Tromp and his group are working to improve CO_2 sequestration monitoring by focusing on proper representation of physical properties in porous reservoirs. Specifically, the researchers are investigating the importance of poroelasticity by contrasting poroelastic simulations with elastic and acoustic simulations. Discrepancies highlight a poroelastic signature that cannot be captured using an elastic or an acoustic theory and that may play a role in accurately imaging and quantifying injected CO_2.

Future research will also include investigation of fundamental physicochemical characteristics required for understanding and rational design of CO_2 separation processes from flue gases using novel solid adsorbents.

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Carbon Science

The Science Group uses both observational data and models to improve understanding of carbon sinks and predict the impact of climate change on the carbon cycle.

The PI's of the Science Group are Michael Bender, Lars Hedin, David Medvigy, Francois Morel, Stephen Pacala, and Jorge Sarmiento.

Highlights

Monitoring Natural Carbon Sinks

- Additional evidence has been found documenting an abrupt shift in the terrestrial carbon cycle in the late 1980's.
- New forest models predict that nitrogen-limited forests will become sinks under CO_2 fertilization, implying that the CO_2 fertilization sink should continue.
- A new project is using observations and models to assess the susceptibility of the Amazon rainforest to climate change.
- Quantification of land sinks in the Princeton Earth System Model indicates that annual carbon storage is roughly equally distributed between managed and unmanaged lands.

Improved Tools for Measuring the Ocean Carbon Sink

- A new instrument for making continuous measurements of the dissolved inorganic carbon concentration of ocean surface waters on oceanographic ships has been constructed and tested, and will be regularly deployed beginning in the summer of 2012.
- A new method has been developed for optimally estimating the historical partial pressure of carbon dioxide at the sea surface (pCO_2) and has been used to quantify the air-sea CO_2 flux since the 1980’s.

New Model Capabilities

- A new model has been developed for simulating ocean food web dynamics and is being used to investigate population shifts in the Eastern Subarctic Pacific.

- A model of heterotrophic bacterial activity and its impact on deep ocean carbon sequestration has been developed for use in ecosytem models.

- The impacts of land use on fires have been incorporated into the Princeton Earth System Model.

Impacts Studies

- Physiological experiments are providing a basis to predict the effects of ocean acidification on phytoplankton growth and production.

- A new model suggests that changes in species distribution and maximum catch potential in the Northeast Atlantic may be strongly affected by predicted changes in the ocean's oxygen content, acidity, and phytoplankton community structure.

- New simulations predict impacts on fish gill function with changes in ocean temperature, O_2, and CO_2.

Causes of Climate Variability

- Studies of unusual glaciological deposits in Antarctica have yielded ice that is much older than that from deep ice cores, and it may be possible to use such deposits to extend the atmospheric CO_2 record 500,000 years or more back in time.

- A new study shows that explosive volcanic eruptions can influence atmospheric CO_2 for decades and contribute to carbon sink variations in the ocean and on land.

Monitoring Natural Carbon Sinks

The Sarmiento and Pacala Groups, joined by new CMI members Lars Hedin and David Medvigy and their colleagues, are working to continuously improve a "Carbon Observing System." The effort uses observational data and models to monitor both short and long timescale changes in the land and ocean carbon sinks, and to provide predictions for the future.

Understanding temporal shifts in terrestrial uptake of atmospheric CO_2

In previous work, Jorge Sarmiento and colleagues detected an abrupt increase in the net land uptake of CO_2 of approximately 0.8 Pg C/yr in 1988. In this study, the net land flux was estimated as the balance of relatively well-known components of the carbon budget: fossil fuel emissions, the observed growth rate in the atmosphere, and the oceanic uptake from state-of-the-art ocean models. A suite of ocean models was used to represent uncertainties in the magnitude and temporal variability of oceanic uptake.

Given the importance of such a shift to the climate system and carbon cycle, a better understanding of it is necessary. In collaboration with researchers at UCLA as part of a study supported by a NASA Carbon Cycle Science grant, the Sarmiento Group has analyzed satellite data of gross primary production, terrestrial respiration and net ecosystem exchange fluxes for the region north of 45°N. In preliminary analyses, the group has detected a corresponding shift in 1987 in annual and spring fluxes of gross primary production and respiration in this region. As a visual support, the fluxes and cumulative fluxes are presented in Figure 13. The shifts detected in satellite data agree with the shift in the net land uptake of carbon, but the magnitude is smaller (the net shift is approximately 0.2 Pg C/yr). Through partial support from NASA Carbon Cycle Science, Claudie Beaulieu in the Sarmiento Group is applying change point detection techniques to other key data sets and model outputs. An improved understanding of this shift and its causes is important for the prediction of future shifts in the carbon cycle.

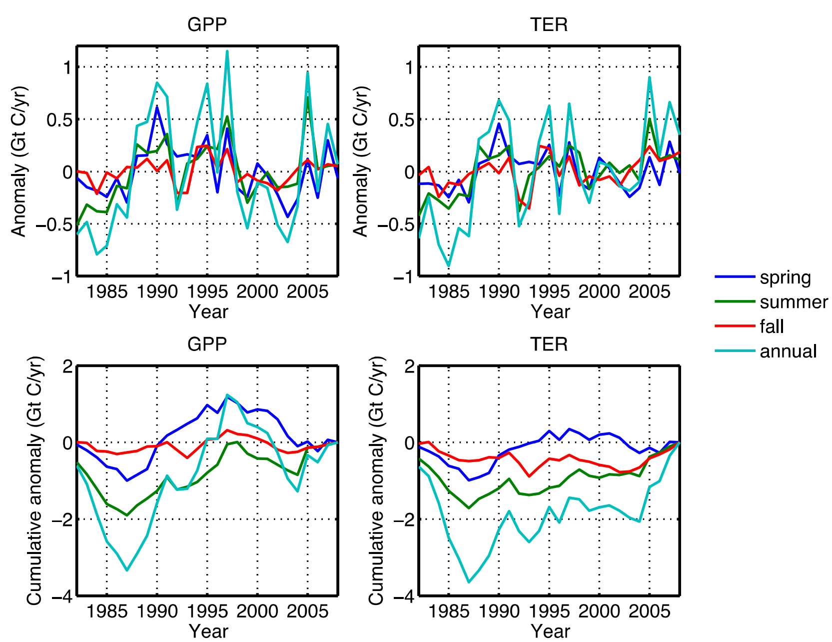

Figure 13. Total fluxes of gross primary production (GPP) and terrestrial respiration (TER) above 45° North anomalies (first row) and cumulative anomalies (second row). The change of slope in 1987 indicates the possibility for a shift. The shift in 1997 is probably due to the change of satellite covering and was accounted for in the analysis.

Understanding CO_2 fertilization of the biosphere

Ray Dybzinski and Stephen Pacala are in the middle of a new project on the future of CO_2 fertilization of the biosphere. An ongoing mystery has been why some CO_2 enrichment experiments result in a large carbon sink, while others do not. Existing global models predict that nitrogen (N) limitation will limit CO_2 fertilization, whereas water limitation will enhance CO_2 fertilization. However, recent data implies that the opposite is true. The researchers now think they can explain why.

New forest models developed by the Pacala Group predict that N-limited forests will become sinks under CO_2 fertilization, but water-limited forests will not. The reason is game-theoretic - because root systems intermingle, both nitrogen and water are best viewed as commons, and so the economics of plant competition is the economics of commons exploitation. Physiologically, water is best thought of as a fuel – it must be evaporated and lost to run photosynthetic machinery. Nitrogen is a structural material, used to make photosynthetic machinery. It is the difference between a fuel and a structural material that makes water-limited plants waste extra production from CO_2 fertilization on new short-lived fine roots that do not create a large or long-lived carbon sink. In contrast, nitrogen-limited plants devote the new production to wood, which creates a large carbon sink. We have a large amount of empirical support for this explanation. It is important because it means that the CO_2 fertilization sink should continue. If it were to fail, as it does when water is limiting, then the amount of mitigation necessary to stabilize at 500 or 550 ppm would double.

In another project investigating the influence of nitrogen cycling on CO_2 fertilization, postdoctoral researcher Duncan Menge initiated a set of experiments to determine the degree of regulation in many types of nitrogen-fixing plants. Plants that adjust nitrogen fixation to meet demand remove more carbon dioxide from the atmosphere, whereas plants that fix nitrogen at the same rate regardless of demand remove less carbon dioxide. Furthermore, plants that always fix at the same rate produce very nitrogen-rich conditions that lead to emissions of the potent greenhouse gas nitrous oxide from soils. Early results suggest that all herbaceous nitrogen fixers from *temperate* habitats fix nitrogen at the same rate regardless of demand, limiting the CO_2 fertilization effect outside the tropics.

The future of the Amazon as a carbon sink

One of the most striking results from models of the Earth System's response to CO_2 pertains to tropical forest ecosystems, and, in particular, the rainforests of South and Central America. If atmospheric CO_2 concentrations continue to increase, some of these computer models predict that increased temperatures and a modified soil moisture regime would cause a catastrophic collapse of the Amazon by the mid-to-late 21st century. Savanna ecosystems would replace rainforests, with possibly severe implications for the 40,000 plant species that currently inhabit the Amazon. Furthermore, 120 billion tons of carbon, currently stored in rainforest biomass, could be released to the atmosphere.

There has been vigorous scientific debate as to whether such outcomes are realistic. A major problem is that models have received limited validation against field data in the tropics, as ecological field studies sample much smaller spatial scales than those simulated by global climate models, and so it is difficult to use these data to evaluate models. To address this scale mismatch, David Medvigy and colleagues have developed a new type of structure ecosystem model that is capable of being directly validated by small-scale field studies, including those being carried out by Lars Hedin's research group. This study thus represents a collaborative effort between modelers and field researchers.

This approach has particular bearing on the following questions: (i) Will constraints by nutrients or water diminish the strength of the tropical forest carbon sink over time? (ii) Will different tropical forest species respond differently to climate change? If so, does species diversity affect the resilience of tropical forests to environmental perturbances? This year, the Medvigy and Hedin Groups will address these questions by developing an empirically-tested framework for studying carbon-nutrient interactions for different tropical species, and by using this framework to evaluate the susceptibility of the tropical forest carbon sink to climate change.

Quantifying carbon sinks on managed lands

The Intergovernmental Panel on Climate Change (IPCC) defined Land Use fluxes as greenhouse gas emissions and removals on managed lands (i.e. "managed land proxy"), including direct anthropogenic effects (e.g., agricultural conversion and wood harvesting) and indirect anthropogenic effects (e.g., CO_2 and climate change). But in the ongoing fifth Climate Model Intercomparison Project (CMIP5), no global Earth System Model (ESM) has been capable of calculating this flux for technical reasons, which obviously impedes the analysis of the coupled climate-carbon cycle system and constrains development of carbon policy grounded in science.

This year, Senior Researcher Elena Shevliakova implemented a modeling approach addressing such limitations and used NOAA/GFDL ESMs to demonstrate the ongoing carbon sink on managed lands (since the 1990's) and unmanaged lands (throughout the 20th century and presently). The sink on managed lands is from substantial re-growth of the secondary forests (1.5 Gt/yr) in both tropics and temperate regions. The ongoing sink on unmanaged lands is substantially smaller in this model (1.6 Gt/yr) than estimated in other studies. The present day warming would be significantly higher if both managed and unmanaged lands had not became a sink of CO_2 in the second part of the 20th century.

Improved Tools for Measuring the Ocean Carbon Sink

The Bender and Sarmiento Groups are improving our understanding of CO_2 fluxes into and out of the ocean surface by increasing the accuracy and spatial coverage of carbon measurements and using a combination of data and models to provide estimates of historical fluxes.

Better shipboard measurements of dissolved inorganic carbon

The dissolved inorganic carbon (DIC) concentration of seawater refers to the sum of the concentrations of CO_2, HCO_3^-, and CO_3^{2-}. This property is interesting for two reasons. First, it registers the invasion of fossil fuel CO_2 into the ocean. The DIC concentration of surface water is rising annually by about 0.1 moles m^{-3} because of fossil CO_2 uptake. Measuring DIC in seawater continuously, at high accuracy, over repeated cruise tracks will allow us to better quantify ocean uptake, and will also inform us about where fossil CO_2 enters the oceans and mixes after entering. Second, biological activity in the oceans is concentrated in spring and summer, when sunlight is strongest and physical conditions are most favorable. During this time, DIC falls by an amount that depends on the growth of phytoplankton and their extraction of CO_2 from the waters to make biomass. Seasonal measurements of DIC thus allow us to quantify biological productivity.

The Bender Group undertook to make a robust, easily operated instrument that would measure DIC concentrations continuously on oceanographic ships from seawater pumped into the lab, with minimal effort to maintain the instrument during daily operation. The team constructed an instrument that works on the following innovative principle. Seawater is mixed with a solution that has a small amount of bicarbonate labeled with the rare stable isotope of carbon, ^{13}C. The mixture is acidified to convert the DIC into CO_2, and the isotopic composition of the CO_2 is measured using an optical instrument (Picarro Cavity Ringdown Spectrometer). The higher the ratio of natural to spike carbon ($^{12}CO_2$ to $^{13}CO_2$), the higher the concentration of DIC in the seawater. The instrument works continuously under computer control, does one measurement every 8 minutes, and achieves a precision close to the state-of-the-art for the best measurements of discrete samples, about 0.1%. This coming year they will begin deploying it on research cruises, focusing on the Southern Ocean.

Estimating the time-varying air-sea CO_2 flux

Joseph Majkut, a graduate student in the Sarmiento Group, has developed a new method for optimally estimating the historical pCO_2 at the sea surface and used it to quantify the air-sea CO_2 flux and the time rate of change pCO_2 from 1980 through 2010. The method inverts data from surface pCO_2 measurement databases using Markov Chain Monte Carlo methods and a simple model for the time evolution pCO_2. He used an ocean general circulation model from NOAA GFDL, MOM4p1, forced with atmospheric reanalysis to provide estimates of the seasonal and interannual variability in surface pCO_2, which can reduce the bias introduced by the globally sparse sampling. The diagnosed surface fluxes of CO_2 are consistent with time-averaged estimates from other methods and also provide estimates of interannual variability, trends and a full treatment of uncertainty. Majkut demonstrated that trends in surface pCO_2 generally point to increasing fluxes into the ocean over the last three decades, and also that several trends in CO_2 flux previously published are not consistent with this new, globally consistent, estimate.

In the future, this method may be used for detecting and attributing changes in the carbon cycle and the observational schemes necessary to achieve accurate carbon budgets. Every year 30% of the anthropogenic carbon emitted by the burning of fossil fuels dissolves in the ocean and a good estimate of the carbon flux into the ocean is necessary for constraining the global carbon cycle and understanding carbon cycle feedbacks to climate change.

New Model Capabilities

The Sarmiento and Pacala Groups are improving model representations of processes important in carbon-cycle and ecosystem models.

Simulating food web dynamics in the Eastern Subarctic Pacific

The Sarmiento Group developed an end-to-end model architecture that can be used to investigate the ecosystem response to perturbations at both the top and bottom of the food chain. A prototype version of the model has been developed for the Eastern Subarctic Pacific ecosystem. The Eastern Subarctic Pacific has shown decadal variations in ecosystem state, sometimes characterized as regime shifts, that are correlated to the Pacific Decadal Oscillation and have been documented at several trophic levels, from primary producers to top predators. While correlative links between changes in physical properties and population changes at various levels of the food chain have been demonstrated, the underlying mechanisms of these population shifts remain unclear. The end-to-end model for the region fully couples a one-dimensional physical model, a biogeochemical model, and a predator-prey food web model, allowing two-way feedback between all trophic levels. The model has been shown to be capable of reproducing both seasonal and annual climatological conditions, and maintains robust and stable population dynamics when run over decadal to centennial timescales.

Incorporating the role of heterotrophic bacteria in ocean carbon sequestration

One of the main ways carbon is transported and stored in the deep ocean is by sinking of organic particles as part of the "biological pump." Most sinking particles are remineralized (transformed from organic carbon to carbon dioxide) in the mesopelagic zone (150 to 1000 m depth) due to the activity of heterotrophic bacteria. The Sarmiento Group has developed an ecosystem modeling approach to understand the mechanism connecting heterotrophic bacteria with sinking particles in the mesopelagic zone. The 1-dimensional idealized model of a sinking particle includes free-living and attached heterotrophic bacteria, particulate and dissolved organic matter, extracellular enzyme, and hydrolysate. The model is currently being used to determine the predominant process connecting heterotrophic bacteria and sinking particles by manipulating attachment and detachment rates and observing the effect on the free-living bacteria abundance and the remineralization of the sinking particle. Preliminary results indicate that attachment and detachment rates are important for dispersing surface bacteria to the deep ocean.

One of the benefits of this model is that it can be integrated with the dynamics of existing models, i.e. the Martin Curve and the ballast model, currently used in IPCC-class models to predict particle attenuation in the deep ocean. This application will improve understanding of the effects of climate change on carbon sequestration in the ocean because it accounts for the non-linear effects of temperature on the microbial loop, including the rates of molecular diffusivity as well as the rates of bacterial growth and extracellular enzyme function. The processes in the bacterial enzyme model are temperature dependent, so future work will include ocean temperature profiles from the IPCC-class general circulation models to forecast the effects of climate change on sinking particle remineralization over the next century.

Improved representations of fire in vegetation models

Global models of vegetation fire are critical for understanding the carbon cycle, but so far none have considered human land uses or the types of fires that result from different land use. Graduate student Sam Rabin is using satellite observations of fire around the world, combined with cropland, pasture, and deforestation data, to identify the fingerprint of each of these land uses on burning. This will not only improve the Princeton model's projections of future burning, but also allow estimation of the fraction of observed fire attributable to each. Future applications of this work include use in global vegetation models as well as helping inform the development of policy related to local/regional fire management and international carbon management efforts such as REDD+.

Impacts Studies

The Morel, Pacala, and Sarmiento Groups are conducting research on the impacts of changing atmospheric and ocean chemistry on marine and terrestrial ecosystems.

Impacts of ocean acidification on phytoplankton

A third of the anthropogenic CO_2 released to the atmosphere dissolves into the surface ocean. What effects the resulting changes in chemistry (called ocean acidification) will have on phytoplankton, the base of the ocean's food chain, is a focus of research in the Morel Group.

To fix inorganic carbon into organic biomass, phytoplankton must concentrate CO_2 via a system known as the Carbon Concentrating Mechanism (CCM). The material and energetic costs of the CCM, which are poorly known, will determine in part the response of phytoplankton to the ongoing CO_2 increase. To provide a quantitative assessment of the CCM efficiency in marine diatoms, the Morel Group has been quantifying the fluxes and concentrations of inorganic carbon species in sub-cellular compartments by mass spectrometry.

Previous work showed that the bioavailability of iron, a key limiting nutrient in the ocean, decreases at the lower pH caused by increasing CO_2. This year, the extension of this work to other essential trace metals has demonstrated that the bioavailability of zinc and cadmium also decreases with pH. This surprising result is explained by the bioavailability of weak organic complexes of the metals whose concentration decreases at low pH.

A focus of continuing work is the effect of ocean acidification on nitrogen fixation by the marine cyanobacterium *Trichodesmium*, the dominant N_2 fixer in the oceans. Because N_2 fixation requires large quantities of iron, its response to ocean acidification is made complicated by the dual (and likely opposite) effects of low pH on iron availability and high CO_2 on photosynthesis.

Impacts of climate change on ocean productivity and marine fisheries

Changes in ocean biogeochemistry and phytoplankton community structure may also affect fish and invertebrate distribution and productivity. In a collaborative study with the group of Daniel Pauly and William Cheung of the University of British Columbia, the Sarmiento Group assessed the sensitivity of projected changes in the distribution and fisheries catch potential to biogeochemical changes in the ocean.

A dynamic bioclimatic envelope model was used that incorporates predictions of physical as well as biogeochemical fields from a fully coupled Earth System Model. The model projects a distribution-centroid shift towards higher latitudes and deeper depths in the Northeast Atlantic (Figure 14). Ocean acidification and reduction in oxygen content reduce growth performance, increase the rate of range shift, and lower the estimated catch potential by 20-30% from year 2005 to 2050 relative to simulations without considering these factors. Consideration of phytoplankton community structure may further reduce projected catch potentials by ~10%.

These results highlight the sensitivity of marine ecosystems to biogeochemical changes and the need to incorporate likely hypotheses of their biological and ecological effects in assessing climate change impacts. The full global response in a large number of such Earth System Model simulations will be assessed in a future study. The goal is to determine the range in responses of the properties used to drive the dynamic bioclimatic envelope model, and to estimate how much uncertainty this variability between models introduces into the maximum catch potential estimates.

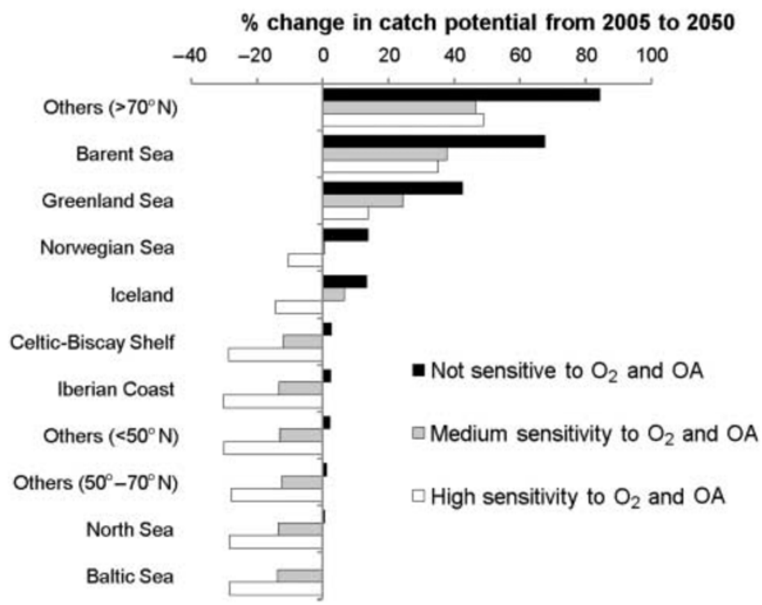

Figure 14. Projected changes in maximum catch potential between 2005 and 2050 (10-year average) in the Large Marine Ecosystems in the Northeast Atlantic with high sensitivity (open bar), medium sensitivity (gray bar), and insensitive (black bar) to changes in oxygen content and pH.

Impacts of ocean acidification and deoxygenation on fish gill function

Changes in ocean biogeochemistry in response to climate change may also impact fish directly through changes in gill function. Fish are aerobic organisms that uptake oxygen and release carbon dioxide in their gills using diffusion gradients. Gas exchange in the gill requires seawater oxygen to be *higher* than blood oxygen and seawater carbon dioxide to be *lower* than blood carbon dioxide. The rising levels of carbon in the seawater environment due to atmospheric absorption of carbon dioxide may therefore have consequences for gas exchange. Oxygen availability is also a concern because oxygen minimum zones appear to be increasing worldwide. The increase in carbon dioxide and decrease in oxygen in the ocean environment may result in a reduction in habitat, and the effect it will have on pelagic fisheries and ecosystems is of increasing concern.

Predicting habitat reduction is difficult because the physiological responses to hypoxic and suboxic levels of oxygen are highly variable among species. To quantify this effect, the Sarmiento Group developed a model that simulates gas exchange along a lamella in the gill of a teleost fish. This model incorporates physics, blood physiology, and gill morphology and can be adapted for different fish species. It is forced with temperature, oxygen, and carbon dioxide, and preliminary results indicate that temperature and carbon dioxide are important factors controlling oxygen uptake. In addition, the researchers are working on quantifying oxygen uptake and predicting habitat thickness for a range of physiological and morphological traits in the global ocean for the present and exploring the potential impacts of climate change over the next century.

In the next year, the Sarmiento Group plans to continue the development of the model and determine the sensitivity of oxygen uptake in fish gills to variations in temperature, O_2, and CO_2 in the environment. Potential adaptation will also be examined by manipulating physiological and morphological parameters in the model.

Terrestrial floral species' response to climate change

Postdoctoral research fellow Adam Wolf of the Pacala Group has developed a set of statistical tools to investigate the response of diverse terrestrial floral species to climate change, and used these tools to investigate change in two main arenas. The first area of investigation was species shifts across the entire California flora, some 3500 taxa, most of which are native or endemic. He developed a statistical method to estimate species shifts using herbarium specimens, which are intrinsically confounded by sampling biases. Subsequently, he applied this method to estimate species shifts across the flora, and found a strong tendency for taxa to move upslope, which reduced experienced warming for these species. Nevertheless, many endemics with small ranges could not move up at a fast enough pace to avoid significant warming over the 20th century.

Causes of Climate Variability

The Bender and Sarmiento Groups are using observations and models to investigate the causes of natural variablity in climate and the carbon cycle.

Search for old ice to be used in reconstructing greenhouse gas concentrations

Snow in polar regions traps air as it is buried and transformed into impermeable ice. This trapped air, sampled in deep ice cores, provides a record of CO_2 variations during interglacial cycles back to 800,000 years before present. Extending this record further back in time would allow us to investigate the role of CO_2 in the somewhat warmer climates of recent geologic time. However, the deepest ice cores yet drilled, targeted to encompass the longest possible continuous records, end at 800,000 years.

Michael Bender and colleagues have studied two Antarctic sites where, because of exotic local glaciology, older ice may be present near the surface. At one site, in the Allan Hills, they found ice much younger than expected, dating to only a little over 100,000 years. The researchers can specifically tie the ice to the last interglacial, and this deposit will be valuable because it provides easily accessible ice to study some aspects of climate during this period. At the second site studied, Mullins Valley, south of New Zealand near the coast, ice was found dating to about 1,300,000 years before present, buried by only about 15 m of shallower ice. This ice is not suitable for direct measurements of CO_2, but the team is in the process of making proxy measurements that will give good estimates of its concentration. Their expectation is that CO_2 will fall in its range of more recent times as measured in ice cores, but this remains to be seen. The discovery of 1,300,000 year old ice raises hopes that even older ice can be found, at relatively shallow depths, in glaciologically favorable regions of Antarctica.

Sensitivity of atmospheric CO_2 and climate to explosive volcanic eruptions

An important part of natural carbon-climate variability is caused by volcanic eruptions both during recent decades and during the preindustrial period. While the direct radiative and dynamical effects of sulfate aerosols from volcanic eruptions on the physical climate system are relatively well known, less emphasis has been placed on investigating the impact of volcanic eruptions on the global carbon cycle and variability in the atmospheric CO_2 record.

The Sarmiento Group assessed the impact of volcanic eruptions on the coupled climate-biogeochemical system by forcing a comprehensive, fully coupled carbon cycle-climate model with pulse-like stratospheric optical depth changes. The model simulates a decrease of global and regional atmospheric surface temperature, regionally distinct changes in precipitation, and a decrease in atmospheric CO_2 after volcanic eruptions (Figure 15). The volcanic-induced cooling reduces overturning rates in tropical soils, which dominates over reduced litter input due to soil moisture decrease, resulting in higher land carbon inventories for several decades. The perturbation in the ocean carbon inventory changes sign from an initially weak carbon sink to a carbon source. Positive carbon and negative temperature anomalies in subsurface waters last up to several decades. The multi-decadal decrease in atmospheric CO_2 yields an additional radiative forcing that amplifies the cooling and perturbs the Earth System on much longer time scales than the atmospheric residence time of volcanic aerosols.

The results have important implications for estimates of the carbon cycle-climate sensitivity γ, expressed as change in atmospheric CO_2 per unit change in global mean surface temperature. On decadal time scales, modeled γ is several times larger for a Pinatubo-like eruption than for the industrial period and for a high emission, 21st century scenario. In a follow-up study the Sarmiento Group will investigate the extent to which initial conditions (i.e., season and phase of El Niño-Southern Ocean Oscillation) and internal variability influence the coupled climate-carbon cycle response to volcanic forcing, and how this affects estimates of the terrestrial and ocean carbon sink efficiency.

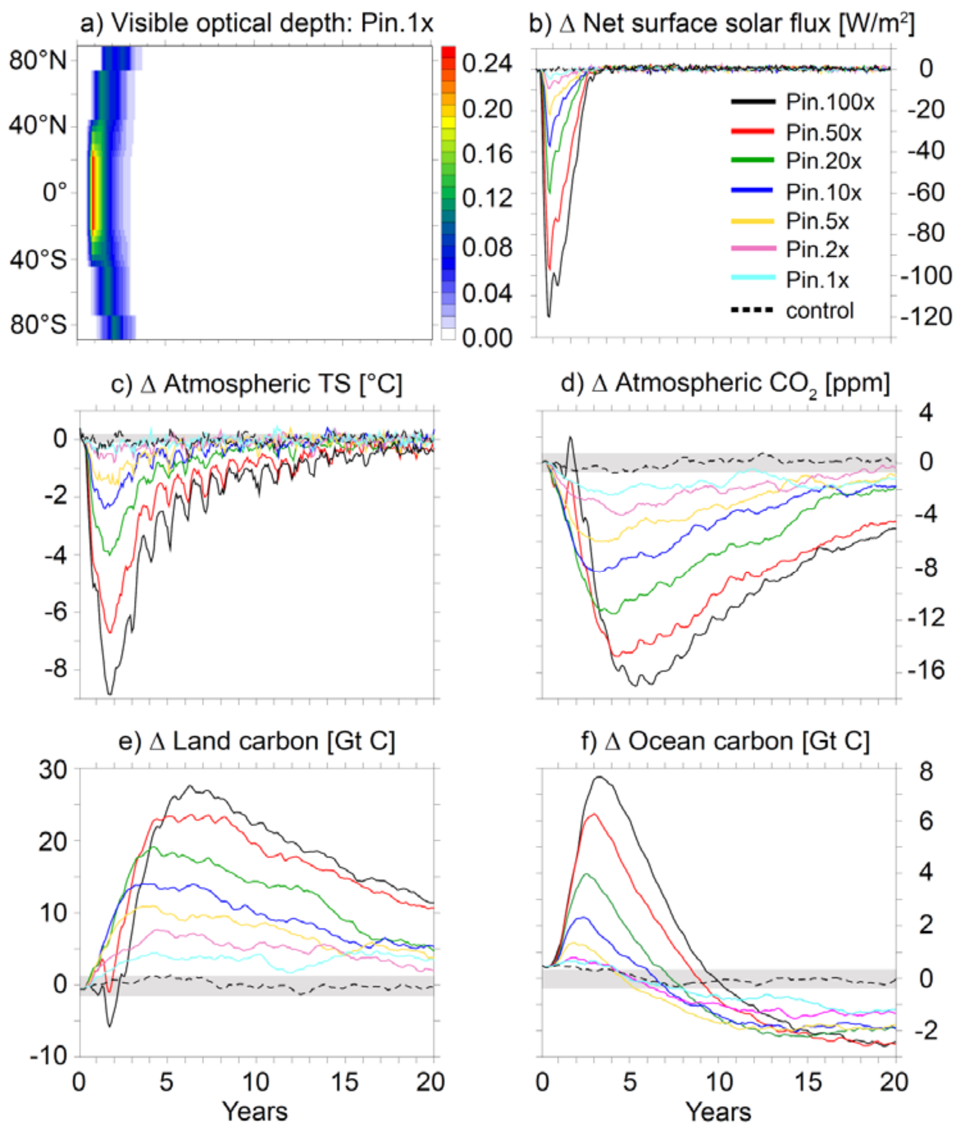

Figure 15. Simulated global responses of the carbon-cycle climate system to different strengths of volcanic eruptions. Time series of changes in (a) prescribed zonal averaged stratospheric optical depth in the mid-visible wavelength for a Pinatubo-like perturbation, (b) net surface solar flux, (c) atmospheric surface temperature, (d) atmospheric CO_2 concentration, (e) land carbon inventory, and (f) ocean carbon inventory. The volcanic eruptions start after half a year.

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Carbon Policy & Integration

The Policy & Integration Group conducts policy-relevant research and synthesizes CMI research for dissemination to broader audiences. The PI's of the group are Alexander Glaser, Michael Oppenheimer, Stephen Pacala, and Robert Socolow.

Highlights

Stabilization Wedges & Other Community Tools

- The Stabilization Wedges concept has been elaborated upon and updated in a new article entitled "Wedges Reaffirmed."
- The Stabilization Wedges concept continues to be a sought-after tool for education in the broader community.
- A game theoretic model suggests that cooperation and foresight can increase the rate of decline of renewable energy prices.
- An effort is underway to develop open-source energy economics models for India.

Assessing Mitigation Options

- A new project explores the implications of large-scale deployment of small modular nuclear reactors, with a particular focus on economics, nuclear waste generation, and proliferation risk.
- The costs and challenges of capturing CO_2 directly from the air have been explored in an APS study co-chaired by Mike Desmond of BP and Robert Socolow.

Communicating Uncertainty

- An analysis of the IPCC approach to communicating climate risks calls for increased transparency regarding disagreements among authors.
- An initial demonstration of a new sea-level rise assessment methodology suggests that sea level rise from Antarctica of greater than 40 cm by 2100 is extremely unlikely.
- A model with fully coupled ice stream and ocean dynamics shows a qualitatively different ice response to ocean temperature than that seen in static ice models.

Wedges and Other Community Tools

"Wedges Reaffirmed"

In 2004, in a paper in Science, Stephen Pacala and Robert Socolow introduced "Stabilization Wedges," a new way of quantifying the level of effort of carbon mitigation (a wedge of automobile efficiency, a wedge of CO_2 capture and storage, etc.). In October 2011, Socolow released a new paper, "Wedges Reaffirmed," on the websites of two non-governmental organizations, Climate Central and the Bulletin of the Atomic Scientist, which elaborates upon and updates the Science paper.

The Science paper proposed the following trajectory for the world's CO_2 emissions: emissions are held constant for 50 years, then decline in the following 50 years to achieve stabilization of the atmospheric concentration in 100 years (Figure 16). Since its publication, the global emissions rate has continued to grow, and it is now about 25% higher. Meanwhile, diplomats and environmentalists are advocating an even more ambitious trajectory. Socolow worries that the dissonance between aspiration and achievement will lead to a loss of resolve. He advocates "iterative risk management," a flexible framework where goals are periodically reset so as to take into account both new science and newly revealed shortcomings of nominal solutions. Iterative risk management is also advocated in the 2011 report of the National Research Council, America's Climate Choices, which Socolow co-authored.

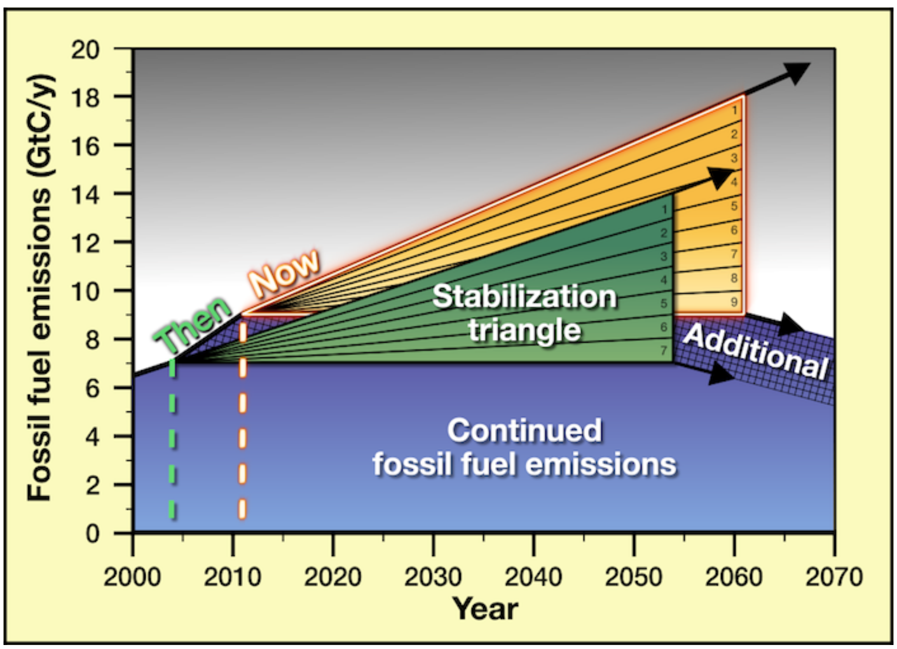

Figure 16. Today, nine wedges are required to fill the stabilization triangle, instead of seven. A two-segment global carbon-dioxide emissions trajectory that starts now instead of seven years ago — flat for 50 years, then falling nearly to zero over the following 50 years — adds another 50 parts per million to the equilibrium concentration (gridded area). The delayed trajectory produces nearly half a degree Celsius (three-quarters of a degree Fahrenheit) of extra rise in the average surface temperature of the earth. (Note that there is a three-year lag in the posting of authoritative global data.)

“Wedges reaffirmed” proposes three messages to improve the communication of the climate change challenge to an electorate that Socolow assumes is more wary than hostile:

1) Concede that, all in all, everyone would wish that our planet were larger so that our consumption patterns mattered less.
2) Emphasize that climate science today is consistent with terrible outcomes, even though the likelihood of such outcomes is highly uncertain, so that action can be motivated by what we don’t know, not only by what we do know.
3) Acknowledge that every mitigation action must be implemented attentively, lest it become a cure worse than the disease.

Compare these messages with the usual assertion that climate change is mostly about green jobs and innovation, that climate science is already definitive, and that government can be counted on to screen out dangerous policies.

Taking advantage of the flexibility of web publishing, ten comments accompanied the article. The comments – by Carter Bales, Ralph Cicerone, Freeman Dyson, Christopher Field, Robert Fri, David Hawkins, Rush Holt, Robert May, Phil Sharp, and Nicholas Stern – span a wide range of perspectives on climate change policy. The totality of the article and comments is a compelling introduction to the current discourse.

The Stabilization Wedges game

The Stabilization Wedges concept continues to be a popular teaching tool in the broader community, and 2011 took Roberta Hotinski, science communication consultant to CMI, to several events around the U.S. In June, Hotinski spoke and led the wedges game at this year’s Research Experience in Carbon Sequestration (RECS) in Birmingham, Alabama. In the fall, she facilitated a week-long wedges exercise as part of “Energy@Stanford and SLAC: Energy Research for the 21st Century,” an interdisciplinary summer course for over 100 Stanford graduate students from 19 departments.

In 2011 Hotinski worked with Capital Region Unitarian Universalists of New York (CRUUNY) Green Sanctuary members on a grassroots wedges game. With just a $1000 grant from The St. Lawrence District of the Unitarian Universalist Social Justice Council, the Sanctuary members organized a successful event in November at Rensselaer Polytechnic Institute in Troy, NY. The game was attended by U.S. Congressman Paul Tonko and Troy Mayor Elect Lou Rosamilia in addition to a broad spectrum of environmental stakeholders from the region, including church members, professors, students, lobbyists, and environmental professionals (Figure 17).

Hotinski also fields questions about the stabilization wedges concept from individuals and organizations on a weekly basis, particularly requests to reproduce the iconic wedge images in textbooks and other educational materials. In addition, online supporting materials for the wedges were viewed by over 2000 visitors to the CMI website.

Figure 17. Participants in the CRUUNY-organized game led by Hotinski (third row, 6th from left) included U.S. Congressman Paul Tonko (second row, second from left with yellow tie), Troy Mayor-Elect Lou Rosamilia (second row third from left) and members of the local community.

Learning rates and a green energy deployment game

A new collaboration on renewable energy deployment has been developed between the Policy & Integration Group and Easwaran Somanathan, Professor, Indian Statistical Institute, New Delhi, and Reed Visiting Professor at PEI (2010-2011). International climate negotiations have made limited progress, but individual countries and regions have implemented various policies related to emission reduction, including promotion of renewable energy. The aim of this project is to study this phenomenon.

A game theoretic model was proposed to analyze the deployment of a green technology (Solar PV) by the U.S., the E.U., and China. Shoibal Chakravarty, associate research scholar at PEI, and Somanathan developed a model in which the decision makers have limited foresight and the rest of the world is always short-sighted. Green energy is three times more expensive than fossil energy initially, but costs go down with rising deployment. The three regions/countries may choose to be short-sighted ("myopic"), cooperate (form a "coalition"), or play a self-interested strategy (a "non-cooperative Nash game"). The model shows that cooperation and foresight bring down the costs of green energy to parity with fossil energy 4-8 years faster that the myopic case. One interesting result is that self-interested behavior with foresight (the Nash game) is a good second-best strategy to cooperation. The main result is that long-term policies can be very effective in accelerating the deployment of green energy.

The project website http://strategicdeployment.googlecode.com has the computer models and data used in this study.

Open source climate economics models

Another Policy & Integration Group project aims to bring energy-economics and climate economics-models into the open source domain. Open source versions of some Integrated Assessment Models like DICE and RICE have been developed. The group's next goal is to develop energy-economics models for India. The models are written in Python, an open source programming language, using an open source modeling software (COOPR, https://software.sandia.gov/trac/coopr), and also other open access research software in the Operations Research community (COIN-OR http://www.coin-or.org/). The models can serve both as research and educational tools and the open access design can facilitate the contribution of other experts in this field. A dedicated website will be setup for the project shortly.

Assessing Mitigation Options

Re-engineering the nuclear future

A new project led by Alexander Glaser explores the shapes of alternative nuclear futures looking in particular at emerging technologies that may be potential game changers. The first phase of the project focuses on Small Modular Reactors (SMR), reactor designs that have power levels of less than 300 MW, a fraction of the typical power level of reactors that have been constructed in the last two decades. Many consider SMR the most serious candidate technology in the nuclear area in the aftermath of the Fukushima accidents.

SMR are currently under development in the United States, Russia, China, France, Japan, and South Korea, and a wide variety of designs with distinct characteristics are under development. The project so far has focused on reviewing these designs and exploring different ways of classifying them, with the aim of creating a public database that would provide users with essential information about them. Further research will review and analyze proposed SMR designs and examine the implications of a large-scale deployment of this technology with a particular focus on economics, nuclear waste generation, and proliferation risk.

A second arena of work has been exploring how nuclear power would fit into a modern low-carbon energy system that may be more decentralized than today's system and emphasize flexibility, energy efficiency, and small-scale solutions. As the first step, the project team has started working with the Global Change Assessment Model (GCAM), an Integrated Assessment Model that is widely used to project energy futures and associated greenhouse gas emissions, in order to improve the characterization of nuclear power in this model. Further analysis will explore the sensitivity of modeling results to the assumptions made about different types of nuclear technologies, including SMR (Figure 18).

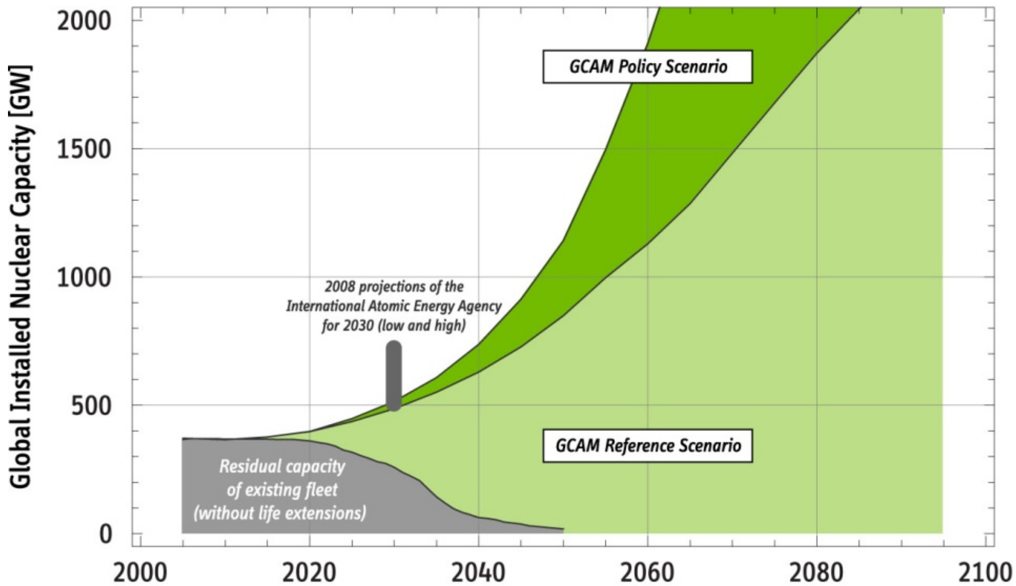

Figure 18. Integrated Assessment Models (IAM) typically project very large increases in global nuclear power use for the second half of the 21st century. In the Policy Scenario shown here, global installed nuclear capacity approaches 2000 GW-electric by 2060 (more than five-times larger than today) and provides 23% of total projected electricity. This project aims to illuminate the sensitivity of IAM results to underlying assumptions about the nature of nuclear power technologies that may be available and to assess options for managing some of the risks associated with such large-scale reliance on nuclear power.

Exploring prospects for direct capture of carbon dioxide from air

2011 saw the publication by the American Physical Society of a major technology assessment, Direct Air Capture of CO_2 with Chemicals, which presents the results of a multi-year study led by Michael Desmond (BP) and Robert Socolow. Systems achieving direct air capture (DAC) are giant scrubbing devices (Figure 19), where ambient air flows over a chemical sorbent (either liquid or solid) that selectively removes the CO_2. The CO_2 is then released as a concentrated stream for disposal or reuse, while the sorbent is regenerated and the CO_2-depleted air is returned to the atmosphere.

DAC is now included in discussions of long-term climate change policy because very large deployment might someday enable the world to lower the atmospheric CO_2 concentration at a rate of perhaps one part per million per year (ppm/yr), gradually reducing the negative impacts of climate change. (Right now, the concentration is increasing two ppm/yr.) DAC may also eventually have a role to play in countering recalcitrant decentralized CO_2 emissions, such as emissions from buildings and vehicles, which prove expensive to reduce by other means.

However, the message of the report is "first things first." Aggressive deployment of DAC makes little sense until the world has largely eliminated centralized sources of CO_2 emissions, especially at coal and natural gas power plants, either by substitution of non-fossil alternatives or by capture of nearly all of their CO_2 emissions. It is much cheaper to capture the emissions of CO_2 in the flue gas of a coal power plant than to remove CO_2 from ambient air where it is 300 times more dilute.

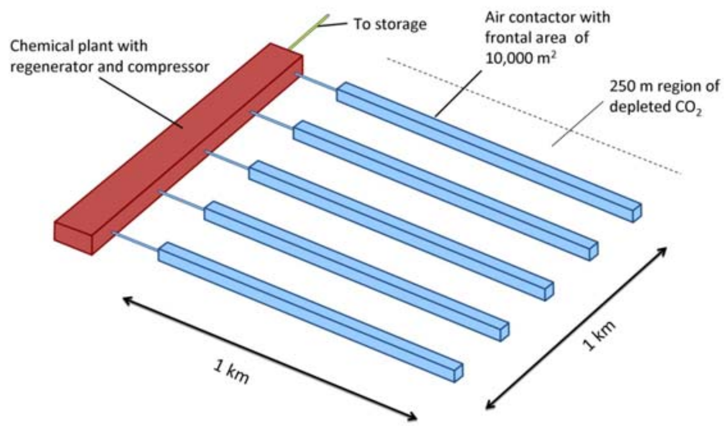

Figure 19. Schematic representation of a facility for capturing 1 $MtCO_2$/yr. The facility consists of five structures, each 10 meters high and 1 km long, and could collect 1 $MtCO_2$/yr if air passed through at 2 m/s and 50% of the CO_2 were collected. The structures are spaced 250 meters apart, and the footprint of the system is roughly 1.5 km^2. Approximately six of these systems would be required to compensate for the emissions of a 1 GW coal plant. Buildings not to scale

This is an interesting research frontier. Quoting from the press release: "A variety of science and engineering issues will determine the ultimate feasibility and competitiveness of DAC…[Needed are] alternative strategies for bringing air into contact with chemicals, new chemistries for sorption and regeneration, materials that can operate effectively and efficiently over thousands of consecutive cycles, and low-carbon energy sources for power and heat in order to avoid emitting more than one CO_2 molecule into the atmosphere for each CO_2 molecule captured."

As a follow-up, in May 2011 Socolow and CMI researcher Massimo Tavoni organized a meeting in Venice on "negative emissions," a state of the world where more CO_2 is removed from the atmosphere than added to it. DAC might be a contributor to such a world, and so might biological strategies on land or in the ocean. The meeting sought to improve communication between modelers of century-scale mitigation of climate change (who are already including negative emissions trajectories in their models) and experts on various negative emissions strategies. The talks presented will appear in a special issue of *Climatic Change* edited by Tavoni and Socolow.

Communicating Uncertainty

Communicating risks in IPCC reports

While serving on the National Research Council's Committee for America's Climate Choices, 2009-2011, Socolow became aware of the difficulties experienced by the Intergovernmental Panel on Climate Change (IPCC) in communicating risks to the public. Helped by private exchanges with a few IPCC leaders, Socolow was able to reconstruct some of the internal disagreements that had prevented the IPCC from dealing in a forthright way with the possibility of the early arrival of one or more of the widely discussed very nasty disruptions to societal well-being associated with climate change. He developed his findings in an article in the October 2011 issue of Climatic Change, "High-consequence outcomes and internal disagreements: tell us more, please." The entire issue, edited by fellow Policy & Integration Group member Michael Oppenheimer and Gary Yohe, is devoted to the communication of uncertainty in IPCC documents.

Socolow reveals that in the preparation of the most recent IPCC report on climate science (the report of Working Group 1 for the Fourth Assessment Report), the lead authors were unable to reach agreement about how to express the probability of responses of the climate system to climate change that are worse than those falling in a band called "likely." Figure 20, which was not published, was prepared at a time when some authors wanted to assign this region a probability of "17%," while others wanted to say only that responses in this zone "cannot be excluded," without assigning any numerical probability. In the end, "cannot be excluded" was chosen, and the fact that two views were in contention was not reported. Socolow urges the authors of the next report (the Fifth Assessment Report), currently in preparation, to be more forthcoming about their differences. He also proposes specific rules that would encourage the use of quantitative analysis consistently.

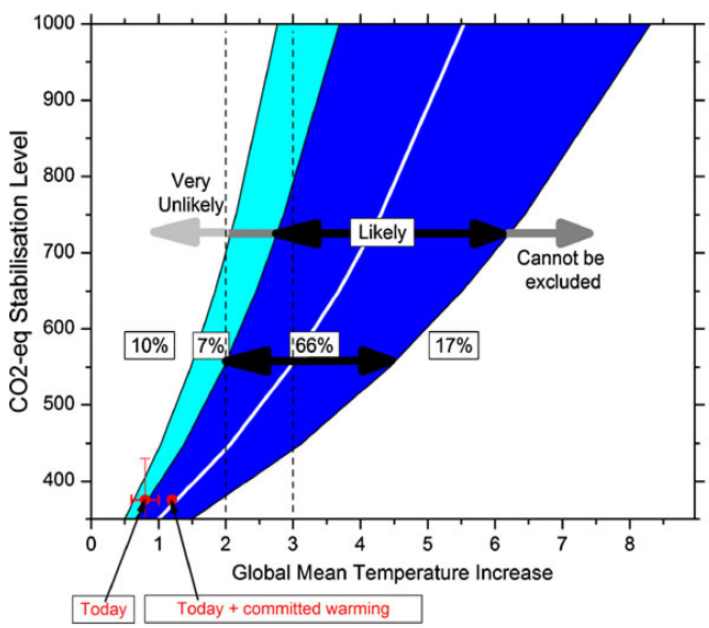

Figure 20. The uncertain relationship between the stabilized concentration of greenhouse gases in the atmosphere and the long-term global mean increase in surface temperature (relative to pre-industrial times). The units for the x and y axes are ºC and ppm, respectively. The Figure was prepared by Martin Manning to facilitate discussion in Working Group 1 during the preparation of the IPCC Fourth Assessment Report, but was not published.

Socolow and Oppenheimer have been able to recruit several formidable faculty members in the social sciences and humanities to explore the communication of uncertainty through a new university-wide program. Led by Robert Keohane, a political scientist who studies international institutions, a faculty group has embarked on a three-year project sponsored by the Princeton Institute for International and Regional Studies (PIIRS). The project brings together climate scientists, ethicists, and experts in several social sciences, as well as people who are specifically interested in communication across disciplines. Senior and junior visiting scholars have been recruited to be in residence during academic year 2012-13, when the project will be in high gear.

Policy-relevant information on sea level rise

Despite increasing awareness of the potential for rapid ice sheet change, sea level rise (SLR) projections in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) decreased as their quantitative uncertainty range narrowed. Effective policy decisions demand a more complete and transparent accounting of sources of sea level change. However, weak observational constraints on the century-timescale ice sheet response, and the lack of a comprehensive model, have led to difficulties in quantifying the SLR contribution of Antarctica and Greenland. The Oppenheimer group is focused on 1) presenting ice sheet projections in a form that is amenable to climate-related decision-making and 2) improving the comprehensiveness and robustness of ice sheet models.

Improving the utility of sea level projections

Last year, the Oppenheimer Group presented a novel approach to projecting ice sheet-driven sea level change that integrates expert judgment, data constraints, and state-of-the-art coupled models. Because SLR projections using this method are probabilistic and explicitly account for the locations and rates of ice discharge, ice loss rates implied by global paleoclimate and/or semi-empirical analyses may be examined in greater detail. This probabilistic framework also facilitates risk analyses and uncertainty reduction efforts.

An initial demonstration of the technique suggests that sea level rise (SLR) from Antarctica of greater than 40 cm by 2100 (implied by several recent analyses) is extremely unlikely (see Figure 21). The form of ice discharge scenarios, their associated uncertainty, and the correlation in ice loss between ice drainages control the tail area of sea level distributions (the information that is most relevant for climate policy and coastal management decisions). This initial analysis will be improved by the assimilation of regional and simplified dynamic models and data constraints. Researchers plan to incorporate this framework into integrated assessment models and decision analyses, with the ongoing goal of improving communication across the science-policy interface.

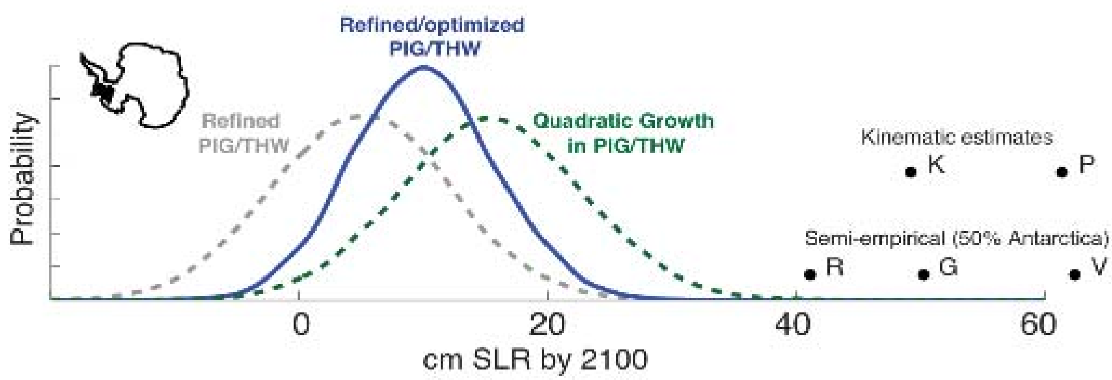

Figure 21. Probability distributions of the 2000-2100 Antarctic sea level contribution for selected sets of discharge assumptions. Green line is the SLR distribution with quadratic discharge growth in Pine Island Glacier and Thwaites Glacier drainage basins (PTW, black area on map at left); grey indicates linear discharge growth in PTW, refined by regional ice sheet model results; blue solid line indicates linear discharge growth in PTW, with projections optimized by continental mass loss observations. The results show very low probablility of SLR reaching upper bounds implied by recent kinematic and semi-empirical analyses (dots).

Ice sheet-ocean coupled modeling

The Oppenheimer Group employs a hierarchy of models to study physical processes at the margins of ice sheets. With collaborators at GFDL, Johns Hopkins, and MIT, they are developing a state-of-the-art model that can examine key physical processes in the ice-ocean system and be incorporated into larger-scale numerical models, elucidating global climate/ice sheet feedbacks. Simulations conducted with these models have already identified several key steps in the evolution of the coupled system, illustrating the time and spatial resolution required by large-scale models.

Researchers have also studied the sensitivity of ice streams to ocean temperature, showing a response that is driven by favored locations of ice shelf thinning (Figure 22). Ocean- or ice-induced changes in ice thermodynamics, iceberg calving, and shear margin strength may significantly change these results, and the group continues to develop process-based parameterizations to assess their influence.

Given uncertainty in the timing and nature of historic forcing, the transient present-day state of the ice sheet, and parameter and model uncertainty, constraints on the past behavior of ice streams may be best obtained using an ensemble approach. We have recently performed a perturbed physics ensemble using a simplified coupled model. The Bayesian precalibration technique we are employing is applicable to large-scale, more complex models, and will improve uncertainty characterization in sea level projections.

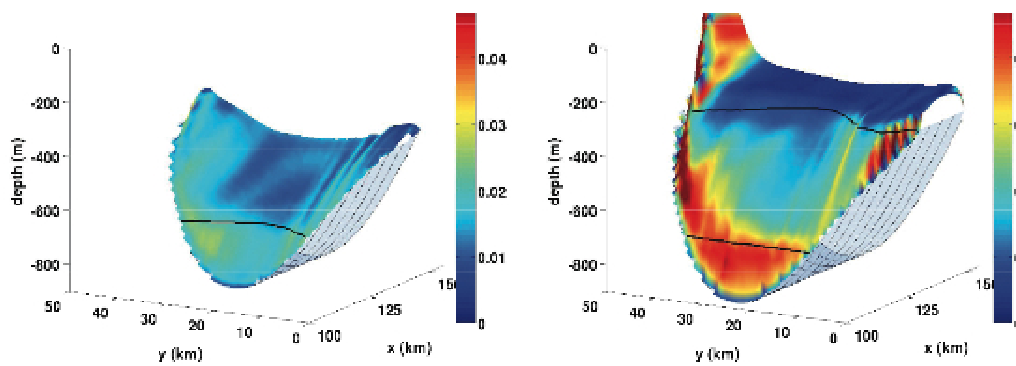

Figure 22. Final steady-state ice shelf cavity geometries with a deep ocean temperature of (left) 0.0°C and (right) 1.8°C. Upper surface is ice shelf basal elevation, and lower surface is bedrock elevation - the size of the cavity under the ice increases with increases in water temperature, indicating a thinning of the ice shelf. Coloring is magnitude of basal slope (increasing basal slope of ice sheet is a positive feedback that speeds basal melting). Perspective is from the grounded domain, looking seaward. Thick lines denote 700 m and 300 m depth contours.

Policy & Integration Publications

Goldberg, D.N., C. M. Little, O. V. Sergienko, A. Gnanadesikan, R. Hallberg, and M. Oppenheimer. "Investigation of land ice-ocean interaction with a fully coupled ice-ocean model, Part 1: Model description and behavior. In review.

Goldberg, D.N., C. M. Little, O. V. Sergienko, A. Gnanadesikan, R. Hallberg, and M. Oppenheimer. Investigation of land ice-ocean interaction with a fully coupled ice-ocean model, Part 2: Sensitivity to external forcings. In review.

Little, C.M., D. Goldberg, O. Sergienko, and A. Gnanadesikan. "On the coupled response to ice shelf basal melting." *Journal of Glaciology*. Accepted.

Little, C.M., M. Oppenheimer, and N. Urban. "Assessing ice sheet driven sea level rise using a probabilistic, bottom-up approach." In review.

Socolow, R., and M. English. "Living ethically in a greenhouse." In: The Ethics of Global Climate Change. Denis G. Arnold, ed., Cambridge University Press, Chapter 8, pp. 170-191. Chapter doi:10.1017/CBO9780511732294.009. 2011

Socolow, R. Book Review of Burton Richter's, Beyond Smoke and Mirrors: Climate Change and Energy in the 21st Century, in *American Journal of Physics 79*.1, p. 141. doi:10.1119/1.3485282. 2011.

Socolow, R. "7 Billion People, 30 Gigatons of CO_2, 1 Warming Planet: Population & Climate in the 21st Century." The Crux, *Discover Magazine*, November 18, 2011.

Socolow, R. "High-consequence outcomes and internal disagreements: tell us more, please." *Climatic Change*, 108(4), 775-790(16). 2011.

Socolow, R. "Wedges Reaffirmed," a short essay by Robert Socolow and Ten solicited comments on the essay, Climate Central and Bulletin of the Atomic Scientists websites. 2011.

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