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Introduction

The Carbon Mitigation Initiative (CMI) at Princeton University is a university-industry partnership sponsored by BP that began in 2000. Both parties are committed to a rigorous research initiative to address the ever-increasing challenges associated with the climate problem. This past November BP renewed CMI’s contract for an additional 5 years, carrying the program forward through 2020.

In addition, in November 2014 the administering entity for CMI, the Princeton Environmental Institute, underwent a leadership transition. François Morel, the Albert G. Blanke, Jr. Professor of Geosciences and a CMI principal investigator (PI), became the Institute’s new director for a second term, having presided over the early years of CMI during his first term (1998 to 2005). Morel succeeded CMI co-director Stephen Pacala, the Frederick D. Petrie Professor of Ecology and Evolutionary Biology, who completed a nine-year term as director (2005 to 2014).

The research hallmark of CMI is connectivity across science, technology and policy to offer an integrated assessment of earth-systems science, carbon mitigation options, and societal responses. A major component of the next five years is a concerted effort to enhance integration and outreach and to provide sound information about climate science that will enable effective public policy discussion.

The CMI program currently includes approximately 20 lead faculty and over 70 research staff and students at Princeton. During the latest renewal process, CMI was restructured to form three research work groups: Science, Technology, and Integration and Outreach.

**CMI Science** focuses on how terrestrial vegetation and the oceans soak up carbon and thereby determine the fraction of the carbon dioxide emitted into the atmosphere that actually stays there (the fraction is about one-half). CMI science increasingly features close collaboration with Princeton’s neighbor, the Geophysical Fluid Dynamics Laboratory of the U.S. Department of Commerce. A recent and growing component of CMI addresses climate variability and departures from the historical frequency of extreme events, such as heat waves, droughts and hurricanes.

**CMI Technology** studies energy conversion in conjunction with CO₂ capture and storage. Capture studies include both biological and fossil fuel inputs. Storage studies emphasize leakage pathways and now also investigate storage in shales. The program on advanced batteries continues.

**CMI Integration and Outreach** introduces new conceptual frameworks that are useful for climate change policy. One effort seeks to make the emerging statistical analyses of extreme events more accessible. A second effort focuses on improving the risk-assessment framework for the current scientific understanding of sea level rise. A third explores the value for climate policy analysis of adding a new component to traditional carbon accounting that tracks “committed emissions,” i.e., the future emissions that are likely to result when a power plant or vehicle or addition to infrastructure is placed into service.
In this report, each of the PIs or team of PIs has selected to feature one research highlight from 2014 and has provided context for the work. These highlights are supplemented by a complete list of the year’s peer-reviewed and submitted publications.

For more information, visit us at CMI’s website - http://cmi.princeton.edu - or email us at cmi@princeton.edu.
CMI Science focuses on how terrestrial vegetation and the oceans soak up carbon and thereby determine the fraction of the carbon dioxide emitted into the atmosphere that actually stays there (the fraction is about one-half). CMI science increasingly features close collaboration with Princeton’s neighbor, the Geophysical Fluid Dynamics Laboratory of the U.S. Department of Commerce. A recent and growing component of CMI addresses climate variability and departures from the historical frequency of extreme events, such as heat waves, droughts and hurricanes.

Research Highlights – At a Glance

**Stephen Pacala:** A newly completed model for the terrestrial biosphere more accurately simulates the role of forests as a carbon sink and the accelerated growth of trees, despite the limitations from below-ground resources.

**David Medvigy and Lars Hedin:** Simulations reveal how nitrogen fixation determines the rate of tropical forest regrowth and amount of carbon uptake in a recovering tropical forest.

**Michael Bender:** Recent advances in instrumentation enable independent measurement of leaf photosynthesis and respiration rates, giving insight into leaf metabolism to model carbon uptake from the biosphere.

**Jorge Sarmiento:** Innovative float technology and high-resolution modeling are dramatically improving our view of the harsh and remote Southern Ocean.

**François Morel:** Field studies in Antarctica and lab experiments with cold-adapted microalgae yield new insight into the efficient sequestration of CO2 by high latitude oceanic ecosystems and their response to a global climate.

**Michael Bender:** Million-year old ice has been retrieved from Antarctic glaciers. Analyses of this ice and its trapped air shows that climate was warmer, and CO2 concentrations higher, than in more recent times.
A Durable Global Land Sink Thanks to Durable CO$_2$ Fertilization

Principal Investigator: Stephen Pacala

At a Glance

A newly completed model for the terrestrial biosphere more accurately simulates the role of forests as a carbon sink and the accelerated growth of trees, despite the limitations from below-ground resources.

Research Highlight

In recent years, a fundamental shortcoming has been recognized by theorists of biosphere climate models. Most of the carbon in the biosphere and a large fraction of the carbon in soils is living or dead wood from forest trees, and for this reason, the future of the land carbon sink depends on the long-term enhancement of forest growth by carbon dioxide (CO$_2$) fertilization. To model this interaction more accurately, the Pacala group completed in 2014 a fundamentally new version of the Princeton-Geophysical Fluid Dynamics Laboratory (GFDL) land model for the biosphere and its interactions with the atmosphere, its greenhouse gases and climate processes. The model has been seven years in the making, supported by CMI funding. It is expected to be the default land model at GFDL for at least a decade.

The simulation work of many labs, including the Pacala group, shows how a failure of the land carbon sink would make global climate change much worse. In a 2014 publication, the Pacala group’s finding indicates that without a historical land sink, atmospheric CO$_2$ concentration would currently be 80 ppm higher—an 80% increase in anthropogenic carbon accumulated in the atmosphere since the industrial revolution. The new model is based on a mathematical advance that more accurately models the competition for light among individual trees, without directly simulating each tree. Previous papers show this formulation capable of predicting the observations of forest dynamics, including changes in carbon to nitrogen ratio (C/N) that occur either along natural gradients in plant productivity or from CO$_2$ fertilization.

Many studies predict the land sink will eventually diminish and turn to a carbon source because trees will become limited by below-ground resources (i.e. soil water, nitrogen and phosphorus). For this reason, a half dozen expensive experiments were carried out over the last two decades, in which intact forests were exposed to a doubled CO$_2$ concentration for ten years. Contrary to expectation, the trees continued to show accelerated growth despite clear evidence of limitation from below-ground resources. Two mechanisms were found to be responsible:

- trees increased their ratio of carbon to nitrogen by increasing the amount of wood relative to fine roots and leaves (C/N ratio ~300 for wood, ~30 for leaves, ~50 for fine roots) and by increasing the C/N of leaf and root tissue; and

- plants increased the availability of nitrogen by “priming” soil microbes with easy-to-digest carbon sources in the form of root exudates.

The root exudates caused the microbes to increase in abundance, so that there were more of them to digest undecomposed organic matter and thus liberate the nitrogen in the organic matter.
The new model’s description of decomposition can also simulate the priming of microbes by plant root exudates. The new model’s predictions were tested against a wide range of data, and results agree for both diurnal and annual carbon fluxes, growth rates of individual trees in the canopy and understory, tree size distributions, and species-level population dynamics during succession. The model was also used to show how the optimal strategy for rate of wood production—namely, a strategy that can outcompete a species with any other strategy, all else being equal—shifts as a function of the atmospheric CO₂ concentration. The simulations predict that carbon sinks caused by CO₂ fertilization will continue despite water limitation. Figure 1.1 shows wood production (carbon for left panels, tree diameter growth for right panels) in the Northern Midwest of the US at preindustrial (top) and double preindustrial (bottom) CO₂, and for several kinds of trees (with different root-leaf ratios on the horizontal axis and growing either alone (dark symbols) or in a multispecies stand (open symbols)). The results show wood production is predicted to remain 2-3 times higher under doubled CO₂.

Figure 1.1. Net Primary Productivity (NPP, left axis) and Diameter at Breast Height (DBH, right axis) versus Root/Leaf area ratio.

Reference

Individual-Based Dinitrogen Fixation and Biodiversity Interact to Determine Tropical Forest Carbon Uptake

Principal Investigators: David Medvigy and Lars Hedin

At a Glance

Simulations reveal how nitrogen fixation determines the rate of tropical forest regrowth and amount of carbon uptake in a recovering tropical forest.

Research Highlight

The premise of this research project is that nutrient dynamics strongly regulate the ability of tropical forests to sequester atmospheric carbon dioxide\(^1\)\(^-\)\(^3\). Recent findings imply the existence of an ecosystem-level carbon-nitrogen feedback mechanism (symbiotic with certain types of bacteria) in which dinitrogen fixing trees can provide the nitrogen needed to maintain high forest growth rates, following any type of forest disturbance that reduces tree population (see Figure 1.2.1)\(^4\). However, field-based evaluation of this feedback has been difficult because

- the carbon pools of a forest equilibrate slowly, over decades to centuries of ecological succession;
- experimental inhibition of nitrogen fixation is not possible in real-world forests; and
- nitrogen fixers may influence forest succession, but this interaction is difficult to isolate.

To address these problems, the Medvigy and Hedin groups examined carbon-nitrogen feedbacks by applying a simulation model to 64 large-scale plots distributed across 300 years of forest succession at the Agua Salud Project, Panama (see Figure 1.2.2). Field observations of plant traits were used to develop a representation of plant diversity in the model. This model representation consisted of different plant functional types (PFTs), where each PFT was endowed with a characteristic combination of traits seen in the observations. The model represented the large-scale plots by assigning the observed trees to PFTs according to their traits. This trait-based approach contrasts with the conventional approach of treating all tropical forest trees identically. The model can thus resolve PFT-nutrient feedbacks by evaluating nutrient dynamics within ensembles of spatially-linked individual trees of differing PFTs. The results showed that nitrogen fixation accelerates forest carbon accumulation, doubling the accumulation rate in early succession (0-30 years following disturbance) and increasing carbon storage in old-growth forests by 10%. An indirect effect on carbon accumulation was also found, showing how fixation interacted with the abundance of different PFTs. These results helped the Medvigy and Hedin groups to infer that nitrogen fixation can support the sequestration of a substantial quantity of carbon in the land biosphere (~24 petagrams of carbon) if extended to tropical forests worldwide.

Regrowing tropical forests currently contribute to over 40% of terrestrial carbon uptake\(^5\). These forests will remain a critically important element of the terrestrial carbon cycle as tropical deforestation continues in the coming decades\(^6\). This initiative has thus identified nitrogen fixation as essential for rapid tropical forest regrowth. This result runs counter to the conventional interpretation that tropical forests are nitrogen-rich\(^7\).
This work is expected to be of broad interest to climate change scientists, ecologists, earth-system modelers, policy-makers, and practitioners conserving and restoring tropical forests. Modelers may improve the representation of biological nitrogen fixation in the next generation of earth-system models. Practitioners may ensure biodiversity and functional diversity are present in reforested landscapes. Policy-makers may use this information to make decisions about how to use tropical lands (i.e., agriculture versus reforestation).

This project is now expanding to include investigation of nitrogen-phosphorus feedbacks on ecosystem carbon accumulation. Phosphorus (P) availability is particularly low in lowland tropical forests because there is little parent material P available to provide fresh input of P through weathering. This lack of P results in P-limitation in tropical forests. Despite the importance of P, none of the climate-carbon cycle models participating in the 5th Assessment Report of the Intergovernmental Panel on Climate Change included P dynamics. This project will address this deficiency with the following objectives: (1) develop a model for P cycling in terrestrial ecosystems, including the interactions of P with nitrogen (N); (2) constrain critical model uncertainties using new and existing field and LIDAR remote-sensing measurements; and (3) incorporating P and P-N dynamics into terrestrial biosphere models and carrying out simulations to assess the impacts of coupled P-N dynamics on the simulated terrestrial carbon sink.

Figure 1.2.1. N₂-fixing nodules on the roots of the common neotropical tree *Inga* help to provide more than 50% of the nitrogen needed to support 50 tons per hectare of carbon recovery in forests by 12 years following disturbance. (Photo courtesy of Sarah Batterman.)
Figure 1.2.2. Landscape and forests surrounding the Agua Salud Project research site in Panama. (Photo courtesy of Sarah Batterman.)

References


Studies of Photosynthesis and Respiration in Leaves

Principal Investigator: Michael Bender

At a Glance

Recent advances in instrumentation enable independent measurement of leaf photosynthesis and respiration rates, giving insight into leaf metabolism to model carbon uptake from the biosphere.

Research Highlight

Until recently, the gross rates of photosynthesis and respiration by leaves (how much carbon is adsorbed versus how much released) was immeasurable in sunlight; instead, only the net rate of carbon assimilation was measurable. Using an instrument and methods developed over several years (see Figure 1.3), it is now possible to study differences of leaf respiration rates in the light and in the dark, and infer the causes for differences in these rates. The instrument is centered around a mass spectrometer that makes ultra-high precision measurements of the oxygen $O_2$ concentration of air (rises due to photosynthesis, falls due to respiration). It also measures the abundance of an isotope tracer of $O_2$ that is unaffected by respiration and reflects the gross rate of photosynthesis. The measured rates of photosynthesis and respiration record basic plant processes, allowing for the calculation of other properties that describe the function of leaves. David Medvigy, a plant modeler working with Michael Bender and postdoctoral associate Paul Gauthier, has begun installing new processes in his models with guidance from these experiments. This work to date confirms the basic paradigm of photosynthesis and respiration in leaves that is used in all models of the land biosphere. It also suggests an important modification associated with the fact that the process of respiration slows down in the light, and reveals the mechanistic basis for this slowdown.

The ultimate goal of this work is to measure rates of photosynthesis and respiration in leaves, interpret the biochemical controls on these processes, use the data to characterize net carbon dioxide ($CO_2$) uptake by leaves, and implement the new insights into models of the land biosphere. These models are basic tools that are used to estimate how the land biosphere will change with time in global warming scenarios. The results of these studies are being implemented into models used to formulate policies for the management of forests and grasslands. They may have implications for agricultural yields as well.

Experiments performed with these innovative methods will help advance understanding of a range of basic processes, including the movement of $CO_2$ molecules in leaves, activities of photosynthetic enzymes, and the efficiency of different modes of carbon fixation, in addition to photosynthesis and respiration.
Figure 1.3. A bean leaf being illuminated in a cuvette. Photosynthesis and respiration rates are measured from the change in the concentration of $O_2$ and isotope tracers as air flows through the cuvette. (Photo courtesy of the Bender group.)
The Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) Project

Principal Investigator: Jorge Sarmiento

At a Glance

Innovative float technology and high-resolution modeling are dramatically improving our view of the harsh and remote Southern Ocean.

Research Highlight

The new Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project combines cutting edge robotic float technology with high-resolution earth system modeling to expand our understanding of the Southern Ocean. Headed by Jorge Sarmiento of CMI’s Carbon Science Group and funded by the National Science Foundation, SOCCOM involves 25 researchers at 13 institutions around the U.S. and has an operating budget of $21 million over six years. The impetus for the project comes primarily from modeling research, including key studies carried out by the Sarmiento Group with CMI support, that suggests the Southern Ocean surrounding Antarctica plays a very important role in the planet’s carbon and climate cycles. Such theoretical studies indicate that

- the Southern Ocean accounts for half of the planetary ocean uptake of anthropogenic carbon from the atmosphere and the majority of its uptake of heat (Sarmiento group analysis of the Fifth Coupled Model Intercomparison Project, CMIP 5; Refs. 2,3); and

- the impacts of ocean acidification from rising carbon dioxide (CO₂) are projected to be most severe in the Southern Ocean, approaching ecosystem tipping points within a few decades6,7.

Until now, the biogeochemical (BGC) observations needed to test these model-based hypotheses have been sparse due to the harsh environment limiting access to the region by research vessels, particularly during the Southern hemisphere winter. To escape the limitations of ship-based measurements, the SOCCOM project is taking advantage of Argo autonomous float technology, which has already been widely deployed throughout the world’s oceans. SOCCOM scientists have augmented conventional robotic Argo floats (which measure ocean temperature and salinity) with newly developed biogeochemical sensors to measure carbon (indirectly determined by measuring pH), nitrate nutrients, and oxygen (see Figure 1.4.1). SOCCOM is the world’s first large-scale BGC Argo deployment and will increase the number of biogeochemical measurements made monthly in the Southern Ocean by a factor of 10-30 (with the higher increase in the Southern Hemisphere winter, when observations are scarcest).

A total of 200 floats are planned for deployment over the six-year term of the project. Since the spring of 2014, the SOCCOM team has deployed 24 BGC floats via two Southern Ocean cruises that sailed from Hobart, Tasmania and Cape Town, South Africa. Figure 1.4.2 shows a snapshot of pH provided
by measurements taken along the trajectory of the Hobart-based GO-SHIP repeat hydrography
cruise P16S (angled axis). The blue low pH water in the lower waters of the southernmost float is due
to upwelling of deep water rich in dissolved inorganic carbon from decomposition of organic matter.
The red high pH water in the surface ocean is due to low dissolved inorganic carbon from biological
uptake. The deepening of this high pH water in Float 9095 is due to a combination of seasonal
biological uptake, and the horizontal movement of this float across the so-called Polar Front which
marks a boundary between waters with different properties. These floats are now complementing
the first annual record of the combined chemical and biological changes over broad regions of the
Southern Ocean, and analysis of the newly collected data is underway.

Data from the floats are being made available to the public in real time at the SOCCOM website
(http://soccom.princeton.edu) and will also be incorporated into the global Argo data system to
provide easy access to researchers around the world. The project will also transfer sensor technology
to commercial float developers and will work to ensure that the findings of the SOCCOM project
reach the widest possible audience, including policy makers and the general public.

Several more BGC floats will be deployed this spring on cruises from Argentina and Tasmania, and
the SOCCOM team is currently working with collaborators to organize the deployment of 37 floats
to be built in 2015. The remainder of the floats will be launched between now and 2020. Combined
with high-resolution modeling carried out under the project, SOCCOM’s leading-edge observations
will help researchers better understand the inner workings of the Southern Ocean and its current
impacts on Earth’s climate and biosphere. Predictive model simulations carried out under SOCCOM
will also help researchers anticipate how changes in the Southern Ocean will impact global climate
in the future.

Figure 1.4.1. Loading (inset) and deployment of a BGC Argo robotic float. (Inset photo courtesy of Hannah Zanowski,
Princeton University. Outset photo courtesy of Annie Wong, University of Washington.)
Figure 1.4.2. pH measurements collected by BGC floats at three southern latitudes, launched from a GO-SHIP cruise along the south to north P16S cruise track. The map shows the south to north P16S cruise track as well as the locations of measurements made by BGC floats 9092, 9095, 9254, which are denoted by the black, green, and yellow dots, respectively. The vertical section cutting diagonally across the figure is pH measured at depths ranging from 0-1000 m, collected along the ship track at the time the floats were deployed. The vertical sections projecting out to the right show the time history of pH from BGC floats 9092, 9095, 9254 between April 2014 and January 2015. Figure courtesy of Ken Johnson, Monterey Bay Aquarium Research Institute (MBARI).

References


High Productivity of Antarctic Ecosystems and their Response to Global Change

Principal Investigator: François M.M. Morel

At a Glance

Field studies in Antarctica and lab experiments with cold-adapted microalgae yield new insight into the efficient sequestration of CO₂ by high latitude oceanic ecosystems and their response to a global climate.

Research Highlight

High latitude oceans are major contributors to global primary phytoplankton production with the Southern Ocean alone accounting for around 20% of annual global biomass. A large proportion of this production is confined to continental shelf regions such as the Western Antarctic Peninsula, where intense phytoplankton blooms, common in the spring, provide the basis for a short food web, transferring algal biomass to krill, seals and whales with high efficiency and resulting in a high degree of carbon dioxide (CO₂) sequestration. The physiological and biochemical adaptations that allow Antarctic phytoplankton to grow rapidly and sustain high productivity in very cold water are not well understood.

Field data from a six-month deployment at Palmer station (see Figure 1.5) in the Western Antarctic Peninsula, complemented with laboratory experiments on model phytoplankton species, has provided the Morel group with new insights into the adaptations responsible for high biological productivity in cold waters. These results also provide a basis for predicting the most likely responses of Antarctic flora to changing environmental conditions.

In high latitude ecosystems, enzymatic cellular processes for organisms fundamentally slow down due to low temperature. However, cold-adapted microalgae resolve this problem by

- having many of their key enzymes exhibit small structural variations that allow relatively rapid turnover rates at low temperatures (biochemical adaptation); and

- synthesizing far larger cellular concentrations of the essential enzymes for which no cold-adapted form exist (physiological adaptation).

The net result is a biochemical composition of high latitude phytoplankton different from that of temperate species, that includes an unusually high protein content.

In addition, high latitude marine ecosystems exhibit relatively low rates of respiration. This is due to the synthesis of high energy compounds (ATP) via photochemical rather than respiratory processes and the long duration of the light period in the austral summer.

High latitude oceans and the Western Antarctic Peninsula are now experiencing some of the most extreme warming on the planet; the low buffering capacity of high latitude seawater will result in a particularly intense degree of acidification in response to rising anthropogenic CO₂. The Morel
group’s studies of the mechanisms controlling the rate of photosynthetic biomass production in high latitude marine ecosystems will help ascertain how Antarctic (and Arctic) marine ecosystems respond to ongoing warming and acidification. These experimental results provide a basis for collaboration with colleagues at the Geophysical Fluid Dynamics Laboratory to develop Earth System Models with mechanistic representation of biological processes suited to high latitude oceans.

The ultimate goal is to more robustly assess the consequences of climate warming and acidification to carbon uptake and biogeochemistry in the Arctic and Antarctic oceans.

Figure 1.5. Postdoctoral Associates from the Morel Group arriving at Palmer station by zodiac after gathering samples and field measurements. (Photo courtesy of Jodi Young.)
Studies of Greenhouse Gases and Antarctic Climate 1,000,000 Years Ago

Principal Investigator: Michael Bender

At a Glance

Million-year old ice has been retrieved from Antarctic glaciers. Analyses of this ice and its trapped air shows that climate was warmer, and CO₂ concentrations higher, than in more recent times.

Research Highlight

Ice below the surface of glaciers contains air that was trapped in earlier times, during the compaction of ancient snow. Scientists have extracted this ancient air and analyzed it to determine how the atmospheric carbon dioxide (CO₂) concentration changed continuously with time over the past 800,000 years. The Bender group’s research program documents climate history from the record of ancient ice sampled at the Allan Hills in Antarctica. Sample cores were easily acquired of “chunks” of ancient ice, driven to the surface as the glacier flowed over subglacial mountains (see Figure 1.6). The ice dates back to 1,000,000 years, representing the planet in a different climate configuration from that of the last 800,000 years. This work reveals that atmospheric CO₂ concentrations were tightly linked to global temperature and the size of the great glaciers during this earlier regime. The data also show that average CO₂ concentrations dropped by 10’s of parts per million (pre-industrial CO₂=280 ppm) 800,000 years ago, when glacial cycles became much more intense.

This research program was undertaken in collaboration with John Higgins at Princeton University and researchers at the University of Maine and Oregon State University. Studies of greenhouse gases in these samples show the close link between CO₂ and climate extends back beyond 800,000 years, to the earlier world of shorter glacial-interglacial cycles with smaller amplitudes. In general, this work extends the physical evidence for a close link between greenhouse gas concentrations and climate.

This work strengthens evidence for a close link between CO₂ and climate. It adds to the broad body of evidence supporting climate models that simulate a key role for CO₂ in global warming. Finally, it provides additional constraints on models of Earth’s climate and how climate will change due to natural and anthropogenic perturbations.

The Bender group will return to the Allan Hills, for additional studies with two objectives. The first is to obtain a broader picture of climate properties around 1,000,000 years ago. The second is to extend the ice core record of climate and greenhouse gas concentrations further back in time.
Figure 1.6. Drilling for old ice in the Allan Hills, Antarctica. A tube of drilled ice is being retrieved. The drill is lowered on a wire coiled around the winch behind the core tube. The curtain in the background is a wind-screen. (Photo courtesy of the Bender group.)
Science Publications


Kranz, S. A., J.N. Young, B.M. Hopkinson, J.A.L. Goldman, P.D. Tortell, and F.M.M.


CMI Technology studies energy conversion in conjunction with CO₂ capture and storage. Capture studies include both biological and fossil fuel inputs. Storage studies emphasize leakage pathways and now also investigate storage in shales. The program on advanced batteries continues.

Research Highlights – At a Glance

Michael Celia: Modeling of CO₂ injection in the Marcellus shale formation reveals the need for a very large number of injection wells—approximately 100 additional wells brought online every year—to store CO₂ emissions from Pennsylvania’s five largest coal-fired power plants over a 40 year lifetime.

Howard Stone: Theoretical and laboratory-scale models for the characterization of CO₂-inspired flow in porous media have led to analytical formulae for ready modeling of leakage in sequestration projects.

Craig Arnold: Correlation between a battery’s electrochemical properties and the mechanical stress of its internal materials provides measurements of its state of charge and state of health, which inform the optimization of battery performance for grid systems and portable applications.

Athanassios Panagiotopoulos, Pablo Debenedetti, and Jeroen Tromp: Molecular-based computational tools for predicting fundamental physical and chemical characteristics of H₂O+CO₂ and H₂O-NaCl binary systems are being developed to help interpret the rational design of CO₂ separation processes and long-term CO₂ storage in geological formations.

Eric Larson, Robert Williams, and Thomas Kreutz: Analysis of smaller scale systems for the manufacture of low- or negative-carbon synthetic fuels from biomass and from biomass + natural gas feedstocks reveals that, in the presence of a strong carbon mitigation policy, such systems might be competitive at crude oil prices of less than $100 per barrel and would offer the opportunity for fossil fuel providers to exploit more of their fossil fuel reserves under a carbon budget constraint.
CO₂ Injection into Depleted Shale-gas Wells

Principal Investigator: Michael Celia

At a Glance

Modeling of CO₂ injection in the Marcellus shale formation reveals the need for a very large number of injection wells—approximately 100 additional wells brought online every year—to store CO₂ emissions from Pennsylvania's five largest coal-fired power plants over a 40 year lifetime.

Research Highlight

Research in the Celia group has continued with modeling general aspects of carbon dioxide (CO₂) injection¹⁻⁷ into conventional formations and measuring methane leakage along old wells⁸⁻¹⁰. In addition, a study of the feasibility of injection of CO₂ into depleted shale-gas formations has continued. The idea to inject CO₂ into depleted shale formations has been advanced recently as an alternative or complement to injection into conventional reservoirs. Initial estimates from the literature indicated very large (static) storage capacities¹¹⁻¹²; the current research focuses on realistic estimates of injection rates and the logistical feasibility of different injection scenarios. To address this issue, the Celia group conducted a thorough review of gas production data for the Barnett formation in Texas as well as two different regions of the Marcellus shale formation in Pennsylvania (Southwest Pennsylvania (SW PA) and Northeast Pennsylvania (NE PA)). The Celia group developed a model for multi-component gas flow within the various formations, including the movement of methane (CH₄) and CO₂. The model includes equations of state, sorption of both CH₄ and CO₂, and formation parameters derived from matching production data.

The results in Figure 2.1.1 show cumulative injected mass of CO₂ into a typical well in the three formations as a function of time. The NE PA region has the best performance, because the formation is much thicker in the northeast than in the southwest, and because length of horizontal wells has become noticeably longer in NE PA. While the northeast location has the best behavior, the amount that can be injected into one well is still orders-of-magnitude smaller than the emissions from a typical coal-fired power plant: ultimate cumulative mass injected in one well is about 0.5 Million Tonnes (Mt) CO₂, while the output from one large coal-fired power plant over that time (40 years) is on the order of 200 Mt CO₂. It is worth noting the total mass injected has an upper limit due to the assumptions of the one-dimensional model; more detailed simulations may show some additional capacity, but the additional amount is expected to be insignificant.

Large stationary sources in Pennsylvania were identified and the CO₂ emissions were mapped to existing (both drilled and permitted) shale-gas wells. Figure 2.1.2 shows both sources and wells. If the CO₂ produced by the large sources in southwest Pennsylvania is injected into wells in southwest PA, essentially all wells in the region (approximately 6,400) are needed over a time period of 40 years (more than 150 new wells each year). If the higher-injectivity wells in Northeast Pennsylvania are used instead, then the number of wells will be 3,800 (about 100 wells per year). Note that use of wells in Northeast PA requires longer pipelines to be built.

For either of these cases, it is reasonable to ask if it is more economically and logistically feasible to build a large pipeline west of the Illinois Basin, and use conventional reservoirs such as the Mt
Simon formation to sequester the CO$_2$. A comprehensive economic and feasibility study is currently ongoing, to clarify advantages and disadvantages among these different options for CO$_2$ transport and injection.

![Figure 2.1.1.](image1.png)

Figure 2.1.1. Cumulative mass of CO$_2$ injected as a function of time for a typical well in the Barnett, Southwest PA Marcellus, and Northeast PA Marcellus formations. Note that half of the ultimate capacity is reached after about 5 years for all three curves. (Figure courtesy of the Celia group.)

![Figure 2.1.2.](image2.png)

Figure 2.1.2. Stationary sources of CO$_2$ (triangles with size scaled to amount of emissions), and existing and permitted shale-gas wells (all dots). The gray shaded region indicates the Marcellus shale formation in Pennsylvania. Purple dots (6,400 or them) identify wells needed to store 40 years of emissions from the five large sources in southwest Pennsylvania (orange triangles); green dots (3,800 of them) identify wells in northeast Pennsylvania to store the same emissions. (Figure courtesy of the Celia group.)
References


Analytical and Laboratory-Scale Models for the Characterization of CO₂-inspired Flows in Porous Media

Principal Investigator: Howard A. Stone

At a Glance

*Theoretical and laboratory-scale models for the characterization of CO₂-inspired flow in porous media have led to analytical formulae for ready modeling of leakage in sequestration projects.*

Research Highlight

The Stone Group has investigated a variety of subsurface fluid flow problems inspired by carbon dioxide (CO₂) sequestration. In these applications it is critical to characterize the rates at which two fluid phases (e.g., supercritical CO₂ and water) rearrange in a porous medium. The fluid dynamics will be influenced by confinement of the flowing fluids, and it is critical to model processes such as fluid injection, buoyancy-driven spreading, and leakage. In particular, leakage could occur from an edge (or crack) in the porous medium, or along a porous boundary; such modeled processes may be very useful to characterize leakage from underground sequestration sites. The research program’s models are inspired by the various processes relevant to field studies, and are simplified representations of large-scale numerical simulations common to industrial-scale studies. That said, the model has been refined in collaboration with Michael Celia, to more accurately approximate a field situation. This collaboration has benefitted both research groups and has been made possible by the unique research partnerships afforded by the CMI initiative. Figure 2.2 summarizes research results for confined configurations without leakage, as a phase diagram that describes how the shape of the fluid-fluid interface during fluid injection can vary with time (T is a dimensionless time, defined as the real time rescaled by a characteristic time for the fluid flow in the porous medium) for different ratios M of the displaced fluid to the injected fluid.

The Stone Group has made several new modeling contributions to the field of fluid flow in porous media, in particular analytical descriptions that practitioners may use to rapidly estimate spreading and/or leakage rates for geometries typical of many underground environments. Analytical descriptions provide simple formulae for important physical processes such as fluid spreading during or after a fluid injection process. Such results allow the inclusion of important physical parameters such as the fluid density and viscosity, the porosity and permeability of the porous medium (which help to characterize the resistance of the medium to flow), and leakage paths for the fluid into the surrounding matrix. Also, laboratory experiments have been performed to test the basic premises of the different models and to check the analytical predictions for spreading and leakage rates. The laboratory studies also provide a convenient platform for visualizing the kinds of dynamics envisioned as relevant for subsurface flow. The focus on confinement effects for various flow regimes may be relevant for the transport of fluids (e.g., CO₂, H₂O) in pipelines.

The results of this research provide analytical formulae for easy modeling of flow in underground reservoirs. These results can readily inform policy and regulatory frameworks by providing first-order estimates for the leakage rate and the horizontal span of a CO₂ sequestration project. The Stone group is planning to use this approach of analytical and laboratory-scale models of geophysical phenomena to study ice flows in narrow straits. This problem was introduced to the group by
scientists at the Geophysical Fluid Dynamics Laboratory (GFDL) who currently utilize complex numerical simulations to model climate change and the dynamics of ice flow relevant to the Arctic. It is anticipated this alternative approach to the problem will lead to a synergistic collaboration with the GFDL.

Figure 2.2. Flow regimes for fluid injection into a confined porous medium. Five distinct dynamical regimes are identified, depending on two dimensionless groups: \( M \), the viscosity ratio of the displaced fluid to the injected fluid, and \( T \), the dimensionless time. The regime boundaries are indicated by symbols (numerical estimates) and dashed curves (analytical estimates). Typical shapes of the fluid-fluid interface are also shown in each of the individual regimes.

Reference

Measuring and Optimizing Battery Performance

Principal Investigator: Craig Arnold

At a Glance

Correlation between a battery’s electrochemical properties and the mechanical stress of its internal materials provides measurements of its state of charge and state of health, which inform the optimization of battery performance for grid systems and portable applications.

Research Highlight

Energy storage is playing an increasingly important role throughout the energy infrastructure, from powering hybrid and electric vehicles to offsetting the inherent intermittency of renewable energy generation. Electrochemical batteries are a particularly attractive option for energy storage and come in many form factor shapes and sizes. However, two key challenges affecting the adoption of batteries in grid level and portable applications are

- the ability to obtain an accurate measure of the amount of charge stored at any given time (state of charge); and
- the ability to obtain an accurate measure of how much longer the battery can last before it needs to be replaced (state of health).

The Arnold group is studying novel means to measure the state of charge and state of health, in order to manage optimal battery performance under demanding real-time applications. The focus of this research is on understanding the relationship and coupling between mechanical and electrochemical properties.

Figure 2.3.1 demonstrates how the mechanical stress (force per unit area) in a lithium-ion battery varies as a function of the amount of charge stored in it\(^1\). As the battery charges, lithium ions in the battery move into the negative electrode, leading to internal expansion and an increase in the measured mechanical stress inside the battery. The stress increases approximately linearly with respect to the amount of charge stored in the battery cell. As the battery discharges, the internal stress decreases as lithium is now removed from the negative electrode. Thus, the measured stress of the battery directly correlates with the amount of charge stored in the cell, i.e. the state of charge.

Figure 2.3.2 demonstrates the peak mechanical stress in a battery as a function of the state of health\(^2\). State of health is a ratio of the amount of charge delivered by the battery for a given cycle to the amount of charge delivered when the battery is new. Thus, the state of health represents the number of charging and discharging cycles: 100% state of health represents a fresh battery and typically 85% would represent a battery needing replacement. Over time, the maximum stress in the battery cell gradually increases due to irreversible transitions in the battery materials. Correlating this stress to the amount of charge stored in the cell gives a simple linear dependence and an accurate measure of the amount of lifetime left in a usable cell, to directly predict when batteries should be replaced before catastrophic failure.
As batteries charge and discharge, changes in the shape and mechanical properties of their materials occur. Over time, permanent changes in these materials lead to a degradation in *electrochemical performance*—the ability to store charge and to transfer charge quickly with little dissipation—resulting in an end of usable battery life. The Arnold group has found such electrochemical degradation to manifest as changes in battery mechanical properties, which can be easily measured without disassembling the cell. Thus, a simple mechanical measurement enables inference of the electrochemical state—the state of charge and state of health—of a battery, making it possible to manage charging and discharging for the optimization of energy storage performance either at the grid level or in portable storage applications. Engineers and system designers can easily incorporate the locally linear relationship between mechanical and electrochemical properties, as real-time information for the control and optimization of battery systems.

The Arnold Group continues to investigate the underlying physical principles for measuring electrochemical performance, with plans to develop a commercial device based on these principles that permits use of the basic technology in real-time within an industrial setting.

![Figure 2.3.1. Oscillations in the measured stress of a battery as a function of the charging and discharging that occurs over many cycles.](image)
Figure 2.3.2. Battery state of health (SOH) compared to measured peak stress in the cell. 100% SOH represents a fresh battery and typically 85% would represent a battery needing replacement.

References


Molecular Modeling of CO₂ Capture and Storage

Principal Investigators: Athanassios Panagiotopoulos, Pablo Debenedetti, and Jeroen Tromp

At a Glance

Molecular-based computational tools for predicting fundamental physical and chemical characteristics of H₂O+CO₂ and H₂O-NaCl binary systems are being developed to help interpret the rational design of CO₂ separation processes and long-term CO₂ storage in geological formations.

Research Highlight

Over the past year, the research collaboration between Panagiotopoulos and Debenedetti (CBE), and Tromp (Geosciences) has focused on obtaining the phase behavior and transport properties for the H₂O+CO₂ and H₂O-NaCl binary systems. For the engineering design of carbon dioxide (CO₂) sequestration processes, accurate predictions of properties for these mixtures at conditions found in geological reservoirs are required. Experimental data are often not available over the complete range of conditions of interest; predictive, molecular-based models coupled with computer simulations can reliably interpolate and (it is hypothesized) extrapolate from limited experimental information. These simulations can also help discriminate among conflicting sets of experimental data.

The research group found that phase partitioning and interfacial properties of these systems can be predicted with moderate accuracy using existing atomistic models. However, it appears that future modeling needs will require development of improved force fields (intermolecular potential models). Several force field combinations were examined for the H₂O+NaCl system and used to calculate the vapor pressure, liquid density, viscosity and vapor-liquid interfacial tension as a function of salt content. The group has also optimized the intermolecular potential parameters for the H₂O+CO₂ system¹ in an attempt to reconcile conflicting sets of experimental measurements²⁻³, as shown in Figure 2.4.

The long-term goals of this work include the development of reliable, molecular-based models for the thermophysical and adsorption properties of components and systems involved in geological carbon sequestration. The group plans to focus efforts on the development and testing of polarizable force fields⁴⁻⁵, which can accurately capture both aqueous and non-aqueous solution environments. These have not been as well developed as non-polarizable force fields because of their higher computational cost.
Figure 2.4. On left, a schematic representation of a two-phase system with a CO₂-rich top phase and a H₂O-rich bottom phase; on right, the composition of the coexisting phases predicted from simulations with different models (points) and sets of experimental data (lines). There is significant disagreement among experimental measurements for the top (CO₂-rich) phase.

References


Negative-Emission Biofuels

Principal Investigators: Eric Larson, Robert Williams, and Thomas Kreutz

At a Glance

Analysis of smaller scale systems for the manufacture of low- or negative-carbon synthetic fuels from biomass and from biomass + natural gas feedstocks reveals that, in the presence of a strong carbon mitigation policy, such systems might be competitive at crude oil prices of less than $100 per barrel and would offer the opportunity for fossil fuel providers to exploit more of their fossil fuel reserves under a carbon budget constraint.

Research Highlight

The Energy Systems Analysis group, led by Eric Larson, Robert Williams, and Thomas Kreutz, is investigating the prospective performance and economics of gasification-based systems for producing electricity and synthetic fuels from an input feedstock that is biomass or a combination of biomass and natural gas, with most carbon dioxide (CO₂) emissions captured and stored (CCS systems). The group has designed systems that consume no more than 1 million dry tonnes of biomass per year, a logistical maximum that may be truck-delivered in the US to a single site. Two systems designed produce 3,500 and 7,000 barrels per day of Fischer-Tropsch (FT) synfuels, respectively, and are small relative to “gas-to-liquid” plants, such as the Pearl project in Qatar producing 140,000 barrels per day.

There are four principal arguments for investigating smaller systems:

- in contrast to the high costs for large, advanced fossil-only projects (e.g., Southern Company’s Kemper County $6.2 B integrated gasification combined cycle plant with CCS) the financial risk for investing in moderate output energy systems is lower;

- exhausted shale gas wells may offer inexpensive storage for small volumes of CO₂ (280 to 720 thousand tonnes per year for the systems investigated here);

- at small scales, biomass gasifiers operated at atmospheric pressure can be used, which greatly facilitates feeding biomass into the gasifier; and

- improved synthesis economics with recent commercial development of advanced, factory-producible reactors for catalytic synthesis of fuels in modules with capacities of a few hundred barrels per day (see Figure 2.5.1). This is far smaller than the 20,000 barrels per day capacity of conventional reactor modules used at the Pearl project.

This research examines a biomass-only “Bio/CCS+” and a hybrid natural gas “BioNG/CCS” system, each consuming about ⅔ of the maximum biomass. The hybrid system’s feedstock is about half biomass and half natural gas (on an energy basis). The outputs are synthetic FT fuels and CO₂, with a small net electricity co-product (7% to 15% of energy products). Removal of CO₂ from synthesis gas is already required for fuels synthesis, so there is very little incremental cost for capturing this CO₂ (the expense is mainly for CO₂ compression).
In collaboration with Lynn Loo (design of the plant) and Michael Celia (CO₂ storage in shale gas wells), the group has explored systems that may be located over the Marcellus shale formation, a region where biomass, cheap shale gas, and pre-drilled CO₂ storage sites exist. The Celia group has estimated prospective rates at which CO₂ can be injected into depleted shale gas wells in the Marcellus formation, and these are well-matched to the CO₂ capture rates for the two systems.

The lifecycle greenhouse gas (GHG) emissions (in metric tonnes of equivalent CO₂eq per unit of liquid fuel energy, denoted as t CO₂eq), including contributions from the plant and from fuel combustion in a vehicle, are significantly lower than from equivalent petroleum-derived fuels: if petroleum-fuel emissions are taken, for reference, to be +1, emissions for BioNG/CCS are +0.42 and for BioCCS+ are -0.82. In the BioNG/CCS case, CO₂ storage accounts for 15% of the carbon in the feedstocks, and 36% is vented at the plant. In the Bio/CCS+ case, 59% of input biomass carbon is stored underground as CO₂, and only 4% is vented.

Figure 2.5.2 shows bands of prices of crude oil that would make each of these options competitive with petroleum-derived fuels, at various GHG emissions prices. The tops of the bands represent first-of-a-kind (FOAK) plants with capital costs assumed to be twice those developed in this conceptual estimating study. Experience might lead to cost reductions (“learning by doing”) equivalent to fractions of these bands. The calculations assume a well-head gas price of $3 per million BTU and a biomass cost of $5 per million BTU, with CO₂ stored in nearby spent shale gas wells. With FOAK capital costs and with zero GHG emissions price, fuels produced via a BioNG/CCS built in the near term would be competitive with petroleum-derived fuels when the oil price is $120 per barrel while Bio/CCS+ requires a crude oil price 70% higher. The BioNG/CCS is more competitive than Bio/CCS+ due primarily to lower feedstock costs and secondarily to scale-economy benefits and process efficiency improvements. A price on GHG emissions makes both systems more competitive and affects the Bio/CCS+ system the most, i.e., the breakeven oil price for Bio/CCS+ falls rapidly with increasing GHG emission price. The two cost lines for FOAK systems cross at $65 per barrel, when the GHG emissions price is about $130/t CO₂eq.

According to the Intergovernmental Panel on Climate Change (IPCC), if the global community were on an energy track consistent with limiting global warming to 2°C under market-based climate-change-mitigation policies, the GHG emissions price would rise (in 2012 $) from almost $60/t CO₂ in 2020 to $100/t in 2032 and to more than $220/t in 2050. This work suggests that for such an emissions price trajectory BioNG/CCS might be economically deployed early in the next decade, and that Bio/CCS+ systems could become attractive options soon thereafter. The IPCC has also shown that if likely global warming is to be limited to no more than 2°C, biomass energy with carbon capture and storage (BECCS) technologies that provide negative emissions will probably be needed to stay within the allowable remaining cumulative CO₂ emissions (about 1 trillion tonnes): BECCS systems with negative emissions could provide an opportunity for carbon credits that would enable a fossil fuel provider to use more of its fossil fuel reserves under such a carbon budget constraint.

The Energy Systems Analysis Group will expand its investigation of alternative processes for production of low and negative emissions liquid transportation fuels, including pyrolytic and biochemical systems, as well as additional gasification-based pathways with and without fossil fuel coprocessing.
Figure 2.5.1. Module for FT synthesis at small scale (about 175 barrels per day liquids production).

Figure 2.5.2. Prospective economics of negative emissions biofuels (Bio/CCS+) improve more rapidly with increasingly stringent carbon policy than those for hybrid biomass/natural gas systems (BioNG/CCS). Inset table results are taken from Ref.1.
References


Technology Publications


Williams, R.H., 2014. Capture technology cost buydown in CO$_2$ EOR market applications under a state or regional Alternative Energy Portfolio Standard. Poster presented at GHGT-12 (Austin, TX), 6-9 October, 2014.


CMI Integration and Outreach introduces new conceptual frameworks that are useful for climate change policy. One effort seeks to make the emerging statistical analyses of extreme events more accessible. A second effort focuses on improving the risk-assessment framework for the current scientific understanding of sea level rise. A third explores the value for climate policy analysis of adding a new component to traditional carbon accounting that tracks “committed emissions”—the future emissions that are likely to result when a power plant or vehicle or addition to infrastructure is placed into service.

Research Highlights – At a Glance

Stephen Pacala: Novel analyses of extreme weather data have revealed unanticipated statistical patterns in heat exchange between the oceans and atmosphere and have identified a trend of increasing frequency for extreme weather events in modern times.

Michael Oppenheimer: Probabilistic estimates of future sea level rise were developed with the help of detailed information about the Antarctic ice sheet. These estimates have been developed in collaboration with those engaged in coastal risk management against storm-driven flooding in several coastal cities around the world.

Alexander Glaser and M.V. Ramana: The technical characteristics of leading small nuclear reactor designs do not allow them to simultaneously address the major challenges confronting the expansion of nuclear power.

Robert Socolow: Fossil fuels are so abundant that, for any plausible carbon budget target, even a weak one, attractive fossil fuel will be left in the ground. Two new schemes—commitment accounting and carbon budgets—quantify constraints on this abundance for multi-decadal planetary fossil fuel use within two- and three-degree climate change targets.
Anthropogenic Signals in Extreme Climate Events

Principal Investigator: Stephen Pacala

At a Glance

Novel analyses of extreme weather data have revealed unanticipated statistical patterns in heat exchange between the oceans and atmosphere and have identified a trend of increasing frequency for extreme weather events in modern times.

Research Highlight

The Climate Variability Project for the last two years has been investigating the effects of climate change on climate variability in general and extreme weather in particular. The Pacala group has focused on extremes of heat and precipitation, on drought, and on the repeated instances of warming hiatus that have occurred since the late 19th century. In the past year, postdoctoral associate Monica Barcilowska has produced a new analysis of the periods of warming hiatus in data. The analysis identifies a periodic statistical pattern with a 66-year period of variation in heat exchange between all the ocean basins and the atmosphere. Barcilowska is also producing new global analyses of extreme precipitation, drought and heat waves. Postdoctoral associate Dan Li is focusing on urban environments and has built a new urban tile into climate models to analyze historical data and perform computational experiments to model the impact of large cities on local extreme weather, including extreme heat.

The research is motivated by the remarkable and counter-intuitive historical record of very large increases in the frequency of extreme weather since the 1960’s and 70’s. The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) shows that nighttime high temperatures that occurred only once in 20 years during the 1970’s, occurred on average once in 8 years by the 1990’s. For the last three years, the Bulletin of the American Meteorological Society (BAMS) has published an annual special issue with papers attempting to estimate how the odds of an extreme weather event have changed because of anthropogenic greenhouse gases and aerosols. Many of these papers calculate increases of 10- to 100-fold or more. How can the extremes change so much when the mean climate has changed very little? Figure 3.1 suggests one way to understand this phenomenon, expressing the probability density of a weather event as a plot of severity (e.g., maximum temperature in a heat wave or maximum 24-hour precipitation) versus return time (the reciprocal of the annual probability of occurrence). These plots are almost invariably asymptotic at high return times, because physical laws prevent arbitrarily high levels of severity. A small increase in the mean severity shifts the climate from the blue to the red curve. There are many examples like this in the literature produced by climate models for extremes of temperature, precipitation and drought including several in each BAMS special issue. Very large changes in return time can occur for the most extreme events because the return time-severity plots are flat at levels of high severity.

The consequences of such changes in variability are significant. Extreme weather creates direct risks for many of the world’s capital assets, from ports and floating platforms lashed by storms to withered crops. Abrupt changes in public opinion and carbon policy might be triggered by damaging weather, whether or not the triggering event is caused by climate change due to anthropogenic greenhouse gases.
Figure 3.1. Schematic showing how a small change in the climate can result in a large decrease in the return time (measured in number of years between events) of a severe extreme event (in this example, measured as the maximum annual temperature in degrees Fahrenheit). The blue circle shows an event in the 1970’s with a return time of ~875 years and a severity of 130 °F. If the average severity changes a few degrees from the 1970’s to the 2000’s (shift from blue to red curve) then the return time of a 130 °F event decreases to ~350 years (the red circle) because the curve is flat at high severities. (Figure courtesy of the Pacala group.)
Estimates of Local Sea Level Rise and Flood Probability for a Warmer World

Principal Investigator: Michael Oppenheimer

At a Glance

Probabilistic estimates of future sea level rise were developed with the help of detailed information about the Antarctic ice sheet. These estimates have been developed in collaboration with those engaged in coastal risk management against storm-driven flooding in several coastal cities around the world.

Research Highlight

The major uncertainty driving coastal risk management is the frequency of so-called “fat tail” probabilistic climate events, uncommon at the current time and in the past. However, sea level rise is leading to a gradual increase of this probability. According to some models, the current 100-year flood level could return with a yearly frequency by the year 2100. The Oppenheimer group’s studies show the uncertainty in the probability of such events is controlled by the future behavior of the Greenland and West Antarctic ice sheets, as they respond to global warming. At present, no reliable continental-scale process-based model for this behavior exists. This research program is developing alternative ways to project ice sheet behavior and sea level rise probabilities, in the absence of such a model. The program used methods combining multiple, independent lines of evidence to infer probabilities, including past measurements of ice sheet mass loss and regional-scale models of parts of the ice sheets, especially in Antarctica1,2.

A representative result is seen in Figure 3.2. Panel (a) shows the projected sea level in 2100, in meters, under a commonly-referenced business-as-usual scenario for emissions. In northern Europe, values are notably lower than the Global Sea Level mean (GSL=0.79 m). The low values are due to the retreat of the Greenland ice sheet which reduces the gravitational pull of northern water toward Greenland and also produces crustal rebound—both effects offsetting some of the effect of ice loss. Panel (b) shows the uncertainty range for the estimate of sea level rise, also in meters. Estimates of the range are anomalously large in the same northern Europe region, reflecting uncertainties in the estimates of the ice sheet loss rate and in the resulting gravitational and crustal effects.

The program operates in collaboration with efforts in coastal cities around the world to plan risk management against higher sea levels. Oppenheimer is a member of the New York Panel on Climate Change, advising the New York City Mayor’s Office on how to build resilience in response to the increasing risk of climate change. This advisory role has resulted in a direct connection between the findings of this program and policy implementation. Other researchers at Princeton, such as Ning Lin of Civil and Environmental Engineering (also a member of the New York City Panel), have collaborated to implement the findings of this project for specific risk estimation methods that take into account flood damages, and the methods are now used by the city’s risk managers and planners. Interaction with New York City civic institutions reveals that climate risk management is only beginning to emerge as a continuous policy activity; planning and implementation of coastal reliance still lags far behind.
The next stage for this program will explore two different issues, critical to improving the utility of predictive modeling. (1) Other uncertainties in the basic calculation of flood probabilities will be explored: Sea level and storm intensity are not independent, yet current probabilistic methods treat them as such. The program will estimate the covariance of sea level and storm intensity, to refine flood probability estimates. Preliminary modeling suggests this effect is important. (2) Other lines of evidence will be included by a formalized methodology to produce a consistent approach to sea level estimation. In particular, an “expert elicitation” will be conducted.

Figure 3.2. (a) Median projection and (b) width of likely range of local-sea level rise (in meters) for the year 2100 under the IPCC’s high-emissions scenario for representative concentration pathway RCP 8.5."
References


Re-Engineering the Nuclear Future

Principal Investigators: Alexander Glaser and M.V. Ramana

At a Glance

The technical characteristics of leading small nuclear reactor designs do not allow them to simultaneously address the major challenges confronting the expansion of nuclear power.

Research Highlight

Nuclear power continues to be an important component for the planned energy infrastructure of several countries; one motivation for this choice is its potential for climate mitigation because of the low level of carbon emissions as compared to fossil fuels. During the past year, the Re-engineering the Nuclear Future project led by Alexander Glaser and M.V. Ramana has assessed the technology of various small modular reactors (SMRs)—with power outputs of 10 to 300 megawatts—currently proposed as a means to facilitate the expansion of nuclear power. A particular focus of this assessment is evaluating the risk of nuclear weapons proliferation that might come with the adoption of these different reactor designs.

Along with Zia Mian, Ramana examined the potential for SMRs that are being developed to overcome various specific challenges confronting nuclear power, in particular (1) economic competitiveness, (2) potential for catastrophic accidents, (3) production of radioactive waste, and (4) linkage to nuclear weapon proliferation. Mian and Ramana analyzed the technical characteristics of different kinds of SMRs and argued that all four of the problems cannot be simultaneously solved. The leading SMR designs under development involve choices and trade-offs between desired features. For example, one way that nuclear engineers have tried to reduce the quantity of radioactive waste generated has been to design reactors that operate with fast neutrons (i.e., neutrons that haven’t been slowed down by a moderator). This feature results in the production of about twice as much plutonium per unit of electricity produced and at nearly six times the concentration (475% more) in the spent fuel, compared to standard light water reactors. This implies a higher risk of proliferation because a much smaller quantity of spent fuel is needed to separate enough plutonium to make one or more nuclear weapons. Historically, the production of plutonium through reprocessing of spent fuel has been the proliferation pathway of greatest concern. Although the initial build up of plutonium stockpiles globally was to manufacture weapons, since the end of the Cold War, the stockpile of plutonium from the reprocessing of civilian spent fuel has been fast growing (see Figure 3.3).

Glaser also supervised a student study of molten salt reactors, SMRs that use nuclear fuel dissolved in a liquid carrier salt. Molten fuel is continuously cycled in and out of such a reactor; outside the reactor, unwanted fission products are removed and makeup fuel is added. This form of continuous fuel processing prevents build-up of various isotopes within the reactor that would otherwise slow down the fission process and impede a sustained chain reaction. Not all isotopes need to be removed, however, and different MSR designs do involve different levels of chemical processing. This continuous processing of fuel creates a proliferation risk, facilitating the extraction of weapons-usable materials (e.g. plutonium) from the fuel. Postdoctoral associate Ali Ahmad and Glaser’s computer simulations showed these reactors offer significant advantages in uranium requirement...
(when compared to conventional light-water reactors), and specific design choices could increase or decrease associated proliferation risks.

Over the last few years, there has been much hope invested in small modular reactors helping with a revival of nuclear reactor construction in countries with many existing nuclear plants as well as with allowing smaller countries with no nuclear plants currently to set up their first reactors. Several governments around the world are supporting the development and deployment of SMRs in a variety of ways. But if the construction of SMRs is to not lead to increased nuclear weapon proliferation, proliferation resistance must be adopted as an explicit criterion at the outset.

Glaser and Ramana propose to examine in detail some of the characteristics of SMRs that have been held out as distinctive, including the possibility of constructing them underground and their potential for relatively rapid changes in power output as a way to meet fluctuating electric demand, and study the impact of these deployment on the economic competitiveness of SMRs.

Figure 3.3. Evolution of the global plutonium stockpile from 1945 to the present. Figures for plutonium in mass units (kg) are converted into weapon equivalents by assuming that 3 kg of plutonium are used to make a weapon in case of plutonium explicitly produced for weapon purposes and that 5 kg of plutonium are needed to make a weapon in case of plutonium separated from spent fuel generated by civilian nuclear power reactors. Although the nuclear weapon stockpile has declined since the end of the Cold War, the plutonium content of weapons that have been dismantled is still part of the stockpile since there is so far no widely accepted method for disposing the plutonium. (Graph courtesy of the Glaser group.)
References


Commitment Accounting, Committed Emissions, and Carbon Budgets

Principal Investigator: Robert Socolow

At a Glance

Fossil fuels are so abundant that, for any plausible carbon budget target, even a weak one, attractive fossil fuel will be left in the ground. Two new schemes—commitment accounting and carbon budgets—quantify constraints on this abundance for multi-decadal planetary fossil fuel use within two- and three-degree climate change targets.

Research Highlight

Recently1, Robert Socolow and Steve Davis (University of California at Irvine) introduced “commitment accounting” as a scheme for estimating total future greenhouse gas emissions (“committed emissions”) for durable capital investments. Their paper was restricted to power plants, but commitment accounting can be extended to vehicles, roads and infrastructure, refineries, oil and gas fields and oil and gas provinces. The “carbon budget” is a related concept: introduced in the recently released Fifth Assessment Report of the Intergovernmental Panel on Climate Change, this budget is the total amount of carbon dioxide (CO₂) that can be emitted into the global atmosphere for a given climate change target. Together, commitment accounting and carbon budgets address the long residence time of CO₂ in the atmosphere.

Key Findings

At present, corporations and governments hardly ever estimate and report the total amount of CO₂ that will be emitted by newly constructed coal or natural gas power plants during their period of operation. These institutions report only CO₂ emissions year by year. Commitment accounting provides a second performance metric that highlights future emissions, once the number of years of operation is assumed. Commitment accounting updates its estimate of total remaining emissions for a plant throughout its lifetime, taking into account plans for early retirement, plant-life extension, retrofit, etc.

Figure 3.4.1 shows the committed emissions from global power plants, as of each of the years 1950 to 2012. The emissions are disaggregated by world region (panel a) and by fuel (panel b). It is assumed that power plants, irrespective of when they were built and what fuel they burn, will run for 40 years. Moreover, it is assumed that any plant operating in that year that is older than 40 years will be shut down immediately; the estimate of committed emissions increases very little when this assumption is relaxed. The two panels of Figure 3.4.1 show that total global committed CO₂ emissions have risen steadily throughout this period—not heading downward even once, year to year—and are now approximately 300 billion tons. In addition, panel (a) shows that committed emissions are now dominated by newly industrializing regions. Panel (b) emphasizes the world’s continued reliance on coal power despite the rapidly growing share of natural-gas-fired power plants (the share of committed emissions for gas plants rose to 27% in 2012, from 15% in 1980). Not shown here, coal remains dominant everywhere in the developing world except for the Middle East, where natural gas is used for new power. These results reveal that a high-carbon future is being locked in by the world’s
capital investment in power plants and fossil-fuel-based infrastructure, during the same period when societal pressures are mounting to limit the world’s commitments to future global emissions.

*Implications for Targets and Policy*

As the world takes climate change more seriously, the long-term implications of the production and use of fossil fuels will undergo increasing scrutiny. A disciplined discussion of multi-decadal issues is emerging.

According to the most recent Intergovernmental Panel on Climate Change (IPCC) Synthesis Report, about 1700 billion tons of CO$_2$ have been produced through combustion of fossil fuels in the industrial age (1870-2011), and almost one degree Celsius of warming of the earth’s surface has resulted. Much discussion of climate change policy today focuses on a target of no more than two degrees Celsius of warming of the planet’s surface, relative to pre-industrial times. The Synthesis Report finds that when another 1300 billion tons of CO$_2$ have been emitted, the planet’s temperature will reach this ceiling. At today’s rate of fossil fuel CO$_2$ emissions, 35 billion tons of CO$_2$ per year, the budget for the two-degree target would be fully spent approximately in 2050. The commitment to 300 billion tons of future CO$_2$ emissions from existing power plants uses up about a quarter of this budget. The budget is less strict if Carbon dioxide Capture and Storage (CCS) becomes an important climate strategy: CCS reduces the committed emissions associated with investments in power plants and industrial facilities, thereby loosening the constraints imposed by carbon budgets.

The new IPCC report also provides results for a three-degree target, even though this target is rarely discussed by policy makers. The three-degree carbon budget is larger by an additional 1500 billion tons of CO$_2$, corresponding to another 40 years of emissions at today’s rate and a fully spent budget around 2090. To the extent that the emissions rate continues to climb (it is now 50% greater than fifteen years ago), a fossil fuel era consistent with a three-degree target would be closed off even sooner.

To what can be compared the 1300 and 2800 billion tons of CO$_2$ emissions that are the IPCC’s central estimates for the two-degree and three-degree targets, respectively? 1000 billion tons of CO$_2$ would be produced from the combustion of about 2 trillion barrels of oil, or 20,000 trillion cubic feet of gas, or 300 billion tons of coal. Using these equivalencies, estimates of the resource base by Rogner (including “additional” resources) can be restated in units of billions of tons of CO$_2$ produced via burning: oil at 8000, gas excluding clathrates at 3000, clathrates at 40,000, and coal at 20,000. Thus, Rogner’s findings reveal the carbon in the world’s buried hydrocarbons today greatly exceeds the carbon that would bring three degrees Celsius of warming. For another comparison, see Figure 3.4.2, drawn by Ian Vann, which shows one view of the future of oil consumption, with one trillion barrels already produced and four trillion barrels (2000 billion tons of CO$_2$ emissions) of production ahead; by itself (i.e., neglecting gas and coal), these emissions will be nearly sufficient to produce three degrees of warming.

The carbon budget concept is going to lead to new conversations about inexorable choices:

- How should fossil fuel production be spread over the next decades?
• How should fossil fuel production be spread over the countries of the world?

• Should any uses be favored over others?

• Should natural gas be extracted in preference to coal, because nearly twice as much energy can be delivered from natural gas when it is burned, for the same quantity of CO₂ emissions?

• How large could be the role of CCS, including CCS in combination with Enhanced Oil Recovery (EOR)?

Future Plans

Estimation of committed emissions for infrastructure and upstream fossil fuel activity will be quantified and introduced into the emerging discussion of carbon budgets.

References


2 IPCC Climate Change 2014, Synthesis Report. The relevant table is on p. 68.


Figure 3.4.1. Remaining cumulative emissions for the world’s power plants, as of each year from 1950 through 2013. Panels (a) and (b) are disaggregated by regions of the world and by fuel, respectively.

Figure 3.4.2. Schematic scenario for future production of crude oil. 1 T is one trillion barrels. Alternate scenarios are obtained by adding or removing 1T rectangles. Burning 1 T of crude oil produces approximately 500 billion tons of CO₂.
Enhanced Integration and Outreach to Provide Sound Information to Foster Effective Public Policy Discussion

At a Glance

Several new communications and outreach initiatives are being conducted within and alongside CMI, designed to provide various audiences with information about the climate problem and potential solutions in ways that enhance participation.

Outreach Highlight

The outreach component of the Integration and Outreach Group has three targets: our sponsors at BP; the Princeton University community; and the larger world of government, business, and civil society (including the major environmental non-governmental organizations).

Outreach to CMI sponsors takes the form of tailored summaries of CMI research and inputs to BP publications, designed to stimulate and augment BP’s engagement with climate change issues. In 2014, emphasis was placed on communicating insight into climate variability, in an ongoing project led by Stephen Pacala that draws heavily on the expertise of Princeton’s neighbor, the Geophysical Fluid Dynamics Laboratory, one of the two major global climate modeling centers in the U.S.

Outreach at Princeton aims to broaden the faculty’s involvement with climate change. One example is the newly created Climate Futures Initiative, co-led by Melissa Lane (Professor of Politics), Marc Fleurbaey (Professor in Economics and Humanistic Studies, Professor of Public Affairs), and Robert Socolow. The initiative focuses on “climate and ethics.” It evaluates and contrasts normative and positive concepts and methodologies now being used in analyses of the future, especially as that future is affected by climate change. The project is an outgrowth of a three-year (2011-2014) project, Communicating Uncertainty: Science, Institutions, and Ethics in the Politics of Global Climate Change, sponsored by the Princeton Institute for international and Regional Studies.

Outreach to the wider world is achieved through the participation of CMI researchers in numerous venues. Michael Oppenheimer played major roles in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). He served as a coordinating lead author of Chapter 19 of the Working Group II report, a member of the writing team for the Summary for Policy Makers of that report, and a member of the core writing team of the Synthesis Report, forming the ultimate piece of the IPCC Fifth Assessment Report. Pacala chairs the board of Climate Central, a non-profit organization in Princeton dedicated to providing the public and policy-makers with clear and objective information on climate change trends and impacts. He is also a board member of the Environmental Defense Fund. Socolow is on the advisory board of the Lawrence Berkeley National Laboratory. Socolow also leads the “distillate project” of Princeton’s Andlinger Center of Energy and the Environment. Aimed at interested non-experts, the project prepares introductions to specific low-carbon technologies. The first distillate, completed in 2014, addresses grid-scale electricity storage and intermittent renewable energy.
Integration and Outreach

Publications


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